water

MDPI

Article

Modeling Operations in System-Level Real-Time Control for Urban Flooding Reduction and Water Quality Improvement—An Open-Source Benchmarked Case

Jiada Li [1,*], Ryan Johnson [2] and Steven Burian [3,4]

[1] New York State Department of Health, Albany, NY 12208, USA
[2] Civil and Environmental Engineering, University of Utah, Salt Lake City, UT 84112, USA; ryan.c.johnson@utah.edu
[3] Alabama Water Institute, University of Alabama, Tuscaloosa, AL 35487, USA; sburian@ua.edu
[4] Civil, Construction and Environmental Engineering, University of Alabama, Tuscaloosa, AL 35487, USA
* Correspondence: jiadali2017@gmail.com

Abstract: Advancements in smart sensing and control technologies enable urban drainage engineers to retrofit stormwater storage facilities with real-time control devices for mitigating stormwater in-site overflow, downstream flooding, and overloaded total suspended solids (TSS) in drainage pipes. While the smart technology can improve the performance of the static drainage systems, coordinatively controlling multiple valve and gate operations poses a significant challenge, especially at a large-scale watershed. Using a benchmark stormwater model located at Ann Arbor, Michigan, USA, we assessed the impact of different real-time control strategies (local individual downstream control and system-level multiple control) on balancing flooding mitigation at downstream outlets and TSS reduction at upstream storage units, such as detention ponds. We examined changes in peak water depth, outflow, and TSS as indicators to assess changes in water quantity and quality. The results indicate that system-level control can reduce peak water depth by up to 7.3%, reduce flood duration by up to 34%, and remove up to 67% of total suspended solids compared with a baseline uncontrolled system, with the outflow from upstream detention ponds being the most important hydraulic indicator for control strategy rule set-up. We find that system-level control does not always outperform the individual downstream controls, particularly in alleviating flooding duration at some downstream outlets. With urban growth and a changing climate, this research provides a foundation for quantifying the benefits of real-time control methods as an adaptive stormwater management solution that addresses both water quantity and quality challenges.

Keywords: smart stormwater; system-level control; downstream flooding; total suspended solids; SWMM; Python

check for updates

Citation: Li, J.; Johnson, R.; Burian, S. Modeling Operations in System-Level Real-Time Control for Urban Flooding Reduction and Water Quality Improvement—An Open-Source Benchmarked Case. *Water* **2024**, *16*, 3078. https://doi.org/10.3390/w16213078

Academic Editor: Chin H Wu

Received: 26 July 2024
Revised: 7 October 2024
Accepted: 21 October 2024
Published: 28 October 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Climate change is currently challenging stormwater management practices by increasing the magnitude, frequency, and duration of extreme rainfall events [1,2]. Such phenomena trigger stormwater quantity and quality issues such as higher peak runoff rates and larger pollutant loads in urban catchments [3]. Amplified stormwater discharge can exceed the capacity of urban drainage systems, cause more frequent system overloading, and increase the costs of stormwater infrastructure management and maintenance. In 2010, stormwater flooding problems affected 178 million people around the world and resulted in total economic losses exceeding USD 40 billion [4]. Due to frequent water quality and quantity challenges, it is of great importance to rehabilitate the existing urban drainage systems (UDSs) to account for the uncertain urbanization and climate changes.

Most UDSs with limited conveyance capacity cannot cope with or adapt to rapid water quantity and quality changes [5]. Engineers address stormwater system shortcomings by

enlarging existing stormwater facilities or physical structural components, having feasibility implications due to high costs [6] and adverse life cycle impacts on the environment due to the reduction/degradation of affected land areas [7,8]. To minimize the effects of increasing system component sizes, stormwater stakeholders need alternative stormwater management solutions. One potential alternative is real-time control (RTC) for reducing water quality stress and mitigating flood severity [9–11].

RTC is an adaptive, efficient, and low-cost practice. Prior studies applied RTC to optimizing the operational efficiency in water distribution systems [12], adapting stormwater drainage systems to changing conditions [13,14], and improving water quality in ecosystems [15]. With interest in alternative stormwater management approaches, previous researchers have used RTC for a range of purposes such as combined sewer overflow (CSO) reduction, flooding mitigation, greenhouse gas emissions control, energy-saving, and total suspended solids (TSS) removal [16–18]. Prior studies formulate the control rules to improve TSS removal efficiency from 41% to 89% [19], maintain the urban water cycle post-development [20], and reduce CSO volume by up to 50% [21].

The need for watershed-scale performance objectives in operating multiple distributed storage assets raises questions about the effectiveness of local-scale RTC strategies for optimizing system-wide outcomes. Previous RTC research, such as individual local control at a single storage pond, does not consider system-wide operational benefits and impacts [22]. To solve the raised questions, the individual control was implemented in a straight-forward way, bringing many localized benefits such as reductions in flooding volume and pollutant loads to identifying sites of storage ponds in some recent studies [23]. Given the local flooding and water quality benefits demonstrated using RTC, questions remain about whether local-scale RTC strategies for operating a single storage facility can meet the watershed-scale performance objectives when operating multiple distributed storage assets, owing to the spatial variability of precipitation and land-cover changes [24]. Prior studies found that optimal performance at an individual storage pond might not necessarily cause a favorable outcome at the system level [25–27] because upstream controls may inadvertently release water volume to downstream catchments contributing to increased flooding, similar to passive detention basins.

Modeling system-level real-time control (RTC) operations require not only the step-by-step implementation and emulation of control strategies within a stormwater model but also careful consideration of the physics-based hydraulic and hydrologic processes being simulated. For instance, in system-level control involving multiple storage units, the intensity and frequency of the upstream rainfall-runoff events significantly impact control operation patterns at downstream storage facilities [28]. To simulate the coordinated operations ranging from upstream to downstream control sites, this study employs a set of open-source benchmark models that incorporate both site-specific control logic and system-level hydraulic dynamics.

Despite advancements in open-source RTC tools, the integration of system-level RTC operations with drainage flow patterns to maximize stormwater benefits—such as reducing local flooding duration and improving system-wide water quality—remains underexplored. This research addresses this gap by modeling system-wide RTC operations, spanning from upstream detention ponds to downstream outlets, with the dual goals of mitigating flooding and enhancing water quality. We develop rule-based control strategies and implement a stepwise RTC simulation with the objective of evaluating the impact of these operations on water quantity and quality improvements across the watershed. Based on the simulation outcomes, we propose an index-based assessment to quantify RTC performance, contributing valuable insights for decision-makers to balance the trade-offs between minimizing downstream flooding and reducing upstream TSS pollutant loads.

2. Methodology

2.1. Overview of the Case Study

To evaluate the feasibility and performance benefits of system-wide real-time control (RTC), we selected Ann Arbor, Michigan, USA (Figure 1a), as the study location. The area covers 0.8 km^2 and is highly urbanized, with over 80% impervious surfaces. Land use includes residential (15%), commercial (55%), and industrial (30%) zones. The region frequently experiences persistent and intense summer precipitation, leading to unexpected stormwater discharges that exacerbate water quality issues like the total suspended solids (TSS) overloaded in drainage pipes. A key concern for urban flooding is the risk of overflow in initial storage basins and detention ponds, causing downstream flooding.

