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Influence of governance structure on green stormwater infrastructure investment

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ABSTRACT

Communities are faced with the challenge of meeting regulatory requirements mandating reductions in water pollution from stormwater and combined sewer overflows (CSO). Green stormwater infrastructure and gray stormwater infrastructure are two types of water management strategies communities can use to address water pollution. In this study, we used long-term control plans from 25 U.S. cities to synthesize: the types of gray and green infrastructure being used by communities to address combined sewer overflows; the types of goals set; biophysical characteristics of each city; and factors associated with the governance of stormwater management. These city characteristics were then used to identify common characteristics of "green leader" cities—those that dedicated > 20% of the control plan budget in green infrastructure. Five "green leader" cities were identified: Milwaukee, WI, Philadelphia, PA, Syracuse, NY, New York City, NY, and Buffalo, NY. These five cities had explicit green infrastructure goals targeting the volume of stormwater or percentage of impervious cover managed by green infrastructure. Results suggested that the management scale and complexity of the management system are less important factors than the ability to harness a "policy window" to integrate green infrastructure into control plans. Two case studies—Philadelphia, PA, and Milwaukee, WI—indicated that green leader cities have a long history of building momentum for green infrastructure through a series of phases from experimentation, demonstration, and finally—in the case of Philadelphia—a full transition in the approach used to manage CSOs.

1. Introduction

The connection of impervious surfaces directly to streams via stormwater infrastructure has resulted in a consistent decline in the ecological integrity of urban aquatic ecosystems (Meyer et al., 2005; Shuster et al., 2005; Walsh et al., 2005a; Schueler et al., 2009). A range of stormwater control measures (SCMs), also referred to as stormwater best management practices (BMPs), can be installed in suburban and urban areas to help mitigate stream water-quality degradation. For the past few decades, urban stormwater control has focused on large, centralized conveyance-based systems. These "gray" infrastructure systems use pipe networks to direct stormwater to a receiving waterway or store and slowly release stormwater using large ponds or storage tanks. Over the last decade, there has been growing recognition that static large-scale infrastructure may not meet current and future needs as urban areas continue to grow and as climate change alters expected precipitation regimes (Ahern, 2011; Palmer et al., 2015). Green stormwater infrastructure has been suggested as a more resilient option to supplement or replace gray infrastructure (e.g., pipes and storage tanks) because it is more flexible and multi-functional in the face of future extreme weather events (Grimm et al., 2016; Moore et al., 2016). We use the term 'green stormwater infrastructure' to include practices that manage stormwater runoff at the source where it is generated through the promotion of on-site storage, infiltration, and evapotranspiration. This includes SCMs such as bioretention, infiltration trenches, tree box filters, green roofs, and permeable pavement.

The debate over the use of gray or green infrastructure for stormwater management continues (Palmer et al., 2015). City managers are grappling with how to balance costs with meeting water-quality requirements for Federal National Pollutant Discharge Elimination System (NPDES) permits, calling for improved control of stormwater and an 85% reduction in combined sewer overflows (CSO) into local waterways (US EPA, 1994). Combined sewer systems are those in which one pipe carries both stormwater and wastewater. When the capacity of

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the combined sewer system is exceeded during storms, CSOs occur, i.e., excess stormwater with mixed sewage is discharged directly to local waterways. For cities with combined sewer systems, meeting reduction targets will require investing millions, and in some cases billions, of public dollars in water infrastructure in the coming decades. The U.S. Environmental Protection Agency (EPA) estimated capital investments of $48.0 billion are needed over the next 20 years for publicly owned treatment works to address CSOs and meet water-quality objectives of the Clean Water Act (US EPA, 2016). Of the $48.0 billion in documented needs, 20 communities indicated $4.2 billion is needed specifically for green infrastructure projects.

Common gray infrastructure solutions to reduce CSOs include the construction of large-scale projects such as underground tunnel or tank storage systems, upsized pipes, and sewer separation. In contrast, green infrastructure solutions require investments in multiple small-scale projects, in which amended soils and vegetation capture and infiltrate stormwater at the source where it is generated. Green stormwater infrastructure solutions include practices such as bioretention (e.g., bioswales and rain gardens) and retention basins. There is an increasing trend in implementing decentralized approaches to water management in local communities, such as green stormwater infrastructure like rain gardens (Walsh et al., 2005b; Gleick, 2003). But widespread adoption of these approaches remains limited due to institutional and organizational barriers, including fragmented responsibilities, lack of coordination among city authorities, limited institutional capacity, resistance to change, and lack of market incentives (Roy et al., 2008; Keeley et al., 2013; Brown et al., 2013; Chaffin et al., 2016). Perceived risk and lack of experience installing green stormwater infrastructure remains another barrier (Oolorunkiya et al., 2012). Even with these uncertainties, several U.S. cities have incorporated a city-wide green infrastructure program to address CSOs (e.g., Philadelphia, PA, Green City Clean Waters Program and Milwaukee, WI, Fresh Coast Green Solutions). The green infrastructure program in Milwaukee was motivated by the need for measures beyond what gray infrastructure could provide, as the city had already invested millions in storage tunnels (Keeley et al., 2013). The green infrastructure program in Philadelphia sparked from experimentation in green infrastructure pilots, billing, and organizational structure (Fitzgerald and Laufer, 2017). These cities have committed to substantial financial investments in green infrastructure approaches.

In this study, we set out to identify “green leader” cities that are planning to invest substantially in green infrastructure to address CSOs and examined if there are common structural aspects of governance in communities that are investing substantially in green stormwater infrastructure to address CSOs. Support for green infrastructure was gauged based on financial commitments for green approaches to address CSOs outlined in control plans. We gathered data on green infrastructure implementation from 25 U.S. cities with combined sewer systems. We characterized two factors associated with governance of the combined sewer system: 1) scale and complexity of system management and 2) the regulatory setting in which stormwater management decisions are made. Two case studies are presented as examples of development of gray and green infrastructure programs in the two cities with the largest proportional investment of green infrastructure in the long-term CSO control plan.

