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Modeling the Effectiveness of Rain Barrels, Cisterns, and Downspout Disconnections for Reducing Combined Sewer Overflows in a City-Scale Watershed

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Abstract

Green Infrastructure / Low Impact Development (GI/LID) is an increasingly popular strategy to manage urban stormwater for individual properties, but the aggregate effect on runoff reduction at the city scale has not been thoroughly investigated. This study examined the potential combined effects of rain barrels, cisterns, and downspout disconnections on combined sewer overflows (CSOs) for a medium-sized urban center. To support a citywide analysis, a novel simulation strategy was implemented using the Storm Water Management Model (SWMM). In this new approach, a *modeling at the source* technique for subcatchment delineation was combined with a set of R-language utilities to automatically configure GI/LID management scenarios. The reconfigured SWMM model was used to examine 99 distinct management scenarios based on different sizes, numbers, and locations of the targeted GI/LID features for the city of Buffalo, New York. For a typical hydrologic year, the deployment of large residential rain barrels (1000-gallon) resulted in up to a 12% reduction in predicted CSO volume, while the inclusion of large commercial-roof cisterns (5000-gallon) contributed up to an additional 12% reduction. Large variations in the predicted CSO reductions were observed across the various management scenarios, and the simulation tools were able to identify locations where the GI/LID features were most effective. In general, the *modeling at the source* approach and the R-language tools substantially enhanced the utility of SWMM for evaluating the effectiveness of GI/LID deployment as a CSO management strategy at the city scale, and the methodology can readily be adapted to cities with similar CSO issues.

Keywords Combined sewer overflow · GI/LID · Rain barrel · Cistern · Downspout disconnection · City-scale watershed

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1 Introduction

Urbanization alters the natural hydrological cycle by replacing pre-development vegetated areas with impervious surfaces (McGrane 2016). Urban catchments typically exhibit reduced evapotranspiration and infiltration, leading to higher runoff peaks and volumes (Shuster et al. 2005; Rodrigues et al. 2021). Urban runoff conveys pollutants that cause sedimentation problems in the sewer system and water quality impairments (Fontecha et al. 2021 and 2020). For cities with combined sewer systems (i.e., stormwater and sanitary flow in the same pipes), excessive runoff can cause the discharge of untreated wastewater as combined sewer overflow (CSO) to receiving water bodies (Saharia et al. 2019).

Green Infrastructure / Low Impact Development (GI/LID) is an increasingly popular approach for CSO control; typical features include rain barrels (RBs), cisterns, downspout disconnection (DSD), porous pavement, green roofs, and so on. GI/LID features reduce runoff and provide additional benefits to the urban community that include reduction of urban heat island effects and conservation of ecosystem functions (Benedict and McMahon 2002; Gill et al. 2007; Brears 2021). RB and cistern are two popular GI/LID features consisting of storage tanks located near rooftops to capture rainwater before it flows into the sewer system (Steffen et al. 2013). They manage stormwater on-site while providing harvested rainwater for potable or other use (Litofsky and Jennings 2014). DSD redirects runoff from rooftops to lawns or other pervious surfaces. The low cost, simple installation, and low maintenance of DSD make it a compelling strategy for runoff mitigation of residential and commercial rooftops. Because they all operate on rooftop runoff and can be deployed together, RBs, cisterns, and DSDs were selected as the targeted GI/LID features for this study.

The hydrologic efficacy of GI/LID can be typically assessed through field monitoring and/or numerical modeling. Field monitoring provides measured data on the performance of an already built GI/LID at the local site scale, while numerical models can assess GI/LID effectiveness at larger scales and can be configured to represent future scenarios of interest such as climate change and urbanization trends; as such, modeling is an essential tool to evaluate the potential effectiveness of GI/LID design plans. Most previous studies of RBs, cisterns, and/or DSDs have typically focused on a single rooftop for performance analysis (e.g. Campisano et al. 2017; Litofsky and Jennings 2014; Steffen et al. 2013). Few studies have addressed the combined effects of a large number of RBs, cisterns, or DSDs using a large-scale hydrological model (Ahiablame et al. 2013; Chen et al. 2019; Liu et al. 2015; Walsh et al. 2014). From a modeling perspective, analyzing the effectiveness of GI/LID on overall runoff reduction is relatively easier than CSO reduction since it is not necessary to simulate the complex hydraulic processes governing the subsequent water transport in the sewer system (Montalto et al. 2007; Tavakol-Davani et al. 2016; Tao et al. 2017). As a result, most previous studies address GI/LID features for runoff control rather than CSO control, which could be misleading if the reduction in runoff volume is not similar to that in CSO volume (Ghodsi et al. 2016a, b; Ghodsi et al. 2020; Torres et al. 2020; Jia et al. 2020).

