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# Identifying barriers to decentralized stormwater infrastructure implementation at different levels of urban flood governance – A case study in Eastern Pennsylvania, US

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ABSTRACT

Stormwater green infrastructure (GI) has been applied as a method to address urban flooding for over forty years. However, GI has not yet been widely utilized across the US. Prior studies identified some challenges with technical, engineering, and socioeconomic aspects of GI, but detailed examination of non-scientific papers to identify and analyze real-world barriers that may hinder the implementation of GI has not yet been done. To achieve this goal, we conducted a meta-analysis of 351 public documents from federal, state, and 62 municipalities in Eastern Pennsylvania to systematically review the support of different levels of government for implementing GI. We summarized barriers in three categories: 1) governance and policy: failure to integrate GI into existing stormwater management policies due to unclearly defined responsibility and infrequent policy updates, 2) stormwater fees and credits: inequity in stormwater fee structures and debate of stormwater credits connected to GI, and 3) public education and outreach: most municipal governments provide little or no stormwater and GI-related information to their residents, but some municipalities with higher population density have tried to offer more. These barriers will restrain the original intention and vision of GI implementation and cause difficulties in effectively conveying GI's information from the federal and state levels to municipalities and residents. Our discussion highlights these difficulties of GI implementation at all governmental levels and shed light on potential solutions to address these barriers.

## 1. Introduction

Urban flooding poses a growing threat to society with tremendous economic loss, social disruption, contamination of water sources, and increasing water-borne and water-related diseases (IPCC, 2014; Rainey et al., 2021). When excessive stormwater overwhelms the capacity of drainage systems, it causes urban flooding that inundates properties in a built environment, which is especially concerning in densely populated areas (FEMA, 2015). The conventional solution to urban flooding problems is to rely on grey infrastructure such as reservoirs, levees, and drainage pipes. This grey infrastructure plays a critical role in preventing drainage overflows during extreme rainfall events (Bakhshipour et al., 2019; Beloqui, 2020). There are a lot of previous studies that provide more comprehensive information regarding the framework and analysis results of the asset life cycle, depreciation, and return on investment for grey infrastructure, compared to green infrastructure (Coombes et al., 2002; Linton, 2018). These previous analyses contribute to our comprehensive understanding of grey infrastructure, which provide an advantage in the decision-making process regarding flood mitigation since decision-makers can easily understand the cost and effect of these grey infrastructures (Clean Water America Alliance, 2011; Copeland, 2014). However, grey infrastructure has limitations, such as 1) relatively few benefits for the environment, society, and economies (Bakhshipour et al., 2019; Beloqui, 2020; Jarden et al., 2016); 2) higher construction and maintenance costs due to their large sizes (Beloqui, 2020; Copeland, 2016); and 3) reduced infiltration from creating additional hard surfaces (i.e., concrete or asphalt) that will increase the stormwater runoff volume (Jarden et al., 2016).

As a complement to grey infrastructure, green infrastructure (GI) can mitigate urban flooding with additional economic, environmental, and social benefits (Copeland, 2014; Li et al., 2019; Sørup et al., 2019). Different names have been used for GI, like "low impact development"

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or "best management practices" in the US, "sustainable urban drainage systems" in the United Kingdom, "water sensitive urban design" in Australia, "low impact urban design and development" in New Zealand, and the "sponge city" concept in China (Dhakal and Chevalier, 2017; Fletcher et al., 2015; Li et al., 2019; Li et al., 2020). Conceptually, GI is a nature-based method to reduce stormwater runoff by infiltrating, evaporating, and detaining stormwater to mimic predevelopment hydrology (Copeland, 2016; Mentens et al., 2006). GI can be applied in various forms and across different spatial scopes. For example, GI projects include rain gardens at the household level, detention ponds at the community level, or a network composed of these GIs at the watershed level (Tauhid, 2018). Based on its functionality, GI can be categorized into three types: storage, infiltration, and evapotranspiration. By minimizing stormwater quantity and peak flow, storage and evapotranspiration GI alleviate flooding induced by "everyday" (i.e., smaller magnitude) storms (Brudermann and Sangkakool, 2017; Dhakal and Chevalier, 2017; Holman-Dodds et al., 2003). Infiltration GI removes pollutant loadings to protect drinking water resources (Conway et al., 2020; Copeland, 2014; Coutts and Hahn, 2015; Dhakal and Chevalier, 2016) and support ecosystem service, which helps humans sustain and enhance ecosystem health (Coutts and Hahn, 2015). In addition, GI provides the opportunity for every individual to contribute to the control of floods. Several previous studies (Bissonnette et al., 2018; Conway et al., 2020; Lennon and Scott, 2014) have already argued for the necessity of shifting urban flood management from solely grey infrastructures to joint grey and green infrastructures. However, although the multi-benefits of GI have been studied as mentioned above, and various GI-related projects have been initiated (Fletcher et al., 2015), GI has not been widely adopted in urban areas (Brudermann and Sangkakool, 2017; O'Donnell et al., 2017; Hopkins et al., 2018; Li et al., 2019).

Previous studies identified a wide range of barriers that hinder GI installation mostly via a view of the scholarly literature. Copeland (2014) summarized the potential barriers to integrating GI into stormwater programs in the United States (US) into four categories: technical, legal and regulatory, financial, and community and institutional. Dhakal and Chevalier (2017) analyzed policies from city to federal scales for ten US cities and grouped identified barriers into five categories: federal and state policy, city policy, governance, resource, and cognitive. Qi and Barclay (2021) reviewed the literature to identify the social barriers of GI implementation in the US, and categorized them into demographic constraints, public engagement, and governance. In a broader context, Qiao et al. (2018) reviewed the literature to summarize the barriers from a governance perspective, then categorized the barriers into actors, resources, rules of the game, and discourse. They found the significant barriers stem from unclear leadership and responsibilities, lack of funding, lack of cost data, lack of space and knowledge, lack of uniform guidelines, and lack of stakeholder participation. Other studies (Gashu and Gebre-Egziabher, 2019; Li and Bergen, 2018; Li et al., 2019; Li et al., 2020; Matthews et al., 2015; O'Donnell et al., 2017; Wihlborg et al., 2019) identified similar barriers in different contexts around the world.

Although the studies mentioned above vary in geography, time, perspective, and method, they revealed barriers in three categories that recurred in most of the studies: "governance and policy," "economic incentive" (such as "stormwater fee and credit programs"), and "public education and outreach." Therefore, this paper will focus on these three categories of barriers for our analysis. In the rest of the manuscript, we define the "governance and policy" as the rules made by different levels of government for GI installation decision-making, which involves many stakeholders. The "stormwater fee and credit programs" is the additional financial burden on property owners and potential economic incentives to the property owners who install, operate, and properly maintain qualified GI to relieve that burden for stormwater management purposes. The "public education and outreach" category is the effort of the public sector to raise awareness of stormwater management and GI benefits. Note that in the process of barriers identification, parts of these three categories overlap. For example, there are laws and regulations that specify how the stormwater fee and credit program should be implemented. When the "governance and policy" category is involved, we will focus on the information flow among different government levels to understand government-to-government communication. When addressing the other two categories, we will focus on the information flow from government to people (e.g., municipal government using websites to promote the benefits of GI to residents).

The primary goal of this paper is to examine the barriers that hinder GI installation in the abovementioned three categories in a case study area: Eastern Pennsylvania in the US. We define "barrier" as inconsistency and ambiguity in the documents from different level of governments about GI implementation and the insufficient effort from governments to raise the awareness among residents about stormwater management and/or GI benefits. We conduct a meta-analysis of public documents such as laws, regulations, plans, reports, and press releases related to existing stormwater management and GI policies in all three categories listed above. We use the Preferred Reporting Items for Systematic Reviews Meta-Analyses (PRISMA) framework (Moher et al., 2009) to collect and identify the reviewed documents, and a manual "text-mining" approach is used to check the inconsistency and ambiguity of the collected documents. For the "public education and outreach" category, we also use the Education and Outreach Index, which was modified from the Nexus Index developed by Raub et al. (2021), to quantitatively evaluate governments' effort to raise public awareness. Accordingly, the main contribution of our study is to improve a comprehensive understanding of practical barriers to GI implementation in the Northeast US by conducting a thorough review of grey literature (i.e., laws/codes, government reports, and government websites, etc.). Additionally, our study provides a guide on method transfer to other study areas regarding GI implementation barriers identification in the Discussion section.