2. Background

Numerous factors influence local managers' decisions to implement green or gray infrastructure approaches to address CSOs. To explore the factors influencing governance decisions, we examined some of the socio-political drivers of stormwater infrastructure transitions from gray to green approaches in U.S. cities. The water management regime and governance can be characterized according to its structural dimensions, including institutions, vertical and horizontal flows of influence, and policy arenas (Pahl-Wostl, 2007). Fragmented responsibilities can be an important impediment to sustainable, watershed-scale stormwater management because responsibilities are spread across multiple jurisdictions and among different levels of government (Roy et al., 2008). Therefore, we hypothesized that cities that are able to integrate green stormwater infrastructure at the city-scale will have sewer authorities operating at smaller geographic scales (i.e., city versus county) with low municipal complexity (i.e., fewer municipalities in service area). The lack of a legislative mandate can also be an impediment to watershed-scale changes to the types of SCMs installed for stormwater management. Therefore, we characterized the regulatory setting, specifically if there was a Federal consent decree in each of the study cities to examine the timing of regulatory change, CSO control planning, and the initiation of green infrastructure programs in each city. A Federal consent decree is a binding agreement between the EPA and the sewer authority that establishes the terms, compliance schedule, and cost commitment to address CSOs in that community.

The integration of green stormwater infrastructure as a strategy to improve urban water quality provides a unique opportunity to relate municipal adaptability or the lack of adaptability to stormwater governance, since green stormwater infrastructure is a relatively new innovation in U.S. cities. City-scale integration of green stormwater infrastructure can be viewed as a technological transition. Geels (2002) defines a technological transition as a major change in the way societal functions are fulfilled. The control of urban stormwater can be used as the societal function while the shift from large, centralized gray treatment systems to smaller, distributed green infrastructure systems can be viewed as the transition. Growth of new policies and initiatives can be fostered when the problem, solution, and political streams all converge (Kingdon, 1984). This convergence and the opening of a “policy window” together can allow policy entrepreneurs to gain support and launch new ideas, resulting in major agenda change that occurs quickly during a "spasm of reform" (Kingdon, 1993). Thus, we frame the development of a city’s CSO long-term control plans, hereafter referred to as the control plan, as the opening of a policy window in which green infrastructure can be infused under certain conditions. We examined on a broad scale whether green infrastructure is integrated during that window in 25 communities, and we then focused on two case studies of green infrastructure program development in Milwaukee, WI, and Philadelphia, PA.

3. Methods

3.1. Study cities

The majority of cities with combined sewer systems in the United States are located in the Northeast, Upper Midwest, and Pacific Northwest (Fig. 1). To span the range of geographies associated with combined sewer systems, 25 study cities were selected, including the top 10 cities with the greatest number of CSO outfalls (Fig. 1). All study cities have large combined sewer systems serving 50,000 people or more, representing about 24% of all communities with large CSO systems. No small CSO systems (serving less than 50,000 people) were included in this analysis. The city set included eleven cities with small combined sewer service areas of $< 100\,km^2$, nine with medium-sized combined sewer service areas of $101–250\,km^2$, and five with large CSO service areas of $> 250\,km^2$. The annual average CSO volume ranged from a maximum of 30 billion gallons in New York City, NY, to a minimum of 700 million gallons in Albany, NY (Table 1).

3.2. Data sources

There was no national system to track milestones related to CSO control plans and consent degrees, rather each EPA region developed their own tracking system (US EPA, 2015). Therefore, we used existing literature and municipal reports as the primary data sources for this analysis. The EPA's CSO Control Policy indicates that communities with

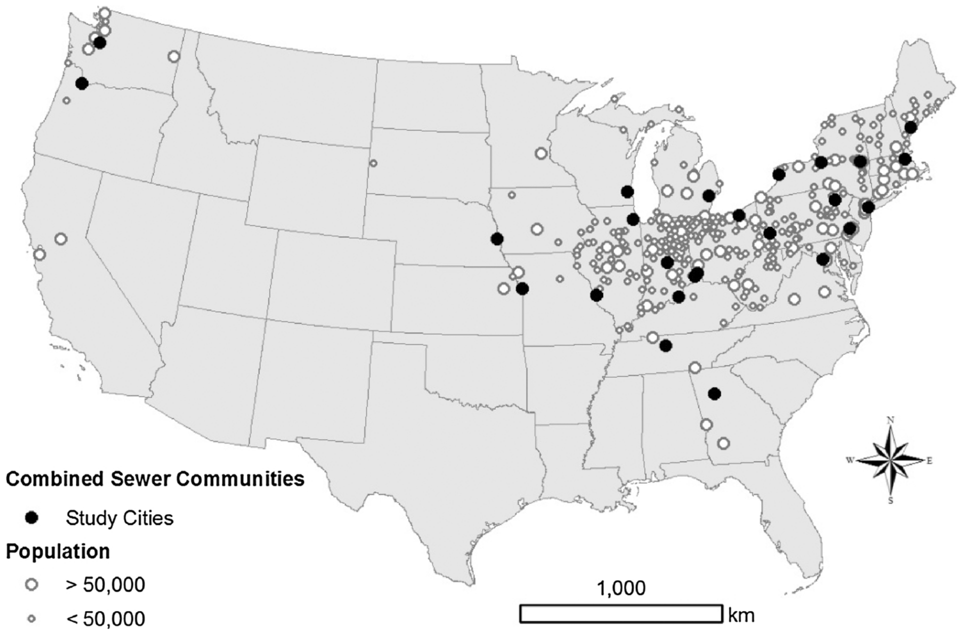

Fig. 1. Location of large (population > 50,000) and small (population < 50,000) communities with combined sewer systems in the United States. Study cities are large communities that span the geographic range of combined sewer communities in the United States.

