Green and Smart: Perspectives of City and Water Agency Officials in Pennsylvania toward Adopting New Infrastructure Technologies for Stormwater Management

Green and/or Smart? Perspectives of City and Water Agency Officials in Pennsylvania Towards Adopting New Infrastructure Technologies for Stormwater Management

Ting Meng, Ph.D., Department of Urban Studies and Planning, Massachusetts Institute of Technology, tmeng@mit.edu

David Hsu*, Ph.D., Department of Urban Studies and Planning, Massachusetts Institute of Technology, ydh@mit.edu

Bridget Wadzuk, Ph.D., Department of Civil and Environmental Engineering, Villanova University, bridget.wadzuk@villanova.edu.

*Corresponding author ydh@mit.edu.

Abstract

Stormwater runoff associated with urbanization is one of the main factors hindering continued progress towards cleaner water. The state of Pennsylvania has older cities and towns, ample water resources, and water quality problems that are all connected by aging, existing infrastructure for stormwater management. As older cities and towns begin to invest in new infrastructure, they have two, relatively new technology options: first, green infrastructure, and second, "smart" infrastructure, which adds sensors, controls, and communications. This paper examines how officials from cities and water agencies perceive these two solutions for their current stormwater management problems. Semi-structured interviews were conducted with officials from the five cities and towns throughout Pennsylvania that have enacted stormwater fees to fund further infrastructure investment. Responses indicate that the officials perceive green infrastructure as performing inconsistently across its life cycle and requiring labor-intensive maintenance. These officials hold positive views about smart infrastructure but want more information on performance and costs to reduce runoff. This study suggests research and tools that would help these officials address their stormwater management problems.

Key words: green infrastructure, smart infrastructure, sustainable water management, stormwater, technology adoption

Introduction

Stormwater runoff associated with urbanization and increased impervious areas has well-documented negative impacts on water quality, watersheds, and aquatic systems (NRC 2008; EPA 2011; Brabec 2002; Arnold and Gibbons 1996; Lee 2003; Thurston 2006). The U.S. Environmental Protection Agency (EPA) has issued progressively stricter criteria on stormwater runoff management through federal regulations for municipal separate storm sewer systems (MS4), combined sewer overflows (CSOs), and Total Maximum Daily Loads (TMDLs). In addition to more traditional infrastructure approaches such as upgrading existing sewers and adding storage and treatment capacity – the so-called "gray" approach – cities and water agencies have two relatively new technology options for stormwater management.

The first approach to meeting these regulations, strongly supported by the U.S. EPA and environmental organizations over the past ten years, has been to encourage the use of green infrastructure (GI) that uses decentralized systems to detain or infiltrate water, either by building new systems or retrofitting existing ones. Numerous researchers have also argued that GI can provide substantial benefits to watershed restoration and the community (Wise 2008; Gaffin, Rosenzweig, and Kong 2012). As a result, several cities have initiated GI efforts to meet their environmental and regulatory goals. However, GI remains in many places a new or emerging approach, and at present, adoption of GI is still heavily concentrated in certain regions of the United States (Washburn 2015).

A second, complementary approach that is emerging are "smart" technologies for stormwater management, which add digital technologies such as sensors, controls, and communication networks to existing or new physical infrastructure. Smart GI services are defined in this study as active or self-reporting technology platforms that add sensors, controls, communications, and/or intelligence to green infrastructure approaches. These platforms can potentially increase GI performance by first capturing and integrating data from real-time weather forecasts, system conditions, and even social media; then analyzing this data; and enabling real-time interaction with the water environment through monitoring, control, and management.