The state-of-the-art urban hydrological models, such as the Storm Water Management Model (SWMM), are typically configured in a semi-distributed fashion. A typical model is composed of a limited number of lumped subcatchments, with each subcatchment is simply divided into pervious and impervious areas to represent different land cover and land use types. For GI/LID analysis, a site suitability analysis must first be performed to identify suitable sites for appropriate GI/LID practices (Chen et al. 2019; Liu et al. 2015; Torres

et al. 2020). For these subcatchments, the relevant GI features can be represented using a GI/LID model to simulate their effects. However, this approach can be perceived as burdensome because of the need for the independent suitability analysis, the significant modifications to already complex hydrological models, and the possible increase in computational processing time.

To address the issues of efficiently evaluating the effectiveness of GI/LID for CSO reduction at the city-scale, we propose a novel *modeling at the source* approach in conjunction with R-language utilities for SWMM modeling. In the *modeling at the source* approach, each unit is composed of up to 13 different overlapping types (lawn, house, street, etc.) of subcatchments that process runoff differently. With these subcatchment classifications, suitable sites for RB, cistern, and/or DSD can be directly determined without a separate suitability analysis. A simple set of R-language utilities was developed to automatically configure different management scenarios for SWMM models based on different sizes, numbers, and locations of GI/LID features. We selected the city of Buffalo, New York, USA, as the case study to analyze and compare the effectiveness of RBs, cisterns, and DSD for reducing CSO volume and activation frequency at the city-scale.

2 Methodology

2.1 SWMM and the Modeling at the Source Approach

SWMM is widely utilized to simulate rainfall-runoff processes and the behavior of GI/LID features (Rossman 2010). SWMM divides the model domain into geographically distinct subcatchments. Each subcatchment can be further divided into subareas that represent pervious/impervious surfaces with/without depression storage. Using the LID tool, SWMM can easily model numerous types of GI/LID features such as rain barrels/cisterns, rain gardens, green roofs, permeable pavements, and vegetative swale (Platz et al. 2020). While the SWMM/LID approaches provide substantial flexibility, practical drawbacks include the need to configure each GI/LID feature individually and the lack of dedicated model output that indicates how much flow is intercepted by the GI/LID (Campisano et al. 2017).

The *modeling at the source* approach utilizes spatially overlapping subcatchments to add relevant details without the need for additional spatial resolution (Gheith and Lu 2018; Gheith et al. 2017). In this method, each unit (traditional SWMM subcatchment) can be represented using up to 13 overlapping source-level subcatchments that represent different hydrologic functions (see Fig. 1). Each of them is represented by a new subcatchment in SWMM. This approach recognizes that different features (roofs, lawns, pavement, etc.) receive and generate runoff differently. It has been successfully utilized for the SWMM models of the city of Buffalo (Arcadis 2018) and several other municipalities.

The benefits of the *modeling at the source* approach are immediately evident in developing alternative scenarios to compare GI/LID strategies. For traditional SWMM models, it may be difficult to identify feasible sites for GI/LID features. For example, for RBs, cisterns, and DSD, potential sites are residential and commercial rooftops. However, a traditional SWMM model may only consider the total impervious area in a subcatchment, without differentiating rooftops from other impervious areas such as parking lots. The *modeling at the source* approach addresses this problem by defining different types of subcatchments. Four of the thirteen source-level subcatchments (see Fig. 1) represent various
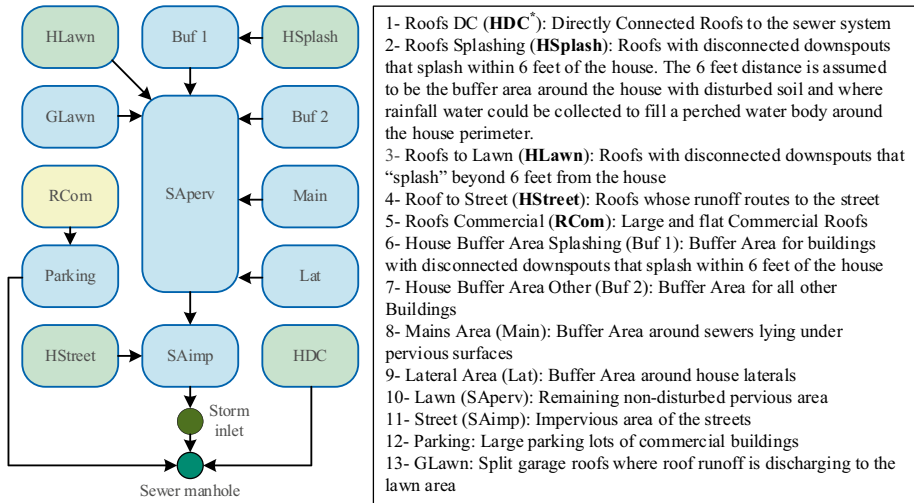
| | | | 1- Roofs DC (**HDC**[*]): Directly Connected Roofs to the sewer system |
| HLawn | Buf 1 | HSplash | 2- Roofs Splashing (**HSplash**): Roofs with disconnected downspouts that splash within 6 feet of the house. The 6 feet distance is assumed to be the buffer area around the house with disturbed soil and where rainfall water could be collected to fill a perched water body around the house perimeter. |