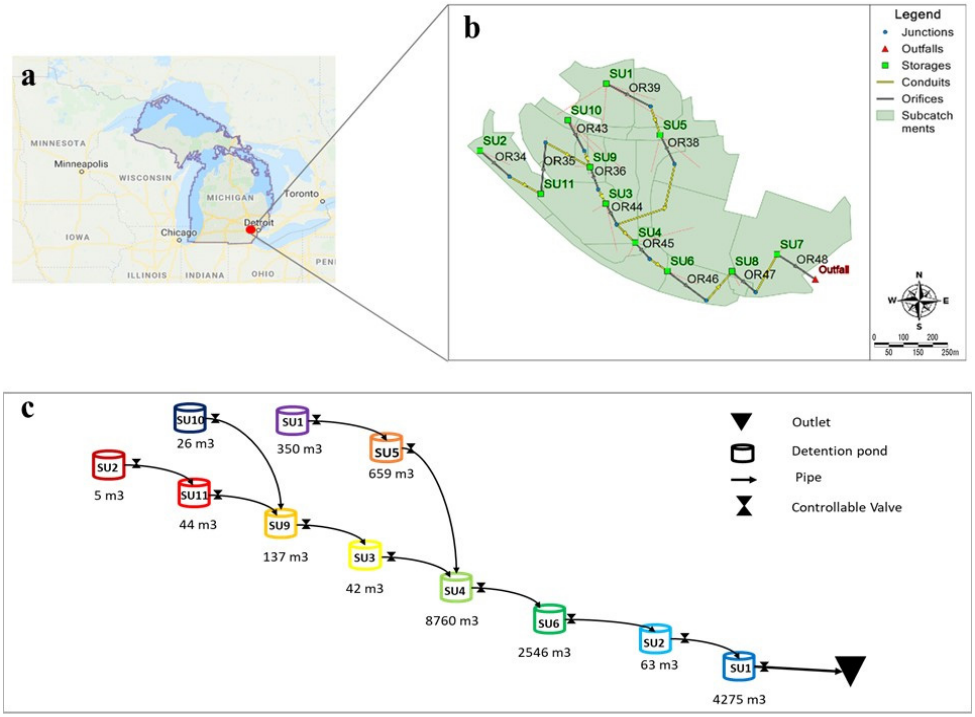


Figure 1. Overview of the studied watershed in Ann Arbor, Michigan, USA. (**a**) Location of the urban watershed in southeast Michigan, USA; (**b**) the 'gamma' SWMM model composed of storage units (SU), conduits, orifices (OR), and valve to automatically adjust gate opening/closing and downstream outfall; (**c**) simplification of volume capacity for the designated detention ponds.

The stormwater drainage system for this case study has been modeled using the 'gamma' SWMM model within the open-source Pystorms package [28]. This benchmarking framework makes smart stormwater network control problems more accessible to control experts by allowing for the easy cross-comparison of control strategies and promoting broader community engagement. However, while the case study and model are well described, the specific challenges of this area—such as stormwater on-site overflow, downstream flooding, and overloaded TSS—are not adequately addressed in terms of how the proposed RTC methodology specifically mitigates these issues. This gap needs to be clarified for a comprehensive understanding of the model's relevance to the region's unique stormwater challenges. Figure 1b presents the gamma stormwater model of Pystorms, which includes 19 sub-catchments, 10 junctions, 11 conduits, 11 orifices, and 11 detention ponds (SU1 to 11). The watershed has 11 storage detention ponds, ranging in volume from 5 m^3 to 8760 m^3 (Figure 1c). Most of the upstream detention ponds (e.g., SU2 with 5 m^3) have a small volume capacity, while the downstream detention ponds (e.g., SU4 with 8760 m^3 and SU1 with 4275 m^3) have a large volume capacity (Figure 1c). More information regarding the gamma model and the Pystorm package can be found at https://www.pyswmm.org/home (accessed on 20 October 2024).

2.2. Control Rule Design

The control rules are designed to ensure that water discharges across the system are managed efficiently, minimizing the risk of both local overflow and downstream flooding. The reasoning for the control rules is grounded in a balance between water retention in detention ponds and the gradual release of water to avoid overwhelming downstream infrastructure.

- Baseline Depth (BD): This represents the water depth at which normal storage is maintained without risking overflow. It is determined based on historical data, system storage capacity, and regulatory guidelines.
- Threshold Depth (TD): TD marks the depth at which downstream flooding may begin to occur, triggering preventive actions to reduce runoff and relieve pressure on downstream facilities.
- Maximum Depth (MD): MD is the critical level where local overflow occurs. If exceeded, the system must prioritize discharging water to prevent excessive flooding in storage basins.

These depths were established through historical data analysis (e.g., rainfall intensity, duration), local engineering expertise, and system characteristics. Table 1 provides specific BD, TD, and MD values for each control rule and the corresponding actions for the orifice valves. These manually defined depths are estimated and averaged based on the measured dimensions of the local detention ponds from the utility department.

Table 1. Water depths used for control rule simulation BD: the measured baseline water depth, TD: the measured threshold water depth, MD: the measured maximum water depth).

Controller ID	Storage Unit ID	Orifice ID	BD (m)	TD (m)	MD (m)
1	SU1	OR39	0.78	2.00	2.91
2	SU2	OR34	0.78	2.30	2.91
3	SU3	OR44	0.78	2.00	2.91
4	SU4	OR45	0.78	2.30	2.76
5	SU5	OR38	0.78	2.00	2.47
6	SU6	OR46	0.78	2.00	2.47
7	SU7	OR48	0.10	2.00	2.76
8	SU8	OR47	0.78	2.00	2.61
9	SU9	OR36	0.78	2.00	2.61
10	SU10	OR43	0.78	2.00	2.47
11	SU11	OR35	1.39	2.00	2.47

A control rule defines the logic governing real-time control (RTC) operations and plays a critical role in improving both total suspended solids (TSS) management and flood prevention. In this system, the control logic is represented as a multi-linear function that characterizes the relationship between water depth in storage units and the corresponding orifice valve settings, which automatically regulate gate openings and closures. Table 1 outlines key water depth values, including actual water depth (AD) during simulations, baseline water depth (BD) without triggering local overflow, threshold water depth (TD) that leads to downstream flooding, and maximum water depth (MD) that causes local overflow. To enhance system understanding, it is essential to clarify how these water depths affect system performance and control objectives. BD is determined based on the water level that allows for normal storage without exceeding capacity. TD is set as the depth at which runoff from upstream results in downstream flooding, while MD is the maximum allowable water depth before local overflow occurs. These depths are defined using historical data analysis (e.g., rainfall intensity, flooding duration), local stormwater management regulations, and insights from local engineers and authorities. By identifying these thresholds, the control rules are designed to prevent both downstream flooding (exceeding TD) and local overflow (exceeding MD) [29]. With these water depths, we

design the control rules to determine the orifice valve status and gate opening percentage during simulations.

The control rules adjust the orifice valve settings based on real-time water depth measurements and are designed to manage both water discharges and system performance. The specific control rules are:

1. Rule 1: During a rainfall event, the orifice valve closes the gate to store water and minimize the risk of downstream flooding.
2. Rule 2: If the AD in the detention pond reaches the predefined BD, the orifice valve keeps the gate closed until downstream flooding begins to subside.
3. Rule 3: If the AD is between BD and TD but runoff persists, the orifice valve opens the gate to 25% to lower water levels in the detention pond and prevent overflow.
4. Rule 4: If the AD is between TD and MD and runoff continues, the orifice valve opens the gate to 75%, reducing flooding duration at downstream nodes.
5. Rule 5: If the AD exceeds MD, the orifice valve fully opens the gate (100%) to prevent flooding across the entire system.

These rules integrate the physical characteristics of the system, including storage unit capacity, interconnections between upstream and downstream areas, and local precipitation patterns, to optimize control strategies and system performance.

2.3. Control Strategies

To assess the effectiveness of real-time control (RTC) in mitigating flooding and enhancing water quality, we implemented four distinct control strategies in our case study. These strategies are designed to automate the actions of actuators, which adjust gate openings through orifice valve operations, in response to varying water levels.