## 2. Overview of the study area

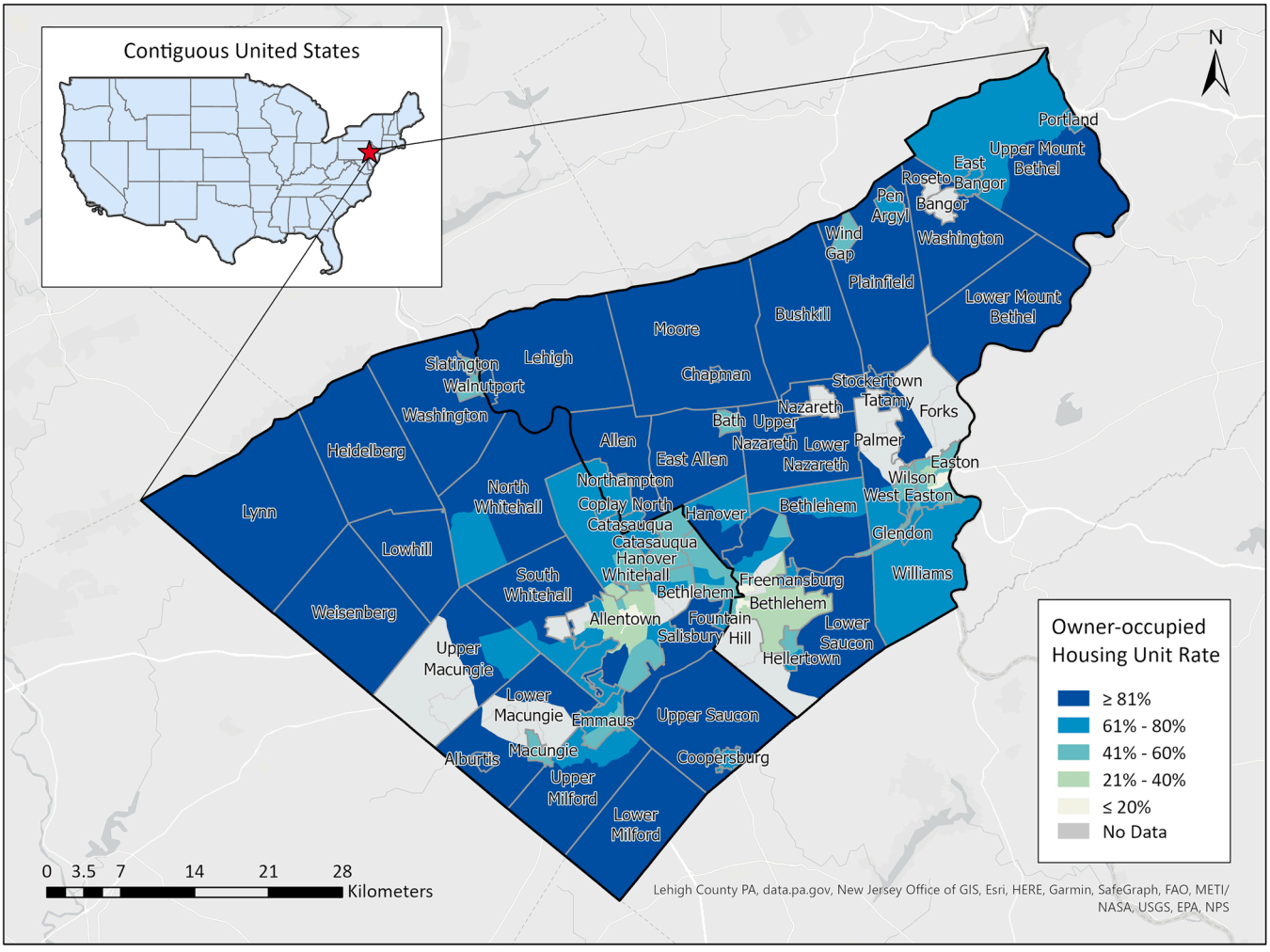
We use two counties in Eastern Pennsylvania, US, as our study area. Before we move into the details of GI promotion and implementation in this area, we provide an overview of the government structure in the US: federal, state, county, municipality, and their counterparts in other countries for international readers. The federal government in the US is equivalent to the central government in other countries, serving as an overarching national government responsible for broader governance across different levels. Two federal agencies oversee the GI-related activities in the US: the United States Environmental Protection Agency (EPA) and the Federal Emergency Management Agency (FEMA). The state government in the US, controlling a subdivision of the country, is equivalent to the provincial or cantonal government in other countries. In this paper, the state agencies that are responsible for GI implementation are the Pennsylvania Department of Environmental Protection (PA DEP) and the Pennsylvania Emergency Management Agency (PEMA). The county government, controlling a subdivision of a state, is equivalent to a shire or parish government in other countries. Lehigh and Northampton Counties in Pennsylvania are the focus on this paper. In some states, like our case study area, two or more counties can form a regional planning commission responsible for the development of watershed-based stormwater plans (PDCED, 2014). Finally, the municipal government is the smallest geographical unit and at the bottom of the government structure with different names such as city, town, borough, and village. They are responsible for meeting the stormwater management and flood mitigation needs, consistent with federal, state and county regulations, and developing and implementing stormwater-related municipal ordinances.

The flood concerns of the municipal governments and high rate of property ownership can play a key role in adopting GI (Brown, 2008; Montalto et al., 2013). Previous studies concluded that economic incentives and supportive policy instruments will foster the adoption of decentralized stormwater infrastructure (Green et al., 2012; Lieberherr

and Green, 2018; Pakizer et al., 2020). Because of the decentralized nature of GI, a high level of installation is necessary to achieve the meaningful benefits of GI at the municipal scale (Montalto et al., 2013; Lieberherr and Green, 2018). Therefore, incentive policies from the municipal government towards property owners, such as stormwater fee and credit programs, should be considered as a key pathway to promote GI installation (Brudermann and Sangkakool, 2017). There are 1851 stormwater fee programs implemented by municipal governments across 41 states in the US, and this amount is increasing at an average rate of 3 % over five years (Campbell et al., 2016; Campbell et al., 2017; Campbell, 2018; Campbell, 2019; Campbell, 2020; Campbell and Bradshaw, 2021). The stormwater fee is a recurring charge for using municipal services to convey and process the stormwater runoff in compliance with state and federal regulations (NAFSMA, 2006). The two most common methods to calculate the stormwater fee are the variable rate, based on the usage of the services, typically defined by the impervious area, and the flat rate, which charges an equal value to all property owners (Tasca et al., 2017). Stormwater fees gained popularity among municipal governments because they create a dedicated revenue that can only be used for stormwater management programs and projects, thereby ensuring that funds are available to support long-term plans for GI in a municipality (Zhao et al., 2019). Many municipalities also offer stormwater fee credits to property owners, which provide a specific economic incentive to control a portion of stormwater generated from their property by installing GI (Malinowski et al., 2020). Four municipalities in the Lehigh Valley have stormwater fee and credit programs at the time of writing (2022).

Following the government structure from the federal to the municipal level as mentioned above, GI is promoted under two jurisdictions in the US, each with similar governance but differing in purposes. For stormwater quality control, the EPA supervises stormwater management under the Clean Water Act (1972) to address water quality and pollution issues (Copeland, 2014). The EPA developed National Pollutant Discharge Elimination System (NPDES) permits to regulate point sources that discharge pollutants into waterbodies. Most state governments are authorized by the EPA to perform the permitting, administrative, and enforcement tasks of the NPDES program (US EPA, 2022a). The EPA first proposed using GI to fulfill NPDES requirements for water pollution control in 2007 (US EPA, 2007). FEMA is charged with flood mitigation under the Robert T. Stafford Disaster Relief and Emergency Assistance Act of 1974. FEMA helps states and counties to develop hazard mitigation plans by identifying hazards and risks in communities and then helping states explore effective methods to reduce potential losses (FEMA, 2022). In recent years, FEMA has suggested integrating GI into Local Hazard Mitigation Plans (FEMA, 2015) and using GI to increase community resiliency (FEMA, 2021; US EPA, 2018).

Our study area: Lehigh and Northampton Counties in Pennsylvania, commonly known as the Lehigh Valley (Fig. 1), is a region that spans 1879 square kilometers and contains 62 municipalities. This region was chosen for analysis because the natural conditions and socioeconomic characteristics represent a typical “bedroom community” in the Northeastern US. From the hydro-climatic perspective, maximum daily




Data Source: U.S. Census Bureau, 2019 American Community Survey (ACS) 5-Year Estimates; U.S. Census Bureau, 2020 TIGER/Line Shapefiles.

**Fig. 1.** Location and owner-occupied housing unit rate in Lehigh Valley, PA, USA.

precipitation, and the number of days with precipitation greater than 2.54 mm (0.1 in.) have been increasing since 1894 (Lawrimore et al., 2016, Fig. S1 in the Supplementary Material) in the Lehigh Valley. These upward trends are indications of wetter conditions in the future. In addition, climate change will result in more frequent extreme events in the region (Kermanshah et al., 2017; Singh et al., 2014), which means that future heavy rainfall events will likely cause more floods. According to previous reports (Best, 2014; Best, 2019; Church, 2018; Malinchak, 2014; Sroka-Holzmann, 2011), the Lehigh Valley has been affected by floods for a long time, and various municipalities have been discussing solutions including stormwater fee and credit programs (details below) since early 2010 s.