1- Roofs DC (**HDC**[*]): Directly Connected Roofs to the sewer system
2- Roofs Splashing (**HSplash**): Roofs with disconnected downspouts that splash within 6 feet of the house. The 6 feet distance is assumed to be the buffer area around the house with disturbed soil and where rainfall water could be collected to fill a perched water body around the house perimeter.
3- Roofs to Lawn (**HLawn**): Roofs with disconnected downspouts that "splash" beyond 6 feet from the house
4- Roof to Street (**HStreet**): Roofs whose runoff routes to the street
5- Roofs Commercial (**RCom**): Large and flat Commercial Roofs
6- House Buffer Area Splashing (Buf 1): Buffer Area for buildings with disconnected downspouts that splash within 6 feet of the house
7- House Buffer Area Other (Buf 2): Buffer Area for all other Buildings
8- Mains Area (Main): Buffer Area around sewers lying under pervious surfaces
9- Lateral Area (Lat): Buffer Area around house laterals
10- Lawn (SAperv): Remaining non-disturbed pervious area
11- Street (SAimp): Impervious area of the streets
12- Parking: Large parking lots of commercial buildings
13- GLawn: Split garage roofs where roof runoff is discharging to the lawn area

Fig. 1 Subcatchments included in the modeling at the source approach. * Bold items are discussed in detail in the following sections

types of residential roof subcatchments (HDC, HLawn, HSplash, and HStreet) and RCom represents commercial rooftops.

2.2 Automating Modeling Processes using R-language Utilities

A typical city-scale SWMM model could include thousands of subcatchments that are potentially suitable for one or multiple types of GI/LID. Thus, an enormous number of CSO management scenarios could be configured based on different sizes, numbers, and locations of GI/LID features, so assembling manually would be practically infeasible. To address this issue, we developed a set of R-language utilities to automate the processes of I) building scenarios and configuring SWMM input files, II) running SWMM models, and III) post-processing the modeling results (Fig. 2). More details on the pre- and post-processing processes can be found in the Supplementary Material. The developed R codes are publicly available at *https://github.com/HamedGhodsi90/CSO-Activation-Function*.

3 Case Study

The city of Buffalo, NY, USA, located at the eastern end of Lake Erie, has a current population of approximately 256,000 people. The city maintains approximately 1,368 km of sewer lines, of which 1,271 km are combined sewers. There are 53 permitted CSO outfalls. For compliance modeling, CSO discharges are assessed through 253 locations within the collection system that are designated as Sewer Patrol Points (SPPs), in part because SPPs can be more reliably monitored in the field. Therefore, in the Results and Discussion that follow, references to CSO "overflow" and "activations" are directed at the simulated SPP associated with each CSO rather than the CSO outfalls.
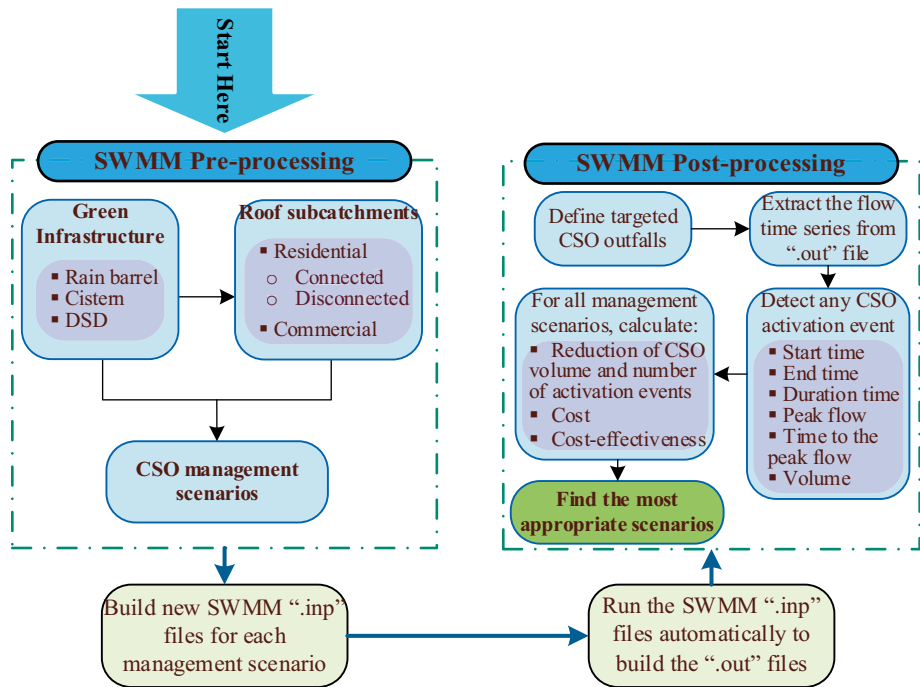
Fig. 2 Methodology for modeling and analyzing CSO reduction strategies

3.1 The City of Buffalo SWMM Model

The urban hydrological model for the city of Buffalo was developed and recently updated by Arcadis using SWMM and the *modeling at the source* approach (Arcadis 2018). The Buffalo SWMM model includes 8,839 junctions, 4,217 storages, 9,201 conduits, 8 pumps, 4,194 orifices, and 271 weirs, while the surface hydrology is represented by 59,725 source-level subcatchments over 6,764 spatially distinct geographic areas.