- Baseline Strategy (Baseline): This is the control simulation without any orifice valves adjusting gate openings. It serves as the reference scenario to evaluate the benefits of RTC by comparing it with the other strategies.
- Downstream Control (Downstream): This strategy focuses on preventing downstream issues by adjusting only the valve (OR 48 in Figure 1) at the most downstream location. The local gate, associated with the actuator, adjusts based on water levels, while no other orifice valves in the system are activated. This strategy focuses solely on downstream control, managing water discharges at the lowest point in the system.
- System-wide Control with Uniform Rules (Sys_S): This strategy uses uniform thresholds for all valves, ensuring synchronized system-wide responses to prevent flooding and water quality issues. In this system-level strategy, all 11 orifice valves are actively managed. The gates are adjusted based on uniform control thresholds—specifically, the same baseline depth (BD), threshold depth (TD), and maximum depth (MD) for all orifice valves, as defined in Table 1. This approach aims for coordinated system-wide control using identical water depth triggers across the network.
- System-wide Control with Differentiated Rules (Sys_D): This strategy applies differentiated thresholds, customizing responses based on the local characteristics of each detention pond, and also manages all 11 orifice valves, but each valve follows a unique set of control rules. The BD, TD, and MD thresholds vary based on the specific location and characteristics of each storage unit, as shown in Table 1. This differentiated approach tailors the control of each valve to local conditions, optimizing system-wide performance by accounting for varying storage capacities, flow dynamics, and hydraulic responses.

Table 2 summarizes the four control strategies (Baseline, Downstream, Sys_S, Sys_D), showing how they differ in terms of valve operations and control rules applied. In each strategy, the target control objects are the detention ponds highlighted in Figure 1c. The actuators physically represent orifice valves located at key nodes in the system. These actuators sense water levels and adjust the gate openings accordingly to prevent local and downstream flooding while also improving water quality by managing discharges.

Table 2. The implemented control strategies and control rules (control rules are from Section 2.2).

Control Strategies	Controlled Objects	Actuators	Targeting Location	Rules Used in This Control Strategies
'Baseline' control	none	passive orifices	flooded nodes and all detention ponds	rule 1
'Downstream' control	orifice valve OR1	proactive orifice	downstream outlet and SU1	rules 1, 2, 3, and 5
'Sys_S' control	all orifice valves	proactive orifices	flooded nodes and all detention ponds	rules 1, 2, 4, and 5
'Sys_D' control	all orifice valves	proactive orifices	flooded nodes and all detention ponds	rules 1, 2, 3, 4, and 5

2.4. Co-Simulation Set-Up

Simultaneously modeling control strategies and stormwater flooding needs a hydraulic–hydrologic model integrated with the step-wise control operations. We developed the RTC modeling in the open-source tool PySWMM with the benchmarked gamma model within the Pystorm package [30]. The modeling execution provides the hydraulic states (e.g., water depth and pipe flow) as inputs for control asset settings (e.g., orifice gate opening). We ran the co-simulations, which are defined as co-simulating control strategies and hydraulic-hydrologic processes, for a 48 h (5 July 2014 00:00 to 6 July 2014 24:00)-long RTC simulation under a rainfall event with an average 1.15 inches/hour intensity spanning the first 24 h period (00:00 to 24:00)—an average event during rainy seasons.

2.5. Controller Performance Index

The Controller Performance Index keeps track of key model results to compare different control strategies. This includes the objectives of keeping the peak water depth of the upstream detention ponds below the threshold line (TD), mitigating the flooding duration of downstream sites, and reducing pollutant loads. Using the gamma model simulation outputs of Section 2.2, we compute peak depth shaving efficiency (PDSE), pollutant removal efficiency (PRE), and flooded-hour reduction (FR) as indicators of the real-time controller performance.

PDSE (Equation (1)) is for evaluating the performance of the real-time controller in reducing the peak depth of upstream detention ponds.

$$PDSE_{[i]} = \left(\frac{Peak\ Depth_{[i,b]} - Peak\ Depth_{[i,c]}}{Peak\ Depth_{[i,b]}} \right) \times 100\% \quad (1)$$

where PDSE[i] is the peak water depth shaving efficiency for the ith storage unit fraction [%]; Peak Depth[i,b] is the peak water depth for the ith storage unit under the baseline simulation strategies [m]; and Peak Depth[i,c] is the peak water depth for the ith storage unit under the control simulation strategies [m].

PRE (Equation (2)) is for evaluating the performance of the real-time controller in removing total suspended solids in the upstream detention ponds.

$$PRE_{[i]} = \left(\frac{TSS_{[i,b]} - TSS_{[i,c]}}{TSS_{[i,b]}} \right) \times 100\% \quad (2)$$

where PRE[i] is the pollutant removal efficiency for the ith orifice fraction [%]; TSS[i,b] is the load of TSS for the ith orifice under the baseline simulation strategies [kg]; and TSS[i,c] is the load of TSS for the ith orifice under the control simulation strategies [kg].

FR (Equation (3)) is for evaluating the performance of the real-time controller in shortening the flooding duration of downstream nodes. A total number of 11 junctions

(outlet, J2, J3, J4, J5, J6, J7, J8, J9, J10, J11) corresponding to the upstream detention ponds are the targeted locations.

$$FR_{[i]} = Flooded\ Hour_{[i,b]} - Flooded\ Hour_{[i,c]} \quad (3)$$

where FR[i] is the flooded-hour reduction for the ith flooded node [hour]; FR[i,b] is the flooded-hour reduction of the ith flooded node under the baseline simulation strategies [hour]; and FR[i,c] is the flooded-hour reduction of the ith flooded node under the control simulation strategies [hour].

3. Results

We investigated the changes in water quantity and quality at storage ponds and the downstream outlet under the proposed four different control strategies. For Section 3.1, we aim to explore the correlations between the stepwise operation in gate openings and water quantity changes in the detention pond. For Section 3.2, we aim to investigate how the RTC strategies affect the water quality changes. Due to the number of similar detention ponds in the study, we selected SU1, SU4, and SU9 detention ponds as representative storage units to exhibit the findings since the detention ponds have varying volumes from small to large.

3.1. Water Quantity Changes under RTC

RTC operations re-shaped the patterns in outflow, overflow, and depth for each storage detention pond. Figure 2 shows the temporal changes (5 July 2014, 00:00 to 24:00) in control and hydraulic simulations corresponding to the storage unit (detention pond) SU1. All three control strategies (Downstream, Sys_s, and Sys_D) require the orifice valves to close the gate as inflow grows and then to quickly open the gate to 100% at the inflow hydrograph peaking time. The gate opening to 100% is because the water depth of SU1 is over the predefined MD, so the orifice valve completely opens the gate to prevent upstream flooding, following rule 4. From 01:00 to 03:00 on 5 July 2014, the detention pond, SU1, makes full use of volume to store inflow, according to control rule 1. As the water level reaches the TD, detention pond SU1 discharges the retained water into downstream pipes to avoid local overflow or flooding based on the logic of control rules 2 and 3. The adaptive water releasing and storing process of these two system-level control strategies balance the upstream and downstream from over-loading, with the gate opening decreasing as the inflow declines. When the inflow declines, the gate opening fluctuates for the final 12 h (6 July 2014 36:00 to 48:00,) and ends the simulation with a 100% opening. The gate openings seek to control flow output to downstream nodes from the water depth jumps. In this work, the frequent fluctuations in gate openings can be attributed to the water depth jumps between the TD and MD during this period. Although the rain completely stops at the first 24 h (6 July 2014, 00:00 to 24:00), the delay of runoff generation and concentration in the sub-catchments allows inflow to enter the storage tank during the next 24 h (6 July 2014, 00:00 to 24:00). Owing to control rules 5 and 6, adjustments in orifice valves adapt to the flow coming and discharging in the final stage, which causes the opening fluctuations in the final 12 h (6 July 2014, 12:00 to 24:00 in Figure 2).

