ABSTRACT

Title of Dissertation: **GREEN INFRASTRUCTURE IN INTEGRATED URBAN WATER MANAGEMENT: MODELING AND SOCIAL-ECOLOGICAL SYSTEM APPROACHES**

Leila Mosleh, Doctor of Philosophy, 2020

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Urbanization, climate change, increasing water demand, deteriorating water quality, and insufficiencies in system resilience have encouraged city planners to consider integrated urban water management (IUWM) as a solution. One of the main benefits of IUWM is looking into stormwater as a resource to decrease the need for potable water and put less burden on wastewater treatment systems and the environment. Green infrastructure (GI) is an essential part of stormwater management that is designed to mimic the natural hydrological cycle and allows for infiltration, capture and reuse, and treatment of stormwater. This dissertation is designed to inform urban water decision-makers with a special focus on GI via assessment and management frameworks and stakeholder engagement.

In my first study, I provided a comparative study of IUWM models aimed at assisting users to select the most appropriate model according to any specific needs. Our results

showed that most of IUWM models included stormwater management and GI selection, but do not consider ecosystem services evaluation and the supply and demand from GI. Following these deficiencies of the available models, in my second study, I looked into the stakeholders' knowledge, perception, and practice of GI with respect to ecosystem services supply and demand. The results showed the study of supply and demand, as well as ecosystem disservices, can help the selection of effective forms of GI to address the priority of stakeholders and environmental issues. Selection of the right type of GI is important for the sustainability of GI in providing ecosystem services, but so is monitoring and evaluation of GI. Thus, my third study focused on developing a generalized social-ecological framework for assessing urban stormwater GI resilience. The results of this study showed that assessing resilience requires linking indicators to critical functionality of GI, as well as a social-ecological approach that goes beyond design and technical specifications. This study can help prioritize resources to address goals related to building resilience. In my last study, I aimed to refine and co-produce a specific social-ecological framework for stormwater GI resilience with stakeholders that links to perceived barriers and challenges of implementing GI. Stakeholders co-created indicators considering current GI challenges and linked them with resilience management dimensions. This framework could inform the management of adverse events and improve resilience by decision-makers and multi-stakeholders in various sectors related to GI planning, design, and implementation.

GREEN INFRASTRUCTURE IN INTEGRATED URBAN WATER MANAGEMENT: MODELING AND SOCIAL-ECOLOGICAL SYSTEM APPROACHES

by

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Chapter 1: Review of Role of Green Infrastructure in Integrated Urban Water Management and Urban Resilience

Introduction

One of the vital components of any urban area is the water system: adequate and high- quality water supply, sanitation, and drainage service to its populations (Marlow et al. 2013). However, in numerous cases, the conventional ways of providing those services do not fulfill the recent goals of environmentally sustainable development with a lower impact on the environment while being economically feasible (Mitchell 2006). Urbanization, climate change, increasing water demand, deteriorating water quality, and insufficiencies in system resilience have made the urban water management an ever-challenging task (Aye et al. 2014; Chang et al. 2012; Makropoulos et al. 2008; Werbeloff and Brown 2011). Aging infrastructure is another major issue in the United States that brings a major financial demand for future developments and rehabilitation that worsen the current situation in the urban water sector (Xue et al. 2015). Due to the current issues in conventional water management, considering components of urban water system, including drinking water, wastewater, and stormwater as independent of each other, is not practical anymore (Rauch et al. 2012; Werbeloff and Brown 2011).

Compared to traditional approaches to water management that include large centralized infrastructure and command and control approaches, a move toward integrated social-ecological systems that includes the integration of infrastructure and biophysical systems with the socio-economic, environmental, and institutional contexts should be better at provision of water for human use and environmental conservation (van de Meene et al. 2011). The term social-ecological system was first used by Berkes et al. (2000) to highlight the integrated concept of human roles in nature. Focusing only on one dimension, either the social or ecological, may not be sufficient to gain a sustainable and resilient outcome or may limit the scope of information used to draw conclusions (Folke et al. 2005). Social-ecological systems are often complex and made up of several subsystems as well as involving related economic, political and social settings. Finding ways to sustainably manage interconnected social-ecological systems in urbanized environments has become more important as the human population, demand, and the level of economic development have increased. To overcome this complexity and reach a sustainable governance system we need to go beyond simple solutions and provide general analysis frameworks that can be used to conduct multi-dimensional research and accomplish better policy analysis (Ostrom and Cox 2010).

Integrated Urban Water Management

The term water sensitive urban design was first introduced in 1990s in Australia, as practitioners initiated to investigate and explore approaches for more integrated urban water management (Lloyd et al. 2002). Integrated urban water management (IUWM) is a method to design and manage different components (water supply, wastewater, and stormwater) in municipal water systems holistically. IUWM guides urban water managers to select the water supply and resources that is emitting fewer greenhouse gases (Aye et al. 2014). It is an approach that allows urban water utilities to manage these three components in a way to minimize their impact on the natural environment and maximize the socio-economic benefits to community improvements (Shiroma Maheepala et al. 2010). Integrated approaches in urban water management have been the focus of numerous studies and have been named differently in the growing body of literature such as IUWM (Maheepala et al. 2010; Marlow et al. 2013; Mitchell 2006), sustainable urban water management (Brown and Farrelly 2009), total water cycle management (Chanan and Woods 2006), and water sensitive urban design (Wong 2006). IUWM enhances the involvement of social and economic factors, and creates overall community improvement (Maheepala et al. 2010). Successful urban water management should be able to translate IUWM concepts into well-functioning conventional urban development, decreasing the effect of urban development on water bodies and increase the acceptance among the water sectors and land development agents. However, there are still needs to better integrate IUWM components, especially stormwater management, into the total urban water system management (Mitchell 2006).

Decentralized water systems are focused for management to help with lessening demand for drinking water, bring wastewater services close to its generation, and reducing the need for extension of existing infrastructure. The former is accomplished by enhancing water reuse in local areas through recycling wastewater and stormwater harvesting (Burn et al. 2012). Recharging stormwater into the groundwater aquifers not only reduces urban flooding but also can recharge groundwater and increases baseflows during the low flow season (Kirshen et al. 2018). IUWM reflects the recent trends toward rethinking stormwater runoff as a novel water resource, rather than a waste product (Walsh et al. 2012). However, conventional (gray) infrastructure for stormwater management systems consists of pipes and canal systems which are unifunctional, aiming at collecting stormwater and discharging it to local water bodies (Kitha and Lyth 2011). Although conventional practices are used to divert excess stormwater from the urban environment to protect flooding in many cases it is combined with the sewer system, which causes combined sewer overflow and discharges a significant source of pollution to receiving water systems (Lau et al. 2002). Approximately 700 cities across the United States have combined sanitary and sewer systems that likely to overflow during heavy precipitation that produces 850 billion gallons of combined sewer overflow discharge each year, affecting the ecosystems and public health (Kondo et al. 2015).

Green Infrastructure

Green infrastructure (GI) is an emerging form of urban greening and an essential part of sustainable urban stormwater management systems. In this dissertation, I will refer to GI as stormwater GI: management systems that are designed to mimic the natural hydrological cycle process, thus using a natural approach that allow infiltration, evapotranspiration, capture and reuse of stormwater, conveyance, and stormwater treatment (Fryd et al. 2012; USEPA 2008). Compared with traditional gray approaches, stormwater GI approaches are seen as less expensive to reduce combined sewer overflow (Mguni et al. 2016). In urban areas, GI is implemented in different forms (such as urban trees and forests, green roofs, rain gardens, etc.), each with differing abilities to provide ecosystem services (Ellis 2013; Flynn and Traver 2013; Pugh et al. 2012; Raje et al. 2013). There are three main functions that are aimed by GI: to reduce the runoff quantity by controlling and slowing the runoff rate, to improve the quality of stormwater before entering surface water by passive treatment, and improving biodiversity in the urban environment (Charlesworth et al. 2003; Walker et al. 2012). Despite these main functions, there are challenges associated with GI. For example, although the impact of stormwater runoff is regularly recognized at watershed scale, stormwater GI are usually designed for smaller scales and the effectiveness in smaller scales does not always translate to effectiveness for watershed scale (Jefferson et al. 2017). Also, the effectiveness of GI for water quality shows that although it shows reduction in pollution in many cases, there are cases that report the pollutants reaches the water table (Bhaskar et al. 2016).

The desired functions of GI can be studied and managed as ecosystem services provided to people and municipalities. The Millennium Ecosystem Assessment defines ecosystem services as the benefits people gain from ecosystems (Millennium Ecosystem Assessment 2005). Ecosystem services include runoff reduction (Spatari et al. 2011), air purification (Demuzere et al. 2014), improving public health (Kaźmierczak 2013), cooling through shade provision (Stewart and Oke 2012), urban heat island mitigation (Livesley et al. 2016), and reducing energy consumption (Simpson 2002). Simultaneously, GI also provides for cultural needs of residents by providing recreational activities, aesthetic values, and education services (Lovell and Taylor 2013). A notable benefit of GI to city planners is its multifunctionality (compared to gray infrastructure), or the ability to provide multiple ecosystem services to diverse stakeholders (Connop et al. 2016). We can use the multifunctionality of GI to optimize functions of urban GI for sustainable GI planning. Multifunctional GI in which ecosystem services provision is as planned, can aid the conversion of social-ecological systems to more sustainable environments which are more resilient to unpredictable future environments (Lundy and Wade 2011; Pelorosso et al. 2016).

A primary interest of researchers in the area of social-ecological systems has been on evaluating the resilience in confronting disturbances over time (Ostrom and Cox 2010). GI is a strategy that cities use to enhance resilience, “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” (NRC 2012). Depending on the type of GI and scale of implementation, GI can improve both long-term and short-term resilience through the ecosystem services. For example, in response to climate change, GI can mitigate urban heat extremes, mitigate storm vulnerability, reduce combined sewer overflow, and improve human well-being (Meerow and Newell 2019; Pennino et al. 2016; Saleh and Weinstein 2016; Sutton-Grier et al. 2015). Geospatial planning expanding GI implementation is one of the approaches to enhance the cities resilience (Collier et al. 2013; Matthews et al. 2015). GI is found to be more flexible than massive old underground pipes and pumps (Mell 2016; Palmer et al. 2015). Flexibility is a significant feature in confronting climate change and its uncertainty (Foster et al. 2011; Mell 2016). To enhance the resilience of cities, GI itself must also be resilient to changes associated with climate change to allow systems to return to the previous state after disturbances. This return can be either naturally or with management assistance (Kitha and Lyth 2011). For instance, biological diversity is an important factor in GI design that can lead to self-organizing ability of GI regarding absorbing disturbances naturally and regenerating and rearranging the system after a disturbance. Species that may seem unnecessary or redundant may become critical in respond to a disruption (Folke 2006). In addition, management assistance such as monitoring for adaptive management could be part of the coping strategy to address probable shocks. Investigating how disturbance impacts GI and frequently updating information about climate change and human effect and how it affects disturbance management can be part of monitoring for adaptive management. The information from monitoring can be used to update risk assessment in planning and come up with strategies for adaptive management after a disturbance (Dale et al. 2001). Although GI is an essential approach to provide urban resilience, considering the demands of urban areas and connecting those demands to the ecosystem services helps to reach the demand of growing cities and climate change (Wang et al. 2018).

Many approaches to accomplish urban resilience and sustainability of water resources link to local provision of multiple ecosystem services (Calderón-Contreras and Quiroz-Rosas 2017; Schewenius et al. 2014). Landscape management to enhance the delivery of multiple functions at the same time while decreasing the ecosystem disservices is one of the challenging areas of ecosystem services research (Bennett et al. 2009; Carpenter et al. 2009). To address this challenge, study of ecosystem services supply and its association to demand is necessary (Zoderer et al. 2019). Ecosystem services supply is defined as the ecosystem's potential to deliver biophysical and social services (Villamagna et al. 2013) and ecosystem services demand as the level of services desired by people. The linkage and balance between ecosystem services supply and demand especially for urban water management are essential for satisfactory provision of an ecosystem service for the need within a defined region (Baró et al. 2015; Cumming et al. 2006; Manning et al. 2018; Maron et al. 2017). Connecting supply and demand could support recognizing the area that has the capacity to provide ecosystem services and where the demands are for those services (Castro et al. 2014; Wei et al. 2017). Furthermore, it is important to study the perception of various types of stakeholder for multiple supply and demand as interests, priorities, and needs are different and stakeholders value ecosystem services differently (Díaz et al. 2011; Martín-Ló Pez et al. 2012; Wei et al. 2017). As there might be similarities in the perceptions of ecosystem services supply by stakeholders, the ecosystem services demands may differ and cause potential conflict in landscape management. How stakeholders perceive ecosystem services supply and demand is an integral component to connecting ecosystem services provision and management decisions and identifying the potential conflicts can allow for more effective policy and management decisions (Zoderer et al. 2019).

Integrating stakeholder perceptions and water resources management

To successfully connect ecosystem services supply and demand, managers and stakeholders' perceptions and priorities are needed to inform GI practice for urban water resource management. Stakeholders' perceptions and support are increasingly attracting managers' attention for implementation of water resource management (Stave 2003). Recently, the concept of government as the individual decision-maker has been substituted by including a large number of stakeholders in diverse institutional settings. Until recently, management included technical experts working based on the assumptions that water resources can be predicted or controlled (Pahl-Wostl 2007). However, factors such as climate change, rapid dynamics of socio-economic development, and globalization are increasing the degree of uncertainty faced by water resource managers. This uncertainty requires a more adaptive and flexible management approach to allow for a more rapid learning cycle and more rapid assessment and implementation of new insights (Folke et al. 2003).

One way to facilitate changes in the understanding and practices of stakeholders in a complex situation, such as IUWM, is the use of appropriate and practical tools that are designed for evaluation of actual situation by involving multi-stakeholders (Goudie 2009; Ison et al. 2011). To facilitate changes from conventional urban water management to a more integrated approach, familiarizing decision makers and stakeholders with appropriate tools is key. The implementation of IUWM is reliant on the development of decision support tools to assist urban water managers to make up for the deficiencies of traditional management and to evaluate water management components and their interactions holistically. Although personal knowledge, experience, and belief of decision-makers would affect the decision process, the incorporation of stakeholder's input in the process of social learning could be very useful for sustainable integrated urban water decision making (Pearson et al. 2009). Models are one of the elements of decision-making in urban water management that examine and quantify future potentials and restrictions of different scenarios within the setting of sustainable water management and finally is a step to assist the decision-maker to select the best alternative, such as type of GI (Makropoulos et al. 2008).

Objectives of Dissertation and Overarching Approach

Like all environmental systems, water resource management includes natural components, connected human-engineered systems, and associated human socio-economic systems (Gunckel et al. 2012). Urban water management as a socio-ecological system involves all persons or groups who are affected by water governance efforts (Wiek and Larson 2012). Addressing water sustainability requires the knowledge of this socio-ecological system and various management and evaluation tools. This dissertation is designed to inform urban water decision-makers with a special focus on GI via assessment and management frameworks and stakeholder engagement. My research includes four main objectives:

Objective 1: To provide a comparative study of IUWM models aimed at assisting users to select the most appropriate model according to any specific needs

Objective 2: To study stakeholder knowledge, perception, and practice of GI ecosystem services supply and demand

Objective 3: To develop a generalized social-ecological framework for assessing urban stormwater GI resilience based upon literature studies

Objective 4: To refine and co-produce a specific social-ecological framework for stormwater GI resilience with practitioners to incorporate local barriers and assessment feasibility

Knowledge of available models in the context of IUWM is key in the complex decision analysis framework. Here, I did a comparative study of the most common and recently developed IUWM models. It provides guidance to water managers with the selection of the most appropriate modeling tools with provision of detailed application of models (**Objective 1**). The deficiencies of available models in considering and quantifying ecosystem services supply and demand, lead us to study ecosystem services supply and demand of GI by evaluating stakeholder perceptions to help improve management decisions surrounding GI implementation (**Objective 2**). I selected

Tucson, Arizona as a case study because it faces water sustainability issues due to the water scarcity in a dry climate but is also trying to implement broad goals of water harvesting and revegetation of the city. This research enables us to better quantify the linkage between ecosystem services and management policies for water sustainability. To be able to optimize GI ecosystem services we need to identify how resilient GI is, and this requires an evaluation framework that assesses the level of resilience toward disturbances. Thus, I developed a framework to study and evaluate the GI resilience in the context of the socio-ecological system which could better help the decision-makers and stakeholders to assess the degree of resilience in GI and to also identify category(s) that can improve this resilience (**Objective 3**). This assessment framework could enhance the functions of the intended GI to better address water sustainability issues and other ecosystem services. Finally, I involved various stakeholders' input to enhance the practicality of these assessment tools for a specific setting (the Anacostia Watershed), thus enabling movement toward a more comprehensive assessment and implementation of new insights (**Objective 4**) (Figure 1). I addressed these objectives through sets of different methods including a literature review approach and framework development (objective 1 and 3), an online self-administered survey of stakeholders (objective 2), and a focus group workshop and interviews with critical managers (objective 4).

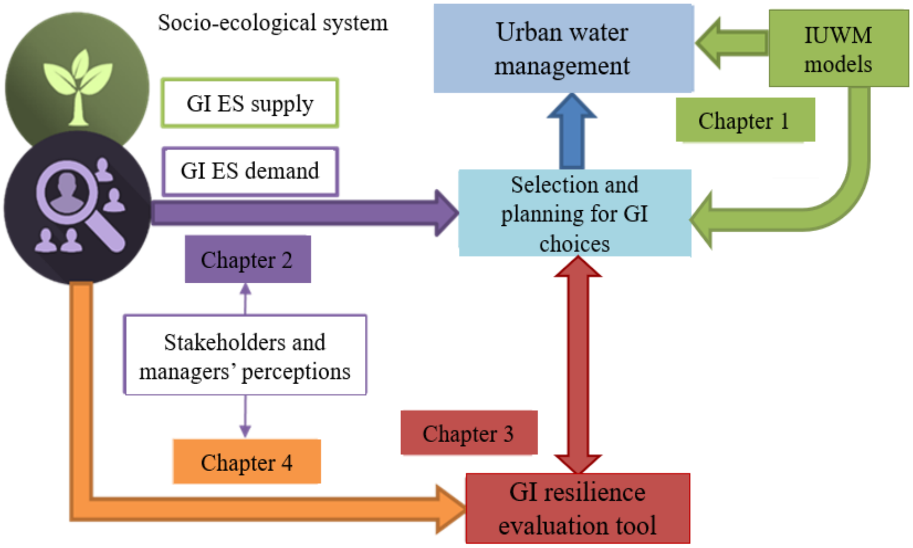

Figure 1 Research scope. In chapter 1, a comprehensive framework on Integrated Urban Water Management (IUWM) model selection will be developed for urban water managers. In chapter 2, the stakeholders' perceptions on green infrastructure (GI) ecosystem services supply and demand is investigated. These two chapters would help to inform appropriate GI selection. In chapter 3, a GI resilience assessment tool was developed and in chapter 4, stakeholder perceptions were used to refine this resilience framework for a specific case. These last two chapters can be used to evaluate the resilience of GI.

Decision-making in the urban environment is often complex and brings in multiple aspects with various points of view and priorities of stakeholders. A traditional approach where cost is the single decision criterion cannot guarantee desirable results (Ho et al. 2010), since stakeholder-oriented criteria were neglected. Often, more qualitative factors reflecting decisions, such as various stakeholder perceptions, are not part of the decision process, and decisions are made based upon quantitative factors such as cost or a single decision-maker's opinion (Kiker et al. 2005). Making a decision in a complex system usually is made based on the multidisciplinary knowledge and factors that include ecological and social aspects (Kiker et al. 2005). For example, one of the important factors in the decision making of urban GI is to consider ecosystem services provision as well as stakeholder priorities. However, IUWM models focus on a limited set of functions and do not considered GI multifunctionality, nor do they consider ecosystem services supply and demand especially in selecting GI alternatives (Chenevey and Steven Buchberger 2013; Last 2010; Mitchell and Diaper 2005; Mitchell and Diaper 2006; Poustie and Deletic 2014). Although frameworks for spatial and temporal evaluation of ecosystem supply and demand have been created recently through mapping and geospatial approaches (Burkhard 2014; Burkhard et al. 2012; Dobbs et al. 2014; Larondelle et al. 2014; McPhearson et al. 2016), there is still a clear gap in application of perceptions and objectives related to GI ecosystem services into urban planning and the decision process (Cortinovis and Geneletti 2018). Thus, this study aims at investigating the ecosystem services supply and demand of various stakeholders and produce recommendation for selection of GI based on the needs of an urban environment.

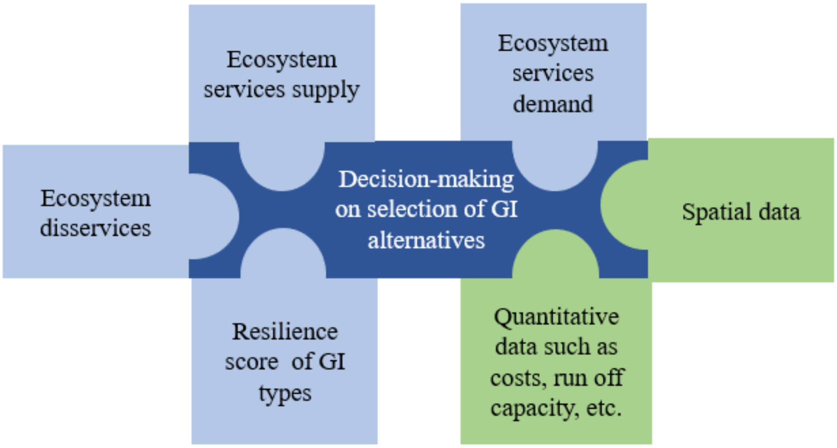

Figure 2 The outcome of this study including ecosystem services supply, demand, ecosystem disservices, and resilience score of GI can be used in addition to spatial data and quantitative data to inform decision making through multi-criteria decision analysis

Chapter 2: Role of Models in the Decision-Making Process in Integrated Urban Water Management: A Critical Review

Abstract

Integrated urban water management (IUWM) has become a necessity due to the high rate of urbanization, water scarcity, and climate variability. Managing urban water systems in which stormwater, wastewater, and drinking water sectors affect each other is a difficult task that requires a holistic view and using right tools in decision-making. IUWM models are tools that allow decision makers to deal with the conflicts in managing urban water systems. Although models are useful tools, the wide range of available models with many different capabilities make it challenging for the users to select an appropriate model for specific goals. There are also many models that have been used more in research activities rather than in real-world practices. This review aims at providing a practical guidance for decision makers to select the appropriate models. In this review we provided descriptions and strengths of several popular IUWM models. Then, we introduced a list of comprehensive indicators that might be of interest to decision makers, and compared the models. We also discussed detailed application of those models in a comparative way and introduced the input requirements. Furthermore, we provided a procedure to select the appropriate model in the management environment. We found that most of the models' applications are focused on supply and demand, wastewater and graywater reuse, and hard engineering in stormwater management. Few models consider social factors and policy strategies. There is a need for new areas such as water-energy nexus and evaluating ecosystem services to be included in the models.

Keywords: Integrated urban water management; models; decision support tool; urban water cycle

1- Introduction

Urbanization, increasing water demand, changing social attitudes toward water consumption, climate change, water scarcity, deteriorating water quality, and insufficiencies in system resilience have made the urban water management an ever challenging task (Marlow et al. 2010; Makropoulos et al. 2008; Werbeloff and Brown 2011; Chang et al. 2012; Nancarrow et al. 2010; Aye et al. 2014). In addition, there is a major financial demand due to aging infrastructure and future developments that exacerbate the current situation in urban water sector (Xue et al. 2015; WHO 2014). In the face of these challenges, the traditional approach to water management, in which components of urban water system (i.e. source water, drinking water, wastewater, or stormwater) are considered independent of each other, is no longer viable (Wolfgang Rauch et al. 2005; Werbeloff and Brown 2011). Integrated urban water management (IUWM) is a method to design and manage different components in municipal water systems holistically (i.e. water supply, wastewater, and stormwater) and guides urban water managers to select the water supply that is emitting less greenhouse gases (Aye et al. 2014). IUWM increases the involvement of social and economic life, and to creates overall community enhancement (Maheepala et al. 2011). IUWM was first introduced in late 20th century (Braga 2001). IUWM comprises various approaches as an alternative solution, such as developing decentralized water and wastewater systems (Aye et al. 2014; Larsen et al. 2013; Maurer 2013; Tchobanoglous and Leverenz 2013), fit-for-purpose practices, graywater/rainwater reuse (Cook et al. 2009; Xue et al. 2015), implementing green infrastructure to manage stormwater, and energy recovery (Ma et al. 2015). Although the concept of IUWM has been developed more than two decades ago, the transition to a more sustainable design is slow. In addition, well-documented cases of IUWM can be barely found, even in pioneering countries in IUWM such as Australia (Elliott and Trowsdale 2007; Marques et al. 2015; Sitzenfrei et al. 2014; Mitchell 2006). Therefore, we feel one way to assist the decision-makers to implement the IUWM in complex systems such as water management in urban area is to better familiarize them with decision support systems and different tools such as models.

The implementation of IUWM is reliant on development of decision support tools to assist urban water managers to make up for the deficiencies of traditional management and to evaluate water management components and their interactions holistically. Decision support systems (DSSs) are systems that gather all of the relevant information from a variety of sources needed for decision-making processes and the end-users (Poch et al. 2004). Despite the potential uncertainty associated with DSSs, they can help an individual or group of people to make the best feasible decision regarding water resources among various alternatives by considering all the elements that play role in a decision making process (Price and Vojinovic 2011). DSSs in urban water management account for environmental factors such as ecology, climate, the economy, etc. and not just water related data. Figure 1 shows different components of a DSS in urban water system management and uncertainty in different steps that decision-makers often deal with during the decision process (Li et al. 2006; Weng et al. 2010). Decision-makers have different approaches to select the best alternative when they face multiple objectives that are sometimes conflicting. Among these approaches scenario analysis, multi-objective programming (MOP) and multi-criteria decision analysis (MCDA) are especially helpful (Figure 1). MOP would be useful when there is a conflict between objectives, while MCDA would allow decision-makers to select the most appropriate option among various alternatives (Fattahi and Fayyaz 2010; Weng et al. 2010). However, personal knowledge, experience and belief of decision-makers would affect the decision process. The incorporation of stakeholder's input in the process of social learning could be very useful for sustainable integrated urban water decision making (Pearson et al. 2009). Models are one of the elements of decision-making in urban water management that requires database as an input. The output of models are required in order to examine and qualify future potentials and restrictions of different scenarios within the setting of sustainable water management and finally is a step to assist the decision maker to select the best alternative (Figure 1) (Makropoulos et al. 2008).

