A Call to Record Stormwater Control Functions and to Share Network Data

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https://doi.org/10.1061/JSWBAY.0000971

Introduction

Urban stormwater is an ongoing contributor to the degradation of the health of many watersheds and water bodies. In the United States, federal regulations (e.g., Clean Water Act) require monitoring and reporting of relevant water quality metrics in regulated waterbodies to ensure standards are being met. However, decisions about how to manage urban stormwater are left up to state or other local agencies. Although this approach allows for local adaptation and innovation, it has also led to isolated holding of implemented stormwater control data at the city level and inconsistent terminology surrounding stormwater control measures (SCMs) between cities and regions (Fletcher et al. 2015; Minton 2000, 2007; WEF and ASCE-EWRI 2012). In particular, at this time—when the types of SCMs are shifting to include smaller, distributed SCMs (Chocat et al. 2001; Delleur 2003; Roy et al. 2008; WEF and ASCE-EWRI 2012)—the isolated management of SCM inventories is a significant missed opportunity to improve stormwater management through information sharing among cities, agencies, and researchers (Marsalek 2013; Minton 2000; Taira et al. 2018).

As an increasing number of regulated cities seek solutions to protect environmental resources while fulfilling their regulatory obligations, sharing reliable information is imperative, particularly for small and midsize communities that might lack the resources needed to adequately address these issues. Sharing SCM inventories would allow cities seeking to pursue newer approaches to stormwater management to gain insights from cities that have already attempted them. Sharing SCM inventories could also enable cross-watershed comparisons to help isolate and understand the effects of different SCM approaches at the city or catchment scale (Bell et al. 2016; Hale 2016; Hopkins et al. 2020; Jefferson et al. 2017; Marsalek 2013). Furthermore, sharing SCM inventories could move terminology and record-keeping practices toward a more universally interpretable format that conveys details about SCM form and function (Minton 2000; WEF and ASCE-EWRI 2012), which would lead to more consistent sets of design criteria (Minton 2007) and would help practitioners select appropriate SCMs and SCM systems to meet specific objectives (Taira et al. 2018; WEF and ASCE-EWRI 2012).

Here, our overall objective was to address the isolated management of implemented SCM inventory data in the hope of improving the communication, decision making, and evaluation of stormwater management across cities. Our overall objective includes two research questions: (1) Are cities across the United States or within states using comparable SCM nomenclature? and (2) Is it feasible to develop an SCM nomenclature that efficiently and effectively communicates SCM function?

Access to SCM inventories from many cities was required to meet our overall objective of addressing the need for better SCM information sharing (Driscoll et al. 2015; Taira et al. 2018) and to answer our research questions. However, such a database does not currently exist. Therefore, we first collected SCM inventories from several cities (e.g., geospatial data; Choat et al. 2021). Then, we

J. Sustainable Water Built Environ., 2022, 8(2): 02521005

explored SCM terminology in the city inventories and considered function-based nomenclature to address the ability to efficiently and effectively communicate SCM functions (Bell et al. 2019; Fletcher et al. 2015; McPhillips and Matsler 2018; Minton 2000, 2007). We used an existing nomenclature (WEF and ASCE-EWRI 2012) and k-means clustering to determine whether SCMs cluster differently based on the functions of quantity control, pollutant control, biological, or other unit processes.

SCM Inventories and Data Sharing

Background on SCM Network Data Sharing

Efforts to identify challenges in stormwater management often identify the lack of data sharing as an impediment. For example, all but one of 23 municipal officials from communities implementing new SCM types—sometimes collectively known as green infrastructure (GI)—agreed that communication of knowledge from other cities implementing GI is critical to the development of a GI program (Driscoll et al. 2015). For a city that has already adopted GI to share what it has learned allows the newly adopting city to have the insight and know-how related to what has worked and not worked and to inform them of unforeseen challenges. Additionally, a team of transportation drainage experts from agencies in twelve states across the United States highlighted the importance of developing and sharing information and being clear about definitions for a robust approach to GI implementation (Taira et al. 2018).

Efforts to share information about SCMs are ongoing, such as the International Stormwater BMP database (Clary et al. 2002, 2020). However, these efforts are focused on the performance of individual SCMs (i.e., site-scale SCM networks) as opposed to city-scale SCM networks. To achieve all desired outcomes, stormwater management should be designed and applied across site-level and watershed scales (Roy et al. 2008; Taira et al. 2018; WEF and ASCE-EWRI 2012). Information on existing SCMs at the watershed scale would help advance stormwater management to meet watershed goals. Furthermore, to understand ecosystem services provided by SCMs and responses in physical and biological integrity to urbanization, understanding the integrated effects of stormwater (e.g., SCM) networks is essential (Hopkins et al. 2015; Parr et al. 2016; Vogel et al. 2015).

Background on SCM Terminology

When SCM data are available, comparisons among cities are frequently burdened by inconsistent and vague terminology (Bell et al. 2019; Fletcher et al. 2015; McPhillips and Matsler 2018; Minton 2000; Prudencio and Null 2018). Much of the inconsistency can be attributed to an evolution of SCM terms over time and by region, where particular terms might be used in a city or region because they have been designated or defined by the regional regulatory agency (Fletcher et al. 2015). Calls have been made for a simplified SCM nomenclature based on either function (Minton 2000; Shrestha and Brodie 2011; WEF and ASCE-EWRI 2012) or form (i.e., construction materials, SCM sizes, and contributing areas; Bell et al. 2019). Shrestha and Brodie (2011) developed a formal nomenclature focused on physical treatment systems capable of receiving and treating high and variable flow rates and effective at removing suspended solids to a nonpotable water quality. Despite their narrow focus on specific SCM types, the proposed nomenclature, including two primary treatment mechanisms and up to four sublevels, quickly became complex.