The Buffalo SWMM model has been calibrated to flow volumes and peak flows measured at 112 flow meters located at SPPs, for the period of September 2016 to June 2017 (excluding January and February, two-month winter dormancy period). The calibration occurred in two phases: I) under dry weather conditions and II) under wet weather conditions. The calibration used a continuous period covering different seasons, so the model can properly represent the interaction of time-dependent phenomena between, during, and after discrete wet-weather events. The model was also evaluated for the post-calibration monitoring period of July to September 2017 (Arcadis 2018).

3.2 Typical Hydrologic Year

To assess annual average CSO activations for the long-term control plan, the rainfall time series in year 1993 was selected, which has been recognized by regulators (i.e., the New York State Department of Environmental Conservation) as representative of typical

rainfall patterns in the city of Buffalo (Malcolm Pirnie/Arcadis and Buffalo Sewer Authority 2017). The annual rainfall in 1993 is 1,032 mm, which is within a 5% deviation from Buffalo's average annual rainfall from 1941 to 2019, 985 mm. For evaluating GI/LID scenarios, the 7-month freeze-free period between April (the last spring frost) and the end of October (the first fall frost) in 1993 was selected as the study period. The precipitation time series (15-min time interval) for the freeze-free period were obtained from the weather station located at the Buffalo Niagara International Airport (Network ID# GHCND: USW00014733). The total precipitation during this period is 605 mm and the maximum rainfall intensity is 19.3 mm/hr. The rainfall time series is shown in Appendix B. Supplementary data.

3.3 GI/LID Scenarios

Three sizes of RBs for the residential roof subcatchments (HDC, HLawn, HSplash, and HStreet) were considered: 75 gallons (RB-75), 150 gallons (RB-150), and 1000 gallons (RB-1000), with the vertical dimensions of 0.91 m, 1.47 m, and 1.65 m, and areas of 0.31 m^2, 0.39 m^2, and 2.29 m^2, respectively. One size of cistern 5000 gallons (cistern-5000) was considered for the commercial roof subcatchments (RCom). Cistern-5000 has a height of 2.59 m and an area of 7.3 m^2. In addition, typical values were assigned to the drain coefficient (50.8 mm/hour or 2 inches/hour) and the drain delay (12 h) (Abi Aad et al. 2010). They are selected based on available RBs in the market and also cover a wide range of RB/cistern volume.

The potential numbers of RBs and cisterns were based on the areas of the residential and commercial roof subcatchments, respectively. One more RB was assigned for every 186 m^2 of residential roof area (Walsh et al. 2014), while one more cistern was assigned for every 2000 m^2 of commercial roof area. For example, one RB was assigned for a residential roof subcatchment with area $< = 186$ m^2, and two RBs were assigned for a residential roof subcatchment with $186 < area < = 372$ m^2, and so on.

Economic costs for RB-75, RB-150, RB-1000, and cistern-5000 were assigned at $120, $250, $700, and $2,500, respectively. Operation and maintenance costs were specified at approximately 10% of the RB/cistern cost. The DSD operation was estimated as $30 per downspout, based on the assumption of installation by the homeowner. Although these particular unit costs were specified for the case study, any of these values could be easily adjusted to conform to local conditions or to explore cost sensitivity using the post-processing tools developed in this study.

4 Results and Discussion

4.1 Simulated Management Scenarios

The maximum number of potential RBs was 58,781, distributed across residential rooftops as follows: 9,433 in HLawn (roofs to lawn), 32,038 in HSplash (roofs splashing), 3,564 in HStreet (roofs to street), and 13,746 in HDC (directly connected roofs to sewer) (Table 1). A smaller number of cisterns (5,343) were assigned to the commercial rooftops, although the total surface area of commercial rooftops (7.63 km^2) is close to the residential rooftops

Table 1 Number and area of the rooftop subcatchments and GI/LID features. Details of the subcatchments' definition can be found in Fig. 1

	Rooftop subcatchment					Commercial
	Residential					
	HLawn	HSplash	HStreet	HDC	Summation	RCom
Number	4,568	4,690	3,144	4,686	17,088	3,297
Area (km²)	1.31	5.52	0.29	2.11	9.23	7.63
Area (%)	1.3%	5.5%	0.3%	2.1%	9.2%	7.6%
Rain barrel #	9,433 (16%)	32,038 (55%)	3,564 (6%)	13,746 (23%)	58,781	-
Cistern #	-	-	-	-	-	5,343

(9.23 km²). The commercial and residential rooftops represent 7.6% and 9.2% of the total surface area, respectively. Among residential roofs, HSplash has the largest area, followed by HDC and HLawn, while HStreet has the smallest area.

