Green Stormwater Infrastructure

Subjects: Environmental Sciences

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Green stormwater infrastructure (GSI), a nature-inspired, engineered stormwater management approach that mimics natural hydrological processes to improve water quality and reduce localized flooding events.

Keywords: stormwater management ; social factors

1. Introduction

Urbanization can affect the hydrologic functions of urban watersheds and precipitation patterns [1][2][3][4][5]. The consequential increased use of impervious surfaces results in substantial increments of stormwater runoff volume and peak flow [6]. Thus, the transition from the conventional approach into a more sustainable stormwater management paradigm which includes green stormwater infrastructure (GSI), is indispensable to reducing substantial environmental, economic, and social damage [7][8][9]. Hence, there is also a need to understand the hindrances and limitations in GSI implementation.

GSI offers a promising solution to stormwater management by mimicking natural hydrological processes to reduce localized flooding events and water quality improvement through decentralized natural or engineered processes to treat stormwater runoff at its source [10]. In the US (United States), awareness of GSI has slowly increased over the past two decades. Its historical progress in stormwater management and background knowledge is documented in several in-depth publications [11][12][13][14]. Research teams across nations have developed various GSI practices and in addition, retrofits and hybrid measures on different spatial scales (such as watershed scale and site scale, etc.) with diverse primary purposes have been developed [15][16][17][18][19][20]. The details on these practices are well documented in the literature [21][22][23][24][25][26][27][28].

Numerous studies have evaluated the performance of GSI, particularly in economic and technical aspects [14][29][30][31][32]. GSI provides extra benefits to the community, such as raising property values, enriching life quality, and providing adaptable climate resilience [33][34][35]. Urban stormwater management has advanced gradually over the last two decades, thus various terminologies are used to define new principles and practices, where the concepts behind them often overlap [14][36]. Using these different terms may reduce effective communication in certain circumstances, such as when documenting all the alternative stormwater practices used in the US to assess their performance in general [36]. To avoid confusion, the term GSI was used throughout this work in referring to all types of multi-purpose structural stormwater management practices that involve natural processes for runoff volume and water quality control.

Despite the progress, there are limited study efforts on non-technical factors, such as public perceptions and knowledge, that could explain the slow advancement in the wide adaptation of GSI to the desired level for stormwater management and sustainability capacity building [37]. The contradiction between the low implementation rate of GSI in major regions of the US and the actual demand to address climate change impacts suggests that certain factors are hindering the relevant decision-making processes [38][39]. Furthermore, a study discovered the mismatch in the percentage of their survey participants that expressed an intention to support GSI and the number of those who actually adopted GSI [40]. This result is in agreement with the findings in an exhaustive review [41]. Irrational decision-making behaviors in energy-related decisions have been interpreted through the cognitive bias perspective [42][43], where cognitive biases can be defined as a belief that hampers one's ability to make rational decisions given the facts and evidence [44]. It has been supported by various studies that cognitive biases are influential in decision making and planning [44]. Yet, little attention has been given to the potential influence of cognitive biases in GSI implementation, despite numerous studies on perceptions of various GSI stakeholder groups [45][46][47]. This study aims to bridge this knowledge gap.

Historically, quantitative decision support tools have been developed with the main aim to maximize GSI performance to control runoff and water pollution and to be cost-effective [48][49][50][51][52]. On the other hand, despite the extensive attempts made to expand the assessment work to include the social aspect of decision support [17][48][53][54][55][56][57][58][59][60][61][62][63][64], they lack a deeper understanding of the public perceptions and associated cognitive bias perspective to resolve the implementation dilemma from a bottom-up approach [65] as examined in other environmental issues [43][44]. This shortcoming can affect the expected outcomes envisioned by major decision-makers [42][66]. This study focuses on the barriers that could be linked to biased perceptions due to social factors in GSI development and implementation.

This work was conducted to examine the relevant social factors through the lens of cognitive biases, which may lead to implementation barriers during GSI adoption processes. The scope of social factors can vary significantly as they are commonly assessed in combination with factors from other dimensions, such as socio-ecological, social-cultural, socio-economic, and socio-technical factors [10][67][68][69][70]. We use a concept adapted from Gifford and Nilsson [71] to define social factors as the internal differences among people and the contextual factors that define them in this study. This study aims to understand the potential connections of cognitive biases with these barriers, and to recommend an approach to analyze and address the associated problems. Studies have been conducted to analyze cognitive biases with agent-based modeling (ABM) in various contexts [72][73][74]. However, no study has done a similar analysis in the context of GSI implementation. ABM is a methodology that can incorporate the autonomy, heterogeneity, and adaptability of individuals in a social system to study the resulting global patterns through a bottom-up approach [75][76]. It is also an approach that can carry exploratory simulations for a deeper understanding of the underlying adaptive behaviors and interactions that could lead to the emergence of phenomena that was previously overlooked [40]. However, the models developed solely based on social and physical science are usually fragmented in their fields, rely on qualitative analysis, or are difficult to incorporate into quantitative models [77].

