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# Managing urban stormwater for urban sustainability: Barriers and policy solutions for green infrastructure application

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ABSTRACT

Green infrastructure (GI) revitalizes vegetation and soil, restores hydro-ecological processes destroyed by traditional urbanization, and naturally manages stormwater on-site, offering numerous sustainability benefits. However, despite being sustainable and despite being the object of unrelenting expert advocacy for more than two decades, GI implementation remains slow. On the other hand, the practice of traditional gray infrastructure, which is known to have significant adverse impacts on the environment, is still ubiquitous in urban areas throughout the world. This relationship between knowledge and practice seems unaccountable, which has not yet received adequate attention from academia, policy makers, or research communities. We deal with this problem in this paper. The specific objective of the paper is to explore the barriers to GI, and suggest policies that can both overcome these barriers and expedite implementation. By surveying the status of implementation in 10 US cities and assessing the relevant city, state and federal policies, we identified 29 barriers and grouped them into 5 categories. The findings show that most of the barriers stem from cognitive limitations and socio-institutional arrangements. Accordingly, we suggest 33 policies, also grouped into 5 categories, which span from conducting public education and awareness programs to changing policies and governance structures.



## 1. Introduction

Scientific studies and evidence have shown that conventional practices of urbanization and stormwater management are unsustainable (Chow, 1964; National Research Council, 2009; Savini and Kammerer, 1961). By removing vegetation and topsoil and creating impervious structures, urbanization destroys natural biodiversity and hydrological processes. As a result, urban societies are disconnected from nature and deprived of ecosystem services—the benefits nature provides to humans (Millennium Ecosystem Assessment, 2005)—such as flood control, fresh air, clean water, and natural beauty. Due to reduced vegetation, paved surfaces, and disrupted drainage connectivity, urban landscapes transform most rainwater into stormwater runoff. Traditionally, a network of curb-gutter-pipe, called gray infrastructure, is used to convey the runoff to a downstream drainage system. However, while gray infrastructure efficiently mitigates the problem of flash floods in urban areas, it leads to significant adverse effects downstream. The flow picks up pollutants from urban landscapes, transports them to receiving waters, and degrades receiving water quality. In addition, the expedited conveyance of the increased quantity of runoff increases the rate, peak, and frequency of flooding downstream which pose a bigger threat to public safety, property, and socio-economic activities. Rainwater, a vital resource of fresh water, is thus converted to a flooding and water pollution nuisance due to an inappropriate management approach. On the other hand, the impervious surfaces prevent rainwater from infiltrating the soil. The lack of rainwater infiltration results in water scarcity in the subsurface that leads to a decrease in groundwater recharge. A decrease in groundwater recharge then results in a lack of dry-weather base flow in the downstream waterways which threatens the freshwater ecosystem. This flow of consequences indicates that the conventional approach can pose significant adverse effects on the environment, economy, and society (Chow, 1964; Leopold, 1968; National Research Council, 2009)—traditionally considered the three pillars of sustainability.

GI is an alternative approach to stormwater infrastructure that restores the hydrological and ecological functions of the landscape and manages stormwater on-site by utilizing the natural processes

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of soil and vegetation. It is known by different names in different places: “low impact development” in the US, “water sensitive urban design” in Australia, “sustainable urban drainage system” in the UK, and “low impact urban development” in New Zealand (Marsalek and Chocat, 2002). By employing green roofs, permeable pavements, rain gardens, vegetated swales, and various other methods, GI restores ecosystem structures, revives biodiversity, and regenerates ecosystem services that include but are not limited to: carbon sequestration, flood control, water quality improvement, climate change adaptation, and groundwater recharge (Dhakal and Chevalier, 2016). In other words, the technology reestablishes the socio-ecological connectivity destroyed by urbanization (Gómez-Baggethun et al., 2013; Tzoulas et al., 2007) and improves the quality of life (Breuste et al., 2015). Studies have shown that GI costs significantly less than gray infrastructure (e.g., Baerenklau et al., 2008; Foster et al., 2011; Shaver, 2009; US EPA, 2015). For example, case studies conducted in six US cities and three New Zealand cities have shown that it might be possible to save from 15% to 64% on construction costs by using GI instead of gray infrastructure (Shaver, 2009). Additionally, since GI measures usually utilize the natural processes of soil and vegetation, it requires considerably less manufactured materials than gray infrastructure whose elements—including curbs, gutters, inlets, manholes, and pipes—use manufactured materials. Thus, the benefits of GI not only include cost-effectiveness but also material efficiency, the two additional sustainability attributes argued by Dhakal and Oh (2011). Scholars (e.g., Tzoulas et al., 2007; Young, 2009) therefore argue that GI is an underpinning element of urban sustainability. However, despite an abundance of knowledge regarding GI's sustainability benefits, over two decades of unrelenting advocacy from experts, and examples of successful implementation in different climatic regions, the implementation of GI seems surprisingly slow (Dhakal and Chevalier, 2015; Heaney and Sansalone, 2012; Rijke et al., 2013). On the other hand, gray infrastructure is still ubiquitous in urban areas throughout the world, even as it can (as above) appear environmentally inappropriate. The unaccountable relationship between knowledge and practice in terms of stormwater infrastructure, which has not yet received adequate attention from research communities, academics, or policy makers, is the problem that this paper deals with.

It is important to note that there are some struggles with finding the causes behind the sluggishness in using GI. Among the limited peer-reviewed literature available, Roy et al. (2008) conducted a comparative study of the US and Australian contexts and identified these 7 barriers common to both countries: uncertainties in cost and performance, lack of engineering standards and guidelines, fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, funding constraints, and resistance to change. Brown and Farrelly (2009a) reviewed the available literature to examine the status of sustainable water management over a wider context, local to international, and identified 12 barrier types, mostly related to governance, resources, regulations, and perceptions. In a subsequent paper, the authors (Brown and Farrelly, 2009b) surveyed three Australian cities, Perth, Melbourne, and Brisbane, from the perspective of urban stormwater management, and grouped the identified barriers into three major categories: management arrangements and responsibilities, regulations and approval processes, and capital and maintenance costs. Recent case studies from the UK conducted in England and Ireland (Matthews et al., 2015) and Newcastle (O'Donnell et al., 2017) also revealed the presence of socio-institutional, perceptual, and resource-related issues as major obstacles. Despite the variability in geography, time, scope, scale, context, and the name and number of listed barrier categories, all the above studies implicate similar barriers, most of which stem from personal perception and existing socio-institutional setups including policy and governance. These findings are consistent with what Niemczynowicz (1999) earlier presented as the future challenges of urban water management. Many of the identified barriers outlined by the above studies are rooted in social and organizational cultures, practices, and processes, and hence are difficult to overcome—as argued by Brown and Farrelly (2009a). As indicated by many of the above studies (e.g., Brown and Farrelly, 2009a; Niemczynowicz, 1999; Roy et al., 2008), overcoming such barriers requires not only developing a new individual and socio-institutional mindset through education and awareness, but also improving socio-institutional arrangements such as governance and policies. This paper focuses on policies.

