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Stormwater Green Infrastructure Resilience Assessment: A Social-Ecological Framework for Urban Stormwater Management

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Abstract: Urban areas are increasingly vulnerable to the effects of climate change. Stormwater Green infrastructure (SWGI) is seen as an approach to increase the climate resilience of urban areas, because they can buffer precipitation changes brought on by climate change. However, SWGI features themselves need to be resilient to climate change to be able to contribute to the resilience of cities. Thus, we aimed to develop a SWGI resilience assessment framework that could be used to identify challenges and to inform decisionmakers' efforts to enhance resilience. We developed a resilience assessment framework based upon a resilience matrix approach to recognize effective resilience categories for SWGI by reviewing the literature on critical functionality and barriers to implementation and operation. These categories for SWGI included policy, design, maintenance, economic factors and social factors that influence SWGI functionality. We then identified specific aspects under each category that could be used for assessing SWGI resilience, recognizing that SWGI has critical functionalities and factors controlling its viability. Unlike other SWGI assessment frameworks that are focused on ecosystem services as a final outcome, we worked from a socio-ecological perspective in order to include socio-economic and policy factors and design and planning aspects that affect service provision. Developing a resilience assessment framework is critical for management because it can reveal the specific challenges facing SWGI resilience that have traditionally been overlooked, such as maintenance and social factors. This specific framework can also lead to efficient planning and management by identifying interrelations and hierarchical relationships of categories that influence resilience. Application of this framework will rely upon expert input to connect broad dimensions with specific indicators for SWGI to local priorities in resilience planning.

Keywords: stormwater green infrastructure; climate resilience; ecosystem services; challenges; assessment framework; socio-ecological

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1. Introduction

Climate change poses risks to urban infrastructure, quality of life and entire municipal systems [1]. With the projected increases in temperature and shifts in rainfall intensity due to climate change, there will be an increase in threats from storm events related to flooding and combined sewer overflows (CSO) and heat waves stemming from extreme heat and droughts [2–6]. The response to climate change stressors is often framed as a resilience challenge, i.e., the ability to "prepare and plan for, absorb, recover from and more successfully adapt to adverse events" [7]. These challenges will be exacerbated in cities, so building urban resilience through management and development is a necessity [4]. As a result, adaptation approaches are needed to minimize risks and to sustain well-being in urban areas in anticipation of a changing climate [8].

Water resource sustainability is connected to the concept of urban climate resilience because of the need to moderate the effect of extreme precipitation on stormwater runoff and combined sewer overflows, as well as drought impacts on water availability [9,10].

Stormwater Green Infrastructure (SWGI) development is one of the approaches suggested to improve the resilience of cities [11–13]. SWGI is a network of natural and semi-natural green spaces designed to infiltrate and treat surface runoff, but may mitigate or help adapt to the effects of climate change [14]. SWGI planning is broadly accepted in policies for stormwater management as an approach for resilient spatial planning and environmental sustainability goals [11,15,16]. While SWGI is being expanded in cities as a network to convey [17], we argue that SWGI itself also needs to be resilient to be able to contribute more broadly to this resilience [18].

Assessment approaches are needed to identify the ways in which to enhance SWGI resilience, especially for confronting climate change [19,20]. One assessment approach that reflects broad and general considerations of resilience is the "resilience matrix" [21,22] which identifies four broad categories that influence resilience, including both physical and non-physical domains: physical, information, cognitive and social factors. The matrix approach involves evaluating each of these domains with respect to resilience dimensions [23], as aligned with the National Academy of Science's definition of resilience as the ability to: "1. absorb, 2. recover from and 3. adapt to adverse events" [23]. We focus on aspects of the resilience matrix that can be influenced and changed by managers and focus only on the absorb, recover and adapt phases [23]. To implement the resilience matrix, general domains and categories for assessing resilience are specified for the unique setting or case [24]. This expansion of the resilience matrix for studies of community disaster resilience and coastal flood events has defined specific categories for infrastructure, engineering, environmental, hydrological, social, economic and institutional domains [25–27].

Selecting the categories for resilience assessment tools should be done in a way to address the specific system and the resilience challenges and threats that system might face. Recent studies of SWGI have identified and characterized these challenges, but they have not yet been integrated into resilience assessment approaches. For example, challenges for SWGI relate to its structure, design and function but also relate to its adoption and implementation [28]. There are challenges that are critical for the function of SWGI, such as socio-economic and financial barriers, that influence on-going maintenance of SWGI [29–31] and technological, institutional and perceptual challenges [30,32,33] Although social factors, especially social justice and equity, tend to be neglected factors in SWGI planning, they have a critical role in urban resilience [34–36]. Often, the importance of maintenance in addressing the resilience is overlooked, or only the financial aspects of maintenance are taken into consideration as a barrier [31,37,38], but other facets such as biophysical aspects and a maintenance plan, or mutual knowledge and communication between the maintenance sector and other stakeholders, can be overlooked. Expanding the resilience matrix approach for SWGI would require specific inclusion of the factors and challenges that influence its continued functionality.

Our goal here is to develop a climate resilience assessment framework for SWGI. The specific focus is on expanding the resilience matrix [24] by identifying (1) specific categories that are essential for the resilience of SWGI and (2) specific aspects to with which assess this resilience. Ultimately, these spaces can be developed into specific and measurable indicators that will enable the rating and ranking of SWGI through an assessment framework in order to improve and plan for local resilience. We develop categories and aspects by reviewing literature related to the constraints on function and the challenges of implementing SWGI. We will begin by defining the system boundary and critical functions that need to be maintained over time, followed by specific categories and aspects for resilience assessment. Finally, we will offer a resilience assessment framework specific to SWGI that can be used to evaluate the resilience of SWGI in urban areas.