2- Models in IUWM Systems

Alongside with the management, urban water modeling and simulation have progressed as an operational tool for addressing urban water challenges (Bach et al. 2014). Models assist policy makers to obtain their goals in planning and policy making for urban water problems (Blind and Gregersen 2005; Bach et al. 2013). Integrated urban water management models (IUWMMs) are needed to study the connections and alteration of the three components of IUWMs to recognize the future opportunities and restrictions in various systems by considering the framework of sustainability (Makropoulos et al. 2008). The transition from a traditional view to the IUWM systems has been reflected in the models as well (Schmitt and Huber 2006). However, integrating different components into a single model package has its own challenges. Sufficient knowledge of each component is required, and a meaningful output is not simply the sum of each component. IUWM systems are complex and are not just a simple linkage of individual subsystems (Schmitt and Huber 2006; Bach et al. 2014; Mitchell et al. 2007). The simulation of quantity and quality of the water and consideration of fit-for-purpose approaches are significant in such models. In addition, they should be able to represent different components of urban water such as wastewater and stormwater separately (Mitchell et al. 2007). In integrated systems some complexities are inevitable. Complexities such as introduction of a new subsystem and the interaction by the required subsequent features needs to be considered (Bach et al. 2014).

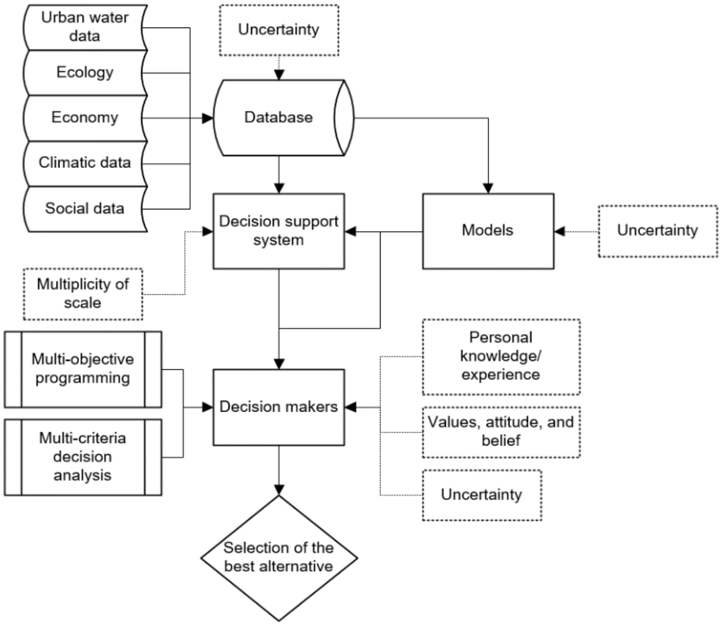

Figure 1 Decision making in urban water systems and role of models in this system. Uncertainty and multiplicity of scale are associated with DSS in different steps (Price and Vojinovic 2011)

In recent years, a number of IUWMMs have been developed and reviewing of IUWMMs could play an important role to encourage implementing more IUWM principles. In addition, reviewing models could provide a useful source for urban water managers and practitioners to compare available modeling tools for decision making. Also, the outcomes of such reviews can be used for educational purposes and policy making (Elliott and Trowsdale 2007). In recent years, IUWMMs have been reviewed by several researchers. For instance, Mitchell et al. (2007), screened 65 commercial free available models and looked into 7 models to evaluate their technical basis. They provided an overview of those 7 models based on the spatial and temporal scale, and components of integrated water such as drinking water (i.e. water flows, water quality, water demand, and water supply sources), stormwater, wastewater, and groundwater processes. House-Peters and Chang (2011) have looked at the IUWMMs through the lens of coupled human and natural systems. Uncertainty, resilience, interaction within the temporal and spatial scales, and the conversion of model to dynamic modeling were also evaluated. Bach et al. (2014), investigated some of the IUWMMs and classified them into 4 groups from the lowest level of integration which is Integrated Component-based Models (ICBMs) to the highest level of integration which is Integrated Urban Water System Models (IUWSMs). The other types are Integrated Urban Drainage Models (IUDMs) and Integrated Water Supply Models (IWSMs), which integrate either the drainage or supply and lastly, the Integrated Urban Water Cycle Models (IUWCMs) that connect IUDMs to IWSMs. The highly integrated IUWSMs, integrate various urban water “infrastructures” and “disciplines”. In such systems, social, economic, climatic, and energy factors are included in the model wherever it’s relevant. Renouf and Kenway (2016) evaluated urban water model and categorized these approaches to four groups of urban water system modeling, urban metabolism, consumption approaches, and complex systems. In each approach the direct and indirect water flows were evaluated. Peña-Guzmán et al (2017) reviewed urban water cycle simulation and management models from 1990 to 2015. They looked at the geographical distribution of the model usage and categorized the model based on popularity. In their review, the authors looked at the applications of the models reported by other researchers. They concluded that most of the models have been used in academia rather than in real decision-making environments.

Over the past few decades, an increasing and varied body of IUWM modeling literature has arisen, provided categorization of the models (Bach et al. 2014; Renouf and Kenway 2016), studied temporal and spatial scales of models (Mitchell et al. 2007), and dynamics of the models (House-Peters and Chang 2011). However, the slow adoption of these models into the practice especially in decision-making environment shows the lack of practical tool for model selection based on the specific needs and application of models. Although several papers started to look into the application of models (Bach et al. 2014; Peña-Guzmán et al. 2017), the level of investigation in those papers is not enough to enable the users to compare and select the most appropriate models and there is still a lack of detailed evaluation of IUWMMs capabilities in a comparative way to enable the users to gain enough information on available modeling tools. In addition, the dominant approach that is presented in the former review papers is to promote developing IUWMMs rather than using the models. As a result, users, particularly decision makers and urban water managers, may find it difficult when investigating into these literatures to select the appropriate modeling tools according to their needs. As such, there is a need for better presentation of IUWMMs capabilities, and where they may find value in practice. In the current review papers the applications of models that have been used by other researchers were emphasized. However, there is also a need to consider the entire capability of the models. There is not one document that gathers all the essential capabilities that might be useful for decision-making. Moreover, several capabilities were not emphasized enough or neglected including cost, energy, governmental policies, and social factors. In addition, the types of inputs were not highlighted for the users which we think as an important factor for selecting a model (especially for those not experienced in the field). Knowing the input requirements will help the user to evaluate the available data and what they need to gather as each case has its own unique characteristics and data availability.

In response to the named challenges, this critical review aims to review and compare the most common IUWMMs and presenting an applicable way to use IUWMMs in decision making process. A lot of reviewed literature centered on IUWMMs, lacks the detailed information on the applications, output, and required inputs of the models. Also, the authors found the need for practical procedure to assist the practitioners to select the appropriate model. Thus, this review includes main phases such as introduction of selected IUWMMs, investigating and comparing detailed models' application, models' input requirement, and a procedure to help the users to select the best model according to their goals. This will pave the way toward using IUWMMs for better decision-making in urban water managements. This framework is intended to be used by professionals involved in urban water management and aimed to promote multi-stakeholder teams in drinking water, stormwater, and wastewater to work under the bigger concept of integrated urban water management.

3- Review Approach

The review process includes five steps: (1) models were selected, and a systematic literature review on models description, and their characteristics and strengths was conducted; (2) 10 indicators were selected for models' comparison and assessment; (3) models were investigated according to the indicators, and application subcategories of the models were identified; (4) inputs of models were categorized; and (5) a framework for selecting the best models based on users objectives was provided. This review and the framework provided here advances current knowledge by highlighting not only the essential indicators derived from the models that are beneficial for model selection, but also step by step process to make it easier for model selection.

We identified 32 IUWMMs from literature that included three main components of IUWM (stormwater, wastewater, drinking water). Then, we selected thirteen commonly used models based upon the availability of records and documentation that could be analyzed, that these related documents were in English, and that they were publicly accessible. The emphasis of this review is on models that cover all components of urban water cycle (drinking water, stormwater, and wastewater). Thus, models with less degree of integration were not included. The information gathered for these models are based on reviewing published manuscripts (between 1999 and 2017), conference proceedings (including Urban Drainage Modeling, Rural Development, and Estuaries and Coast), case studies, model websites, model developer interviews, and user manuals of the models. Our evaluation is based on the latest version of models that were available in early 2018. We considered 10 key essential indicators based on the challenges faced by cities and under each indicator we listed potential application of the models to address those challenges.

4- Results and Analysis

4-1- Model Selection

In the first phase of this research we conducted a rapid assessment of an extensive systematic search of papers including scientific papers, practical reports and literature from experts and model developer to identify available models in IUWM that have been developed since 1999. This led to screening 500 peer-reviewed journal articles and reports, planning documents, case studies, models' manual, and practical reports available on the models. This process was done by screening the titles, abstract, and keywords that includes three components of IUWM including drinking water, wastewater, and stormwater between the years 1999 to 2017. During this effort, we assessed the state-of-the-art knowledge on the type of models, year of development, developers' information, development objectives, and the availability of the models (Table 1). After reviewing the models, the gathered information has sent to either model developer or experts working closely with models for verification. The models that we identified include: Sobek Urban, Aquacycle, Hydro Planner, WaterCress, Water Balance Model (WBM), Urban Cycle, Urban Volume and Quality (UVQ), MIKE URBAN, Urban Water Optioneering Tool (UWOT), City Water Balance (CWB), Dynamic Adaptation for eNabling City Evolution for Water (DAnCE4 Water), Watershed Management Optimization Support Tool (WMOST), and WaterMet[2]. These models are either addressing the previous model's deficiencies or were developed to introduce new capabilities in urban water management (Table 1). For instance, HydroPlanner addresses the issue with former models such as IQQM, WATHNET, and RELM as they do not include the wastewater recycling. Also, UVQ is successor of Aquacycle model with additional options such as contaminant simulation and snow modeling capacity. More explanation on the development intention of IUWMMs and other introductory information are presented in Table 1. Additional information on the features and advantages of these models were collected from the literature including the spatial and temporal scales these models operate. Models such as Sobek Urban considers seconds and minutes as a temporal scale (Ji et al. 2003); however, models such as WMOST considers longer intervals of daily and monthly (Detenbeck et al. 2018a). The spatial scales vary from lot to watershed scale in various models (Table 2). We also include the information about water flow and water demand. In addition, we include if any model considers changes in the system such as morphological change, changes in demand, storage and climate change, etc. (Table 2). Furthermore, the strengths and advantages of the models in which each model differs from the others were identified (Table 2).

Of note is many other models have been identified during the first step of the review process (e.g. DUWSim, WaND-OT1, DMM, Urban Metabolism, Urban Developer, City Drain3, MUSIC, Re-Visions, and VIBE). However, there was not enough available information to discuss indicators for these models. In addition, some of these models are the engine (or foundation) of the models that we included in the review. As a result, we did not include these models in the review.

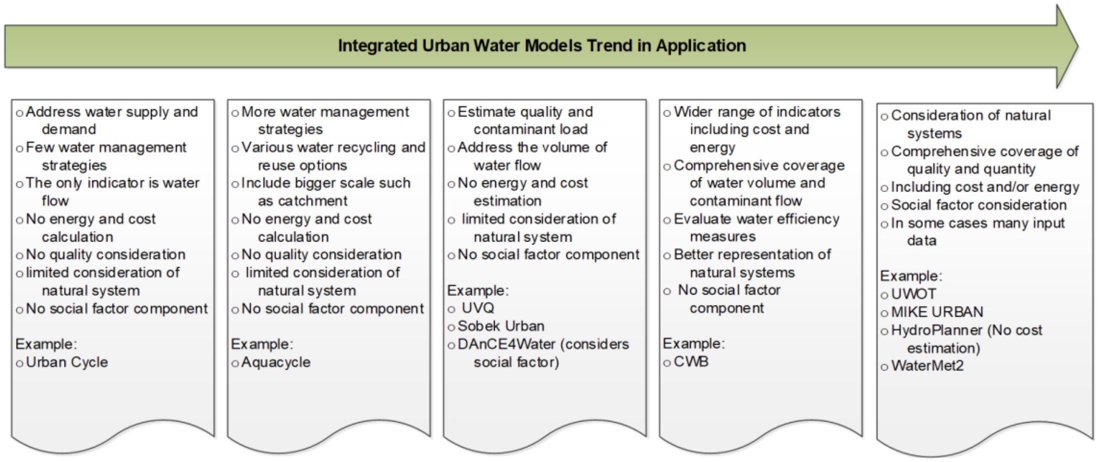

Figure 2 Categories of development and application of integrated urban water management models (IUWMMs)

Figure 2 represents the trend in development and application of the reviewed IUWMMs. Initially, the focus of the models (e.g. Urban Cycle) were to address the basic needs such as water supply and demand and only few strategies were available in such models for water management including rainwater harvesting and wastewater recycling strategies. Then, models such as Aquacycle started to include more water management strategies (i.e. rain tanks, subsurface direct graywater irrigation, aquifer storage (Last 2010)). Also, they include larger spatial scales such as catchment level (Table 2). Further in the development, models were able to estimate quality of water (i.e. UVQ, Sobek Urban, DAnCE4Water) (Bach et al. 2012; Tjandraatmadja et al. 2013; Faraji 2015). Wider range of indicators such as cost, and energy estimation were added later to the models. One example of this category is CWB. Models in this category consider more contaminants such as waterborne pathogens. In addition, these models have better representation of natural systems (Last 2010). Social factors (i.e. considering change in end user behavior, technological, and demographic change) are added in the latest steps of this trend development (Figure 2).

Table 1 Introductory information for selected models

Model	Type	Year	First developed by	Development intention	Availability	References and case studies
Sobek Urban	IUWCMs	1999	Deltares	Model explores irrigation and drainage system, sewerage, flooding simulation, water quality, canal and waterway control system design and optimization.	https://www.deltares.nl/en/software/sobek/#service-packages	(Schwanenberg and Becker 2017; Faraji 2015; Betrie et al. 2011; Prinsen and Becker 2011; Ji et al. 2003; Vanderkimpen et al. 2009)
Aquacycle	IUWCMs	2001	Cooperative Research Center for Catchment Hydrology (CRCCH)	Expanded previous models. Integrated water cycle, water reuse, include strategies such as rain tanks, stormwater system and wastewater collections, aquifer storage, and graywater irrigation.	Freeware from https://toolkit.ewater.org.au/Tools/Aquacycle	(Bach et al. 2014; Chenevey and Steven Buchberger 2013; Donia et al. 2013; Duong et al. 2011; ewater n.d.; Gires and De Gouvello 2009; Lee et al. 2010; Mitchell et al. 2001; Pak et al. 2010; Peña-Guzmán et al. 2017; Schulz et al. 2012; Shuklaey et al. 2011; Situmorang 2008)
Hydro Planner	IUWCMs	2001	Commonwealth Scientific an Research Organization (CSIRO)	Address the issue with former tools such as IQQM, WATHNET, and RELM that do not include the wastewater recycling in calculating the demand. Comprised of seven modules that can link the models in different areas. Simulate the whole urban water cycle, water flow, and constituent modeling, to familiarize urban water managers with the water cycle components and their interactions.	Contact CSIRO Land and Water	(Mitchell et al. 2007; Mirza et al. 2013; Maheepala et al. 2005; Grant et al. 2006; Peña-Guzmán et al. 2017; Kinsman et al. 2012)
WaterCress	IUWCMs	2002	Clark and Cresswell	Answers the problem with the feasibility of selected alternative system layout. Simulate water flow through the natural and build environment.	Freeware from: http://www.waterselect.com.au	(Peña-Guzmán et al. 2017; WaterCress 2015; Clark et al. 2002; Beh et al. 2015a; Beh et al. 2015b; Clark et al. 2015; Beh et al. 2014)
Water Balance Model (WBM)	IUWCMs	2004	Quality/Quantity Simulation model (QUALHYMO)	Aid governments to reach acceptable urban water health and environmental security outcomes. A decision support tool that connects engineering and planning to reach the sustainability goals such as economic sustainability, decreasing environmental value, increasing social value, and creating recreational prospects.	Free basic model http://waterbalance.ca/	(Bach et al. 2014; Bhaskar and Welty 2012; Binder et al. 1997; Charalambous et al. 2012; Chèvre et al. 2013; Richard Clark et al. 2002; Elliott and Trowsdale 2007; Haase 2009; Järvi et al. 2011; Marteleira et al. 2014; Peña-Guzmán et al. 2017; Renouf and Kenway 2017; Van Rooijen et al. 2005)
Urban Cycle	IUWCMs	2005	Hardy et al.	An object-oriented model aiming to address the growing and changing requirements of water division in Australia. It is aimed for “adoption of continuous simulation, hierarchical network modelling, and the careful management of computational complexity.”	Contact M. Hardy	(Bach et al. 2014; Peña-Guzmán et al. 2017; Hardy et al. 2005; Mitchell et al. 2007a,b; Thyer et al. 2008; Hardy et al. 2007; Barton et al. 2007; Hardy et al. 2003)
Urban Volume and Quality (UVQ)	IUWCMs	2005	Mitchel et al.	Aquacycle successor with extra options such as contaminant simulation and snow modeling capacity, simulating constituent load and water flow volume from source to discharge, and water management alternative evaluation.	Contact CSIRO Land and Water	(Gurung and Sharma 2014; Bach et al. 2014; Mitchell et al. 2007; Marleni et al. 2015; Mitchell and Diaper 2006; Mitchell and Diaper 2005; Gurung et al. 2015; Peña-Guzmán et al. 2017; Poustie and Deletic 2014; Cook et al. 2013; Leitner 2013; Tjandraatmadja et al.

Model	Type	Year	First developed by	Development intention	Availability	References and case studies
						2013; Martinez et al. 2010; Cook et al. 2010; Sharma et al. 2010)
MIKE URBAN	IUWCMs	2007	Danish Hydrological Institute (DHI)	This model overcame one dimensional SWWM limits in flood simulation by combining 1-D sewer modeling with 2-D overland flow modeling and incorporates current resources, demand, distribution, and runoff models.	Purchased from DHI, requiring a license	(Bach et al. 2014; Bisht et al. 2016; Gražina and Žibas 2013; Hammond et al. 2012; A. Liu et al. 2010; Mark et al. 2001; MIKE DHI 2017a, 2017b; Mitchell et al. 2001; Mitchell et al. 2007; Peña-Guzmán et al. 2017)
Urban Water Optioneering Tool (UWOT)	IUWCMs	2008	Water Cycle Management for New Developments WaND	"Provide guidelines and decision support tools for the implementation and assessment of efficient and sustainable water management interventions in new urban developments with due consideration to social, environmental and health associated factors."	https://www.watershare.eu/tool/urban-water-optioneering-tool/start/	(Baki and Makropoulos 2014; Bouziotas et al. 2015; Koutiva and Makropoulos 2012; Makropoulos et al. 2008; Christos K. Makropoulos and Butler 2010; Papariantafyllou and Makropoulos 2013; Peña-Guzmán et al. 2017; Rozos et al. 2010; Rozos and Baki 2011; Rozos and Makropoulos 2013)
City Water Balance (CWB)	IUWCMs	2010	Sustainable urban Water Management Improves Tomorrow's City's Health (SWITCH) Last	Better representation of natural system, access to broader range of alternatives comprising sustainable urban drainage system, calculate life cycle energy use and whole life cost analysis. Designed for decentralized system.	Freeware from: http://www.switchurbanwater.eu/res_software.php	(Bach et al. 2014; Last 2010; Mackay and Last 2010)
Dynamic Adaptation for eNabling City Evolution for Water (DAnCE4 Water)	IUWSMs	2011	Monash University, University of Innsbruck, Centre for Water Sensitive Cities and Melbourne Water	Simulate dynamics of both urban system and societal features, considers both urban planning factors and demographic data	http://www.dance4water.org	(Bach et al. 2011; Peter M. Bach, McCarthy, et al. 2013; Peter M Bach et al. 2012; Haan et al. 2012; Rauch et al. 2012; Urich et al. 2011; Urich, Bach, et al. 2013; Urich, Sitzenfrei, et al. 2013)
Watershed Management Optimization Support Tool (WMOST)	IUWCMs	2013 V3-2018	United States Environmental Protection Agency	Decision support tool at local and small watershed. Includes hydro-processor, screen a wide range of potential water resources management options considering environmental and economic sustainability.	https://www.epa.gov/exposure-assessment-models/wmost	(USEPA 2013a,b; Detenbeck et al. 2015; Detenbeck et al. 2018a,b)
WaterMet[2]	IUWCMs	2014	Exeter University and NTUA	Metabolism based modeling, quantify resource flow (water and energy), water energy nexus, environmental impact on IUWM. Conceptual and mass-balance-based, quantify metabolism, focus on sustainability issue.	https://www.emps.exeter.ac.uk	(Behzadian and Kapelan 2015; Behzadian et al. 2014a; Behzadian et al. 2014b)

Table 2 Models characteristics and strengths

Model	Spatial Scale	Temporal Scale	Water flows	Water demand	Change Consideration	Strength/advantages	References
Sobek Urban	River catchment, neighborhood, region, city	Minutes-seconds	Quantify both water flows and other main fluxes related issues consider desired specified flow.	Coupled demand with network of nodes	Morphological changes	Real-time control, very user-friendly interface, schematize problem and organize needed data	(Schwanenberg and Becker 2017; Ji et al. 2003; Prinsen and Becker 2011)
Aquacycle	Unit block, cluster (suburb), catchment	Daily	Temporal distribution of water flow	Diurnal variation	Change in storage within the system	Strong model to introduce the substitute for imported water, estimation of daily, monthly, and annual water demand, simplicity, rapid run time.	(Bach et al. 2014; Chenevey and Steven Buchberger 2013; Donia et al. 2013; Duong et al. 2011; ewater n.d.; Gires and De Gouvello 2009; J. Lee et al. 2010; V.G. Mitchell et al. 2001; Pak et al. 2010; Peña-Guzmán et al. 2017; Schulz et al. 2012; Shukla et al. 2011; Situmorang 2008)
Hydro Planner	Town, region	Daily	WS, SW, WW, receiving water module	Projection of water demand and changing scenarios	Examines water demand, climate change, population growth, and technological change	The end use model software such as REALM is linked to this model for supply-demand stability. Integrates climate change, demographic variation, and land use alteration in predicting supply and demand. Inclusive coverage of urban water volume and constituents.	(Mitchell et al. 2007; Mirza et al. 2013; Maheepala et al. 2005; Grant et al. 2006; Peña-Guzmán et al. 2017; Kinsman et al. 2012)
WaterCress	Lot, neighborhood, region	Daily	The model simulates daily flows and volume within a boundary	Diurnal variation	Error adjustment factor can be applied in case of rapid changes.	Contains all the available sources such as stormwater, groundwater, water from desalination sources, imported water, and traditional catchment sources. Effect on environment and natural system. Reliability of water supply, water quality, and average cost. Bigger scale than Aquacycle and better representation of a city.	(Peña-Guzmán et al. 2017; WaterCress 2015; Clark et al. 2002; Beh et al. 2015a,b; Clark et al. 2015)
WBM	Subdivision, catchment	Hourly or sub-hourly	No flow rate		In new version, the model adds an infiltration system	Widely used, especially for stormwater management. Assess the efficiency of site planning on stormwater management to achieve stormwater control under various conditions such as different land use, land cover, and climate scenarios. Four situations are considered by WBM: site surface alteration, site controls on base flow discharge, detention pond storage, and stream erosion.	(Bach et al. 2014; Bhaskar and Welty 2012; Binder et al. 1997; Charalambous et al. 2012; Chèvre et al. 2013; Richard Clark et al. 2002; Elliott and Trowsdale 2007; Haase 2009; Järvi et al. 2011; Marteleira et al. 2014; Peña-Guzmán et al. 2017; Renouf and Kenway 2017; Van Rooijen et al. 2005)

Model	Spatial Scale	Temporal Scale	Water flows	Water demand	Change Consideration	Strength/advantages	References
Urban Cycle	Lot, neighborhood, suburb	Sub-hourly (sub-daily)	Model detailed SW peak flows but not base flows	Diurnal variation	NA	Alternative selection by hierarchical network modeling, compared with traditional strategies. Simulating very detailed run off, demand, and wastewater. Able to predict the peak flow.	(Bach et al. 2014; Peña-Guzmán et al. 2017; Hardy et al. 2005; Mitchell et al. 2007a,b; Thyer et al. 2008; Hardy et al. 2007; Barton et al. 2007; Hardy et al. 2003)
UVQ	Lot, neighborhood, suburb, town, region	Daily	Temporal distribution of water flow	Diurnal variation	Non-structural changes to the system	It provides performance necessities for treatment processes to enhance reuse options and reduce environmental impacts, simplicity, rapid run time, and exploring 50 different scenarios	(Bach et al. 2014; Peña-Guzmán et al. 2017; Mitchell et al. 2007a,b; Marleni et al. 2015; Mitchell and Diaper 2006; Mitchell and Diaper 2005; Gurung et al. 2015; Gurung and Sharma 2014; Poustie and Deletic 2014; Cook et al. 2013; Leitner 2013; Tjandraatmadja et al. 2013; Martinez et al. 2010; Cook et al. 2010; Sharma et al. 2010)
MIKE URBAN	Neighborhood, suburb, town, region	Sub-hourly	Detailed flow rate of SW, WW, and WS	Diurnal variation	Considers urbanization, socioeconomic trends and climate change	Commercially used, it is a complex model, detailing flow rates in water supply, stormwater and wastewater. Very comprehensive algorithm for water quality. High detail but little run-time feedback between distinct water streams.	(Bach et al. 2014; Bisht et al. 2016; Gražina and Žibas 2013; Hammond et al. 2012; Liu et al. 2010; Mark et al. 2001; MIKE DHI 2017a, 2017b; Mitchell et al. 2001; Mitchell et al. 2007; Mitchell et al. 2007; Peña-Guzmán et al. 2017)
UWOT	Lot, neighborhood, region, city	10-min to monthly	Instead of simulating flow, the generation, aggregation and transmission of a demand signal simulated.	Demand signal including the quantity of the demand and quality of the water supply	Simulation of changes in behavior by frequency of use (demand oriented approach)	Incorporates Simulink/ MATLAB and Microsoft Excel into a decision support tool. Include sustainability factors such as environmental, economic, social and technical; includes indoor water efficiency usage and sustainable urban drainage options.	(Peña-Guzmán et al. 2017; Makropoulos et al. 2008; Rozos and Makropoulos 2013; Baki and Makropoulos 2014; Papariantafyllou and Makropoulos 2013; Koutiva and Makropoulos 2012; Rozos and Baki 2011; Bouziotas, et al. 2015; Makropoulos and Butler 2010; Rozos et al. 2010)
CWB	Neighborhood, city scale	Daily	Assessing sustainability in water flow	Demand input is based on per-unit area demand	Based on IPCC, the worst case scenario is used so the more extreme climate could be modeled.	Combine water efficiency options of UWOT and reuse options of Aquacycle but in much greater details. Best operation in larger scales.	(Bach et al. 2014; City Water Balance (CWB) _ Local Urban Partnerships n.d.; Last 2010; Mackay and Last 2010)
DAnCE4 Water	Lot, neighborhood, region, city	Daily		Diurnal variation	Change in different urban planning rules in future scenarios, climate and demographic change	Support SWWM, consider social, economics, urban form, ecology, energy and a number of sustainability indicators. Include 'what if' scenarios for dynamic evaluation	(Bach et al. 2011; Urich et al. 2012; Urich, Bach, et al. 2013)

Model	Spatial Scale	Temporal Scale	Water flows	Water demand	Change Consideration	Strength/advantages	References
WMOST	Watershed with the flexibility in the number of HRU*	Daily-monthly	Water flow of SW,WW, potable water, and combined sewer system	Demand time series for both potable and non-potable- Demand management	Future climate and growth scenario	WMOST models the environmental impacts and costs of management decisions in a watershed scale, including the impacts of decisions. Includes combined sewer overflow simulation and minimization.	(Detenbeck et al. 2018a,b)
WaterMet2	Neighborhood, region, subcatchment, catchment	Daily	Daily water flow rate, include graywater inflow.	Diurnal variation	GHG flux as a dominant factor in climate change	The main advantage is the evaluation of metabolism-based performance of water system.	(Behzadian et al. 2014; Behzadian and Kapelan 2015)

*HRU: Hydrologic response unit, SW: Stormwater, WW: Wastewater

4-2- Models' Assessment Indicators

In the second phase of the research, we categorized users' need in IUWM into several indicators that are needed in urban water management. These indicators are not being addressed well or been neglected in the earlier review papers. After categorizing different sectors in IUWM and looking into models' description and characteristics, we selected ten indicators that plays crucial role in the process of decision making in IUWM. These indicators include drinking water management (DWM), wastewater management (WWM), stormwater management (SWM), water balance, flood management (FM), quality, energy estimation, cost calculation, social factors, and policy (Table 3). DWM, WWM, and SWM were selected as our indicators because they are the three main components of IUWM, and as expected all the models cover them (Table 3). We selected, which is the main component of urban water cycle as the next indicator. Water balance is a vital indicator because it allows the users to define flows and different type of water (i.e. drinking water, stormwater, and wastewater) in the urban water cycle. FM is another important indicator selected here as it enables urban water managers to estimate the flood and damage due to the possibility of flooding in future and reduce the risks. Water quality is another important indicator which enables users to track the contaminants in urban water management. Energy and cost are also included as assessment indicators. Energy has a strong connection to water usage and management and needs to be investigated in IUWM. Also, cost is always an important factor for decision makers and is always needed for comparing various scenarios. Social factors and policy strategies are two of the indicators that are parts of complex urban water management that most of the time are not seen in connection to urban water cycle in decision-making process and in models (Table 3). Thus, we aim to see if the models cover these two indicators and to what extent. In the second stage, models were evaluated with regards to these indicators. Social factors, costs, and energy are among the less-frequent indicators (Table 3). In the third stage, the details of each indicator as presented in the models have been investigated. Of note is Table 3 can be a screening step by which users can quickly decide which models are more useful to meet their specific goals.

