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Development of a scenario-based stormwater management planning support system for reducing combined sewer overflows (CSOs)

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Abstract

Using combined sewer systems to handle excess stormwater runoff is common in older urban areas. Combined sewer overflow (CSO) events occur when hydraulic capacity is exceeded, and untreated wastewater discharges to surface waters. As urban population density increases, and more demand is placed on infrastructure, CSO events happen more often and cause serious environmental problems and public-health risks. Recently, green infrastructure (GI) has been integrated with existing gray infrastructure (GrayI) to reduce CSO events. However, there lacks a goal-oriented planning framework for eliminating CSOs at a watershed/sewershed scale. Moreover, existing stormwater simulations based on catchments or other geographic units, do not consider spatial variation within the unit, such as distribution, attribution, ownership, and management of GI. We propose a scenario-based Stormwater Management Planning Support System for CSOs (SMPSS-CSO) to provide a platform for reducing CSO events by coordinating parcel-based installations of GI. We applied the SMPSS-CSO to a sewershed with a single CSO location in Cincinnati, Ohio and developed four scenarios representing increased use of GI (rain barrels, green roofs, porous pavements, and detention basin) based on its cost, difficulty of installation, and property ownership. Runoff quantity, time of concentration, and peak flow rate were simulated using the curve number method. Our analysis shows a 41% reduction in stormwater runoff is necessary to eliminate CSO events for a two-year rainfall, required 97.25% of private and 27.59% of public parcels to install GI. GI alone cannot eliminate CSO events in this sewershed and must be incorporated with additional GrayI (e.g., storage tanks, pipes). The SMPSS-CSO has the potential for including multiple stakeholders' preferences and concerns in the searching for preferable scenarios.

Keywords

CSO; stormwater management; green infrastructure; scenario planning; planning support system

1. Introduction

The conversion of natural landscapes to impervious areas has modified the hydrology of watersheds by increasing stormwater runoff and flood risks, and decreasing soil infiltration and stream base flow (Dewan, 2013; O'Driscoll et al., 2010; Roy et al., 2014). Many sewer systems in older cities were initially designed to intake stormwater runoff, domestic sewage, and industrial wastewater in a combined sewer system—still a common wastewater conveyance method in many large cities around the world, especially in older systems (Liao et al., 2015). With a sufficient rainfall magnitude, the combined flow overwhelms the capacity of the wastewater treatment system (conveyance system and/or treatment plant), and combined sewer overflow (CSO) events occur, resulting in untreated wastewater and stormwater discharges to surface waters (Alyaseri and Zhou, 2016; Garofalo et al., 2017; Miskewitz and Uchrin, 2013; Ouattara et al., 2014).

For many communities with combined sewer systems, CSOs are one of the greatest challenges in meeting water quality standards (USEPA, 2014) because CSOs contain domestic, commercial, industrial, and stormwater pollution that can cause serious environmental problems and public-health risks (Alliance for the Great Lakes, 2012; USEPA, 2014). Decreasing or eliminating contaminated runoff that enters local natural water bodies from CSOs for many cities across the country is part of a federal mandate issued by United States Environmental Protection Agency (EPA) under the Clean Water Act (Postel and Thompson, 2005; Salzman et al., 2001).

In Cincinnati, Ohio, United States, some CSO events can occur after as little as a 6.5 mm rainfall. In 2016, approximately 26,283 million liters (6,943 million US gallons) of combined flow were discharged into surface waters (mainly Mill Creek and Ohio River) via CSOs (<http://www.projectgroundwork.org/projects/reporting.htm>). CSO events and volumes discharged are likely to increase in the Cincinnati area if stronger storms, higher river levels, and flooding become more frequent and severe as climate patterns change (US Army Corps of Engineers and Ohio River Basin Alliance, 2017). To reduce CSOs and achieve compliance with the Clean Water Act, the Metropolitan Sewer District of Greater Cincinnati has launched one of the largest public works projects in the city's history, called Project Groundwork (<http://projectgroundwork.org/>). In addition, Cincinnati has the comprehensive plan for increasing the amount of green infrastructure (GI) throughout the city to mitigate climate uncertainty and reduce CSO events.

