Barriers to Real-Time Control of Stormwater Systems

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Abstract: Real-time control of stormwater infrastructure is an emerging technology that can improve stormwater system function. However, this technology has not been adopted widely, nor is it typically addressed within current stormwater regulations. This study addressed these gaps by identifying barriers to the adoption of real-time controls of stormwater and exploring ways in which real-time controls of stormwater can fit within current regulatory frameworks. To identify barriers, a survey was distributed to municipal and consultant stormwater engineers in Wisconsin. The results indicated that cost, operations and maintenance, and failure to qualify for regulatory credits are significant perceived barriers to real-time control of stormwater. Municipal engineers were reluctant to adopt real-time controls and were concerned with regulatory credits for real-time controls. In light of these concerns, a case study was performed to evaluate how a detention pond augmented with a real-time control valve at the outlet performed in terms of common stormwater design standards and regulatory criteria, including peak flow reduction and total suspended solids (TSS) removal. Model results indicated that the controlled pond reduced the magnitude of peak flows. It also improved annual total suspended solids removal from 70% to 96%, thereby exceeding the 80% TSS removal requirement for municipal separate storm sewer systems in many US states. Given the identified barriers and model performance, this study discussed potential paths forward for overcoming barriers in attributing regulatory credits to real-time controls of stormwater. **DOI: 10.1061/JSWBAY.0000961.**

Author keywords: Stormwater; Real-time control; Emerging technologies; Urban runoff; Stormwater regulations; Barriers to technologies.

Introduction

Stormwater management faces significant challenges including aging infrastructure (Grigg 2019), changing precipitation patterns (Mallakpour and Villarini 2017; Reidmiller et al. 2018), evolving regulations (Albright 2012), and growing water quality impairments (USEPA 2019). These challenges require adaptive and resilient management solutions that can address the needs for flood control, climate resiliency, and mitigation of surface water pollution. Existing structural stormwater management solutions, such as traditional gray infrastructure, detention ponds, green infrastructure, and wetlands, commonly are used to manage stormwater systems. However, this built infrastructure often is designed to remain in place through many decades, and may not have the adaptive capacity to adequately address increasing changes in climate, rapid land development, and growing water quality impairments. Therefore, it is important to consider new and innovative approaches to stormwater management that can dynamically manage stormwater runoff.

Real-time control or active control of stormwater infrastructure is a technology that can help to meet many of these challenges. Real-time control of stormwater systems joins sensors, actuators, and weather and model-based runoff forecasts to adaptively manage stormwater runoff. Real-time controls have been used for decades to control flows within combined sewer systems (Trotta 1976), and more recently have been applied in separated stormwater systems to improve runoff management. Model results demonstrated that real-time control systems can improve removal of pollutants such as total suspended solids (TSS) by 29%–44% and improve peak flow reduction by up to 50% in detention ponds (Gaborit et al. 2016, 2013; Muschalla et al. 2014; Sharior et al. 2019). Furthermore, actively controlled detention ponds can achieve similar performance to uncontrolled ponds during low-return-period events with only half the storage volume (Wong and Kerkez 2018). The recent proliferation of research in this area has led to the potential for real-time controls to become part of smart stormwater networks, in which sensors and valves are managed actively to optimize detention and conveyance of stormwater runoff (Kerkez et al. 2016).

However, despite the potential of real-time control of stormwater to improve runoff management, this technology has not been adopted on a broad scale. This could be due to several barriers to implementation, including unfamiliarity with the technology, increased potential for legal liability due to failure, or unclear or unavailable regulatory crediting (Strifling et al. 2019). The most challenging of these may be the regulatory credits issue. Stormwater management is a regulatory-driven field in which cities and developers manage stormwater runoff to remain in compliance with local, state, and federal statutes and regulations (McDonald and Naughton 2019). If there is no incentive from state or municipal stormwater regulations in the form of credits attributed to real-time controls for peak flow or water quality reductions, then adoption of real-time control technologies is highly unlikely. To date, there is

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little evidence that governments have directly addressed real-time controls of stormwater within their stormwater regulations, and methods to provide regulatory credits for reductions in flood peaks or improved water quality remain poorly defined. Furthermore, it is unclear where these barriers persist among different stormwater management stakeholders such as municipalities and engineering consultants. There is a clear need therefore for a better understanding of the barriers to real-time control of stormwater and methods to overcome them through regulatory changes.

This project addressed these gaps by identifying barriers to real-time control of stormwater and exploring ways in which real-time control of stormwater can operate within current regulatory frameworks. Specifically, this paper (1) reports the results of a survey of municipal and consultant stormwater engineers to identify barriers to stormwater real-time controls and explore differences in perceived barriers among these groups, (2) summarizes engineering design criteria and regulations across the US to determine what regulatory criteria real-time controls of stormwater will need to address, and (3) developed a case study model of a detention pond to evaluate the performance of real-time controls in the context of regulatory criteria. In doing so, we identified several practical barriers to adoption of real-time control of stormwater and explore options for overcoming regulatory barriers. Ultimately, this study contributes to the advancement of an emerging technology that can protect human and environmental health through improved flood control and pollution mitigation.

Methodology

Survey of Municipal and Consultant Stormwater Engineers

We surveyed municipal and consultant stormwater engineers to identify perceived barriers to real-time control of stormwater. The survey was developed by the authors with input from regulators at the Wisconsin Department of Natural Resources (WDNR), personnel at the Milwaukee Metropolitan Sewerage District (MMSD), and consultants who implement real-time stormwater controls. The goals of the survey were to evaluate the respondent's familiarity with real-time controls and to identify perceived values and barriers to implementing real-time control of stormwater.

The survey recipient sample included 695 practicing municipal (125) and consultant (570) stormwater engineers in the state of Wisconsin, as provided by an internal database of stormwater engineers from the WDNR. Municipal engineers are defined as those who work at a municipal separate storm sewer system (MS4) and who are required to apply for permits to the WDNR to discharge stormwater as part of the Wisconsin Pollutant Discharge Elimination System (WPDES) regulatory program. Consultant engineers are defined as those who work at a private consulting firm to design stormwater infrastructure. Because of their unique roles in stormwater management, there may be differences in the perspectives of these groups that influence the barriers to stormwater technologies.

The survey consisted of 10 questions that were a mixture of open-ended, closed-ended multiple choice, and Likert-scale questions (Appendix). The survey instrument underwent an informal review by a survey expert at the Marquette Law School Poll to check for bias and effective use of language. After it was finalized, the online survey was sent by email through survey software Qualtrics. The data from this survey were summarized to identify perceived barriers to real-time controls, and ANOVA was applied to evaluate the differences between the response given by municipal and consultant engineers.