This study is therefore structured to understand how officials in five cities, towns, and their associated water agencies in Pennsylvania view green and/or smart infrastructure as possible solutions for stormwater management. Pennsylvania provides an interesting case study for a number of reasons. First, the state has many older cities and towns, ample water resources, and water quality problems that are all connected by aging, existing infrastructure for stormwater management. Pennsylvania has the largest number of CSOs of any state in the U.S.: 20% of all CSOs in the U.S.; and they range from big to small and are similar to other combined sewer systems in the U.S. (EPA 2004). Frequent wet weather events combined with aging sewer infrastructures place a heavy burden on stormwater management practices to comply with water quality standards and protect the region's water resources. As a result, state regulations are being revised to incorporate greener approaches to stormwater management (Washburn 2015). Second, this study focuses on the all five cities and towns in Pennsylvania that have enacted specific stormwater fees to fund future investments in stormwater infrastructure. These are the communities that are and will continue to be making choices about their strategy and approach to new technologies. Additional funds have also been available to support GI from other sources. For example, in 2009, $44.6 million in federal stimulus funds in turn was leveraged into more than $66 million for Pennsylvania on green water infrastructure (American Rivers 2010), and the William Penn Foundation and others are actively funding study of this problem. Third, this study focuses on officials within local governments and water management agencies, because they are responsible for the envisioning, planning, and management of GI initiatives and are in the best position to promote sustainable stormwater management on a larger scale (Young and McPherson 2013; EPA 2016b). There has been little study, however, of how officials in cities and water agencies, who often must make decisions about future infrastructure investments, view these new and evolving technologies. To the best knowledge of the authors, no other similar studies explore the attitudes and perspectives of officials toward smart infrastructure or services in the area of stormwater management.

The subsequent sections of the paper address the literature related to implementation of green and/or smart infrastructure for stormwater management; stormwater management and GI initiatives in Pennsylvania and in the five cities and towns; the methodology of the semi-structured interview approach; and the results, conclusions, and implications of this study.

Background of urban stormwater management

The water pollution impacts of stormwater are closely related to urbanization, impervious surfaces, and how it is managed within stormwater infrastructure. In cities with combined sewer systems, where sewer pipes collect both stormwater runoff and domestic/industrial wastewater, heavy rain events often cause sewer overflows. Discharges of untreated wastewater from CSOs directly to nearby streams, rivers, and other water bodies have major adverse effects for both human and aquatic systems. These aging combined sewer systems exist in as many as 772 cities and towns, and serve 40 million people nationwide (EPA 2015).

Stormwater management strategies that address stormwater runoff and related water pollution fall into two categories: gray and green infrastructure. The gray approach replaces and upgrades existing sewer mains or makes other improvements to traditional infrastructure to increase the storage, conveyance and treatment capacity of the system, such as tanks, pipes and tunnels, and wastewater treatment plants, respectively (EPA 2008; City of Lancaster 2011). Green infrastructure for stormwater management involves a range of soil-water-plant systems that protect, restore, or mimic the natural water cycle (PWD 2015c; American Rivers 2015). This green approach includes rain gardens, green roofs, pervious pavement, and constructed wetlands. Traditional centralized gray infrastructure is designed to move stormwater away from the built environment quickly, while the aim of green infrastructure is to reduce and treat stormwater at its source while delivering many other environmental, social, and economic benefits (EPA 2008).

Implementation of Green infrastructure

Recent policy memos from the Office of Water at the EPA strongly encourage the use of GI to address water quality issues, which were integrated into National Pollutant Discharge Elimination System (NPDES) permits and CSO long-term control plans (EPA 2016a). Following such guidance, several major cities including Philadelphia, Seattle, Washington, D.C., and Chicago have integrated GI in their water management plan to meet their environmental goals and regulatory standards. For example, according to the Green City, Clean Waters Program in Philadelphia, over the next 25 years, the city plans to spend $1.2 billion on green infrastructure and transform approximately 4,050 hectare (10,000 acres) of impervious area to “greened acres”, or about one-third of the combined sewer system treatment area (PWD 2011).