Others have proposed simpler function- or process-based nomenclature. Minton (2007) proposed a naming framework that attempted to reduce the number of names used for SCMs that provide the same or similar functions. Minton identified a hierarchy of considerations for naming SCMs. The base consideration was on what principles an SCM is based (e.g., chemistry of precipitation and sorption of pollutants), followed by unit processes (e.g., sedimentation, filtration), unit operations (i.e., the "box" in which unit operations occur or SCM form), and systems (i.e., one or more unit operations). Based on those considerations, Minton then placed SCMs into subfamilies and families (i.e., groups of systems with common key characteristics) that were to be used as SCM names. Minton proposed five families of SCMs, namely, *basins*, *swales*, *filters*, *infiltrators*, and *screens*.

The Water Environment Federation (WEF) and American Society of Civil Engineers' Environmental and Water Resources Institute (ASCE-EWRI) built heavily on Minton's work in WEF Manual of Practice No. 23 and ASCE Manuals and Reports on Engineering Practice No. 87 (WEF and ASCE-EWRI 2012). Similarly to Minton, they produced a nomenclature for SCMs based on the processes provided by them, for which SCMs were grouped based on similar quantity control (e.g., peak flow attenuation, infiltration), pollutant control (e.g., sedimentation, sorption), biological (e.g., plant metabolism, nitrification/denitrification), and other unit processes (e.g., pathogen dieoff, temperature reduction) (Table 1; WEF and ASCE-EWRI 2012). They provided a coarse nomenclature with five groups (MOP-coarse) and a finer nomenclature with 21 groups (MOP-fine). Their MOP-coarse nomenclature consisted of *basins*, *swales and strips*, *filters*, *infiltrators*, and *gross pollutant traps*, nearly identical to the five families of SCMs identified by Minton (2007).

Previous efforts (Minton 2000, 2007; Shrestha and Brodie 2011; WEF and ASCE-EWRI 2012) have highlighted the desire for SCM functions to be easily communicated. They have also made clear that due to overlapping functions between SCMs, it is virtually impossible to use SCM nomenclature alone to communicate all of the information that might be of interest to professionals, researchers, or others in the field regarding SCMs (Minton 2007; WEF and ASCE-EWRI 2012). Despite the clear challenges created by overlapping SCM functions, Minton (2007) expressed hope that his proposed naming convention, which was largely reiterated by WEF and ASCE-EWRI, would be slowly adopted over time by states and provincials and included in city stormwater manuals. By exploring the SCM inventories that we collected, we were able to investigate the extent to which these proposed naming frameworks have been integrated into practice by cities.

SCM Inventory Collection

We attempted to gather SCM inventories from 32 cities and three counties, but three cities and all counties never responded to our request, three cities did not maintain an SCM inventory, and the other three cities were unwilling to share their SCM inventories due to security concerns or because their inventories were incomplete. Twenty-three cities shared SCM inventories through personal communication or via their online access portals (Choat et al. 2021). Although we would have preferred to have received inventories from more cities, we are only aware of existing SCM database comparison studies that include three or fewer cities at a time (Hale 2016; McPhillips and Matsler 2018); therefore, having access to SCM inventories from 23 cities was a significant improvement. The cities included in our study were from eight climatic zones (Fig. 1; Beck et al. 2018). Nine had historic or current combined sewers present, and 15 were MS4 phase I cities with city populations ranging from about 37,000 to more than eight million persons. Seven cities had combined sewers and MS4 phase I permits. We suspected that cities in different climates might use different

Table 1. Nomenclature and associated unit processes

MOP-coarse	MOP-fine	Quantity control: Peak flow attenuation	Quantity control: Runoff volume reduction	Quantity control: Infiltration	Quantity control: Dispersion	Quantity control: ET	Quantity control: Runoff collection usage	Pollutant control: Sedimentation	Pollutant control: Flotation	Pollutant control: Laminar separation	Pollutant control: Swirl concentration	Pollutant control: Sorption
Basins	Wet basins	x	x	—	—	x	x	x	x	—	—	x
	Wetlands	x	x	—	—	x	x	x	x	—	—	x
	Dry basins	x	x	x	—	—	—	x	—	—	—	—
	Vaults and swirl concentrators	x	—	—	—	—	—	x	x	—	x	—
	Oil water separators	—	—	—	—	—	—	x	x	x	—	—
	Forebays	—	—	—	—	—	—	x	x	—	—	—
	Cisterns	—	x	—	—	—	—	x	—	—	—	—
	Basin unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Swales and strips	Swales	—	—	x	x	—	—	—	—	—	—	—
	Strips	—	—	x	x	—	—	x	—	—	—	—
Filters	Sand filters	x	—	—	—	—	—	x	x	—	—	—
	Bioretention	x	x	x	—	x	x	x	x	—	—	x
	Landscaped roofs	x	—	—	x	x	—	—	—	—	—	x
	Drain inlet inserts	—	—	—	—	—	—	x	—	—	—	—
	Manufactured filters	—	—	—	—	—	—	x	—	—	—	—
	Filter unknown[a]	—	—	—	—	—	—	—	—	—	—	—
	Gravel wetland[a]	—	—	—	—	—	—	—	—	—	—	—
Infiltrators	Infiltration basins	x	x	x	—	—	—	x	x	—	—	x
	Infiltration vaults	x	x	x	—	—	—	x	—	—	—	x
	Trenches	x	x	x	—	—	—	x	—	—	—	x
	Dry wells	x	x	x	—	—	—	x	—	—	—	x
	Permeable pavement	x	x	x	—	—	—	—	—	—	—	x
	Infiltration unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Gross pollutant traps	Screens nets baskets racks	—	—	—	—	—	—	—	—	—	—	—
	Hoods	—	—	—	—	—	—	—	x	—	—	—
	Gross pollutant trap other[a]	—	—	—	—	—	—	—	—	—	—	—
	Gross pollutant trap unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Disconnection[a]	Disconnection[a]	—	—	—	—	—	—	—	—	—	—	—
Other[a]	Other[a]	—	—	—	—	—	—	—	—	—	—	—
	Stormwater conveyance[a]	—	—	—	—	—	—	—	—	—	—	—
Unknown[a]	Unknown[a]	—	—	—	—	—	—	—	—	—	—	—