Review of MS4 Postconstruction Permit Language and Criteria

To identify how real-time control of stormwater might fit within existing regulatory frameworks and design criteria, we reviewed both state-level and municipal-level engineering design criteria for postconstruction stormwater management. State-level review included (1) National Pollutant Discharge Elimination System (NPDES) guidelines and regulations as written in state regulatory codes, and (2) state-level departmental standards such as those of the state Department of Natural Resources (DNR) or Department of Environmental Quality (DEQ). Municipal review included postconstruction stormwater management guidelines provided at the city or district level. State and municipal engineering design criteria for postconstruction stormwater management were identified through internet searches of governmental websites, and relevant data from these criteria were cataloged in an internal database.

Within the guidelines for postconstruction stormwater management, we searched for quantitative metrics such as mandatory pollutant load reductions, peak flow standards, or infiltration requirements, and recorded this information in a database. These documents typically define the stormwater mitigation requirements for new developments or redevelopments that seek to protect the downstream environment from adverse impacts of runoff; however, this study focused on criteria for new developments because these typically are more stringent than those for redevelopments. They also are easier to compare because they are applied uniformly to all new developments, as opposed to redevelopment criteria that often are scaled based upon increases in impervious area. In some cases, requirements for new development are based upon the size of the development, and in these cases the most stringent regulatory criteria were selected. The database was reviewed to identify the most common guidelines and trends in stormwater criteria, which then were used as a basis to compare the results of a modeled stormwater pond with a traditional passive outlet against the same pond with a real-time control retrofit.

Model of Controlled Detention Pond

We used the USEPA Stormwater Management Model (EPA SWMM) to evaluate the impact of a real-time control placed on a stormwater detention pond outlet within the context of the previously identified regulatory criteria (Rossman 2015). The stormwater pond is located in Milwaukee, Wisconsin and drains an area of approximately 0.2 km^2, of which 91% is impervious. The stormwater pond has a surface area of approximately 5,760 m^2, a permanent pool at a depth of 4.8 m, and a maximum depth of 6 m. The original outlet structure had a 0.6-m opening above the permanent pool level and a riser at the maximum depth, with a 1.2-m-diameter outlet pipe. This structure was modified with a valve placed upstream of the outlet pipe to control all flow through the outlet structure. A pressure transducer and water quality probe were placed at the center of the pond to record water level and turbidity, and periodic water quality samples were collected at this location and tested for TSS. Using these samples, an empirical relationship between TSS and turbidity was developed for the site, and continuous measurements of turbidity were used as a surrogate for TSS.

The model was forced with 30 years of hourly precipitation measured at Mitchell International Airport in Milwaukee, Wisconsin that were obtained from NOAA (2021) SWMM model was modified using a Python software package called PySWMM (McDonnell et al. 2020) that acts as a wrapper around the EPA SWMM computational engine. In PySWMM, control algorithms were developed in Python to simulate a real-time stormwater

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control using an on–off control rule. This controlled the release of the valve based upon a critical threshold height (h_c) of 6 m, which represented the maximum depth of the pond. The valve remained closed if the height of the pond was below h_c. However, if runoff entering the pond caused the water level to exceed h_c., the valve opened to prevent flow from going over the emergency spillway. After the pond level dropped to the permanent pool depth of 4.8 m, the valve closed again. This type of control rule was intended to increase retention time to improve pollutant settling while still minimizing uncontrolled outflow. Details of the data collection, model development and model calibration were given by Sharior et al. (2019).

Ithe present study, four model simulations were carried out: predevelopment, postdevelopment with no pond, postdevelopment with a passive pond, and postdevelopment with real-time control at the pond outlet. The results of the model were evaluated based upon how the performance of the pond met stormwater regulatory criteria as identified in the previous section. This included comparison of peak discharges from the SWMM model with predevelopment conditions (e.g., City of Milwaukee 2018). In addition, we compared the TSS loads in the model to TSS reduction standards (e.g., City of Portland 2016). We also developed peak-duration and load-duration curves under each condition to evaluate how the real-time controls impacted return period flows and sediment loads based on the model output.

Results and Discussion

Barriers to Implementation Survey

The survey was sent to a sample of 695 municipal and consultant stormwater engineers, and resulted in a 6.7% response rate (47 total: 29 consultants, and 18 municipal engineers). The first two survey questions focused on evaluating the types of stormwater challenges and technologies that affected the respondent's communities [Figs. 1(a and b)]. Regarding challenges, 42 of 47 survey respondents reported flooding concerns; 39 of 47 reported water quality degradation issues; and 8 experienced combined sewer overflows. Respondents who selected Other indicated challenges of costs and best management practice upgrades. In terms of technologies, 35 of the 47 respondents reported that green stormwater infrastructure had been implemented within their communities, followed by 20 who reported water quality monitoring and 15 who reported flow monitoring. Six of the 47 respondents indicated that they had real-time controls within their communities, whereas five respondents indicated that they had none of the listed technologies. Those who indicated Other primarily listed traditional dry detention ponds to reduce TSS and for volume control.

Additional questions focused on the respondents' familiarity with and perceptions of real-time controls and their capability and likelihood of implementing real-time control of stormwater. Most respondents had slight or moderate familiarity with real-time controls, but nearly 30% of the respondents indicated that they were not at all familiar with them [Fig. 1(c)]. Half the respondents were not sure if real-time controls were an effective way to manage stormwater, 38% perceived them to be effective, and 11% perceived them to not be effective [Fig. 1(d)]. Similarly, 43% of respondents agreed or strongly agreed that there are advantages to a stormwater real-time control system that would be beneficial to their organizations or communities, and 11% disagreed [Fig. 1(e)]. The two final Likert-scale questions focused on their organizations' capability and likelihood of implementing real-time control, and responses to each question were similar, with nearly 50% respondents selecting neutral [Figs. 1(f and g)]. Only 19% of respondents indicated that their organizations would be likely or extremely likely to consider implementing real-time controls, indicating that barriers to implementation exist.

To identify some of these barriers, respondents were asked about their perceived concerns with real-time controls, and results indicated that costs and operations and maintenance were their largest concerns (Fig. 2). These concerns are practical, because stormwater management budgets often are constrained, and it can be a challenge to allocate resources in a way that is most impactful for stormwater improvements (Allerhand et al. 2012). In addition, operations and maintenance of stormwater infrastructure often accounts for a significant portion of stormwater budgets (McDonald and Naughton 2019). Following costs and operations and maintenance, performance uncertainty and regulatory barriers or credits were the next greatest concerns. Because these systems are a new technology with limited applications in the survey respondents' jurisdictions (13%), respondents may have concerns about how well these systems perform. In addition, it remains unclear how respondents might receive regulatory credit for the systems, either as a consultant meeting local design criteria or as a municipality setting criteria and implementing infrastructure to meet the requirements of the statewide WPDES program.