combined sewer systems should develop a control plan that details the characteristics of the combined sewer system, evaluates a series of solutions to meet CSO reduction targets, and describes the selected option and implementation schedule to meet reduction targets (US EPA, 1995). The most recent CSO control plan for each study city served as the primary data source. We were able to obtain formal control plans for 19 of the 25 cities. For the other six communities, we supplemented our dataset with sewer authority reports and websites containing information on system characteristics and CSO control programs. Focusing on the most recent control plan in each city allowed for the

Table 1
Sewer system characteristics for each study city. Cities are listed in descending order based on the number of CSO outfalls.

Study Community	Primary Sewer Authority	Management Scale	Total Service Area (km^2)	Percent of Service Area that is Combined	Annual CSO Volume (billion gallons)	Number of CSO Outfalls
New York, NY	New York City Department of Environmental Protection	City	473	60%	30	426
Chicago, IL	Metropolitan Water Reclamation District of Greater Chicago	County	971	42%	11.5	393
Cincinnati, OH	Metropolitan Sewer District of Greater Cincinnati	County	300	40%	11.5	215
Pittsburgh, PA	Allegheny County Sanitary Authority	County	137	17%	9	215
St. Louis, MO	Metropolitan St. Louis Sewer District	County	194	14%	13.3	199
Philadelphia, PA	Philadelphia Water Department	City	166	60%	13.1	175
Indianapolis, IN	Water Citizens Energy Group	County	145	20%	7.8	132
Cleveland, OH	Northeast Ohio Regional Sewer District	Multi-County	207	23%	5	126
Milwaukee, WI	Milwaukee Metropolitan Sewerage District	Multi-County	61	6%	1.1	117
Louisville, KY	Louisville and Jefferson County Metropolitan Sewer District	Multi-County	96	10%	2.8	115
Northern Kentucky, KY	Sanitation District No. 1 of Northern Kentucky	Multi-County	26	4%	1.9	97
Albany, NY	Albany County Sewer District and Capital District Regional Planning Commission	County	56	27%	1.2	92
Kansas City, MO	Kansas City Water Services	City	150	18%	6.5	90
Boston, MA	Massachusetts Water Resources Authority	Multi-County	36	3%	3.3	84
Detroit, MI	Detroit Water and Sewer Department	City	613	25%	2.8	81
Syracuse, NY	Onondaga County Department of Water Environment Protection	County	28	4%	4	72
Scranton, PA	Scranton Sewer Authority	City	34	63%	0.7	68
Buffalo, NY	Buffalo Sewer Authority	City	262	92%	1.7	65
Washington, DC	District of Columbia Water and Sewer Authority	Multi-County	51	3%	3.3	60
Portland, OR	Portland Bureau of Environmental Services	City	110	29%	6	42
King County, WA	King County Wastewater Treatment Division	County	123	11%	2.3	38
Portland, ME	Portland Water District	County	19	49%	0.7	33
Nashville, TN	Metro Water Services	County	31	6%	5	32
Omaha, NE	City of Omaha Public Works	City	117	16%	3.8	29
Atlanta, GA	Atlanta Watershed Management	City	49	8%	5.1	9

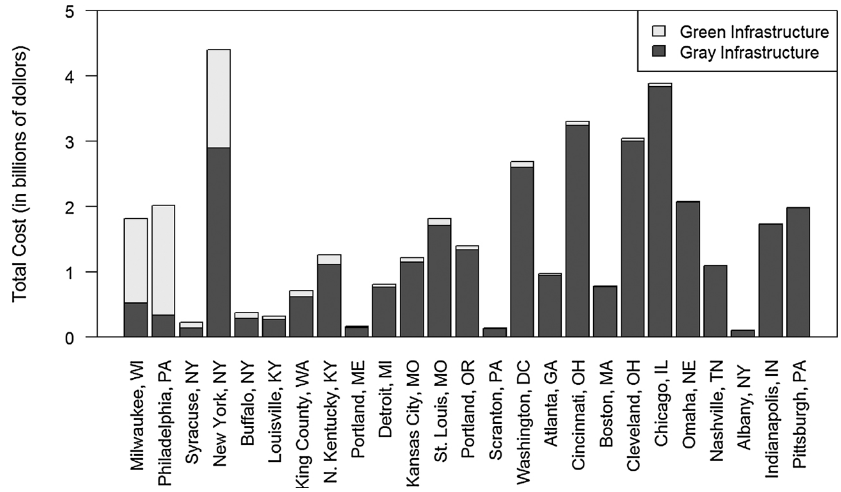

Fig. 2. Investments in green and gray infrastructure in each city's most recent control plan. Cities are ranked from left to right in descending order based on the proportion of total control plan cost to be invested in green infrastructure.

inclusion of a large number of cities. This cross-sectional approach is limited in terms of the ability to characterize previous investments to CSO controls within each city associated with older control plans. Therefore, we included Milwaukee, WI, and Philadelphia, PA, as two case studies that highlight the emergence of green infrastructure programs within these communities.

3.3. Green performance factors

Green performance was determined using two indicators: the proportion of green terms used in each control plan and the proportion of funds allocated to green infrastructure in the control plan. The proportion of green terms used in each control plan was determined for the 19 cities with a formal control plan. Textual analysis was completed using the tm package in R Studio (RStudio, Inc., Boston, MA) (Feinerer and Hornik, 2015) to quantify the proportion of green and gray infrastructure terms used in each control plan. Each control plan was converted from a pdf to a text file and organized into a corpus of documents. Transformations were performed to convert all words to lowercase and remove numbers, punctuation, special characters, English stop words, and white space. Words were stemmed to derive the base or root form of each word by stripping suffixes such as "ing", "ed" and "s".