We analyzed policies of 10 US cities, relevant state and federal policies, and other available literature to diagnose the obstacles and explore policies that can both overcome the barriers and expedite the adoption of GI. We identified 29 barriers and grouped them into 5 categories. The findings show that most of the barriers stem from cognitive limitations and socio-institutional arrangements. Accordingly, we suggest a set of 33 policies, also grouped into 5 policy types, which span from conducting education and awareness programs to changing existing policies and governance structures.

## 2. Study approach and scope

The research consisted of two phases. In the first phase, we explored the existing barriers through a critical analysis of literature available. The materials that were extensively analyzed included peer-reviewed journal articles, books, the US Constitution, US laws and regulations, court decisions, municipal codes and manuals, and the US EPA case study reports. Literature on ecosystem services was also reviewed. Ruhl et al. (2007) provide a comprehensive analysis on the status of US law and policy on ecosystem services, and the National Research Council (2009) provides a detailed review of urban stormwater management challenges in the US. These two publications were analyzed in detail. The US EPA has recently published six individual reports on GI barriers and opportunities in six US cities: Dallas, Texas; Camden, New Jersey; Macatawa Watershed, Michigan; Neosho, Missouri; Phoenix, Arizona; and Los Angeles, California (US EPA, 2016). These reports were analyzed along with their city codes. Another case study of 12 cities conducted by the US EPA (2010) was also reviewed.

In the second phase, we synthesized normative policy recommendations to address the barriers identified in the first phase. For this, policy tools and strategies adopted by four US cities (Seattle, Washington; Portland, Oregon; Chicago, Illinois; and Philadelphia, Pennsylvania) were analyzed against the barriers identified in the first phase. These cities have been using GI relatively widely (Chen et al., 2013). The documents examined included ordinances, codes, manuals, and standards that influence the adoption of GI and the maintenance of ecosystem services. Finally, based on the findings, a policy framework was proposed. Though the focus of the study was on select US cities, the relevant publications on non-US cities, especially cities in the UK and Australia, were also analyzed.

While the options of green measures—such as green roofs, rain barrels, infiltration trenches, and rain gardens—can vary significantly from location to location, our study revealed that adopting GI faces similar cognitive and socio-institutional challenges of implementation regardless of location. Cognitive barriers, for example, stem from a lack of awareness, a particular socio-cultural mindset, and reliance on traditional institutional arrangements, whether it is in the US, the UK, Australia, or any other country. Therefore, with some location-specific adjustments, the findings of this paper should be applicable to non-US cities as well.

**Table 1**
Barriers to implementation of GI.

| Types | Specifics | Description |
|---|---|---|
| 1. Federal and state policy barriers | 1.1. Constitutional protection of private property | Prevents enforcement of GI on private parcels. |
| | 1.2. Court law: law of diff used surface water | |
| | 1.2.1. Common Enemy Rule | Fundamentally contradictory to the concept of GI. |
| | 1.2.2. Law of Natural Drainage | Restrictive to urban development. |
| | 1.2.3. The Reasonable Use Rule | Can be relatively friendly to GI, but insufficient. |
| | 1.3. Federal statutory law | |
| | 1.3.1. Insufficient statutory goal in the Clean Water Act (CWA) | The CWA does not include maintenance of hydro-ecological integrity of watershed as a goal. |
| | 1.3.2. Responsibility versus authority dilemma | Cities have no direct authority to control stormwater from private parcels but has responsibility to manage it. |
| | 1.3.3. No flow control provision | Focused on pollutant loading, not flow quantity. |
| | 1.4. State statutory laws | Some states have preventive policies. |
| | 1.5. Lack of stewardship of ecosystem services | No economic incentives for owners to protect ecosystem services. |
| | 1.6. Decoupling of intercoupled jurisdictions | E.g., quality and quantity control responsibilities are under different authorities. |
| | 1.7. Lack of design and maintenance standards | No national standards and codes are available. |
| 2. City policy barriers | 2.1. Regulatory threshold | Too high threshold to trigger stormwater management requirements. |
| | 2.2. Problems in codes and guidance documents | Presence of conflicting or confusing provisions and absence of suitable provisions. |
| | 2.3. No provision for off-site mitigation | Code does not allow for off-site control. |
| | 2.4. Use restriction | Prevention in the use of available spaces for GI. |
| | 2.5. Requirement to use gray system | Mandatory provisions to route flow to gray. |
| | 2.6. Restriction on rainwater harvesting | Rainwater harvesting not allowed. |
| | 2.7. No maximum limit on facility size | Provision for minimum requirement, but not maximum limit. |
| | 2.8. Pavement material requirement | Requirement of traditional pavement material. |
| | 2.9. Curb requirements | Generally, curb is mandatory in the code. |
| | 2.10. Lack of financial incentives | No incentives for private parcel owners. |
| 3. Governance barriers | 3.1. Pro-gray arrangements | Centralized and exclusively technocratic governance. |
| | 3.2. Fragmented governance | Fragmented spatial and functional jurisdiction. |
| | 3.3. Lack of coordination | Both within and outside the government. |
| | 3.4. Lack of public engagement | Practically, citizens have no role to play in final decision making. |
| 4. Resource barriers | 4.1. Lack of financial resources | Lack of public/private investments on GI. |
| | 4.2. Lack of data on cost and performance | Historical performance data is not available. |
| | 4.3. Dearth of human resource | Shortage of workforce trained on GI. |
| 5. Cognitive barriers | 5.1. Pro-gray mindset | Public accustomed to using gray infrastructure. |
| | 5.2. Unawareness about gray infrastructure and GI | Public unaware of harms/benefits of gray/green. |
| | 5.3. Perceived risk on cost & performance | Fear of higher cost and lower performance of GI. |
| | 5.4. Risk aversion attitude & reluctance to change | Unwillingness to shift to a new technology due to fear of taking perceived risks of using it. |
| | 5.5. Hesitation to take maintenance responsibility | Due to fear of lack of maintenance knowledge as well as intention to avoid perceived burden. |

## 3. Findings and discussions

### 3.1. Barriers

The barriers identified in the study are grouped and presented in Table 1, and are discussed as follows.

#### 3.1.1. Federal and state policy barriers

The study revealed significant barriers prevailing across federal and state policies including but not limited to provisions in the US Constitution, case laws, and statutory laws. While private property rights are considered fundamental to a free and democratic society, the constitutional protection of the right under the Fifth Amendment to the US Constitution, which prohibits both the physical and regulatory taking of private property for public purposes, also can prevent municipalities from implementing GI on private property.

Though such "takings" are allowed if "just compensation" is made, the Fourteenth Amendment guarantees a "due process" before such takings, which creates legal and political proceedings that can give rise to complications for GI implementation. Furthermore, a lack of further constitutional clarification on "takings" and "just compensation" (Ruhl et al., 2007) can result in controversies that lead to litigations.