Because these two groups—municipalities and consultants—have different roles within stormwater management, they may perceive these barriers differently. Therefore, we performed an ANOVA test of the means of the two groups' responses about their perceived concerns with real-time controls. Although none of the responses were statistically significant ($p < 0.05$), the greatest difference between the two groups was for regulatory credits ($p = 0.21$), with more concern from municipal engineers (3.61) than from consultants (3.18). This may be because municipalities are the entities responsible for complying with the National Pollutant Discharge Elimination System Municipal Separate Storm Sewer System regulations set by each state. In Wisconsin, this program requires that municipalities demonstrate a modeled 80% TSS removal within their jurisdictions (Wisconsin 2010). Therefore, municipal engineers may be more concerned with how real-time controls translate to regulatory credits for stormwater infrastructure. Cost was the second greatest difference between the two groups ($p = 0.22$), with more concern among municipal engineers (4.44) than among consultants (4.1). This could be because municipalities fund a significant amount of stormwater infrastructure, and although consultants are also concerned with costs, they ultimately provide a service and do not own stormwater infrastructure.

We performed ANOVA tests of the means of the two groups for additional Likert-scale questions in Fig. 1. Results indicated that municipal engineers were more likely to disagree with several supporting statements regarding real-time controls. For example, municipal engineers indicated that they were less likely to consider implementing stormwater real-time controls ($p = 0.046$) and less likely to agree that there are advantages to a stormwater real-time control system that would be beneficial to their organizations or communities ($p = 0.05$). In this case, municipal engineers may be less likely to implement real-time controls due to their greater concerns with regulatory credits and costs, as identified previously, among other factors. Finally, municipal engineers also were less likely to agree that real-time controls are an effective way to manage stormwater runoff ($p = 0.16$).

In summary, these survey results identified several barriers to the implementation of real-time controls, with cost, maintenance, performance uncertainty, and regulations being the greatest concerns. In addition, the results demonstrated that there are distinct differences in the perspectives between engineering consultants

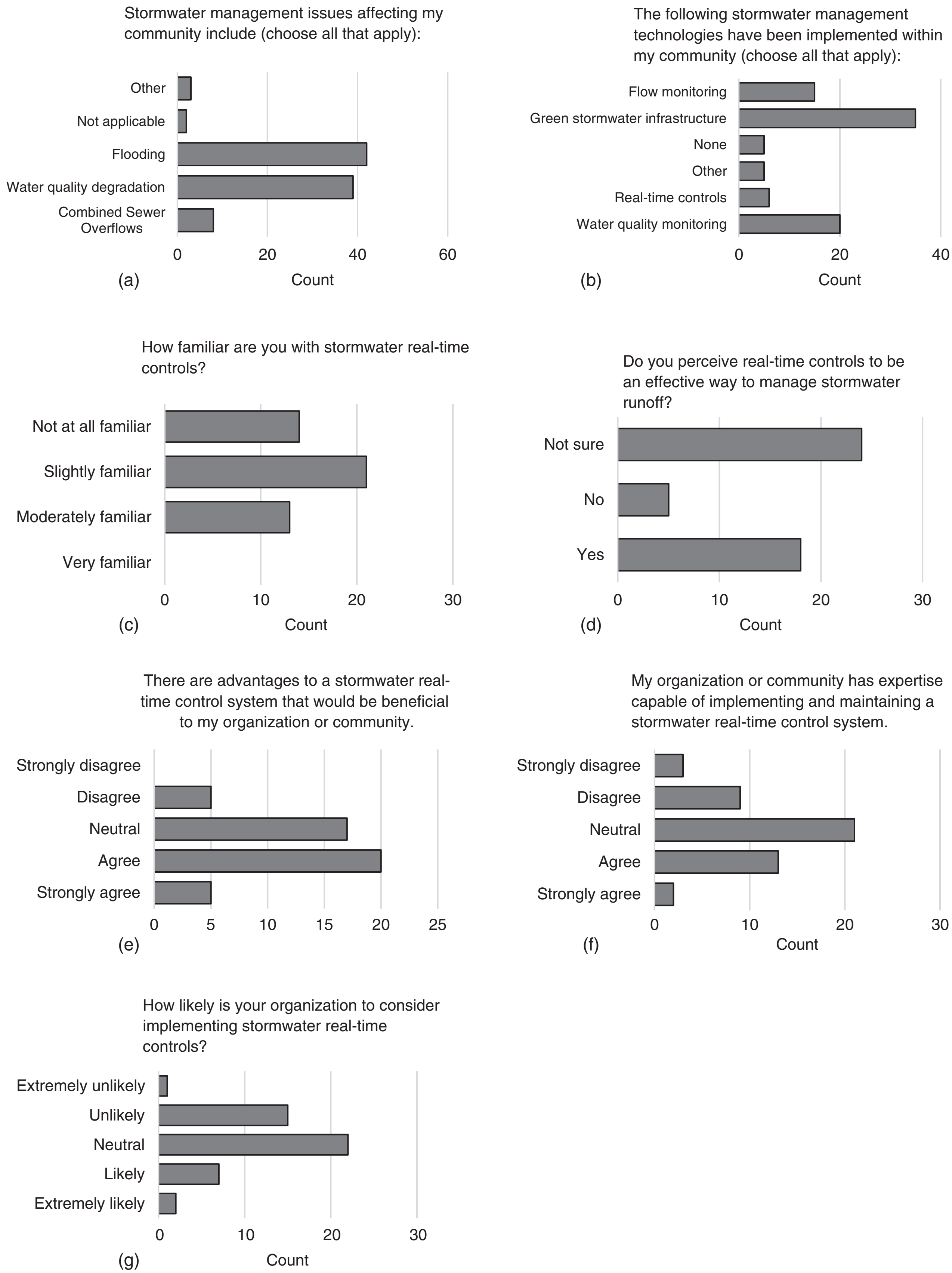

Fig. 1. Survey responses to questions focused on community stormwater issues and technologies: (a) identification of issues; (b) identification of technologies; (c) familiarity with real-time controls; (d) perception of real-time controls; (e) advantages of real-time controls; (f) capability of implementing real-time controls; and (g) likelihood of implementing real-time controls.