2. Method and Approach

2.1. Resilience Matrix Framework Approach

Our goal was to identify a model method for developing a resilience assessment approach or tool. We searched Google Scholar for the term "resilience assessment tool" in

May 2020 and yielded 218 matches. We screened the title and abstracts of these documents to see if they focus on describing or developing tools and approaches for assessing resilience. We found assessment tools developed for assessing resilience in different settings and scopes, such as community resilience, urban resilience, building and infrastructure resilience and disaster resilience [39,40]. We found that 23 of those documents referred to a "resilience matrix" [24] and we identified six highly cited (100 or more citation) documents that applied the matrix. The resilience matrix [24] was selected as a model for our resilience assessment because it considered social-ecological (i.e., not just design or technical) aspects of resilience and considered multiple meanings of the word resilience. Thus, we conducted another search using the term "resilience matrix" and yielded 507 matches. Among those matches, we extracted the most highly cited documents (over 100) and found 12 documents. Half of these documents and almost all of them that were developed after 2013 were based on or refer to the general framework developed by Linkov, Eisenberg, Bates et al. (2013). This framework has been successfully applied in different systems but not yet to GI [24]. Thus, we started to build from the resilience matrix in the context of SWGI, using these documents as a guide.

For the SWGI system, we identified categories that influence the resilience of SWGI (see below) and included the dimensions of resilience that are related to resilience management (absorb, recover, adapt), as we focus on aspects that can be influenced and changed by managers and only on these three dimensions, which can influence and address resilience through management and decision-making related to SWGI. Therefore, we modified the resilience matrix to a 5×3 matrix. To develop this framework for application to SWGI we: (1) describe the system boundary and explain exactly what we mean by SWGI (as there are different definitions in the literature), (2) identify the critical functions of SWGI that need to be maintained to ensure functionality and health, (3) identify categories and detailed aspects that are needed to assess the critical functionality and (4) identify the resilience dimension for each aspect [21].

2.2. Literature Review on SWGI and Resilience

The first step in applying the resilience matrix framework is to identify the categories that affect resilience that are specific to SWGI. We searched the literature on SWGI that included categories from a broad social–ecological perspective (rather than just a technical or design perspective). To find this literature, we searched Google Scholar in 2018 (updated in 2020) using keywords such as "stormwater green infrastructure", "challenges" and "urban resilience" in order to identify challenges and barriers that affect the functionality and resilience of SWGI. We selected key papers and documents that reviewed, categorized and listed SWGI challenges and barriers. These included key highly-cited reviews and conceptual papers that connect SWGI to barriers and resilience concepts: Ahern (2011); Dhakal and Chevalier (2017); Gashu and Gebre-Egziabher (2019); Kronenberg (2014); Matthews et al. (2015); Staddon et al. (2017); Thorne et al. (2018); Tian (2011); Zuniga-Teran et al. (2020). We used these papers to identify the broad categories in our resilience matrix for SWGI. The most common categories mentioned in the texts were from technical and design perspectives. In these papers, we also looked into factors that are usually neglected but are essential for the SWGI not to fail (such as maintenance and social factors). These factors were sometimes implicit but were noted as factors needed for the SWGI to continue functioning under conditions of stress or disturbance. We linked observed categories and factors by theme, combining and summarizing for consistency. For example, "economic factors" were sometimes referred to as financability, the cost of design, or the cost of maintenance. "Policy factors" were also described as regulations, political will, leadership, etc. Ultimately, the five categories in our resilience matrix for SWGI, are: policy, design, maintenance, economic factors and social factors. These categories also align with those highlighted by publications that focus on the link between green infrastructure and environmental benefits as experienced or analyzed in the context of the COVID-19 pandemic [41–43].

With these general categories for SWGI, we identified detailed aspects for the framework. We started with papers that were used to identify the general categories, but expanded the SWGI literature for this step by searching Google Scholar for each of the broad categories (policy, design, maintenance, economic factors and social factors) crossed with keywords, such as "green infrastructure" "resilience" "function". This search allowed us to find papers in order to identify any aspects related to the general categories, as well as aspects that are critical for either resilience or ecosystem functionality of SWGI. The list of the scope of the papers and aspects are included in Table 1.

Table 1. Category aspects for policy, design, maintenance, economic factors and social factors.

Category	Aspect	Description	References
Policy	The existence of application-oriented frameworks and periodic audit	Policy to develop an applicable framework and evaluation system to check for system resilience and monitoring	[44–47]
	Consider multi-functionality in policy	Considering SWGI delivering multiple social ecological benefits not solely for harmonizing cost and environmental conservation	[48–52]
	Policy to provide incentives and awareness	Providing incentives by local government to homeowners and provide a platform to promote ecological learning among sectors, public and resource users and group of interest	[9,46]
	Incorporate scientific knowledge in management	Knowledge transfer and integration into policy over time such as updating and identifying new risks into SWGI	[35,53–55]
	Connection and collaboration among sectors	Providing platforms for multi-stakeholders to collaborate, learn and create knowledge to cope with change and disturbances and find best management practices	[46,55–57]
	Policy for financial constraints	Policy for properly allocate resources to phases related to GI such as design, implementation and maintenance.	[54,56]
	Update regulations regularly	Updating SWGI regulations to overcome the risks of unsuitable design and maintenance- updating existing national standards and regulations to incorporate the SWGI concept	[35,58]
	Integral local and federal rules and regulations	Check for lacking, conflicting, or restrictive local and federal rules	[59,60]
Design	Location	Design with considering needs of a location-Spatial planning for identifying priority areas for the demand of an area or required services	[61–67]
	Climate	Design with considering the climate of a region, climate change and projections of extreme events	[38,68,69]
	Capacity for runoff capturing	Design the capacity of SWGI to capture extensive runoff-considering larger storm event such as a hundred or two-hundred years	[60,70,71]
	Resilient biophysical components	Design for resilient plant pallet and soil media design for extrafiltration during extreme storm event	[72–75]