Current adoption of GI is still concentrated in limited regions of the United States (Washburn 2015). A few existing studies have explored barriers and challenges of integrating GI. For example, Keeley et al. (2013) and Rowe et al. (2016) explore the financial, administrative, political, and technical dimensions of stormwater management and identify funding as one of the primary barriers to GI installation. Washburn (2015) examines the status of GI initiatives in southwestern Pennsylvania and argues that encouraging GI expansion requires more up-front investment in research, planning, and community engagement. Kabisch (2015) argues that development pressure, financial constraints, loss of expertise, and low awareness of green benefits are major challenges in urban green governance. However, while there have been several studies on the hydrological and water quality impacts of GI after construction (Davis 2008; Czemiel Berndtsson 2010; Emerson and Traver 2008), there have been few studies on post-construction management practices such as operations and maintenance, in spite of their crucial role to the long-term success of GI (EPA 2013).

Smart technologies for stormwater management

Rapidly evolving digital technologies are an opportunity to add sensing, instrumentation, communication, and intelligent control systems to water infrastructure, allowing the capture of information, analysis of data, and potentially, real-time interaction between managers, infrastructure, and the environment. Ocampo-Martinez et al. (2013) argue that optimal control in water systems could enable improved energy efficiency, cost minimization, and environmental protection. For example, a combined sewer overflow network with embedded sensors was deployed to monitor, control, and reduce CSO events (Ruggaber et al. 2007). Collaborative wireless sensor networks have been demonstrated for use in water quality monitoring, control, and management (Zia, Harris, and Merrett 2014). These smart technologies aim to improve system performance and resilience by enhancing situational awareness, real-time monitoring, predictive control, crisis response and recovery, and self-healing operations (Rasehk et al. 2016). However, a key argument is that smart technologies must be shaped to respond to the needs of water management officials and agencies (Wang et al. 2015).

Stormwater management and GI initiatives in Pennsylvania

Due to more stringent federal regulations and increasing stormwater management costs, many cities and municipalities nationwide have instituted stormwater management fees to generate a stable funding source for the construction and maintenance of sewer systems (PWD 2015d). This study focuses on all five cities and towns in Pennsylvania – Philadelphia, Mt. Lebanon, Meadville, Lancaster, and Radnor – who have established stormwater ordinances with fees to fund future stormwater infrastructure (Campbell 2014). Since funding is usually considered to be a major challenge in building GI, investigating the municipalities with dedicated and stable revenue sources enables this study to concentrate on further challenges, particularly post-construction management practices, which were found above to be under-studied. Basic community characteristics such as population, area, and sewer types, as well as the dates that stormwater fees were enacted, are shown in Table 1. The location of these communities and relevant watersheds are indicated in Figure 1. Stormwater management and GI implementation in the selected communities will be discussed in the following subsections.

Philadelphia

Philadelphia is one of America's oldest cities with an approximate population of 1.5 million and seven major sub-watersheds. The combined sewer system covers almost two-thirds of the city's total sewer service area, serving more than three-quarters of the city's residents (PWD 2015a). Philadelphia's sewer system has about 4,830 kilometers of sewers (3,000 miles), 175 CSO regulating chambers, and 164 CSO outfalls (PWD 2015e). The Philadelphia Water Department (PWD) has established a number of new policies to promote GI: a parcel-based billing system based on impervious surface in 2010 (Featherstone et al. 2011), and Green City, Clean Waters, a 25-year program to manage the city's CSOs, that was adopted in June 2011. This plan commits to using GI to reduce stormwater pollution and achieve the required water quality standards. PWD has estimated that employing green infrastructure instead of just relying on traditional infrastructure will reduce stormwater pollution by 85% and save the city $5.6 billion (PWD 2015b). So far, there have been over 1,100 green stormwater projects in Philadelphia, including a variety of practices such as tree trenches, rain gardens, porous paving, and swales (PWD 2015b). PWD offers several funding mechanisms to support the implementation of GI. In addition to the Green City and Clean Waters program, PWD has created two additional grant programs for non-residential private organizations to reduce their design and installation cost of stormwater management practices.