Considering four types of residential and one type of commercial roof subcatchments as well as three different sizes of RBs and one size of the cistern, and the possibility of DSD operation, a total of 99 CSO management scenarios were configured, as shown in Table 2. The baseline scenario (without any GI/LID implementation) was designated as scenario zero (S0). The first scenario (S1) represents the situation in which RB-75 was implemented for HLawn subcatchments. Similar scenarios (S2-S6) implement RB-75 for HSplash, HStreet, HDC, HDC & HStreet, and all residential roof subcatchments, respectively. Similar approaches were applied for scenarios 7 to 12, 13 to 18, and 19 to 24, implementing other sizes of RBs (one RB-150, two RB-150, and RB-1000, respectively). For scenario 25, cisterns were implemented for commercial rooftop subcatchments (RCom). Scenarios 26 to 49 were similar to scenarios 1 to 24 but with cisterns added to the commercial rooftops. For scenario 50, the downspouts were disconnected (DSD approach) for the directly connected rooftops (HDC). Scenarios 76–99 are similar to 1–24 but with DSD implementation for HDC subcatchments. Totally, 99 SWMM input files were configured and the output files were analyzed using the developed R-language utilities.

4.2 Performance of the Management Scenarios

4.2.1 The Baseline Scenario

For the baseline scenario (current condition), a total of 1,194 SPP activation events were predicted during the 7 months (April to October) in 1993, with a total overflow volume of 5.4 million m³ (Mm³). The activations occurred at 142 out of the 253 SPPs (~56%). The spatial distribution of the activation events across all SPPs is shown in Fig. 3. The overflow volume and the number of activations vary greatly among the SPPs, indicating the importance of conducting GI/LID effectiveness analysis at the city scale due to the spatial variations.

Table 2 CSO management scenarios

Scenario	GI type*	Subcatchment*	Scenario	GI type	Subcatchment
0	-	-	1	RB-75	HLawn
2	RB-75	HSplash	3	RB-75	HStreet
4	RB-75	HDC	5	RB-75	HDC & HStreet
6	RB-75	All residential roof subcatchments	7 – 12	RB-150	The same as scenarios 1—6
13 – 18	2 RB-150	The same as scenarios 1—6	19 – 24	RB-1000	The same as scenarios 1—6

Scenario	GI type	Subcatchment	Scenario	Subcatchment
25	Cistern		RCom	
26 –49	Cistern + RB (the same as scenarios 1–24)		RCom (for cistern) & residential roofs	
50	DSD		HDC	
51—74	DSD + RB (the same as scenarios 1–24)		HDC (for DSD) & residential roofs	
75	DSD + Cistern		HDC (for DSD) & RCom (for cistern)	
76—99	DSD + Cistern + RB (the same as scenarios 1–24)		HDC (for DSD) & RCom (for cistern) & residential roofs	

*RB-75: rain barrel 284 L (75 gallons); RB-150: rain barrel 568 L (150 gallons); RB-1000: rain barrel 3785 L (5000 gallons); Cistern: cistern 18,927 L (5000 gallons); Sub-catchment definition details can be found in Fig. 1.
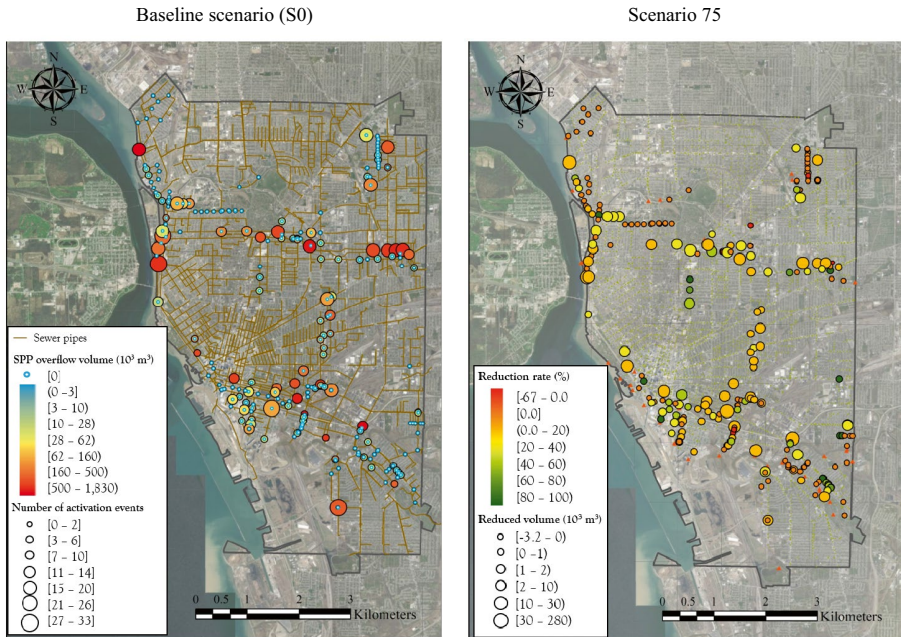
Fig. 3 Map of the City of Buffalo, New York, U.S. Overflow volumes and number of activation events at SPP locations for the baseline scenario (S0) is shown in the left. The colors represent the overflow volume, and the sizes show the number of activation events. In the right, the effect of implementing scenario 75 (DSD operation in HDC subcatchments and cistern-5000 in commercial rooftops) on SPP location is illustrated. The colors represent the volume reduction rate (%) and the sizes show the total volume reduction (Mm^3) in each SPP location