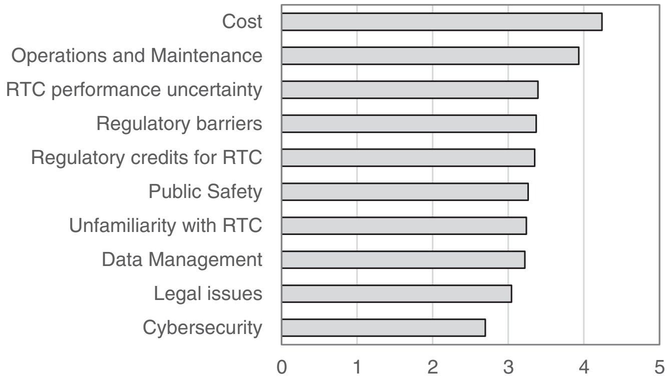

Fig. 2. Average response to the question "In implementing stormwater real-time controls, how concerned are you about the following? (1—not at all concerned; 2—slightly concerned; 3—don't know/not sure; 4—moderately concerned; 5—very concerned)."

and municipal engineers that may influence the barriers to real-time controls. Among the concerns with real-time controls, the greatest disagreement between consultants and municipal engineers involved regulatory credits for real-time controls. This is not surprising, because municipalities are primarily responsible for obtaining permits for their stormwater discharge through the NPDES and total maximum daily load (TMDL) programs. Furthermore, the unavailability of regulatory credits for real-time controls could be a nonstarter for many municipalities that would consider real-time controls as a way to manage stormwater runoff. Therefore, given these findings, we sought to evaluate how real-time controls could fit within a regulatory credit system.

Review of Municipal Engineering Design Criteria

We reviewed stormwater engineering design criteria at the state and municipal level, and selected criteria that fit within the categories of water quality, peak flow, and volume control. In total, stormwater guidelines from 15 municipalities and 12 states were identified, and commonalities were identified among municipal and state criteria for peak flow and water quality controls. Peak flow controls generally require developers to match the postdevelopment peak runoff rate to the predevelopment runoff rate for design storms that range between 1-year and 100-year events; however, within this range, the specific events varied considerably. Water quality guidelines generally require a TSS removal rate between 70% and 85%, and 19 of 27 guidelines required 80% removal. In addition to TSS, five of the guidelines also had requirements for the removal of total phosphorus (TP), and one guideline had requirements for the removal of total nitrogen (TN). Volume controls were less consistent, and generally required sites to capture, detain, infiltrate, or treat a volume of runoff. In some cases, this volume was based upon a design storm or a specified rainfall depth that is computed based upon various factors that may include soil composition, impervious surfaces, or a difference between the pre- and postdevelopment runoff.

In many cases volume and water quality requirements were the same. For example, in Nashville, Tennessee, stormwater guidelines require developers to capture and treat up to 1 in. of the runoff from impervious areas (Nashville and Davidson County 2016). The Nashville standard is both a volume (capture) and water quality (treat) guideline, and is provided in lieu of a direct removal percentage of pollutants. In most of the cases, the TSS pollutant removal percentage must be demonstrated through a modeling approach; however, some regulations assume a percentage removal of pollutants given a total water volume that is captured, infiltrated, and/or treated. For example, in Maryland, it is assumed that 80% TSS and 40% TP removal will be achieved if a specified volume of water is captured and treated, as computed based upon rainfall depth and impervious area (Maryland Department of the Environment 2000).

Although these results demonstrated typical requirements for postdevelopment stormwater management in terms of overall site outcomes, in most cases there also are additional requirements beyond general volume, peak flow, or water quality controls. These include guidelines specific to green infrastructure such as maximum drawdown times, limits on water quality effluent concentrations, or minimum infiltration rates. In other cases, there are erosion criteria that go beyond peak flow reductions for locations where outfalls discharge to streams. Portland, Oregon requires a reduction of the 2-year 24-h peak flow to one-half of the predevelopment conditions in cases in which discharging flows could cause channel erosion (City of Portland 2016). There also are special cases that call for additional requirements, such as in developments located within combined sewer regions or that discharge to impaired urban streams (Maine DEP 2019). Finally, in locations with stormwater fees, there may be tax incentives for developers to go beyond the minimum requirements listed in Table 1 (e.g., City of Portland 2011).

The purpose of identifying these criteria was to determine the flow and water quality goals that real-time controls of stormwater must meet in order to receive regulatory credit. Volume control requirements were the most inconsistent, and included various requirements to infiltrate, capture, or treat with green infrastructure. Therefore, volume criteria are difficult to generalize across states and municipalities. Peak control requirements were fairly consistent across all states, with requirements to match postdevelopment to predevelopment peak flows. In addition, real-time control of the stormwater outlet will have a direct impact on flow rates leaving the pond, and therefore it significantly can influence the ability of the pond to meet peak flow rate requirements. It also will impact the overall detention time, which influences the total settling volume of pollutants and therefore the TSS removal percentage. Therefore, TSS removal requirements largely were consistent across all states and municipalities. The following section therefore evaluated how the real-time control of stormwater impacts peak flow reductions and TSS removal through a case study of a detention pond augmented with a real-time control.

Model Results

Given the focus of many regulations on peak discharge and TSS load, we evaluated the impact of the real-time control on peak flow rates and TSS loads at the case study location. A simulation was run using 30 years of rainfall data, and found that the real-time controlled pond outperformed the passive pond with respect to both peak flow and TSS load reductions.

The real-time control had lower peak discharges than the passive pond across all runoff durations, as illustrated by the duration curves for peak flow [Fig. 3(a)]. These duration curves represent the exceedance probability for different peak flow rates based upon the modeled scenarios of predevelopment, postdevelopment with no pond, postdevelopment with a passive pond, and postdevelopment with a pond augmented with a real-time control. The 5-year peak runoff event decreased from 1.06 m^3/s (37.4 cfs) with the passive pond to 0.12 m^3/s (4.29 cfs) with the real-time control [Fig. 3(a)]. The real-time control peak runoff also matched the predevelopment peak runoff for high flows with low exceedance probabilities, which is important because all regulations identified in Table 1 require the