Historically, stormwater, or diffused surface water, was perceived as a nuisance. Courts therefore established case laws (also known as court laws) for draining it off the site instead of using on-site (Dellapenna, 1991). Accordingly, the laws are called drainage laws and are defined according to one of the three doctrines: the Common Enemy Rule, the Law of Natural Drainage, and the Reasonable Use Rule (Dellapenna, 1991; Urban Drainage and Flood Control District, 2008; Weston, 1977). The Common Enemy Rule regards stormwater runoff as a common enemy and allows a landowner to protect his/her land by any means necessary, regardless of the possible consequences to others (Dellapenna, 1991). This can encourage hydrologic disruptions, which is contrary to the concept of GI. As discussed earlier, GI regards stormwater as a resource, not an enemy, and utilizes it on-site by reestablishing the disrupted hydrology. The Law of Natural Drainage, or the Civil Law Rule, restricts any modifications of land that disturb the natural flow of surface water. It can, however, prevent development, and is therefore not appropriate in an urban context. The Reasonable Use Rule allows for the modification of land and drainage. It also allows for a negative impact on other properties if (i) there is a reasonable necessity; (ii) reasonable care be taken to prevent the possible damage; and (iii) the benefit reasonably outweighs the harm (Urban Drainage and Flood Control District, 2008; Weston, 1977). Since GI has the potential to prevent damage by on-site treatment, it can be used to satisfy the second condition. However, the difficulty can arise due to the transaction cost required to acquire information on the possible damage and due to an arguably high potential of controversy over what level of care is the "reasonable care." Such controversies can lead to litigations. If the ecosystem services provided by GI had an economic value with its property right assigned to the landowner, GI would potentially satisfy the first and third conditions as well. However, since US law provides no property rights for them and most ecosystem services have no economic value (Lant et al., 2008; Ruhl et al., 2007), no one has an incentive to protect or install GI on their private parcels.

The primary federal statute that governs stormwater in the US is the Clean Water Act (CWA) (33 USC §§1251–1387). Its objective is to "restore and maintain chemical, physical, and biological integrity of the Nation's waters" (§101(a)), but not to restore and maintain the hydrological integrity of landscapes, an inevitably important component of urban ecology. The CWA does not only ignore hydrologic attributes such as surges in volume and timing of discharge (National Research Council, 2009), its implementation also overlooks two of its own statutory concerns, physical and biological integrity, by focusing only on chemical integrity (Adler, 2007). The act is based on a permit scheme, called the National Pollutant Discharge Elimination System (NPDES) (§402), which requires an NPDES permit if there is a discharge of pollutants by a person from a point source into navigable waters (§§301, 502). However, as defined by the statute, stormwater is neither a pollutant nor does it come from statutorily defined point sources. Since the parcels that generate stormwater do not have "discernable, confined, and discrete conveyance," which are the three essential statutory conditions for a source to be a point source (§502(14)), they are not point sources, and hence are not subject to NPDES. Thus, the NPDES scheme puts the responsibility of managing Municipal Separate Storm Sewer System (MS4) upon cities without providing legal authority to control private parcels, which comprise a significant portion of the actual sources generating the flow. This results in the "responsibility versus authority dilemma," as termed by Dhakal and Chevalier (2016). Total Maximum Daily Load (TMDL) (§303), which refers to the maximum allowable amount of a pollutant that a water body can receive and still meets quality standards (McCulley, 2002; US EPA, 2009), is another provision of the CWA which is applied to control pollutants in the impaired waters. However, since stormwater is not a pollutant, its quantity cannot be regulated by using TMDL. In Virginia Department of Transportation v. United States Environmental Protection Agency (2013), a federal court did not authorize the EPA to control stormwater flow as a surrogate for sediment. In addition, TMDL is normally activated only after waters get impaired, but has no role in land development activities (National Research Council, 2009). Thus, the CWA does not have provisions that require the restoration of hydrologic processes and vegetation, two fundamental features of GI.

Barriers also exist in state laws and policies. For example, the State of New Jersey does not authorize cities to charge landowners a fee based on the amount of stormwater generated from their land, thereby barring cities to implement an effective economic incentive, discussed later. In Missouri, though the state law does not prevent such a fee, recently the State Supreme Court disallowed the city of St. Louis the implementation of a user charge based on impervious areas, deeming the charge a tax and requiring voters' approval pursuant to the State Constitution (Zweig v. Metropolitan St. Louis Sewer District, 2013).

Even as a kind of natural capital that provides numerous other ecosystem services, the status of GI in the US law and policy is discouraging. Due to the absence of marketable values for most ecosystem services, such as air purification and natural beauty, owners cannot sell them in markets for profit. Legal avenues exist neither for owners to charge recipient of the services, nor for the recipients to ensure the unabated supply of the services from the owners (Ruhl et al., 2007). As a result, a rational landowner is encouraged to destroy natural capital and develop his/her land to maximize the economic benefits. Ecosystem services thus lack the stewardship they require and are destined to be ruined. Ruhl et al. (2007) term this predicament the "tragedy of ecosystem services".

The decoupling of stormwater regulation and land-use regulation in the federal regulatory arrangement (National Research Council, 2009) poses another significant obstacle to GI. In such a scenario, the land-use policy, which controls development activities, is likely to disregard landscape hydrology and result in developments noticeably contrary to the concept of GI. The absence of design and maintenance standards or general guidelines for GI has become a problem that discourages urban stormwater system designers from adopting GI. This has the effect of motivating them toward a gray approach, whose standards and guidelines are already available.

*3.1.2. City policy barriers*

We explored 10 major issues in city policies that can obstruct the adoption of GI (Table 1). One is the threshold area that sets into motion a city's regulatory requirement of stormwater management. Currently, a wide variation exists across cities. For example, in Camden, NJ and Neosho, MO, stormwater management is required if the development area exceeds 1011.71 $m^2$ and 929.03 $m^2$ respectively; whereas in Dallas, TX, the threshold is 4046.86 $m^2$. These values are significantly higher than the thresholds set by some other cities such as Washington DC and Portland, each of which has a threshold value of 464.52 $m^2$. If the threshold value is too high, such as the one in Dallas, it may result in the uncontrolled development of a significantly large area.

The presence of conflicting or confusing provisions and the absence of suitable provisions in codes and guidance documents are other obstacles. For example, in Camden, the land development ordinance (§577) states that it allows turf blocks for off-street parking; paradoxically, it does not permit materials that are susceptible to vegetative growth. The State of Missouri requires land development permits for a disturbance of one acre or more, while Neosho, a city in the state, does not require such a permit, challenging the state's requirements. The city code of Dallas does not define, permit, or encourage GI as a means of stormwater management. Though the city has created a voluntary Integrated Stormwater Management (iSWM), the code is not clear about whether using the iSWM complies with the city code. Some cities such as Dallas and Phoenix, do not allow off-site mitigation, which prevents landowners from installing GI off-site or paying an in-lieu fee to city agencies in case it is technically or financially not feasible for them to install GI on-site. The absence of a provision for off-site mitigation prevents the establishment of an allowance market, discussed later. The restriction on the use of open spaces also prevents the installation of GI on such spaces. In Phoenix, for example, the zoning ordinance does not include GI in the list of the elements allowed in the open spaces. Camden's code prevents the use of rain barrels and cisterns near building foundations, whereas in the Greater Los Angeles Region, the public right-of-way is not allowed for stormwater control access. Camden follows the National Standard Plumbing Code 2009, which requires to route runoff from impervious surfaces to a storm sewer where available. The code also does not have provisions to use harvested rainwater for activities such as toilet flushing and irrigation. In Phoenix, rainwater harvesting has been deemed impractical due to the local precipitation regime (US EPA, 2013), essentially restricting the use of rain barrels.