Mt. Lebanon

Mt. Lebanon is a town of approximately 33,000 people in Allegheny County within the Ohio River Watershed and has two sub-watersheds. In Mt. Lebanon, the majority of existing stormwater infrastructure was developed in the early 1900s, including about 121 kilometers (75 miles) of storm sewers, and over 2,500 catch basins along with drains, curbs, and gutters throughout the municipality (Mt. Lebanon 2015). Such aging infrastructure can no longer accommodate the volume of stormwater runoff from heavy wet weather events, causing street flooding and water pollution. In 2011, the Mt. Lebanon Commission approved an ordinance establishing a fee for the construction and maintenance of the municipal storm drain system, including sewers and drains to collect and manage stormwater (Mt. Lebanon 2011). Instead of solely focusing on gray infrastructure such as pipes and treatment plants, Mt. Lebanon started to implement GI as complementary solutions, including a rain barrel rebate program, community environmental education, permeable pavements, and wetland maintenance (Mt. Lebanon 2012).

In addition, stormwater management fee credits were offered to incentivize property owners to install additional GI (Washburn 2015).

Meadville

Meadville is a town of approximately 13,000 people in northwest Pennsylvania (French Creek Valley Conservancy 2015). The city's current stormwater management system includes over 48 kilometers (30 miles) of stormwater pipes, and more than 1,200 catch basins or inlets along with swales and culverts. It is over 100 years old and has reached the end of its design life. As the only MS4 municipality in Crawford County, the city is required to comply with the pollution limits set by their MS4 permit. Recently, reduced staffing and limited funding has impacted the city's maintenance of the sewer system. In October 2012, Meadville passed a new ordinance that established the Stormwater Management Program and User Fee to provide a dedicated funding source to the operation, administration, maintenance, repair, and improvement of the city's stormwater management system (Meadville 2012). The city also offers fee reduction to selected property owners if they convert impervious surfaces into pervious ones; and provides credits to encourage various green practices onsite.

Lancaster

The Conestoga River flows through the city of Lancaster (population 59,325) and eventually into the Chesapeake Bay. Like Philadelphia, Lancaster relies on a combined sewer system that covers 45% of the city, and other parts of the city have separated sewer systems to convey stormwater and sewage (City of Lancaster 2011). While the sewer system is generally able to manage and clean the water flowing through this system, during large wet weather events the combined sewer system exceeds capacity, and an untreated stormwater and sewage mix is released directly into the Conestoga River. Each year, Lancaster is responsible for about 3.8 billion liters (1 billion gallons) of polluted water entering the nearby water bodies (City of Lancaster 2011). Moreover, the EPA established stringent pollution limits for all communities located within approximately 166,000 square kilometers (64,000 square miles) of the Chesapeake Bay Watershed (American Rivers 2010). Given such infrastructure challenges and water quality goals, in May 2011, Lancaster laid out a 25-year plan to eliminate the combined sewer overflows from the watershed through green infrastructure. In 2014, Lancaster established a stormwater management fee in order to provide a stable funding source for stormwater collection and management activities (City of Lancaster 2014). Lancaster's Green Infrastructure Plan has been estimated to save over $160 million for the city as compared to solely traditional gray infrastructure solutions, such as expanding the treatment plant and holding tanks (City of Lancaster 2015). To date, Lancaster has implemented a number of new green infrastructure projects, including green roofs, pervious paving, rain gardens, planter boxes, and trees. In addition, the city is employing a range of tools to encourage green solutions, including a project to green impervious surfaces in public schools, incentives for residential and commercial property owners to retrofit existing surfaces with green infrastructure, and a standard to address the first flush of stormwater runoff, which requires property owners to manage the first 25.4 millimeters (1-inch) of rainfall on new impervious surfaces (City of Lancaster 2011).