Table 1. *Cont.*

Category	Aspect	Description	References
Design	Multi-functionality	Design and manage as multifunctional resource-the main feature of SWGI in delivering multiple ecological, social and economic benefits to confront multiple challenges	[34,47,76–78]
	Biodiversity	Design with considering diversity of species within functional groups that have different responses to disturbance and stress	[34,47,79–81]
	Redundancy	Design with similar species that provide the same, similar, or backup functions so if one specie is removed there should be enough density of remaining species to complete the desired function	[34,79,82,83]
	Stakeholder collaboration	Design based on the scientific knowledge and collaboration of scientists, planners and designers to incorporate ecological knowledge to adaptive design	[34,84–86]
Maintenance	Check for plant health and coverage	Vegetation maintenance including checking for the healthy plants and prevent invasive species and establishment of monoculture	[87,88]
	Cleaning debris and drainage area	Check for basin/inlet/and outlet through routine inspection to prevent clogging	[87]
	Sediment loading	Pretreatment or continuing maintenance for sediment accumulations and clogging especially in urban areas	[88–92]
	Mosquito production	Check for stagnant, shallow water resulting from improper drainage in SWGI to prevent mosquito production and potential health risks that concern the residents	[87,93,94]
	Soil compaction	Check for soil compaction around SWGI during heavy machinery to prevent storage and infiltration reduction and decrease in groundwater recharge	[87,95,96]
	Pollution build-up	Check for the possibility of accumulating pollutants under infiltration basins and groundwater contamination	[97]
	Knowledge and skill	Identifying appropriate maintenance level, frequency and skill needed for each maintenance activity as well as checking for maintenance staff knowledge for each activity	[87,98,99]
	Cost of ongoing maintenance	Appropriate functionality of SWGI overtime is dependent on adequate funding for maintenance cost within a designed lifecycle	[60,77,100–103]
Economic	Targeted planning to finance SWGI activity	Having key priorities on the activities that need financial support and ensure the success and continuity of SWGI	[77]
	Using available tool for best investment	Tools that analyze the whole lifecycle costs for making decisions about choosing the best investment among existing partners or select the best practice for targeted stakeholders.	[100,104–107]

Table 1. *Cont.*

Category	Aspect	Description	References
Economic	Life cycle cost	Consider the whole life cycle include a satisfactory level of construction, administration and monitoring considering the frequency and monitoring of SWGI	[77,101]
	Incentives for SWGI implementation	Direct incentives to homeowners to implement or maintain SWGI in their property through direct incentives inspires contribution	[9,50]
	Plan for multiple use and stakeholder collaboration	Managing cost through planning for multiple uses (multifunctionality) of SWGI with parallel stakeholders	[101,108,109]
Social	Public knowledge and outreach	Community engagement and increase level of knowledge through various techniques such as workshops	[56,110–115]
	Equity	Check for the vulnerability and proportional access to SWGI in confronting great storm events in high-income versus low-income communities	[35,50,116–119]
	Active citizenship	Engagement of a community that does not start from government and is also referred to as a bottom up governance	[5,120–123]

3. Framework Description

3.1. System Boundary Description for Stormwater Green Infrastructure

Identifying the system scope or boundary is the first step in evaluating a system's resilience. This concept has been referred to as "resilience to what", or the initial boundaries of the system [66,124]. Green infrastructure has a broad range of definitions [125], from trees in urban areas to engineered structures that support ecological processes (i.e., green roofs and rain gardens). Here, our system boundary is any type of green infrastructure that is used for stormwater management. SWGI can be thought of as an economical tool for managing rain events and delivers numerous public benefits [87]. These benefits can be multifunctional compared to gray stormwater infrastructure (pipe drainage, etc.) which only provides the single benefit of moving stormwater away from built urban environments [87]. To specify our system boundary for SWGI, here we focus on the engineered green infrastructure used for stormwater management and exclude non-engineered green spaces (such as parks or urban forests). While non-engineered green spaces may also be able to mitigate stormwater flows, they are not the focus of this study, because it is difficult to control their function by managing the design process. We also exclude engineered structures without biological components, such as rain barrels and pervious pavements (Figure 1).

3.2. Critical Functions of Stormwater Green Infrastructure

An aspect of resilience is the ability to tolerate disturbance and still retain basic functions and structures [126]. Thus, resilience assessment should identify critical functions that must be maintained during a stress or disturbance event, or identify other non-critical functions that provide benefits which may contribute to resilience after a stress or disturbance event [21]. Here, we identify critical functions for resilience assessment as the primary ecosystem services SWGI provides for stormwater management and we recognize that SWGI can also provide secondary ecosystem services (Table 2). We identify flood protection and water purification as the primary ecosystem services of SWGI related to stormwater management (Table 2). Measurable (either through quantitative or qualitative means) ecosystem services are essential to explicitly assess the multiple functions of SWGI in resilience assessment [84].