Table 3 Integrated urban water management indicators and their availability in the models

Model indicator	Sobek Urban	Aquacycle	Hydro Planner	WaterCress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4Water	WMOST	WaterMet2
DWM	×	×	×	×	×	×	×	×	×	×	×	×	×
WWM	×	×	×	×	×	×	×	×	×	×	×	×	×
SWM	×	×	×	×	×	×	×	×	×	×	×	×	×
Water Balance	×	×	×	×	×	×	×	×	×	×	×	×	×
FM	×			×				×			×	×	
Quality	×		×	×	×		×	×	×	×	×	×	×
Energy	×		×		×			×	×	×			×
Cost				×	×			×	×	×		×	×
Social Factors			×					×	×		×		
Policy											×	×	

DWM-drinking water management, WWM-wastewater management, SWM-stormwater management, FM-flood management

4-3- Models’ Application

During the third phase of the research, which is the most significant part of this review, models were investigated according to the assessment indicators that were identified during the second phase. After the screening phase, the potential users need to know more details under each indicator. Thus, in this stage we provided application’s subcategories to better help the user to select the most appropriate model according to the detail needs (Table 4). For example, there are eleven models that take into account the water quality in urban water management. However, each model considers a different group of water contaminants. As a result, we specified subcategories (Table

4) such as general contaminants, waterborne pathogens, nutrients, salinity, and sediments and dissolved substances. These subcategories help the users to be able to select the model according to specific water quality issues in the current system. Here, we introduced each indicator and the details under each indicator that the models cover.

Drinking Water Management

Drinking water management is covered by all of the models as it is one of the main components of IUWM. However, when look more carefully, the details in which the models consider this component are very different. While all the models cover water supply and demand, their approaches are sometimes different. For instance, Aquacycle estimates monthly or annual water demand, yield, and consumption (Pak et al. 2010) while, Hydro Planner is capable of developing the regional water allocation and water availability analysis. Hydro Planner also considers the growing effect of urban development, land use change, and climate change and takes into account water supply management strategies (Maheepala et al. 2005). Utilizing these strategies assist with maximizing the supply reliability and minimizing the negative effects on receiving water bodies (Kidmose et al. 2015). UVQ provides water demand scenarios and management and is capable of considering supply and demand at different spatial scales (Marleni et al. 2015; Poustie and Deletic 2014). UWOT is also able to manage the optimal distribution of demand to available resources (Marteleira et al. 2014). WaterCress evaluates a range of conventional and unconventional alternatives as well as the stability of water supply (Last 2010). The leakage reduction is an important issue in the water industry and water-distribution systems. It can cause a notable loss in water resources (Vairavamoorthy and Lumbers 1998). Annually, more than 32 billion m^3 is lost during the delivery of water supply. Of note is a number of models, such as MIKE URBAN (MIKE DHI 2017a), UVQ (Leitner 2013), WBM (Marteleira et al. 2014), WMOST (Detenbeck et al. 2018b) and CWB (Poustie and Deletic 2014; Martinez et al. 2010; Hoffman 2000), take into account water losses and provide leakage analysis and reduction. Efficient water distribution design can mitigate the challenges with such systems. Efficient design and quality management is one of the capabilities of MIKE URBAN(Gražina and Žibas 2013; Thorndahl et al. 2016). CWB simplifies city water systems temporally and spatially in distribution systems (Last 2010) and UWOT also covers transmission and distribution of water as an urban water balance (Papariantafyllou and Makropoulos 2013). Other models partially cover the distribution system or do not include it at all. For instance, Urban Cycle is not able to evaluate systems with transferred back water to upstream nodes or complex distribution systems with multifaceted functioning rules, linking to the accessibility and use of water, dictate how flows are controlled (Graddon et al. 2010).There is only one model (WaterCress) that allows the users including farmers to model their own water supply capacity, planners to develop water allocation plans, and designers to link any source of water to any demand (WaterCress 2015; Cresswell et al. 2011). Other capabilities of the models such as water treatment options, abstraction from hydro-systems, and alternative water infrastructure options, are described Table 3.

Wastewater Management

Wastewater management including collection, treatment and reuse is another important capability of the models in IUWM. More than half of the reviewed models include these wastewater management capabilities (Table 3). Some of the reviewed models also consider additional components in wastewater management. For instance, WaterCress considers the wastewater treatment plant extension design (Marks et al. 2006). Hydro Planner is capable of simulating wastewater, associated constituent generation, and routing processes via wastewater modules (Grant et al. 2006). Hydro Planner considers wastewater and supply water, their interactions, and how they affect the environment (Maheepala et al. 2005). Aquacycle is capable of storage analysis, and characterization of wastewater quantity and temporal and spatial distribution(Ewater 2018; Mitchell 2005). UVQ has the ability to specify different water systems within neighborhoods and the order in which stormwater and wastewater flows from one neighborhood to another (Mitchell and Diaper 2005). UVQ compares wastewater management alternatives against the traditional approaches and considers the nutrient loads and treatment removal efficiency (Poustie and Deletic 2014).

Leakage analysis and reduction is crucial due to its significant impact on groundwater and soil pollution reduction. Leaky sewage system has been identified as one of the main sources that contaminate groundwater (Ellis et al. 2003; Wakida and Lerner 2005). Sulfide gas formation is another issue that must be managed in wastewater system as it causes toxicity to sewer workers and concrete corrosion (Zhang et al. 2008; Hvitved-Jacobsen et al. 2002). Among the models, MIKE URBAN covers the wastewater leakage analysis and reduction and sulfide gas formation analysis (MIKE DHI 2017a). MIKE URBAN is capable of supporting the city’s water and wastewater master plan and enabling the user to make future simulations for a cost-effective and resilience wastewater collection system, capacity management and operational maintenance. MIKE URBAN does the geocoding of catchment networks, wastewater loads, and demand distribution. It optimizes system performance to decrease the problem with combined sewer overflow and estimates the effect of river flooding on the sewer system. MIKE RBAN combines 1-D sewer modeling with 2-D overland-flow modeling (MIKE DHI 2017a).

It is also important to consider if the model can consider centralized versus decentralized wastewater management technologies. For example, CWB simulates the water flow but it is designed only for decentralized technology and does not estimate the cost and energy usage of centralized systems (Last 2010). Urban cycle, for instance, is capable of very detailed water demand and wastewater simulation at sub-daily time scales (Graddon et al. 2010). Table 3 represents other capabilities of models in wastewater management.

Stormwater Management

It is now known well that stormwater management involves more than just drainage design and flood risk reduction, which have been practiced traditionally. The traditional practice is changing into more sustainable stormwater management, and it is evident not only in flood reduction, but also in pollution minimization, urban landscape improvement, and drainage investment reduction (Brown 2005). Almost all of the models include the drainage design (Table 3). But as models consider sustainability more, they look at stormwater as a resource that can be captured and reused (i.e. aquifer recharge) (Duong et al. 2011). For example, Aquacycle has the capability to cover alternative strategies such as rain tanks, cluster stormwater systems, catchment stormwater systems, subsurface direct greywater irrigation, aquifer storage, and wastewater recycling at unit, cluster and catchment level. Also, the Aquacycle basic model works similarly to Urban Cycle; however, Urban Cycle includes less alternative strategies (Last 2010). All of the reviewed IUWMMs are able to design and evaluate at least some of the best management practices (BMPs). Rainwater harvesting, an important aspect of stormwater management and reuse, is also covered by most of the models (Table 3). Models like UVQ (Poustie and Deletic 2014) and Hydro Planner are able to simulate the constituent generation and routing process in stormwater management system (Pak et al. 2010). Aquacycle is among the models that not only focuses on hard engineering, but also considers the impact of green infrastructure on the water balance (Chenevey and Buchberger 2013).

WaterCress (Marks et al. 2006), Aquacycle (Donia et al. 2013), UVQ (Mitchell and Diaper 2005, 2006), and WBM (Marks et al. 2006) consider stormwater harvesting, water storage, and its size optimization. WBM allows users to assess the efficiency of site planning with stormwater management strategies (e.g. absorbent landscaping, infiltration facilities, green roofs, and rainwater harvesting) and attaining expansion goals for rainwater detention and runoff control under different land uses, soil, and climate conditions (Beckers et al. 2009). UVQ explores the influence of shifting urban system and grade of drainage connectivity on the features of stormwater runoff (Mitchell and Diaper 2006). This model emphasizes the interconnections of the water supply, stormwater and wastewater system, the direction in which stormwater moves from one neighborhood to the other, and the capability to identify different water systems within the neighborhood (Mitchell and Diaper 2005).

Graywater reuse and rain harvesting for non-potable uses are great alternatives for conserving water (Al-Jayyousi 2003). Among the models reviewed in this study, Aquacycle reflects subsurface irrigation with graywater (Donia et al. 2013), WBM is capable of using graywater for non-potable (Marteleira et al. 2014) uses, and UWOT has the integration through recycling scheme including graywater, treated water, and rainwater (Rozos and Makropoulos 2012).

Water Balance

One of the initial applications of water-cycle models is to assess the water balance in the system. This application enables users to identify the different flows (water, wastewater, and stormwater). Water balance is the movement of water in the hydrological cycle—in our case, the urban cycle. The basic water balances in all of the models is the changing in storage, which is sum of input minus sum of outputs (Mitchell et al. 2003) (Eq. 1).

Eq.1 $$(P + I) = (E + D) + \Delta S$$

Where, ΔS is change in storage, P is precipitation, I is imported water E is evapotranspiration, and D is drainage. In places with an unconnected drain system, D consists of D_w as wastewater and D_s as stormwater (Mitchell et al. 2008a). Models included in this review can perform the water balance, a primary need in urban water cycle. Aside from performing the daily water balance, Aquacycle considers the various water recycling options and their influences on the water cycle as they may increase the water supply and decrease wastewater and stormwater (Mitchell et al. 2003). Aquacycle's outputs consist of water balance, with daily values for precipitation, evapotranspiration, piped water supply, stormwater, drainage and wastewater collection (Duong et al. 2011). Several models developed after Aquacycle, such as

UVQ, consider contaminant loads at each receiving point under different scenarios in the total water cycle (Mitchell and Diaper 2005).

Water Quality

Eleven models can perform the water-quality analysis at different levels. In MIKE URBAN, the user can track age of water, dissolved contaminant fate, growth of microorganisms, and decay of substances. Users can consider mass inflow rate and concentration level to determine the water quality. MIKE URBAN models the bulk flow reactions by n^{th} order kinetics and pipeline reactions by zero or first order kinetics. The critical water quality features in MIKE URBAN are water age analysis, chlorine concentration and path, and concentration of pollutant analysis (DHI 2018b; Gražina and Žibas 2013). Sediment, dissolved substances, transport modeling, water quality risk analysis (Liu et al. 2010), and water distribution system operation efficient design and quality management are among the capabilities of this model (Gražina and Žibas 2013). MIKE URBAN uses the EPANET engine for water quality in pipe systems (DHI n.d.). The catchment module in Hydro Planner supports the linking of models that can simulate contaminant and run-off generation (Grant et al. 2006; S Maheepala et al. 2005). Hydro Planner is capable of constituent balance analysis, including sediment, nutrients, pathogens, and contaminants (Grant et al. 2006). In addition to the quality of supply water (Marks et al. 2006; WaterCress Hydrology 2015), WaterCress does salinity tracking and water quality ranking et al. 2002). UVQ shows the application needs of treatment procedures and tools to accomplish user indicated water quality discharge attributes as well as the specifics of water flow and quality from land blocks areas (Mitchell and Diaper 2005). WBM also tracks and simulates the water quality and contaminant load (Järvi et al. 2011). CWB explores water-borne contaminants using a basic image of city water systems (Last 2010). In UVQ, contaminants are conveyed on a monthly or yearly basis within an urban area. UVQ predicts and track the contaminant load and its primary sources (Mitchell and Diaper 2005,2006; Marleni et al. 2015). In this model, stormwater, wastewater, water supply, and groundwater are represented at the same time. In addition, it covers the impact of different water management strategies on contaminant flow in the urban environment and its effect on subsurface discharge and surface water (Mitchell and Diaper 2005). It also looks at contaminant load and imported water contaminant concentration (Martinez et al. 2010; Poustie and Deletic 2014; Wolf et al. 2007). Water Met^2 considers the quantification of nutrients and waste in urban regions (Kourosh Behzadian and Kapelan 2015). WaterCress can track salinity changes from source to sink as well as other general water quality parameters (Clark et al. 2002) (Table 3).

Flood Management

Urban water managers have a great interest in flood management and estimating flood damage in order to evaluate the adaptation measures and to address increased flood risks (Olsen et al. 2015; Zhou et al. 2012). Flooding costs, especially in urban areas, are high and need careful attention to prevent large-scale damage (Freni et al. 2010). Flood management has been included in 5 models studied in this research. Of note is some of the models have been initially developed to perform flood management modeling and simulation as one of their main capabilities. For instance, flood management is the main use of MIKE URBAN and Sobek Urban. Assessment, monitoring, and optimization of drainage system are among the important function of these two models (Peña-Guzmán et al. 2017). MIKE URBAN is able to simulate flood extension and inundation. MIKE URBAN model simulates 2D overland flow and GIS integration. It also able to simulate flood extension and inundation (Bisht et al. 2016). It provides emergency response planning for urban flooding and solutions for local urban flooding through the design of mitigation measures such as efficient drainage systems (Hammond et al. 2012; DHI 2017b; Bisht et al. 2016; DHI 2018a). Since MIKE URBAN is a two-dimensional model, it can also be used to determine the impact of boundary walls on flooding (Bisht et al. 2016). In addition, MIKE URBAN evaluates the effects of river floods on sewers and estimates maximum water depth for flood assessments (MIK DHI 2016; Olsen et al. 2015). WaterCress is likewise capable of flood modeling, but it links the model with hydrological databases. It also provides the capacity to run real-time resource and flood assessments (WaterCress 2015). DAnCE4Water considers indicators for performance of urban water infrastructure. These indicators are rates of sewer overflows and flooding (Renouf and Kenway 2017). The WMOST model has a flood damage module which calculates the damage caused by flood and the cost for its management.

Energy

Energy is becoming a crucial factor for decision makers due to its strong interconnection to water sectors in urban water systems. Until recently, analysis of energy implications in water- and wastewater-related strategies has been very limited despite many challenges such as the growth of energy consumption and prices (Baki and Makropoulos 2014). For urban water services, energy is linked with water in different stages such as bulk water harvesting and transport, water treatment, water distribution, wastewater collection and treatment, and finally effluent discharge. The energy associated with stormwater and decentralized supplies are less considered in urban water management. The reason is stormwater and decentralized supplies are comparatively minor components of urban water supplies. For instance, the water and energy use linked with rainwater tanks are not comparable to urban water supplies. There are three ways for energy considerations in models including estimation of energy consumption, lifecycle energy use, and energy and greenhouse gas (GHG) emission. Hydro Planner has the capability to quantify system-wide energy usage and GHG emissions at various scales and under different management scenarios (Mirza et al. 2013). MIKE URBAN can model the cost of operating pumps. Within the Pump Energy Editor, the user can define a method for cost calculation. UWOT is capable of modeling water-energy interaction in the whole urban water system (Baki and Makropoulos 2014). This model takes into account the energy used in pumping potable water, groundwater, and seawater desalination and required for pumping, treating, and discharging water (both potable and reclaimed) in the distribution system (Papariantafyllou and Makropoulos 2013). The simplified life cycle energy is used in the form of spread-sheet models and used for both water supply and treatment using published values for energy consumption per cubic meter. It calculates lifetime energy use as the addition of embodied energy of all the parts, energy consumption of fuels for construction, maintenance, and operation. It also takes into account the electricity needed for pumps and the energy needed for chemical treatments (Mackay and Last 2010). CWB considers life cycle energy and costs. It calculates a simplified life cycle inventory of energy. This can be listed as construction, operation and decommissioning (Last 2010).

Cost

Cost is one of the important indicators especially when decision makers are evaluating and comparing multiple scenarios. There are different levels of calculating cost in urban water systems. Whole life costing, capital and operating cost, and operational and maintenance cost are different cost levels that have been included in the reviewed models. Of note is some of the reviewed models consider more than one level of cost. For instance, UWOT considers both whole life costing and capital and operating cost. In addition, it considers other qualitative indicators, such as life cycle cost, willingness to pay, affordability, and associated financial-risk exposure (Last 2010; Makropoulos et al. 2008) In addition, UWOT provides information concerning water demand and investment costs for the substitute local water technology configuration (Koutiva and Makropoulos 2012). WMOST considers operational and maintenance cost and cost-benefit analysis (Last 2010; Detenbeck et al. 2018b). WaterCress, enables users to estimate capital, operating, and unit cost of functioning system components (Barton et al. 2007; Cresswell et al. 2011; Marks et al. 2006). CWB calculates the whole life cost, including the costs of capital, construction, maintenance and operation. In CWB, costs occurred during the lifetime of the asset are adjusted to net present value (Mackay and Last 2010). Water Met^2 considers operational and maintenance cost which is dependent on the electricity and fuel per cubic meter of amount of water consumption (Behzadian et al. 2014a) (Table 4).

Social Factors

Integrated urban water systems are multifaceted and understanding the dynamics of such systems, from supply sources to end users, is complex (Ewater 2018). In addition to change in hydrology and precipitation rate, behavioral changes also affect the water resources. Behavioral changes can be linked with climate change and change in demand (Cavanagh et al. 2002). End user behaviors are variable due to the introduction of alternative water resources, such as water management options and direct and indirect drivers for water consumption (Campbell et al. 2004; Cavanagh et al. 2002; Grant et al. 2006; Jorgensen et al. 2009). In addition, researchers state that social awareness and exposure to water deficiency in various parts of the world has caused people to value water and consume it less (Beal et al. 2010; Jones et al. 2011; Jorgensen et al. 2009). Demographics (e.g. age, income level, education level, and family size) and household characteristics (e.g. house size and type, outdoor facilities, and water technologies) also affect environmental behavior (Koutiva and Makropoulos 2012). We should consider anticipating the demand at the end-use level and how different factors such as climate change may alter this behavior. Very few models have considered social factors. Hydro Planner, for example, can simulate the effect of end user behavior alteration on the performance of supply system and the water quality. The user can use Hydro Planner to evaluate supply system. This model takes into account the probable changes in climate, population, technological change and variations in future demands and management (Maheepala et al. 2005). UWOT also considers changes in behavior, including the time series of frequency- of- use and technological change (Rozos and Makropoulos 2013). UWOT includes other social indicators such as risk to human health, acceptability, participation/ responsibility, public awareness, and social inclusion. These indicators are qualitative, so they are rated in 5 rates (Makropoulos et al. 2008). In addition, one of the functions of UVQ is considering water usage behavior and changing in household occupancy (Mitchell and Diaper 2006). End-use data can be used in Urban Cycle for various demand reduction scenarios to evaluate their effect on design indicators. Six end-use categories (toilet, shower, dishwasher, washing machine, tap, and outdoor) can be considered in a household level (Thyer et al. 2008).

The impact of population growth and urbanization on the frequency and magnitude of flooding (Huong and Pathirana 2013; Semadeni-Davies et al. 2008) and water quality problems are not negligible (Arora and Reddy 2013; Hatt et al. 2004). HydroPlanner evaluates future scenarios such as population growth and potential changes in demand, while MIKE URBAN simulates a number of scenarios by considering demography, urbanization, and other parameters (MIK DHI 2016).

Although these models include social factors to some extent, there is still lack of proper tools to evaluate socio-technical features. DAnCE4Water is one of the IUWMMs aimed at addressing the societal dynamics issues. This model deals with social and institutional implications of urban water systems rather than biophysical implications. It considers different scenarios of urban water servicing explanations in meeting water-related societal needs (Haan et al. 2012).

Policy

Governmental policies influences land use plans and growth boundaries which can be important in the decision-making process of managers. There are only two models considering this indicator. DAnCE4Water covers the governmental policy assumptions and assesses policy influences by showing market reactions (Urich et al. 2012). WMOST permits water resources managers to assess policy management option within a watershed. Managers can specify the limits of land area under each management situation in case the physical limitations are associated with policy requirements (Detenbeck et al. 2018a).