Table 1. Summary of stormwater regulations in cities and states

Location	Volume controls	Volume rainfall depth	Peak controls	Peak design storm[a]	Water quality removal	Source
Cities						
Anchorage, Alaska	—	—	Match (pre × 1.05) to post	2–100 years	80% TSS	Municipality of Anchorage (2016)
Boise, Idaho	—	—	Match pre to post	2, 5, 10, and 50 years	80% TSS	City of Boise (2018)
Boston, Massachusetts	Infiltration	0.25–1.5 cm (0.1–0.6 in.)[b]	Match pre to post	2 and 10 years	80% TSS	Boston WSC (2013)
Chapel Hill, North Carolina	Match pre to post	2 years 24 h	Match pre to post	1, 2, and 25 years	85% TSS	Chapel Hill PWD (2005)
Charleston, South Carolina	Infiltration	5 years	Match pre to post	2, 10, and 25 years	80% TSS	Charleston County (2007)
Charleston, West Virginia	Capture/infiltrate	2.5 cm (1 in.)	Match pre to post	1, 2, 10, and 25 years	Capture/infiltrate	City of Charleston (2014)
Chicago, Illinois	Capture	1.3 cm (0.5 in.)[c]	Match pre to post	10 and 100 years	—	City of Chicago (2014)
Little Rock, Arkansas	Match pre to post	25 years, 6 h	Match pre to post	25 years, 6 h	—	City of Little Rock (2016)
Milwaukee, Wisconsin	Infiltrate with GI	1.3 cm (0.5 in.)[c]	Match (pre × 1.1) to post	2 and 100 years	80% TSS	City of Milwaukee (2018)
Minneapolis, Minnesota	—	—	Match pre to post	2, 10, and 100 years	70% TSS	Minneapolis PWD (2017)
Billings, Montana	Capture	50 years, 24 h	Match pre to post	2, 10, 50, and 100 years	80% TSS, 30% TN, and 50% TP	Billings PWD (2016)
Nashville, Tennessee	Capture and treat	2.5 cm (1 in.)	Match pre to post	2, 5, 10, 25, 50, and 100 years	80% TSS	Nashville and Davidson Co. (2016)
Newark, New Jersey	Infiltrate	2 years[d]	Match pre to post	2, 10, and 100 years	80% TSS	City of Newark (2017)
Portland, Oregon	—	—	Match pre to post	5, 10, and 25 years	70% TSS	City of Portland (2016)
Milwaukee, Wisconsin	Detain with GI	1.3 cm (0.5 in.)[c]	Match (pre × 1.1) to post	2, 100 years	80% TSS	City of Milwaukee (2018)
Georgia	Capture/infiltrate	2.5 cm (1 in.)	Match pre to post	1, 25, and 100 years	80% TSS	AECOM et al. (2016)
Massachusetts	Infiltration	0.25–1.5 cm (0.1–0.6 in.)[b]	Match pre to post	2 and 10 years	80% TSS	Massachusetts (2008)
South Carolina	Infiltration	1.3 cm (0.5 in.)	Match pre to post	2 and 10 years	80% TSS	South Carolina DHEC (1993)
Michigan	Match pre to post	2 years 24 h	Match pre to post	2 years	80% TSS	Michigan DEQ (2014)
Delaware	—	—	Match pre to post	2, 10, and 100 years	80% TSS	Delaware DNR and The Environmental Management Center, Brandywine Conservancy (1997)
Minnesota	Filter/infiltrate	1.3 cm (0.5 in.)	Match pre to post	10 and 100 years	80% TSS	Minnesota PCA (2005)
Tennessee	Capture	2.5 cm (1 in.)	Match pre to post	2–100 years	80% TSS	Tennessee DEC (2012)
New Jersey	Infiltrate	2 years[c]	Match pre to post	2, 10, and 100 years	80% TSS	New Jersey (2016)
New Hampshire	Infiltrate	0–1 cm (0–0.4 in.)[b,c]	Match pre to post	10 and 50 years	Capture and treat 2.5 cm (1 in.)[c]	McCarthy (2008)
New York	Capture	1 years, 24 h[c]	Match pre to post	10 and 100 years	80% TSS; 40% TP	New York State DEC (2015)
Maine	Capture and treat	2.5 cm (1 in.)[c]	Match pre to post	2, 10, and 25 years	Capture and treat 1 in.[c]; TP[e]	Maine DEP (2019)
Maryland	Capture and treat	(2.3–2.5 cm) (0.9–1 in.)[c]	Match pre to post	2 and 10 years	80% TSS; 40% TP	Maryland Department of the Environment (2000)
Vermont	Infiltration	(0.25–1 cm) 0.1–0.4 in.[b]	Match pre to post.	10 and 100 years	80% TSS; 40% TP	Vermont ANR (2002)
Wisconsin	Infiltrate	Annual precipitation[c]	Match pre to post	1 and 2 years	80% TSS	Wisconsin (2010)

Note: GI = green infrastructure.
[a]24-h storm unless otherwise noted.
[b]Varies based upon hydrologic soil group.
[c]Volume computed from impervious area.
[d]Infiltrate volume equal to difference between pre- and postdevelopment runoff.
[e]Allocation of pollutant load based upon departmental decision.

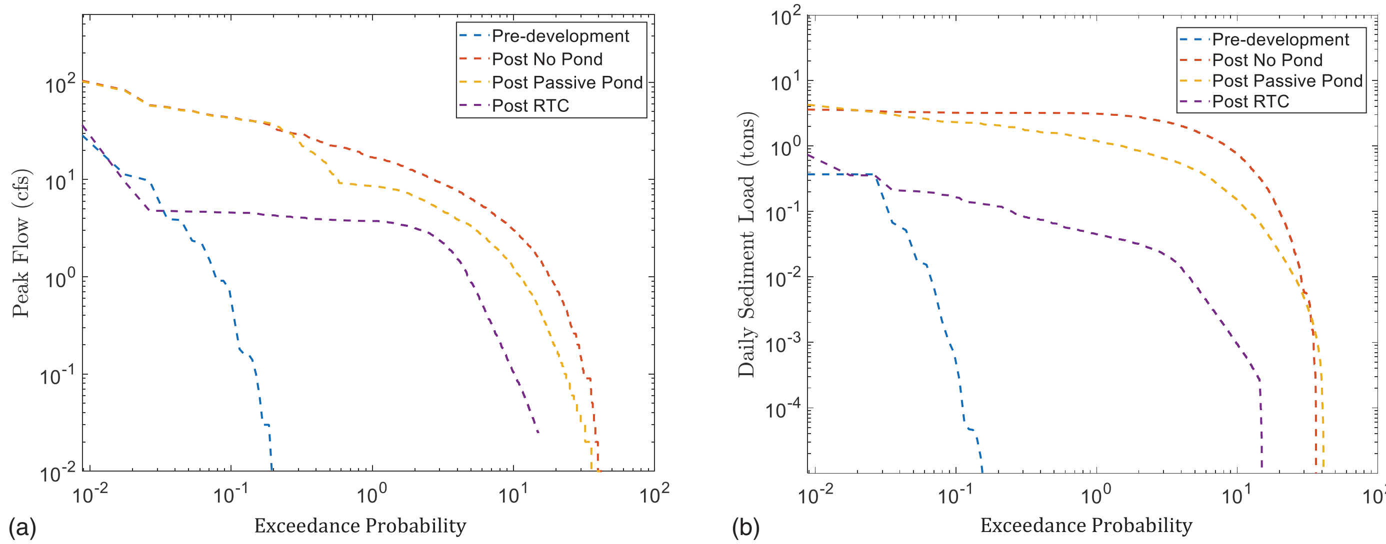

Fig. 3. Duration curves for (a) daily peak discharge; and (b) TSS load.

postdevelopment peak flows to match those of the predevelopment. This also indicated that the real-time control can capture stormwater and reduce flow rates during high-runoff events. However, because the real-time control model retains water for peak flow reduction and sediment settling, the peak discharge for many smaller events is increased, as evident by the increase in the median peak flow rate from 0.025 to 0.106 m^3/s (0.9 to 3.74 cfs) [Fig. 3(a)].