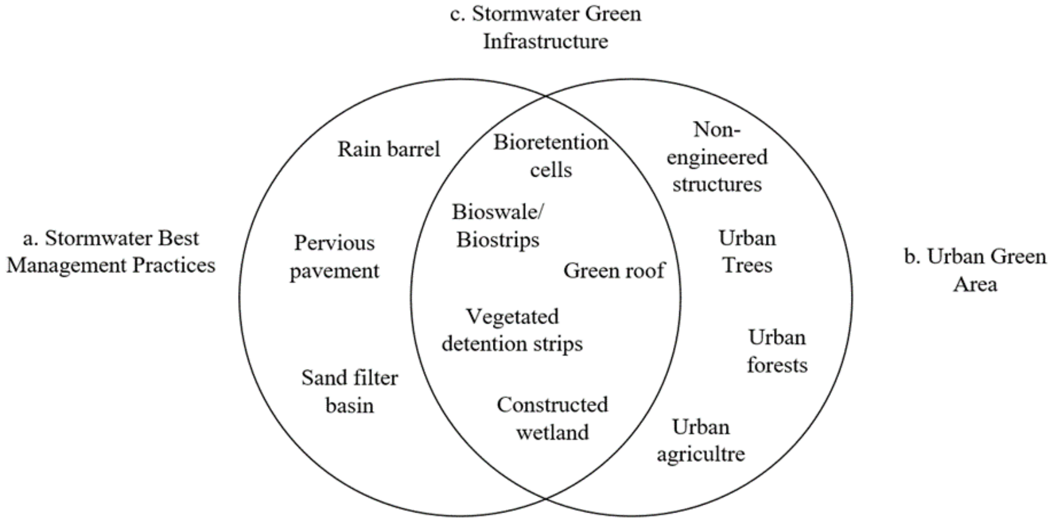

Figure 1. Defining stormwater green infrastructure practices. (**a**) Stormwater Best Management Practices are engineered practices, including both green and non-green components. (**b**) Urban Green Area includes both engineered and non-engineered practices that have green components. (**c**) Stormwater green infrastructure is at the intersection of these and includes engineered practices with green components.

Table 2. Stormwater green infrastructure ecosystem services [56,79,127,128].

Ecosystem Services	Details	Primary ES	Secondary ES
Regulating services	Local climate regulation-urban heat island mitigation		√
	Global climate regulation		√
	Flood protection	√	
	Groundwater recharge		√
	Air quality regulation		√
	Erosion regulation		√
	Nutrient regulation		√
	Water purification	√	
	Pollination		√
	Disease regulation		√
Provisioning services	Energy usage reduction		√
	Fresh water		√
Cultural Services	Recreation and Aesthetic value		√
	Environment for social communication		√
	Intrinsic value of biodiversity		√
	Spiritual		√
	Educational		√
	Human wellbeing		√
	Supports economic activities such as tourism		√
	Access to quiet		√
Supporting services	Nutrient cycling		√
	Carbon sequestration		√
	Primary production		√
	Soil conservation		√

ES: Ecosystem services, √ shows if the ES belongs to primary or secondary services.

We followed the descriptions of Mays (2009) on the functions of SWGI and the processes of various SWGIs to capture stormwater and related these functions to critical functionality in the context of resilience. Types of SWGI (Table 3) include infiltration practices, vegetated open channel practices, filtering practices, detention ponds, retention ponds, wetlands, and sloped vegetated areas [68]. We assume that the primary ecosystem services (Table 2) are the same as the basic functions that are defined in SWGI literature (Table 3), yet these basic functions may be more specific than the ecosystem services. Although the basic functions of all SWGI can be summarized as flood protection and water purification, each SWGI is designed to function through different processes. For instance, infiltration practices capture the runoff through infiltration and vegetated open channels capture the runoff by transporting water (Table 3). Some SWGI is designed with a focus on water purification such as wetlands, while other SWGI is designed for flood control as their primary function and with water purification as the secondary function (Table 2).

Table 3. Stormwater green infrastructure types, definitions and processes (adapted from [68]).

Category	Definition	Processes	Subcategory
Infiltration practices	A vegetated, open impoundment where incoming stormwater runoff is stored until it gradually infiltrates into the soil strata.	- Flood protection through infiltration - Pollution reduction, increase stream quality	Infiltration basins Infiltration beds Infiltration trenches Bioinfiltration swale
Vegetated open channel practices	Open channel with vegetation that conveys stormwater runoff and provides treatment as the water is conveyed.	- Flood protection through transporting water - Stormwater quality treatment	Grass channel Vegetated channel Wetland channel Vegetated swale
Filtering Practices	An engineered soil matrix with mulch and vegetation on top and perhaps an underdrain to prevent overflowing	- Runoff conveyance - Filtration of sediments by grass or vegetation - Infiltration to the soil - Biological and chemical treatment	Bioretention area Biofiltration swale Overland flow filtration
Detention Ponds	low lying area that is designed to temporarily hold a set amount of water while slowly draining to another location.	- flood protection - Slowly infiltrate - Prevent flash flood	
Retention Ponds	Retention pond is designed to hold a permanent pool of water that fluctuates in response to precipitation and runoff.	- Maintain a certain water capacity - Deposit sediments and improve water quality	Micropool extended detention pond Wet ponds Wet extended detention ponds Multiple pond systems
Wetlands	an artificial wetland to treat stormwater runoff. Constructed wetlands are engineered systems that use natural functions vegetation, soil and organisms to treat wastewater.	- Main function water treatment - flood protection	
Sloped vegetated area	evenly sloped vegetated areas that treat sheet or overland flow from adjacent surfaces	- Slow runoff velocity - Filter out sediments and pollution - Some infiltration into underlying soil	Filter strips Vegetated filter strips
Green roof	A green roof, or rooftop garden, is a vegetative layer grown on a rooftop.	- Enhance stormwater management - Enhance water quality	