From the socioeconomic perspective, the total population of Lehigh Valley was 687,508 in the 2020 US Census Survey (approximately 6 % increase from 2010), and it is the third most populated metropolitan area in Pennsylvania (USCB, 2020a). Many residents commute to New York City or Philadelphia every day (LVPC, 2022). The owner-occupied housing unit rate is greater than 60 % in most municipalities of the Lehigh Valley (USCB, 2020b), which means most residents own their house, as shown in Fig. 1. As they are property owners rather than renters, most residents are responsible for taking care of their properties and have the right to decide whether to install GI (Barona et al., 2021). Thus, GI can potentially be promoted as a solution to address widespread localized urban flooding in this region.

## 3. Methodology

### 3.1. Preferred reporting items for systematic reviews and meta-analyses

To identify the barriers in GI implementation, we conducted a web-based search on governmental websites and local news websites to collect materials (laws, regulations, plans, official reports, manuals, brochures, and press releases) for the meta-analysis. In total, we explored 76 websites, as summarized in Table 1.

The document collection and selection process followed the PRISMA (Moher et al., 2009) framework and was performed in two phases: identification and screening. Identification used a text mining approach to recognize relevant documents that contained keywords. The three steps of identification were determining keywords, composing search criteria, and searching. First, we determined keywords based on key concepts that addressed the goal of this study. In the governance and policy category, our focus was on stormwater management and flood mitigation; in the stormwater fee and credit programs category, we concentrated on economic incentives; and in the public education and outreach category, we aimed to improve public understanding and participation. Thus, "stormwater management," "flood mitigation," "stormwater fee," "stormwater credit," "education," and "outreach" were keywords for document identification. In addition, to ensure all documents included our focus on GI, we added "green infrastructure" as another keyword. Furthermore, synonyms, jargon/informal usage, general and specific terms, alternate spellings, and abbreviations were also listed as keywords. For example, "best management practice," "rain barrel," and "GI" are synonyms, specific term, and abbreviation of green infrastructure, respectively. It should be noted that the discussion of GI in this study was not limited to any specific type. Similarly, in referring to GI projects, we did not distinguish between those installed on public or private land, nor were they confined to a specific spatial scope. In addition, we limited our federal-level search to public websites, federal codes, and regulations, EPA, and FEMA only. We used the title number to preliminarily limit documents with irrelevant content. For example, when we searched for US Code, we only searched for contents under Title 33: Navigation and Navigable Waters, and Title 42: The Public Health and Welfare. The second step of identification was to compose four search criteria using Boolean operators to combine the keywords with the same category (and title number), as shown in Table 2.

Then, in the third step of identification, we applied search criteria 1–4 to successively search and classify the documents according to the order of the criterion matched. The detailed search criteria used in each official electronic publication website are listed in the Supplementary Material (Table S1). In the end, we identified 583 documents in this phase.

**Table 1**
Websites used to collect documents for meta-analysis in this study.

| Website | Type | URL |
|---|---|---|
| **1. Federal** | | |
| (1.1) United States Code | Official Electronic Publications | https://www.govinfo.gov/app/collection/uscode/2019/ |
| (1.2) Code of Federal Regulations | Official Electronic Publications | https://www.ecfr.gov/cgi-bin/ECFR?page=browse |
| (1.3) U. S. Environmental Protection Agency - Green Infrastructure | Government Agency | https://www.epa.gov/green-infrastructure |
| (1.4) Federal Emergency Management Agency - Hazard Mitigation Planning | Government Agency | https://www.fema.gov/emergency-managers/risk-management/hazard-mitigation-planning |
| **2. State** | | |
| (2.1) Pennsylvania Consolidated Statutes | Official Electronic Publications | https://www.legis.state.pa.us/cfdocs/legis/LI/Public/cons_index.cfm |
| (2.2) Pennsylvania Code | Official Electronic Publications | https://www.legis.state.pa.us/cfdocs/legis/CH/Public/pcde_index.cfm |
| (2.3) Pennsylvania Department of Environmental Protection | Government Agency | https://www.dep.pa.gov/Business/Water/CleanWater/StormwaterMgmt/Pages/default.aspx |
| (2.4) Pennsylvania Emergency Management Agency | Government Agency | https://www.pema.pa.gov/Mitigation/Pages/default.aspx |
| **3. County** | | |
| (3.1) Lehigh Valley Planning Commission | Planning Commission | https://www.lvpc.org/ |
| (3.2) The Morning Call | Local News | https://www.mcall.com/ |
| (3.3) Lehigh Valley Live | Local News | https://www.lehighvalleylive.com/ |
| (3.4) WFMZ | Local News | https://www.wfmz.com/ |
| **4. Municipal** | | |
| (4.1) eCode360 | Official Electronic Ordinance | https://ecode360.com/login/ |
| (4.2) American Legal Publishing | Official Electronic Ordinance | https://www.amlegal.com/ |
| (4.3–4.63) Alburtis Borough and 60 other municipal government websites* | Government/ Official Electronic Ordinance | http://www.alburtis.org/ |

* Glendon Borough does not have an official website.

**Table 2**
Search criteria for identifying relevant documents in Web-based searches.

| No. | Search Criteria |
|---|---|
| 1 | content: ("GREEN INFRASTRUCTURE" or "BEST MANAGEMENT PRACTICE" or "LOW IMPACT DEVELOPMENT" or "NATURAL INFRASTRUCTURE" or "DECENTRALIZED METHOD" or "SUSTAINABLE AND GREEN SOLUTION" or "INNOVATIVE STORMWATER PRACTICE" or "INNOVATIVE METHOD" or "RAIN GARDEN" or "RAIN BARREL" or "INNOVATIVE STORM WATER PRACTICE" or "GI" or "BMP" or "LID") |
| 2 | content: ("STORMWATER MANAGEMENT" or "FLOOD MITIGATION" or "STORMWATER CONTROL" or "STORMWATER DISCHARGE MANAGEMENT CONTROL" or "LOCALIZED FLOOD CONTROL" or "LOCALIZED FLOOD REDUCTION" or "MINOR PHYSICAL MITIGATION" or "HAZARD MITIGATION" or "STORM WATER MANAGEMENT" or "STORM WATER CONTROL" or "STORM WATER DISCHARGE MANAGEMENT CONTROL") |
| 3 | content: (("STORMWATER" or "FLOOD" or "STORM WATER") AND ("UTILITY" or "FEE" OR "TAX" or "SERVICE FEE" or "SUF" or "INCENTIVE" or "CREDIT")) |
| 4 | content: (("STORMWATER" or "FLOOD" or "STORM WATER") AND ("EDUCATION" or "OUTREACH")) |

After identifying 583 documents, we screened them and removed duplicates (e.g., bill that was passed as an ordinance, or an old version of the document) and preserved the latest document, if there are revisions or updates from multiple years. We also removed irrelevant documents (e.g., documents related to stormwater but focused on industrial construction or rural areas, or local documents from outside the Lehigh Valley) to maintain our scope. The final sample for the systematic review included 351 documents that highlight governance and policy, stormwater fee and credit programs, and public education and outreach efforts from different levels of government. The entire PRISMA framework is summarized in Fig. 2. A comprehensive list of these documents is provided in the Supplementary Material (Table S2).

### 3.2. Quantification of education and outreach effort

The PRISMA process described in the previous section can be considered as a qualitative analysis using a manual "text-mining" approach. To quantitatively evaluate the education and outreach efforts from different government agencies, we applied an Education and Outreach Index, which was adapted from the Nexus Index by Raub et al. (2021), to grade each "component" (described below) on municipal government websites that discussed stormwater management and contained GI-related education and outreach. We divided this index into two parts: the stormwater management index and the GI index, as shown in Table 3.

The stormwater management index was used to evaluate general educational and outreach efforts on stormwater management topics. There were five components that contributed to this index: "Methods of Presenting Information," "Impact/Importance of Stormwater Management and Flood Mitigation," "Regulation/Plan of Stormwater Management," "Municipality's Responsibility," and "Resident's Responsibility." Each one was assigned a grade between 0 and 4. The GI index was used to evaluate educational and outreach efforts specifically focused on GI promotion. Similarly, three components contributed to this index: "Definition and Benefits," "Guides of Installation and Maintenance," and "Collaboration with GI Partners." Each one was assigned a grade of 0 or 1. In both the stormwater management index and the GI index, 0 indicates the stormwater web page does not exist, or the evaluation criteria were not met. Detailed grading standards for the stormwater management index and the GI index are documented in the Supplementary Material (Text S1, Text S2). We summed all components to calculate the final grade from these two indices. Therefore, the highest scores for the stormwater management and the GI indices were 20 and 3, respectively. We provide examples of "Method of Presenting Information" component of the stormwater management index in Fig. 3 to show stormwater web pages from three of the 62 municipalities that received scores from high to low, to visualize the grading process.