A term document matrix was then formed to count the frequency of all one-, two-, and three-word phrases in each control plan. This matrix was used to develop a vocabulary of gray and green terms used in the documents (Supporting information Table S1). Gray terms were grouped into five gray infrastructure categories: tunnel, treatment plant, storage tank, sewer separation, and other gray terms. Green terms were grouped into four green infrastructure categories: green infrastructure as a general term, green space, bioretention, and other green terms. The total count of all green and gray terms, as well as terms in each category, were determined for each control plan and divided by the total number of words in each document. Green infrastructure implementation goals outlined in the control plan were also compiled. Green infrastructure goals were grouped into five goal categories: volumetric, monetary, project-based, impervious-based, or no clear goal.

The proportion of funds allotted for green infrastructure was determined using cost estimates for the recommended plan in each control plan. If a control plan was not available for a city, then cost information was estimated using the sewer authority's website and other planning documents. For each city, total control plan cost, gray infrastructure cost, and green infrastructure cost was determined. Communities were then grouped into three green infrastructure investment categories with < 5%, 5–20%, and > 20% of the total control plan budget invested in green stormwater infrastructure. Communities with > 20% of the control plan budget devoted to green stormwater infrastructure were considered "green leader" communities. We also identified the five communities with the highest amount of green funding normalized by annual CSO volume and by the area of the combined sewer system.

3.4. Stormwater governance factors

A set of stormwater-governance factors in each city was quantified based on common barriers to green infrastructure identified in other studies (Roy et al., 2008; Oolorunkiya et al., 2012). Governance factors focused on two main categories, scale and complexity of the management system and regulatory drivers. Management system scale was identified as the geographic scale (i.e., city, county, or multi-county) at which the primary managing sewer authority operated in each community. System complexity was determined by normalizing the total number of municipalities in each sewer authority by the sewer service area in square kilometers. Communities with < 0.02, 0.02–0.04, and > 0.04 municipality/km^2 were grouped into low, medium, and high complexity, respectively. A higher complexity score indicated more municipalities per area served by a sewer authority.

A second complexity factor considered the types of water streams (i.e., drinking water and wastewater) the sewer authority managed. Cities were grouped based on whether the primary sewer authority managed only wastewater or wastewater and drinking water. For regulatory factors, the calendar year when control plan implementation started and the presence or absence of a Federal consent decree were recorded. These governance factors were then compared to green performance categories to assess commonalities between green stormwater infrastructure investment and governance factors.

4. Results

4.1. CSO control plan costs

The total cost of each city's control plan was split into investments in gray and green infrastructure (Fig. 2). Four communities had control plans costing more than \$3 billion, including New York City, Chicago, Cincinnati, and Cleveland (Supporting information Table S2). There was a positive linear relation between total control plan cost and baseline CSO volume ($R^2 = 0.56$, $p < 0.01$), the number of combined sewer outfalls ($R^2 = 0.59$, $p < 0.01$), and the size of the combined sewer service area ($R^2 = 0.32$, $p < 0.01$). Total control plan costs in Detroit and Buffalo normalized by area were lower than expected given

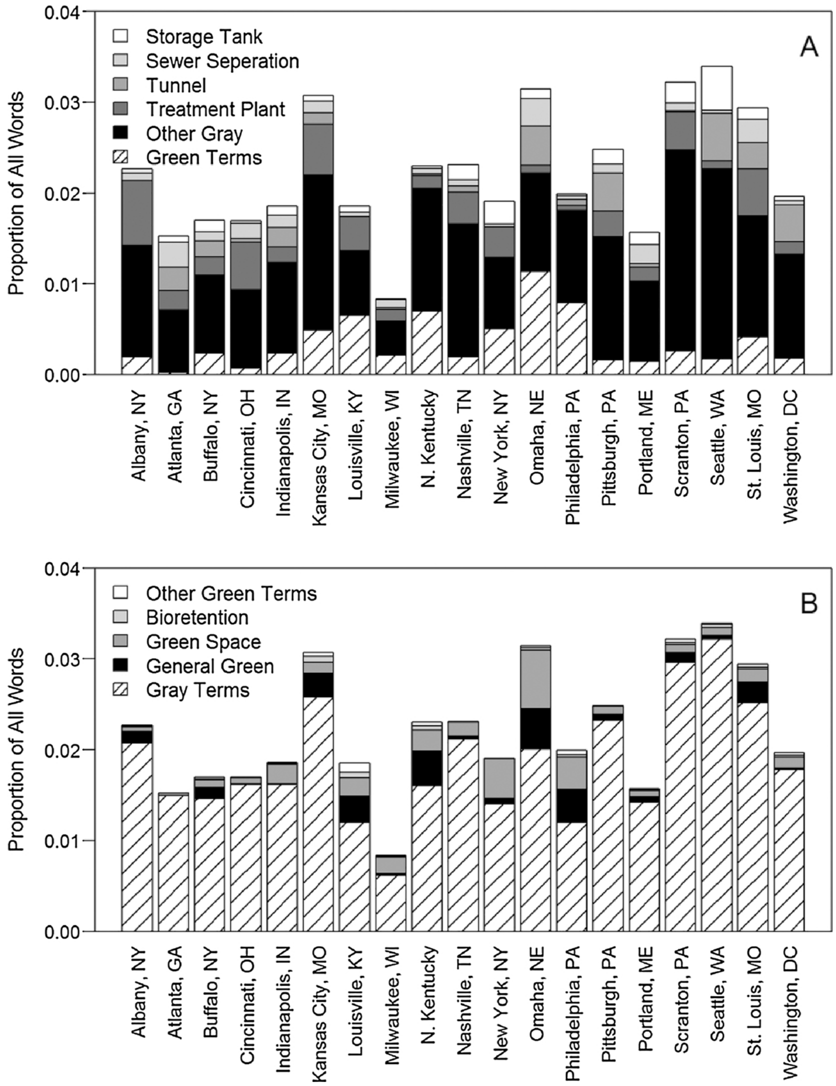

Fig. 3. The proportion of gray (A) and green (B) infrastructure terms mentioned in the city control plan. Proportions represent the fraction of all words in the document. The cities listed include only the 19 cities from which formalized control plans were obtained.