3.3. Selecting Categories for Stormwater Green Infrastructure Resilience Assessment

To manage and maintain the critical functions of SWGI, the factors that affect functionality and resilience need to be identified. Our review of SWGI challenges described barriers to functionality and resilience [30,33–36,38,103,129–131]. We identified SWGI challenges that relate to its functionality, adoption and implementation in order to identify the five categories that can affect GI resilience (Figure 2). Planning, design and institutional barriers are commonly emphasized in the literature and categorizations of SWGI challenges, especially with regards to provision of design standards and policy [28,30,32,33,103]. There are barriers related to socio-economic and investment provision for implementation and on-going costs of SWGI, such as maintenance [30,31]. Maintenance is one of the important factors for viability and functionality over the SWGI lifespan when receiving sustainable ecosystem services, yet it is usually neglected, or an afterthought, and has not been considered in the design process [29,31]. Although maintenance is not often considered as a separate category, we decided to include maintenance as such to emphasize its importance in the resilience of SWGI and the sustainability of ecosystem services. One of the critical factors, not only for on-going maintenance but also for supporting public and private applications of GI in resilience planning and implementation and monitoring of SWGI, is adequate funding and economic factors [38,132]. Thus, we considered economic factors as one of the main categories. Another important but neglected factor for SWGI resilience is the consideration of social factors, especially social justice, equity and awareness [32,34,35,133]. Social justice is one of the most likely factors to be ignored, leading to a lack of engagement and consideration of the diverse voices, needs and social opinions when resilience planning [35,131]. Cross-sectoral, multi-scale stakeholder engagement with those who impact or are being affected by these barriers in the process of decision-making would help to inform resilience planning and implementation by identifying how to tackle the causes and consequences of a specific change [134].

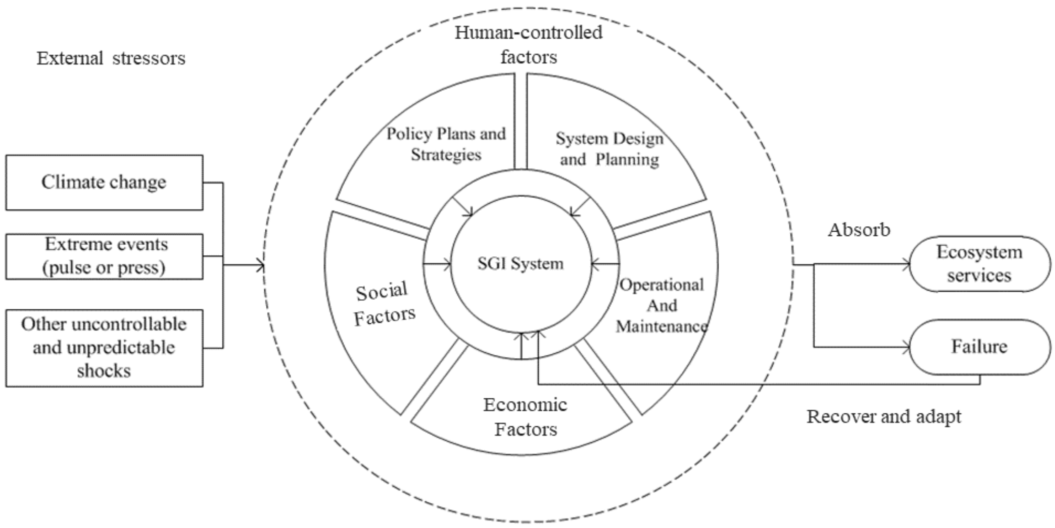

Figure 2. SWGI system. External stressors and human-controlled factors affect the resilience of SWGI. Five main factors that influence SWGI resilience are discussed in the paper (policy, design, maintenance, economic factors and social factors) and aspects within each are presented in Table 1. Resilience here has three different aspects: (i) resistance to the stressors lead the system to continue its basic functions and deliver ecosystem services as the system absorbs the stress. The system may also (ii) recover and (iii) adapt, in order to return to the stage to deliver the desired ecosystem services.

There are barriers to SWGI, or categories that effect its implementation and development, mentioned in the literature that we did not explicitly include. For example, the category of "innovation" mentioned in the literature [28,36] that necessitates the collaboration of scientists, engineers, planners and practitioners to co-create novel designs. We did not include innovation as a separate category, but emphasize its importance under each of the related categories. For example, multi-stakeholder collaboration is important for design, but can be related to other categories that influence implementation, such as policy. There are other categorizations and barrier types that seem to overlap with each other, such as capacity, and structural, contextual and technical barriers that are implicitly considered under the current categories in our framework [130].

From this literature review we identified five general categories of challenge that link to resilience: (1) policy, (2) design, (3) maintenance, (4) economic factors and (5) social factors. Although external drivers (i.e., climate patterns) and uncontrolled factors (i.e., invasive species) might affect the viability of SWGI, our focus here is on factors that can be addressed directly through the management and decision-making of SWGI itself. Below, we describe each of the main categories that influence resilience and describe aspects within each of these main categories that can be used to assess the resilience of SWGI (Figure 2). Specific aspects within each main category that we developed from our literature review are described in Table 1.