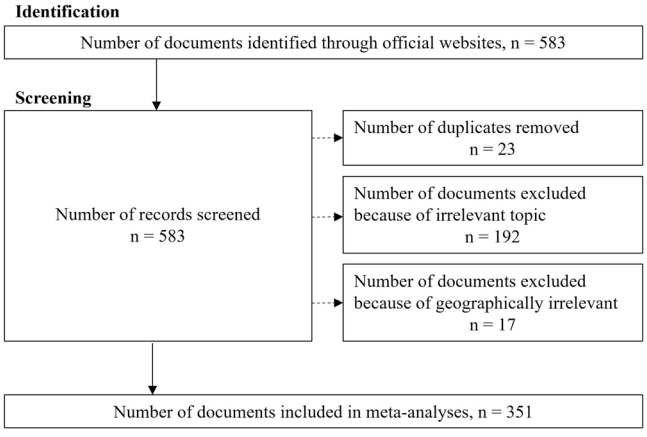



**Fig. 2.** Revised PRISMA process of systematic review.

**Table 3**
Grading criteria and potential points for each component of education and outreach index (including stormwater management index and green infrastructure index).

| **Education and Outreach Index** | | |
|---|---|---|
| **Stormwater Management Index** | **Potential Points** | **Scoring Criteria** |
| Methods of Presenting Information (Multimedia Component) | 0, 1, 2, 3, 4 | One point was given to each method: text, image, video, or interactive webinar/workshop used in this component. Zero points were assigned if there was no material provided or the material included no information about stormwater. |
| Importance/Impact of Stormwater Management and Flood Mitigation | 0, 2, 4 | Two points were given for information related to stormwater quantity or quantity. |
| Regulation/Plan of Stormwater Management | 0, 1, 2, 3, 4 | One point was given for each level of governmental regulation (municipal, county, state, or federal) in the material. |
| Municipality's Responsibility | 0, 2, 4 | Two points were given for information related to either conventional (e.g., pavement removal) or green infrastructure. |
| Resident's Responsibility | 0, 2, 4 | Two points were given for information related to conventional (e.g., pavement removal) or green infrastructure. |
| **Green Infrastructure Index** | **Potential Points** | **Scoring Criteria** |
| Definition and Benefits of Green Infrastructure | 0, 1 | One point was given for defining and introducing the benefits of green infrastructure. |
| Guides for Green Infrastructure Installation and Maintenance | 0, 1 | One point was given for providing technical guidelines to residents to help them install and maintain green infrastructure. |
| Collaboration with Green Infrastructure Partners | 0, 1 | One point was given for collaborating with different levels of agencies, departments, research institutes, and non-governmental organizations. |

## 4. Result

In this section, we first present a descriptive analysis of all reviewed documents. Then we organize the results of our review, the identified barriers to GI implementation, into three categories: governance and policy, stormwater fee and credit programs, and public education and outreach.

### 4.1. Descriptive analysis

Fig. 4 shows the descriptive analysis of all 351 documents, organized by document type, document theme, and document level. Fig. 4(a) shows the results by document type and the Government Document (GD), and Laws and Regulations (LR) are the most common. Together, they represent approximately 65 % of total reviewed documents. Because this study seeks to clarify the management of GI, which is often motivated by laws and regulations (e.g., statutes at the federal and state levels, and ordinances at the municipal level), there are many LR documents reviewed. GD documents include memoranda, technical guidelines, and fact sheets that explain specific laws and regulations from different perspectives to stakeholders. 76 % of the documents in the GD and LR categories directly mention GI, but most documents in the Newspaper Article (NA) and Stormwater Web Page and Pamphlet (WP) categories do not directly mention GI. This result implies that the authors or creators of NA and WP content may not yet recognize the importance of GI. Their target audience is the public, compared to GD

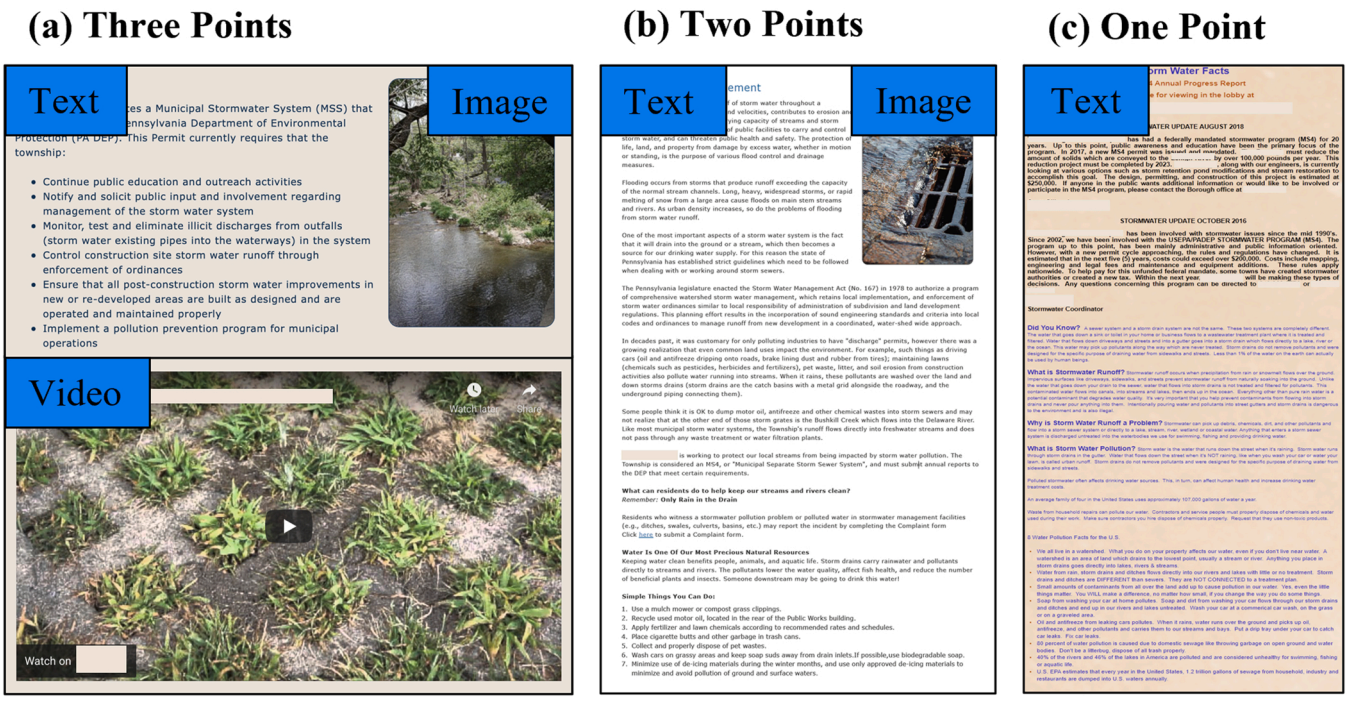



**Fig. 3.** Scores of example web pages in Method of Presenting Information component of stormwater management index. (a) Three points for using text, image, and video. (b) Two points for using text and image. (c) One point for using text.

and LR content, whose target audience is government officials and professionals. Another possible reason might be that the public is unfamiliar with GI, so the authors of NA and WP may avoid using terms such as GI and instead use vague expression strategies (e.g., using "innovative stormwater systems" to represent GI).

Fig. 4(b) shows the results by document theme. We identify five themes: Stormwater Management (SM), Stormwater Fee and Credit (FC), Public Education and Outreach (EO), Flood Mitigation (FM), and Flooding Problems (FP). Most documents are related to SM and FC, as shown in the inner circle. For SM documents, most directly mentioned GI, because GI is explicitly promoted by the NPDES program to protect water quality. However, in the FC theme, the situation is reversed. This is because most stormwater fee documents do not explicitly discuss credit programs, and therefore, they do not explain the typical requirement for property owners to install GI to get credit. In the EO, FM, and FP themes, nearly half of the documents explicitly mention GI, which implies that GI can be further promoted in these themes.

Fig. 4(c) shows the results by government level. More than half of the documents (63 %) are from the municipal level, which is not surprising given there are 62 municipalities in the Lehigh Valley. The second largest percentage of documents is from the federal level, and the fewest documents are from the state level. These results might imply a potential gap exists at the state level in general stormwater management documents. In the outer circle, many documents are directly related to GI at the federal and county levels. However, at the state and municipal levels, the percentage of documents that mentioned GI is only about 50 %. This result implies that GI promotion may not be well transferred from the federal to the municipal level.