Compared with inflow and overflow patterns, the changes in outflow keep the same fluctuation with gate opening in the three control strategies. We find that the frequent gate actions are mostly adjusted by the downstream orifice valves OR 2, 3, and 5, and a majority of full orifice gate openings occur at the inflow hydrograph peaking time (e.g., Figure 2). In Figure 2A, we find that both gate opening and tank outflow go down in the first 12 h (5 July 2014, 00:00:00 to 5 July 2014 , 24:00:00), followed by a significant increase, and then they gently decline between the second and third 12 h period (6 July 2014, 00:00:00 to 6 July 2014, 12:00:00), ending up with frequent jumps in the final 12 h (6 July 2014, 12:00:00 to 6 July 2014, 24:00:00).

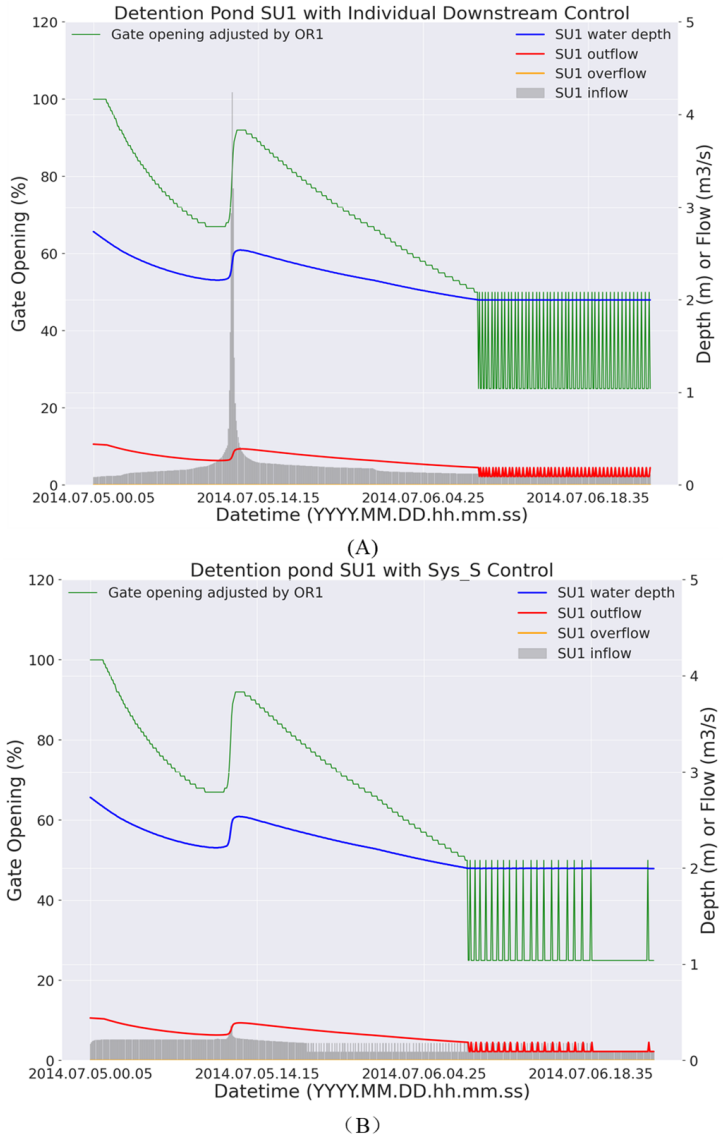


Figure 2. Use of the representative orifice valve OR1's opening (attached to storage pond SU1) to illustrate a highly comparable time-series pattern correlation between hydraulic indicators (water depth, inflow, outflow, and overflow) and the control actions to the corresponding gate opening.

Interestingly, changes in water depth align with gate openings for only the first 36 h (5 July 12:00:00 to 6 July 24:00:00) despite a linear relationship between water depth and gate operation. Comparing Figure 2A,B, it becomes evident that outflow plays a more crucial role than other hydraulic factors (inflow, overflow, and water depth) in driving temporal changes in gate openings across control strategies. Similar results were observed for detention ponds SU4 and SU9, as shown in Figures 3 and 4, respectively.

The 'Sys_D' control shows a similar pattern to the 'Sys_S' control, while the orifice openings of the 'Sys_D' control appear relatively larger and earlier for SU4 and SU9 (Figures 3 and 4). Fewer fluctuations in gate opening require less energy for orifice valve and actuator operation, indicating that the control system is more stable in the 'Downstream' and 'Sys_S' controls. These steady operations in orifice valves are beneficial for avoiding abrupt actions and the sudden opening of gates in practice. The gate openings in the 'Sys_D' control require more energy to operate (i.e., electricity supply), as well as system instability that may be magnified. Thus, 'Sys_D' is more likely to result in wear on actuators (orifice valves).

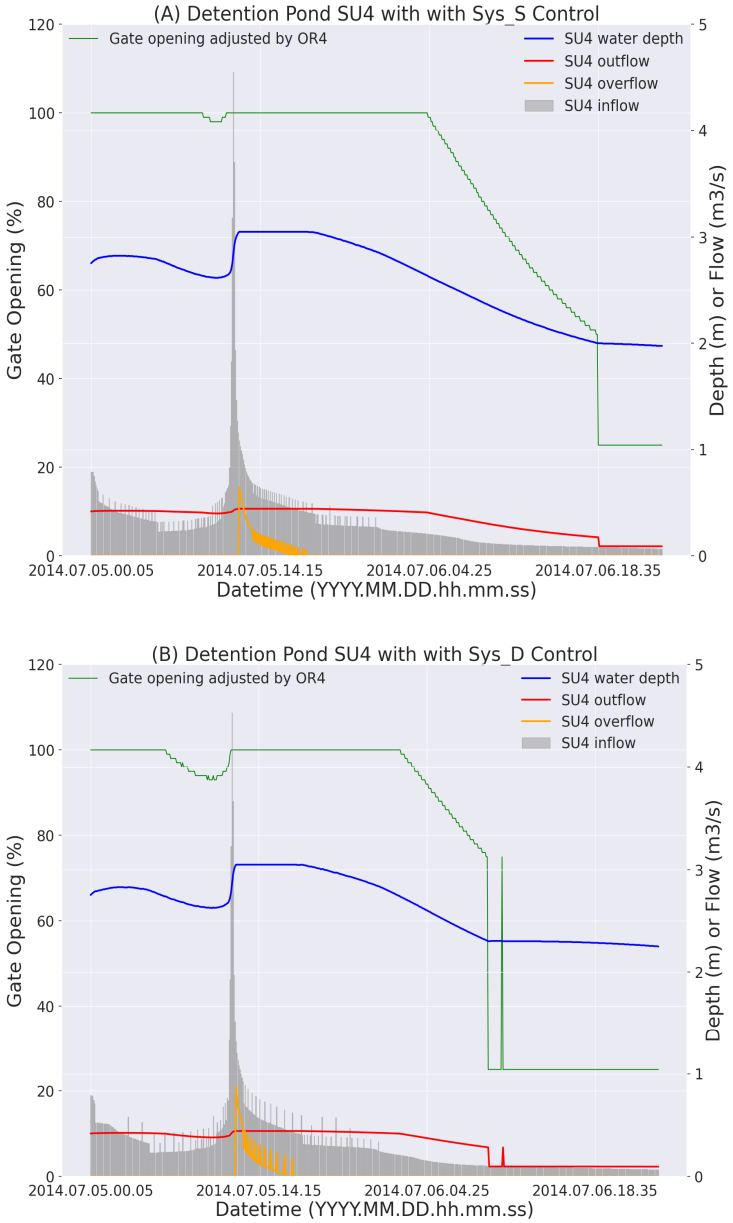


Figure 3. Use of the representative orifice valve OR4's opening (attached to storage pond SU4, which is one of the representative downstream assets with small capacity) to illustrate a highly comparable time-series pattern correlation between hydraulic indicators (water depth, inflow, outflow, and overflow) and the control actions to the corresponding gate opening.