To overcome the problem of CSOs, it is recommended that developed urban areas be retrofitted with Low Impact Development (LID) and Best Management Practice (BMP) to infiltrate, evapotranspire, store, and detain stormwater runoff at different levels of performance and effectiveness (Carpenter et al., 2016; DiBlasi et al., 2009; Li et al., 2009; Lucas and Sample, 2015; Rizzo et al., 2018). LIDs are small-scale, localized source control measures aimed at increasing detention capacity and controlling stormwater runoff in a relatively simple, decentralized, more natural manner (Abi Aad et al., 2010; Damodaram, et al., 2010; Dietz, 2007; Prince George's County, MD, 1999) and include rain barrels or cisterns, green roofs, porous pavements, rain gardens, and others. BMPs are defined as larger scale, centralized approaches that treat stormwater runoff at the end of a drainage area and

are oriented to control pollution from runoff (Fletcher et al., 2014; Gilroy and McCuen, 2009; USEPA, 2000, 2007). Examples include bioswales, tree trenches, vegetated strips, wet/dry ponds, and others. GI has played an important role in the implementation of LIDs and BMPs by using coupled vegetation and soil systems to manage stormwater runoff, expanding natural processes in the built environment, increasing storage, and enhancing infiltration and evapotranspiration (Carpenter et al., 2016). GI provides flexible size, discrete layout, cost-effective investment, environment-friendly design, and other advantages (e.g., ecosystem services) in populated urban areas for stormwater management, compared to gray infrastructure (GrayI; such as, curbs, gutters, and pipe conveyance systems) (Dietz and Clausen, 2008; Gittleman et al., 2017; Moglen et al., 2003; Prince George's County, MD, 1999) in most towns (Fletcher et al., 2014).

Many studies have measured, monitored, or simulated the effectiveness of GI installations at reducing CSO events. However, most field-based case studies have focused only on comparing peak flow and total flow, and pre- and post-implementation of a single type of GI at a site or a block scale. For example, Trowsdale and Simcock (2011) built and monitored a bioretention site to reduce peak flow and increase hydrochemical efficiency. Other studies have shown that green roofs were effective in retaining precipitation during storm events and nutrient losses were low because of successful retention of water (Carpenter et al., 2016; Teemusk and Mander, 2007). The common practice used in simulations of stormwater runoff quantity and quality is to develop scenarios for different types of GI in combination at a watershed scale. For example, Ahiablame and Shakya (2016) simulated four land use scenarios with different amounts of porous pavements, rain barrels, and rain gardens as retrofitting technologies at watershed scale using EPA Storm Water Management Model (SWMM) and concluded LID practices could help reduce runoff and mitigate flooding risk in existing urban areas. Lucas and Sample (2015) compared GI and GrayI scenarios at the block scale and showed that GI provided a more sustainable solution (e.g., minimizing cost, flooding, and erosive flows) than GrayI for CSO event mitigation. They used the Soil Conservation Service Curve Number method to simulate and compare runoff regimes for existing and proposed community gardens in New York City (Gittleman et al., 2017).

Nonetheless, we lack a planning or management practice for an entire watershed or sewershed aimed at eliminating CSO events at designated rainfall intensities (e.g., 2-year rainfall). Although GI provides many advantages for managing water quantity and quality of stormwater runoff, it is likely that a combined green-gray infrastructure approach is necessary to eliminate issues resulting from CSO events. Moreover, simulating and comparing different scenarios for GI installations, before implementation at the watershed scale, provide a suitable framework for planning practices. Oftentimes, frequently used tools to model catchments (e.g., SWMM), arbitrary areas (e.g., National Stormwater Calculator), or other geographic units (e.g., soil unit, administrative area, etc.) overlook how GI is implemented at a parcel-scale and limit public participation in the planning process. Variation within the catchment or geographic unit for spatial distribution, attribution, ownership (private or public), and management or maintenance of GI remains unclear in terms of their impacts and potential.

To address the above-mentioned shortcomings in studies of GI implementation, we propose a scenario-based Stormwater Management Planning Support System for CSOs (SMPSS-CSO). The purpose of SMPSS-CSO is to provide a platform for modeling different GI practices/options used in conjunction with GrayI to reduce or eliminate CSO events and provide a tool for sewershed management used by decision makers and stakeholders.

Features of SMPSS-CSO include:

1. It is a goal-oriented planning support system (PSS) for which the primary goal is to eliminate CSO events. Different scenarios are developed for various combinations of GI and GrayI at a sewershed scale. Peak flows at specific CSO are simulated and compared. A feedback function makes the scenarios dynamic in searching for CSO event elimination.
2. It is a parcel-based PSS that provides the exact capacity and location of GI at legally authorized spatial units--parcels. It can account for the layout of GI, parcel owner responsibilities (e.g., building, maintaining, and managing GI), benefits to land owners, and collaboration of large scale GI, and provide a blueprint of implementation for local planning department.
3. It is a PSS that engages the public and enables multiple stakeholders (households, industrial, commercial, and community agents) to participate in decisions related to GI installation practices for runoff control.
4. It tests alternative scenarios with assumptions reflecting users' preferences.
5. It assists decision-making with scenario comparisons and feedback presented in charts, tables, and maps at individual parcel or aggregated sewershed scales and provides a mechanism for visualization and assessment.

In this paper we first present the architecture of the SMPSS-CSO and methods used for modeling runoff quantity. Then we apply the model in a sewershed (CSO #488) located in the Mill Creek watershed in Cincinnati, Ohio to illustrate the main functions of the SMPSS-CSO. The paper concludes with suggestions to eliminate CSO events for the study area and future improvement of the SMPSS-CSO.