Traditionally, engineering design standards only consider engineering functionality and enforce minimum requirements on the size of facilities such as parking space (in both geometry and number), lane width, and roundabout radius. Since the standards generally disregard the impacts of land disturbance, they do not generally set the maximum limits. Consequently, the current requirements for various amenities differ from city to city. For example, the Phoenix City Code requires a minimum length of 5.5 m for parking spaces, while 4.57 m is enough (US EPA, 2013). For double-loaded aisles, 6.7 m is enough, but the zoning code requires a minimum width of 11.27 m. In Dallas and Macatawa, the minimum required width for a travel lane is 3.65–3.96 m, which can be reduced to 3.04–3.65 m or even less (US EPA, 2014, 2013). The city codes of Phoenix and Camden require a minimum of 15.24 m for a cul-de-sac radius, which can be 10.67 m or less (US EPA, 2014, 2013). Fire codes also require paved wide streets, the full width of which is used only rarely. Such requirements result in the creation of unnecessarily large impervious areas.

There are some city codes, which require specific pavement materials, and do not allow pervious materials on streets, sidewalks, parking lots, driveways, and other hard surfaces. For example, the Street Planning and Design Guideline of Phoenix requires asphalt for on-street parking and alleyways. The city's code also does not explicitly allow pervious paving materials in off-street parking. The code requires all sidewalks to be surfaced with Portland cement. Curb requirement provisions are other barriers which prevent the flow of road runoff into adjacent vegetated areas. For example, in Phoenix, the zoning code requires curbs where the urban density equals or exceeds 3 lots per gross area. Camden also requires raised curbs and does not allow curb cuts, flush curbs, curb pullouts, or bumpouts. A lack of financial incentive and an absence of necessary regulations are also critical barriers in some cities. For example, the City of Phoenix does not offer any incentives, such as cost sharing, reduction in street width/parking requirements, or assistance with maintenance, to property owners who utilize pervious materials (US EPA, 2013). In Camden, though the Land Development Ordinance sets impervious cover limits, there are no additional incentives for further reductions.

#### *3.1.3. Governance barriers*

Governance has a leadership role in the implementation of infrastructure technologies. The current governance was designed for and is adept at governing centralized gray infrastructure (Dhakal and Chevalier, 2016), therefore it inherently supports gray, not GI. As opposed to GI, which is a decentralized approach requiring the involvement of many stakeholders, the existing governance is centralized and exclusively technocratic. Another major governance barrier is the prevailing institutional fragmentation of both spatial and functional jurisdictions for stormwater management at both local and higher levels. Spatially, the mismatch of hydrologic and political boundaries results in the different governance entities for different portions of the same hydrologic unit. Functionally, even the highly-interrelated functions are under different leaderships. For example, water quality control is governed by the US EPA, whereas flood control is under the jurisdiction of the US Army Corps of Engineers. Since different agencies generally have differing, and sometimes conflicting, priorities and goals, interjurisdictional collaboration is inevitable for effective implementation of GI. However, previous case studies show that there is generally a lack of such collaboration in many cities (e.g., Cettner et al., 2013; Huron River Watershed Council, 2014).

Inadequacy of motivation and opportunities for public involvement is another obstacle in the current governance model (Dhakal and Chevalier, 2016). Though, the Stormwater Phase II Rule adopted by the US EPA requires “public participation and involvement,” the current practice of public involvement is usually limited to participation in education, outreach and cleanup programs. In case when public comment is requested as required by the Stormwater Phase II Rule, these comments are highly likely to be disregarded in the final decision (Dhakal and Chevalier, 2016).

#### *3.1.4. Resource barriers*

One of the most cited barriers in earlier studies is the lack of financial resources (e.g., Copeland, 2014; Huron River Watershed Council, 2014; Keeley et al., 2013; Porse, 2013; Thurston, 2012; Tryhorn, 2010). Given its cost-effectiveness and other general benefits, the GI approach should not have been financially problematic, at least in comparison to the gray approach. However, a problem exists for two reasons. First is the existing practice of using funds from general revenue, the stormwater management portion of which is intended for gray infrastructure development and maintenance on public land. The legal restrictions generally discourage investing these public funds on private properties (Keeley et al., 2013). Second is the absence of a market for most ecosystem services, other than provisioning services, since these services are not monetized due to the lack of a proper tool. As a result, the financial benefit of GI is undervalued. Consequently, the payback period for GI projects becomes longer than a decade, discouraging private investors (Valderrama et al., 2013) and resulting in a lack of financial market for project financing (Clune and Braden, 2007). As observed by Valderrama et al. (2012), currently there is no existing approach for bringing private investments into stormwater retrofit projects. Additionally, stormwater issues cannot compete with other more critical aspects of existence, such as food, security, and shelter, in securing an appropriate budget from the general fund. As a dedicated funding source, many cities have established stormwater utility fees (Porse, 2013), which have faced legal challenges in some other cities (Keeley et al., 2013).

A lack of data on cost and performance is another highly cited barrier in most of the studies (e.g., Copeland, 2014; Huron River Watershed Council, 2014). In the absence of such data, the adoption of GI appears risky to the municipal staff, policy makers, and public, discouraging them to embrace the technology. In addition, the lack of formal coursework and research opportunities in university engineering programs, along with the limitations of other training opportunities in the market (Clune and Braden, 2007), leads to a dearth of sufficient professionals with GI expertise in the job market (Tian, 2011; US EPA, 2014). As a result, many cities face a shortage of staff for its design and installation (Barbosa et al., 2012; LaBadie, 2010; National Research Council, 2009).

#### *3.1.5. Cognitive barriers*

Our study reveals that mindset, unawareness, fear, attitudes, and perceptions are other factors that discourage landowners, water resource managers, and policy-makers to use GI. We have categorized these intangible factors as cognitive barriers. On one hand, there is some doubt among professionals about the reliability of GI (Brown, 2008; Copeland, 2014; Porse, 2013) giving rise to some fear of liability concerns on the implementation of the technology (Olorunkiya et al., 2012). On the other hand, there is a legacy of unrestrained access to city's gray infrastructure for discharging runoff from private parcels without paying the direct costs. As a result, there exists reluctance in the public to switch to GI from gray. The perceived risks, which primarily arise from the absence of historical data, of higher cost and lower performance of GI, combined with risk aversion attitudes, are highly cited factors in literature (e.g., Clune and Braden, 2007; Nylen and Kiparsky, 2015) that lead to such reluctance. The reluctance persists also due to the unawareness among the public about how the gray system is environmentally inappropriate and how GI manages stormwater sustainably. Moreover, due to the fear of improper maintenance (Hammitt, 2010) and attitudes to avoid perceived burden, landowners hesitate to take maintenance responsibility and are encouraged to oppose the installation of GI on their land.