investments in other similarly sized communities. All communities included some investment in green infrastructure in their control plan, except for Pittsburgh (Fig. 2). The three communities that invested the most dollars toward green infrastructure investment per CSO area and per CSO volume were Milwaukee, Philadelphia, and Northern Kentucky. Eight communities invested at least 10% of their overall control plan budget in green infrastructure. Five communities invested at least 20% of their control plan budget in green infrastructure. These five "green leader" communities were Milwaukee, Philadelphia, Syracuse, New York City, and Buffalo (Fig. 2).

4.2. Green and gray infrastructure terms in control plans

Gray infrastructure terms were more common than green infrastructure terms in all control plans (Fig. 3A). Seattle's control plan had the highest proportion of gray infrastructure terms, with the most discussion of terms in the tunnel and storage tank categories. Omaha had the most discussion of terms in the sewer separation category and Albany had the most discussion of terms in the treatment plant category. Milwaukee had the lowest usage of gray infrastructure terms, with the majority of terms in the other gray term category (Fig. 3A). Albany and New York City were the only control plans that did not include terms in the tunnel term category.

Omaha, Philadelphia, and Northern Kentucky had the most frequent mentions of green terms (Fig. 3B). The most common green term category was green space, which included terms related to open space, parks, restoration, and trees. General usage of the terms "green infrastructure" or "green" were the next most common green terms used in control plans. Louisville and Kansas City had the most frequent usage of terms in the bioretention and general green term categories (e.g., downspout disconnection, porous pavement, green roofs). Green term categories related to specific types of green infrastructure SCMs (see Supporting information Table S1) were used the least overall, but mentioned the most in Louisville's control plan (Fig. 3B). The control plan for Atlanta had the fewest mention of green terms and included only terms in the green space term category. There were no significant correlations between the proportion of green words or gray words and site context variables including combined sewer system area, number of CSO outfalls, and CSO volume ($p > 0.05$).

4.3. Green infrastructure goals

The primary green infrastructure goal in each city was identified (Table 2). Volumetric goals were the most common goal category, serving as the primary goal in 32% of the study cities. Volumetric goals were typically phrased in terms of millions of gallons of combined

Table 2
Primary green infrastructure goals reported in each study city control plan.

Goal Category	Cities with Goal	Proportion of Cities with Goal Type	Number of Green Leader Cities with Goal Type
Volumetric	8	0.32	2
Projects	6	0.24	0
Monetary	4	0.16	0
Impervious	3	0.12	3
No Clear Goal	1	0.04	0

sewer water captured by green infrastructure. Project counts were the next most common goal category, serving as the primary goal in 24% of cities. Project-based goals were typically phrased in terms of the number of demonstration projects installed. Monetary goals were found in 16% of the cities, with goals typically phrased in terms of a commitment to spend so many millions of dollars on green infrastructure. Impervious-base goals were the least common goal type and typically phrased in terms of the percent of impervious surfaces to be managed using green infrastructure. The three cities with impervious-based goals set targets at 10%, 20%, and 34% of impervious surfaces managed by green infrastructure in New York, Buffalo, and Philadelphia, respectively. Only one city, Albany, had no clear green infrastructure goal in the control plan. Cities with large investments in green infrastructure (> 20% of the control plan budget) had either volumetric or impervious-based goals (Table 2). The three control plans with the largest proportion of green words had a green infrastructure goal in the project count category.

4.4. Scale and complexity of CSO management

The scale and complexity of stormwater management in each community was examined by characterizing the geographic scale the sewer authority operates, the complexity of municipalities, and the streams of water managed by the sewer authority. The majority of the sewer authorities serving the study communities operated at the county or city scale, with only six authorities serving multiple counties (Table 3). Medium or high municipality complexity was more common than low municipal complexity, occurring in 40% and 36% of the study cities, respectively (Table 3). Managing wastewater only was the most common water stream managed, occurring in 60% of the study cities examined.

4.5. Governance and regulatory factors

Governance factors were compared to categorical variables describing the percentage of green funds in each city. Overall, there was no clear relation between scale of management, complexity of management, or water systems managed and the three green infrastructure funding categories (Fig. 4). All three funding categories included sewer authorities operating at each of the three scales (Fig. 4A). The majority of the green leader communities had a sewer authority that operated at the city scale (Table 3). Communities with high municipal complexity were in the in 20% or less funding categories (Fig. 4B). Green leader communities had low to medium municipal complexity. All three funding categories had sewer authorities that managed only wastewater or wastewater and drinking water (Fig. 4C). Of the 11 communities with sewer authorities that managed both wastewater and drinking water, 54% of them operated at the city scale (Supporting information Table S2).

Table 3
Summary statistics for community governance factors.