3.3.1. Policy

Policy links the goal of systems to actions and allocation of resources [22]. Policy and institutional rules outline how different activities are carried out, along with mechanisms for mitigation plans to ensure that overall plans are implemented. Policy can enhance resilience by establishing the connection between various elements of a system. For example, if local governments plan for community engagement and consider community actions, society could effectively cooperate in managing risks or actively engaging with climate adaptation plans by implementing SWGI [135]. Policy is also important for adaptive management because policies reveal procedures that build or sustain resilience by learning from the consequences of adverse events [46]. Policies to create action platforms and flexible multi-level governance provide an opportunity to create knowledge and cope with stressors. Providing incentives that encourage learning and transfer ecological knowledge into institutional structures can encourage adaptive management [46]. Adaptive management strategies can operate across several scales, including, federal, state and local levels. For example, stormwater management is a part of the Federal Water Pollution Control Act and Clean Water Act (CWA) that also obliges states to implement SWGI for non-point source pollution [136], but the implementation of GI to manage stormwater and meet CWA requirements occurs at the municipal level. These policies and strategies at federal and local levels should be aligned with each other to promote resilience in cities.

Policy aspects focus on local-scale policies that control SWGI in a municipality. First are aspects that show how organizations work together. Policy should provide a path for smooth relationships and collaboration among stakeholders [57]. Collaboration and connection provide the ability to learn from each other and create knowledge that could result in diverse management options to handle disturbances [46]. Collaboration can also be between science and policy, as a common policy challenge is the lack of knowledge transfer from scientists to city planners [54]. Science-policy integration is also needed to identify new risks for systems, an important challenge as climate change impacts unfold in the future [53]. Policies to break down barriers between silos of SWGI knowledge and practice may help find more effective and efficient solutions to urban environmental challenges [65,137].

The second type of aspect checks for the existence of application-oriented frameworks that actively check for system resilience [47]. Policy can also stimulate and enforce existing monitoring systems [46]. Improper design, inadequate performance data and insufficient maintenance can all be caused by lack of standards and evaluation frameworks, which can lead to resilience challenges [36,44,45,111].

The third type of policy aspect provides financial incentives or promotes awareness in order to increase the capacity of a social-ecological system to cope with shocks and surprises [46]. Providing incentives from local government promotes the implementation of SWGI. For example, cities or local counties can pay homeowners to provide downspout disconnection (such as what was achieved in Portland), waiving stormwater-fees or increasing site permeability (i.e., the case of Washington D.C.) [9]. Policy can also provide a platform to promote ecological learning and knowledge building in institutional structures among different sectors and for the public and resource users. For example, government could encourage ecosystem friendly approaches to design, such as promoting ecohydrological fluxes, or avoiding monoculture in plant design. Policy can also promote participatory approaches to planning, where scenarios are developed that respond to resilience challenges [46].

3.3.2. Design

Enhancing resilience capacity through landscape and urban planning necessitates that designers are aware of the disturbances that cities are likely to confront. This knowledge should reflect the frequency and intensity of disturbances and the processes of SWGI that can respond to these events while remaining functional [138]. Spatial planning to find priority areas and identify required ecosystem services will support management of disturbances. Resilience planning requires the consideration of the ecology of landscapes (i.e., to mitigate floods or urban heat islands) that extend beyond the political boundaries of an urban area [56]. To have a strategic system design, interdisciplinary knowledge is needed to define strategic goals that are consistent with policy, economy and community factors. Design that is based on scientific knowledge can provide ecosystem services, as long as the fulfilling and respecting of social values are part of the goals of building SWGI [84,86]. The collaboration of scientists, planners and designers is necessary to combine ecological goals into practice [85]. This collaboration and integration with ecological knowledge could help implement adaptive design; however, there are challenges to the design process. Deficiency of data on the quantification of ecosystem services, the cost of SWGI construction and performance and lack of technical familiarity and skills are among the barriers facing SWGI planning and adaptive design. Lack of design standards that simplify the design, planning and implementation of SWGI is seen as a factor that may lead to failure [59].

To enhance SWGI resilience through design factors, assessment of two main types of aspects is needed: (1) site-specific needs and (2) services and functions people want from SWGI. For site-specific needs, planners need to consider the broad climate of specific regions. For instance, some forms of SWGI are not recommended or preferred in arid and semi-arid areas such, as retention ponds and wetlands, but such practices such are recommended [68]. Other specific design components emphasized in the literature for resilient design are multi-functionality, (bio- and social) diversity, redundancy and modularization, adaptive planning and design, and multi-scale network and connectivity [34,128] (Table 1). A second set of aspects relate to the services people need or want from SWGI. These services either relate to critical functions, such as primary ecosystem services, or other benefits that are categorized in secondary ecosystem services (Table 2). One of the main primary services and critical function of SWGI is the capability to capture runoff. Thus, it is essential to consider the capacity for runoff capture to handle increasingly frequent large events in the design process [139]. Considering larger storm events than is currently common in design, such as 100 or 200-year events, can help cope with the larger storm events expected with climate change [60]. For climate resilience design, it is critical to incorporate anticipated climate change in designing SWGI and to consider both precipitation quantity and intensity in future, as current design standards are based on the storm events from the past [140].

3.3.3. Maintenance

Even with adequate planning and design of SWGI, assurance of critical functions cannot be possible without proper maintenance. Maintenance is often an afterthought and there is a lack of technical recommendations for SWGI maintenance [29]. Re-framing maintenance priorities in current planning and policy is a necessity to maintain functionality and even to help SWGI gain social acceptance [38]. Some states and municipalities do have a legal requirement for inspection. For instance, the owners of SWGI in St. Louis, Missouri, need to annually report that the legal requirements of maintenance are met (i.e., litter collection, sediment removal, monitoring water retention, MSD, 2018). The responsibility for maintenance of public property belongs to the county or city, but for private property owners local authorities either provide incentives for maintenance or other alternative financing approaches, such as public–private partnerships, infrastructure improvement districts and dedicated clean water funds [141,142] Some municipalities provide guidelines and manuals for various types of SWGI and indicate potential areas and aspects of SWGI that need attention. Despite these efforts, maintenance is often insufficient or variable due to the barriers against provision of adequate and stable funding for operations and maintenance of SWGI [29,142].