Table 4 Details of model's application

Indicators	Application	Sobek Urban	Aquacycle	Hydro Planner	Water Cress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4Water	WMOST	Water Met^2	Ref
DWM	Supply and demand	√	√	√	√	√	√	√	√	√	√	√	√	√	(Maheepala et al. 2005; Mitchell 2005; WaterCress 2015; Mitchell and Diaper 2005, 2006; Last 2010; Gražina and Žibas 2013; Duong et al. 2011; Marleni et al. 2015; Gurung et al. 2015; Poustie and Deletic 2014; Beh et al. 2014, 2015a; Barton et al. 2007; Marteleira et al. 2014; Marks et al. 2006; Grant et al. 2006; Baki and Makropoulos 2014; Thyer et al. 2008; Bach et al. 2013; Behzadian et al. 2014a; Detenbeck et al. 2018a)
	Water availability analysis			√											(Maheepala et al. 2005)
	Water distribution								√	√	√	√	√	√	(Mitchell 2005; Last 2010; Gražina and Žibas 2013; Papariantafyllou and Makropoulos 2013; Graddon et al. 2010; Bach et al. 2013; Behzadian et al. 2014a; Detenbeck et al. 2018b)
	Regional water allocation			√											(Maheepala et al. 2005)
	Leakage analysis							√	√		√		√		(DHI 2018a; Mitchell et al. 2003; Donia et al. 2013; Duong et al. 2011; Poustie and Deletic 2014; Leitner 2013; Martinez et al. 2010; Rueedi et al. 2009; Detenbeck et al.2018a)
	Hydro system abstraction									√					(Baki and Makropoulos 2014)
	Allow farmer, designer, and planner to model their own need				√										(WaterCress Hydrology 2015)
	Alternative water infrastructure option				√										(Mitchell and Diaper 2005)
	Treatment option						√	√		√				√	(Graddon et al. 2010; V. G. Mitchell and Diaper 2006; Papariantafyllou and Makropoulos 2013)
WWM	Wastewater and graywater reuse		√	√		√	√			√	√		√	√	(Behzadian et al. 2014; Detenbeck et al. 2018a; Donia et al. 2013; Kinsman et al. 2012; Mitchell and Diaper 2005; Mitchell et al. 2003)
	Wastewater treatment options		√	√						√				√	(Donia et al. 2013; Papariantafyllou and Makropoulos 2013; Mirza et al. 2013; Behzadian et al. 2014a)
	Wastewater storage/capacity		√						√				√		(Donia et al. 2013; Roldin et al. 2012; Mitchell 2005; Mitchell et al. 2008b; Detenbeck et al, 2018a)
	Neighborhood WW flow							√							(Mitchell and Diaper 2005)
	Simulation of sewer flow	√	√					√	√		√	√	√		(Last 2010; Marleni et al. 2015; Mitchell et al. 2003; Thorndahl et al. 2016; Mitchell 2005; Situmorang 2008; Mitchell et al. 2008a; Renouf and Kenway 2017; Faraji 2015; Detenbeck et al. 2015)
	Leakage reduction							√	√						(MIKE DHI 2017a; Rueedi et al. 2009)
	Sulfide gas formation analysis								√						(MIKE DHI 2017a)
	Extension design				√										(Marks et al. 2006)
	Effect of river flood on sewer								√						(MIK DHI 2016)
SWM	BMPs	√	√	√	√	√	√	√	√	√	√	√	√		(Chenevey and Buchberger 2013; Grant et al. 2006; Donia et al. 2013; Shukla et al. 2011; Gurung et al. 2015; Gurung and Sharma 2014; Thyer et al. 2008; Last 2010; DHI 2017b; Mirza et al. 2013; Mackay and Last 2010; Paton et al. 2014; Urich et al. 2011; Bach et al. 2012; Schmitter et al. 2016; Detenbeck et al. 2018a)

Indicators	Application	Sobek Urban	Aquacycle	Hydro Planner	Water Cress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4Water	WMOST	Water Met^2	Ref
	Drainage design	√	√	√	√	√	√	√	√	√	√		√	√	(Maheepala et al. 2005; Bisht et al. 2016; QUALHYMO 2017; Last 2010; WaterCress 2015; Mitchell and Diaper 2006; Duong et al. 2011; Makropoulos et al. 2008; Poustie and Deletic 2014; Hardy et al. 2003; Behzadian et al. 2014a; Faraji 2015; Detenbeck et al. 2018a)
	Rain water treatment/ reuse		√	√	√	√	√	√		√					(Bisht et al. 2016; Zhang et al. 2009; Duong et al. 2011; Shukla et al. 2011; Mirza et al. 2013; Cresswell et al. 2011; Papariantafyllou and Makropoulos 2013; Rozos and Makropoulos 2012; Koutiva and Makropoulos 2012; Graddon et al. 2010; Behzadian, et al. 2014a)
	Optimizing storage size		√		√			√			√			√	(Donia et al. 2013; Gires and De Gouvello 2009; Last 2010; Mitchell and Diaper 2006; Cresswell et al. 2011; Marks et al. 2006; Goonrey et al. 2009)
	Runoff management			√		√	√			√		√	√		(Beckers et al. 2009; Graddon et al. 2010; Makropoulos et al. 2008; Grant et al. 2006; Marks et al. 2006; Urich et al. 2011; Behzadian, 2014a; Detenbeck et al. 2018b)
	Impact of GI on Water balance		√												(Chenevey and Buchberger 2013)
	Average run off assessment				√								√	√	(Marks et al. 2006; Detenbeck et al. 2018b)
	Rainfall inflows and infiltration mitigation								√				√		(Bisht et al. 2016; Detenbeck et al. 2018b)
	Planning for measures considering overland flow								√						(DHI, 2018a)
Water balance	Entire water cycle modeling/water balances	√	√	√	√	√	√	√	√	√	√	√	√	√	(Pak et al. 2010; Beh et al. 2015; Mitchell and Diaper 2006; Mitchell and Diaper 2005; Baki and Makropoulos 2014; Papariantafyllou and Makropoulos 2013; Rozos and Baki 2011; Beh et al. 2014b; DHI 2018; Barton et al. 2007; Mirza et al. 2013; Thyer et al. 2008; Urich et al. 2011; Behzadian and Kapelan 2015; Faraji 2015; Detenbeck et al. 2018a)
	Climate change			√					√			√	√		(Hammond et al. 2012; Grant et al. 2006; Maheepala et al. 2005; Urich et al. 2011; Detenbeck et al.2018a)
	Different water servicing/demand		√					√				√	√		(Mitchell and Diaper 2005; Mitchell and Diaper 2006; Urich et al. 2012; Detenbeck et al. 2018b)
Energy	Energy production and consumption estimation	√		√					√	√	√				(Mirza et al. 2013; Last 2010; DHI 2018a; Schwanenberg and Becker 2017)
	Life cycle energy use										√				(Last 2010)
	Energy and GHG emission linkage			√										√	(Behzadian et al. 2014; Mirza et al. 2013)
Quality	General contaminants	√		√	√	√		√		√	√	√	√	√	(Marleni et al. 2015; Maheepala et al. 2005; Last 2010; Mitchell and Diaper 2005, 2006; Shukla et al. 2011; Poustie and Deletic 2014; Järvi et al. 2011; Clark et al. 2002; Makropoulos et al. 2008; Rauch et al. 2012; Behzadian and Kapelan 2015; Faraji 2015; Detenbeck et al. 2018a)
	Waterborne pathogens			√							√				(Last 2010; S Maheepala et al. 2005)
	Nutrient			√										√	(Behzadian and Kapelan 2015; Maheepala et al. 2005)
	Salinity				√										(Richard Clark et al. 2002; Cresswell et al. 2011)
	Sediment and dissolved substances			√					√						(Liu et al. 2010; S Maheepala et al. 2005)
Cost	Whole life costing									√	√				(Last 2010; Mackay and Last 2010)
	Cost benefit analysis								√				√		(Detenbeck et al. 2018a; DHI n.d.)
	Capital and operating cost				√					√					(Barton et al. 2007; Cresswell et al. 2011; Koutiva and Makropoulos 2012; Marks et al. 2006)

Indicators	Application	Sobek Urban	Aquacycle	Hydro Planner	Water Cress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4Water	WMOST	Water Met^2	Ref
	Operational and maintenance cost												√	√	(Detenbeck et al. 2018a;Behzadian et al. 2014a)
Social factors	Changing end user behavior			√			√	√		√					(Maheepala et al. 2005; Mitchell and Diaper 2006; Rozos and Makropoulos 2013; Thyer et al. 2008)
	Technological change			√						√		√			(Maheepala et al. 2005; Rozos and Makropoulos 2012; C. Urich et al. 2012)
	Demography and urbanization			√					√			√			(DHI 2017a; Maheepala et al. 2005; Urich et al. 2011)
FM	Flood simulation/ assessment	√			√				√			√	√		(WaterCress 2015; Bisht et al. 2016; Urich et al. 2013; Faraji 2015; Vanderkimpen et al. 2009; Detenbeck et al. 2018b)
	Design of mitigation measures								√						(MIK DHI 2016)
	Emergency response planning								√						(MIK DHI 2016)
	Estimation of potential risks	√							√						(Faraji 2015; MIK DHI 2016)
	Damage costs												√		(Detenbeck et al. 2018b)
Policy												√	√		(Detenbeck et al. 2018a; Urich et al. 2012)

4-4- Models Input

During the fourth phase of this research, the input requirement of the reviewed models was identified. Identifying of the required inputs for the models can help the users to see what type of data is needed as an input for each IUWMMs. Obviously, depends on the outcome a user is looking for, the input requirements are different. We can divide the input requirement into two parts including primary and secondary inputs. The primary inputs are climate, water flow, land use and land cover, population, and contaminants. Precipitation and evapotranspiration are the most important climatic inputs that are required by all of the reviewed models. Temperature, rainfall intensities, and antecedent dry days are also needed in some of the models. Water flow including drinking water, wastewater, and stormwater input data is another primary input. Water volume, drinking water leakage, imported water, maximum water depth for flood assessment, daily demand time series, water availability for supply and demand, water consumption (indoor such as kitchen water use, bathroom, toilet, and laundry and outdoor such as garden irrigation) are among water flow data. Wastewater flow run off (roof, pavement, garden, road, and public open spaces), stormwater volume, stormwater (effective area, soil store capacity, and drainage factor) are other data requirements for water flow. Land use/ land cover is another main input (pervious and impervious areas) that is required in some of the models. Population data and household occupancy are important inputs to estimate per capita water demand. Contaminant loads are the inputs for models with the capability of contaminant simulation. Other inputs of these models are capacity and estimation of needed storage, maximum storage volume, and tank size. Secondary inputs are not common among models. For example, MIKE URBAN, due to its capability needs, inputs such as catchment characteristics, node and link input, location and physical characteristics of manholes, pipe, canals, and GIS data. Thus, for such inputs, user need to first select a model and based on the specific needed output, collect related data. Furthermore, knowing the spatial and temporal scale of the models (Table 2) can also help the user to see the data interval needed for the input.

4-5- Selecting the Models

Decision- support tools based on IUWMMs has become progressively popular in coupled human-natural systems. In the last stage of this review, we provided a procedure to better help with selection of the most appropriate model based on specific needs and available data. The iterative procedure is presented in Figure 3. The proposed procedure includes (1) determination of the goals (2) selection of the indicator(s) (3) study the capabilities of available models, (4) identifying the input requirements, (5) and, finally, selecting the best option.

The starting point is to specify the overall goal and the needs in urban water systems. Problem identification is the first step that usually incorporates in urban water frameworks (Garcia et al. 2016; Hellstro 2000; Pearson et al. 2009). The purpose here is to evaluate the limits of the current urban water system and identify the objectives to move forward with decision-making in different spatial and temporal scales. Defining the system boundaries and specifying the scale is a crucial step in determination of the goal and could be helpful to ultimately select a model (Table 2). Attempts to define the needs of the system is an important prerequisite for selecting the goal indicators.

The next step is to select the goal indicators. Table 3 represents the preliminary information for the users. Through screening, the user can initially select the models that could be useful for reaching the goal. This step is useful to eliminate the models that are not addressing the goal and pave the path for better analyzing the models with the capability of achieving the objectives. For instance, if one of the main goals of an urban water manager is flood management, a user can screen the Table 3 and initially select Sobek Urban, WaterCress, MIKE URBAN, DAnCE4Water, and WMOST. Thus, we don't need to investigate the rest of the models. One of the important paces in such iterative process is to evaluate the current knowledge of the user and take steps back to modify the intention and problem definition. If the user is not sure what indicator to select in this step, more study within the boundary on the limitations of the system is needed. After new insight has been gain from the study of the current system, the user can continue selecting a model.

The next step is to evaluate the models and finally select the best model. Comparing models with desired indicators is not always enough for selecting model. To better decide which model fits the user's specific purpose more details on application of the models are required (Table 4). For example, in the case of flood management, if the user is interested in estimating potential risks beside flood simulation, then Sobek Urban and MIKE URBAN are the two models that can be used. When damage cost is more important, then WMOST is the more appropriate model.

Following the model selection, the next step is determination of input requirement. The inputs are totally depending on the spatial and temporal scale of the urban water system and the specific goals of the user. Section 3-4 of this paper introduced the primary and secondary input needed for such models; however, this step requires more specific data based on the goal of the users. For instance, if the user interested in tracking water quality, then obviously, the input data in the case of salinity as the targeted pollution is different from the case of waterborne pathogens input. As mentioned earlier, determination of the input is also dependent on temporal and spatial scales (Table 2). If the user reaches a point that two or more models are appropriate for her specific purpose and there is not enough data available, the user can use the model that needs less input requirement. For instance, CWB needs hourly or sub-hourly data, while Aquacycle only requires daily data. Thus, if graywater reuse is the purpose, Aquacycle can be used, which needs less data than CWB.

After determination of the input requirements, user can collect information for the specific case studies. The user can use the collected data to run the model and finally get the output (Figure 3). The final step is to evaluate the output in order to achieve the desired goal. If the user gains insufficient output, the gathered input data can be checked to improve the results.

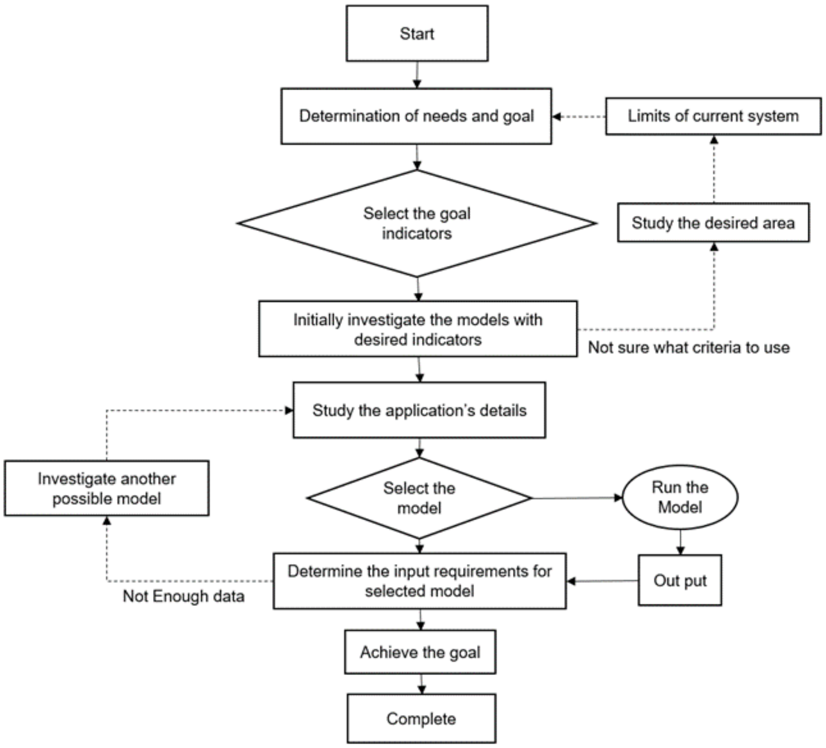

Figure 3 Decision-making procedure for selecting IUWMMs

5- Conclusions

Integrated urban water management is gaining attention due to the high rate of urbanization, water scarcity, and climate variability. Handling urban water resources in which drinking water, wastewater, and stormwater (three main components of urban water cycle) interact with each other is not an easy task. A holistic view on integrated urban water management under different circumstances can be better achieved if the users select the right tool for decision making. Models has gained attention as those are tools that allows decision makers to treat the system considering the system dynamics and the interaction among different component of water cycle. Although models are great tools in decision making process, the specific needs of each system are different and without knowing the details of models' application, selection of the most appropriate model is a challenging task. Thus, this review was undertaken to introduce commonly used IUWMMs, their characteristics, strengths, and practically compare their detailed capabilities. This article reviews characteristics and the focus of each model and then introduces ten important indicators that might be the interests of decision makers and practitioners. Evaluating IUWMMs considering the included indicators can be the first step for model selection. Consequently, the detailed application provided here further assist the users for better IUWMMs selection. In addition, we introduced common types of input to help the users to know the primary and secondary input requirements for IUWMMs. Ultimately, this review presents a decision-making framework for decision-makers and practitioners to select the best model that meet their goals. This framework will help decision makers select the most appropriate model. This paper aims to assist decision-makers to use the IUWMMs as currently such models are usually used in academia. However, we aimed to promote using IUWMMS in decision making environment. Also, available review papers' focus on the technical part of the models and seem to be more beneficial to model developers.

This review was undertaken to highlight the detailed application of IUWMMs. Through this process we perceived that in the drinking water section, the vast majority of the models are focused on water supply and demand. However, leakage analysis in water distribution systems which contributes to a great loss in urban water resources only considered by several models. Wastewater and graywater reuse is the capability of many models which is very beneficial in IUWM but extension design of wastewater network which is needed in further wastewater development is only covered by one of the models. Also, in stormwater management the focus of models is largely on hard engineering and other important considerations such as impact of green infrastructures on water balance are less reflected. By analyzing other indicators, we found out that few models take into account the social and policy, although those factors are very influential on the decision-making process. The results highlighted in this article show that IUWMMs have the potential to fulfill the user's need. Thus, the procedure introduced herein assist the decision makers to step by step select the goal indicators based on the current issues in their water system and finally select the best model. This article provides the potential to move toward implementing the concept of IUWM that has not still completely applied in decision making environment.

Despite the growing development of IUWMMs, there are still several important gaps in the outputs of the models. Emphasizing IUWMMs' limitations are helpful for the future development. In the future, IUWMMs needs to be more integrated as existing models includes individual systems in one package without considering interconnections. The analysis of separate systems such as energy or water system are undertaken usually but without considering water-energy nexus even in the integrated models that are designed to be as an integrated package. Considering this interrelationship is critical to help with potential synergies and concerns. For instance, identifying drinking water supply and demand is in connection with the energy needed in water treatment system and pumping water into distribution system. One of the reasons behind this might be the separation between the institutional entities that manage water and energy and the disconnection and fragmentation between them. Also, the commonly used models in these two systems are different. Thus, integrating those in IUWMMs can be beneficial for potential multi-stakeholder teams.

Also, the dynamics of social characteristics of urban environment needs to be considered in futures of IUWMMs. Although demographic changes and end-use-behavior has been covered by several models using different scenario analysis, more anthropogenic influence on urban water systems such as influence of income level and social status should be incorporated into models. Furthermore, ecosystem services evaluation is another feature that can be added to models specifically in stormwater management. Providing options on selecting various needed ecosystem services such as provisioning, regulating, cultural, and supporting services which can be led to the best option selection is missing in the models. This could be useful for comparing different water management scenarios when a decision-maker wants to decide among various options. For instance, it enables decision makers to compare different stormwater BMPs suitable for a specific area not only from the cost and their capacity to mitigate stormwater but also based on the other benefits such providing cultural and supporting ecosystem services for people living in that area. Finally, models need to have the upgrading capability based on the applications needed by decision makers. More involvement of decision makers in model development to provide feedbacks will enable the developers to improve the models' capabilities as some of the models lacks these capabilities.

Lastly, although this article tried to attract the decision maker's attention and pave the way for better urban water management, other users such as model developers, researchers, managers, and other entities can also benefit from the results of this research. There is an improving trend toward using IUWMMs more in the decision making, and recent models cover the deficiencies found in earlier models. But there are still more improvements needed that are necessary. Including ecosystem services and water-energy nexus in the models are the examples of such deficiency. Models require to have the capability of upgrading with the application needed by decision makers to address new needs. Finally, there is a need to move toward using models that consider natural systems, economics, social and policy factors.

6- Acknowledgement

The authors would like to thank Josh Mendes from MIKE URBAN-DHI, Drs. Ashok Sharma, Mukta Sapkota, Stwart Burn, Chiros Makropoulos, Marc Soutter, Mircea Stancu, and Jeremie Bonneau for their advice and feedback on collected data and on integrated modeling literature.

Chapter 3: linking Stakeholder Perceptions of Ecosystem Service Supply and Demand for Green Infrastructure Decision-making in a Semi-arid City

Abstract

Green infrastructure (GI) is an approach to managing stormwater at its source that also delivers many ecosystem services. To effectively manage cities using GI ecosystem services the linkages between provision of services and governance priorities and ecosystem service demands need to be made explicit. Identification of stakeholder knowledge and objectives in GI decision-making contexts with respect to ecosystem services may improve urban planning; yet this information are rarely explicit in local contexts and cases. We aim to address this gap by asking, how do ecosystem services influence environmental stakeholders' perceptions and practice of GI in Tucson, AZ? This study utilizes an online survey to investigate the perception of 63 managers and practitioners on ecosystem services' supply and demand, ecosystem disservices, and the connection between perception and practice of stakeholders in this region. Results indicate that prioritization of stakeholders are exclusive to the unique environmental condition and urban design in this semi-arid environment focus on water sustainability and urban heat mitigation. We found strong agreement in environmental perceptions between different management sectors. We observed matches (as well as mismatches) between the ecosystem service priorities and important environmental issues. Ecosystem services prioritized by stakeholders revealed a unique classification of ecosystem services that reflects stakeholder priorities. Our findings suggest the study of ecosystem services supply and demand, as well as increased knowledge about the limitations and disservices on various types of GI, can inform local urban management. These findings from a semi-arid city suggest that understanding stakeholder knowledge, perceptions, and priorities should be important for other regions where GI is being implemented as an environmental solution to provide ecosystem services.

Keywords: Green infrastructure, ecosystem services, ecosystem disservices, semi-arid regions, environmental management

1- Introduction

Green infrastructure (GI) is an approach to managing stormwater at its source that also delivers many environmental benefits or ecosystem services (USEPA 2019). Governments, organizations, and researchers are promoting an expansion of GI implementation to enhance ecosystem service provision to address issues of runoff reduction, air quality, microclimate and urban heat islands, and public health issues (Berkooz 2011; Livesley et al. 2016; Meerow and Newell 2017; Mell 2016). In urban areas, GI is implemented in different forms (such as urban trees and forests, green roofs, rain gardens, etc.), each with differing abilities to provide ecosystem services (Ellis 2013; Gill et al. 2017; Pugh et al. 2012; Raje et al. 2013). A notable benefit of GI to city planners is its multifunctionality, or the ability to combine multiple functions and using limited space more efficiently to provide ecosystem services to diverse stakeholders, compared to gray infrastructure (Ahern 2011; Connop et al. 2016). The multifunctionality of GI does require consideration of trade-offs and the balance of service supply and demand in planning and design (Hansen and Pauleit 2014)

Despite the growing interest in GI, there are limits and challenges associated with GI in practice. For instance, stakeholders are skeptical of the ability of practices to provide the level of ecosystem services expected and if investing on GI will provide those benefits (Copeland 2014). There is a gap in “locally- specific” application of ecosystem services in planning and governance that accounts for differences in climates and suitable plants between regions (Kabisch 2015; Koo et al. 2019). In developing best management practices in planning, planners and managers need to identify ecosystem services to address a wide range of stakeholder perspectives, however these perspectives may be poorly understood (de Groot et al. 2010). To meet the growing complexity and scale of ecological challenges, there are demands for higher levels of stakeholder engagement in developing solutions for these challenges (Young and McPherson 2013). Understanding the perceptions of local actors such as planners at city and local level, decision-makers, and local stakeholders to identify relationship between local demands and provision of locally relevant ecosystem services is essential in locally complex situation (Kabisch 2015; Koo et al. 2019).

To effectively manage cities using GI ecosystem services, the linkages between ecosystem services provision (ecosystem service supply) and governance priorities (ecosystem service demand) need to be explicit across sectors and spatio-temporal scales (Burkhard 2014; Klug and Jenewein 2018). Urban ecosystem service supply and demand have been well documented across spatial and temporal scales, primarily through mapping and geospatial approaches (Dobbs et al. 2014; Larondelle et al. 2014; McPhearson et al. 2013). While mapping approaches to ecosystem services have shown the spatial variation and ability of urban spaces to provide ecosystem services, for services to be effective in guiding planning and decision making, there is a need to connect to local governance practice and evaluation across sectors (Opdam 2013). Cortinovis, & Geneletti, (2018) showed a clear gap in application of ecosystem services in planning despite existing methods for mapping and evaluation, and proposed an approach that explicitly considers goal setting, multifunctionality, and service demand as a way to enhance the role of ecosystem service science in urban planning (Cortinovis and Geneletti 2018). Such an approach would address criticisms of models such as the ecosystem services cascade(Haines-Young and Potschin 2018), that give primacy to ecological structures and functions over perceptions and socio-cultural values that govern ecosystem service provision (Spangenberg et al. 2014; Zoderer et al. 2019).

Despite the need to consider perceptions and values in the balance of ecosystem services supply and demand, few studies investigate *both* supply and demand (Baró et al. 2017; Schirpke et al. 2019). Consideration of both supply and demand informs management by identifying potential mismatches between scales of supply and demand (Castro et al. 2014; Wei et al. 2017). Furthermore, interests, priorities, and needs differ among groups (Díaz et al. 2011; Geijzendorffer et al. 2015; Martín-Ló Pez et al. 2012; Wei et al. 2017), and identification of how stakeholders perceive ecosystem services supply and demand and any potential conflicts can allow for more effective policy and management decisions (Zoderer et al. 2019). One of the potential challenges in implementing the ecosystem service concept are disconnects in how universal frameworks (MEA 2005; TEEB 2010; Wallace 2007) align with local and practical perceptions and framings of ecosystem services (Crossman et al. 2013; Seppelt et al. 2012).

The degree of ecosystem service knowledge transfer from research to policy and decision-making is low, despite the growing number of studies such as developments of tools and models, landscape planning, and increasing awareness and communication (Haase et al. 2014; Luederitz et al. 2015). Although general recommendation can be derived from such studies for land management and planning, they are less likely influence practice without involvement of local stakeholders (Haase et al. 2014). Yet, stakeholders' viewpoints on ecosystem services supply and demand are poorly described or limited to a few services(Baró et al. 2015; Cumming et al. 2006). Understanding how landscape can be managed with respect to the multifunctionality of GI helps with understanding of the potential outcomes for policy and management and it can be achieved by involving the diversity of stakeholders to evaluate supply and demand (Kremer et al. 2016). In addition, stakeholder perceptions of ecosystem disservices (Lyytimäki and Sipilä 2009) can impact decisions about GI in practice as they affect perceptions of trade-offs. Thus, identifying stakeholder knowledge and objectives in decision-making contexts with respect to the transfer of ecosystem services may improve landscape planning and decision-making in urban areas (Haase et al. 2014; Luederitz et al. 2015).

This paper aims to answer, how do ecosystem services influence environmental stakeholders' perceptions and practice of GI? To answer this we used an online survey of managers and practitioners in Tucson, AZ to specifically ask: (1) what is stakeholder's knowledge of environmental and water-related issues in Tucson, (2) what ecosystem services stakeholders want from (demand) and think that different types of GI provide (supply), and (3) what connections exist between stakeholders perceptions of environmental and water issues and their priorities (practice). Our results imply that the unique water resource challenges of the semi-arid environment connect to stakeholders' prioritization for GI. We found several matches between priorities and practices with respect to ecosystem supply, demand, and disservices. However, we also observed some mismatches between stakeholder ecosystem service priorities and their view of environmental issues that may be due to a scale mismatch. In this case, GI is implemented at local scales, but some concerns such as groundwater recharge is a challenge that is managed at larger spatial scales.

2- Method

2-1- Study Area

We focus on Tucson, AZ (including the metropolitan area extending into Pima County, AZ) and how those places are using GI to address water sustainability. Tucson is a semi-arid city, with very hot summers (temperatures reaching over 38°C) and average annual precipitation around 300 mm with summer monsoon rains accounting for half of the annual precipitation (Pessarakli 2019). Growing population in the area (Pima County was just over 1 million in 2018 (Bureau of Reclamation 2019) has increased demand for potable water. The city of Tucson is dependent on allocations from the Colorado River through the Central Arizona Project (CAP) and its own aquifer (Central Arizona Project 2017; Kuhn et al. 2017). Outdoor water consumption accounts for 45% of potable water consumption in Tucson and the primary outdoor water usage is for landscaping irrigation. There is a desire to increase green spacing in the area that requires water for irrigation. Considering the population growth and impact of climate change, the current system might not be able to provide that water need for irrigation in the future (Kuhn et al. 2017). On the other hand, Tucson receives annually more rainfall than the total demand that if harvested and used at its origin can cover notable portion of potable water that is used for outdoor activities (Korgaonkar et al. 2018; Kuhn et al. 2017).