### 3.2. Driving GI ahead: the suggested policies

Policy, which provides the guidelines for collective human actions for shared outcomes (Meehan, 1985), is crucial to drive a technology's implementation (Arent et al., 2017; Holzer and Schwester, 2016). As discussed by Birkland (2010), and for the purpose of this paper, by policy we mean constitutions, laws, statutes, regulations, court decisions, and agency or leadership decisions. Governance is an inevitable aspect of policy, since it provides a platform for the political process required for policy making and plays a leadership role for policy implementation. Based on this scope and definition of policy, we suggest 33 policy tools grouped into 5 categories: federal and state level policies; city policies; alternative governance; innovative funding mechanism; and education, awareness, award, and recognition (Table 2).

#### 3.2.1. Federal and state level policies

Amending the constitution in regard to private property rights is very complex, not only because of the politically complicated process it requires but also due to the challenges it may pose to the basic rights of freedom and democracy. Since the drainage law doctrines were developed through court cases, their modification evolves over time with changes in circumstances or new knowledge—as acknowledged by Justice Scalia in Lucas v. South Carolina Coastal Council (1992). Therefore, constitutional amendment and change in drainage laws are beyond the scope of this paper. For relatively prompt policy actions, other statutory and regulatory approaches are required within the given constitutional framework. Recently, some initiatives have been proposed and even accepted at the federal level. For example, the US Congress recently added §313 to the CWA to require the federal government to pay stormwater fees as a "reasonable service charge" to the concerned city agencies or utilities which provide stormwater management services for the federal properties. Some bills have been introduced in the house to support the implementation of GI (e.g., H.R. 4648, 2016; H.R. 1775, 2015), which have included many important provisions, such as federal financial assistance for research and implementation. However, the bills do not include provisions to address many of the barriers in the CWA. An example of this is the absence of restoring hydro-ecological integrity in the statement of statutory goals.

At the federal and state levels, we suggest nine policy actions (Table 2) including the amendment of the CWA (§101(a)) to add hydro-ecological integrity of the urban landscape as one of its goals. The inclusion of hydro-ecological integrity as a statutory goal will equip and encourage the US EPA to formulate and enforce regulations for installing GI on private parcels. It is also necessary to add a statutory provision to the CWA that incorporates flow or impervious cover as a measure of stormwater loading (National Research Council, 2009). Subsequently, a provision allowing cities to enforce flow control on private parcels will become necessary. Such flow control provisions would establish the CWA's jurisdiction over water quantity, and help the US EPA and cities enforce regulations to control stormwater quantity on-site. Congress has already established such a statutory provision in the Energy Independence and Security Act of 2007, where all new federal developments with a footprint larger than 464.5 $m^2$ require the restoration of predevelopment hydrologic characteristics like temperature, rate, volume, and duration of flow. Similar provisions with a more stringent threshold should be added to the CWA to control land development under any ownership. We also suggest adopting a federal statutory provision that requires planning, zoning, and development in conformity with the hydrologic features of the landscape. This will ensure that development activities cause as little damage as possible to the vegetation and natural hydrology. For this, interconnected functions such as land-use planning, stormwater management, and flood control need to be brought under one federal institutional umbrella, or, at the very least, have a strong coordination that will overcome conflicting policies and actions that discourage GI implementation.

Existing national standards and codes for the design and maintenance of roads, parking lots, plumbing, and fire safety need to be updated to incorporate the concept of GI to the maximum practical extent. As for other civil engineering infrastructures, national standards and guidelines should be created for the design, construction, and maintenance of GI. Such standards not only overcome potential risks of inappropriate design and maintenance, but also encourage design and maintenance staff to incorporate GI, and furthermore help maintain consistency. To minimize the area of paved surface, the maximum limit on the size of facilities (e.g., lane width and radius of roundabouts) should be fixed nationally. Additionally, as a financial incentive to install GI, we suggest providing federal and state tax exemptions or credits on GI material and installation cost to motivate landowners, developers, and manufacturers to adopt the technology.

In the absence of a federally enforced threshold of land development that initiates stormwater management regulations, states have enforced their own thresholds. However, a wide variability exists in such thresholds, most of which are too high. Currently over three-fourths of states—such as Texas, Missouri, Illinois, and Michigan—have a threshold of 4046.86 $m^2$ of disturbed area; whereas, other states—such as Washington, Florida, Delaware, and Maryland—have more stringent thresholds (US EPA, 2011). In Maryland and Delaware, the threshold is 464.5 $m^2$ of disturbed land, whereas in Florida it is 371.6 $m^2$ of impervious cover. The State of Washington has enforced thresholds on both disturbed areas and impervious surfaces, which are 650.3 $m^2$ and 185.8 $m^2$ respectively. The threshold of 4046.86 $m^2$ currently adopted by most states is too high because it leaves a significant portion of land development activities, especially on private residential parcels, out of regulatory control from stormwater management perspectives. Though a high threshold value at federal and state level does not restrict a city from adopting a more stringent threshold, it also does not encourage a city to do so. Consequently, a city, such as Dallas (discussed earlier), can adopt the parent state's too high threshold. Therefore, we recommend adopting a more meaningful national threshold for both disturbed and impervious areas so that most of the land perturbation activities in all cities will come under regulatory control.

#### 3.2.2. City policies

In the US, a city can enact legislation as authorized by its parent state to govern activities within its jurisdiction. Since land-use planning, zoning, and storm water management are carried out by cities, the city policies play a crucial role for adopting GI. Generally, courts also uphold local decisions in matters of land use (Thomas, 2008). Even within the current federal and state policy regimes, many cities, such as Portland, Seattle, Chicago, and Philadelphia, have enacted several city policies and this has resulted in the significant implementation of GI. This shows that, while a change in federal and state policies is necessary to facilitate and encourage cities, cities by themselves can develop and enforce several policies that drives GI implementation. We suggest 13 city-level policies, which are presented in Table 2.