The dynamic adjustment of gate openings through the orifice valve, guided by preset control rules, allows for the adaptive control of water flow. The orifice valve dynamically adjusts gate opening based on the preset control rules. Figure 4 presents changes in gate open/close states for three representative ponds during the simulation procedure. More spatial and temporal changes in the openings of the other eight gates are presented in Figures S1 and S2 of Supplementary Materials for 'Sys_S' and 'Sys_D' controls, respectively. These automatic adjustments in gate openings offer researchers an opportunity to gain insight into how gates can be controlled by real-time rules and then adapt to the water quantity and quality changes.

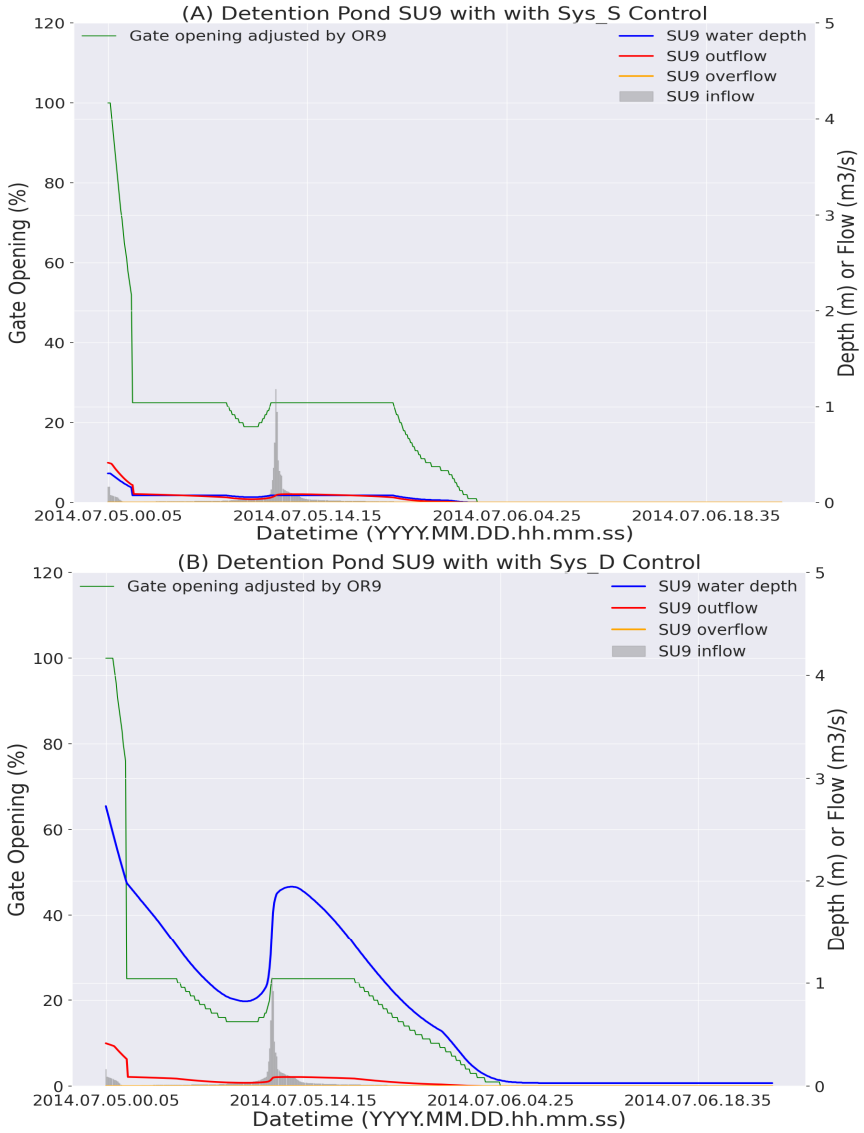


Figure 4. Use of the representative orifice valve OR9's opening (attached to storage pond SU9, which is one of the representative upstream assets with small capacity) to illustrate the correlation between hydraulic indicators (water depth, inflow, outflow, and overflow). The effectiveness of the proposed system-level control strategies and the water depth demonstrate a highly comparable time-series pattern to the corresponding gate opening.

3.2. Water Quality Changes under RTC

The three control strategies produce favorable results for mitigating TSS loadings compared to the uncontrolled baseline, demonstrated by TSS loading decreases of over 50% when using the 'Sys_S' or 'Sys_D' controls (Figure 5). For example, the TSS loading of upstream storage ponds SU8, 9, 10, and 11 noticeably declines. The reduction of TSS loading for 'Sys_D' (with a minimum of 120.83 kg and a maximum of 137.39 kg) is larger than for the 'Sys_S' control (with a minimum of 91.39 kg and a maximum of 117.63 kg), inferring that the 'Sys_D' control is more capable of alleviating pollutant loads than the 'Sys_S' control.

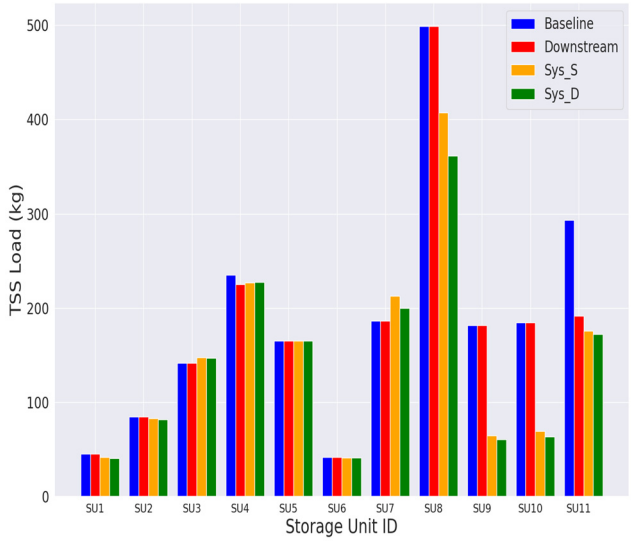


Figure 5. Assessing the effectiveness of the three control strategies to mitigate the TSS load at the detention ponds compared with the TSS load amount in the uncontrolled baseline.

There are variations in TSS percentage changes at the outlet depending on the different control strategies. We observe a slight decrease in TSS load when comparing the 'Downstream' control to the baseline. For example, at storage unit SU4, there is a drop of approximately 10 kg of TSS compared to the baseline. Figure 6 illustrates that the 'Sys_D' control is the most effective approach for maximizing TSS at the downstream outlet (42% TSS reduction), followed by the 'Sys_S' control (40% TSS reduction) and the individual 'Downstream' control, exhibiting a modest decline in TSS percentage (34.71% TSS reduction). These RTC strategies provide a benchmark for achieving water quality objectives without sacrificing the water quantity objectives.

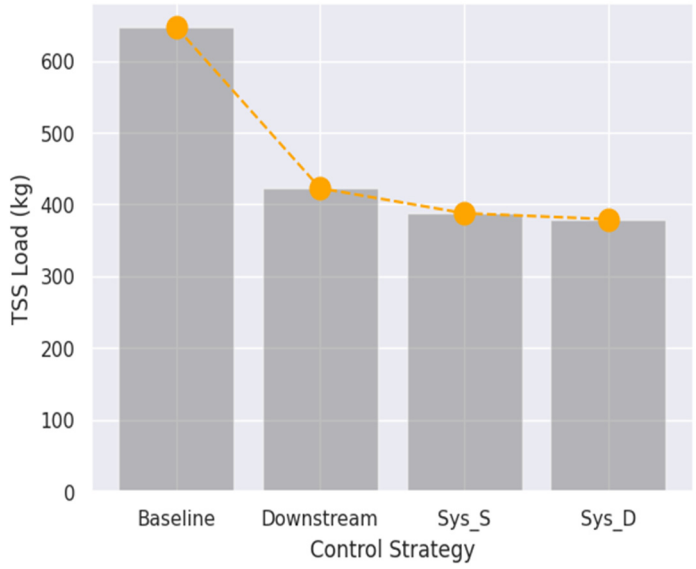


Figure 6. Assessment of the performance of the three proposed control strategies in reducing the TSS load at most downstream outlets: a decreasing trend from baseline to system-level control.