4.2.2 RBs for Residential Rooftops (Scenarios 1–24)

As shown in Fig. 4, for the HLawn subcatchments (S1, 7, 13, and 19), the impacts of small RBs (RB-75 and RB-150) were negligible, while the larger RBs (two RB-150 and RB-1000) decreased the overflow volume and activation events by approximately 1%. The lack of impact for the HLawn subcatchments is due to several factors, including the relatively small roof area (only 1.3% of total area), the high depression storages in the lawn pervious area, and the infiltration capacity. The results imply that installing RBs for residential roofs where roof downspouts already discharge to a lawn (not a sewer) will not be substantially effective on CSO mitigation.

The increased CSO volume for S1 and S7 was unexpected. Although surface runoffs from the HLawn subcatchments were generally reduced, the overall volume of CSOs was found to slightly increase for these two scenarios. After a series of numerical experiments to examine parameter sensitivity and possible discretization artifacts, the explanation for the counterintuitive S1/S7 behavior remained unclear. However, it is noted that the simulated differences in CSO volume were very small compared to the total CSO volume (<0.3%), which can be neglected. Nonetheless, such findings highlight the need for caution in applying large-scale hydrological models to analyze the effect of individual small-scale GI/LID features.
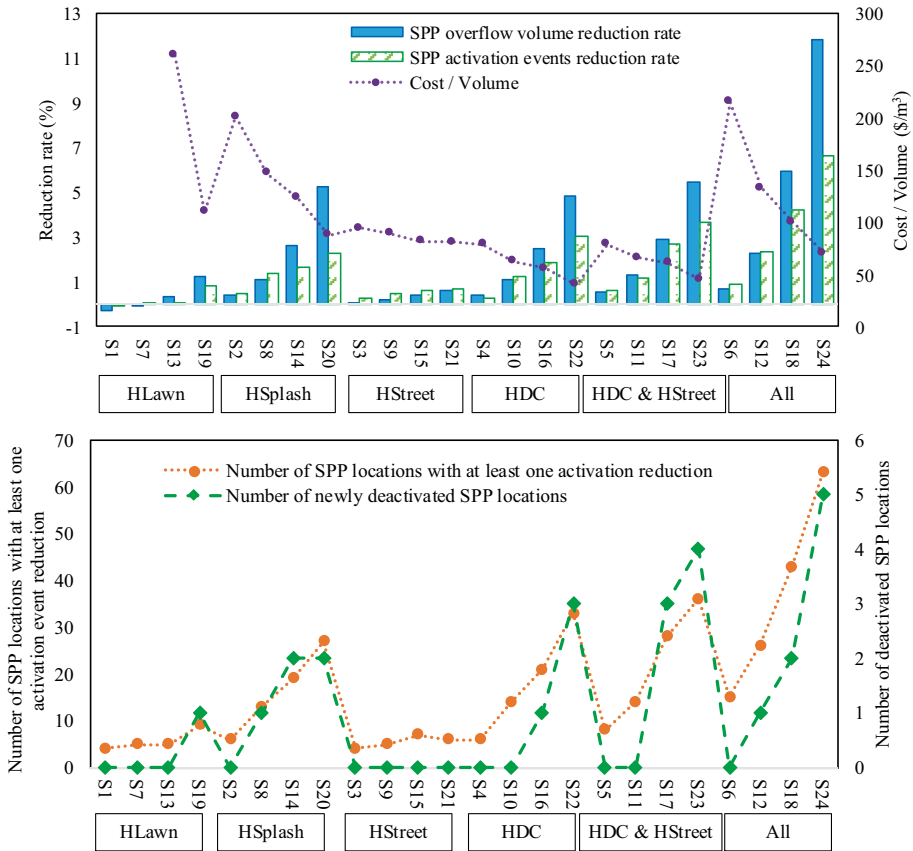
Fig. 4 a) The reduction rate of SPP overflow volume and activation events, and the normalized cost index (cost per m^3 of CSO volume reduction). b) The number of SPP locations with at least one activation reduction and the number of SPP locations that are completely deactivated (i.e., no CSO event). HLawn: Roofs to Lawn (beyond 6 feet from the house); HSplash: Roofs Splashing (within 6 feet from the house); HStreet: Roofs to Street; HDC: Roofs DC; All: HLawn & HSplash & HStreet & HDC