As suggested in many studies, we recommend that each city also

**Table 2**
Policy measures for overcoming barriers and encouraging GI implementation.

| Policy categories | Policy measures | Targeted barriers |
|---|---|---|
| 1. Federal and state policies | 1.1. Add hydro-ecological integrity as a statutory goal of the CWA. | 1.3.1 |
| | 1.2. Establish flow (or its surrogate such as impervious area) as a control measure. | 1.3.3 |
| | 1.3. Enact statutory provisions to allow cities to enforce flow control regulations on private parcels. | 1.1,1.2, 1.3.2 |
| | 1.4. Require cities to conduct planning and development based on hydrologic features. | 1.6, 3.2 |
| | 1.5. Integrate intercoupled functions under one institutional umbrella. | 1.6, 3.2, 3.3 |
| | 1.6. Audit & amend other relevant policies & standards (e.g., plumbing) to incorporate GI. | 1.7, 1.4, 2.2 |
| | 1.7. Establish national design & maintenance standards & guidelines for GI. | 1.7 |
| | 1.8. Provide federal & state tax exemptions or credits on GI materials and works. | 2.10 |
| | 1.9. Enact a nationwide development threshold that triggers SWM requirements. | 2.1 |
| 2. City policies | 2.1. Audit codes and eliminate or amend conflicting and confusing provisions. | 2.1–2.9 |
| | 2.2. Remove mandatory requirements for curb and allow curb cuts. | 2.9 |
| | 2.3. Remove requirements for impervious pavement material in driveways. | 2.8 |
| | 2.4. Remove requirement for minimum parking space in transit served areas. | 2.2, 2.7 |
| | 2.5. Remove requirement to route stormwater to gray system. | 2.5 |
| | 2.6. Create guidance documents and manuals for design and maintenance of GI. | 2.2, 1.7 |
| | 2.7. Enact ordinance that requires on-site stormwater retention using GI. | 2.2 |
| | 2.8. Allow use of GI in open spaces where technically feasible. | 2.4 |
| | 2.9. Allow rainwater harvesting where climatically feasible. | 2.6 |
| | 2.10. Assign fair share of responsibility to each stormwater generator. | 2.10 |
| | 2.11. Adopt market-based incentives (Table 3) to motivate private landowners. | 1.5, 2.10, 4.1 |
| | 2.12. Allow off-site mitigation or in-lieu fee. | 2.3, 2.10, 4.1 |
| | 2.13. Enact liability transfer ordinance to allow landowners to transfer maintenance liability to a third party licensed by the city. | 4.3, 5.5 |
| 3. Alternative governance | 3.1. Restructure the governance to establish two-tier model as discussed in Dhakal and Chevalier (2016). | 3.1–3.4 |
| | 3.2. Establish a regional watershed level agency to facilitate and fund research, education, data collection, collaboration, and creation of market for ES. | 1.5, 4.1, 4.1, 4.2 |
| | 3.3. Establish a functional mechanism at each level for communication, interaction, and coordination within government agencies and with stakeholders outside. | 3.1–3.4 |
| 4. Innovative funding mechanism | 4.1. Establish stormwater fee and allowance trading as revenue sources as well as incentive mechanism. | 1.5, 2.10, 4.1 |
| | 4.2. Ensure stable policies, such as 10–15year fee schedule (Valderrama et al., 2013), to tackle uncertainty & motivate private financiers. | 4.1 |
| | 4.3. Create municipal green bonds. | 4.1 |
| 5. Education, awareness, award, and recognition | 5.1. Establish education and outreach programs to raise public awareness on benefits of GI, harms of gray, and about how GI works. | 1.2, 3.4, 5.1–5.5 |
| | 5.2. Have programs in place to train existing staff responsible for stormwater management and other related functions. | 4.3 |
| | 5.3. Encourage universities to offer research opportunities and courses on GI to graduate and undergraduate civil engineering students. | 1.2, 4.2, 4.3 |
| | 5.4. Include courses on GI and ecosystem services in K-12 (Kindergarten to 12th grade) curriculums. | 1.2, 5.1–5.5 |
| | 5.5. Establish award and recognition programs to encourage individual and social capital. | 3.4, 5.1 |

audit its existing policies; find unclear, contradictory, and pro-gray provisions; and remove or amend them. For example, the provisions that require raised curbs for roads, impervious pavement for residential driveways and parking lots, and minimum parking spaces for transit-served areas should be eliminated. Any code, such as the National Standard Plumbing Code, which requires impervious areas to drain to a sewer system, should be either amended or replaced by a new code. Provisions in fire codes that require paved streets wide enough for fire trucks should be ammended to reduce the additional pavement because the additional width required is very rarely used. Appropriate vegetative or other pervious surfaces could be used on the additional width. Any regulatory restrictions on open spaces, including setbacks, that prevent the use of the spaces for GI should be repealed, and technically viable GI should be allowed in such open spaces. Rainwater harvesting should also be allowed where doing so is climatically feasible.

Having guidance documents and manuals is critically important for the design, installation, and maintenance of GI. In the absence of such documents, other cities' documents (such as those of Seattle and Portland) can be adopted with some context-sensitive adjustments. When viable, cities should enact "command and control ordinances" that require on-site stormwater retention to maintain or restore predevelopment hydrology. They can also use GI as a condition of development permit approval. Many cities in the US and abroad have embraced such policies. For example, Portland requires a new or redevelopment project to manage stormwater on-site, and a new city building to have a green roof over at least 70% of its roof area. Chicago requires any building with a footprint over 1393.5 $m^2$ or any parking lot over 696.75 $m^2$ to either manage the first half inch of rain on-site or reduce the prior imperviousness by 15%. Command and control ordinances are exercised in other countries as well. Tokyo, Japan, requires private buildings larger than 1000 $m^2$ and public buildings larger than 250 $m^2$ to have 20% of the rooftop greened; whereas Linz, Australia, requires green roof on all new buildings larger than 100 $m^2$ (Carter and Fowler, 2008). We also suggest having a policy that ensures a fair share of stormwater management responsibility among all storm water generators based on the relative extent of hydrological disruption and the additional discharge generated due to the land development activities. For example, among two landowners with equal impervious areas, the responsibility of the owner whose impervious area is constructed on more pervious soil should be greater. Such a policy will discourage development on more pervious land, and also help correct the responsibility versus authority dilemma discussed earlier.