3.3. Control Performance Comparison

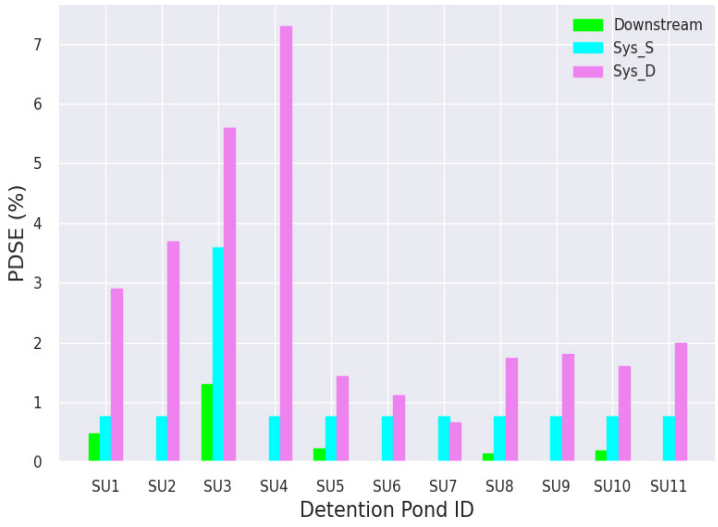
The 'Downstream' control strategy is the most effective at reducing downstream flooding compared to either system-level control approach. In contrast, the 'Sys_D' control consistently achieves the highest Percentage Depth Stress Elimination (PDSE), reaching up to 7% at SU4. The largest PDSE values at SU8 (5.1%) and SU10 (3.2%) are observed under

the 'Downstream' control (Figure 7a). These differences in PDSE suggest that managing the most downstream gate significantly improves the reduction of water depth in the downstream detention ponds.

Flood Reduction (FR) analysis shows that system-level control outperforms 'Downstream' control at all flooded nodes, except at the outlet. At the outlet, the FR for the 'Downstream' control is higher than that of the system-level control. Actuators in the 'Sys_S' and 'Sys_D' strategies demonstrate significant FR improvements at nodes located below large-volume downstream detention ponds (e.g., nodes J2, J3, and J4, located below SU2, SU3, and SU4, respectively), as shown in Figures 1 and 7b. The most significant reduction in flooding hours occurs at J2, where the FR of the 'Sys_D' strategy (34 h) is 35% higher than that of the 'Sys_S' control (22 h). In contrast, the upstream nodes (J5–J11) show only slight reductions in flooding duration. However, the 'Downstream' control makes a notable impact at the outlet (the most downstream 'outfall' junction), where it outperforms other control strategies (Figure 7b). The 20% increase in FR at the outlet suggests that individual downstream control is more effective at preventing flooding at the outfall than the system-level control.

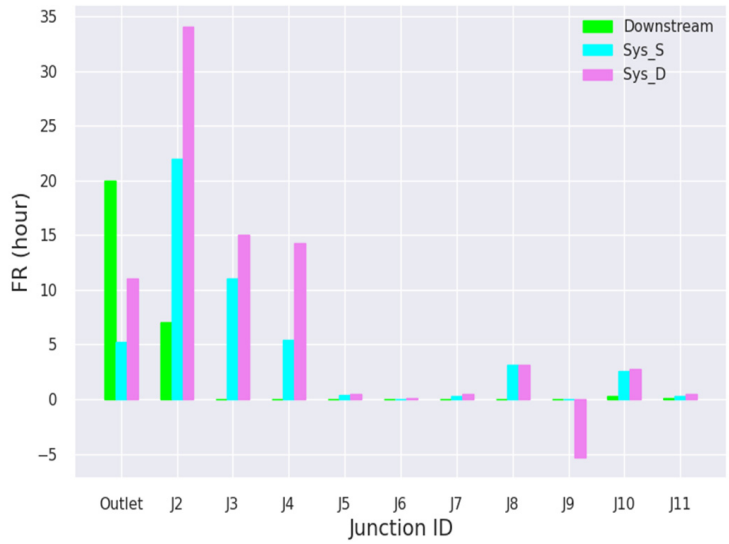
In terms of total suspended solids (TSS) removal, there is little difference in Pollution Reduction Efficiency (PRE) between the 'Sys_S' and 'Sys_D' strategies. Both system-level controls show significantly higher PRE values compared to the 'Downstream' control (Figure 7c). The 'Sys_S' and 'Sys_D' controls achieve a PRE of over 60%, while the 'Downstream' control remains below 10%, highlighting the advantages of system-level control for water quality improvement. The only exception is detention pond SU11, where the 'Downstream' control reaches a PRE of 35%, closer to the 40% achieved by 'Sys_S' and 'Sys_D'. These results indicate that the downstream actuators have a minimal impact on overall water quality improvements.

System-level control proves to be more effective in reducing water quantity stress (PDSE and FR) at downstream detention ponds with large storage capacities, while it also shows superior performance in improving water quality (PRE) at upstream detention ponds with smaller storage capacities. The size and location of detention ponds play a key role in the effectiveness of RTC in managing water quality and preventing overloading. The simulation results show that PDSE is concentrated in the large downstream detention ponds (SU1, SU2, SU3, and SU4), whereas the most significant PRE improvements occur in the smaller upstream detention ponds (SU8, SU9, SU10, and SU11). This variation in storage size and location allows for shorter detention times and faster TSS transport from the upstream ponds to the downstream ponds.

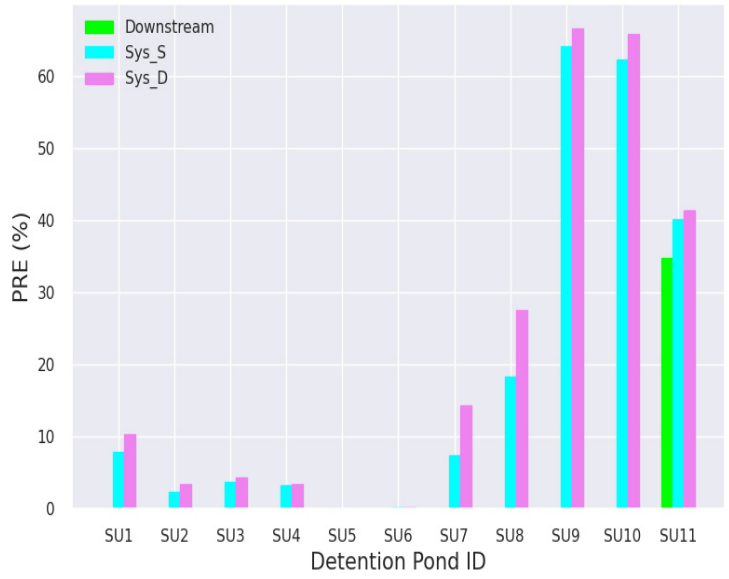


(**a**)

Figure 7. *Cont.*



(**b**)



(**c**)

Figure 7. Comparison of the performance of the three control strategies over the proposed water quantity and quality indexes, (**a**) PDSE), (**b**) FR, and (**c**) PRE, showing system-level control generally outperforms the downstream control.

4. Discussion

4.1. Benefits of Real-Time Control

This study highlights the benefits of system-level RTC to reduce the impacts of flooding and improve water quality. We find system-level control as a trade-off between upstream storage capacity and downstream flooding mitigation [31]. For example, during extreme rainfall, the gate will be closed and water from the storage pond will slowly discharge into the downstream flooded locations in Figure 1. If the gate is closed too much or remains closed too long, there will be overflow issues in upstream detention ponds. Figure 7b exemplifies the negative impacts on flooding duration at junction J9 with increased flooding.