Stormwater is managed to deal with flooding from monsoon rains primarily using streets to convey water out of neighborhoods. However, there is growing interest in harvesting stormwater flows to meet outdoor irrigation and revegetation goals and as a solution to water resource challenges in the Tucson region (Radonic 2019). Hydrologic simulations suggest water availability at the lot scale during monsoon events to meet the outdoor demands in drier months (Korgaonkar et al. 2018). Currently, there are a number of water-harvesting facilities in public, commercial, and residential places that capture runoff through GI. Water harvesting is considered a strategy that is beneficial both on the demand and supply side (Brooks 2006). Tucson considers rebates to the resident for such strategies called "Water Conservation Rebates" (City of Tucson 2019). Ongoing research seeks to identify connections between GI design and ecosystem services (Luketich et al. 2019; Pavao-Zuckerman and Sookhdeo 2017), and to evaluate water harvesting programs and policy motivations and effectiveness (Elder and Gerlak 2019; Radonic 2019)

2-2- Survey Instruments

2-2-1- Participants

We conducted a questionnaire between April 2019 and June 2019 to gather information about stakeholder perceptions of GI ecosystem services. We selected the stakeholders to represent critical managers and practitioners of environmental governance, and practice, and water harvesting and GI management in Tucson and Pima County. This includes representatives from city-level and county-level government and agencies, environmental utilities, non-profit organizations, and engineering and design firms. The questionnaire was distributed a total of 117 stakeholders, and we had a response rate of approximately 54% or 63 respondents.

2-2-2- Survey Design

We conducted the survey through Qualtrics (Qualtrics Labs Inc 2009). In this survey, three types of GI were included: rain barrels and cisterns, rain gardens, and urban trees (Figure 1). Although rain barrels and cisterns are household-scale GI, the perceptions of practitioners and managers are important for developing design standards, policies, and incentives for residential implementation. The survey included both closed-ended and opened-ended questions in five sections. In the first section, the stakeholders' general and specific knowledge of Tucson's current and future environmental situation and knowledge of GI were investigated. The statements asked whether there is a need to substitute other sources for freshwater, control stormwater, recharge groundwater, and improve the quality of surface water. We also asked about the efficacy of current strategies for water management in Tucson, such as the delivery of water from the CAP to deal with water supply. Also, there were statements on the effect of future conditions such as climate change and population growth on water resources. General environmental knowledge was determined by asking the respondent to indicate on a 5-point Likert scale (1=strongly disagree-3=Neutral- 5=strongly agree) the level of agreement regarding Tucson’s needs on water-related statements and usefulness of GI in providing water. This was followed by more specific questions on their familiarity with types of GI and their effectiveness in runoff capturing methods.

Figure 1 Urban trees (a), rain gardens, (b), and Cisterns (c)- types of green infrastructure in this study

In the second section, stakeholders were asked on how important each type of GI is in providing various types of ecosystem services. We selected ecosystem services from Millennium Ecosystem Assessment (MEA 2005) relevant to water harvesting and water use through GI. Respondents were provided 15 types of ecosystem services and they were asked to rate, on the scale of 1-5, how important each type of GI is to provide the listed ecosystem services (ecosystem service supply). *Ecosystem services supply* was determined by asking stakeholders to answer a 5-point Likert scale (1= not important, 2= slightly important, 3= important, 4= fairly important, 5= very important) on the level of ecosystem services each type of GI (urban tree, rain garden, and cistern) can provide. Again, respondents were provided the same 15 ecosystem services. Stakeholders were asked to prioritize GI ecosystem services that they think are important for GI to provide, representing *service demand*. Respondents ranked the 15 ecosystem services from most to least important. In the third section, the stakeholders were asked to assess ecosystem disservices that the three types of GI may cause from the stakeholders' point of view and any strategies that their offices might use to mitigate the concerns. Here, respondents were asked to rate on the scale of 1-5, how concerned they are with 10 ecosystem disservices for each type of GI. In the fourth section, the respondents were asked on a 5-point Likert scale, what they think about the environmental challenges and concerns currently in this area (i.e. flooding, environmental justice, poverty, property value, etc.) related to how GI could be useful to address the challenges. In the fifth section, we asked questions about the stakeholders' professional background and training and demographics.

2-2-3- Analysis

Descriptive statistics were used to determine central tendencies and frequencies for responses to knowledge questions. For general environmental knowledge, negatively worded questions were used as well as positively worded questions to reduce acquiescent bias. Reverse coding was used to remove mismatch for the level of agreement and the increasing scale. Thus, for those negatively worded statements, responses expressed disagreement interpreted as agreement with high level of environmental knowledge. As a result, higher scores on the 5-point Likert scale means a higher level of general knowledge on Tucson situation and efficacy of GI. Chi-squared test of associations (Rea and Parker 2014) was used to determine the relationships between level of knowledge and demographic variables of sector, role in the office, duration of employment, expertise, degree, major, duration of living in

Tucson, duration of living in southwest, participation in low impact development (LID) conference, LID member, and if the office required to follow stormwater discharge for small municipal separate storm sewer system (Appendix 1).

A cluster analysis was performed in Minitab 18, (Minitab Inc.) using complete linkage method. Cluster analysis uses a distance matrix to group factors that are different from other groups and identifies homogenous clusters when the grouping is not known. In this study, clustering was used to see the differences among stakeholder rankings of the 15 ecosystem services. The results are displayed as a dendrogram to highlight perceived groups of services.

A cumulative weighted score was used to compare ecosystem services ranked by stakeholders by demographics and professional background. Cumulative weighted score is the average of a set of scores where each set carries a different amount of importance regarding the score each stakeholder allocated to ecosystem services (from 1-15). Each score is calculated as shown in Equation 1: ω is the rank value (1-15), x is the score stakeholders assigned to each ecosystem services (1-5), N is the total number of stakeholders that ranked the service, and S is the cumulative weighted score.

Equation 1

$$S = \frac{\sum_{i=1}^{n} \omega_i \, x_i}{N}$$

Kruskal-Wallis and Mann-Whitney U-tests were used (due to non-parametric data; Corder and Foreman 2011) to assess relationships between demographic variables and other response variables: environmental knowledge, ecosystem services supply, ecosystem services demand, ecosystem disservices, and severity of environmental concerns in Tucson (Appendix 1). The comparison of between means was carried out using non-parametric Tukey test to determine difference between type of GI (Zar 1984) (Figure 2).

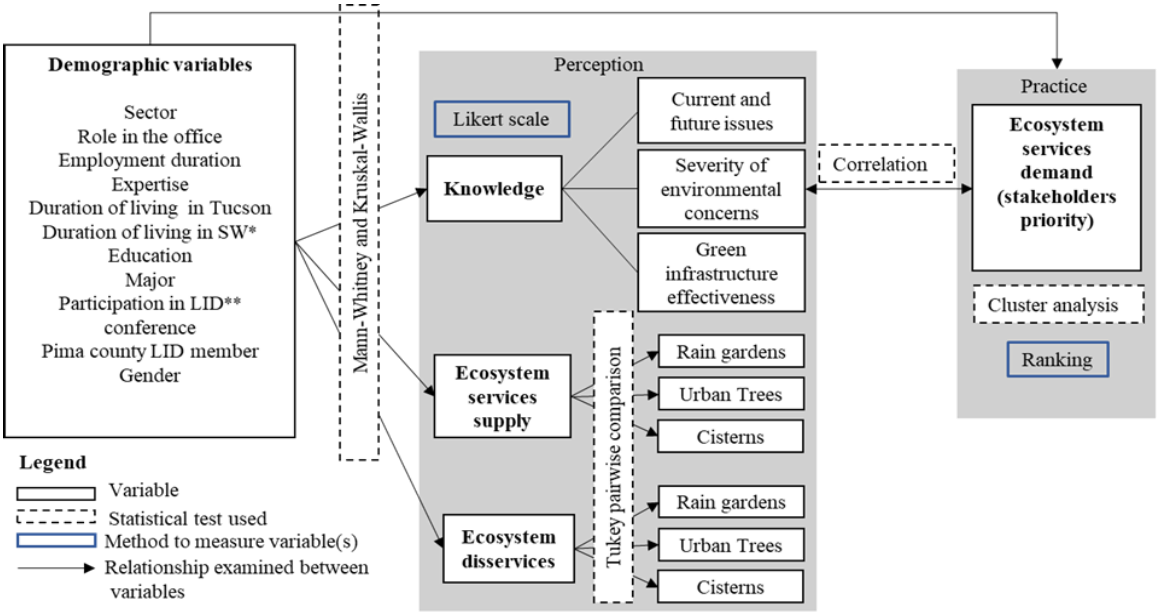

Figure 2 Conceptual diagram of the analysis used to assess the variables in this study of stakeholder perception of green infrastructure and ecosystem services in Tucson, AZ (Adapted from Baptiste, Foley, and Smardon 2015) * SW=Southwest **LID=Low impact

3- Results

We used a survey of environmental managers and practitioners in Tucson and Pima County to determine how ecosystem services influence environmental stakeholders' perceptions and practice of GI. Below we describe responses that characterize stakeholder knowledge and perception of environmental and water issue, perceptions on ecosystem services supply and demand, prioritization of services with respect to environmental issues, and perceived ecosystem disservices of GI.

3-1- Stakeholder Knowledge and Perception of Environmental and Water Issues Knowledge

Due to current water sustainability issues in the region and critical needs to substitute water resources in near future (Guo 2017), we evaluated stakeholder knowledge of the current water system in Tucson. We asked stakeholders if they agree or disagree with statements about water resources in the Tucson region. We did not find differences in knowledge and perception of environmental issues and challenges among professional sectors. We found stakeholders strongly agreed with statements designed to explore knowledge on water resource and environmental issues that are unique to the semi-arid setting of Tucson. For example, most of the respondents indicated that there is a need to substitute other sources for freshwater (87%, n=55, M=4.53, SD=0.91) (percentage indicates the percent of stakeholders that strongly agree and agree with environmental and water issues). Furthermore, the majority of respondents stated that the current water supply alternatives (i.e., CAP delivery) (71%, n=45, M= 2.25, SD=1.30) and groundwater extraction (90%, n=57, M=4.52, SD=0.86) are not sustainable ways to deal with water supply issues. Stakeholders expressed the need for alternative water resources and insufficiency of current water management strategies (82%, n=52, M=1.81, SD=1.04). Moreover, the stormwater control (92%, n=60, M=4.67, SD=0.74) and groundwater recharged (95%, n=60, M=4.65, SD=0.72) were perceived as highly important priorities.

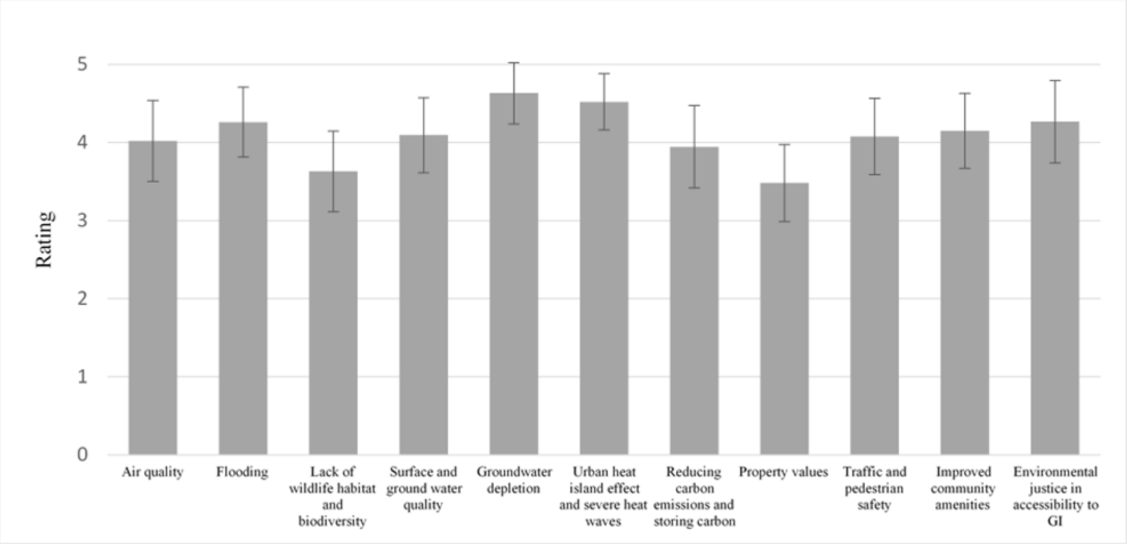

Figure 3 Mean stakeholder ratings of severity of environmental concerns (1-5) for using and implementing types of green infrastructure in Tucson, AZ. Error bars represents standard error.

Stakeholders rated the severity of the general environmental challenges concerns that GI might be a potential solution for in Tucson (Figure 3). Groundwater depletion, urban heat islands, and flooding are the environmental concerns ranked highest by stakeholders (Figure 3). We assume that these ratings of concerns related to stakeholder practice. Groundwater depletion (80%, n=57, M=4.56, SD=0.86) was the strongest environmental concern (percentage indicates the percent of stakeholders that ranked the environmental issue as important and very important). Flooding (68%, n=57, M=4.2, SD=0.94), urban heat island and severe heat waves (68%, n=57, M=4.06, SD=1.01), environmental justice (51%, n=57, M=4.1, SD=1.067), and water quality (56%, n=57, M=3.91, SD=1.03) are also among the highest concerns of stakeholders. Concerns about wildlife habitat, biodiversity, and property values were ranked lowest by the stakeholders.

We asked about stakeholders' perception of the efficacy of different types of GI to serve as an alternative water resource. The majority of respondents stated the importance of GI as a supplemental or even primary water resource (89%, n=56, M=4.28, SD=0.93) and 95% of stakeholders expressed implementing GI as a helpful approach to deal with future challenges (n=60, M=4.72, SD=0.68). A large number of respondents (75%, n=47) indicated that infiltration and retention are among the most effective ways of capturing stormwater. Stakeholders perceived rain gardens as the most cost-effective means of water harvesting (54%, n=34). Cisterns and rain barrels were perceived as the most difficult to install and maintain mostly due to the initial cost, maintenance cost, change in the quality of water, and lack of technical knowledge in installation and maintenance (56%, n=35). We did not find any significant associations between stakeholder demographics (including professional sector, major, degree, duration of employment, duration of living in Tucson and southwest, role in the office, being a low impact development member, attendance of low impact development conferences, and gender) and environmental and water issues knowledge (Appendix 1-Table 2).

3-2- Stakeholders' Perception on Ecosystem Services Supply and Demand

As a measure of ecosystem service supply, we asked stakeholders to rate the potential for different GI types to provide ecosystem services. Stakeholders indicated that water harvesting for future use, stormwater reduction, and education opportunities are the strongest ecosystem services provided by cisterns (Figure 4). Rain gardens are viewed to provide more pollinator support compared to cisterns and urban trees. Urban trees are perceived to be more effective in air quality regulation, carbon sequestration, moderation of extreme heat events and urban heat island.

We asked stakeholders to rank their demand ecosystem services and they expressed a higher demand for urban heat island mitigation, stormwater reduction, water harvesting, and biodiversity enhancement (Figure 4). To investigate the connection between ecosystem services supply and demand, we selected the highest ranked demands and compared the ratings for different types of GI (Table 1). Stakeholders rated urban trees as the most effective approach for moderation of extreme heat events and urban heat island reduction. They perceived rain gardens to be the most efficient GI for reducing stormwater, but cisterns were the most efficient for water harvesting and storage. Additionally, both urban trees and rain gardens were perceived as important factors for biodiversity enhancement.

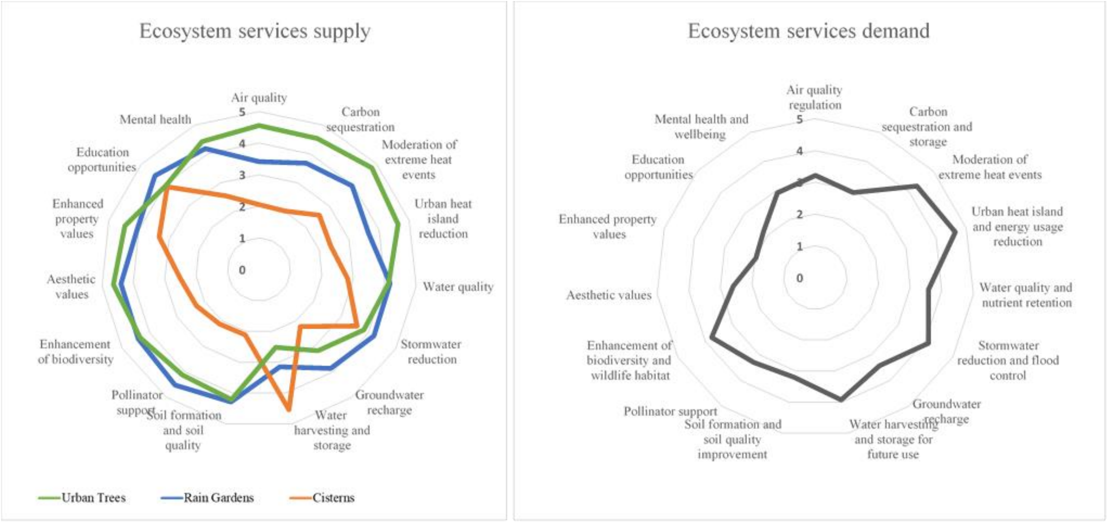

Figure 4 Radar diagram showing ecosystem services supply (left) demand (right) by rain garden, cistern, and urban trees as rated by stakeholders in Tucson AZ. Stakeholders rated ecosystem services supply on a scale of 1-5. Stakeholders ranked ecosystem services demand from 1-15 and rankings were scaled to 5 for comparison.

We found that stakeholders in different sectors have different ecosystem service prioritizations (Figure 5). While this survey focuses on GI practitioners in Tucson and thus is not a statistically randomized sample, interesting trends emerge between sectors when we compare the weighted average of each ecosystem service ranked by each sector/type of stakeholder (Figure 5). For example, engineering firms valued stormwater reduction and water harvesting more than aesthetics compared to environmental utilities. Environmental utilities on the other hand, valued regulating services such as air and water quality compared to other sectors (the results of environmental utility sector must be considered with caution due to the small sample size). Stakeholders in city and county level governments valued urban heat island and energy usage reduction and moderation of extreme heat events more than other sectors. Stakeholders in non-profit organizations valued various ecosystem services without a clear top priority (Figure 5).

Table 1 Mean rating of ecosystem services supply by GI types as rated by stakeholders in Tucson, AZ on a scale of 1-5.

GI Type	Moderation of extreme heat events	Urban heat island mitigation	Stormwater and flood reduction	Water harvesting and storage	Enhancement of biodiversity
Urban Trees	4.81	4.61	3.83	2.53	4.33
Rain Gardens	3.96	3.70	4.20	3.17	4.34
Cisterns	2.54	2.47	3.59	4.51	2.34
Significance level^	***	***	*	***	***

^ Statistical differences between GI types within the column at * $p \geq 0.05$, ** $p \geq 0.01$, *** $p \geq 0.001$ significance values.

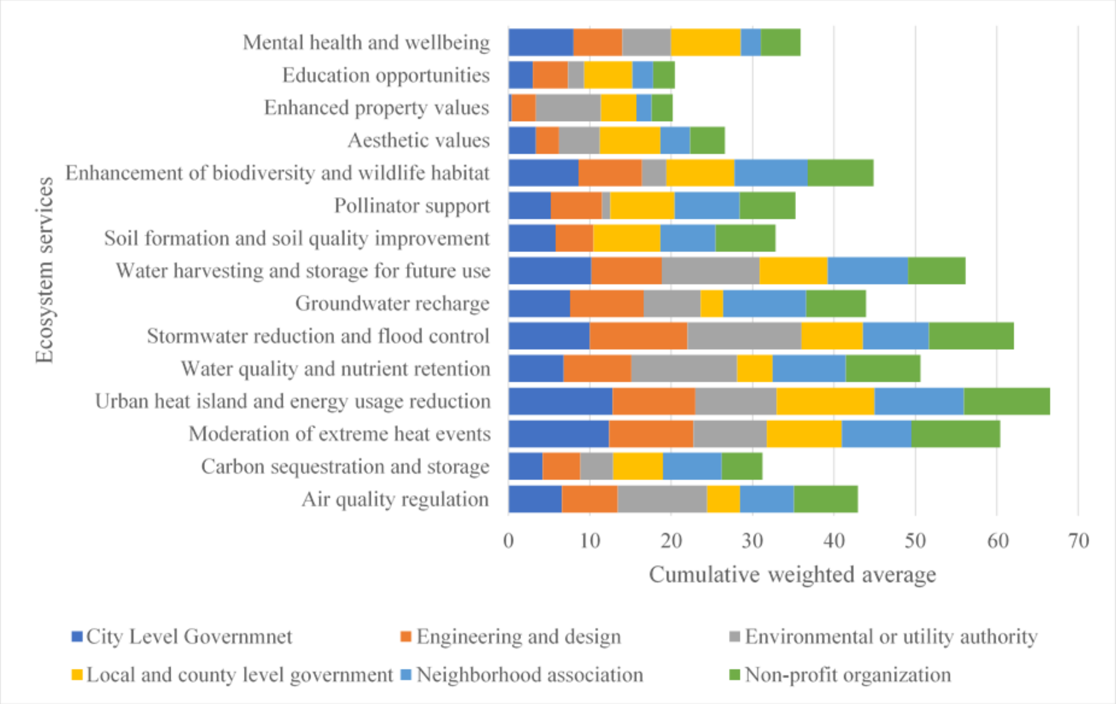

Figure 5 Ecosystem services priorities from green infrastructure ranked by various sectors. A cumulative weighted score was used to compare ecosystem services rankings as perceived by stakeholders from different sectors and backgrounds. Cumulative weighted average is the average of a set of scores where each set carries a different importance regarding the score each stakeholder allocated to ecosystem services (from 1-15).

3-2-1- Classification for Stakeholders' Perception

We used agglomerative hierarchical clustering to distinctly classify similar ecosystem services prioritized by stakeholders (Figure 6). This revealed a unique classification of ecosystem services in Tucson, AZ relative to established schemes, such as the MEA (MEA, 2005) and is indicative of local stakeholder priorities (Figure 6). The water-related factors (water harvesting and storage, water quality, stormwater reduction, groundwater recharge, and water quality) grouped into one cluster and heat-related factors (moderation of extreme heat event and urban heat island reduction) also grouped into one cluster (Figure 6). These two clusters are the most important services expressed as critical demands of stakeholders reflecting the unique urban and environmental conditions in Tucson (Figure 4). Environmental quality factors (air quality and soil quality) were also grouped. Pollinator support and enhancement of biodiversity grouped into one cluster. Finally, aesthetic values, enhanced property values, and education opportunities were grouped (Figure 6) and seem to be less prioritized by stakeholders (Figure 5). We found no significant correlations between GI practice (as indicated by the priority of stakeholders) and their perceived environmental challenges and concerns.

Stakeholders ranked the ecosystem disservices of GI and reported maintenance

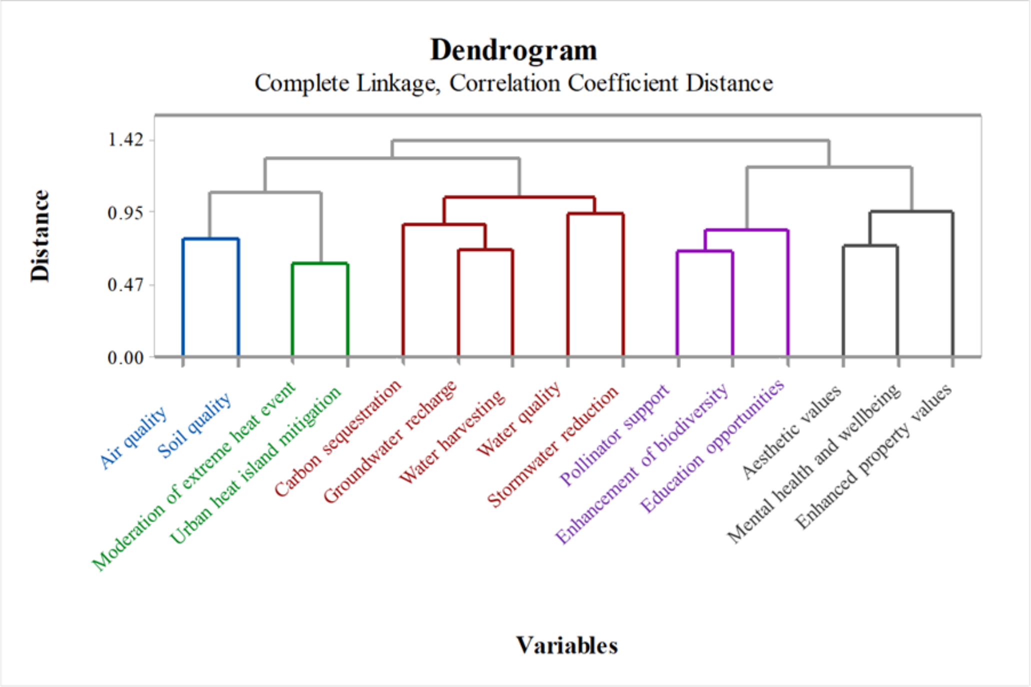

Figure 6 Dendrogram assessing clustering among ecosystem services demand of stakeholders in Tucson, AZ. Using cluster analysis. Complete linkage with correlation coefficient distance was used to cluster the ecosystem services.

costs, installation and maintenance time, obstruction of views (and links to safety), and potential health risks as the most important GI disservices (Figure 7). Stakeholders were concerned with different ecosystem disservices of different GI types (Table 2) when we compared the mean importance of the top five disservices (Figure 7) for the three types of GI. Maintenance cost was the strongest disservices among the stakeholders and rain gardens are perceived to have the highest cost among other types of GI. Rain gardens are perceived to have the most time-consuming installation and maintenance. Urban trees have unique concerns as obstruction of views and the production of leaf litter, and damage to physical property, with less perceived health (Figure 7- Table 2). Cisterns are thought to have slightly higher health risks.