	Number of Communities	Number of Green Leader Communities
Management Scale		
City	9	3
County	10	1
Multi-county	6	1
Management Complexity		
Low	6	4
Medium	10	1
High	9	0
Water Streams Managed		
Wastewater only	14	3
Wastewater and drinking water	11	2

Regulatory influences were examined by comparing the year that each community's control plan started and the proportion of green infrastructure funds allocated in each control plan. We used the 2007 EPA memorandum on using green infrastructure to protect water quality as the key regulatory influence on green infrastructure implementation because it allowed and encouraged communities to use green infrastructure to reduce runoff and CSO inputs to local waterways (US EPA, 2007). Five control plans were started prior to 2007, while the remaining control plans began after 2007 (Fig. 5). Communities with large investments in green infrastructure had control plans that started after 2007. All control plans that started prior to 2007 had low proportions of green infrastructure investment (Fig. 5).

5. Discussion

5.1. Term usage and funding mismatches

Content analysis of gray and green term usage indicated a wide range of term categories used in each control plan (Fig. 3). In some cases, the usage of gray terms aligned fairly well with funds dedicated to gray infrastructure. There was a significant negative correlation ($R^2 = 0.29$, $p < 0.05$) between the usage of gray terms and the proportion of the control plan budget dedicated to green infrastructure. In contrast, there were no significant relations between green term categories and the proportion of the control plan budget dedicated to green infrastructure. The usage of green terms in the control plan was not a strong predictor of green infrastructure investment.

The difference between green term usage and green funding allocations suggests a potential mismatch between what is discussed in the control plan and what is actually translated to on-the-ground implementation. For example, Omaha had the most frequent usage of green infrastructure terms but less than 1% of the city's control plan budget was dedicated to green infrastructure. Rather than reflecting substantial investment in green infrastructure, the usage of green terms in Omaha might reflect a green infrastructure goal based on project counts. The lack of terms about specific types of green infrastructure suggested that green infrastructure was discussed in very general terms in control plans, often lacking specific details about how green infrastructure projects will be implemented. One limitation of this study approach is that we analyzed only the most recent control plan in each community. Some communities have developed multiple phases to their control plans or developed a green infrastructure plan subsequent to the control plan that outlines goals in more detail. Those plans were not assessed. All five green leader cities had a green infrastructure plan that supplemented the control plan.

5.2. Green infrastructure and management scales

Identifying the most appropriate blend of gray and green infrastructure to manage CSOs is a challenge. Based on the 25 cities we examined, planning documents indicated that city managers are discussing the use of green infrastructure and beginning to implement green infrastructure at both small and large scales. The question remains how and why those cities we identified as "green leaders" were able commit to green infrastructure through substantial investment in

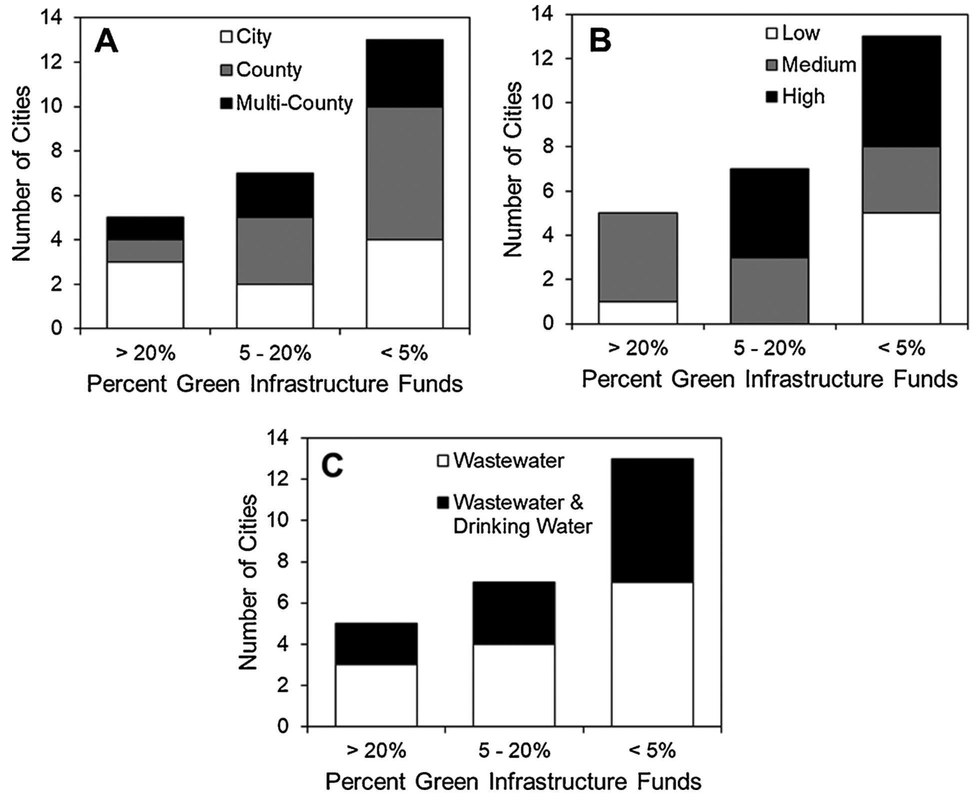

Fig. 4. Count of communities in each green infrastructure funding category for each management scale category (A), complexity category (B), and water streams managed (C).