The presence of an actual maintenance plan or guideline. and that those plans address key biophysical features of SWGI, are the primary aspects of resilience. These plans structure the evaluation of whether the current status of SWGI matches its design, and if it continues to function. This set of aspects typically consists of a maintenance checklist, including checking for plant health, cleaning debris and drainage areas, checking for sediment loading, mosquito production, soil compaction and pollution build-up. A second type of maintenance aspect relates to knowledge and communication of maintenance crews and their communication of issues in feeding back to the design stages. Specific details here include identifying what level of skills is needed for any type of maintenance, selecting a well-informed maintenance crew for each activity and planning for knowledge updates [87,98,99]. The third type of maintenance concerns relate to financial aspects. Financial support for ongoing maintenance can assure the appropriate functionality of SWGI over time, but this importance is often not reflected in municipal budgets [77]. Maintenance costs of SWGI are still an active area of study and decisions about who might be the party responsible for maintenance are still ongoing [60,102,103]. However, there are tools for estimating these costs [100,101] (that may facilitate decision making regarding maintenance. New cost-effectiveness modeling approaches that link watershed-scale performance with maintenance cost assessments hold promise for evaluating the role of SWGI in climate adaptation [143].

3.3.4. Economic Factors

The economic dimension of SWGI resilience is similar to policy in that it intersects and supports other categories, such as design, maintenance and social factors. Funding allocation and prioritizations are needed to reliably support the cost and benefits of SWGI through design, implementation and maintenance [28]. The costs associated with SWGI include both one-off and ongoing costs. One-off costs are the capital costs needed for planning, designing and implementing SWGI. Ongoing costs refer to protection, management and monitoring of SWGI on a regular basis over time [77]. Failure due to financial barriers can cause obstacles to critical functions, both in the construction and maintenance of SWGI. In addition, a lack of integration of programs and resources and lack of coordination between different sectors can lead to financial constraints and multiple budget lines for similar activities [59]. Economic factors include not only a lack of budget lines or adequate funding levels, but also a lack of resources and data to support cost-benefit decision making. These data relate to future maintenance needs and the ecosystem service valuations for SWGI. Economic factors are not only important for the design process and maintenance of SWGI but also affect community willingness to implement SWGI [111,144]. It is important to note that valuation approaches for SWGI may under-value benefits, especially when seeking to account for multifunctionality in a holistic manner [145].

Economic aspects for assessing SWGI resilience can be considered in three groups. First are the direct costs needed for the design process and maintenance that may also consider life cycle costs and plans for multiple uses. Targeted planning and clear priorities to ensure the success and continuity of SWGI functionality are required, given the realities of limited municipal budget allocations [77]. Available tools to analyze the economics of SWGI can determine whole lifecycle costs or cost-benefit ratios [104–107]. The second group of aspects show incentives, especially those for implementation and maintenance of SWGI on private properties, as private landowners may see maintenance as a financial burden, and tax incentives could inspire more contributions [9]. The third group of aspects show cost savings due to multi-stakeholder collaboration, providing multiple benefits. For example, planning for multiple ecosystem services that can be set in one location, which meet both primary and secondary functions for SWGI (Tables 1 and 2), such as the infiltration system beneath a building, green roofs on the top of a building and wildlife corridors over or under roads, provide benefits beyond stormwater management [109].

3.3.5. Social Factors

As cities start to incorporate adaptation planning with SWGI, it is important for local governments to focus on social factors to promote community engagement, as well as to promote equity. Lack of knowledge of SWGI and its multifunctional benefits among residents, managers and policymakers can cause difficulties in the continuation of SWGI functionality. Moreover, there is a need to appreciate the potential tradeoffs between co-benefits when looking to SWGI as a climate resilience solution [146]. This lack of information may lead to a lack of appreciation of SWGI features and cause them and their resilience to be ignored in decision making [59]. Moreover, little is known about how residents and urban managers might react to efforts to increase the extent of SWGI [147]. This lack of information may lead to limited engagement by residents [148], which may impact SWGI management on private property. Another important social factor in the context of climate change is social vulnerability and equity, especially as minoritized communities may have a reduced capacity to respond to climate-related impacts while often bearing more of the burden of impacts stemming from racist planning, policy and financial practices [133,149].

Aspects of social factors can be placed into two groups. The first relates to equity, which is one of the basic principles for resilience building [119]. Sociodemographic aspects for measuring and understanding vulnerability include income, age, education, race and housing condition. Climate-related risks are higher for low-income communities, ethnic minorities, the elderly and children [144]. These marginal and vulnerable communities are exposed to greater environmental harms. Furthermore, the distribution of green spaces and ecosystem services is strongly connected to factors such as income, proportion of renters and minority populations [117,118,149]. The second group of social factors relate to public engagement. Engagement can come from governments or from community members (referred to as bottom up governance or active citizenship) [122]. Active community members contribute to ecological, social and institutional resilience [120] through a variety of means [122,123]. Government plans for dissemination and outreach affects the willingness of a community to implement SWGI [111]. Participatory approaches, such as workshops, can help residents to develop a vision of their community [113]. Community engagement can be integrated into planning and design [56,114,115], where it can increase satisfaction with outcomes and build trust in designers and planners [56].