Simulation results indicate the spatial and temporal changes in gate openings by system-level RTC can minimize the risks of system instability, energy consumption, and costs caused by flooding events, similar to previous studies [2,9,32]. In our simulations, the TSS removal efficiencies are around 5% to 10% greater under 'Downstream', 'Sys_S', or

'Sys_D' controls than the baseline. Within this range of TSS removal efficiency, the system-level control outperforms the 'Downstream' and baseline control strategies in removing TSS. From the simulations, the results indicate rule-based control strategies improve water quality and are consistent with prior research [33,34].

We find that RTC performance demonstrates a strong relationship with the size and location of detention ponds. Water depth is a key parameter of detention pond volume and is an essential input variable for most RTC studies [2,35,36]. The storage volume determines how long the facilities can retain stormwater and identifies when the orifice gate should open or close. For instance, the water discharged from the upstream storage basin will propagate to the downstream detention ponds, with outflow driving orifice action and inflow controlling the orifice gate status. Consistent with other research, we find that the optimal controller size selection contributes to the performance of the system-level RTC.

4.2. Opportunities for Improvement and Future Work

We identified four opportunities to improve the effectiveness of the system-level control strategies. Given that this study evaluated controller performance, there is an opportunity to advance the model by calibrating field observations. Calibrating the model using measurements and field testing will support an application-based RTC-system evaluation for assessing the potential realized benefits of integrating system-level RTC into operations. Second, we determined the controller settings of the system-level control strategies (Table 2) using a manual and experimental estimation, which is labor-intensive work. Optimized control algorithms such as model predictive control [37] and fuzzy logic control [17] could reduce computational costs, improve control effectiveness, and increase the effectiveness of systems-level RTC. Third, the research investigates water detention pond depth-based RTC strategies, and there is potential to improve pollutant removal efficiency by up to 60% as using water depths as a driver of gate operations can downgrade RTC performance concerning water quality [38,39]. We found detention pond outflow may be a more appropriate indicator than inflow to improve the system-level control with steady orifice adjustments. A flow-based RTC deserves investigation for improving control behavior. Finally, a forecast-informed RTC framework could more efficiently control the stormwater system by discharging storm volume before extreme events to increase the capacity of the USG to withstand threats and adapt to future uncertainties [2,40,41]. Future work can use observed and projected rainfall sequences to examine the research gaps identified by this study to improve RTC performance.

5. Conclusions

The implementation of smart stormwater real-time control (RTC), guided by rule-based logic, shows promising results in mitigating system-wide water quantity and quality overloading, surpassing the capabilities of individual local controls and uncontrolled systems. The goal of this study is to leverage smart real-time control technology to drive stormwater resilience and sustainability research. We presented the design, implementation, and evaluation of various system-level RTC strategies using multiple performance indexes, including peak depth shaving efficiency (PDSE), pollutant removal efficiency (PRE), and flooded-hour reduction (FR), from upstream to downstream target sites. The research findings are valuable for engineers and operators as the RTC simulation strategy identifies vulnerable sites before peak flow events and helps inform valve, gate, and pump rules to optimize efforts and minimize frequent operations. This study reveals three key findings:

(1) The dynamic adjustments in orifice gate settings, driven by events, offer researchers and practitioners the opportunity to examine how system-level RTC strategies effectively tackle hydraulic variations in water depth, outflow, and inflow within the stormwater system. Among these hydraulic indicators, it is evident that the outflow from detention ponds plays a crucial role as a system-level RTC indicator, influencing gate operations. Through simulations of control rules and water quantity indicators,

local stormwater management can proactively implement measures to avert system instability and mitigate disruptions during extreme events.

(2) System-level control demonstrates superior performance compared to other controls in improving water quality and reducing floods. The system-level RTC surpasses individual downstream and baseline control strategies, yielding significant improvements such as a PDSE of up to 7.3% (compared to 1.4%), PRE of up to 67% (compared to 35%), and FR of up to 34% (compared to 20%). The individual downstream controls exhibit the most effective reduction in outlet flooding duration among all evaluated control methods.

(3) A valuable insight from this study is the impact of storage control placement on UDS performance and translatability to other systems. We found that downstream-controlled storage assets with large volumes substantially alleviate hydraulic stress, while upstream-controlled storage ponds with smaller volumes effectively remove total suspended solids. The findings should inform the design and redesign of urban stormwater collection systems, including how storage site selection and capacity optimization can enhance the benefits of reducing water quantity and quality overloading.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w16213078/s1, Figure S1: Spatial and temporal changes of the orifice opening percentage on 'Sys_S' control scenario (orifices OR 1, 4, and 9 are presented in the main text of manuscript). Figure S2: Spatial and temporal changes of the orifice opening percentage on 'Sys_D' control scenario (orifices OR 1, 4, and 9 are presented in the main text of manuscript).

Author Contributions: Conceptualization, J.L.; Data curation, J.L.; Formal analysis, J.L.; Investigation, J.L.; Methodology, J.L.; Funding acquisition, R.J and J.L.; Resources, J.L; Software, J.L.; Validation, J.L.; Visualization, J.L.; Writing—original draft, J.L.; Writing—review and editing, J.L., R.J. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data and models used in this study can be accessed upon the request of the corresponding author.

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

References

1. Van der Werf, J.A.; Kapelan, Z.; Langeveld, J. Real-time control of combined sewer systems: Risks associated with uncertainties. *J. Hydrol.* **2023**, *617*, 128900. [CrossRef]
2. Li, J.; Burian, S. Evaluating real-time control of stormwater drainage network and green stormwater infrastructure for enhancing flooding resilience under future rainfall projections. *Resour. Conserv. Recycl.* **2023**, *198*, 107123. [CrossRef]
3. Shao, W.; Keim, B.D.; Braud, D.H. Adaptation of Urban Drainage Systems to Climate Change: A Case Study in the Gulf Coast Region, USA. *J. Hydrol.* **2020**, *586*, 124857. [CrossRef]
4. Liu, W.; Zhao, X.; Li, W. A Guide to Urban Flood Risk Management under Climate Change: Strategies and Practices. *J. Environ. Manag.* **2021**, *284*, 112024. [CrossRef]
5. Sharma, D.; Kumar, P. Green Infrastructure and Climate Change Resilience: Evaluating the Effectiveness of Urban Planning Strategies. *Environ. Sci. Policy* **2022**, *127*, 141–151.
6. Casal-Campos, A.; Fu, G.; Butler, D.; Moore, A. An Integrated Environmental Assessment of Green and Gray Infrastructure Strategies for Robust Decision Making. *Environ. Sci. Technol.* **2015**, *49*, 8307–8314. [CrossRef]
7. Tavakol-Davani, H.; Burian, S.J.; Devkota, J.; Apul, D. Performance and cost-based comparison of green and gray infrastructure to control combined sewer overflows. *J. Sustain. Water Built Environ.* **2016**, *2*, 04015009. [CrossRef]
8. Sun, L.; Xia, J.; She, D.; Ding, W.; Jiang, J.; Liu, B.; Zhao, F. A predictive fuzzy logic and rule-based control approach for practical real-time operation of urban stormwater storage system. *Water Res.* **2024**, *266*, 122437. [CrossRef]
9. Li, S.; Leitão, J.P.; Wang, Z.; Bach, P.M. A drainage network-based impact matrix to support targeted blue-green-grey stormwater management solutions. *Sci. Total Environ.* **2024**, *912*, 168623. [CrossRef]
10. Kerkez, B.; Gruden, C.; Lewis, M.; Montestruque, L.; Quigley, M.; Wong, B.; Bedig, A.; Kertesz, R.; Braun, T.; Cadwalader, O.; et al. Smarter stormwater systems. *Environ. Sci. Technol.* **2016**, *50*, 7267–7273. [CrossRef]
11. Troutman, S.C.; Love, N.G.; Kerkez, B. Balancing water quality and flows in combined sewer systems using real-time control. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 1357–1369. [CrossRef]