2. Methods

2.1 SMPSS-CSO structure

A PSS combines a group of computer-based methods and models into a system to support a unique professional planning task, in whole or part (Geertman and Stillwell, 2004; Harris and Batty, 1993). It can be used to assist public and community leaders in developing, assessing, and comparing scenarios, and to empower parcel owners and residents to make informed decisions (Fu et al., 2016). The architecture of SMPSS-CSO includes scenario generation, scenario modeling (GI suitability analysis and runoff modeling), and decision-making modules (Fig. 1).

SMPSS-CSO starts with scenario generation that pulls together existing and potential policies relevant to stormwater management practices and assumptions or parameters for scenario modeling. Referring to scenario planning, the baseline scenario (business as usual)

describes a type of development that captures the historical trend and without any additional change in current policy (Varum and Melo, 2010). Considering multiple possible alternative scenarios allows planning in a holistic manner and enhances the ability to deal with uncertainties during the decision-making process (Burt and van der Heijden, 2003; Hiltunen, 2009; Varum and Melo, 2010). Alternative scenarios reflect different development strategies, policies, and preferences for using GI and GrayI in stormwater management. Through scenario generation, users provide storylines and assumptions to define different scenarios. Users can experiment with scenarios based on their preferred types, amounts, locations, and sequences of GI and GrayI installations, and associated social and economic concerns of the community. SMPSS-CSO requires spatial and non-spatial data of the study area to support scenario modeling. It also incorporates public participation by allowing individual residents, neighborhood groups, businesses, planning commissions, or any stakeholder to provide input for selecting the adjustable assumptions and parameters used in scenario generation and modeling, reflecting their thoughts for GI implementation. They, or their representatives, could be recruited and organized by the local planning commission through a public meeting, open house, or other public participation forums (Fu et al., 2016).

The modeling module uses input data, scenario assumptions, and user input to conduct a GI suitability analysis. Results of suitability analyses are presented as consequent scenarios through maps, figures, and tables. Because SMPSS-CSO is an open system, simulation models can be added or removed according to the needs of planners and stakeholders or adjusting the parameters to get the desired modeled outcome. Selecting models related to CSO events, we propose three groups of basic models: runoff quantity, time of concentration, and peak flow rate. Models may be replaced with other models deemed more appropriate for a given site, or other models can be added, such as, adding a runoff water quality model.

Another important component of SMPSS-CSO is how it uses scenario comparison to support planning decisions. SMPSS-CSO conducts “what-if” analyses by comparing the effects of different scenarios, and it helps build consensus among stakeholders on a preferred alternative (Waddell, 2011). In other words, the optimal forecasting outcome will be explored by adjusting scenario parameters, based on resulting indicators, until a desired outcome is reached (FHWA, 2012) (e.g., select the most effective scenario for reducing runoff quantity and peak flow rate from different GI installation scenarios). Simulated peak flows from different scenarios are compared with the activation threshold (flow at which overflow begins) of the target CSO outlet to derive a preferred scenario, or provide feedback to the scenario generation module if the resulting peak flow rate is greater than the capacity of the combined sewer system. Finally, when the maximum amount of GI is installed (e.g., no more available space for GI installations), and no more stormwater runoff reduction is possible or warranted for reasons of cost, additional installation of GrayI (storage) is suggested. SMPSS-CSO is developed with CommunityViz (v5.0; City Explained, Inc., Lafayette, CO), a PSS software and extension of ArcGIS.

2.2 Study area

The City of Cincinnati is the county seat of the Hamilton County, Ohio, United States. The 1.40 km² sewershed associated with CSO #488 lies in the Southern Carthage neighborhood of Cincinnati and is part of the Mill Creek watershed (Fig. 2). The sewer system (i.e., GrayI) consists of 14.48 km of pipe and serves 1016 parcels. When the flow rate of combined stormwater and wastewater sewage exceeds the activation threshold (0.28 m³/s) of CSO #488, the excess effluent is discharged directly into the Mill Creek, bypassing the treatment plant. Dominant land uses (>80%) are public service (civic), industrial, commercial, and single family residential. About 55% of land is privately owned; the City of Cincinnati owns the remaining 45%. The average sanitary peak flow rate during dry weather is 0.021 m³/s for CSO #488.

Most data come from government databases or public websites and are readily available (Table 1). These data include shapes of parcels, impervious surfaces, soil type, sewer lines, slope of terrain, and CSO location, for example. The parcel layer includes parcel id, land use type, ownership, and parcel area in the attribute table. The sewer line shapefile provides segment id, segment type (e.g., gravity), size (e.g., diameter of pipe), shape (e.g., circle), material (e.g., brick, concrete, vitrified clay pipe, etc.), slope, length, and direction of flow (e.g., to CSO point or treatment facility). Land cover data were used to derive pervious surfaces. Driveways, paved parking, and sidewalks were converted from line to polygon features and merged with buildings and road pavement as impervious areas on a given parcel. Tree canopy and other vegetated areas made up pervious surfaces. All data processing and preparation are conducted using ArcGIS 10.5 (ESRI, Redlands, CA).