Table 1. (*Continued.*)

MOP-coarse	MOP-fine	Pollutant control			Biological				Other			
		Precipitation	Coagulation	Filtration	Plant metabolism	Nitrification denitrification	Sulfate reduction	Organic compound degradation	Pathogen dieoff	Temperature reduction	Disinfection	Screening
Basins	Wet basins	—	—	—	x	x	x	x	x	—	x	x
	Wetlands	—	—	—	x	x	x	x	x	—	x	—
	Dry basins	—	—	—	—	—	—	—	—	—	—	—
	Vaults and swirl concentrators	—	—	—	—	—	—	—	—	—	—	—
	Oil water separators	—	—	—	—	—	—	—	—	—	—	—
	Forebays	—	—	—	—	—	—	—	—	—	—	—
	Cisterns	—	—	—	—	—	—	—	—	—	—	—
	Basin unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Swales and strips	Swales	—	—	—	x	—	—	—	—	x	—	—
	Strips	—	—	—	x	—	—	—	—	x	—	—
Filters	Sand filters	—	—	x	—	x	—	—	—	—	x	—
	Bioretention	x	x	x	x	x	—	x	—	x	x	—
	Landscaped roofs	—	—	—	x	—	—	—	—	x	—	—
	Drain inlet inserts	—	—	x	—	—	—	—	—	—	—	—
	Manufactured filters	—	—	x	—	—	—	—	—	—	—	—
	Filter unknown[a]	—	—	—	—	—	—	—	—	—	—	—
	Gravel wetland[a]	—	—	—	—	—	—	—	—	—	—	—
Infiltrators	Infiltration basins	x	x	—	—	x	—	x	x	x	x	—
	Infiltration vaults	x	x	—	—	x	—	x	x	x	x	x
	Trenches	x	x	—	—	x	—	x	x	x	x	—
	Dry wells	x	x	—	—	x	—	x	x	x	x	—
	Permeable pavement	x	x	—	—	—	—	x	x	x	x	—
	Infiltration unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Gross pollutant traps	Screens nets baskets racks	—	—	—	—	—	—	—	—	—	—	x
	Hoods	—	—	—	—	—	—	—	—	—	—	—
	Gross pollutant trap other[a]	—	—	—	—	—	—	—	—	—	—	—
	Gross pollutant trap unknown[a]	—	—	—	—	—	—	—	—	—	—	—
Disconnection[a]	Disconnection[a]	—	—	—	—	—	—	—	—	—	—	—
Other[a]	Other[a]	—	—	—	—	—	—	—	—	—	—	—
	Stormwater conveyance[a]	—	—	—	—	—	—	—	—	—	—	—
Unknown[a]	Unknown[a]	—	—	—	—	—	—	—	—	—	—	—

Source: Modified from WEF and ASCE-EWRI (2012, Table 4.2).
Note: Row headings with an [a] under MOP-coarse and MOP-fine were added to the original table to allow all listed SCMs to be placed in a category. Reported unit processes (x) are from the original Table 4.2 (WEF and ASCE-EWRI 2012).