Radnor

Radnor Township is a town of approximately 31,000 residents, and is part of the Darby and Cobbs Creek watershed, with some portions of town located near Gulph and Mill Creeks. It has a separate sanitary and stormwater system with 203 kilometers (126 miles) of sewer pipes and 379 million liters (100 million gallons) of monthly flow of waste water (Radnor Township 2015). Radnor is challenged with maintenance of aging infrastructure that is in places 100 years old, flood safety, water quality protection, as well as MS4 permit requirements. Since the late 1970s, the township has required stormwater management, typically in the form of gray infrastructure solutions. In 2005, the Board of Commissioners passed a comprehensive stormwater management ordinance, which required all areas in the township to comply with the ordinance developed by Delaware County in an effort to protect the Darby & Cobbs Creek watersheds (Radnor Township 2005). In October 2013, a stormwater fee instituted by the Radnor Board went into effect to fund the operation, administration, maintenance, repair, and improvement of the stormwater management system, and to meet regulatory requirements (Radnor Township 2013). The stormwater fee has also been used to support green infrastructure development through incentive programs. Several green infrastructure projects have been installed throughout the township, including porous paving under two existing parking lots, a green roof at a local middle school, as well as a rain garden at a municipal building. The Stakeholder Advisory Committee established by the Board assists in the selection and prioritization of projects, and also implements the township educational programs. In addition, Radnor Middle School established a "Watershed Program" for seventh-graders that integrates traditional subjects such as social studies and science with watershed education and associated water management practices.

Methodology

Semi-structured interviews were conducted with stormwater officials and professionals in each community, focusing on the relationship of stormwater management and the perceptions of GI and related smart GI services. The interviews asked about three main areas: first, the current status of stormwater management in each community, including stormwater runoff, major issues caused by runoff, management strategies, funding sources, and major procedural challenges;

second, the role of GI in the community's long-term plans and post-construction concerns; and third, stormwater agencies' perception of smart services with a focus on new technology adoption and design requirements.

A total of ten officials from the five cities, towns, and their water agencies were selected, as these agencies are primarily responsible for managing stormwater infrastructure. One interviewee was a professional acting on behalf of one of the smaller towns. Interviews were conducted in May and June of 2015 and focused on the barriers, challenges, and attitudes of these officials towards GI and related smart infrastructure services. Interviews were guided by a pre-determined outline of questions, but the semi-structured format allowed the conversation to stray from the outline in order to capture additional information when it was needed or offered. The outline of questions is shown in the supplemental appendixes as Table S1. Interviews were conducted by phone or in-person, and lasted approximately 30 to 40 minutes. The interviewees were officials from the Public Works Department, Water Department, Engineering Department, and stormwater programs, and they were directly responsible for developing and implementing infrastructure for stormwater management.

Besides interviews conducted in the summer of 2015, follow-up web-based surveys were distributed to all five selected communities in Pennsylvania. The main goal of the follow-up surveys is to explore more about the stormwater agencies' perceptions toward smart GI services. The questionnaire was designed and revised between September 2015 and February 2016, and launched online through Qualtrics between March and June 2016. Four out of five communities (except Radnor Township) participated in this follow-up survey and shared their perceptions on several major issues regarding the adoption of smart GI services. These issues include benefits of GI that may be enhanced through implementation of smart devices, additional functions that smart GI may provide, and concerns that may hinder the potential adoption of smart devices. A three-level Likert scale was employed to measure the degree of city and water agency officials' perceptions. The choice options were "not important," "somewhat important," and "very important." The particular survey questions are shown in the supplemental appendixes as Questionnaire S1 .

Results

As stated above, results from interviews conducted with stormwater agencies are organized into three major aspects: major issues surrounding stormwater management; the role of GI in the community's long-term plans and post-construction concerns; and their perceptions of smart GI services. In addition to the interviews, results from the on-line surveys are also summarized in Table 2 and discussed below. However, Radnor Township did not reply to the follow-up survey.