2.3 GI selection

In urban areas with combined sewer systems, some stormwater runoff goes to the inlets of the combined sewer system, and some runoff enters surface waters. To eliminate CSO events, decentralized installation of GI (i.e., LIDs) can help increase infiltration and detention of stormwater and, therefore, reduce the volume of stormwater runoff entering the sewer system. To illustrate the SMPSS-CSO system, we examined the following GI options: 1) on residential parcels disconnecting downspouts from the stormwater sewer system, installing rain barrels (typically 265 l (~70 gal) each) to capture runoff from roofs, and on industrial/commercial parcels installing green roofs, where appropriate, and rain barrels when a green roof will not work; 2) installing porous pavement to replace existing impervious surfaces for off-street parking lots and private driveways of residential and industrial/commercial parcels; and 3) on city-owned (public) parcels replacing impervious sidewalks with porous pavement and installing a large-scale detention basin (i.e., BMPs). If the volume of stormwater runoff collected exceeds the storage capacity or infiltration rate of the GI, the excess water becomes part of the runoff. There are four types of GI tested in this study to illustrate dataflow and functions of SMPSS-CSO. A more complete analysis would include other GI technologies such as rain gardens, street swales, curb extensions, and wetlands, among others.

GI type, location, and size are finalized based on the suitability analysis. Criteria used for suitability analysis are based on factors following USEPA's stormwater BMPs design guide

(Schueler et al., 2007; USEPA, 2004; Table 2). Soil is categorized into one of four hydrologic soil groups (A, B, C, or D) according to their minimum infiltration rate (NRCS, 1986).

2.4 Runoff quantity modeling

The modeling component of runoff includes three parts—runoff quantity, time of concentration (T_c), and peak flow rate—each of which are existing/established models. We use the curve number (CN) method from Technical Release 55 (TR-55) to estimate runoff (NRCS, 1986). The CN method is widely used to estimate runoff quantity from a given volume of rainfall, and is based on land cover (Chin, 2017; Nidhi et al., 2017; Zhang et al., 2016). This model was selected because 1) it is suitable for small catchment runoff simulations at a parcel-scale; 2) it incorporates the influence of soil type, land cover, and human activities on the process of runoff generation, so management practices can be considered as variables in GI selection and implementation; and 3) it is appropriate because SMPSS-CSO focuses on the event-based runoff quantity and peak flow rate at the outlet of a catchment with decentralized GI, and not on a detailed routing of runoff.

According to the TR-55 report (NRCS, 1986), runoff is estimated from daily precipitation using a retention coefficient S (or I_a) (Eqs.1 to 3):

$$S = \frac{1000}{CN} - 10 \quad (\text{Eq.1})$$

$$I_a = 0.2 * S \quad (\text{Eq.2})$$

$$\text{if } P > I_a, Q = \frac{(P - I_a)^2}{P + 4 * I_a}; \text{ if } P < I_a \quad (\text{Eq.3})$$

where, S is retention coefficient; CN is curve number; I_a is initial abstraction; P is precipitation (in); and Q is runoff depth (in).

CN values refer to TR-55 for urban areas based on hydrologic soil groups and land use. Our study area had four land use categories and three hydrologic soil groups (B, C, and D), resulting in 12 different CN values (Table 3).

T_c is estimated by summing all the travel time for consecutive sections for runoff travel from one location to another in a sewershed. The travel time of the sheet flow within the parcel is not considered in this study. The combined sewage and stormwater travel time in the sewer pipes and Manning's equation (Eq.4 and Eq.5) for water surface profile can be used to estimate average flow velocity (NRCS, 1986).

$$V = \frac{1.49 * r^{\frac{2}{3}} * s^{\frac{1}{2}}}{n} \quad (\text{Eq.4})$$

$$T_c = \frac{L}{3600 * V} \quad (\text{Eq.5})$$

where, V is the average velocity (ft/s); r is the hydraulic radius (ft) of pipe; s is slope of the pipe (ft/ft); n is Manning's roughness coefficient based on pipe material (NRCS, 1986); T_c is time of concentration (hr); L is the longest flow length in pipe (ft).

Peak discharge rate at the outlet is calculated following Eq.6 and Eq.7 (NRCS, 1986):

$$q_p = q_u * A_m * Q * F_p \quad (\text{Eq.6})$$

$$\log_{10}(q_u) = C_0 + C_1 * \log_{10}T_c + C_2 * [\log_{10}T_c]^2 \quad (\text{Eq.7})$$

where, q_p is peak discharge (ft³/s); q_u is unit peak discharge (csm/in or ft³/s per sq. mile of drainage area per inch of runoff); A_m is drainage area (mi²); Q is runoff (in); F_p is pond and swamp adjustment factor (adopting $F_p = 1.00$ for no pond and swamp areas); C_0 , C_1 , C_2 are coefficients obtained from TR-55.