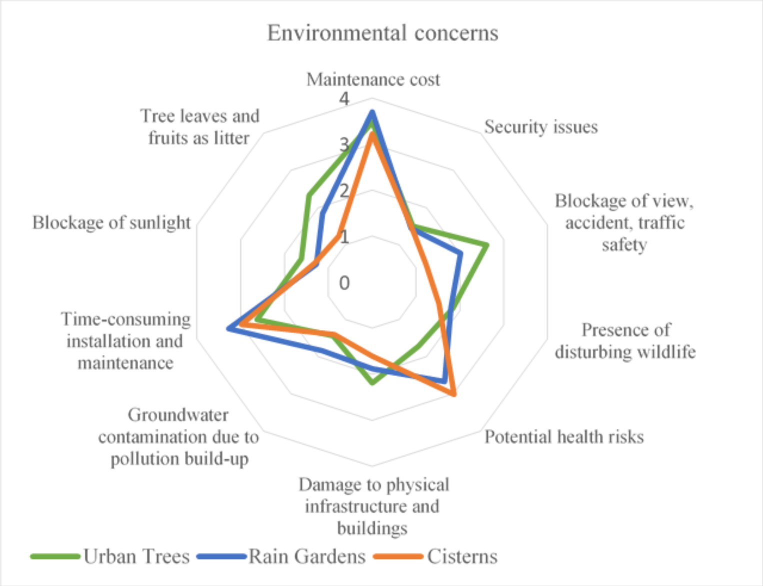

Figure 7 Radar diagram showing ecosystem disservices of urban trees, rain gardens, and cisterns as rated by stakeholders in Tucson, AZ. Stakeholders rated ecosystem disservices on a scale of 1-5.

Table 2 Mean comparison of top GI ecosystem disservices as rated on a scale of 1-5 by stakeholders in Tucson, AZ. All ecosystem disservices are ranked in Figure 7.

GI Type	Maintenance cost	Time-consuming installation and maintenance	Blockage of view, accident, and traffic	Potential health risks	Damage to physical infrastructure
Urban Trees	3.47	3.275	2.615	3.02	2.19
Rain Gardens	3.70	2.981	2.019	2.67	1.88
Cisterns	3.22	2.627	1.23	1.72	1.61
Significance level	***	*	***	***	*

^ Statistical differences between GI types within the column at * $p \geq 0.05$, ** $p \geq 0.01$, *** $p \geq 0.001$ significance values.

4- Discussion

We investigated stakeholders' environmental knowledge, supply and demand for GI ecosystem services, and connections between stakeholder perception and practice (prioritization) among various environmental managers and professionals in the Tucson region. We found that stakeholders have a high level of knowledge reflecting the semi-arid setting of Tucson and that there were no significant differences in environmental perception between sectors. We observed matches (as well as mismatches) between the ecosystem service priorities and important environmental issues. Clustering approaches to classify similar ecosystem services prioritized by stakeholders revealed a unique classification of ecosystem services indicating stakeholder priorities that differed from established schemes (MEA 2005). These findings on stakeholder knowledge, perceptions, and priorities in Tucson, AZ provide implications for other regions where GI is being implemented as an environmental solution to provide ecosystem services.

4-1- Stakeholder Knowledge about Environmental Challenges and Concerns

We found stakeholders have a high level of knowledge of water-related environmental issues, reflecting the semi-arid setting of Tucson. In addition, we did not find differences in knowledge and perception of environmental issues and challenges among professional sectors. The degree of knowledge regarding current water-related issues in the Tucson region (Figure 3) indicates that the respondents support the need for water resource alternatives and believe that current water strategies cannot meet demand. Our findings also confirm that practitioners view GI implementation as a multifunctional approach to deal with current urban water management problems. This perception reflects recent trends towards rethinking stormwater runoff as a novel water source, rather than as a waste product (Walsh et al. 2012). In fact, in Tucson harvested runoff at the lot scale may be sufficient to meet potential demands for outdoor irrigation (Korgaonkar et al. 2018). Residents in Tucson are already beginning to use harvested water for landscaping (Radonic 2019); however, barriers still exist to widespread adoption of GI for water harvesting purposes (Staddon et al. 2018). Urban water management needs transformative change in practice that addresses technical, economic, social and institutional challenges (Brown et al., 2009; Ferguson et al., 2013; Wilfong & Pavao-Zuckerman, 2020) Such a fundamental change requires identification of the socio-environmental benefits of stormwater as a resource (Walsh et al. 2012). Understanding stakeholder perceptions can promote systems thinking for water management and support such transformations in perception (Rebekah R Brown 2005; Lee and Yigitcanlar 2010).

Despite the potential for disciplinary influences, we did not find differences in perceptions of environmental issues among professional sectors, nor did we find significant associations between environmental knowledge and factors such as, professional sector, education level, and duration of living in Tucson and southwest (Appendix 1- Table 2). This high level of knowledge on important current and future environmental issues shows the potential for agreement among stakeholders and movement toward an integrated approach to GI implementation (Cousins 2017), and the potential for fewer conflicts among sectors managing water-related issues. This high level of consensus on issues and also on the multifunctionality of GI could lead to novel strategies such as cost-benefit sharing among different sectors despite different backgrounds in order to reach a reliable and sustainable water resources management and associated socio-ecological benefits (Paavola 2016). In fact, solving current challenges of GI planning likely requires collaboration among different professionals to establish new cross-disciplinary collaboration approaches that are supported by system thinking (Hansen and Pauleit 2014).

4-2- Perceptions of Ecosystem Services Supply and Demand

Stakeholders thought that the ecosystem services and disservices of different forms of GI were different (Figure 4, 7, and Table 1). For example, stakeholders perceive urban trees and rain gardens as more effective than cisterns for moderation of extreme heat events and urban heat island mitigation (Figure 4 and Table 1). Stakeholders ranked high demand for the supply of moderation of extreme heat events, urban heat island mitigation, stormwater reduction, water harvesting and storage, and enhancement of biodiversity (Figure 4). Urban trees have previously been found to be the most effective and least costly method of urban heat island control, corroborating stakeholder opinion in this case (Norton et al. 2015; Solecki et al. 2005). However, to support decision making for GI planning, awareness of urban trees' potential benefits might not be enough to motivate planting and quantification of those benefits and the feasibility of implementation are crucial. We also found that stakeholders may have concerns about the cost of implementation and maintenance of urban tree cover (Figure 7). For example, cisterns, the GI form that was thought to be the most effective at meeting the most important demands (Figure 4) was also mentioned by the majority of respondents as one of the more difficult type of GI to install and maintain (Table 2), and is also perhaps not a cost-effective means of water harvesting. The ultimate effectiveness of GI and its costs and benefits have uncertainties from both biophysical and socio-political factors that need to be characterized in order to better inform management decisions (Ding et al. 2015; W. Liu et al. 2016).

Study of the ecosystem services supply and demand can help to select the right GI to address the priorities of stakeholders vis-á-vis environmental issues in the Tucson region. The capacity of an ecosystem to provide ecosystem services differs from the actual services delivered to the society (Burkhard et al. 2012; Nedkov and Burkhard 2012; Villamagna et al. 2013). GI may produce certain regulating, provisioning, cultural, and supporting services, but it is critical that the GI services provided match stakeholder demand. Thus, selecting the right type of GI that best matches the stakeholders need was aimed in this study. Our results imply that the ecosystem services that stakeholders want more are more likely to be provided by rain gardens and trees than by cisterns themselves (Figure 4). In future planning and incentive programs (City of Tucson 2019), passive GI should be promoted or paired with active harvesting to meet ecosystem services demands.

We found strong familiarity and knowledge of environmental issues for stakeholders engaged in policy, design, maintenance, and implementation of GI. This might suggest a relatively low barrier to adoption of GI. However, knowledge and perceptions of managers might not be enough to overcome barriers go GI adoption, as policy and management options are also inhibited by the views of residents (Gartin et al. 2010). While residents' knowledge of GI types and its effectiveness for water management is typically lower than that of stakeholders (Baptiste 2014; Baptiste et al. 2015; Maeda et al. 2018; Turner et al. 2016), residents' knowledge and behavior can play a role in adoption that can be addressed with bottom-up policy and education approaches to enhance implementation (Maeda et al. 2018). Moreover, the interaction between residents' and practitioners' knowledge plays an important role in improving the quality of urbanized watersheds. This is especially important with GI such as rain gardens and cisterns, as they are mostly implemented in the residential areas but have high technical and maintenance considerations (Figure 7). In addition to knowledge, there might be differences in goals (demand) and functionality (supply) of ecosystem services from point of view of stakeholders and residents. Although there may be differences in priorities (demand) and functionality (supply), interactions between stakeholders and residents can help bridge the effective supply and demand connection. Future work should address these differences and could also promote stakeholder-resident interactions and partnerships.

4-3- Linking Stakeholder Knowledge and Perception to Practice

We aimed at filling the current gap in application of the concept of ecosystem services of GI by connecting the ecosystem services to local governance. Our results suggest that in some instances, there is a strong connection between environmental perception and ecosystem services goals and priorities for GI (Figure 3 and Figure 4). For example, urban heat island mitigation and flooding effects were rated as high priorities for ecosystem service provision and as significant environmental challenges (Figure 3 & 4). This connection may arise because stakeholders across sectors and with various backgrounds likely interact with similar issues in a similar way due to the basic and tangible needs of a semi-arid region facing water scarcity (Jacqueline Lau et al. 2018). Our respondents are generally stakeholders who work closely to address these common issues and are engaged with GI. Lau et al. (2018) found that in a resource management setting dealing with direct subsistence needs, that differences in perception and practice may be reduced. In our semi-arid setting, it is likely that water resources function similarly as a provisioning ecosystem service and set up convergences in perceptions and practice between different sectors and groups. Recognizing how different stakeholders perceive and prioritize ecosystem services is a vital step for effective ecosystem service-based approaches (Daw et al. 2015; Sikor et al. 2014). Implementing ecosystem services in environmental planning requires connection to local governance perception and practices in order to be effective in guiding planning and decision making (Opdam 2013), which can be achieved through active research collaboration (Palo et al. 2016).

Surprisingly, we found some mismatches between stakeholders' perceptions of environmental challenges for the Tucson region and their demand for GI ecosystem services (Figure 3 & 4). For example, the majority of stakeholders stated that ground water depletion is the most critical problem in Tucson (Figure 3) yet did not prioritize recharge as a GI ecosystem service. Biodiversity enhancement was rated among the highest service priorities but was perceived as one of the least important environmental issues (Figure 3). These mismatches in priority and practice may also reflect stakeholder views on multifunctionality of GI and the notion that GI is better at providing other ecosystem services in this case (Figure 4.a.), despite GI being thought generally to provide groundwater recharge services (USEPA 2019). Differences in scales of management may also explain the mismatch between knowledge and practice of stakeholders. Often, scale mismatches appear between the scale that stakeholders have influence on and scales that ecological process occurs (Cumming et al. 2006; Lambin 2006). In Tucson, GI is managed and installed at the lot and neighborhood scale, while groundwater depletion occurs and is managed at the watershed and city scale. One way to solve this mismatch is the collaboration of local actors (i.e. stakeholders involved in neighborhood planning and site design) to form a comprehensive governance and decision-making system at the larger scale (Bergsten 2014; Termeer et al. 2010; Pelosi et al. 2010). A management system integrated across scales and that considers stakeholder demands, priorities, and shared knowledge systems in landscape management can both reduce mismatches and potential conflicts among stakeholders (Zoderer et al. 2019). This integration may have its own challenges such as cost and time to form the integrated system.

Clustering approaches to classify similar ecosystem services prioritized by stakeholders revealed a unique classification of ecosystem services that indicate stakeholder priorities (Figure 6). This classification differs considerably from established schemes that include provisioning, regulating, cultural, and supporting services (MEA 2005). Here, water sustainability and heat mitigation are among the most critical priorities in the Tucson region (Figure 4,5). We argue that service classification systems (de Groot et al. 2002; MEA 2005; Wallace 2007) should be applied with care when used in planning and management, as the local attributes of cases can influence how stakeholders perceive groups of services. Ecosystem services show complex patterns of utilization and perceptions by receivers and managers of services potentially limiting generalized classification schemes for local management and planning (Boyd and Banzhaf 2007; Fisher and Turner 2008; Fisher et al. 2009;

Wallace 2007). Research collaborations to reveal stakeholder perceptions of ecosystem service clusters may be needed apply classification schemes for local environmental contexts.

5- Conclusion

This study connects stakeholder supply and demand of ecosystem services and the role of GI to address local priorities. Here, we demonstrate convergence in perception of environmental challenges and desired goals from GI. Despite this convergence, there are still challenges on the path to implementation of GI regarding the ability with which practices provide the level of expected ecosystem services and how services connect to the priority of stakeholders and local needs. Evaluating how stakeholders perceive ecosystem services supply and demand can assist the implementation of local knowledge and perception into management and long-term planning to fulfill the needs of a region (Klug and Jenewein 2018; Luederitz et al. 2015). However, as we observed, mismatches between priorities of stakeholders and important environmental issues can arise due to varying spatial scales of management. In addition, as suggested by Burkhard et al. (2014), appropriate institutions should oversee the spatial and temporal scales that match with ecosystem services supply and demand (Burkhard et al. 2014). In the case of GI, focusing on various and appropriate types of GI to fulfill stakeholders’ goals at both local and regional scales can achieve this.

Urban ecosystem services that are effective in managing environmental challenges can be achieved by connecting actual supplies to the demand and priorities of stakeholders. Overall, the study of ecosystem services supply and demand of various types of GI can help to identify the priorities of stakeholders that help to align service supply and demand. Here, consensus on environmental concerns and ecosystem service demand among stakeholders, as well as the multifunctionality of GI, shows the potential for collaboration and management of environmental assets.

6- Acknowledgement

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7- Supplementary Data

Supplementary data associated with this chapter can be found in appendix 1.

Chapter 4: Stormwater Green Infrastructure Resilience Assessment: A Social-ecological Framework for Urban Stormwater Management

Abstract

Urban areas are increasingly vulnerable to the effects of climate change. Stormwater Green infrastructure (SWGI) is seen as an approach to increase climate resilience of urban areas because they can buffer precipitation changes brought on by climate change. However, SWGI features needs to be resilient itself to climate induced changes 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 including policy, design, maintenance, economic factors, and social factors that influence SWGI functionality. We then identified specific indicators under each category that could be used for assessing SWGI resilience, recognizing that SWGI has critical functionalities and factors that controlling its viability. Unlike other SWGI assessment frameworks that are focused on ecosystem services as a final outcome, we worked from socio-ecological perspective to include socio-economic and policy factors, in addition to the 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 that have traditionally been overlooked, such as maintenance and social factors. This specific framework also can 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 for SWGI to local priorities in resilience planning.

Keywords: stormwater green infrastructure, climate resilience, ecosystem services, challenges, assessment framework

1- Introduction

Climate change poses serious pressure to urban infrastructure, quality of life, and entire municipal systems (Hoornweg 2012). Urban development and expansion of impervious surfaces as well as the loss of forests and agricultural areas can also locally intensify the effects of climate change (Gill et al. 2007). 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 from extreme heat and droughts (Austin et al. 2004; Buerge et al. 2006; Kumar et al. 2016; De La Sota et al. 2019; de Zeeuw and Drechsel 2015). The response to climate change stressors is often framed as a resilience challenge, that is, the ability to "prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC 2012). These challenges will be exacerbated in cities, so building urban resilience through management and development is a necessity (De La Sota et al. 2019). As a result, adaptation approaches are needed to minimize risks and to sustain well-being in urban areas in anticipation of a changing climate (Carter et al. 2018).

Water resource sustainability is highly 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 (Foster et al. 2011; Leichenko 2011). Stormwater Green Infrastructure (SWGI) development is one of the major approaches to improve the resilience of cities (Lennon and Scott 2013; Lucas and Sample 2015; Meerow and Newell 2017). SWGI is seen as a network of natural and semi-natural green spaces in an urban area and known as a structure to reduce the effect of climate change either by mitigating or adapting to the effects of climate change (Samora-Arvela et al. 2017). SWGI planning is broadly accepted in policies for stormwater management as an approach for resilient spatial planning and environmental sustainability goals (Lennon and Scott 2013; O'Neill and Scott 2011; Pappalardo et al. 2017). While SWGI is being expanded in cities as a network to convey resilience in cities (Mell 2016), we argue that SWGI itself also needs to be resilient to be able to contribute more broadly to the resilience of cities.

Assessment approaches are needed to identify the ways to enhance SWGI resilience especially for confronting climate change (Dong et al. 2017; Raymond et al. 2017). One assessment approach that reflects broad and general considerations of resilience is the "resilience matrix" (Fox-Lent et al. 2015; Linkov, Eisenberg, Plourde, et al. 2013). This matrix approach identified four broad categories that influence resilience that include both physical and non-physical domains: physical, information, cognitive, and social factors. The matrix approach involves evaluating each of these domains with respect to four resilience dimensions as aligned with the National Academy of Science's definition of resilience (Linkov, Eisenberg, Bates, et al. 2013), the ability to: "1. prepare and plan for, 2. absorb, 3. recover from, and 4. adapt to adverse events” (NRC 2012). This general framework has been successfully applied to specific systems, including cyber systems and community resilience (Fox-Lent et al. 2015; Linkov, Eisenberg, Plourde, et al. 2013). The previous frameworks were all focused on four dimensions of resilience (Fox-Lent et al. 2015; Linkov, Eisenberg, Plourde, et al. 2013), however; the first dimension “prepare and plan for” is known as risk analysis while resilience management refers to the other three dimensions of “absorb”, “recover”, and “adapt” (Linkov et al. 2014). Risk analysis quantifies the probability that system reaches lowest functionality, but it does not focus on how decision-makers can influence and address resilience through management and decision-making related to SWGI. Here, we focus on aspects that can be influenced and changed by managers, and focus only on the absorb, recover, and adapt phases (Linkov et al. 2014). To implement the resilience matrix, general domains and categories for assessing resilience are specified for the unique setting or case (Linkov, Eisenberg, Bates, et al. 2013). 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 (Cutter et al. 2014; Karamouz et al. 2014; Renschler et al. 2010).

Selecting the categories for resilience assessment tools should be in a way to address the resilience of the specific system and the 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 function and also to its adoption and implementation. There are challenges that are critical for the function of SWGI such as socio-economic and financial barriers especially allocating enough budget for on-going maintenance of SWGI (Flynn et al. 2012; Tian 2011; Young and McPherson 2013) and technological, institutional, and perceptual challenges introduced as other main challenges (Kabisch et al. 2016; Kronenberg 2014; Tian 2011) Although, social factors, especially social justice, tend to be neglected factors in SWGI planning, they have a critical role in urban resilience (Ahern 2011; Dhakal and Chevalier 2017; Staddon et al. 2017). Often, the importance of maintenance for addressing the resilience is overlooked, or only financial aspects of maintenance is taken into consideration as a barrier (Maron et al. 2017; Matthews et al. 2015; Young and McPherson 2013) but no other dimensions such as biophysical aspects and maintenance plan, or knowledge and communication between the maintenance sector and other stakeholders. Expanding the resilience matrix approach for SWGI would require specific inclusion of the factors and challenges that influence its continued functionality.

The key aim of the current study is to develop a climate resilience assessment framework for SWGI. The specific focus is on expanding the resilience matrix (Linkov, Eisenberg, Bates, et al. 2013) by identifying (1) specific categories that are essential for the resilience of SWGI, and (2) specific indicators to assess this resilience. Indicators enable us to rate and rank SWGI in urban areas compared to an idealized condition through an assessment framework. We develop these categories and indicators by reviewing literature related to the constraints on function and 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 indicators for resilience assessment. Finally, we will offer a resilience assessment framework specific to SWGI that can be used to evaluate and rate the resilience of SWGI in urban areas.

2- Method and Approach

2-1- Resilience Matrix Framework Approach

Our goal was to identify a model approach 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 (Burroughs 2017; Kozine et al. 2018; Ostadtaghizadeh et al. 2015; Sharifi and Yamagata 2016). We found that 23 of those documents referred to a "resilience matrix" (Linkov, Eisenberg, Bates, et al. 2013) and identified 6 highly cited (100 or more citation) documents that applied the matrix. The resilience matrix (Linkov, Eisenberg, Bates, et al. 2013) 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 also considered multiple meanings of the word resilience. Thus, we conducted another search on "resilience matrix" and yielded 507 matches. Among those matches, we extracted the highly cited documents (over 100) and found 12 documents. Half of these documents and almost all of them that were developed after 2013 was based on or refer to the general framework developed by Linkov, Eisenberg, Bates, et al. (2013). This framework has been successfully applied into different systems but not yet to GI

(Linkov, Eisenberg, Bates, et al. 2013). Thus, we started build off the resilience matrix in the context of SWGI, using these documents as a guide.

The resilience matrix (Linkov, Eisenberg, Bates, et al. 2013) framework comprises of a 4×4 matrix where the vertical axis contains the major subcomponent affecting the resilience of the any system (physical, information, cognitive, and social), and the horizontal axis are resilience dimensions (plan/prepare, absorb, recover, adapt) as defined by the National Academy of Science Definitions of resilience (NRC 2012). For 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 focus only on these three dimensions that can influence and address resilience through management and decision-making related to SWGI. Therefore, we modified the resilience matrix to 5×3 matrix. The creators of the matrix (Linkov, Eisenberg, Bates, et al. 2013) intend for it to ultimately be used to screen systems and identified scores related to dimensions of resilience. Here, we modified the general resilience matrix to be specific for the case of SWGI as a screening step to identify scores related to each category and to check how categories are related to dimensions of resilience. Resilience is assessed by assigning a score to each of the indicators that can be developed by expert opinion. These scores can be used to identify gaps within each category that might weaken resilience and can be monitored over time to record the performance of the system and any intended improvements to resilience.

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 the functionality and health, (3) identify categories and detailed indicators that are needed to assess the critical functionality, and (4) identify the resilience dimension for each indicator. (Fox-Lent et al. 2015).

2-2- Literature review on SWGI and resilience

One of the important steps to apply the resilience matrix framework is to identify the categories that affect resilience that are specific to SWGI. Following Linkov, Eisenberg, Bates, et al. (2013), we read literature on SWGI that included categories from a social-ecological perspective (rather than just a technical or design perspective). To find this literature, we used a second search on Google Scholar in 2018 (and updated in 2020) using keywords such as “stormwater green infrastructure”, “challenges”, and “urban resilience” to find papers to identify challenges and barriers that affect the functionality and resilience of SWGI. We selected key papers and documents that reviewed, categorized, and list SWGI challenges and barriers. These are the important key reviews and conceptual papers that review and connect the SWGI to barriers and resilience concepts, and include, 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: policy, design, maintenance, economic factors, and social factors.

With these general categories for SWGI, we identified detailed indicators for the framework. We started with the papers that used to identify the general categories, but expanded the SWGI literature used 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 to identify any indicators that are related to the general categories, as well indicators that are critical for either resilience or ecosystem functionality of SWGI. The list of the scope of the papers and indicators are included in Table 3.

3- Framework Description

3-1- System Boundary Description for Stormwater Green Infrastructure

Identifying the system scope or boundary is the first step to evaluate a system’s resilience. This concept has been referred to as “resilience to what” or the initial boundaries of the system (Meerow et al. 2016; Meerow and Newell 2016). Also, for each defined system a list of threats including natural disasters and human-made disasters identified (Fox-Lent et al. 2015). Here, our system boundary is any type of green infrastructure that is used for stormwater management. Green infrastructure has a broad range of definitions from trees in urban areas to engineered structures that support ecological processes (i.e., green roofs and rain gardens). Green infrastructure has been defined as an ecological framework required for environmental, social, and economic benefits that sustains life (Benedict and McMahon 2012). Green infrastructure is also defined as an economical, resilient tool for managing humid weather effects that delivers numerous public benefits (EPA 2018). These benefits can be multifunctional compared to gray stormwater infrastructure (pipe drainage, etc.) that provides the single benefit of moving stormwater away from built urban environments (EPA 2018). 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 able to mitigate stormwater to some extent, they are not the focus of this study because we cannot control its 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

One of the critical aspects of resilience is the ability to tolerate disturbance and still retain **basic functions** and **structures** (Walker et al. 2006). Resilience assessment needs to identify critical functions that must be maintained during a stress and disturbance event, or identify other non-critical functions that provide benefits (i.e. secondary ecosystem services-Table 1) that may contribute to resilience after a stress or disturbance event (Fox-Lent et al. 2015). Critical functions are closely related to the boundary and aims of SWGI. Ecosystem services are the benefits people receive from

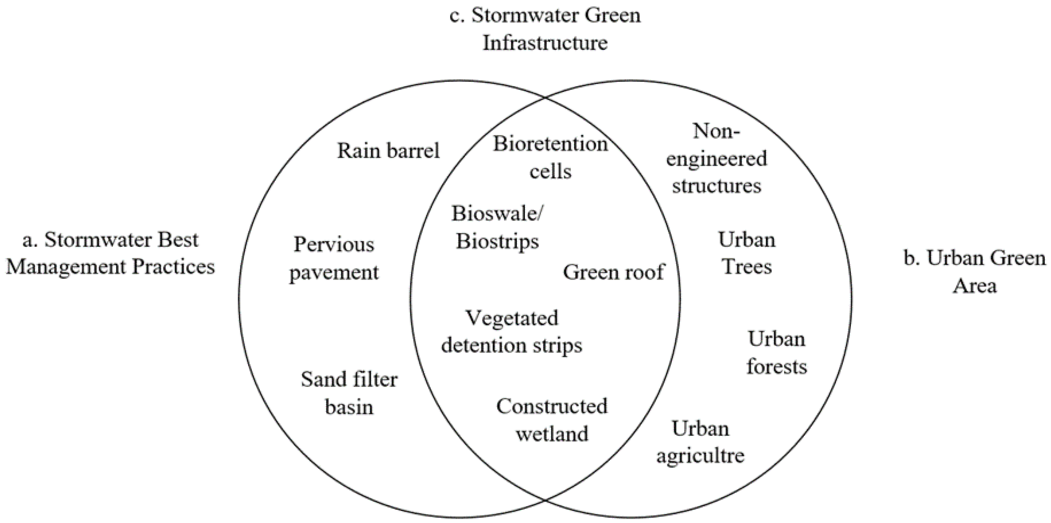

Figure 1 Defining stormwater green infrastructure practices. a. Stormwater Best Management Practices are engineered practices including both green and non-green components. b. Urban Green Area include both engineered and non-engineered practices that have green components c. Stormwater green infrastructure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

an ecosystem and can translate functions into concepts and metrics that managers may be more familiar with (Brendan Fisher, Costanza, et al. 2009; Hansen and Pauleit 2014). Here, we identify critical functions for resilience assessment as the primary ecosystem services SWGI provides, and we recognize that SWGI also can provide secondary ecosystem services (Table 1). We identify flood protection and water purification as the primary ecosystem services of SWGI as related to stormwater management (Table 1). Measurable (either through quantitative or qualitative means) ecosystem services are essential to explicitly assess the multiple functions of SWGI in resilience assessment (Ahern et al. 2014).