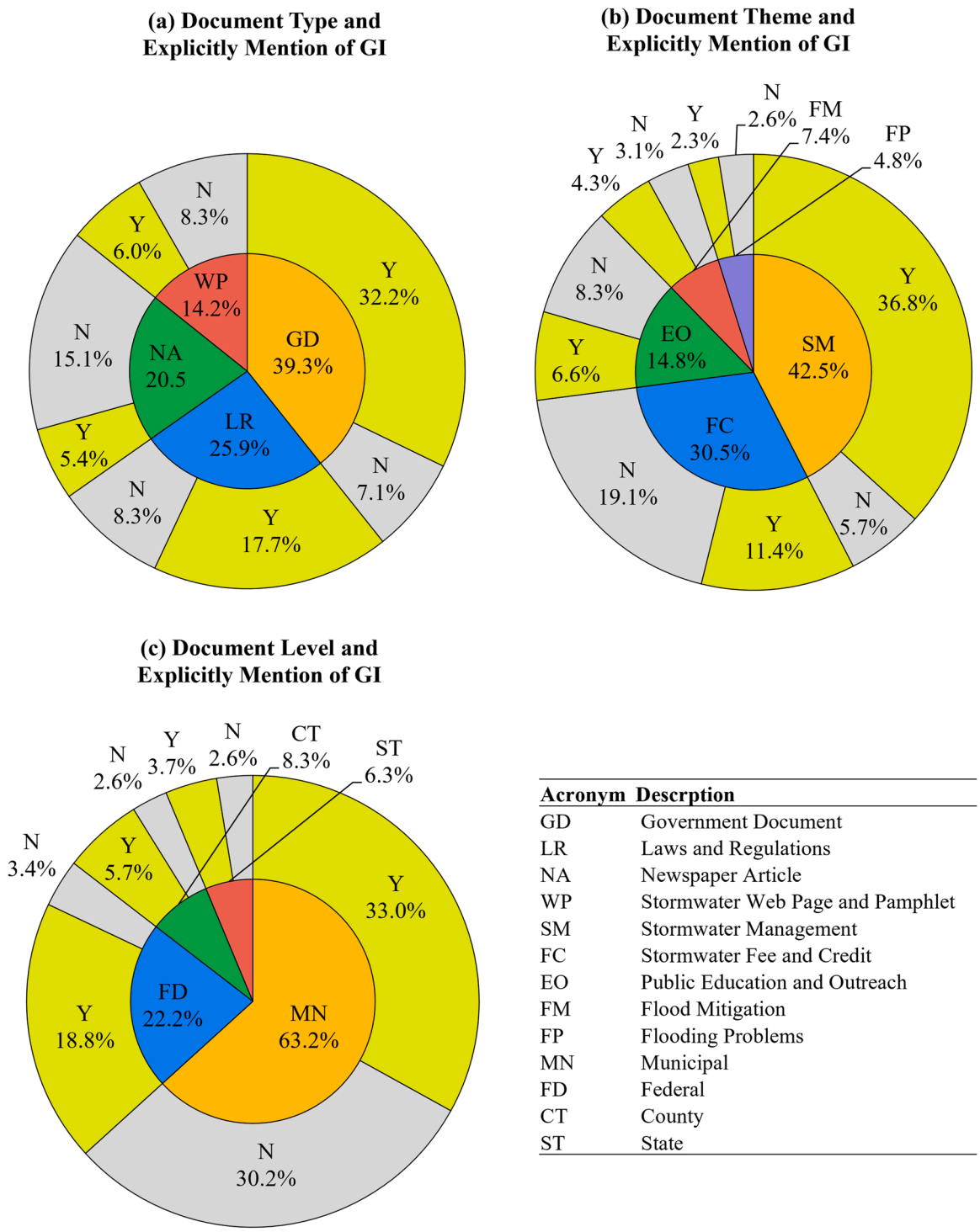
To summarize the results of Fig. 4, explicit mentions of GI are unevenly distributed in different types, themes, and government levels of documents. Each category has several points that link to other categories worthy of further discussion. For example, GI may not be well recognized at the state level (in our case, Pennsylvania) based on limited GI information in the Storm Water Management Act (1978), PA Code (2021), and State Hazard Mitigation Plan (PEMA, 2019). This is the cross-over result of Figs. 4(a) and 4(c). Insufficient GI-related information or activity in NA and WP might hinder the public education and outreach purpose of GI which is the cross-over result of Figs. 4(a) and 4 (b). We organize the following three sections to present identified barriers: 1. inconsistency and ambiguity in the documents about GI implementation and 2. the insufficient effort to raise the awareness of stormwater management and/or GI benefit in three categories.

### 4.2. Governance and policy

We summarized the barriers to GI implementation in governance and policy in Table 4.

The first barrier we identify in the governance and policy category is unclear responsibility for addressing urban flooding at the federal and state levels. Municipalities' stormwater management decisions are mostly used to satisfy EPA's water quality requirements. However, there is no such requirement from FEMA to municipalities because the focus of FEMA is on major disasters that typically occur in riverine or coastal areas. While major flooding in riverine and coastal areas causes greater damage per event, urban floods occur more frequently. Thus, the accumulated damage of urban flooding can be higher than that of more severe but less frequent riverine or coastal flooding (FEMA, 2005). Urban flooding is a topic in both EPA and FEMA jurisdictions, but due to a lack of clearly defined responsibilities, urban flooding lacks a federal agency to lead research. The same relationship exists at the state level between PA DEP and PEMA. Therefore, unclear responsibility is one limitation to promoting the use of GI for addressing localized flooding issues.

The second barrier is a lack of awareness of GI, especially at the state level, which leads to a lack of transmission of GI ideas from federal to municipal governments. In Pennsylvania, the concept of GI has not been explicitly incorporated into statute, code, or hazard mitigation plans. For example, the PA Storm Water Management Act of 1978 (the Act) requires counties to prepare and adopt watershed-based stormwater management plans. The Act also requires municipalities to adopt and implement stormwater ordinances consistent with these plans. However, since this Act was written before GI emerged in the US in the 1990 s (Fletcher et al., 2015), it does not encourage integrating GI into county plans or municipal ordinances. Therefore, an amendment might be




| Acronym | Descrption |
|---|---|
| GD | Government Document |
| LR | Laws and Regulations |
| NA | Newspaper Article |
| WP | Stormwater Web Page and Pamphlet |
| SM | Stormwater Management |
| FC | Stormwater Fee and Credit |
| EO | Public Education and Outreach |
| FM | Flood Mitigation |
| FP | Flooding Problems |
| MN | Municipal |
| FD | Federal |
| CT | County |
| ST | State |

**Fig. 4.** Descriptive analysis of reviewed documents. The total of the inner circle and the outer circle each independently represents 100 % (i.e., 351) of the reviewed documents. Each segment of the inner circles for parts (a), (b), and (c) represents the percentage of the document type, theme, and government level, respectively. The segments of the outer circles are divisions of each corresponding inner circle segment and show the percentage of documents (out of the 351) that explicitly mention GI or its equivalent terms (e.g., best management practice, low-impact development) (Y) or do not (N). It should be noted that the documents which do not directly mention GI have also been reviewed because their contents, such as the policy and governance of stormwater management and flood mitigation, stormwater fee and credit, or education and outreach, are still relevant to facilitating GI installation.

needed at the state level to promote the use of GI to achieve the goals of the Act. Currently, the regional planning commissions formed by county governments are left to determine whether GI can be used to comply with the Act. In our study area, the Lehigh Valley Planning Commission decided to adopt GI for compliance with the Act by providing a model stormwater ordinance for local municipalities to adopt, based on the watershed in which they are located (LVPC, 2018). The model stormwater ordinance provides stormwater calculation methodology, standard designs for GI, and supplementary information on GI benefits. Because of the availability of a model stormwater ordinance, 94 % (as shown in the Supplemental Material Table S3) of the municipalities in Lehigh Valley have adopted a stormwater ordinance. And among these

**Table 4**
Summary of identified barriers for promoting green infrastructure implementation in governance and policy.

| Governance and Policy Barriers | Example |
|---|---|
| (Federal and State) Unclearly defined responsibility | No agency was specifically responsible for addressing urban flooding. |
| (State) Unaware of green infrastructure | Failed to merge green infrastructure into a mitigation plan. |
| (County) Lack of updated ordinance | Lack of updated IDF curve for green infrastructure design. |
| (Municipal) Fragmented policy | Different policy boundaries led to multiple ordinances within one municipality. |

municipalities, 97 % (as shown in the Supplemental Material Table S3) of them explicitly mention GI or its synonyms like "best management practices" in their stormwater ordinances. Explicitly encouraging the use of GI in the stormwater ordinance can be seen as an endorsement of GI implementation by the municipal government.