2.5 Combination of GI and GrayI

Some studies have shown the ability of GI for runoff detention is limited, especially in a heavy storm (Ahiablame and Shakya, 2016; Tavakol-Davani et al., 2016; Teemusk and Mander, 2007). Therefore, we propose in SMPSS-CSO a more realistic solution for eliminating CSO events is to use a combination of GI and GrayI. This is needed to increase detention and infiltration capacities and reduce peak discharge rate if the maximum amount of GI is installed on all available parcels, and the peak discharge flow is still more than the activation threshold of the CSO point. Storage utilities, such as tunnels or tanks, were selected in this study because the combined runoff and sewerage are already in pipes or channels. Estimating the capacity of storage utilities is calculated using Eq.8 (NRCS, 1986):

$$\frac{V_s}{V_r} = C_0 + C_1 * \left(\frac{q_o}{q_i}\right) + C_2 * \left(\frac{q_o}{q_i}\right)^2 + C_3 * \left(\frac{q_o}{q_i}\right)^3 \quad (\text{Eq.8})$$

where, V_s is volume of storage utilities; V_r is volume of runoff, q_o is peak outflow discharge; q_i is peak inflow discharge. C_0 , C_1 , C_2 , C_3 are coefficients obtained from TR-55 for rainfall distribution type II (NRCS, 1986).

3. Results

3.1 Scenario development

A baseline scenario and three alternative scenarios were developed, and the type, amount, and allocation of GI are described below for each scenario (Table 4). The sequence for developing alternative scenarios starting with using private parcels and eventually including public parcels; starting with less expensive GI options to more expensive ones; and from easy installations to more difficult options. The baseline scenario is 2017-year land use data without GI installed in the sewershed, and consists of 27% grass land, 15% forest land (trees), 45% impervious areas, and 13% other. Peak flow of runoff is simulated at a specified rainfall intensity (see below).

The first alternative scenario (Alter1, building-related GI) represents installation of rain barrels and green roofs on all suitable private parcels according to suitability criteria (Table 2). Rain barrels are installed on all residential buildings ($n = 680$ buildings) with sloped roofs. The capacity of rain barrels for each roof is set as 0.76 m^3 (200 US gallons). If the rain collection for a 2-year rainfall intensity is less than 0.76 m^3 , the detention volume of rain barrels is adjusted to the actual volume of stormwater collected (Eqs.1–3). The sewershed has 57 buildings with flat roofs suitable for installation of green roofs. The storage capacity of green roofs is calculated using Eqs.1 to 3, based on the roof area and 2-year rainfall intensity. Green roofs can retain stormwater to a depth of 72.6 mm.

The second alternative scenario (Alter2, porous pavement GI) represents installation of porous pavement on driveways and paved parking lots, in addition to the Alter1 scenario. The total area of eligible driveways is $14,331 \text{ m}^2$ and the total area of eligible paved parking lots is $241,549 \text{ m}^2$. The surface of driveways and parking lots will be converted from impervious to pervious surface in the scenario modeling section. Pervious surface is not a standard land cover in TR55 but estimates of $CN = 60\text{--}72$ have been proposed (Ballesterio and Roseen, 2011). We used $CN = 65$ in this study for driveways and paved parking lots converted to porous pavement. The CN value could be adjusted when different, or more appropriate, values are made available.

The third alternative scenario (Alter3, public owned GI) represents, on public-owned land, replacing impervious pavement with porous pavement for sidewalks, and installing a detention basin in addition to the Alter2 scenario. The total area of sidewalks converted from impervious to pervious is $24,837 \text{ m}^2$. For the installation of a detention basin, we identified a drainage area of $50,818 \text{ m}^2$ where the current land use type is grass land. The capacity of the detention basin is designed to receive runoff from the drainage area to store 35.4 m^3 as computed using Eqs.1 to 3 (based on drainage area and 2-year rainfall intensity). Alternatively, the user can set this value based on desired assumptions (see section 3.2).