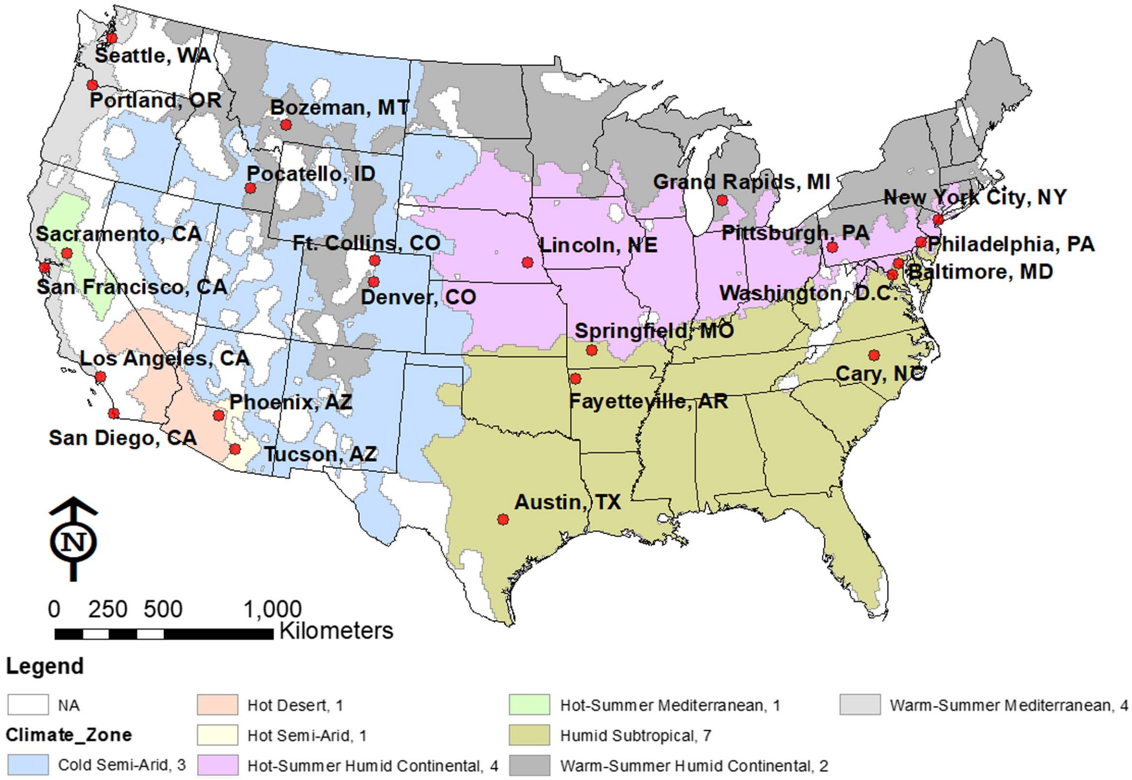

Fig. 1. Map of 23 United States cities. Legend defines Köppen climate zones and presents how many cities fall within each zone. “NA” represents climate regions that do not contain a studied city. (Data from Beck et al. 2018.)

SCM types and that cities with combined sewers or MS4 phase I cities might be more incentivized to record and implement SCMs. Therefore, we felt confident that our 23 cities were reasonably representative of diverse stormwater settings found in cities across the United States.

Of the 23 cities that were able to share their inventories, some had online portals that made downloading the inventories easy, and others had inventories that they were able to send to us. We already had some of the inventories in our possession from previous efforts (e.g., Hale 2016; McPhillips and Matsler 2018). Most of the inventories we received came as geospatial data, whereas some came as lists of SCMs. We did not utilize the spatial attributes of the inventories in this study, but those datasets are available online (Choat et al. 2021) for the cities that allowed us to share their data.

Analysis of SCM Terms and Types (Question 1)

Despite the relatively small number of SCM groups identified by Minton (2007) and WEF and ASCE-EWRI (2012; i.e., five coarse groups or families and approximately 21 fine groups or subfamilies), 378 different terms were listed by the 23 cities in their SCM inventories (Table S1). Although many different terms were used for SCMs, these had little commonality across cities. The SCM term that appeared in the largest number of SCM inventories was *rain garden*, which appeared in nine of 23 cities. *Bioretention*, *green roof*, and *unknown* appeared in eight inventories (Table 2). The inclusion of the surprisingly common term *unknown* implied that these cities were aware of some type of facility but did not know the type of facility. The only other term appearing in seven or more inventories was *dry well*. Table 2 presents the number of cities including each SCM type, the number of times each SCM type was listed in the city inventories, the total number of SCM terms used to describe each type of SCM, and the three most common terms used to describe each SCM type and the number of cities reporting that term.

Because federal regulation leaves the management of stormwater to state and other local agencies, such as state departments of environmental quality, we evaluated whether SCM terms were similar for cities within the same state. Four states had multiple cities with inventories: California, Colorado, Pennsylvania, and Arizona. In California, Los Angeles’ inventory included 13 terms, Sacramento’s included 9, San Diego’s included 11, and San Francisco’s included 33. Out of those, the only common SCM terms used among the cities included *vegetated swale*, which appeared in Sacramento’s and San Diego’s inventories, and *bioretention*, which appeared in San Diego’s and San Francisco’s inventories. In Colorado, Denver’s inventory included 17 terms, and Fort Collins’ included 13. Out of those, only *unknown* appeared in both inventories. In Pennsylvania, Philadelphia included 26 terms, and Pittsburgh included 13. *Porous pavement*, *green roof*, and *other* appeared in both inventories—a small number compared with the total number of terms included. The two SCM inventories from Arizona cities had the fewest SCM terms and the most similar SCM terms out of cities in the same state, suggesting that Arizona cities use a simpler and more standardized nomenclature. Phoenix included eight SCM terms and Tucson included only four. Three of the four terms included by Tucson also appeared in Phoenix’s inventory: *detention basin*, *retention basin*, and *bioretention*.