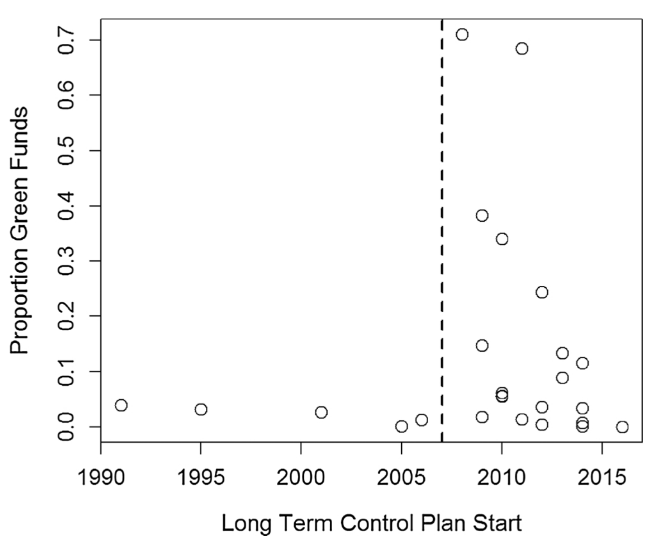

Fig. 5. Year each community's control plan started and the proportion of funds invested in green infrastructure. The dashed line indicates 2007, the year in which the EPA memorandum supporting the use of green infrastructure was issued.

the control plan budget. We hypothesized that green infrastructure installation is most challenging for cities with a sewer authority that manages the sewer system at a large spatial scale (e.g., multiple counties) and that serves many municipalities (high complexity). However, our data synthesis found that the cities investing substantially in green infrastructure had sewer systems that spanned the range of spatial scales from city to county to multi-county, had a wide range of combined sewer system drainage areas from small to large (23–473 km^2), and were communities with low to medium municipal complexity (Fig. 4).These results suggest that substantial investment in green infrastructure can occur across multiple scales and complexities of combined sewer system management.

5.3. Importance of green infrastructure goals

Based on the factors examined, the most common characteristics of the five green leader cities was an explicit green infrastructure goal that focused on managing a particular volume of stormwater or a certain proportion of impervious surfaces using green stormwater infrastructure. For instance, Philadelphia, Buffalo, and New York City were the only communities with impervious-based goals, with these communities planning to manage 34%, 10–20%, and 10% of impervious surfaces in the service area with green infrastructure, respectively (Table 2). Milwaukee and Syracuse had volumetric goals, planning to manage 740 and 247 million gallons, respectively. In Milwaukee, the volumetric goal was set to capture the first 0.5 inch of rainfall on impervious surfaces in the city. These large-scale goals focused on source control likely require substantially larger investments in green infrastructure than those cities with goals based on project counts or a monetary commitment to green practices.

5.4. Regulatory drivers and past investments in gray infrastructure

Regulatory factors were identified as a potential driver of greater proportions of green infrastructure investment in control plans. Control plans starting after 2007 were more likely to include a larger proportion of the budget towards green infrastructure (Fig. 4). All of the green leader cities had control plans that started after 2007, the year in which the EPA issued a memorandum encouraging the use of green infrastructure approaches in lieu of traditional approaches to meet permit requirements. The EPA memorandum opened a policy window allowing sewer authorities to insert green approaches into their control plans. But as we see from funding allocated towards green infrastructure, not every city took advantage of this opportunity (Fig. 4). Other factors were also in play.

In some communities, previous investments in gray infrastructure may have provided the flexibility to experiment with green approaches. In the case of Portland, substantial financial investment was placed on constructing three deep tunnel systems to store combined sewer water. These three CSO tunnel projects were completed between 2000 and 2011, thereby reducing annual CSO volume by 99% in the Columbia Slough and 94% in the Willamette River (Portland Bureau of Environmental Services, 2018). The construction of CSO tunnels in Portland reflects the large investment (> $1 billion) in gray infrastructure to meet permit requirements for CSO reductions. Towards the end of tunnel construction, the city launched the Grey to Green Initiative in 2008 with the goal to construct 920 green street facilities, 43 acres of green roofs and plant 83,000 trees (Portland Bureau of Environmental Services, 2010). Previous investments in gray infrastructure in Portland may have paved the way for more recent investments in green infrastructure, giving the city flexibility to experiment with green approaches in the right-of-way and on private property.

In many cases a combination of factors likely influenced city investments in gray and green infrastructure. It is possible that the green leader cities had a champion, or policy entrepreneur, who was able to capitalize on this policy window to integrate green infrastructure into the control program. In the next two sections, we explore the timing of control planning in the top two communities: Milwaukee, WI, and Philadelphia, PA, to examine the roles that regulatory setting and planning leadership may have played in these cities.

5.5. Milwaukee, WI: early gray investment and strong regulatory backing of green infrastructure

Regulatory drivers and early investments in gray infrastructure likely played a role in Milwaukee's $1.3 billion investment in green infrastructure. Milwaukee committed to investing approximately 71% of the total control plan budget in green infrastructure practices (MMSD, 2013). This is the largest proportional investment in green infrastructure of all the control plans examined in this study. Between 2008 and 2035, the city is planning to implement green infrastructure practices that can capture the first 0.5 inch of rainfall on impervious surfaces, the equivalent of 740 million gallons of stormwater storage (MMSD, 2013). The combined sewer system in Milwaukee is managed by the Milwaukee Metropolitan Sewerage District (MMSD), which provides wastewater services to 28 communities in the region. From the 1970s through 2010, the MMSD invested $3.9 billion in gray infrastructure including three phases of CSO tunnels with a total storage capacity of 521 million gallons, upgrades to wastewater treatment plants, and sewer rehabilitation projects (MMSD, 2010). Since the deep tunnel systems began operation in 1994, the average annual CSO volume dropped from 8 to 9 billion gallons to an average of 1 billion gallons per year (MMSD, 2009).