When RBs were implemented for the HSplash subcatchments (S2, 8, 14, and 20), total CSO volume was reduced by up to 5% and the number of activation events was reduced by 2%. The larger impact reflects the fact that the HSplash subcatchments account for 55% of the rooftop area (5.5% of the total area). However, the greater impact is associated with a higher cost. In general, it becomes more cost-effective as the RB size increases. The most cost-effective scenario is RB-1000, which has a normalized cost of $87.2/m^3 of CSO volume reduction.

For the HStreet subcatchments (S3, 9, 15, and 21), the low reductions in CSO volume and frequency (less than 1%) can be attributed to the small area of the subcatchments. For the HDC subcatchments (S4, 10, 16, and 22), the implementation of RB-1000 can result in reductions up to 0.26 Mm^3 of CSO volume and 36 activation events (approximately 3%). RB-1000 for HDC subcatchments (S22) is the most cost-effective among scenarios 1–24, with a potential volume reduction of approximately 5% at a normalized cost of $40.2/m^3.

Furthermore, the number of activation events is reduced at 33 SPPs (23% of the 144 active SPPs), with three SPPs completely deactivated (no CSO).

Implementing RBs (RB-75, RB-150, two RB-150, and RB-1000) for all residential roof subcatchments (S6, 12, 18, and 24) shows the CSO volume reduction of 0.7%, 2.35%, 6%, and 12%, respectively, and RB-1000 is the most cost-effective ($70.7/m^3). SPP activation events can be decreased in 63 SPPs, with five SPPs becoming completely deactivated. In summary, utilizing RBs for rooftops disconnected to the sewer (HLawn and HSplash) is less cost-effective than the connected rooftops. Moreover, larger RBs with more storage capacity seem generally more cost-effective.

4.2.3 Cisterns for Commercial Rooftops (Scenarios 25–49)

Implementing cistern-5000 for every 2000 m^2 of commercial rooftops (S25) results in a 12% reduction for both the SPP overflow volume and activation frequency. The cost of this scenario was 14.7 million dollars ($23/m^3). The activation events were reduced at 84 SPPs, with seven SPPs completely deactivated. Compared to the RB scenarios, cisterns for commercial rooftops were more cost-effective, presumably because of the larger storage volume.

The results of scenarios 1 to 49 are illustrated in Fig. 5 for a better comparison, which reflect the simultaneous use of cisterns for commercial rooftops and RBs for residential rooftops. The maximum overflow volume reduction among these scenarios occurred in scenario 49, which included the cistern-5000 and RB-1000 in the commercial and residential rooftops, respectively, at the cost of 60 million dollars ($48.3/m^3). The combination resulted in a substantial reduction in overflow volume (23%) and frequency (19%). Activation events were decreased in 112 SPP locations (77% of the total), with 11 completely deactivated.

4.2.4 DSD and Comparison Among the Management Scenarios

Among all management scenarios, the predicted SPP overflow volume reduction ranged from negligible to approximately 24%, while the reduction in SPP activation frequency ranged from negligible to 20%. The lowest normalized cost index ($2.7/m^3) was achieved
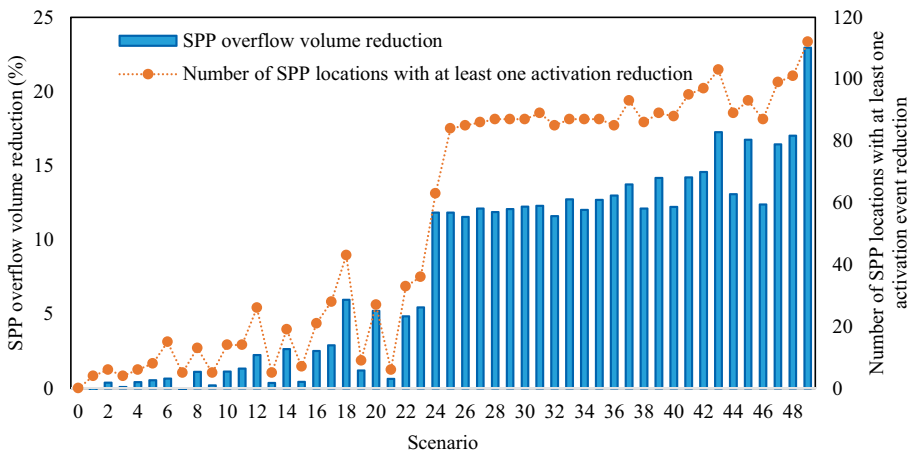