12. Creaco, E.; Campisano, A.; Fontana, N.; Marini, G.; Page, P.R.; Walski, T. Real time control of water distribution networks: A state-of-the-art review. *Water Res.* **2019**, *161*, 517–530. [CrossRef] [PubMed]
13. Hathaway, J.M.; Bean, E.Z.; Bernagros, J.T.; Christian, D.P.; Davani, H.; Ebrahimian, A.; Fairbaugh, C.M.; Gulliver, J.S.; McPhillips, L.E.; Palino, G.; et al. A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges. *J. Sustain. Water Built Environ.* **2024**, *10*, 04023014. [CrossRef]
14. Feng, W.; Lei, X.; Jiang, Y.; Wang, C.; Liao, W.; Wang, H.; Xinghui, G.; Feng, Y. Coupling model predictive control and rules-based control for real-time control of urban river systems. *J. Hydrol.* **2024**, *636*, 131228. [CrossRef]
15. Zhang, P.; Cai, Y.; Wang, J. A simulation-based real-time control system for reducing urban runoff pollution through a stormwater storage tank. *J. Clean. Prod.* **2018**, *183*, 641–652. [CrossRef]
16. Kroll, S.; Fenu, A.; Wambecq, T.; Weemaes, M.; Van Impe, J.; Willems, P. Energy optimization of the urban drainage system by integrated real-time control during wet and dry weather conditions. *Urban Water J.* **2018**, *15*, 362–370. [CrossRef]
17. Li, J. A data-driven improved fuzzy logic control optimization-simulation tool for reducing flooding volume at downstream urban drainage systems. *Sci. Total Environ.* **2020**, *732*, 138931. [CrossRef]
18. Muschalla, D.; Vallet, B.; Anctil, F.; Lessard, P.; Pelletier, G.; Vanrolleghem, P.A. Ecohydraulic-driven real-time control of stormwater basins. *J. Hydrol.* **2014**, *511*, 82–91. [CrossRef]
19. Sharior, S.; McDonald, W.; Parolari, A.J. Improved reliability of stormwater detention basin performance through water quality data-informed real-time control. *J. Hydrol.* **2019**, *573*, 422–431. [CrossRef]
20. Sun, C.; Puig, V.; Cembrano, G. Real-time control of urban water cycle under cyber-physical systems framework. *Water* **2020**, *12*, 406. [CrossRef]
21. Wong, W.K.; Xu, S.; Liao, Z. Dynamic Overflow Risk Management in Urban Drainage Systems: A Machine Learning Approach for Real-Time Control. *Water Res.* **2022**, *216*, 118277. [CrossRef]
22. Parker, E.A.; Grant, S.B.; Sahin, A.; Vrugt, J.A.; Brand, M.W. Can smart stormwater systems outsmart the weather? Stormwater capture with real-time control in southern California. *ACS EST Water* **2021**, *2*, 10–21. [CrossRef]
23. Sadler, J.M.; Goodall, J.L.; Behl, M.; Bowes, B.D.; Morsy, M.M. Exploring real-time control of stormwater systems for mitigating flood risk due to sea level rise. *J. Hydrol.* **2020**, *583*, 124571. [CrossRef]
24. Sun, L.; Xia, J.; She, D.; Guo, Q.; Su, Y.; Wang, W. Integrated intra-storm predictive analysis and real-time control for urban stormwater storage to reduce flooding risk in cities. *Sustain. Cities Soc.* **2023**, *92*, 104506. [CrossRef]
25. Schmitt, Z.K.; Hodges, C.C.; Dymond, R.L. Simulation and assessment of long-term stormwater basin performance under real-time control retrofits. *Urban Water J.* **2020**, *17*, 467–480. [CrossRef]
26. Emerson, C.H.; Welty, C.; Traver, R.G. Watershed-scale evaluation of a system of storm water detention basins. *J. Hydrol. Eng.* **2005**, *10*, 237–242. [CrossRef]
27. Sharior, A.; Zhang, Y.; Zhou, H. Real-Time Control of Urban Drainage Systems Using Ecohydraulic Models: An Optimization Approach. *J. Hydrol.* **2023**, *612*, 128271.
28. Rimer, S.P.; Mullapudi, A.; Troutman, S.C.; Ewing, G.; Bowes, B.D.; Akin, A.A.; Sadler, J.; Kertesz, R.; McDonnell, B.; Montestruque, L.; et al. Pystorms: A simulation sandbox for the development and evaluation of stormwater control algorithms. *Environ. Model. Softw.* **2023**, *162*, 105635. [CrossRef]
29. Mullapudi, A.; Lewis, M.J.; Gruden, C.L.; Kerkez, B. Deep reinforcement learning for the real time control of stormwater systems. *Adv. Water Resour.* **2020**, *140*, 103600. [CrossRef]
30. Tryby, M.E.; Buahin, C.A.; McDonnell, B.E.; Knight, W.J.; Fortin-Flefil, J.; Vandoren, M.; Eckenwiler, S.; Boyer, H. Intelligent control of combined sewer systems using PySWMM—A python wrapper for EPA's stormwater management model. *Environ. Model. Softw.* **2024**, *179*, 106114. [CrossRef]
31. Li, J.; Yang, X.; Sitzenfrei, R. Rethinking the framework of smart water system: A review. *Water* **2020**, *12*, 412. [CrossRef]
32. Gomes, M.N., Jr.; Taha, A.F.; Rápalo, L.M.C.; Mendiondo, E.M.; Giacomoni, M.H. Real-time regulation of detention ponds via feedback control: Balancing flood mitigation and water quality. *J. Hydrol.* **2024**, *643*, 131866. [CrossRef]
33. Meng, X.; Li, X.; Nghiem, L.D.; Hatshan, M.R.; Lam, K.L.; Wang, Q. Assessing the effectiveness of site real-time adaptive control for stormwater quality control. *J. Water Process Eng.* **2023**, *56*, 104324. [CrossRef]
34. Shishegar, S.; Duchesne, S.; Pelletier, G.; Ghorbani, R. A smart predictive framework for system-level stormwater management optimization. *J. Environ. Manag.* **2021**, *278*, 111505. [CrossRef]
35. Wong, B.P.; Kerkez, B. Real-Time Control of Urban Headwater Catchments Through Linear Feedback: Performance, Analysis, and Site Selection. *Water Resour. Res.* **2018**, *54*, 7309–7330. [CrossRef]
36. Di Matteo, M.; Liang, R.; Maier, H.R.; Thyer, M.A.; Simpson, A.R.; Dandy, G.C.; Ernst, B. Controlling rainwater storage as a system: An opportunity to reduce urban flood peaks for rare, long duration storms. *Environ. Model. Softw.* **2019**, *111*, 34–41. [CrossRef]
37. Sweetapple, C.; Webber, J.; Hastings, A.; Melville-Shreeve, P. Realising smarter stormwater management: A review of the barriers and a roadmap for real world application. *Water Res.* **2023**, *244*, 120505. [CrossRef] [PubMed]
38. Oh, J.; Bartos, M. Model predictive control of stormwater basins coupled with real-time data assimilation enhances flood and pollution control under uncertainty. *Water Res.* **2023**, *235*, 119825. [CrossRef]

39. Sharma, A.K.; Vezzaro, L.; Birch, H.; Arnbjerg-Nielsen, K.; Mikkelsen, P.S. Effect of climate change on stormwater runoff characteristics and treatment efficiencies of stormwater retention ponds: A case study from Denmark using TSS and Cu as indicator pollutants. *Springerplus* **2016**, *5*, 1984. [CrossRef]
40. Xu, W.D.; Fletcher, T.D.; Burns, M.J.; Cherqui, F. Real-Time Control of Rainwater Harvesting Systems: The Benefits of Increasing Rainfall Forecast Window. *Water Resour. Res.* **2020**, *56*, e2020WR027856. [CrossRef]
41. Lee, E.H.; Kim, J.H. Development of resilience index based on flooding damage in urban areas. *Water* **2017**, *9*, 428. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.