The third barrier is out-of-date watershed stormwater management plans at the municipal level, which may underestimate or overestimate the capacity of GI to mitigate modern stormwater volumes. In the Lehigh Valley, there are 15 watersheds, and each one has its own stormwater management plan. However, of these 15 watersheds, only the Little Lehigh Creek Watershed (1988, 2000, 2005) and Monocacy Creek Watershed (1989, 2018) plans have been updated since their first release in the 1980s. Using out-of-date stormwater management plans might result in underestimating flood impacts. For example, current engineering practice uses the intensity-duration-frequency (IDF) curve to estimate rainfall and calculate runoff volume, stormwater peak flows, pollutant load, and other variables and determine the capacity of the GI. There are two versions of the IDF curve for the Lehigh Valley (located in Pennsylvania Region 4, as defined by the Pennsylvania Department of Transportation, PennDOT): one was issued in 1986, and the other was issued in 2007. Fig. 5 shows these two IDF curves for rainfall depth during 24-hour rainfall events with a return period from 1 to 100 years. The 2007 IDF curve is higher than the 1986 IDF curve at all return periods. 76 % of municipalities in Lehigh Valley still use the 1986 IDF curve, and only six municipalities have adopted the 2007 IDF curve in their stormwater ordinances (Supplemental Material Table S3). Therefore, if these municipalities use the same return period as their design requirement, those using 1986 IDF curve will design for a lower rainfall depth than the 2007 IDF curve. This is especially true for the shorter return periods (1, 2, and 5 years), which are the storm events that most GI is intended to manage.

The fourth barrier is fragmented stormwater regulations within a municipality. A municipality may have to adopt more than one stormwater ordinance if it is in more than one watershed, because of discrepancies between political and watershed boundaries. Having to adopt two or more ordinances that are updated independently, and perhaps inconsistently, from each other may result in different requirements within the same municipality. For example, Upper Nazareth Township overlaps both the Bushkill Creek Watershed and the Monocacy Creek Watershed, which last updated their ordinances in 1992 and 2018, respectively. The Bushkill Creek plan requires use of the 1986 IDF curve, but the Monocacy Creek plan requires use of the 2007 IDF curve. Thus, the prescribed method for the stormwater runoff volume calculation, which is used to design the size of GI, gets inconsistent results within Upper Nazareth Township.

### 4.3. Stormwater fee and credit programs

Stormwater fee and credit programs are a popular way to fund municipal stormwater projects and encourage property owners to install private GI in the US (Zhao et al., 2019). Stormwater fee and credit programs are usually used to fund the development, maintenance, repair, and replacement of existing and future infrastructures, including those for both flood mitigation and water quality management. Another purpose of these programs is to fund the projects that are necessary to meet the requirements of the Municipal Separate Storm Sewer System permit and stormwater ordinance (Borough of Fountain Hill, 2019; City of Allentown, 2017; City of Bethlehem, 2020; City of Easton, 2018). Stormwater fee and credit programs are typically administered by the Municipal Public Works Department or the Stormwater Authority. In the Lehigh Valley, the first stormwater fee and credit program were developed by the City of Allentown in 2018. After that, three municipalities followed: the City of Easton in 2018, Fountain Hill Borough in 2020, and the City of Bethlehem in 2021. We can observe some challenges these municipalities have faced. Since the structure of the stormwater fee and its corresponding policy are important criteria for adoption and success, we evaluate the structure of the stormwater fee and credit programs by equity, dedication, and adequacy. We define equity as residents' ability to pay the stormwater fee and how much services provided by the municipal stormwater system each property owner could receive. We define dedication as spending the funding on building, operating, and maintaining municipal GI projects, and on the credit programs to promote GI to property owners. Finally, we define adequacy as the capacity of the revenue generated by the program to cover potential costs generated from municipal stormwater management (Zhao et al., 2019). We summarize our observations in Table 5.

The first barrier we identify is the possible creation of inequity by fee exemptions for certain properties and flat fees across all properties. Municipalities in the Lehigh Valley exempt public streets, rails, and associated track ballasts from the stormwater fee. However, public streets contribute significantly to the pollutants that enter streams through contaminated stormwater (Sartor and Boyd, 1972). These public streets also contribute to urban flash floods because they are impervious to water. Therefore, these properties should be charged a fee, and in a progressive fee structure this fee would be higher than that

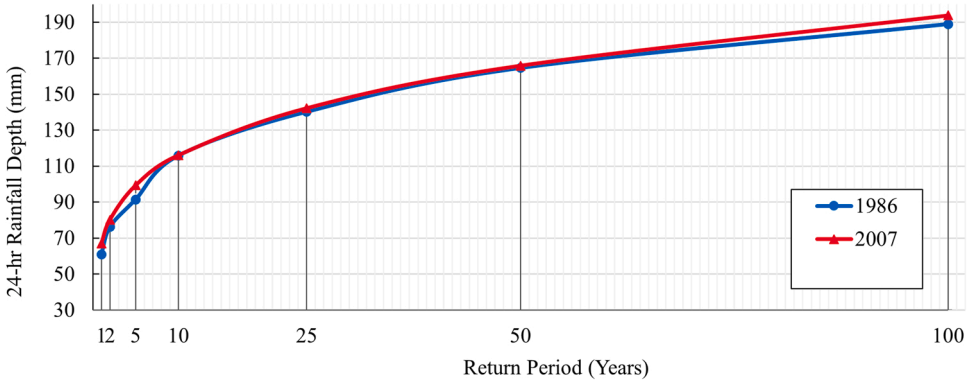



**Fig. 5.** Overlay of 1986 IDF curve (Blue) and 2007 IDF curve (Red) in region 4 of Pennsylvania (PennDOT, 2010, 2015) where Lehigh Valley is located.

**Table 5**
Summary of identified barriers for promoting green infrastructure implementation in stormwater fee and credit programs.

| Stormwater Fee and Credit Program Barriers | Example |
|---|---|
| Inequity in stormwater fee structure | Municipality exempts some properties from paying stormwater fee or municipality applies a flat fee. |
| Lack of prioritization of green infrastructure projects | Unclear regulation for using the funding. |
| Debate of the credit | Lack of credit to residential property owners and conflicting definitions of service fee and tax. |
| High administration and technical threshold | Complex paperwork and efficiency requirements for residential property owner to apply for credit. |

levied on properties that contribute less to the urban flooding and water quality issues. Conversely, some municipalities charge a flat stormwater fee to residential property owners based on the median impervious area of a single-family residential property in that municipality (City of Bethlehem, 2020). Although some property owners are exempt from the fee if their properties are smaller than a certain area, for those who must pay, the flat fee might still cause inequity. Since this flat fee structure disregards the actual property size, property owners with smaller-than-average parcel areas will pay greater stormwater fees per impervious area. These equity issues could further discourage property owners from installing GI.

The second challenge is that the use of stormwater fee revenue for traditional stormwater-related services might impact the success of the stormwater fee program. Here, traditional stormwater-related services refer to services provided by the municipality that are not directly related to the improvement of a stormwater drainage system, such as street sweeping, leaf collection, and land development plan reviews. Funding GI may remain a low priority compared to these services, partially because, unlike with some GI, the effects of these services are readily observable by residents. In our study, the City of Allentown and Fountain Hill Borough avoid this barrier by clearly outlining that traditional stormwater-related services will be funded by general funds and other resources, and that they are more inclined to use the stormwater fee to fund innovative stormwater facilities, such as GI (Borough of Fountain Hill, 2020a, 2020b; City of Allentown, 2020). However, the other two Lehigh Valley municipalities with stormwater fee programs do not outline such restrictions to the public.

It is difficult to estimate how much credit should be granted to property owners. In the Lehigh Valley, property owners can apply stormwater credit as a discount toward the stormwater fee, if they meet the requirements of the credit program and thus help the municipality with stormwater control and pollutant removal. The stormwater credit typically ranges from 10 % to 50 % of the stormwater fee, and it is based on the efficiency of their GI, especially the sediment reduction rate. However, two concerns have been raised by residents. First, some municipalities only provide stormwater credits to industrial property owners, excluding residential property owners. Insufficient space to install GI and negligible contribution to flood mitigation if the installation level is low might be reasonable explanations for why some municipalities decide not to grant stormwater credit to residential property owners. However, this policy may cause residential property owners to oppose the establishment of stormwater fee and credit programs because they cannot get credit like the industrial property owners. Also, the possibility of mitigating urban flooding by achieving a high-level installation of GI is reduced because residential property owners lack the motivation to install GI. Second, the stormwater fee is highlighted as a service fee, rather than a tax, and the fee is based on the volume of stormwater processed. According to this logic, a parcel that does not generate stormwater (e.g., no impervious area or stormwater is totally captured by GI) should not be charged this fee because this parcel does not receive any service. However, the stormwater credit is capped at 50 % of the stormwater fee, which ensures funds for annual monitoring, program administration, and other stormwater-related projects (Borough of Fountain Hill, 2020a, 2020b; City of Allentown, 2018). All properties are charged at least the minimum stormwater fee, effectively making it a tax. These two concerns about stormwater fee programs can lead the public to doubt the benefits of GI and lack clear economic incentives to install it on their property, further limiting implementation.