Table 1 Stormwater green infrastructure ecosystem services (Andersson et al., 2014; Burkhard et al., 2014; Lovell & Taylor, 2013; Millennium Ecosystem Assessment, 2005; Novotny et al., 2010)

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 SWGI to capture stormwater. We related those functions to primary ecosystem services and critical functionality in the context of resilience. Types of SWGI include, infiltration practices, vegetated open channel practices, filtering practices, detention ponds, retention ponds, wetlands, and sloped vegetated areas (Mays 2009) (Table 2). We assume that the primary ecosystem services (Table 1) are the same as basic functions that are defined in SWGI literature (Table 2), yet these basic functions may be more specific than the ecosystem services. Although the basic functions of all SWGI can be summarized into flood protection and water purification, each SWGI is designed to do its function through different processes. For instance, infiltration practices capture the runoff through infiltration and vegetated open channels capture the runoff by transporting water (Table 2). Some SWGI are designed with a focus on water purification such as wetlands, while other SWGI are designed for flood control as their primary function and with water purification as the secondary function (Table 1). Although flood protection and water purification are mentioned as the basic functions, these are related to the biophysical functions of SWGI that need to be maintained to continue functioning and resilience.

Table 2 Stormwater green infrastructure types, definitions, and processes (adapted from Mays et al., 2009).

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	Bioretention area Biofiltration swale Overland flow filtration

		-Infiltration to the soil -Biological and chemical treatment	
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 maintain the critical functions of SWGI the factors and categories that affect the functionality and resilience of SWGI need to be identified. Our review of SWGI challenges described barriers to functionality and resilience (Ahern 2011; Copeland 2014; Dhakal and Chevalier 2017; Gashu and Gebre-Egziabher 2019; Gould and Lewis 2016; Kronenberg 2014; Matthews et al. 2015; Staddon et al. 2017, 2018; Thorne et al. 2018; Tian 2011). From this literature we identified five categories that can affect GI resilience: (1) policy, (2) design, (3) maintenance, (4) economic factors, and (5) social factors. Although there are external drivers such as climate and uncontrolled factors, such as invasive species and pest outbreaks (Friess et al. 2015), might affect the viability of SWGI, our focus here is on the factors that influence resilience that can directly be addressed through management and decision-making related to SWGI itself. We assume that if the resilience of SWGI is improved relative to these factors that affect functionality, then resilience of SWGI and cities to climate change and other external stressors can be supported (Figure 2). We describe these categories below, and outline indices within these categories later in the paper.

We identified SWGI challenges that relate to its functionality, adoption, and implementation to identify the five categories that can affect GI resilience (Figure 2). *Planning, design, and institutional barriers* are common barriers that emphasized in the literature and categorizations of SWGI challenges especially with regards to provision of design standards and policy (Kabisch et al. 2016; Kronenberg 2014; Thorne et al. 2018; Tian 2011; Zuniga-Teran et al. 2020). There are barriers related to socio-economic and investment provision for implementation and on-going costs of SWGI such as maintenance (Tian 2011; Young and McPherson 2013). *Maintenance* of SWGI is one of the important factors for viability and functionality over SWGI lifespan for receiving sustainable ecosystem services, yet it is usually neglected or an afterthought and not being considered in the design process (Flynn et al. 2012; Young and McPherson 2013). Although maintenance is not often considered as a separate category, we decided to include maintenance as a separate category to emphasize its importance on the resilience of SWGI and sustainability of ecosystem services. One of the critical factors not only for the on-going maintenance but also for supporting public and private applications of GI in resilience planning and implementation, and monitoring of SWGI is the adequate funding and economic factors (Matthews et al. 2015; McRae 2016). 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 (Ahern 2011; Dhakal and Chevalier 2017; Kabisch et al. 2016). 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 opinions of society in resilience planning (Dhakal and Chevalier 2017; Gould and Lewis 2016). The 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 cause and consequence of a change (Tompkins and Adger, 2004)

There are barriers to SWGI or categories that effect its implementation and development that are mentioned in the literature that we did not explicitly included here. For example, the category of "innovation" mentioned in the literature (Staddon et al. 2017; Zuniga-Teran et al. 2020) that necessitates the collaboration of scientists, engineers, planners, and practitioners to co-create novel designs. We did not included 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 seems to have overlap with each other such as capacity, structural, contextual, and technical barriers that are implicitly considered under the current categories in our framework (Gashu and Gebre-Egziabher

2019). Below, we describe each of the main categories that influence resilience and also describe indicators within each of these main categories that can be used to assess the resilience of SWGI (Figure 2). Specific indicators within each main category that we developed from our literature review are described in Table 3.

3-3-1- Policy

Policy links the goal of systems to actions and allocation of resources (Linkov, Eisenberg, Plourde, et al. 2013). Policy and institutional rules outline how different activities should be done with mechanisms for mitigation plans to ensure 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 take into account the community social actions, society could effectively cooperate to management a risk or to actively engage with climate adaptation plans by implementing SWGI (Frankenberger et al. 2013). Policy is also important for adaptive management because policies reveal procedures that build or sustain resilience by learning from the consequences of an adverse event (Folke et al. 2002). Policies to create action platforms and flexible multi-level governance provide an opportunity to create knowledge and cope with stressors. Providing incentives (monetary ad non-monetary) that encourage learning and transfer ecological knowledge into institutional structures can encourage adaptive management (Folke et al. 2002). 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 or Clean Water Act (CWA) and the CWA also obliges states to implement SWGI for non-point source pollutions that pollutes the receiving waters (Carter and Fowler 2008), but the implementation of GI to manage stormwater and CSO that is required by CWA occurs at municipal level. These policies and strategies at federal and local levels should be aligned with each other to promote resilience in cities.

To address our assumption that SWGI needs to be resilient itself to enhance the cities resilience, local-scale policies that control SWGI in a municipality are the focus of the indicators we identified. Policy can embrace three types of indicators: first are indicators that show how organizations work together. Policy should provide a path for smooth relationships and collaboration among stakeholders (Sharifi 2016). Collaboration and connection provide the ability to learn from each other and create knowledge that could result in diverse management options to handle disturbances (Folke et al. 2002). Collaboration can also be between science and policy, as a common policy challenge is the lack of knowledge transfer from scientists to city planners (Schiappacasse and Müller 2015). Science-policy integration is also needed to identify

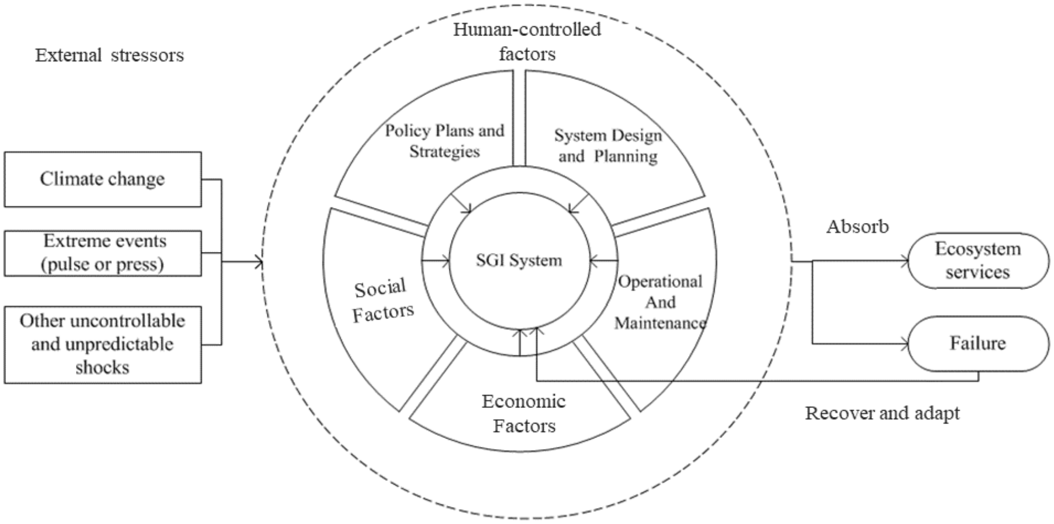

Figure 2 SWGI system- External stressors and human-controlled factors affect the resilience of SWGI. Five main factors that influence SWGI resilience are discussed in the paper (policy, design, maintenance, economic factors, and social factors) and indicators within each are presented in Table 3. Resilience here has three different aspects, (i) resistance to the stressors lead the system to continue its basic functions and delivers ecosystem services as the system absorbs the stress. The system may also (ii) recover and (iii) adapt to come back to the stage to deliver desired ecosystem services.

new risks for systems, an important challenge as climate change impacts unfold in the future (Doremus 2001).

The second type of indicators check for the existence of application-oriented frameworks that actively check for system resilience (Hansen and Pauleit 2014). Policy can also stimulate and enforce existing monitoring systems (Folke et al. 2002). 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 (Baptiste et al. 2015; Campbell et al. 2016; Charlesworth et al. 2014; Staddon et al. 2018).

The third type of policy indicators provide financial incentives or promote awareness to increase the capacity of a social-ecological system to cope with shocks and surprises (Folke et al. 2002). Providing incentives by local government promotes implementation of SWGI. For example, cities or local counties can pay the homeowners to provide downspout disconnection (i.e. such as what was done in Portland) or waiving stormwater-fees or increase site permeability (i.e. case of Washington D.C.)(Foster et al. 2011). Policy can also provide a platform to promote ecological learning and knowledge building in institutional structure among different sectors and for the public and resource users. For example, government could encourage the ecosystem friendly approaches to design (such as promoting ecohydrological fluxes, or avoiding monoculture with plant design). Policy can also promote participatory approaches to planning where scenarios are developed that respond to resilience challenges (Folke et al. 2002).

3-3-2- Design

Enhancing resilience capacity through the 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 (Vale and Campanella 2005). Spatial planning to find the priority areas and identify the required ecosystem services will support resilience to manage disturbances. Resilience planning requires the consideration of the ecology of landscapes that can extend beyond the political boundaries of an urban area (Lovell and Taylor 2013). This kind of priority planning can be for urban flooding (Conine et al., 2004), access to the green space, reducing the urban heat island effect (Madureira and Andreson 2013), adding cooling benefits (Norton et al. 2015), spatial connectivity between people, species and surrounding sites (Auffret et al. 2015), or a combination of benefits (Meerow and Newell 2017). 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 promote providing sustainable ecosystem services, as long as fulfilling social requirements and respecting social values are part of the goals of building SWGI (Ahern et al. 2014; Nassauer and Opdam 2008). The collaboration of scientists, planners, and designers are necessary to combine ecological goals into practice (Felson and Pickett 2005). This collaboration and integration with ecological knowledge could help implement the adaptive design; however, there are challenges for the design process. Deficiency of data on the quantification of benefits of ecosystem services, the cost of SWGI construction and performance, and lack of technical familiarity and skills are among the barriers of 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 (CWAA 2011).

To enhance SWGI resilience through design factors, assessing two main types of indicators is needed: those for site-specific needs and those for the services and functions people want from SWGI. For site-specific needs, planners need to consider the broad climate of 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 practices such as detention ponds are recommended (Mays 2009). 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 (Ahern 2011; Novotny et al. 2010) (Table 3). A second set of indicators relate to the services people need or want from SWGI. These services either relate to critical functions as the primary ecosystem services or other benefits that are categorized in secondary ecosystem services (Table 1). One of these main primary services and critical function of SWGI is the capability to capture runoff. Thus, it is essential that the capacity for runoff capturing to handle frequent large events is considered in the design process. Considering larger storm events than is currently common in design, such as hundred or two-hundred-year events, can help cope with the larger storm events expected with climate change (Keeley et al., 2013). 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 currently the design standards are based on the storm events from the past (McPhillips et al. 2020).

3-3-3- Maintenance

Even with adequate of planning and design of SWGI, assurance of critical functions in time cannot be possible without considerations of proper maintenance. Maintenance is often an afterthought, and there is not much detailed information to describe SWGI maintenance (especially compared with the operation of wastewater treatment systems) (Flynn et al. 2012). Re-framing maintenance positions in the current planning and policy framework is a necessity to keep SWGI functioning and help SWGI gain social acceptance (Matthews et al. 2015). Some states and municipalities have a legal requirement for inspection. For instance, the owners of SWGI in St. Louis, MO need to annually report that the legal requirements of maintenance are met. Maintenance tasks required for various SWGI may include different activities, such as mowing or litter collection, sediment removal, checking plant status, and check water retain after an event. (MSD 2018). Maintenance is a concern for SWGI on both public and private properties. The responsibility of maintenance on public property is to the county or city. For private owners, local governments either provide incentives for maintenance or other alternative financing approaches such as public-private partnerships, infrastructure improvement districts, and dedicated clean water funds (Mahoney 2014; Stevens et al. 2016). Some municipalities provide guidelines and manuals for various types of SWGI and indicating potential areas and aspects of SWGI that need attention. Despite these types of effort, maintenance is often insufficient or differed due to the barriers of securing financing to provide adequate and stable funding for operations and maintenance of SWGI (Flynn et al. 2012; Stevens et al. 2016).

Indicators needed for SWGI maintenance assessment are within three main groups. First, is the presence of an actual maintenance plan or guideline, and those plans address key biophysical features of SWGI. These plans structure evaluating if the current status of SWGI is what was designed for and if it continues functioning. This set of indicators is typically a checklist of maintenance needed for SWGI, including items such as, checking for plant health, cleaning debris and drainage area, check for sediment loading, mosquito production, soil compaction, and pollution build-up. The second type of maintenance indicators is related to knowledge and communication connected to the skills of the maintenance crew and their communication of issues to inform the design team or other related stakeholders. Specific details here include, identifying what level of skills needed for any type of maintenance, selecting a well-informed maintenance crew for each activity, and plans for knowledge updates (Charlesworth et al. 2003; EPA 2009; Mguni et al. 2016). The third type of maintenance indicators are related to the financial aspect of maintenance and the sufficient financing of the costs of frequent maintenance. Cost of ongoing maintenance is important to assure the appropriate functionality of SWGI over time, but the importance of maintenance is not reflected in municipal budgets (Naumann et al. 2011). Despite its importance, maintenance costs of SWGI is still an active area of study and decisions about who might be the party responsible for maintenance are still ongoing (Keeley et al. 2013; Thorne et al. 2018; Sharma et al. 2012). However, there are tools for estimating these costs such (Center of Neighborhood Technology 2009; Jaffe 2010) that may facilitate decision making regarding maintenance. One of the most common types of local incentive are stormwater fee credits or discounts that are used to implement SWGI. However, private developers still think that SWGI can be expensive and costs are seen as a barrier especially for maintenance. Thus, due to the uncertainty for long-term maintenance, it is difficult to persuade communities for SWGI implementation and the potential cost-saving and other benefits of SWGI (Copeland 2014).

3-3-4- Economic Factors

The economic dimension of SWGI resilience is similar to policy in that it intersects other categories, such as design, maintenance, and social factors. Funding allocation and prioritizations are needed to reliably assess and support the cost and benefits of SWGI through design, implementation, and maintenance of SWGI (Zuniga-Teran et al. 2020). There are various types of costs associated with SWGI, one-off costs, and ongoing costs. One-off costs are the capital cost needed for planning, designing, and implementing SWGI and ongoing costs refer to protection, management, and monitoring SWGI on regular basis over time (Naumann et al. 2011). Failure due to financial barriers can cause obstacles to critical functions both through 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 (CWAA 2011). Financial issues are not just a lack of city budget lines at necessary levels, but also a lack data to support cost-benefit decision making. These data relate to future maintenance needs and the ecosystem service values that municipalities can get from SWGI. Economic factors are not only important for the design process and maintenance of SWGI but also affect community willingness to implement SWGI (Baptiste et al. 2015; Vogel et al. 2015).

Economic indicators 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 is required given the realities of limited municipal budget allocations (Naumann et al. 2011). Available tools to analyze the economics of SWGI can determine whole lifecycle costs or cost-benefit ratios (Jayasooriya and Ng 2014; Kennedy et al. 2008; Ozdemiroglu et al. 2013; WERF 2009). The second group of indicators show incentives, especially those for implementation and maintenance of SWGI on private properties, as private landowners may see maintenance as a financial burden, tax incentives could inspire more contributions (Josh Foster et al. 2011). The third group are indicators that can save costs due to multi-stakeholder collaboration, such as planning for multiple uses that benefit parallel stakeholders. For example, planning for multiple ecosystem services that can be set in one location that meet both primary and secondary functions from SWGI (Table 1 &2) such as the infiltration system beneath a building, green roofs on the top of a building, and wildlife corridor over or under roads that provide benefits beyond stormwater management (Van Bohemen 2002).

3-3-5- Social Factors

As cities start to incorporate adaptation planning with SWGI it is important for local governments to focus on strategies to promote community engagement to increase knowledge and awareness, as well as promote equity. Lack of knowledge about SWGI and its multifunctional benefits among residents and citizens to managers and policymakers can cause difficulties for the continuation of SWGI functionality. 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 (CWAA 2011). Moreover, little is known about how residents and urban managers might react to efforts to increase the green area (Byrne and Jinjun 2009). This lack of information may lead to limited engagement by residents (Frantzeskaki and Tilie 2014), which may impact SWGI management on private property. For instance, some residents see the SWGI as a risk to their property as they may provide habitat for wildlife, increase the risks of attacks and accidents, unpleasant noise and odor, and other issues for public and private assets (Byrne and Jinjun 2009). Another important social factor in the context of climate change is social vulnerability and equity as certain communities have lower capacity to respond to climate-related impacts (Lynn et al. 2011).

Indicators to assess to social factors can be put into two groups. The first relates to equity which is one of the basic principles for resilience building (Urban Land Institute 2018). Sociodemographic indicators for measuring and understanding vulnerability include income, housing condition, age, education, and race. Climate-related risks are higher for low-income communities, ethnic minorities, elderly, and children (Vogel 2019). These marginal and vulnerable communities are exposed to greater environmental harms because of the disproportionate availability of environmental benefits (Hendricks et al. 2018; Schwarz et al. 2015). Distribution of green spaces and ecosystem services is an environmental justice issue it is strongly connected to neighborhood characteristics, like income, proportion of renters, and minority populations (Hoang and Fenner 2016; Lin et al. 2015; Smiley et al. 2016). Equitable access to green space is a key factor when assessing the benefits a community gets from GI (Fernández-Álvarez 2017). Second, are factors related to public engagement. Engagement can come from governments or from citizens (referred to as bottom up governance or active citizenship) (Krasny et al. 2014). Research demonstrates that active citizens contribute to ecological, social, and institutional resilience (Buijs et al. 2016) through a variety of means: by increasing and restoring biodiversity (Dennis and James 2016, Chan et al. 2015), enhancing the provision of regulatory ecosystem services (Krasny et al., 2014), contributing to social organization (Veen, 2015), and providing local knowledge (van der Steen et al. 2013). Government plans for dissemination and outreach is an important factor that affects the willingness of a community to implement SWGI (Baptiste et al. 2015). Participatory approaches such as workshops can help the residents to develop a vision of their community (Semenza et al. 2007). Community engagement can be integrated into planning and design (Lovell &Taylor, 2013; Tress and Tress 2003; Shearer 2005) where it can increase satisfaction with outcomes and build trust of designers and planners (Lovell & Taylor, 2013; Al-Kodmany 1999; McCall and Minang 2005).

Table 3 Indicators for policy, design, maintenance, economic factors, and social factors

Category	**Indicator**	**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	(Booth and Charlesworth 2014; Campbell et al. 2016; Folke et al. 2002; Hansen and Pauleit 2014)
	Consider multi-functionality in policy	Considering SWGI delivering multiple social ecological benefits not solely for harmonizing cost and environmental conservation	(Andreucci 2013; Dapolito Dunn 2007; Dunn 2010; Mell 2008; Weber et al. 2006)

	Policy to provide incentive 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	(Folke et al. 2002; Foster et al. 2011)
	Incorporate scientific knowledge in management	Knowledge transfer and integration into policy over time such as updating and identifying new risks into SWGI	(Dhakal and Chevalier 2017; Doremus 2001; Schiappacasse and Müller 2015; Sharifi 2016)
	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	(Folke et al. 2002; Lovell and Taylor 2013; Sharifi 2016)
	Policy for financial constraints	Policy for properly allocate resources to phases related to GI such as design, implementation, and maintenance.	(Lovell and Taylor 2013; Schiappacasse and Müller 2015)
	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	(Dhakal and Chevalier 2017; Mcdonald et al. 2005)
	Integral local and federal rules and regulations	Check for lacking, conflicting, or restrictive local and federal rules	(CWAA 2011; Keeley et al. 2013)
Design	Location	Design with considering needs of a location-Spatial planning for identifying priority areas for the demand of an area or required services	(Ahern 2013; Auffret et al. 2015; Conine et al. 2004; Madureira and Andresen 2014; Meerow and Newell 2017; Norton et al. 2015)
	Climate	Design with considering the climate of a region, climate change, and projections of extreme events	(Matthews et al. 2015; Mays 2009; Ross et al. 2015)
	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	(Fryd et al. 2012; Keeley et al. 2013; Shafer 2011)
	Resilient biophysical components	Design for resilient plant pallet and soil media design for extrafiltration during extreme storm event	(Lee et al. 2016; Lewellyn et al. 2016; Traver and Ebrahimian 2017; Wadzuk and Traver 2012)
	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	(Ahern 2011; Hansen et al. 2019; Hansen and Pauleit 2014; Naumann et al. 2011; Selman 2009)
	Biodiversity	Design with considering diversity of species within functional groups that have different responses to disturbance and stress	(Ahern 2011; Green et al. 2016; Hansen and Pauleit 2014; Hostetler et al. 2011; Kumar 2010)
	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	(Ahern 2011; Green et al. 2016; Mori et al. 2013; Walker 1992)
	Stakeholder collaboration	Design based on the scientific knowledge and collaboration of scientists, planners, and designers to incorporate ecological knowledge to adaptive design	(Ahern 2011; Ahern et al. 2014; Felson and Pickett 2005; Nassauer and Opdam 2008)
Maintena	Check for plant health and coverage	Vegetation maintenance including checking for the healthy plants and prevent invasive species and establishment of monoculture	(EPA 2009; Hatt et al. 2008; Houng Li et al. 2009)
	Cleaning debris and drainage area	Check for basin/ inlet / and outlet through routine inspection to prevent clogging	(EPA 2009)

	Sediment loading	Pretreatment or continuing maintenance for sediment accumulations and clogging especially in urban areas	(Asleson et al. 2009; Brown and Hunt 2011; Hatt et al. 2008; Li and Davis 2008)
	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	(EPA 2009; Lõhmus and Balbus 2015; Russell 1999; Yadav et al. 2012)
	Soil compaction	Check for soil compaction around SWGI during heavy machinery to prevent storage and infiltration reduction and decrease in groundwater recharge	(Burian and Pomeroy 2010; EPA 2009; Pitt et al. 2002)
	Pollution build-up	Check for the possibility of accumulating pollutants under infiltration basins and groundwater contamination	(Kwiatkowski et al. 2007)
	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	(Charlesworth et al. 2003; EPA 2009; Mguni et al. 2016)
	Cost of ongoing maintenance	Appropriate functionality of SWGI overtime is dependent on adequate funding for maintenance cost within a designed lifecycle	(CNT 2009; Jaffe 2010; Keeley et al. 2013; Naumann et al. 2011; Sharma et al. 2012; Thorne et al. 2018)
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	(Naumann et al. 2011)
	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.	(CNT 2009; Jayasooriya and Ng 2014; Kennedy et al. 2008; Ozdemiroglu et al. 2013; WERF 2009)
	Life cycle cost	Consider the whole life cycle include a satisfactory level of construction, administration, and monitoring considering the frequency and monitoring of SWGI	(Jaffe 2010; Naumann et al. 2011)
	Incentives for SWGI implementation	Direct incentives to homeowners to implement or maintain SWGI in their property through direct incentives inspires contribution	(Dunn 2010; Josh Foster et al. 2011)
	Plan for multiple use and stakeholder collaboration	Managing cost through planning for multiple uses (multifunctionality) of SWGI with parallel stakeholders	(Ahern 2007; Van Bohemen 2002; Jaffe 2010)
Social	Public knowledge and outreach	Community engagement and increase level of knowledge through various techniques such as workshops	(Al-Kodmany 1999; Baptiste et al. 2015; Lovell and Taylor 2013; McCall and Minang 2005; Semenza et al. 2007; Shearer 2005; Tress and Tress 2003)
	Equity	Check for the vulnerability and proportional access to SWGI in confronting great storm events in high-income versus low-income communities	(Dhakal and Chevalier 2017; Dunn 2010; Fernández-Álvarez 2017; Hoang and Fenner 2016; Smiley et al. 2016; Urban Land Institute 2018)
	Active citizenship	Engagement of a community that does not start from government and is also referred to as a bottom up governance	(Buijs et al. 2016; Chan et al. 2015; Dennis and James 2016; Krasny et al. 2014; Veen 2015)

4- Discussion

In this study, we developed a resilience assessment framework for urban SWGI climate resilience building off the general "resilience matrix" (Linkov, Eisenberg, Bates, et al. 2013) and a review of SWGI literature. Here, we applied the components needed for resilience assessment to SWGI including defining the system boundary, identifying critical functions and ecosystem services, and identifying categories and indicators to evaluate the 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 (Copeland, 2014; Ahern, 2011; Gould and Lewis, 2016; Sutton-Grier et al., 2015; Young and McPherson, 2013; Zuniga-Teran et al., 2020). We identified indicators under each category using literature review, and connected indicators to management dimensions. Developing a resilience assessment framework can be a useful approach to identify identifying strategies to improve SWGI resilience. This framework should be considered as a preliminary step for further development of a functional assessment tool. Development of a tool may come about by involving stakeholder and expert input into this framework to specify measurable indicators for specific cases. Expert experience could be also helpful for prioritizing indicators and prioritizing the aspects of resilience that are being managed (Fox-Lent et al. 2015; Sharifi and Yamagata 2016) (Table 3).