3.2 User interface for setting assumptions

Scenario design provides storylines and assumptions to define alternative scenarios by reflecting type, amount, allocation, and sequence of different GI installations. CommunityViz software also provides an assumption interface which consists of a slider bar or dropdown list for assigning values that can be set by the user to establish parameters or

assumptions (e.g., rainfall recurrence interval) for scenario modeling (Fig. 3). This function enables the user to change assumptions to achieve desired outcomes or model specific characteristics to generate alternative scenarios. We applied four assumptions in this case study—rainfall recurrence interval, percent of stormwater collected by sewer system, CSO activation threshold, and capacity of detention basin. For example, we used a 2-year rainfall as our selected storm intensity—a depth of 72.6 mm (2.86 in) distributed over 24-hours in the Cincinnati area (Huff and Angel, 1992), but we could have selected other recurrence intervals such as 1-year, 5-year, 10-year, 50-year, 100-year, etc. In developed urban areas, some stormwater runoff will be collected by the inlets of the sewer system and conveyed via pipe or channel to the outlet. The user can set the value of percent runoff collected by the sewer system. The range is 50 to 90 percent and the default value is 70% (Cheri Bush, Metropolitan Sewer District of Greater Cincinnati, personal communication, March 2018). To eliminate CSO events, staying below the activation threshold flow rate of the CSO point is the goal of the SMPSS-CSO. That means GI, or a combination of GI and GrayI, must decrease the peak flow rate at the CSO outlet below the activation threshold to eliminate CSO events. The default value of the third assumption ($0.28 \text{ m}^3/\text{s}$ ($9.9 \text{ ft}^3/\text{s}$)) is the actual activation threshold flow rate for the CSO #488 and values above can result in a CSO event. The slider bar provides a range that tests the influence if the goal is changed. The fourth assumption defines the capacity of the detention basin (35.4 m^3 (1250 ft^3)).

3.3 Scenario comparison

Suitability analysis was conducted to identify suitable locations for different GI types (based on Table 2) and scenarios (Fig. 4). Rain barrels are distributed mainly on the west side of the sewershed because that is where private residential buildings are located, and green roofs are distributed on the east side of the sewershed in the Alter1 scenario. This spatial distribution is due to existing land use patterns. Porous pavements (in Alter2 scenario) on private driveways for single-family are mainly distributed on the west side, and on paved parking lots for multiple-family and commercial-industrial land use are mainly distributed on the east side. Installing porous pavement to replace public owned sidewalk surface (in Alter3 scenario) is mainly along with the main roads in the sewershed. The suitable drainage area is on the east side of the sewershed where we installed the detention basin.

Alter1 scenario installs rain barrels on 680 buildings and green roofs on 57 buildings and utilizes 97.25% of private parcels (Table 4). Alter2 scenario installs $256,173 \text{ m}^2$ porous pavement on driveways and parking lots on about 78% private parcels. Alter3 scenario represents an additional $24,863 \text{ m}^2$ porous pavement on sidewalks and a detention basin (35.4 m^3) in which 27.59% public owned parcels participated.

Four scenarios with different GI installations and assumptions were input into the runoff modeling component. Under the 2-year rainfall event, T_c (0.82 hr) and unit peak discharge, q_u (330.88 csm/in), are the same for all four scenarios based on the same longest pipe lines (12.44 km) in the sewershed (Fig. 2). The average sanitary peak flow rate during dry weather ($0.021 \text{ m}^3/\text{s}$) at CSO #488 is added to the value of q_p for final runoff peak flow rate calculation. Compared to the baseline scenario, Alter1 scenario reduced runoff and peak discharge by 14.17% and 14.12%, accordingly, and increased GI detention volume by 8,172

m³ (storing 5.84 mm stormwater runoff). However, 20,821 m³ of GrayI storage is needed to store 14.87 mm runoff water and reduce the peak flow below the activation threshold of CSO #488 (Fig. 5). The estimated GrayI storage needed for Alter1 scenario is reduced 15.77% storage volume compared to baseline scenario (24,718 m³ for storing 17.66 mm of stormwater runoff).

Alter2 scenario reduced runoff by 38.79% and peak discharge by 38.65% compared to baseline scenario. The installed porous pavement in the Alter2 scenario reduced stormwater runoff by 28.69% and peak discharge by 28.56%, as compared to Alter1 scenario because Alter2 scenario increased infiltration of stormwater runoff with no change in GI detention volume. Accordingly, the estimated GrayI storage needed to reduce the peak flow below the activation threshold of CSO #488 in Alter2 scenario is 14,049 m³ for storing 10.04 mm stormwater runoff, a reduction of 43.16% compared to baseline.

Compared to baseline, Alter3 scenario reduced stormwater runoff and peak discharge by 41.24% and 41.09%, respectively. The porous pavement used for sidewalks along with the use of a detention basin in Alter3 scenario reduced both stormwater runoff and peak discharge by 4%. The GI detention volume in Alter3 scenario increased to 8,207 m³ (storing 5.86 mm stormwater runoff). Accordingly, the estimated GrayI storage needed for Alter3 scenario dropped to 13,370 m³ (storing 9.55 mm stormwater runoff) and reduced 45.91% compared to baseline (Fig. 5).