The model also demonstrated an increase in sediment removal efficiency with the real-time controls. The real-time control reduced sediment loads from the pond based upon the load duration curves [Fig. 3(b)], with the 5-year sediment load decreasing from 2.06 t/day to 0.12 t/day. This was due to the increased settling time in the pond provided by the real-time control, which resulted in lower outflow sediment concentrations even though the median discharge was higher. This also is evident from the distribution of the storm event loads, which increased the annual sediment load removal from 70% to 96%. This improved sediment load reduction is notable because it exceeded the 80% TSS removal required by most regulations identified in the section "Review of Municipal Engineering Design Criteria" (e.g., Table 1).

These results indicate that there are clear benefits and trade-offs of using real-time controls based upon the control rules that were used in this study. The number of extreme peak discharge events and the peak-duration curve [Fig. 3(a)] both were reduced using a real-time control compared with a passive pond; however, the overall median peak discharge was higher. This was because the valve remains closed during a nonzero fraction of time and, therefore, the discharges when the valve is open must be consistently higher on average (Parolari et al. 2018). The real-time control also significantly outperformed the passive pond in terms of TSS removal, with an annual TSS load reduction of 96%. This demonstrated that where pollutant removal is a high priority—such as in impaired watersheds where TMDLs are implemented—augmenting or designing ponds with real-time controls can outperform passive systems in protecting downstream water quality.

Discussion of Implications for Integrating Real Time Controls

This study presented a survey to identify barriers to adoption of real -time controls and presented a case study demonstrating how real-time controls of stormwater can be used to improve performance and meet regulatory criteria. The results of the survey demonstrated that cost, operations and maintenance concerns, and regulatory credits are the most significant barriers to real-time controls of stormwater in the opinions of municipal and consultant stormwater engineers. Municipal engineers were more concerned overall about real-time controls, and the greatest difference in concern between municipal and consultant engineers was for regulatory credits.

To determine how real-time controls might be addressed within current stormwater regulatory criteria, we first reviewed the requirements of state and municipal postdevelopment stormwater management regulations. The regulations largely can be broken down into volume, peak flow reduction, and water quality reduction requirements. Volume requirements had the greatest degree of variation, and included general volume removal, infiltration, or capture across a wide range of precipitation scenarios, including specific rainfall depths (i.e., the first inch of rainfall) or design storms (e.g., a 2-year 24-h storm). Peak flow reduction criteria were more uniform, and all required reducing postconstruction peak flows to some form of predevelopment conditions for storms that ranged between the 1- and 100-year events. Water quality criteria largely required the removal of TSS at rates between 70% and 85%; however, a few states also had nutrient reduction requirements. Due to the uniformity among states and municipalities of peak flow and water quality reduction requirements, these criteria may present the greatest opportunity to demonstrate the value of real-time control of stormwater flows.

Therefore, we developed a case study model to demonstrate how real-time controls impact peak flow and TSS reduction for a detention pond. Results indicated a reduction in TSS pollutant loads from 70% to 96%. However, despite these improvements, the median peak flow rate increased from 0.025 to 0.106 m^3/s (0.9 to 3.74 cfs). The increase in the median flow partially could be mitigated by controlling the flow using a staged release in which the valve is opened only partially after the water level reaches a critical height threshold. Depending upon the site conditions, the increase in median peak flows could cause erosion downstream, and therefore this could be a limitation to using real-time controls. In fact, some regulations require ponds that discharge to a receiving stream to have peak flow rates for the 2-year storm of half that of the predevelopment runoff conditions (e.g., City of Portland 2016).

Given the focus of water quality regulations on TSS both in Wisconsin as well as across the US, these results demonstrate that real-time controls could have a significant positive impact on pollutant mitigation. These results also agree with others in the literature that found that ponds retrofitted with real-time controls can reduce TSS by 29%–44% and improve peak reduction by up to 50% in detention ponds (Gaborit et al. 2016, 2013; Muschalla et al. 2014). This study and others suggest the possibility of a regulatory crediting system for real-time controls of detention ponds that goes beyond the baseline TSS removal rates attributed to passive detention ponds. How credits are awarded might be influenced by several factors, including local precipitation patterns, type of stormwater practice that is controlled, and the control rules used. This study used a control rule based upon a water level threshold; however, there are any number of other rules with which these systems could be controlled and that will impact how the system functions (Sharior et al. 2019). Therefore it is important that these rules are defined clearly within a regulatory system in order to know how the system will function. Therefore, evaluating how rules influence stormwater system function is an important and ongoing area of research.

In our review of regulatory criteria, we found that there generally are two ways in which a water quality removal percentage could be demonstrated: (1) by following a volume reduction guideline, or (2) by demonstrating removal through a modeling approach. Under the first approach, regulators could attribute a greater pollutant removal efficiency to capture and treat with real-time control than they give to standard capture and treat (e.g., Nashville and Davidson County 2016). Under the second approach, the same method could be applied to models that attribute water quality removal efficiencies based upon the practice type (e.g., WinSLAMM). The more difficult decision is defining how much TSS removal to attribute to real-time control systems. In general, these removal efficiencies are based upon research studies, experience, and engineering judgment of the regulators. Given the performance of this case study and others in the literature (Gaborit et al. 2016, 2013; Muschalla et al. 2014; Sharior et al. 2019), it may be appropriate to attribute a TSS removal efficiency that is greater than the typical credits given to a detention pond. However, this would be dependent upon site conditions, the placement of the controls within system, and the rules used to operate the controls, among other factors.

Conclusions

In this study, we performed a survey to identify barriers to real-time controls perceived by municipal and consulting stormwater engineers and found that cost, operations and maintenance, and regulatory credits were significant barriers. In addition, the survey results demonstrated that there are distinct differences in the perspectives on barriers expressed by engineering consultants and municipal engineers, with regulatory compliance being the biggest difference. Based upon a review of stormwater regulations and a modeled case study, we explored how real-time control of stormwater might be able to address these regulatory concerns. The key findings from this study are:

- Only 7% of survey respondents were aware of real-time controls implemented within their communities, but 71% of respondents were slightly or moderately familiar with real-time control of stormwater. This indicates that although real-time control may not be widely adopted among the stormwater community in Wisconsin, it is a technology that is somewhat familiar to stormwater professionals.
- Cost, operations and maintenance, and qualification for regulatory credits were the greatest concerns among survey respondents; the lowest concerns were for cybersecurity and legal issues.
- Of these barriers, the greatest degree of disagreement among municipalities and consultants was regarding regulatory credits ($p = 0.21$), with more concern from municipal engineers than from consultants.
- Municipal engineers also indicated they were less likely to consider implementing stormwater real-time controls ($p = 0.046$) and less likely to agree that there are advantages to a stormwater real-time control system that would be beneficial to their organizations or communities ($p = 0.05$).
- Most stormwater regulations require postdevelopment stormwater management to match peak flows to predevelopment conditions and remove TSS at a percentage ranging between 70% and 85%.
- In a modeled stormwater pond, real-time controls improved TSS removal from 70% to 96%, exceeding regulatory requirements.
- The modeled pond with real-time control had lower peak discharges than the passive pond across all runoff durations. It also matched closely the predevelopment peak flows for return periods that exceeded the 30-year event.