Major issues in stormwater management

Major issues related to general stormwater management identified by the selected communities in Pennsylvania include aging sewer infrastructure, street flooding, water pollution, and regulatory compliance. They are summarized below:

1. Aging sewer infrastructure: four out of five communities had concerns about this. To keep and enhance the capacity of current sewer systems, municipalities have to spend a substantial amount of money each year on the existing pipes and facilities underground, which are decades old. It is estimated that upgrading and rebuilding the existing infrastructure would cost Lancaster $300 million to build and another $750,000 each year for treatment (City of Lancaster 2015).

2. Street flooding: three out of five communities had concerns about this point. Heavy storm events lead to stormwater runoff, which leads to flooding, which eventually leads to property damage, traffic disruptions, and generally impedes the normal life of communities. For example, an official in Radnor stated that street flooding and property damage resulting from stormwater runoff hinders public services by blocking police cars and fire trucks.
3. Water resources and pollution: four out of five communities were concerned about the need to protect surrounding water resources and reduce water pollution from excessive water runoff. Due to stormwater runoff or CSOs, decreased water quality has become a major concern in many regions, and thus communities need to take actions to reduce their untreated water and protect the watershed system. Stricter federal or state policies set a high standard for stormwater management (EPA 2016a) and also placed pressure on these communities. During the interview, an official in Philadelphia remarked, “Our biggest problem is the combined sewer overflows... and the focus of our green infrastructure program is reducing the amount of pollution that comes through the sewer overflows”.
4. Regulatory requirements: four out of five communities discussed their need to comply with environmental regulations, with some facing huge penalties for non-compliance. Complying with the stormwater regulations is a major issue confronting both combined sewer and MS4 municipalities. As an official in Meadville admitted, “We are having a difficult time living up to requirement compliance, which is pretty big.”

Major issues in the role of GI

The focus of the interviews on GI revealed the following:

1. Role of GI in long-term planning: four out of five communities stated slightly different beliefs on the degree and extent of their willingness to use GI. For Radnor, incorporating GI aligns with their long-term goals, but to have a measurable impact, their plan requires a broad and continuous effort on an incremental basis. As an official in Radnor explained, "One little rain garden does not stop flooding, but a large number of these little green tools together would definitely make a difference in terms of enhancing water quality and reducing stormwater runoff." Meadville also aligns GI with their goals of stormwater management in the long run; however, in the short term they treat GI as a complement to, but not replacement for, traditional gray infrastructure.
2. Long-term effectiveness of GI: four out of five communities had concerns about this. Officials interviewed for this study felt that the performance of GI is not consistent over time and under various scenarios. As professionals in Philadelphia pointed out, in the beginning period when the vegetation surface of GI has not been fully developed (e.g., newly planted trees), GI has relatively low capacity but requires more maintenance work such as irrigation. However, given the large upfront cost needed for the design and installation of GI, it needs to work efficiently for a long period of time. An official in Radnor stated, "You want to get benefits for 10, 20, or 30 years". This concern about the long-time effectiveness of GI is consistent with findings in the literature, where, it has been found that performance can change significantly over time (Berndtsson 2010). To some extent, GI is perceived as more uncertain compared with conventional gray infrastructure (Dunn 2010).
3. Operation and maintenance: during the interviews, respondents pointed out that attention should be paid not only to the design and installation of green stormwater tools, but also

to the ongoing operation and maintenance to ensure that GI works efficiently over time. The interviewees cited the heavy maintenance burden of GI as a major challenge, which is consistent with previous research (Zhang et al. 2012). Many green infrastructures, especially those that include vegetation, require regular maintenance to ensure such green tools are functioning properly. An official in Meadville stated, "I worry about the maintenance of those things [GI]… a lot of things are manpower driven." Maintenance tasks include on-site inspection, trash collection, weeding, and irrigation, which are usually labor-intensive. "Maintaining it [GI] year after year can be very costly," one Radnor official said, pointing out that "it has to be maintained and it is labor intensive to let the plants you want to be here alive and keeps the ones you don't want out." Also, GI requires more frequent maintenance. As one official in Philadelphia remarked, gray stormwater infrastructure usually requires only annual maintenance, while most green infrastructure requires monthly maintenance for plant care and trash removal, especially those involving plants and other vegetated surfaces.