2. Identified Social Barriers to GSI Implementation

The barriers to GSI have been studied by numerous international research teams, ranging from individual perceptions and attitudes, financial burdens, resource allocations, and governance rigidity to conflicts across institutions [45][67][79][83][84][85][86]. Barriers originating from social factors may be harder to address, as the values of which are usually difficult to quantify yet should not be overlooked [55][58][65]. Barriers primarily identified as associated with social factors, in terms of their potential influence on the implementation of GSI, are attributed to three main categories from the literature. They mostly cover governance discord, public participation, and demographic constraints (Table 1). Governance refers to the inconsistent strategies among or within governance entities; public participation refers to the involvement of the public in the decision-making of GSI regulations and collaborations; and demographic constraints refers to the general demographic factors, social norms, and perceived environmental concerns. However, there always is a possibility of unrecognized social factors in the published studies. For example, though not directly addressing the issues in stormwater management adaptation, a study brought forth the dilemma in regenerating historical cities of which preserving the historical cores were paramount [87]. It is thinkable that advancing GSI in such areas may encompass greater complexities than others. Additionally, the underlying interrelations across infrastructure sectors and even industries are also likely to influence sustainable decision-making in general [88][89].

Table 1. Relevant social factors that could influence the implementation of GSI in the US.

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
Demographic constraints & public engagement	Race, ownership status, relevant knowledge of GSI, knowledge dissemination platform	Rainwater harvesting, pervious paving, rain gardens, lawn depression	Sub-watershed	Two sub-watersheds in Chesapeake Bay watershed	Private landowners	Knowledge, attitude, and practice questionnaire	[90]
	Age, education, homeownership, prior experience of floods, lack of awareness, underuse of social capital	Rain barrels, rain gardens, and permeable pavement	Region	Knoxville, TN	Private landowners (households)	Survey	[91]

	Limited focus on the multifactional of GSI to respond to local needs, lack of interdepartmental collaboration, and private-public partnership	Green alleys with various GSI features	Region	Various locations in the US	Government agencies, non-governmental organizations (NGOs), community groups	Narrative analysis	[34]
	Conflicting visions in hydro-social relations	GSI in general	Region	Chicago, IL, and Los Angeles, CA	Government entities, NGOs	Interviews, participant observation, literature review, survey	[92]
	Leadership in transitioning governance (informal, multiorganizational)	GSI in general	Region	Ohio	Community NGOs, environmental NGOs/land trust, federal government, local government/regional authority, university /contractor	Social network analysis survey	[93]
Governance	Departmental silos (stakeholders' multiple and competing social perspectives)	GSI in general	Region	Chicago, IL	NGOs, governmental entities	Q-methodology	[94]
	Tensions and convergences among different management strategies	GSI in general	Region	Pittsburgh, PA	Community organizations, municipalities, advocacy groups	Interviews, participant observation	[95]
	Conflicting perceptions, implementation priority, limited focus on the multifunctionality during planning	GSI in general	Region	New York, NY	Agencies, city departments, national and local nonprofits, research institutions	Spatial analyses, survey, interview, participant observation	[78]
	Inequity for disadvantaged communities	GSI in general	Sub-watershed	Los Angeles, CA	Government agencies, non-profits, community organizations, and others	Statistical analyses	[96]

	Failing to recognize the values of social capitals for long-term productivity	Rain gardens, rain barrels	Household site	Cincinnati, OH	Landowners	Experimental reverse auction	[97]
	Perception (status quo bias)	Rain gardens, bio-swales, green alleys with permeable pavement	Region	Cincinnati, OH, and Seattle, WA	Engineering graduate students	Functional near-infrared spectroscopy	[38][97]
Public engagement	Ineffective information dissemination, underuse of social capital	Rain barrels, rain gardens, permeable pavement	Region	Washington DC	Homeowners	Voluntary stormwater retrofit program with statistical analyses	[98]
	Stormwater context (perception of neighborhood-level challenges, town-level stormwater regulation)	Rainwater harvesting, rain gardens, permeable pavers, infiltration trenches, and tree box filters	Cross-scale	Vermont	Residents	Statewide survey	[79]
	Depreciation of community involvement (expertise, education)	GSI in general	Region	Houston, TX	Researchers, community	Participatory action research	[99]