4. Discussion

It is becoming more common for GI to be considered as a solution for stormwater management in urban areas to help address CSO-related problems. Because there is flexibility in the type and placement of GI, it may be less costly than GrayI, and it can provide a number of ecosystem services and benefits to the population (e.g., Chini et al., 2017; Lucas and Sample, 2015), but it does require maintenance (i.e., it is not an install and forget it technology). Many studies have focused on monitoring or simulating the performance of GI on stormwater runoff control at different scales (e.g., at site- or block-scale; Gittleman et al., 2017; Teemusk and Mander, 2007). We developed SMPSS-CSO as a decision tool for developing and testing scenarios at a sewershed scale to provide an integrated gray-green approach to reduce the occurrence of CSO events. To develop the SMPSS-CSO in CommunityViz for this sewershed, we collected necessary data (e.g., parcel, soil, sewer lines, etc.) to conduct a GI suitability analysis and model stormwater runoff. We included four scenarios, one with baseline conditions as control group and three alternative scenarios that include commonly used types of GI. Suitability analysis identified the amount and location for different GI types, and modeling computed stormwater runoff quantity, time of concentration, and peak flow if all suitable land was converted to GI in the sewershed (we recognize such a level of participation is unlikely but demonstrates the utility of the PSS). The decision-making process was based on comparison between simulated peak flow rated and activation threshold of CSO #488. In addition, GrayI storage was calculated for each scenario if GI could not lower the peak flow rate below the threshold of the CSO.

The goal-oriented feature of SMPSS-CSO sets the goal of the scenario analysis as reduced peak flow at the CSO outlet to a value lower than the activation threshold value (i.e., eliminate CSO events). Thus, the SMPSS-CSO not only simulates the performance of GI in runoff reduction but assesses the required combination of GI and GrayI necessary to reduce peak flow of stormwater runoff in the sewershed and thereby preventing a CSO event. This goal differs from previous studies that focused on the effectiveness of GI in reducing stormwater runoff (e.g., Winston et al., 2016; Zahmatkesh et al., 2015). This parcel-based analysis considers the applicability of implementing decentralized GI, albeit in a highly distributed demonstration, by reducing the amount of impervious surface (e.g., roofs, driveways, parking lots, and sidewalks), estimates the total potential amount or area available for GI on each parcel, and provides an opportunity to calculate potential contributions to runoff control. To demonstrate the application of SMPSS-CSO, we developed four extreme scenarios representing increasing costs of GI (low to high), difficulty of GI installation (easy to difficult), and ownership of parcels (private to public). The final scenario, Alter3 scenario, includes a maximum amount of GI implementation on private and public parcels.

Suitability analysis shows about 97% of private parcels are suitable for installing rain barrels, green roofs, and porous pavement to replace existing driveways and paved parking lots. Because of limited public areas consisting of sidewalks and parking lots (the public infrastructure included in scenarios), public parcel participation is limited to approximately 27%. When GI is installed under the different scenarios, the effectiveness in runoff reduction is categorized into detention function (e.g., rain barrels and green roofs) and infiltration function (e.g., pervious pavement). Under the 2-year rainfall, Alter1 scenario only reduced runoff by about 14% through the detention function. This reduction is not sufficient to eliminate CSO events, therefore, following the feedback loop in SMPSS-CSO, Alter2 scenario was initiated. Alter2 scenario increased infiltration and reduced runoff by almost 28%. The same feedback process initiated Alter3 scenario. Comparing the CSO threshold with the peak flow rate after GI installation, we can estimate the amount of GrayI storage necessary to eliminate CSO events. The results indicate that when installing GI to its maximum extent in this sewershed, GI can reduce peak flow rate almost 41% at the CSO point, yet CSO events will not be eliminated during a 2-year rainfall intensity. Therefore, GrayI is needed to increase the storage capacity in order to reduce the peak flow rate and eliminate CSO events.

The purpose of this study was to introduce SMPSS-CSO by demonstrating modeling conditions; we did not examine the effect of vegetation or tree planting on peak flows. SMPSS-CSO would benefit from testing additional scenarios that utilize more realistic plans, incorporating stakeholder input, or testing on other watersheds or sewersheds. The assumption tool in CommunityViz provides an easy-to-use interface for selecting desired parameters or conditions and running alternative scenarios by decision makers and stakeholders. For example, users can change the rainfall intensity from a 2-year to 5-year rainfall to meet stakeholder concerns, rerun scenarios, and compare results. Further, scenarios could be run that represent predicted changes in extreme rainfall events, future land cover change, or new GI options, for example. In addition, SMPSS-CSO is an open system that allows users to customize their goals, add additional models, change

assumptions and parameters for stormwater runoff to meet the needs of decision-makers. For example, users could change their goal from eliminating CSO events to eliminating flooding and identify the combination of GI and GrayI needed to achieve that goal. In addition, stormwater runoff models that estimate water quality could be added to SMPSS-CSO, if stakeholders are interested in such outcomes.