Perspectives towards smart services

Interviewees expressed the following perceptions of smart services added to GI:

1. Definitions of "smart" services: three out of the five interviewed communities had previously heard of smart GI services, while others had not heard about them or were unsure of the definition. Many stormwater officials thought that smart infrastructure was either related to smart growth paths (choosing the smartest way to grow or change the city or township through planning or zoning code) or advanced intelligent technologies. After defining smart GI services in the context of the interviews as the latter, and explaining how they work, more than half of the communities expressed positive

attitudes towards such smart services. A professional from Mt. Lebanon said that their community wants technologies and devices that can monitor topography, save cost, or improve efficiency.

2. Lack of concrete information about performance and costs/benefits: despite positive reactions to smart GI, water management officials asked for more information and analysis on the performance, costs, and benefits of smart services. Three agencies asked for more evidence regarding how much smart services could improve the operational efficiency and the runoff reduction capacity of GI. As officials in Philadelphia and Radnor highlighted, they need to know how smart GI is going to make their water management more efficient. Similarly, a professional from Mt. Lebanon asked whether smart GI would significantly improve the efficiency of their hydrological modelling. This emphasis on understanding smart GI's performance was consistently confirmed in the survey results. Four surveyed communities all agreed that the performance of smart GI functions, such as stormwater volume reduction, nutrient removal, and suspended sediment removal, are all important to them. The first two aspects are very important to three agencies and somewhat important to one agency, while they evenly split on "very important" versus "somewhat important" for the third aspect.

Furthermore, three out of five interviewed stormwater agencies required additional cost-benefit information to consider adding related smart services. The interviewed officials from Lancaster stated, "I think understanding the cost-benefits would be the first thing we need." Similarly, an official in Meadville pointed out that they would worry about increased costs resulting from added smart devices. The follow-up surveys also confirmed the crucial influence of costs and benefits on potential adoption.

Results indicate that one agency is very concerned about increased cost when adding smart devices, and the other three agencies feel somewhat concerned. Similar to the findings about the cost, three out of four agencies claim that they are somewhat concerned (one agency) or very concerned (two agencies) about the benefits that smart GI might bring.

3. Specific needs for smart infrastructure: several respondents also pointed out certain specific requirements for smart GI services. As an official in Lancaster said, "If it benefits, we will certainly be interested with the instrument with a [smart] format especially if it helps with some of the maintenance requirements." Officials in Philadelphia confirm the need to utilize smart systems to address certain maintenance issues, either by saving labor directly or changing the skill level of the needed labor. Results from on-line surveys indicate that relevant functions such as providing alerts for maintenance and providing on-site monitoring are very important (one agency) or somewhat important (three agencies). Moreover, low-cost and easy-to-operate smart GI services with robust performance across various environmental scenarios are important to Philadelphia. In the on-line survey, all four communities reported that providing more consistent performance across seasons are either very important (two agencies) or somewhat important (two agencies) to them. Officials from Meadville confirmed the need for user-friendly smart services, and requested personnel training from service providers, due to a current lack of staff and technology resources.

Conclusions and implications

Fixing Pennsylvania's aging, existing infrastructure for stormwater management is necessary to address its water quality problems. Both GI and smart GI services are relatively new technology options for city and water agency officials in Pennsylvania and elsewhere. While issues of operation and maintenance are receiving increased attention in order to improve the performance and capacity of GI in the long run, integrating smart technologies will require a comprehensive understanding of the needs of city and water agency officials who are leading the development and implementation of stormwater infrastructure.