Fig. 5 SPP overflow reduction rate and the number of SPP locations with fewer activation events, for RB/cistern scenarios 0 to 49
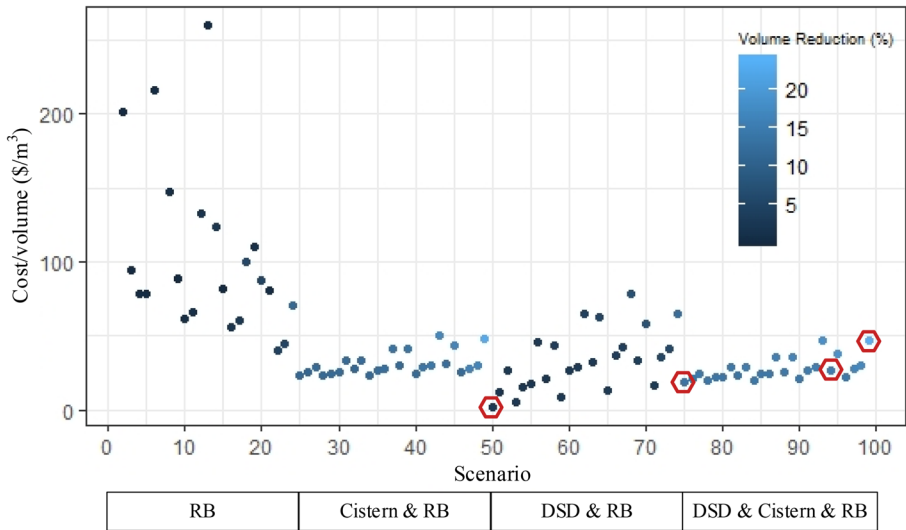
Fig. 6 Normalized cost of the 99 scenarios (red circles indicate the most desirable scenarios: S50 DSD, S75: DSD+Cisterns, S94: DSD+Cistern+RB-1000 HLawn, S99: DSD+Cistern+RB-1000 all)

in scenario 50 (S50). S50 (DSD-only scenario) showed that a 3% reduction in SPP overflow volume and frequency could be achieved with a relatively low cost of 0.4 million dollars, assuming the operation was done by homeowners. Although this scenario was the most cost-effective ($2.7/m³), the potential volume reduction was limited by the number of downspouts available for disconnection.

Figure 6 shows that the RB-only scenarios (S1-24) generate lower CSO reductions at a higher cost. Scenarios that combine DSD with RBs (S50-74) were more cost-effective but achieved only modest reductions in SPP overflow. The most impactful and cost-effective scenarios typically included combinations of DSD and the large-volume RBs and cisterns (red circles in Fig. 6).

Model outputs can also be used to understand the spatial pattern of GI/LID performance. The performance of S75 in terms of volume reduction (m³ and %) at all SPPs is illustrated in Fig. 3. The implementation of the GI/LID in this scenario has the largest effect on SPPs shown by large green circles but does not have much effect on SPPs shown by small red circles. This map can be used to prioritize areas where a particular type of GI/LID is more effective.

5 Conclusion

This study demonstrates how the novel *modeling at the source* approach and R-language utilities can be utilized to evaluate the potential use of GI/LID to reduce stormwater runoff and CSOs at the city-scale. Regardless of the particular results for the illustrative case study, the modeling approach provides flexibility to pursue more focused planning objectives at a high level of detail. Analysis of the management scenarios for Buffalo indicated potential city-wide reductions of CSO volume and frequency of up to 24%, depending on the types and configuration of GI/LID components with residential/commercial rooftops.

In general, the projected reductions corresponded roughly to the land area available for the particular features considered. Further reduction, if desired, would require the deployment of GI/LID to other land types (e.g., streets, parking lots, etc.). DSD was found to be the most cost-effective strategy, cisterns were generally more cost-effective than RBs, and larger RBs were more cost-effective than smaller RBs, although these results were particular to the assumed cost structure and available land surface. The results also identified great spatial variations in CSO volume, as well as the effectiveness of GI/LID on CSO reduction, which means finding the optimal locations of GI/LID can be a promising approach to improve the cost effectiveness.

Although the SWMM model for the city of Buffalo was calibrated and validated, the model performance after adding GI/LID practices cannot be calibrated, which means that the actual effectiveness of the management scenarios' results must be evaluated by post-installation field monitoring. Also, the practical management of RBs/cisterns by homeowners may not conform to modeling assumptions (e.g., 12-h drain delay) and the simulated effectiveness of RBs/cisterns may be overestimated (Jennings et al. 2013). Future research may also address several extensions and refinements, such as including other GI/LID features, applying optimization tools to obtain the optimal GI/LID design, and evaluating GI/LID performance for future precipitation events associated with climate change.

Data Availability Some or all data, models, or code generated or used during the study are available in a repository or online. R-language utilities for SWMM post-processing can be found here: https://github.com/HamedGhodsi90/CSO-Activation-Function.

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