4. Discussion

In this study, we developed a resilience assessment framework for SWGI climate resilience from a general "resilience matrix" [24] and a review of the SWGI literature. Here, we defined system boundaries, identified critical functions and ecosystem services and identified categories and aspects to evaluate SWGI resilience. We identified five categories that support resilient functionality of SWGI that can be related to barriers and challenges of GI identified in the literature: policy, design, maintenance, economic factors and social factors. Developing a resilience assessment framework can be a useful approach in identifying strategies to improve SWGI resilience. This framework should be considered as a preliminary step for further development of a functional assessment tool that could assign scores for measurable indicators. Expert experience could be also helpful for prioritizing indicators and the aspects of resilience that are being managed [21] (Table 1).

The "resilience matrix" [24] suggests general domains and categories for assessing resilience but needs further refinement for specific applications. We identified specific aspects for assessing resilience, recognizing that SWGI has critical functionalities related to ecosystem services and factors. We developed the specifics of this framework so that the indices, as well as its domain and main categories, align with challenges that affect the resilience of SWGI. Other functionalities may require their own categories related to infrastructure, engineering, environmental, hydrological, social, economic and institutional aspects, for specific factors related to coastal flood resilience, community resilience and disaster resilience [25–27].

Several GI assessment frameworks build from the concept of ecosystem services. However, these frameworks do not directly address resilience or the assessment of factors that may cause a lack of functionality in SWGI and, instead, introduce indicators for SWGI ecosystem service delivery. For example, an "ecosystem service toolbox" was proposed as an adaptive design framework to monitor data on ecosystem services performance [84]. This toolbox was developed to address the needs of designers and planners and the lack of standardized indicators that can transfer ecological knowledge to design and promote general sustainability. Other broader landscape frameworks focus on the final delivery of ecosystem services as a way to assess landscape planning through various quantitative, monetary and qualitative approaches [135]. The goal and intended application of an assessment tool will affect its design and components. Our focus was on evaluating SWGI to improve the resilience of ecosystem service provision, so our framework begins with identifying critical functions and broader domains (i.e., policy, design, maintenance, economic factors and social factors) that can affect resilience, rather than focusing only on design aspects or categorizing types of ecosystem services. By integrating domains beyond planning and design aspects of SWGI, our framework reflects the holistic socio-ecological nature of the resilience challenges against which SWGI is being applied in cities.

Building a holistic and informative SWGI resilience assessment tool should consider the interrelationship, interactions and overlaps between indicators. Our framework considers categories as separate features, yet a complex system such as SWGI has dynamic interactions among its components. For example, SWGI maintenance aspects can be related directly to economic factors (maintenance budgets) and also indirectly to policy (maintenance standards and specifications). Although the design process and maintenance are important individually for SWGI resilience, without proper budget allocations and considerations of full lifecycle needs and costs, each individual category might not be sufficient ultimately to meet the holistic resilience goals without considering economics [28,101–103]. Policies are another factor with holistic implications, as policies and funding are closely linked. While there may be potential for disconnections between categories and aspects, there is also the potential for positive feedback. Alignment of policies for SWGI siting with financial practice can address disparities in SWGI practice in minoritized communities [134]. Additionally, social awareness may be a goal of some policies and programs but may also positively affect subsequent policies. As knowledge increases in institutional settings, it can generate new policies and incentives and shift governance structures [35]. The interconnectedness of these aspects reflects the socio-ecological nature of cities and SWGI and draws on principles to enhance resilience, such as managing complex adaptive systems and recognizing the need for polycentric governance [150,151]. Developing indicators that recognize this interconnectedness between aspects is likely to require collaboration and coordination across organizations and departments.

Our resilience assessment framework integrates influences on resilience from a broad socio–ecological domain for SWGI and reflects the current state of the science on the drivers and challenges for SWGI resilience. If this framework is to be developed into a functional tool, involving experts and stakeholders to develop locally relevant metrics for the indicators would be necessary. Local stakeholder input reveals the appropriateness of researcher-defined categories and shows the opportunity for cooperation among responsible parties [21,24]. However, for other systems (such as coastal resilience assessment), researchers refined the resilience matrix into an assessment tool based on empirical data, models and community valuation [152]. Stakeholder and expert involvement can help improve selected indicators and make sense of any assessed data for better implementation. In addition, experts could help to identify metrics for evaluation and the connection of each indicator to different dimensions of resilience responses (absorb, recover and adapt). The learning process coming from expert experience could continuously improve the framework. Application to case studies and collecting evidence-based data also helps to learn from adverse events and the SWGI response to those events through an iterative process, in order to improve the evaluation framework. Moreover, a participatory approach that engages communities in vulnerable locations may also enhance resilience to unforeseen stresses, such as the impact of pandemics on human health [43].

5. Conclusions

We developed a resilience assessment framework for SWGI that builds off a general resilience matrix [24]. Our framework defines critical functionality for SWGI and identify categories that affect the resilience of SWGI. Unlike other SWGI assessment frameworks that focus on ecosystem services as a final outcome, we worked from socio-ecological perspective to include socio-economic and policy factors, along with design and planning aspects that affect service provision. Developing a resilience assessment framework is critical for management because it can reveal the specific challenges for SWGI resilience, such as maintenance and social factors, that have traditionally been overlooked. This specific framework can also lead to efficient planning and management by identifying interrelations and hierarchical relationships of categories that influence resilience. Application of this framework will rely upon expert input to connect broad dimensions and specific indicators regarding SWGI to local priorities in resilience planning.

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