The semi-structured interviews and surveys found that the major concerns of city and water officials related to stormwater management are aging infrastructure, flooding, water pollution, and policy compliance. Major barriers in the post-construction process identified by city and water agency officials are the unstable performance of GI over its life cycle and the perceived heavy maintenance burden especially for vegetated GI. Promoting broader integration of GI requires three further kinds of research and development to address the needs of city and water agency officials and professionals. First, they need advanced research and case studies on the effectiveness and robustness of GI performance, especially those using actual field data. Data on the efficiency of GI for runoff reduction and sediment removal would encourage the adoption of GI among stormwater agencies. Second, the design of GI needs to be further improved to ensure that GI can perform consistently and efficiently throughout its life cycle and across various conditions. Third, city and water agency officials ask for further research efforts to reduce the maintenance burden and associated costs of GI. The attitudes expressed by the city and water agency officials about GI are broadly consistent with previous engineering studies.

Most officials hold positive attitudes towards smart GI services. Smart GI provides opportunities to address the substantial concerns related to long-term operation and maintenance of GI. Actual adoption of smart solutions, however, requires further studies on how smart services can improve the performance and capacity of GI in a cost-effective way. Several aspects of the performance of GI such as stormwater volume reduction, nutrient removal, and suspended sediment removal are expected to be enhanced by smart infrastructure. Furthermore, officials and professionals asked for smart GI to be proven to be lower-cost, user-friendly, robust, and consistent in its performance in various scenarios. Moreover, smart infrastructure should help particularly to reduce the maintenance burden of GI such as providing additional functions such as problem-alerting and on-site monitoring. Overall, our findings are consistent with previous studies but offer additional insights into the perspectives of city and water professionals on GI and related smart infrastructure.

The findings on post-construction barriers for GI, and the perceptions of city and water agency professionals wth regards to associated smart technologies, should be relevant to communities with similar water resources, pollution, and existing infrastructure, as well as more broadly to scholars and practitioners interested in adoption of new technologies such as green and smart stormwater infrastructure. Since managing stormwater through adoption of green and/or smart infrastructure involves many stakeholders in a dynamic process, future studies may examine other aspects of efforts to promote sustainable water management, such as policies, stakeholder engagement, and the improvement of public awareness of stormwater management.

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Supplemental Data

Table S1 and Questionnaire S1 are available online in the ASCE Library (ascelibrary.org).

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Table 1. Summary of Characteristics of All Five Cities and Towns

Community	Stormwater fee enacted	Population (2013)	Area (sq. km)	Sewer system
Philadelphia	July 2010	1,553,165	369	60% combined, 40% separated
Mt. Lebanon	August 2011	33,067	11	Separated
Meadville	October 2012	13,265	11	Separated
Lancaster	March 2014	59,325	19	45% combined, 55% separated
Radnor	October 2014	31,502	36	Separated

Population source: U.S. Census Bureau (2013)

Table 2. Survey Results of Perception on Smart GI

Issues/Response	PHL	Meadville	Lancaster	Mt. Lebanon
Performance				
• Stormwater volume reduction	**	**	**	*
• Nutrient removal	**	*	**	**
• Suspended sediment removal	*	*	**	**
Additional function				
• Providing on-site monitoring	*	*	**	*
• Providing alerts for maintenance	*	*	**	*
• Providing more consistent performance across season	*	*	**	**
Concern				
• Increased cost when adding smart devices	*	**	*	*
• Uncertainty about benefits that smart GI brings	**	**	-	**

Note: PHL=Philadelphia; ** denotes "very important"; * denotes "somewhat important"; - denotes "not important". Also, Radnor Township did not respond to this survey.

Fig 1. Map showing the five cities and towns charging a stormwater fee in Pennsylvania (Watershed drainage areas in *Italic*)

Fig 1. Map showing the five cities and towns charging a stormwater fee in Pennsylvania (Watershed drainage areas in *italics*)