Overall, our findings suggest that there are significant barriers to implementing real-time controls of stormwater, which may be explain why adoption within the survey respondents' communities are relatively low. However, our exploration of regulatory barriers indicated that there may be opportunities to demonstrate the impact of real-time controls on peak flows and TSS removal through a modeling approach. As these technologies continue to mature, studies such as this are important for understanding how real-time control of stormwater fits within the institutional and regulatory environments that drive stormwater management. This understanding can help to provide stormwater practitioners with another stormwater best management practice, ultimately leading to improved stormwater management and downstream water quality.

Appendix. Real-Time Control Survey

Q1. Which of the following describes your profession?
- Municipal engineer/manager
- State regulator
- Engineering consultant
- Academic
- Other (please explain)

Q2. Stormwater management issues affecting my community include (choose all that apply):
- Combined sewer overflows
- Water quality pollution
- Flooding
- None
- Other (please explain)

Q3. The following are stormwater technologies that are implemented within my community (choose all that apply):
- Green stormwater infrastructure
- Flow monitoring
- Water quality monitoring
- Real-time controls
- None
- Other (please explain)

Q4. How familiar are you with stormwater real-time controls?
- Very familiar
- Moderately familiar
- Slightly familiar
- Not at all familiar

Q5. My organization or community has expertise capable of implementing and maintaining a stormwater real-time control system.
- Strongly agree
- Agree
- Don't know
- Disagree
- Strongly disagree

Q6. There are advantages to a stormwater real-time control system that would be beneficial to my organization or community.
- Strongly agree
- Agree
- Don't know
- Disagree
- Strongly disagree

Q7. In implementing stormwater RTCs, how concerned are you about the following? (1—Not at all concerned; 2—Slightly concerned; 3—Don't know; 4—Moderately concerned; 5—Extremely concerned)
- Public safety
- Cybersecurity
- Operations and maintenance
- Cost
- Data management
- Unfamiliarity with RTCs
- RTC performance uncertainty
- Regulatory credits for RTC
- Regulatory barriers
- Legal issues

Q8. Do you perceive real-time controls to be an effective way to manage stormwater runoff?
- Yes
- No
- Maybe
- Not sure

Q9. How likely is your organization to consider implementing stormwater real-time controls?
- Extremely likely
- Likely
- Neutral
- Unlikely
- Extremely unlikely

Q10. Please provide any additional comments.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. The exception are the survey responses, which are confidential per Marquette Universities Institutional Review Board (IRB).

References

AECOM, et al. 2016. *Georgia stormwater management manual 2016*. 1st and 2nd eds. Atlanta: Atlanta Regional Commission.

Albright, S. P. 2012. "Emerging trends in the regulation of stormwater." *Texas Environ. Law J.* 43 (1): 8–23. https://doi.org/10.3868/s050-004-015-0003-8.

Allerhand, J. E., K. B. Boyer, P. E. J. McCarthy, and M. S. Kieser. 2012. "The cost of managing stormwater." *J. Green Build.* 7 (3): 80–91. https://doi.org/10.3992/jgb.7.3.80.

Billings PWD (Public Works Department). 2016. *Stormwater management manual, 123*. Billings, MT: PWD.

Boston WSC (Water and Sewer Commission). 2013. Stormwater best management practices: Guidance document." Accessed December 1, 2020. http://www.bwsc.org/sites/default/files/2019-01/stormwater_bmp_guidance_2013.pdf.

Chapel Hill PWD (Public Works Department). 2005. "Town of Chapel Hill design manual." Accessed December 1, 2020. https://www.townofchapelhill.org/home/showdocument?id=2645.

Charleston County. 2007. "Charleston County stormwater program permitting standards and procedures manual." Accessed December 1, 2020. https://www.charlestoncounty.org/departments/public-works/files/StormwaterTechnicalManual.PDF?v=2.

City of Boise. 2018. "StormWater management: A design manual." Accessed December 1, 2020. https://www.cityofboise.org/media/4271/stormwaterdesignmanualrev2018.pdf.

City of Charleston. 2014. "Stormwater management guidance manual." Accessed December 1, 2020. http://charlestonstormwater.org/wp-content/uploads/2018/03/Table-of-Contents-front-cover.pdf.

City of Chicago. 2014. "City of Chicago stormwater management ordinance manual." Accessed December 1, 2020. https://www.chicago.gov/content/dam/city/depts/water/general/Engineering/SewerConstStormReq/2016StormwaterManual.pdf.

City of Little Rock. 2016. "City of Little Rock stormwater management and drainage manual." Accessed December 1, 2020. https://www.littlerock.gov/!userfiles/editor/docs/public-works/civil/STORMWATERDRAINMANUPDATE08-2012.pdf.

City of Milwaukee. 2018. "Storm water management regulations 120-1, 1–24." Accessed December 1, 2020. https://city.milwaukee.gov/ImageLibrary/Groups/ccClerk/Ordinances/Volume-1/CH120.pdf.

City of Newark. 2017. "Ordinance of the City of Newark, N. J. Title 38, Chapter 10, 1–25." Accessed December 1, 2020. https://waterandsewer.newarknj.gov/resources.

City of Portland. 2011. *Stormwater credit manual*. Portland, ME: City of Portland.

City of Portland. 2016. *Stormwater management manual*. Portland, OR: City of Portland Environmental Services.

Commonwealth of Massachusetts. 2008. "Massachusetts stormwater handbook and stormwater standards, 1." Accessed December 1, 2020. https://www.mass.gov/guides/massachusetts-stormwater-handbook-and-stormwater-standards#-stormwater-handbook-volume-1-.

Delaware DNR (Department of Natural Resources) and The Environmental Management Center, Brandywine Conservancy. 1997. "Conservation design for stormwater management: A design approach to reduce stormwater impacts from land development and achieve multiple objectives related to land use." Accessed December 1, 2020. http://www.dnrec.state.de.us/DNREC2000/Divisions/Soil/Stormwater/New/Delaware_CD_Manual.pdf.

Gaborit, E., F. Anctil, G. Pelletier, and P. A. Vanrolleghem. 2016. "Exploring forecast-based management strategies for stormwater detention ponds." *Urban Water J.* 13 (8): 841–851. https://doi.org/10.1080/1573062X.2015.1057172.