Unclear is why the cities in Arizona used similar SCM nomenclature, whereas the other cities from a given state did not. We explored three possible explanations. First, we investigated whether the terms appeared in both Arizona inventories simply because few terms were included, and they were rather nonspecific. Only one other city used all three shared terms (i.e., Washington, DC). Second, we investigated whether it was due to both Arizona cities being younger cities that are implementing SCMs in areas of new

Table 2. SCM types and terms

SCM class (coarse[a], fine)	No. of cities including SCM	No. of times listed in inventories	Count of terms	Three most common terms (No. of cities listing term)
Basin[a]	22	32,438	104	"Detention Basin," "Rainwater Harvesting," "Detention Pond"
Dry basin	17	8,987	30	"Detention Basin" (6), "Detention Pond" (4), "Underground Detention" (4)
Cistern	11	12,294	15	"Rainwater Harvesting" (6), "Cistern" (3), "Rain Barrel" (2)
Vaults swirl concentrator	10	7,757	28	"Detention Vault" (2), "Sedimentation Manhole" (1), "Water Quality Vault" (1)
Wet basin	7	667	9	"Wet Pond" (3), "Water Quality Pond" (1), "Detention Pond-Wet" (1)
Wetland	7	261	6	"Wetland" (2), "Constructed Wetland" (1), "Wetland Pond" (1)
Forebay	3	2,066	5	"Sedimentation" (1), "Sedimentation Only" (1), "Sediment" (1)
Basin unknown	3	252	3	"Basin" (1), "Storage" (1), "Subsurface Storage System" (1)
Oil water separator	3	154	6	"Oil-Grit Separator" (2), "Vortechs" (2), "Stormceptor" (1)
Infiltrator[a]	22	20,451	64	"Dry Well," "Porous Pavement," "Infiltration Trench"
Permeable pavement	16	2,794	22	"Porous Pavement" (6), "Permeable Pavers" (5), "Pervious Pavement" (3)
Infiltration basin	13	10,919	22	"Retention Basin" (4), "Infiltration Basin" (4), "Retention Pond" (2)
Dry well	10	2,092	6	"Dry Well" (7), "Infiltration-Dry Well" (1), "Drywell-Aggregate Filled" (1)
Trench	9	4,163	9	"Infiltration Trench" (6), "Soakage Trench" (1), "Trench" (1)
Infiltration unknown	5	464	3	"Infiltration" (4), "Infiltration BMPs" (1), "Infiltration Basin or Trench" (1)
Infiltration vault	1	19	2	"Storm Chamber System" (1), "Leaching Tank" (1)
Filter[a]	20	18,767	75	"Rain Garden," "Bioretention," "Green Roof"
Bioretention	19	12,495	30	"Rain Garden" (9), "Bioretention" (8), "Planter" (2)
Sand filter	9	3,104	16	"Sand Filter" (5), "Sand Filtration" (1), "Underground Sandfilter" (1)
Landscaped roof	9	2,249	8	"Green Roof" (8), "Ecoroof" (1), "Extensive Green Roof" (1)
Filter unknown	4	402	5	"Filtration Only" (1), "Filtering System" (1), "Underground Filter" (1)
Manufactured filter	4	388	7	"StormFilter" (2), "Downspout Filter" (2), "Storm Filter-Canister" (1)
Drain inlet insert	3	118	7	"Drainage Insert" (1), "Fossil Filter" (1), "Inlet with Insert" (1)
Gravel wetland	1	2	1	"Submerged Gravel Wetlands" (1)
Other[a]	18	4,597	35	"Other" (6), "Pond" (2), "Shade Tree" (1)
Unknown[a]	16	2,977	17	"Unknown" (8), "Retention" (2), "Filtration System" (2)
Swales strips[a]	15	13,052	25	"Vegetated Swale," "Grass Swale," "Swale"
Swale	14	9,764	16	"Vegetated Swale" (3), "Grass Swale" (3), "Swale" (2)
Strip	8	3,288	9	"Vegetated Filter Strip" (2), "Swales-Vegetated Filter Strips" (1), "Vegetative Filter Strip" (1)
Gross pollutant trap[a]	11	441,288	21	"Catch Basin," "Inlet," "Drop Inlet"
Gross pollutant trap unknown	10	419,130	8	"Catch Basin" (6), "Inlet" (4), "Drop Inlet" (2)
Screens nets baskets racks	4	21,938	9	"Trench Drain" (2), "Catch Basin Drain" (1), "Grated Inlet" (1)
Hood	3	56	3	"Snout" (2), "Modified Manhole with Snout" (1), "Mechanical Separation" (1)
Gross pollutant trap other	1	164	1	"Debris Basin" (1)
Stormwater conveyance[a]	6	5,615	19	"Culvert" (1), "Storm Water Inlet Drain" (1), "Level Spreader" (1)
Disconnection[a]	4	477	9	"Simple Disconnection to a Pervious Area" (1), "Depaving" (1), "Grass" (1)
None[a]	4	122	8	"None" (1), "Proposed" (1), "CDA to a Shared BMP" (1)
Multiple[a]	1	54	4	"Multiple GI Components" (1), "Dual System" (1), "Aqua-Shield-Filter" (1)

Note: MOP-fine SCMs are listed under the MOP-coarse SCM terms to which they belong. For both MOP-coarse and MOP-fine, the number of cities including that SCM, the total number of times that SCM was listed, the number of terms used to label that SCM, and the three most common terms listed by cities representing that SCM are presented along with the number of cities including that term in their inventory. MOP-coarse SCMs are marked by a superscript "a."