When regulatory options are insufficient, market-based tools can be viable alternatives to act beyond the regulatory limits, especially for encouraging private landowners to install GI. Because they are voluntary, they are less likely to be opposed by residents. Currently available potential market instruments and their example applications are presented in Table 3. Though some of these tools, such as an allowance market, are still in the nascent stages in the field of stormwater management, many other options have been increasingly used in some pioneering cities in the US and some other developed countries. In the US, more than 400 cities, towns, and utility districts utilize parcel-based fee systems based on impervious area (Valderrama et al., 2012). A survey of 70 utilities conducted by Valderrama et al. (2012) in 20 states showed that a majority offered credits against stormwater fees for installing GI. As discussed earlier, the US Congress has also added a provision to the CWA requiring the federal government to pay stormwater fees (§313). When designed appropriately, the system of fee (or charge) and allowance trading can together establish a functioning market. If a landowner cannot install GI due to cost or other technical constraints, the landowner should be allowed off-site management within a designated geographical boundary. The off-site control may be owned and operated by any private party or a government agency. If it is owned and maintained by government, the landowner can pay an in-lieu fee, which should be used exclusively for GI. Portland has already adopted this policy, where the collected off-site management fee is put in a "mitigation account" to be used to mitigate the impacts of off-site discharge. However, while the mechanisms of stormwater fees and allowance credits can help channel private investment to the projects yielding the highest environmental benefits (Valderrama et al., 2012), such mechanisms may pose two significant challenges. First, low-income families may not be able to pay the required fee or install GI on their property. To address this problem, cities need to develop financial assistance programs to help the needy residents pay their stormwater bills. As an example, Portland has already established such assistance in various forms that include "bill discounts" and "crisis vouchers." Second, because discharge is a local problem, if a market is created for it, this can easily result in an insufficient number of buyers and sellers, leading to a failure of the allowance market. The viability can be increased by including other co-benefits, such as pollutant control and carbon storage, for trading and expanding the market to larger geo-political jurisdictions. For example, water quality trading can be expanded to regional watersheds and carbon trading can be expanded both nationally and internationally. However, institutional arrangements, such as regional governance discussed in the subsequent section, should be created accordingly. To address the fear among the landowners about maintenance of GI, a city can enact liability transfer ordinance that allows a landowner to purchase maintenance services from a company licensed by the city and transfer the maintenance liability to the company. The involvement of companies in the installation and maintenance of GI helps create and expand GI business. There are other cobenefits of GI, such as enhancement of natural beauty and reduction in the urban heat island effect, that are considered public goods for being non-excludable and non-rivalry. In such cases, direct payment to owners will encourage them to continue having GIs and supplying such services. Development incentives could be another attractive policy with no financial burdens on the government. The market options are explained with example applications in Table 3.

#### 3.2.3. Alternative Governance

Since urban GI requires the involvement of a large number of stakeholders, including societies, individuals, private sectors, institutions, and formal and informal organizations, many scholars (e.g., Dhakal and Chevalier, 2016; Novotny et al., 2010; Roy et al., 2008) indicate that small scale neighborhood-level governance could be appropriate for GI. Novotny et al. (2010) propose small units called "interconnecting clusters" or "ecotones" around the first or second order surface water body. Lant et al. (2008) argue for establishing "ecosystem service districts" to govern ecosystem services and recommend delineating their boundaries in coherence with watershed boundaries. Dhakal and Chevalier (2016) present a two-tier governance model for stormwater governance, consisting of "hydrologic districts" at the neighborhood level and a city agency at the city level. The hydrologic districts would provide small scale governance within the local hydrological boundary, whereas the city agency would utilize the current city jurisdictions to establish coordination with other stakeholders, such as adjoining cities and upper level governments. We recommend using this model to govern GI and ecosystem services because neighborhood level governance would provide a better opportunity for face-to-face interactions and hence foster stakeholder engagement (Cohen, 2012), which is critical for sustainability (Ellis et al., 2010). The stakeholder engagement leads to a shared sense of community and increases a community's sense of ownership (Tryhorn, 2010). The resulted increase in social capital (Mazmanian and Blanco, 2014) will enhance the stewardship of GI. Thus, there will be better care and management of GI assets by the community without being entirely dependent on recurrent funding from the government (Wong and Eadie, 2000). Since the current stormwater permit scheme leaves a great deal of discretion to the regulated community to set their own standards and to self-monitor compliance (National Research Council, 2009), such community stewardship is critically important. Hundreds of thousands of successfully functioning neighborhood scale governance in the US and abroad—such as "homeowners' associations" in the US (McCabe, 2011; Scheller, 2015) and "neighborhood associations" in Japan (Tsujinaka et al., 2014)—justify the viability of such neighborhood scale governance.

The problem of fragmented jurisdictions at city and state levels that results from the prevailing mismatch of hydrologic and political boundaries is a problem the scope of which demands further research. However, we have some suggestions that can help begin a conversation. We suggest establishing a regional watershed-scale governance in each regional watershed, whose jurisdictional boundary would follow the boundary of the watershed. Such a governance mechanism would be in the form of an alliance among those states whose territories lie partially or wholly within its boundary. The regional governance would create guidelines for GI, monitor GI related activities, establish a functional coordination among states within its jurisdiction, and provide both technical as well as financial support to those cities which cannot afford GI. It would also function as a clearing house to collect and share information on GI. Moreover, it would provide a platform for trading ecosystem services other than those of local character, such as carbon sequestration and water quality. Historically, different forms of regional governments have been tried at different times in the US, including the extension of a center city to encompass the region, the formation of regional councils for regional planning and coordination, and voluntary cooperations among governments and sectors through public and private partnerships (Olberding, 2002). Currently, many metropolitan areas are also working as regional governments with the intent to share resources between city cores and their surrounding settlements (Squires, 2002). However, since these traditional mechanisms generally do not follow watershed boundaries, they would not be able to solve the fragmented governance that results from the mismatch of political and hydrologic boundaries. We realize that there is a necessity to reexamine all forms of the current regional governances and restructure them under the regional watershed governances of the type proposed in this paper.

#### 3.2.4. Innovative funding mechanism

Previous studies by other scholars show that, in general, GI costs less than gray infrastructure (e.g., Baerenklau et al., 2008; Foster et al., 2011; Shaver, 2009; US EPA, 2015). However, the approach requires investments not only for installation and maintenance but

**Table 3**
Potential market (or quasi-market) mechanisms and examples.

| Policy mechanisms | Example applications |
|---|---|
| *Stormwater fee and discounts:* This scheme enforces a fee on runoff quantity or impervious area and provides discounts for installing GI. | Seattle enforces annual flat fee for single family and duplex smaller than 929 $m^2$. For all other cases, the annual fee is based on impervious area. Portland enforces off-site (65%) and on-site (35%) charges separately. Flat rate for single family to 4-plex residences, rate per 92.9 $m^2$ of impervious area in other cases. The Clean River Rewards program provides up to 100% of discounts for on-site portion of the charge. |
| *Allowance market:* In this scheme, tradable allowances of discharge are distributed among landowners, who are required to manage additional quantity. One who can manage more than required, can sell his allowances to others willing to buy and use them for their retention requirements. | Stormwater Retention Credit (SRC) program in Washington DC, US. Landowners obtain SRCs for voluntary reduction of stormwater runoff (one SRC per additional gallon reduced above required reduction) using GI. The owners can bank for future use or trade their SRCs in an open market to others who are willing to buy and use to meet regulatory requirements for retaining stormwater (Hoffmann et al., 2013). First of its kind in the nation. |
| *Payment for ecosystem services:* Owners are payed for providing ecosystem services such as flood mitigation, carbon storage, and water purification. | In use by US cities—such as New York, NY; Syracuse, NY; Boston, MA; Portland, OR; Seattle, WA—for protection of watershed that are their critical sources of water supply (Mercer et al., 2011). Used for many other ecosystem services, in countries including the US, China, South Africa, Mexico, Costa Rica, and Nicaragua (Schomers and Matzdorf, 2013). |
| *Rebates, credits, and installation financing*: This includes financing, tax credits, or reimbursements to landowners who install GI. | In Philadelphia, the Tree Vitalization Rebate Program provides a $25 rebate for planting a tree. The Rain Check program provides rain barrels for free and/or helps construct downspout planter, rain garden, or porous paving for a reduced price. In Seattle, the City and King County pays up to total cost of rain gardens and cisterns. |
| *Development incentives:* Developers receive benefits including expedited permitting, and bonuses for floor area, height, density, and space. | Chicago offers expedited permitting process for projects meeting Leadership in Energy and Environmental Design (LEED) criteria. For installing green roof, Philadelphia provides floor area ratio and height bonuses up to 400% and 10.97 m respectively; whereas Portland provides floor area bonus up to 300% of the area of ecoroof installed. |
| *Grants and awards:* Provides money directly to individual landowners or communities for installing GI. | In Chicago, the Green Roof Grant program provides $5000 to residential and small (<929 $m^2$) commercial buildings. In Portland, the Community Watershed Stewardship Program provides up to $10,000 for watershed restoration activities. Philadelphia has Stormwater Management Incentive Program (SMIP) to provide grants for qualified non-residential owners, and Green Acres Retrofit Program (GARP) to provide grants for qualified contractors, companies or projector aggregators. |