Gaborit, E., D. Muschalla, B. Vallet, P. A. Vanrolleghem, and F. Anctil. 2013. "Improving the performance of stormwater detention basins by real-time control using rainfall forecasts." *Urban Water J.* 10 (4): 230–246. https://doi.org/10.1080/1573062X.2012.726229.

Grigg, N. 2019. "Aging water infrastructure in the United States." In *Resilient water services and systems:The foundation of well-being*, edited by P. Juuti, H. Mattila, R. Rajala, K. Schwartz, and C. Staddon, 15–31. London: IWA Publishing.

Kerkez, B., et al. 2016. "Smarter stormwater systems." *Environ. Sci. Technol.* 50 (14): 7267–7273. https://doi.org/10.1021/acs.est.5b05870.

Maine DEP (Department of Environmental Protection). 2019. "Chapter 500: Stormwater management 06-96." Accessed December 1, 2020. http://www.maine.gov/sos/cec/rules/06/096/096c500.docx.

Mallakpour, I., and G. Villarini. 2017. "Analysis of changes in the magnitude, frequency, and seasonality of heavy precipitation over the contiguous USA." *Theor. Appl. Climatol.* 130 (1): 345–363. https://doi.org/10.1007/s00704-016-1881-z.

Maryland Department of the Environment. 2000. "Maryland stormwater design manual, Volumes I and II." Accessed December 1, 2020. https://mde.maryland.gov/programs/Water/StormwaterManagementProgram/Pages/stormwater_design.aspx.

McCarthy, J. 2008. "New Hampshire stormwater manual, 1." Accessed December 1, 2020. https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/wd-08-20a.pdf.

McDonald, W. M., and J. B. Naughton. 2019. "Stormwater management actions under regulatory pressure: A case study of southeast Wisconsin." *J. Environ. Plann. Manage.* 62 (13): 1–22. https://doi.org/10.1080/09640568.2018.1539391.

McDonnell, B. E., K. Ratliff, M. E. Tryby, J. J. X. Wu, and A. Mullapudi. 2020. PySWMM: The Python Interface to Stormwater Management Model (SWMM). *J. Open Source Software* 5 (52): 2292. https://doi.org/10.21105/joss.02292.

Michigan DEQ (Department of Environmental Quality). 2014. *Postconstruction storm water runoff controls program compliance assistance document*. Lansing, MI: Michigan DEQ.

Minneapolis PWD (Public Works Division). 2017. "City of Minneapolis stormwater and sanitary sewer guide." Accessed December 1, 2020. https://www2.minneapolismn.gov/media/content-assets/www2-documents/departments/Stormwater–Sanitary-Sewer-Guide.pdf.

Minnesota PCA (Pollution Control Agency). 2005. "The Minnesota stormwater manual." Accessed December 1, 2020. https://stormwater.pca.state.mn.us/index.php?title=Main_Page.

Municipality of Anchorage. 2016. "Anchorage stormwater manual: Volume 1: Management and design criteria." Accessed December 1, 2020. https://www.muni.org/Departments/project_management/Documents/ASM_Volume1_Final_December2017.pdf.

Muschalla, D., B. Vallet, F. Anctil, P. Lessard, G. Pelletier, and P. A. Vanrolleghem. 2014. "Ecohydraulic-driven real-time control of stormwater basins." *J. Hydrol.* 511 (Apr): 82–91. https://doi.org/10.1016/j.jhydrol.2014.01.002.

Nashville and Davidson County. 2016. Stormwater management manual. Accessed December 1, 2020. https://www.nashville.gov/Portals/0/SiteContent/WaterServices/Stormwater/docs/SWMM/2016/Volume01Regulations/2016_FullSWMMVolume1.pdf.

New Jersey. 2016. "N.J.A.C. 7:8 stormwater management. New Jersey, 1–39." Accessed December 1, 2020. https://www.nj.gov/dep/rules/rules/njac7_8.pdf.

New York State DEC (Department of Environmental Conservation). 2015. "New York State stormwater management design manual." Accessed December 1, 2020. https://www.dec.ny.gov/chemical/29072.html.

NOAA. 2021. "NOAA data tools: Local climatological data (LCD) station ID: WBAN 14839." Accessed December 1, 2020. https://www.ncdc.noaa.gov/cdo-web/datatools/lcd.

Parolari, A. J., S. Pelrine, and M. S. Bartlett. 2018. "Stochastic water balance dynamics of passive and controlled stormwater basins." *Adv. Water Resour.* 122 (Dec): 328–339. https://doi.org/10.1016/j.advwatres.2018.10.016.

Reidmiller, D. R., et al. 2018. *Impacts, risks, and adaptation in the United States: Fourth national climate assessment, volume*. Washington, DC: US Global Change Research Program.

Rossman, L. A. 2015. *Storm water management model user's manual version 5.1*. Washington, DC: USEPA.

Sharior, S., W. McDonald, and A. J. Parolari. 2019. "Improved reliability of stormwater detention basin performance through water quality data-informed real-time control." *J. Hydrol.* 573 (Jun): 422–431. https://doi.org/10.1016/j.jhydrol.2019.03.012.

South Carolina DHEC (Department of Health and Environmental Control). 1993. "Regulation 72-405 through 72-445 standards for stormwater management and sediment reduction." Accessed December 1, 2020. https://www.scdhec.gov/sites/default/files/media/document/R.72-405_72-445.pdf.

Strifling, D., W. M. McDonald, H. Hathaway, and J. B. Naughton. 2019. "Overcoming legal and institutional barriers to the implementation of innovative environmental technologies." *J. Emerging Technol.* 1 (2): 172.

Tennessee DEC (Department of Environment and Conservation). 2012. "Tennessee permanent stormwater management and design guidance manual." Accessed December 1, 2020. https://app.box.com/s/pdl1afehg00s1wwqa94d8qmizyptxw3i/file/25367692645.

Trotta, P. 1976. *On-line adaptive control for combined sewer systems*. Fort Collins, CO: Colorado State Univ.

USEPA. 2019. *The assessment, total maximum daily load (TMDL) tracking and implementation system (ATTAINS)*. Washington, DC: USEPA.

Vermont ANR (Agency of Natural Resources). 2002. "The Vermont stormwater management manual: Volume I—Stormwater treatment standards." Accessed December 1, 2020. https://dec.vermont.gov/sites/dec/files/wsm/stormwater/docs/Resources/sw_manual-vol1.pdf.

Wisconsin. 2010. "Peak discharge performance standard." NR 151.123. Accessed December 1, 2020. https://docs.legis.wisconsin.gov/code/admin_code/nr/100/151/III/123.

Wong, B. P., and B. Kerkez. 2018. "Real-time control of urban headwater catchments through linear feedback: Performance, analysis, and site selection." *Water Resour. Res.* 54 (10): 7309–7330. https://doi.org/10.1029/2018WR022657.