Milwaukee's green infrastructure program began in 2000 with a land acquisition program called GreenSeams that targets properties in flood-prone areas. Subsequently, the city launched a grants program called the BMP Partnership Program in 2002, a rain barrel program in 2004, and a rain garden initiative in 2005. These initial green infrastructure programs demonstrated the feasibility of green infrastructure approaches and likely paved the way for the city's regional green infrastructure program. In 2013, Milwaukee unveiled its plan to eliminate all sewer overflows by 2035 using green infrastructure, putting in place a goal to capture the first 0.5 inch of precipitation on impervious surfaces (~740 million gallons) using green infrastructure (MMSD, 2013). Implementing green infrastructure was deemed a more cost-effective approach than using gray infrastructure to achieve this goal. MMSD estimated it will save $44 million in infrastructure costs by using a green approach rather than constructing additional CSO tunnel storage—green infrastructure will cost approximately $1.75/gallon compared to deep tunnel storage at $2.42/gallon (MMSD, 2013). MMSD realized that measures beyond CSO tunnels would be needed to achieve their goals, and so they began creating incentives to promote green approaches on private and public spaces (Keeley et al., 2013).

With all the momentum that the MMSD had created pushing green infrastructure forward in the 2000s, when the city's NPDES permit came up for renewal in 2013, it was the first permit in the country to include a requirement for green infrastructure. The permit states, "beginning in calendar year 2013, and in each calendar year thereafter during the permit term, the Permittee, working with Partners as appropriate, must ensure that green infrastructure practices/control measures are put in place and maintained in the MMSD service area. The practices and control measures put in place in 2013 and 2014 must cumulatively have an annual design retention capacity of at least 1 million gallons. The retention capacity from 2013 to 2017 shall be increased from *5* million gallons (per original permit) to 12 million gallons." The permit explicitly required the use of green infrastructure as a control measure. The city's heavy investment in gray infrastructure prior to 2010 likely paved the way for its investment in greener approaches, once gray solutions were deemed more expensive.

5.6. Philadelphia, PA: setting the stage for green infrastructure

The phasing in of green infrastructure in Philadelphia can be viewed using a similar framework to that of Brown et al. (2013), which describes a trajectory of green stormwater infrastructure transitions in Melbourne, Australia, from the emergence of the idea, to idea formation, expansion, and finally to regime transition. Idea emergence in Philadelphia began through initiatives such as the West Landscape Project, which engaged the Philadelphia Water Department (PWD) and the media in dialogues about urban green space and restoration during the late 1980s and early 1990s (Madden, 2010). The West Landscape Project explored how to harness vacant urban lots as a resource for urban green space and stormwater control (Spirn, 2005). At the same time, the EPA began issuing consent decrees for combined sewer overflow control and required the development and submission of control plans as part of NPDES permits. The PWD submitted its first control plan in 1997 and included a $4 million effort to conduct watershed planning to identify opportunities and actions to improve water quality in local waterways (PWD, 2009).

During the first control plan, the director of the PWD recognized a potential opportunity to improve coordination between drinking water, wastewater, and stormwater management to simultaneously address CSOs, stormwater control, and drinking water protection (Madden, 2010). In 1999, the Office of Watersheds was created and charged with overseeing the implementation of the first control plan, which included implementing and testing green infrastructure demonstration projects throughout the city (Madden, 2010). Local universities also began testing the effectiveness of green infrastructure through programs such as Villanova University's Urban Stormwater Partnership (Kwiatkowski et al., 2007; Emerson and Traver, 2008). The early 2000s marks the time when experimentation of green infrastructure approaches expanded rapidly in Philadelphia.

In the late 2000s, the CSO issue was then reframed into the idea that Philadelphia could become one of the most sustainable cities in the country (Madden, 2010). The Mayor of Philadelphia announced Greenworks Philadelphia in 2009, creating a plan to make Philadelphia the greenest city in America by 2015 (City of Philadelphia, 2009). During the same time, the PWD submitted its updated control plan to the EPA, and the Philadelphia's Green City, Clean Water Plan was adopted in June 2011. Green City, Clean Water outlined the city's plan to invest $1.67 billion in green stormwater infrastructure over a 25-year period to capture 85% of the CSO volume on an annual average basis (PWD, 2011). This was the first control plan to rely predominantly on green infrastructure to achieve CSO reductions, reducing overflow volume from 16 to 8 billion gallons per year. Similar to Milwaukee, Philadelphia quantified the "triple bottom line" benefits of selecting an all-green approach—ranging from job creation to reductions in urban heating to increasing property values—and determined that a green approach was more cost effective than the gray infrastructure alterative of constructing storage tunnels (PWD, 2011).

The updated control plan developed a performance metric called a "greened acre" with each green acre designed to treat the first inch of runoff from one acre of impervious cover. The implementation of greened acres targeted public rights of way via green streets (38% of the impervious cover), residences (20%), and businesses and institutions (16%) (PWD, 2011). In implementing this plan the city faced numerous hurdles including fostering cross-departmental cooperation given competing departmental values (e.g., aesthetics versus engineering), working within the bounds of city codes and regulations, and resolving how and who would provide necessary maintenance (Fitzgerald and Laufer, 2017). Strong leadership and an environment that encouraged experimentation and innovation allowed for novel solutions to funding, supporting, and carrying out green infrastructure in Philadelphia (Fitzgerald and Laufer, 2017).

6. Conclusions

Our synthesis of green infrastructure investments in 25 communities suggests that the scale and complexity of the stormwater management system is less of a barrier than has been suggested. The green leader cities we identified spanned management scales from city to multi-county and municipal complexity from medium to high (Table 3). The scale and complexity of the management system may be a barrier to green infrastructure in some settings; however, our results indicate that transitions to green approaches can and did occur in localities with complex organizational structures. Our results suggest that issuance of the 2007 EPA memorandum allowing green infrastructure technologies to meet CSO permitting requirements opened a policy window, which when coupled with the right conditions, such as those in Philadelphia and Milwaukee, created momentum for adoption of green infrastructure at the city scale. As the two case studies demonstrate, these green leader cities built momentum and support for green stormwater infrastructure through a series of phases from experimentation, to demonstration, and finally—in the case of Philadelphia—to a full transition in the approach taken.

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Appendix A. Supplementary data

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