Lastly, complex administration processes and requirements to demonstrate the functionality of GI can prevent residential property owners from applying for stormwater credit. Municipalities usually ask residential property owners who want to apply for stormwater credit to meet technical, functional, and maintenance verification requirements for GI. The functionality demonstration and related paperwork requires professional involvement, which adds extra procedure and costs for property owners to apply for the credit. Some municipalities require the property owner to enforce a maintenance agreement for at least 20 years to receive the stormwater credit, which greatly raises the threshold for applying and dampens public enthusiasm for implementing GI (City of Allentown, 2018).

### 4.4. Public education and outreach

The applied Public Education and Outreach indices returned full scores for the federal and state governments since they provide comprehensive information about stormwater management, flood mitigation, as well as technical manuals and successful examples of installing and maintaining GI. This is expected because federal and state governments may have sufficient budgets for public education and outreach efforts to achieve the mission that allowing all parts of society to access accurate information to participate effectively in risk management (US EPA, 2022b). Because of this result, we only compared the results for 62 municipalities in the Lehigh Valley.

Fig. 6(a) shows the score distribution for stormwater management indices. There are two municipalities that get the highest score of 17, and approximately 60 % of municipalities scored less than 8 in our analysis. This suggests that these municipalities have room for improvement in developing effective communications about stormwater management for their residents. The municipality did not have a stormwater web page or any related content on its website earned a “0” for that corresponding category. Containing the fifteen (24 %) municipalities that did not have stormwater web page, approximately 27 % of municipalities had no information on Method of Presenting Information, 32 % on Importance and Impact of Stormwater Management, 52 % on Regulation and Planning, 77 % on Municipality’s Responsibility, and 47 % on Resident’s Responsibility. Missing information on those categories hinders the outreach effort. More than half of the municipalities used one of two Methods of Presenting Information on their web page. Most websites used text, but some websites used pictures or videos to increase visibility and enhance understanding, especially when they introduced GI. For Importance and Impact of Stormwater Management, 27 % of the municipalities only emphasized stormwater quality. Regarding the Regulation and Planning of stormwater management, more municipalities (39 %) mentioned the Storm Water Management Act (1978), a state law, compared with laws and regulations at the federal (34 %) and municipal (23 %) levels. And no municipality described the watershed-based stormwater management plan at the county level. For the Municipality’s Responsibility component, 19 % of municipalities showed a conventional method, such as pipeline rehabilitation, and 15 % of the municipalities presented applications of GI in their stormwater management projects. Thus, most municipalities didn’t use the webpage to keep the residents informed about the plan for the municipal stormwater management projects. For the Resident’s Responsibility component, approximately 53 % of the municipalities suggested activities such as converting mowed grass to meadows, and 21 % of the municipalities suggested that residents consider using GI to mitigate flooding impacts and improve water quality. Most municipalities recognized the

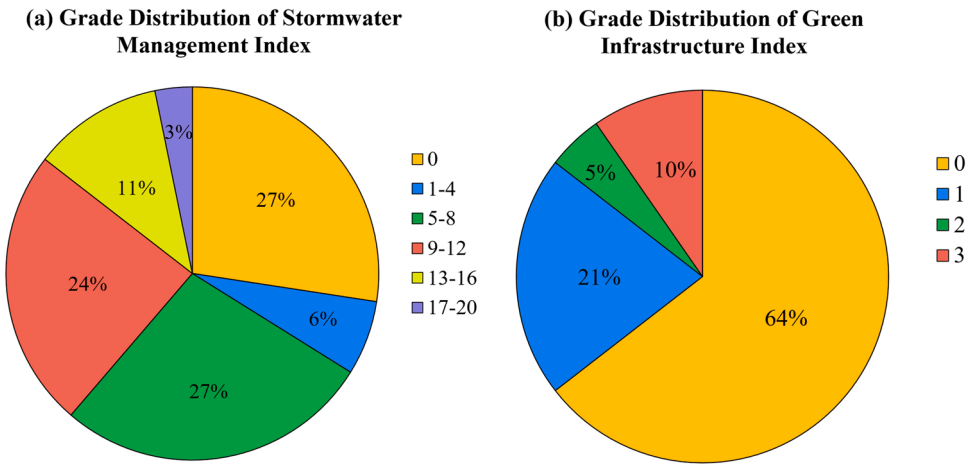



**Fig. 6.** Grade distribution of education and outreach index for (a) stormwater management index and (b) green infrastructure index in the Lehigh Valley (62 municipalities), PA.

importance of resident activities to protect water quality, but they did not discuss the resident's activities for decreasing stormwater volume.

We evaluated municipalities that advocated for GI on their stormwater web page using the GI index, as shown in Fig. 6(b). There are 90 % of the municipalities providing less than the full information (benefit, guidance, and partnership program) available on GI to residents. Not having enough information is a barrier to property owners to install it, because lack of understanding of GI may lead to the residents do not evaluating GI as a possible option for helping them address the stormwater-related problems. Based on these scores, we argue that it is insufficient to mention GI as a concept; it is necessary to introduce the principle and reason to promote GI, and if residents are interested in, the activities they can participate in and where they can get help.

Moreover, we try to explore some possible demographic or socio-economic factors (USCB, 2020c) that might affect the scores of these municipalities (the natural factors should be similar given that these municipalities are all located in the Lehigh Valley). We find that municipalities with higher scores in both the stormwater management index and green infrastructure index tend to have a large population and/or a higher population density (Supplemental Material Fig. S2). There are two explanations of this pattern. First, having a large population and/or high population density in a flood-prone municipality would suggest that more residents are likely to be exposed to flood risk than if the municipality had fewer people and the same flooding issues. Therefore, the municipal government might feel greater pressure to raise awareness about stormwater management among residents. Second, since GI is a decentralized stormwater infrastructure. Compared with grey infrastructure, which typically are large-scale stormwater management projects, GI is more suitable for installation in municipalities with higher population density and small available areas. Therefore, it is not surprising that these municipal governments put more effort into their official websites to promote the benefits of GI. Note that this pattern is only an observation in our study area, and we do not claim there is a causality or a correlation between total population and/or population density and municipal government's public education and outreach effort. The actual reasons that make these municipalities top scorers in both indices will need further research in the future.

## 5. Discussion

### 5.1. Policy-related recommendations for GI implementations

Based on these identified barriers, several recommendations regarding GI implementation are presented in this section. By proactively addressing these barriers, it is possible to improve efficient implementation of GI, thereby realizing the potential benefits of GI (Li and Bergen, 2018). First, the existing institutional management framework for GI should be enhanced. This can be achieved by clearly defining the responsibilities and collaborations between the two federal jurisdictions involved in stormwater management and flood mitigation, and by refining the process, such as regular reviews of current policies and regulations. Updating policies and regulations frequently is important to remove outdated and inconsistent information, ensuring that GI management stays adaptive and responsive to evolving environmental conditions and technological developments. This approach will ultimately contribute to shift towards more sustainable environments.

We also recommend using "policy windows" as opportunities to promote GI implementation (Hopkins et al., 2018; Madden, 2010). This means that decision-makers in municipalities could synchronize GI promoting efforts, such as new regulatory language or fee programs, with the development of other new policies or scheduled updates to existing policies. According to the definition given by Cairney and Zahariadis (2016), the "multiple streams" concept describes the process of decision making as divided as follows: a policymaker identifies a problem to solve (Stream1), the bureaucracy produces a range of possible solutions (Stream2), and the policymaker selects the best choice (Stream3). Following the suggestions from Kingdon (2014) and Cairney and Zahariadis (2016), these streams must join at the same time during a "window of opportunity" for motivating the policymakers to pay close attention to the problem and to select and implement the solution. In our case, municipalities in Lehigh Valley have recognized in the early 2010 s that stormwater management issues have become significant due to increasing urban development and climate change (Stream1). Since then, different pilot programs for GI installation, stormwater ordinance modifications, and funding programs have been established to mitigate urban flooding impacts (Stream2). At the same time, the state issued NPDES permit (of which each municipality has at least one) must be renewed every five years in the Lehigh Valley (US EPA, 2022a). To renew the NPDES permit, municipalities must show the effects of the stormwater management projects and a plan for future stormwater management. Therefore, NPDES permit renewal provides a 5-year window of opportunity for municipalities to learn from each other's experiences and try to incorporate GI components (e.g., stormwater fee and credit programs as a GI incentive for property owners) when they submit their renewal request to PA DEP (Stream3).