	Lack of awareness and responsibility for maintenance, education programs not aligned with local preferences	Stormwater ponds	Community	Southwest Florida	Homeowners, governmental entities	Survey, interviews	[100]
	Lack of awareness, ineffective regulation enforcement	Stormwater ponds	Region	Manatee County, FL	Landscape professionals, residents, government agents	Interviews, surveys, participant observation, and literature review	[101]
Governance & public engagement	Lack of awareness, understanding, and sense of responsibility; geographic disconnection between watersheds and governing entities; fragmentation of responsibility among stakeholder groups	GSI in general	Region	Cleveland, OH, and Milwaukee, WI	Practitioners (regional sewer districts, local governments, community development organizations)	Interviews	[28]
	Lack of awareness and adaptivity in policies to prioritize GSI measures to align with local values	Bioswales, green roofs, street trees, parks & natural areas, community gardens, and permeable playgrounds	Region	New York, NY	Residents and practitioners (individuals professionally engaged in the siting, design, maintenance, public engagement, and/or monitoring of GSI programs)	Preference assessment survey and semi-structured interviews	[46]
	Outdated regulatory constructs, conflicted views among gray and green advocates, jurisdictional overlap, influences of social media coverage, leadership gaps or influence of lobbying	GSI in general	\	USA	Residents, governmental entities, engineers	Narrative analysis	[102]

The unclear distribution of responsibilities among stakeholders can impede the decision-making processes associated with GSI implementation. Particularly, the general public's involvement is the fundamental building block that could be influential in shaping the direction of GSI implementation [17][28][47]. Dhakal and Chevalier [83] stated in their study that, above all challenges, cognitive barriers and socio-institutional factors should be the primary issue to focus on. Furthermore, the multi-sector benefits will only be nuanced if the public is not willing to implement GSI [103]. Similarly, one study stated that sustainable GSI implementation would necessitate the need for structured public participation and local partnerships. They emphasized that, in addition to putting more reach effort onto comprehensive cost-benefit evaluations on GSI, such needed engagement would fortress the networks of non-governmental organizations, county and state agencies, municipal sewer districts, and federal research support, which could lead to a faster adaptation of GSI on larger scales [104]. Therefore, the barriers to the general public to accept GSI are crucial to dissect these aforementioned disconnections and provide practical yet effective decision support. To date, there is a limited number of conceptual frameworks that capture social factors in GSI implementation processes (Table 2). Yet there still is a need for quantitative analysis measures for better decision support for case-based GSI adoption using standardized methods that could assist in horizontal comparison and further knowledge transfer. The frameworks listed in Table 2 were categorized based on their main purpose: Classification scheme (proposed to enhance terminology clarity), planning strategy (suggesting new approaches to be adopted in current management regimes), process conceptualization (promoting a better understanding of complex socio-infrastructure systems), and framework efficacy assessment (evaluating the existing frameworks' usefulness in promoting GSI implementation).

Table 2. Conceptual frameworks that consider social factors in GSI implementation processes.

Framework Nature	Social Factors	Sub-Categories	Stakeholders	Method	Scale	Source
Classification Scheme	Governance, stakeholder engagement	Stakeholder interactions, governance, political contexts	Individuals and groups involved in rule-making processes, property owners	Social-ecological services framework	Cross-scale	[54]
	Public engagement, governance	Policy instrument assessment	Citizens	Policy instrumentations scheme	Region	[56]
	Public engagement, governance	Ownership status, political power	Governmental entities	Topology framework	Region	[64]

	Governance, demographic constraints	Equitable GSI distribution, age, income, education, ownership status	Governmental entities, residents	Green infrastructure equity index	Region	[60]
	Public engagement, governance	Multifunctional strategy, multisectoral communication	All involved in decision-making processes	Millennium ecosystem assessment classification-based framework	Cross-scale	[105]
Planning Strategy	Governance, public engagement, demographic restraints	Adaptive governance, stakeholder participation, inclusion	Governance, nongovernmental organizations, communities, academia, industry	Adaptive socio-hydrology framework	Cross-scale	[106]
	Public engagement	Interdisciplinary collaboration, university-stakeholder partnership, institutional capacity	Universities	Integrated framework combining social-ecological dynamics, knowledge to action processes, organizational innovation	Region	[63]

	Public engagement	Community participation in three themes (context, participation processes and outputs, and implementation results)	City, federal government agencies, community residents, and community NGOs	Public participation conceptual model	Watershed	[61]
	Public engagement, governance	Low stakeholder buy-in, discoordination in management objectives and goal among stakeholders, lack of awareness	Government researchers, stormwater managers, and community organizers	Adaptive management framework	Site	[62]
Process Conceptualization	Governance, public engagement, demographic restraints	Stakeholder interactions, governance and political contexts	All that are involved in stormwater management	Integrated structure-actor-water framework	Cross-scale	[55]
	Public engagement, governance	Hybrid governance envisioning (management and monetary responsibilities)	Regulatory agencies, residents	Multi-criteria governance framework	Cross-scale	[17]
	Public engagement, governance	Perceptions, stewardship, human-environment interactions	Residents	Coupled human and natural systems framework	Region	[58]
Existing Framework Efficacy Assessment	Governance	Governance, capacity, urbanization rate, burden of disease, education rate, political instability	Government agencies, NGOs	City Blueprint® Approach	Region	[53]
	Public engagement, governance	Community education and awareness campaign, multifunctional strategy	Residents, governmental entities	Socio-ecological framework	Watershed	[107]

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