5. Conclusions

This study provided and illustrated a platform for analyzing the outcomes of installing GI and GrayI to eliminate CSO events. Besides general functions of a PSS (e.g., developing, modeling, and comparing scenarios), SMPSS-CSO is designed specifically for eliminating CSO events using parcel-based GI and determining the amount of GrayI needed to meet stated goals. By comparing the peak flow rate and activation threshold at the CSO point, four scenarios with different GI installations were modeled and the storage needed from GrayI were estimated. As demonstrated here, to put our results into practice and reduce CSO events during 2-year rainfall events, the models indicate policy makers need to encourage almost all private property owners to install suitable GI. In addition, the sewer district or community authority would need to replace suitable impervious sidewalks with porous pavement, build a detention basin, and build a storage utility with 13,370 m³ capacity. The combination of GI and GrayI can drop the peak flow rate under the activation threshold of the CSO #488 and eliminate CSO events for 2-year rainfall or less.

The SMPSS-CSO also supports stakeholder participation in the decision-making process of stormwater management. User input for individual parcel information, the assumption interface for modeling parameters, and the scenario generation module are designed in SMPSS-CSO to provide flexibility for considering users' preferences and concerns. Determining which parcels receive GI encourages multiple agents (households, industrial-commercial, and community stakeholders) to participate in managing stormwater runoff. To inform the public, readily understandable figures and tables are generated to enable straightforward comparison of scenarios and provide estimates of the performance of various options for controlling stormwater runoff. Moreover, SMPSS-CSO can summarize the performance of GI in reducing runoff for each parcel, so property owners can understand their contribution to CSO control at a sewershed scale.

This study develops SMPSS-CSO through a case study using the CN model to illustrate its application. Only limited types of GI are considered; engineering details and requirements for construction of GI and GrayI are not included but could be included in the future. The limitations of CN model are presented in TR-55 and are recognized here. Based on results of this study, the GrayI plays an important role in controlling CSOs in this sewershed. Our next step is to add an assessment module with indicators that quantify the benefits and costs of GI and GrayI in order to present ecological, economic, and social incentives for stormwater management.

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Fig. 1. SMPSS-CSO structure for three main modules, scenario generation, modeling, and decision-making.

Fig. 2.
CSO 488 drainage area is part of the Mill Creek watershed (inset).

Fig. 3.

Assumption interface in the CommunityViz provides the ability to set parameters for planning based on desired levels or characteristics of the sewershed.

Fig. 4.
Spatial distribution of suitable GI for different scenarios based on suitability analysis results.

Fig. 5.
Water balance (bars) for each scenario and peak flow rate (line).

Table 1

Data used to run the scenarios as demonstrated in our example were available as shapefiles.

Data	Description	Source
Parcel	Parcel boundaries including parcel id, land use type, ownership, and parcel area	Cincinnati Area GI Dataset (https://caGI.hamilton-co.org/)
Impervious area	Includes buildings, pavement, driveways, paved parking lots, and sidewalks	
Land cover	Land cover for pervious area, including tree canopy	
Soil	Soil type with hydrologic group	
Slope	Slope of land presented as percent slope	
Sewershed	Shape of sewershed boundary	
Sewer lines	Sewer pipes provides segment id, segment type, size, shape, material, slope, length, and direction of flow	Metropolitan Sewer District of Greater Cincinnati (http://www.msdc.org/)
CSO point	CSO 488 with threshold value	

Table 2

Default criteria or constraints of different types of GI for suitability analysis

GI type	Drainage area (km ²)	Slope (%)	Hydrologic soil groups	Stream buffer (m)	Roof type	Cost
Rain barrel	--	--	--	--	--	Low
Porous pavement	<0.012	<15	A or B	--	--	Medium
Green roof	--	--	--	--	Flat	High
Detention basin	<0.080	<15	A, B, C, or D	>30.48	--	Low

Table 3

CN values related to land use type and hydrologic soil groups

Land use	CN for hydrologic soil group		
	B	C	D
Grass land	61	74	80
Forest land (trees)	58	72	79
Impervious areas	98	98	98
Other open space	79	86	89

Table 4

Conditions simulated for each scenario, including GI type, amount, and percent parcel participation in each of four different scenarios. For each successive scenario, GI is added to conditions in the preceding scenario.

Scenario	Baseline	Alternative 1	Alternative 2	Alterternative 3
GI type	NA	Install rain barrels and green roofs	Replace porous pavement on driveways and parking lots	Replace porous pavement on sidewalks and add detention basin
GI amount (count/m ²)	NA	680 buildings receive rain barrels and 57 buildings receive green roofs	14,332 m ² of driveways and 241,841 m ² of paved parking receive porous pavement	24,863 m ² of porous pavement on sidewalks and a 35.4 m ³ detention basin
Private parcel participation	0%	97.25%	97.25% (Porous pavement: 78%)	97.25%
Public parcel participation	0%	0%	0%	27.59%
	Private	-----→		Public
	Inexpensive	-----→		Expensive
	Easy	-----→		Difficult