growth, whereas many other cities are retroactively implementing SCMs in already developed spaces. However, the data did not support this concept because Washington, DC is a much older city. The last possible explanation explored is that common SCM nomenclature is related to statewide and/or regional organizations associated with stormwater. However, we did not identify any statewide associations or agencies in Arizona that might be driving more uniform adoption of SCM terms. It could be that Tucson, being in close proximity to Phoenix (~300 km), has referred to Phoenix when making decisions regarding stormwater. Phoenix established the nonprofit organization (STORM, n.d.) in 2002 in response to federal regulations. The nonprofit's focus is on educating the public about protecting the stormwater quality. The existence of such programs might have led to a more uniform regional SCM nomenclature. We also investigated whether any cities across the country were using the same terms. The cities using common terms were simply those that included many terms. Eleven of the top 12 cities that shared terms in common with another city shared those terms with Washington, DC, for example, which included 157 unique SCM terms in its inventory. Baltimore and San Francisco were the only other cities to share more than 4 terms, and they included 29 and 33 SCM terms in their SCM inventories, respectively. Overall, we found that different SCM terms are used by different cities.

We were also curious to see whether any individual city was using redundant terms to describe its SCMs. If it was, then consolidating the redundant terms under a new label would be easy and would help move SCM terminology toward a more standard nomenclature. To investigate this concept, we looked at cases for which more than one term was used to describe a MOP-fine SCM type within each individual city. Between the 23 cities, multiple terms were used to describe a MOP-fine SCM type 96 times. Of those, 12 cities used potentially redundant terms to describe 19

MOP-fine SCM types. For example, *pervious pavement*, *permeable pavers*, and *porous pavement* were all used by Philadelphia, as were *rain barrel* and *cistern*. In Washington, DC, 15 terms were used to describe permeable surface SCMs, at least some of which seem redundant (i.e., *permeable pavement* and *porous pavement*). Baltimore used *retention pond (wet pond)* and *extended detention structure-wet*, which seem like they might be describing a single SCM type. More information is needed to evaluate whether these labels are redundant, whereas if these cities included expected performance and/or information about the structure or form of these different SCM types, then whether these labels are redundant would be clear. Next, we examined whether a function-based nomenclature might be used to group these unique SCM terms.

Exploring Function-Based Nomenclature (Question 2)

We grouped the terms included in city inventories into broader groups to enable them to be more easily understood and used for cross-city comparison studies (Choat et al. 2021). We did not use all 378 SCM terms because 35 described types of facilities that were not considered SCMs (*other*; e.g., "Green Wall," "Planting Area"); 19 described *stormwater conveyance* (e.g., "Culvert," "Riser"), which we did not consider in our subsequent analysis; 17 terms were too vague to properly place under an SCM category (*unknown*; e.g., "Unknown," "Stormwater Treatment System"); and 8 terms described either proposed SCMs or specified that there was no SCM there (*none*; "Proposed," "CDA to a shared BMP"). Another nine terms described *disconnection* of impervious surfaces (e.g., "Impervious Surface Removal," "Depaving"). However, such terms were only reported by four cities and no two cities reported the same *disconnection* term. After accounting for terms falling into the o*ther*, *stormwater conveyance*, *unknown*, *none*, and *disconnection* categories, 290 terms were placed under the WEF-ASCE nomenclature (i.e., MOP-coarse and MOP-fine).

When it was unclear in which group an SCM term should be placed, documentation from the city using that SCM term was referenced, such as web-based sources describing the design of the SCM. For example, *ROW subsurface pipe-broken stone* was included by New York City, NY. Here, we knew that ROW implies that it was installed in a right-of-way area; however, the function or form of the SCM was unclear. After searching the New York City government websites, we found a document (NYC Environmental Protection, n.d.) that makes clear that this SCM term referred to a perforated pipe with broken stone surrounding it that is meant to allow water to infiltrate into the subsurface. Therefore, we placed this SCM term in the *infiltration basin* MOP-fine group and *infiltrator* MOP-coarse group. For proprietary SCMs that were listed, we referenced the manufacturers' description. In rare cases, the best judgment was used to place an SCM term; however, if there was uncertainty about where to place a term, it was placed in the *unknown* category.

Many possible ways exist to group MOP-fine classes into broader SCM groups. One approach is to use the MOP-coarse classes used by WEF and ASCE-EWRI, building on Minton (2007). Other groupings might be possible when focusing on specific functions. For example, do SCM groups based on quantity-focused functions differ from groups based on pollutant-oriented functions? We sought to understand how the WEF and ASCE-EWRI classifications might differ when using different unit processes (i.e., quantity control, pollutant control, biological control, other, and all).

To investigate whether we could build on the ASCE-WEF nomenclature to enable particular functions of SCMs to be directly communicated, we performed a nonhierarchical and unconstrained clustering using k-means partitioning, where SCMs were clustered based on water quantity, water quality, biological, and other unit processes considered separately, as well as on all of those unit processes considered together (Table 1; Table S2). This resulted in a total of seven function-based grouping schemes for SCM terms: the coarse and fine schemes from WEF and ASCE-EWRI (Table 1) and five k-means clusters based on unit processes. *Gross pollutant traps* were not included in this analysis because they are widely implemented within conveyance pathways in most cities but were only included in eleven of the inventories that we received. The vegan package (Oksanen et al. 2019) in the R statistical programming language (R Core Team 2020) contains preprogrammed tools to assist with statistical ecosystem analysis and was used to perform k-means clustering for which the simple structure index (Dimitriadou 2017) was used to select the optimal number of clusters, k. k-means clustering on binary data (i.e., presence/absence data) essentially uses the number of presence values within each category considered, which can sometimes perform poorly using such data. To ensure that the resulting clusters were reasonable, we inspected them and concluded that they were more similar within clusters than between them, which is the purpose of k-means clustering.