also on multiple other fronts including education, outreach, research, new governance structures, rebates, and rewards. Fortunately, unlike traditional approach, GI has multiple potential revenue sources other than general revenue funds. Examples include revenue collected from stormwater fees (or charges), in-lieu fees, allowance trading, and green bonds, discussed earlier. If designed appropriately, these sources can generate a considerable amount of revenue. As outlined in Valderrama et al. (2013), if regulatory certainty, such as long-term fee schedules, can be ensured, private financiers can invest in GI projects for the revenue to be generated in the form of the avoided stormwater fee. Another way to attract investments is municipal green bonds, which, though currently used on a small scale, is gaining popularity in the US as well as abroad. Recently, for example, Seattle's Sound Transit sold nearly $1 billion of green bonds to help fund regional transit projects; whereas, Johannesburg issued a green municipal bond of $136 billion (Bloomberg and Lille, 2016). Such a bond can be used to construct large scale GI projects. However, at the beginning, especially unless these multiple resources become fully functional, public funds may be required for education, awareness, outreach, demonstration projects, awards and grants, research and development, and the establishment of regional and community-level governances. Currently, gray infrastructure annually requires billions of dollars of public revenue, a significant amount of which will be saved due to GI. If managed appropriately, the saving will provide a significant portion of the funding required by the recommended activities. However, the long-term solution is to develop GI as a business rather than a burden on general revenue.

### 3.2.5. Education, awareness, award, and recognition

In a democratic society, social acceptance plays a central role in mainstreaming a technology. The increased social acceptance of GI can also foster a market, leading to an enhanced GI stewardship as a business, which contributes to establishing a sustainable financing mechanism. A study conducted in the Shephard Creek watershed in Cincinnati, Ohio, USA (Green et al., 2013, 2012) has revealed that the social acceptance of GI can be increased by investing in enhancing human and social capital through education and awareness. Human capital is embodied in the skills, knowledge, and capabilities of an individual, and the relationships among the individuals form the social capital (Colemn, 1988). On the other hand, the social capital provides a “collective forum” for human capital (Green et al., 2012) and shapes the activities of human capital through socially constructed norms and moralities (Onyx and Bullen, 2000). A community with a high social capital also monitors the behaviors of its members, making them accountable for their actions (Bowles and Gintis, 2002). In other words, human and social capitals work synergistically to enhance social acceptance. By removing cognitive barriers and boosting social and individual capital, education and awareness thus play critical roles in expediting the adoption of GI. While the regulatory requirement in the Stormwater Phase II Rule for public education and outreach provides a useful tool to increase public awareness, the policy is insufficient. To have sufficient human resource to fulfill current and future demands, cities should have policies to train their current staff and enhance their expertise in GI. Furthermore, universities should be encouraged to offer courses and research opportunities to graduate and undergraduate civil engineering students who want to specialize in stormwater management. To have a pro-GI society in the future, we suggest teaching GI to K–12 students as well. Federal policies and programs are needed for encouraging academic programs in academic institutions. Award and recognition are other critically important tools which work by motivating individuals to come forward and take leadership roles for promoting GI application. Many cities have adopted such award and recognition programs. Mayor Daley's Green Works Community

Award in Chicago and Philadelphia's Sustainability Award are notable examples.

## 4. Conclusion

Though GI is known to have numerous ecosystem benefits and is regarded as an underpinning element of urban sustainability, its adoption by cities is slow. This paper explores 29 barriers under 5 categories that cause the delay and suggests 33 policy strategies under 5 categories that can both overcome these barriers and expedite implementation. The study suggests that the most critical barriers are cognitive barriers and socio-institutional path dependence. Other barriers, such as resource and policy barriers, are essentially the result of these two barriers. Social acceptance is arguably the most decisive driver of a technology as well as the most effective addresser of its impediments. Enhancing the knowledge of GI through education and awareness, and the resulting removal of cognitive barriers, can develop social acceptance. If social acceptance is high, formulating other pro-GI policies and programs at any level becomes easier. A high social acceptance encourages courts and legislatures to make favorable policy decisions, which will inevitably result in the development of both common and statutory laws. The enhanced social acceptance will also help update engineering standards to incorporate GI. Additionally, it tends to foster markets and bring about GI stewardship as a business that contributes to the generation of sustainable financing.

In addition to social acceptance, the availability of expertise, skilled personnel, champions, and leaders are of paramount importance for driving GI implementation. Therefore, we suggest adopting policies that focus on awareness, education, recognition, training, coordination and engagement. The hydrologic district in the proposed two-tier governance (Dhakal and Chevalier, 2016) provides opportunities to restructure the governance in compliance with hydrological features at the local level, whereas the proposed regional governance addresses the problem of fragmented governance within the watershed's boundary. We also suggest encouraging universities, especially civil and environmental engineering departments, to develop and offer curriculums that include GI and provide research opportunities to students. We should encourage vocational schools to offer training and produce the professionals that will be required by current and future cities to implement GI. To create a pro-GI society in the future, we need to teach K-12 students about the concept, importance, and the reliability of GI through class work and demonstration projects.

Since the focus of our investigation was on 10 US cities, the identified barriers and recommended policy solutions as such are more relevant to the US. However, our examination of available literature from non-US cities, especially in the UK and Australia, shows that most of the barriers and solutions are of global nature. While the selection of alternative forms of green measures—such as green roof, rain barrel, infiltration trench, and rain garden—is highly dependent on location, the study reveals that adopting GI as an approach faces similar cognitive and socio-institutional challenges in cities irrespective of where they are located. Because it is always eventually cost-effective, GI is arguably more suited to low income countries, where many cities are facing unprecedented growth and limited resource. However, due to the prevailing methods of infrastructure planning, the decreased availability of open spaces in traditional cities, and relatively low socio-economic development, the barriers and solutions in existing low-income cities may be somewhat different, which will require further research. Further research is also recommended for defining the institutional structures, functional jurisdictions, authority, and resources for the proposed regional governances as well as hydrologic districts.

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