We observed this pattern of timing GI innovations with NPDES permit renewals in two of the four municipalities that currently have stormwater fee and credit programs in the Lehigh Valley (Borough of Fountain Hill, 2020a, 2020b; City of Allentown, 2018). Other municipalities in the region, such as Bethlehem Township, seem to have

learned from others and are trying to implement GI promotions via stormwater fee and credit programs while they prepare their NPDES renewal (Township of Bethlehem, 2020). To do so, compared to other municipalities, Bethlehem Township started early to communicate with the stakeholders who may be against their proposed program to try to reach a consensus. In the Lehigh Valley, municipalities have typically taken at least one year to establish a stormwater fee program by passing a corresponding ordinance and have started to charge the stormwater fee, at the latest, two and a half years before the next permit renewal. Therefore, municipalities with more than three years until the next renewal have an opportunity to meet the requirements for NPDES renewal by establishing a stormwater fee program to fund stormwater projects. Fig. 7 shows the NPDES renewal timeframe for all municipalities in the Lehigh Valley. Nine municipalities have over three years (at the time this paper was written) until they need to renew their NPDES permit (September 2025). These municipalities have a policy window open to plan for GI promotions and incorporate them into their NPDES renewal.

Our third recommendation is continuously improving public education and outreach activities to increase awareness of GI. For instance, employing multimedia on stormwater webpages and using social media, webinars, and workshops to disseminate information about the benefits, guidelines, and partnership programs related to GI. The content for these advertisements can either be produced by federal government agencies, such as the EPA, in the form of flyers, fact sheets, and short videos, or it can be created by the municipalities themselves. In addition, the timing of these activities also needs to be considered. For instance, scheduling it after extreme storm events or during spring, when residents are likely to engage in gardening, could be an effective strategy.

### 5.2. Transfer methodology for other study areas

To assist other researchers who might seek to identify barriers associated with GI implementation and policy window in other study areas, we present the guideline that explains the adaptation required in data collection and general evaluation procedure. The data collection contains the database used to search documents at different government levels, the search criteria, and reviewing method. First, since data collection can be done completely on governmental websites, it should be performed from the upper-level (e.g., federal) to the lower-level (e.g., municipal) which will provide a big picture of GI-related laws and codes first and then detailed regulations for the specific study area. Also, data collection regarding newspaper articles should focus on local news only (i.e., the county level). Secondly, we use the text mining approach to recognize relevant documents that contained keywords presented in Table 2 can be completely duplicated to identify the relevant documents from the websites following the text mining approach. And then, the screening step will just follow the PRISMA framework to identify final documents for meta-analysis. For the quantitative evaluation of public education and outreach website content, we employ the grading standards of the stormwater management index and the GI index, as documented in the Supplementary Material (Text S1, Text S2) which can be used for any other municipalities' website. Finally, to adapt the concept of using policy window to synchronize GI promotion with other policies, the renewal cycles of different NPDES permits in the specific study area will need to be identified first. This information can usually be sought from the state's Department of Environmental Protection website or EPA website. For example, PA DEP offers a "NPDES Permitted and Waived MS4s Reporting Tool," which assists in searching for NPDES permit information for each municipality.

### 5.3. Limitation and future works

This study used the PRISMA framework to conduct a meta-analysis of non-academic documents as a complement to previous reviews of the socioeconomic barriers in GI implementation. However, several limitations must be highlighted. First, since we applied a text mining-based approach to locate information for analysis, we ignored other information beyond the text, such as decision-making processes behind laws and regulations. Thus, a critical avenue for future study is to conduct interviews and surveys of stakeholders. Interviews with government officials should seek to understand their decision-making processes, including interviewing officials in municipalities without comprehensive stormwater management regulations. These interviews could help researchers and officials in that and other municipalities to identify factors that may be hindering the promotion of GI. A survey would be an ideal way to assess residents' understanding of the effects of stormwater regulation and policy, the effect of public education and outreach, and other factors that may impact an individual's decision to install GI on their property (Abuismail et al., 2024).

Second, although there are county-level supports for stormwater management, such as assistance with, coordination of, and writing grants for watershed planning and assessment, and holding rain barrel workshops (LCCD, 2022), we did not account for these activities, because there are no stormwater laws at the county level in the Lehigh Valley. Therefore, the role of the county in stormwater management and GI promotion needs further study. Third, the reviewed documents in the PRISMA framework only focused on decreasing stormwater volume and improving water quality. Because of the diverse benefits that can be achieved by GIs and different government structures around the world, a

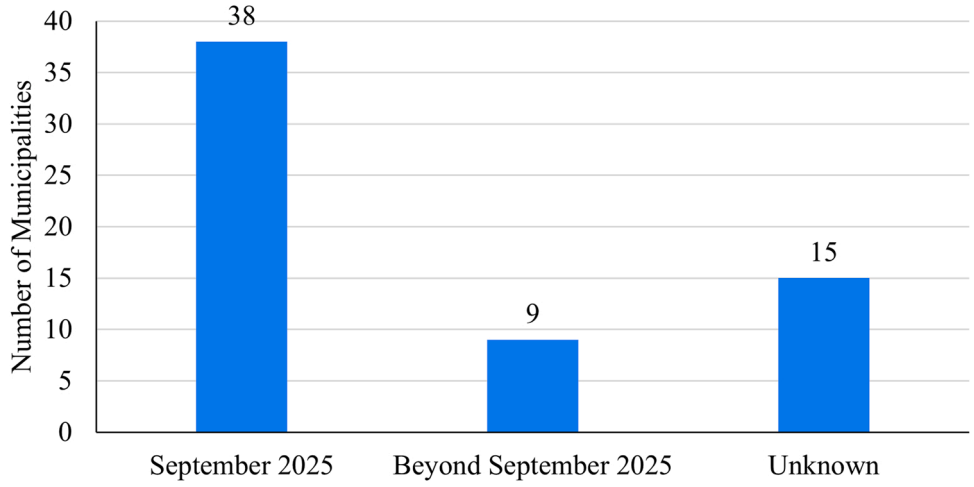



**Fig. 7.** Intervals for NDPES permit renewal in Lehigh Valley (62 municipalities), PA (PA DEP, 2021).

comparison of different barriers' impacts on other benefits, for instance, ecological resilience and water reuse (Hacker and Binz, 2021; Rupiper and Loge, 2019), and the barriers present in different locations (Jia et al., 2017; Gashu and Gebre-Egziabher, 2019; Brudermann and Sangkakool, 2017) could provide a more comprehensive view of GI implementation.

Finally, the relationship between the presence and structure of municipal stormwater fee and credit programs and GI adoption will require a more detailed study. An adequate stormwater credit program should have a reasonable and effective plan to estimate the actual efficacy of GI, which property owners can then use to apply for stormwater credit. However, the current stormwater credit program in the Lehigh Valley uses a flat rate due to technical difficulties (including the lack of a real-time monitoring system to assess the physical functionality of installed GI) making it impossible for the municipalities to estimate the efficacy-based value of the fee and credit. In addition, a cost-benefit analysis of the stormwater credit program, the number of credit applicants, and the amount of credit distributed should all be analyzed to quantify the role of the stormwater credit program in GI promotion.

## 6. Conclusion

This study aims to identify the practical barriers in governance and policy, stormwater fee and credit programs, and public education and outreach regarding urban flooding that may hinder GI installation across different levels of government. The Lehigh Valley, which consists of 62 municipalities in Eastern Pennsylvania, US, is used as a case study. We conduct a meta-analysis of 351 public documents, including laws, regulations, plans, official reports, manuals, brochures, and press releases to achieve the objective. PRISMA was mainly applied for qualitative analysis in the governance and policy and stormwater fee and credit programs categories. In addition, an Education and Outreach Index was utilized to score stormwater web pages on government websites to quantify various governments' efforts to incorporate GI into public education and outreach.

Our results showed that GI was inconsistently incorporated into laws and regulations across levels of government. In addition, the debate of the stormwater fee and credit programs and insufficient efforts to educate the public about stormwater and GI may limit wide-scale implementation of GI. Several barriers to GI promotion are identified in the Lehigh Valley, but we also found that some municipalities with larger populations and/or greater population density are making efforts to promote GI benefits to their residents or learn from other municipalities' experiences and establish their own stormwater fee and credit programs. Policy windows have been highlighted as one of the potential ways forward to promote municipal GI implementation and innovation. Such policy windows are opened for some municipalities in the Lehigh Valley to incorporate GI into their next NPDES renewal documents during the time this paper was written. This proposed method can also be easily adopted for other study areas. To further understand barriers to the installation of GI, future research should evaluate the decision-making processes, knowledge of GI, and perception of stormwater fee and credit programs among government officials and property owners.

## CRediT authorship contribution statement

Qiaochu Sun: Methodology, Data Curation, Formal analysis, Visualization, Writing - Original Draft. Hannah Kushner: Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing Y. C. Ethan Yang: Conceptualization, Methodology, Supervision, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103686.

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