Five groups of SCMs were clustered together regardless of the unit processes (all, quantity, pollutant, biological, or other) used for clustering (those groups of the same shade in Fig. 2 and Table S2 represent the five groups that consistently clustered together). However, these groups included other SCMs depending on the functions considered. For example, *infiltrators* always clustered together, but *dry basins* clustered with infiltrators based on quantity functions; *bioretention* clustered with them based on pollutant functions; *sand filters* clustered with them based on biological functions; and *wet basins* and *wetlands* clustered with them based on other functions. The SCM classification and nomenclature system differed based on the SCM functions considered, indicating little possibility that a universal function-based nomenclature exists for SCMs that communicate all SCM functions. Because the SCM types clustered inconsistently and because even those SCM types within a cluster provide different unit processes, if a city wanted to understand the SCM types that might be applicable for different target functions, such as sedimentation of pollutants, then we recommend referencing Table 1 to identify the individual SCM types that provide that function. Then, Table S1 could be referenced to determine the SCM terms that have been used to describe that SCM type, which would allow them to more easily identify how other cities have utilized that SCM type to solve their challenges.

Why is SCM Nomenclature Still So Heterogeneous between Cities?

Despite efforts to develop a simpler and standardized SCM nomenclature (Minton 2007; Shrestha and Brodie 2011; WEF and ASCE-EWRI 2012), the SCM inventories that we collected have clearly indicated that those efforts have not been widely received or implemented. As Minton pointed out in 2007, the existence of duplicative and overlapping terms is common in the early evolution of new fields. Over time, consolidation of terms occurs as duplicative and poorly defined terms are removed from use. Calling stormwater management a new field is far from accurate (NRC 2009), but the field is rapidly evolving (WEF and ASCE-EWRI 2012). This rapid evolution is occurring in the absence of regulatory or institutional incentives that would motivate a more standard approach to SCM nomenclature, leaving adaptation and innovation to largely occur at the city level.

Allowing cities, counties, or other jurisdictions to adopt custom approaches to stormwater management ensures that they can

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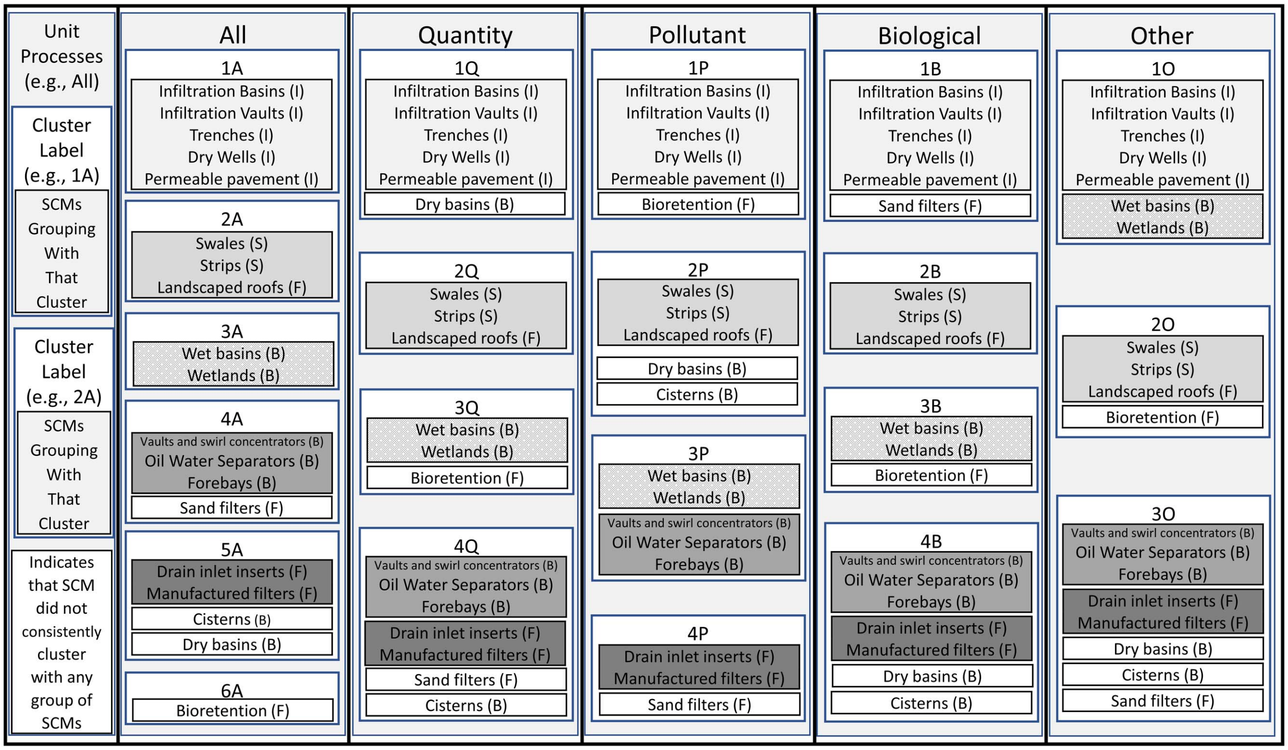

Fig. 2. k-means clusters based on unit processes provided. The farthest left column is a legend for how to interpret the other columns. Each of the other columns presents the clusters of SCMs resulting from k-means clustering using the unit-processes noted at the top of the column (e.g., 1A). For example, boxes 1A–6A present the six clusters of SCMs that resulted when using all unit-processes for clustering. Boxes with the same shades of gray or fill patterns indicate SCMs grouped together despite the unit-processes considered. SCMs in boxes by themselves and without shading (e.g., Cisterns) were not consistently grouped with each other or other SCMs. Original MOP-coarse groups are presented in parenthesis next to each SCM term: (I) = Infiltrators, (S) = Swales and Strips, (B) = Basins, and (F) = Filters. Table S2 in the Supplemental Materials combines Table 1 and Fig. 2 to easily determine the unit processes provided by SCMs in different clusters.

implement location-appropriate methods that, in turn, can drive more diverse approaches and spur innovation. However, being able to communicate the methodology, successes, and failures of local approaches to other cities is necessary to support broadscale adoption of effective stormwater management. To move toward a more standardized nomenclature, we suggest the use of a reference, such as WEF's and ASCE-EWRI's manual of practice (WEF and ASCE-EWRI 2012) that built directly on Minton (2007). For those who lack access to such resources, the tables and figures presented in this article should serve as a good point of reference. Even if we never achieve fully standardized nomenclature, using common references should at least reduce the number of terms being used over time (Minton 2007).

However, our exploration of WEF's and ASCE-EWRI's function-based classifications and how they are grouped based on different types of functions, indicated that using a name to effectively and efficiently communicate all important details about the form and function of an SCM is not possible. After thoroughly exploring the SCM inventories of 23 United States cities, we suggest a shift toward standardized record keeping. We propose that cities have a common subset of fields for the SCM function, which would enable practitioners and researchers to easily understand the stormwater goals and performance in different cities. For example, by using the fields in Table 1, a city could notate the functions intended to be fulfilled by each SCM by marking the presence or absence of that function. Even better would be quantitative estimates of the intended functions, such as the portion of the water entering an SCM designed to be evapotranspired, infiltrated, or used as a water supply. Having inventories of the intended SCM functions ensures that cities are being deliberate about meeting their locally relevant stormwater goals as opposed to implementing newer types of SCMs simply because they have become popular elsewhere. Allowing better tracking of water resources and quality assurance of their SCMs—ensuring they are performing as intended—would benefit cities. Additionally, cities would benefit from easier communication of the specifics of their stormwater plans with other cities—advancing the field of urban stormwater management in general. Additional information that would benefit future stormwater analysis includes spatial data, SCM footprint, contributing area, treatment depth, date installed, and maintenance regimen. Having such data at the catchment scale could represent an important step toward a watershed approach to urban hydrology and enable a robust analysis of stormwater management within and between cities. Understanding how different SCMs have been utilized in different scenarios and moving toward a more standard SCM record-keeping approach would allow locally appropriate methods to continue while enabling easy cross-boundary communication about the specifics of SCMs being implemented.

Conclusions

Being able to compare and contrast how different cities face the common challenge of stormwater management could accelerate the evolution of the field toward effective approaches that result in desired site- and watershed-scale performance. To address the isolated holding of SCM data, we collected SCM inventories from 23 US cities and explored the SCM terminology used across the country and within states. We reveal the following.

1. Cities are not using comparable SCM nomenclature in the United States or within states. A notable exception is that the two SCM inventories that we collected from Arizona used several of the same terms, with three of four terms used by Tucson also being used by Phoenix.
2. A function-based nomenclature that efficiently and effectively communicates the SCM function is not feasible. For all information about SCM form and/or function to be communicated, a complex nomenclator, similar to efforts by Shrestha and Brodie (2011), would be required and would likely not be adopted. Although SCM nomenclature follows a slow evolutionary process toward a more simplified and standardized form, we highly encourage those maintaining SCM inventories to expand them to include information on the function needed to understand the intended and observed performance and effectiveness of an SCM or SCM network.

Information sharing is essential for broadscale adoption of effective approaches that meet the multidimensional and multiscale goals now associated with stormwater management (Marsalek 2013; Minton 2000; Taira et al. 2018). We hope that the SCM inventories that we have collected (Choat et al. 2021) and our exploration of function-based SCM nomenclature will motivate more robust SCM data collection, record keeping, and information sharing and will enable cross-city comparison studies that are invaluable to hydrology and watershed studies.

Data Availability Statement

Some or all of the data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies [Database of Implemented Stormwater Controls (DISC); https://tinyurl.com/HUB-DISC]. Some or all of the data, models, or code that support the findings of this study are available from the corresponding author on reasonable request (SCM data not found in the DISC and code used for analysis).

Acknowledgments

The data used in this analysis were voluntarily shared by many city employees and could not have been completed without their assistance. We acknowledge assistance from Dr. Margaret Garcia, who provided a dry well inventory for Phoenix and Constance Kim, Connor Williams, and Wyatt Young for their efforts in our analysis. This work was partially supported by the USDA National Institute of Food and Agriculture, Hatch project 1015939, and this material is based on work supported by the National Science Foundation under Grant Nos. 1444758, 1828902, and 1444755. Any use of trade, firm, or products names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Supplemental Materials

Tables S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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