Linkov, Eisenberg, Bates, et al. 's (2013) "resilience matrix" suggests general domains and categories for assessing resilience but needs further development for specific applications. The resilience matrix has been successfully applied to coastal resilience (Rosati et al. 2015), community resilience (Fox-Lent, Bates, and Linkov 2015), cyber systems (Linkov, Eisenberg, Plourde, et al. 2013), military systems (Eisenberg et al. 2014), and energy resilience (Roege et al. 2014). We identified for SWGI the specific indicators for assessing resilience, recognizing that SWGI has critical functionalities related to ecosystem services and factors that controlling its viability and resilience. 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 system functionalities may require their own categories related to infrastructure, engineering, environmental, hydrological, social, economic, and institutional aspects for specifics of coastal flood resilience, community resilience, and disaster resilience (Cutter et al., 2014; Renschler et al., 2010; Karamouz et al., 2014; Longstaff et al., 2010).

Several GI assessment frameworks build off 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 (Ahern et al. 2014). This toolbox was developed to address the needs of designers and planners and a 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 (TEEB 2010). The goal and intended application of an assessment tool will affect its design and components. Our focus was on evaluating SWGI in a way to improve the resilience of ecosystem services, so our framework begins with identifying critical functions and the 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 socio-ecological nature of resilience challenges that SWGI is being applied to in cities.

Previous extensions of the resilience matrix into frameworks (Fox-Lent et al. 2015; Linkov, Eisenberg, Bates, et al. 2013) have applied scores to each dimension of resilience using expert judgment approaches. However, getting a reliable quantified measure of resilience is difficult. The consequences of a threat to the resilience of a system may be difficult to measure directly until a system confronts those threats and changes in performance in response to disturbances are observed (Carpenter et al. 2001; da Silva et al. 2012). Often, this is because the data required to measure resilience are rare as the knowledge of the type of disturbance and the response of the system after every exposure is not being monitored most of the time (Alfani et al. 2015; Folke 2006). Instead of focusing on resilience measurement, especially for uncertain disturbances such as climate risks, it might be more efficient for managers to consider "building resilience" (Tyler and Moench 2012). Therefore, expert knowledge and judgment can be used to identify fields and areas of vulnerability to build resilience when facing uncertainty (Tyler and Moench 2012). A scoring system in this case could be based on the total level of consideration of essential indicators needed for system resilience, rather than trying to allocate scores for each dimension of resilience. Our framework can be used as a diagnostic approach for management, where assessing the degree each indicator is fulfilled or not would enable researchers and managers to identify indicators that require attention to build or enhance resilience. Emphasizing the level of consideration of an indicator in real planning and implementation is a factor that has been overlooked in other resilience strategies (Fox-Lent et al. 2015; Roege et al. 2014; Rosati et al. 2015).

One of the critical tasks for building a holistic and informative SWGI resilience assessment tool is to consider the interrelationship, interactions, and overlaps between indicators. Our framework considers categories and indicators as separate features; yet, a complex system such as SWGI has a dynamic interaction among its components. For example, SWGI maintenance indicators can be related to directly to economic factors (related to budgeting) and also indirectly to policy (standards and specifications). Although design process and maintenance are important individually for the resilience of SWGI, without proper budget allocations and considerations of full lifecycle needs and costs, each individual category might not be sufficient to meet resilience goals without considering economic factors (Jaffe 2010; Sharma et al. 2012; Thorne et al. 2018; Zuniga-Teran et al. 2020). Such categories can be also related to policy as policy and funding for different activities are closely linked. While there may be potential for such disconnections between categories and indicators, there is the potential for positive feedbacks as well. For example, social awareness may be a goal of some policies and programs but also may positively affect subsequent policies. As knowledge increases in institutional settings, it can generate new policies and incentives and shift governance structures (Dhakal and Chevalier 2017). Our framework identifies some indicators that are related to each other, such as connection and communication among multi-stakeholders that may positively affect the design and maintenance process and policies that may affect financial aspects. Moreover, indices related to education, awareness, and financial aspects may connect to improved designs and frequent maintenance to improve resilience. Considering indicators as interconnected reflects the socio-ecological nature of cities and SWGI, and draws on recognized principles to enhance resilience, such as managing them as complex adaptive systems and recognizing the need for polycentric governance (Biggs et al. 2012).

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. Other approaches that develop a tool from the resilience matrix (Linkov, Eisenberg, Bates, et al. 2013) are also draw on expert assessment to assign relative rating for resilience assessments. For cases such as community resilience assessment and military systems applications of the resilience matrix, local stakeholder input reveals the appropriateness of researcher-defined categories and shows the opportunity to cooperate among responsible parties (Eisenberg et al. 2014; Fox-Lent et al. 2015). However, for other systems (such as coastal resilience assessment), researchers refined the resilience matrix into an assessment tool based on the empirical data, models, and community valuation (Rosati et al. 2015). 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). Also, the learning process from expert experience could continuously improve the framework. Applying to case study and collecting the evidence-based data also helps to learn from adverse events occurs and the SWGI response to those particular events. It can be used as input through an iterative process to improve the evaluation framework. This can also be used as an input to improve the framework and identify the indicators that have more weight than others.

5- Conclusion

We developed a resilience assessment framework for SWGI by building from a general resilience matrix approach (Linkov, Eisenberg, Bates, et al. 2013). This framework defines critical functionality for SWGI and identify categories affected the resilience of SWGI as identified by reviewing the literature. We identified five categories that influence resilience of SWGI that relate to policy, design, maintenance, economic factors, and social factors. Unlike other SWGI assessment frameworks that are focused on ecosystem services as a final outcome, we worked from socio-ecological perspective to include socio-economic and policy factors, in addition to the 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 that have traditionally been overlooked, such as maintenance and social factors. This specific framework also can 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 for SWGI to local priorities in resilience planning.

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Chapter 5: Linking Stakeholder Prioritization of Barriers and Critical Functionality for Stormwater Green Infrastructure Resilience: Co-producing A Social-ecological Framework for Resilience Assessment

Abstract

Green infrastructure (GI) is increasingly being adopted in cities as a sustainable approach to enhance climate resilience and ecosystem services provision. Despite the potential for GI to enhance urban climate resilience, we argue that GI itself must be resilient to convey the resilience to cities. Therefore, this paper aims to co-create a social-ecological framework to assessment stormwater GI (SWGI) resilience. We engaged a diverse group of stakeholders representing managers, planners, designers, and maintenance workers from the Anacostia Watershed via a focus group. We identified challenges for SWGI under five categories: policy, design, maintenance, economic factors, and social factors. We worked with stakeholders to co-create specific indicators under these categories and link them with resilience management dimensions. Our result show that specifying indicators and dimensions related to critical functions of GI, as well as the challenges that influence them, can help planners and decision-makers prioritize resources to enhance GI climate resilience. Stakeholder discussions revealed that the different design stages of GI pose unique challenges for resilience and that these stages are often overlooked. A collaborative co-production approach for creating a resilience framework is critical as it develops linkages between knowledge and practice. Moreover, a collaborative approach can encourage networks of communication and integrate diverse opinions that can enhance resilience. This framework can inform the resilient management of adverse events and can be used to prioritize resources to enhance GI resilience.

Keywords: social-ecological, resilience, assessment framework, green infrastructure

1- Introduction

Urban populations around the world are becoming more vulnerable to the effects of climate change due to growing cities, the nature of built environments, and current approaches to urban management (Derkzen et al. 2017). Climate change brings more frequent storm events and heat waves, and as consequence damage to urban infrastructure and impairment of public health (Oulahen et al. 2018). As many cities are confronting climate-related concerns, urban planners and decision-makers are progressively developing climate adaptation plans. For urban climate adaptation, a resilience-based approach inspires practitioners to consider both recovery from shocks and stresses that may or may not be predictable, as well as the ability to plan and adapt to impacts from climate stresses (NRC 2012; Walker et al. 2002). Climate change is expected to increase frequency and intensity of climate extremes, such as periods of heavy rain and extreme drought. However, the focus of numerous studies have been more on the effect of climatic means on ecological systems rather than the effects of these climate extremes (Patt et al. 2005; Smith 2011). For cities to be resilient to events with high degrees of uncertainty, or even potentially unpredicted impacts of climate change, planners may need to balance both specific general resilience (Carpenter et al. 2012).

One of the major approaches for enhancing the urban resilience is the development of green infrastructure (GI) (Lennon and Scott 2013). GI refers to the expansion of urban green spaces, such as rain gardens, green roofs, and greenways, that deliver a variety of ecological and social benefits by enhancing ecological functions

(Young and McPherson 2013). GI appears to be promising in improving urban resilience by providing ecosystem services such as flood mitigation, urban heat island reduction, energy usage control, and human wellbeing (Pennino et al. 2016; Saleh and Weinstein 2016; Sutton-Grier et al. 2015). Geospatial planning for how to expand GI is one of the approaches to enhance the cities resilience (Collier et al. 2013; Matthews et al. 2015). For instance, the application of GI spatial planning models in Detroit reveals that placing GI in high priority areas for various purposes such as stormwater reduction, urban heat island mitigation, air quality improvement, and increase in habitat connectivity increases resilience in growing cities (Meerow and Newell 2017). Scenario analysis of GI with consideration of future climate uncertainties and urbanization is another approach to enhance the future resilience in urban areas (Dong et al. 2017). We focus on stormwater GI because the relationship between GI and resilience in cities is mostly focused on its ability to manage stormwater (Ahern 2013). GI has the potential to rely less on centralized stormwater management systems and can deliver redundancy and less vulnerability to disastrous failures (Ahern 2011). GI is more flexible that massive old underground pipes and pumps (Mell 2016; Palmer et al. 2015). Flexibility is an important feature in confronting climate change and its uncertainty (Foster et al. 2011; Mell 2016).

We argue that the elements and networks of GI itself must also be resilient in order to contribute to the resilience of cities. Urban ecosystems have not been well integrated into urban governance and planning for resilience. This is despite the potential for ecosystem services provided by GI to support transitions to more sustainable cities (McPhearson et al. 2014). At the same time, there is increasing recognition that the design of GI is inadequate to meet functional goals under climate change conditions (McPhillips et al. 2020). Additionally, there are several institutional, technological, perceptual, socio-economic, justice, and innovation related factors that draw into question the ability of GI to be resilient in future climates and situations (Ahern 2011; Copeland 2014; Gould and Lewis 2016; Sutton-Grier et al. 2015; Young and McPherson 2013; Zuniga-Teran et al. 2020). One of the main challenges to GI design includes a lack of performance data and deficiency of technical knowledge and expertise, particularly as these data can indicate institutional, technological, and perceptual factors (NRC 2009). Building resilience needs the consideration of social factors, such as equity and meaningful participation of stakeholders, that tend to be overlooked in GI planning (Ahern 2011). 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 opinions of society in resilience planning (Gould and Lewis 2016). Technical aspects, such as maintenance of GI is required for it to function as expected over its lifespan. It is especially important for maintenance to be considered in the design process in a way that is cost efficient for owners and contractors over time (Flynn et al. 2012); however, maintenance is often overlooked in considerations of financing and design standards, with emphasis placed on initial design and implementation (Zuniga-Teran et al. 2020). Financial barriers are also important for GI resilience and illustrate how challenges to GI interact. For example, adequate funding sources for public and private GI (Sutton-Grier et al. 2015) are important for supporting installation, but also on-going maintenance to provide effective ecosystem services

(Young and McPherson 2013), and any desired monitoring of the multifunctionality of GI (McRae 2016).

In order for municipalities to manage these factors and challenges that can affect the resilience of GI, an assessment framework is needed. Assessment frameworks used to inform decisions regarding urban or community resilience to general natural disasters can be illustrative for the specifics of climate resilience (Fox-Lent et al. 2015; Linkov, Eisenberg, Bates, et al. 2013; Linkov, Eisenberg, Plourde, et al. 2013; Sharifi and Yamagata 2016). For example, a "resilience matrix" was developed based on the National Academy of Science (NAS) definition of resilience and included assessing four dimensions of resilience: preparing for, absorbing, recovering from, and adapting to stresses and disturbances (Linkov, Eisenberg, Bates, et al. 2013; Linkov, Eisenberg, Plourde, et al. 2013). This resilience matrix does not specify metrics and is not a formal tool, but does provide a framework that could be used to develop an assessment tool. For example, this framework was used to develop both quantitative and qualitative metrics for disaster resilience for coastal communities (Fox-Lent et al. 2015). An important aspect of adapting this general framework for the specific case of coastal resilience was the inclusion of local experts in identifying suitable indicators that reflected their specific needs and objectives (Fox-Lent et al. 2015). Sharifi and Yamagata (2016) proposed a similar matrix to Linkov, Eisenberg, Bates, et al. (2013) for urban settings and associated each indicator with resilience characteristics (i.e. robustness, stability, flexibility, efficiency, etc.). Sharifi and Yamagata's (2016) matrix shows the importance of developing indicators in order to support application of their resilience assessment tool in urban management. However, their matrix was not developed for a specific urban setting, nor with engaged stakeholder and professional input, limiting its application as an actionable tool to inform resilience decisions (Sharifi and Yamagata 2016).

The participatory processes and co-production of knowledge with stakeholders and decision-makers is essential for the production of reliable, actionable, and socially robust knowledge (Borquez et al. 2017; Gibbons 1999). In knowledge co-production, diverse actors in policy, practice, and science, collectively recognize problems, produce knowledge and put the knowledge into action through partnership, incorporation, and learning procedures (Borquez et al. 2017; Muñoz-Erickson et al. 2017). Dialogue between scientists and stakeholders is beneficial for mutual learning and finding solutions to complex environmental issues (Frantzeskaki and Kabisch 2016). The diversity of stakeholders and decision-makers involved in GI design, planning, and implementation should be seen as an opportunity to complement the work of GI to maximize the effect of climate adaptation in cities (Frantzeskaki et al. 2019; Kabisch et al. 2016). Moreover, integrating elements of urban management, design, planning, and governance can be an opportunity for the co-production of knowledge that allow us to build practical frameworks to advance strategies for GI resilience and satisfies a range of stakeholders perceptions (Raymond et al. 2017). Thus, working with stakeholders to develop assessment tools and frameworks is an important step to linking resilience theory into practice.

Here, we aim to (1) co-create an evaluation framework to assess the resilience of GI using several categories and (2) to develop detailed indicators that relate to three dimensions of resilience (Linkov, Eisenberg, Bates, et al. 2013; Linkov, Eisenberg, Plourde, et al. 2013). This work is the first to engage a diverse group of stakeholder's representatives from managers, planners, designers, and maintenance to co-develop a GI resilience assessment framework. We worked with stakeholders to identify challenges in a specific case study (stormwater management under climate change in the Anacostia River watershed) and incorporated them into a resilience assessment framework. The ultimate goal is to understand how to improve the aspects of the GI system that can absorb a disturbance and in case of functionality loss, the aspects that can help with recovery and adaptation.

2- Method

2-1- Study Area

The Anacostia watershed a highly urbanized watershed that covers three political jurisdictions in the Washington metropolitan area: Montgomery County and Prince George's County in the Maryland, and the District of Colombia (Figure 1). As the urban space has developed, the Anacostia watershed has lost 70% of forestlands and impervious surfaces now cover 25% of the watershed (USEPA 2020). Expanding residential and commercial development, as well as agricultural uses, has led the Anacostia River to be classified as one of the most contaminated rivers in the US (Shamsi 2010). Huge efforts have been implemented to improve the water quality over the last several decades due to regulatory triggers, such as requirements of the Chesapeake Bay total maximum daily load (TMDL), and Municipal Separate Storm Sewer Systems (MS4s) (Maryland Department of the Environment Water Management Administration 2015). The US Environmental Protection Agency (EPA) has targeted grant program to apply GI on a watershed scale, and a multi-jurisdictional Steering

Committee was created to manage and organize such activities (USEPA 2014). Many organizations such as non-profits and government agencies are involved in activities to improve the quality of Anacostia River. In addition, there is a collaboration among agencies in this area such as the Anacostia Restoration Partnership, the Leadership Council for a Cleaner Anacostia, and Urban Waters Federal Partnership (USEPA 2020). Also, the University of Maryland (UMD) serves as a leading research institution within this watershed (Flint and Davis 2007; Mcnett et al. 2011).

Climate change is expected to have significant impacts on the Anacostia Watershed. Climate models suggest that monthly precipitation in the Northeast is projected to increase by about 25.4 mm for December through April by the end of the century (2070-2100) (U.S. Global Change Research Program 2018). Increasing temperatures and shifting the rainfall patterns are likely increase the climatic extremes such as floods and droughts (USEPA 2017). These predicted climate impacts are already being observed. For example, DC area has increased in temperature by 5 to 10 percent in the last century and precipitation forming extreme floods has increases more than 25 percent across the eastern United States since 1958 (USEPA 2017). In response

Figure 1 The Anacostia Watershed (map from www.chesapeakequarterly.netv)

to predicted climate change impacts, several municipalities and organizations in the watershed are developing climate adaptation guiding documents. For example, DC has established the Sustainable DC Plans, Climate Ready DC, with the aim to increase resilience to future climate change while continuing to grow greener and healthier (DC Department of Energy and Environment 2013). Maryland has established a Climate Action Plan (Maryland Department of Environment 2008, 2011) including two strategies to guide adaptation planning at state level. This plan includes (1) addressing the effect of sea level rise and coastal storms, and (2) addressing the change in precipitation and temperature trends and its effect to human health and wellbeing, ecosystems, water resources, and infrastructures (Maryland Department of Environment 2008, 2011).

2-2- Participant Selection

We used a focus group approach in June 2019 to integrate expert knowledge into a co-produced resilience assessment framework. We selected experts as representatives of city-level government, local and county level government, environmental utilities, engineering, design firms, and maintenance agencies to reflect the diversity of organizations that are involved in GI in Anacostia watershed. We made an initial list of all potential participants in the watershed through a phone interview with each center or institution (i.e. Department of Environmental Protection in each county, Anacostia Watershed Society, USEPA, Department of Environment and Energy, maintenance agencies, design, and engineering firms, etc.) and then a representative from each center was identified to attend the focus group. We sought to include representatives from managers, planners, designers, maintenance workers, and experts who directly work with technical, financial, and social aspects of GI. We had 10 representatives participate in the focus group, representing, City of College Park, Montgomery County Department of Environmental Protection, District Department of Environment and Energy, DC Water, Prince George's Low Impact Development Center, AlmaVerde Sustainable Gardening LLC, RK&K Engineering Firm, University of Maryland Sustainability office, and University of Maryland facilities management.

2-3- Focus group

Before the focus group: To prepare participants for the focus group and to gather the basic information, we sent out a pre-survey to stakeholders and asked, their definition of GI definition, their definition of resilient GI, and what they thought the current important resilience challenges to GI are. We reviewed the GI challenges literature including, (Copeland 2014; Ahern 2011; Gould and Lewis 2016; Sutton-Grier et al. 2015; Young and McPherson 2013; Zuniga-Teran et al. 2020) to generate categories of factors that affect GI resilience (Mosleh, 2020, chapter 4). In this review, we identified five categories of factors that can affect GI resilience: (1) policy, (2)

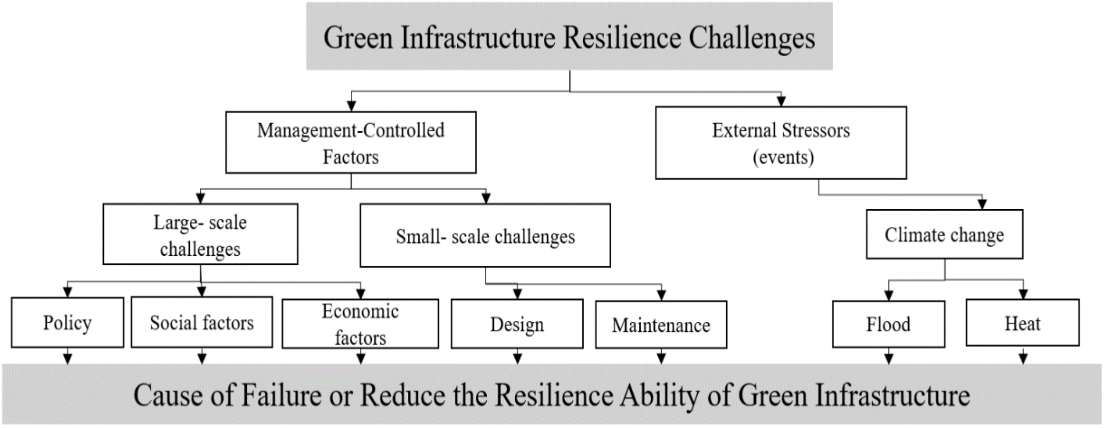


Figure 2 Green infrastructure resilience challenges can be divided into external stressors such as climate change or management-controlled factors. The human factors are the focus of this study. We identified 5 main categories of challenges: policy, social factors, economic factors, maintenance, and design and structured our focus group activity based upon these categories.

design, (3) maintenance, (4) economic factors, and (5) social factors. We categorized stakeholder responses to the pre-survey questions under these five categories (Figure 2).

During the focus group: We held a 2-hour focus group with the 10 participants on the University of Maryland campus in June 2019. The goal was to draw on expert knowledge to co-develop a GI resilience assessment framework. The session included three phases: (1) discussing the pre-survey results and identifying GI resilience challenges, (2) breakout groups to develop indicators, and (3) connecting indicators to resilience categories (Figure 2).

In phase 1, we began with an initial overview presentation and discussion of pre-survey results reflecting stakeholders' views on the definition and resilience challenges of GI. We used a "nominal group" technique to identify as many challenges as possibly by asking individuals to provide their ideas without inviting whole group discussion until after the initial brainstorming activity (Andersen and Richardson 1997). Each expert was asked to first write down GI resilience challenges within the categories of policy, design, maintenance, economic factors, and social factors. In this phase, each participant recorded the challenges in their own area of expertise on a worksheet. Space was also provided for the participants to write challenges for the other categories as well. This initial individual brainstorming was followed by a group discussion of the challenges that included the whole focus group. We recorded group discussions from phase 1 and transcribed voice to text to extract all the challenges discussed during the focus group.

In phase 2, we asked the participants to work in breakout groups that were defined by field: managers and planners, designers and engineers, maintenance inspectors. Then, we asked each group to list important indicators for evaluating GI resilience within the five assigned resilience categories (planning, design, maintenance, social and economic factors). In this phase, experts in similar fields worked together to identify the indicators.

In phase 3, stakeholders investigated the connection of each indicator to specific resilience dimensions of absorb, recover, and adapt (NRC 2012). These dimensions reflect the idea that resilience includes the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (NRC 2012). We asked them to discuss and indicate which dimension of resilience each indicator was related to and show if the indicator can be connected to one or more dimensions of resilience. Relating each indicator to the dimensions of resilience could help GI planners to prioritize resource provision to enhance the climate resilience of GI with respect to local priorities.

After the focus group: We sent a post-survey to the participants to get feedback on the indicators developed at the focus group and for them to develop priorities for the indicators. To prioritize the indicators, we asked stakeholders to rank them by importance within each of the general categories (planning, design, maintenance, social, and economic factors). Indicators were ranked from 1 to n (n= number of identified indicators during the focus group) within each category.

Finally, we used this feedback from the stakeholders to develop a GI resilience assessment framework (Table 3). This co-produced framework includes a set of prioritized indicators of resilience within categories of planning, design, maintenance, social, and economic factors, as well as which aspect of resilience the indicator relates to (absorb, recover, and/or adapt). The focus group participants did not reflect the financial and social sectors and aspects of resilience well. Thus, after the focus group, we contacted specialists at UMD Sea Grant Extension Watershed Protection and Restoration Program and UMD Environmental Finance Center that represented the financial and social aspects. We asked them to reflect on any missing challenges that were identified during the focus group and also asked them to reflect any additional indicators they felt were missing. The final assessment framework (Table 3) also reflects their input.

2-4- Data Analysis

We solicited expert thoughts an opinion on resilience challenges and indicators for GI before, during, and after the focus group. We categorized and tabulated their responses on resilience challenges in order to summarize and to address the initial goals and research questions (Rabiee 2004; Yin 1994). We used a consensus ranking approach (W. D. Cook and Seiford 1978) for the indicator rankings participants provided in the post-survey in order to develop priorities for the indicators. Consensus ranking is a distance-based method aimed at finding a single collective ranking that has minimum distance to each participants' individual ranking (Appendix 2).

3- Results and Discussion

Our goals were to co-produce a resilience assessment framework for stormwater GI and to identify challenges for GI resilience in the Anacostia watershed.

To accomplish this, we performed 3 stages to collect the data, before the focus group through pre-survey, during the focus group through discussion and breakout group activities, and after the focus group through post-survey.

Before the focus group, we asked stakeholders how they define GI, what resilient GI means, and to identify challenges for GI. The aim of this stage is to identify any potential conflict in definitions, as there are multiple definitions of GI and resilience (Escobedo et al. 2019; Folke 2006; Linkov et al. 2014; NRC 2012) . Participants had similar views on the definition of GI, and almost all included concepts of 'natural systems' to 'manage stormwater'. Some of the definitions emphasize the concept of providing 'multiple benefits' especially ecological benefits and 'water treatment' in 'urban areas.' This reflects the growing appreciation for the multifunctionality of GI (Lovell and Taylor 2013; Meerow and Newell 2017), despite being used primarily to manage stormwater in this region. The stakeholders' responses on resilient GI mostly included concepts such as the ability to 'handle extreme events and climate change', being 'less likely to fail/maintain its main functions', and that 'needs low maintenance.' The provided definitions of GI and resilience show that participants have consensus and shows less potential conflict on their point of view about these concepts (Cousins 2017). These definitions also converged with our framings (as researchers) of GI and resilience prior to the focus group.

3-1- Green Infrastructure Challenges

We asked stakeholders about challenges that affect the resilience of green infrastructure before the focus group in the pre-survey. In this phase, we only gathered general information on challenges by asking the most important challenges green infrastructure may face. Most of the responses were focused on the ‘lack/insufficient maintenance’, ‘poor/improper design and installation’, ‘lack of knowledge and education’ and ‘lack of budget’ (Table 1). During the focus group, stakeholders wrote and discussed the challenges considering the pre-defined categories: planning, design, maintenance, social, and economic factors (Figure 2). The challenges discussed during the focus group were the same as what stakeholders had reported before the focus group. (a full record of challenges is reported in Table11-Appendix 2). We will discuss these challenges below as they relate to planning, design, maintenance, social, and economic factors.

Table 1 Green infrastructure (GI) challenges as identified by stakeholders in the Anacostia watershed. The table indicates the number of responses from participants (combined from survey and focus group) that indicated the challenge was important (for challenges repeated more than 4 times) and categories identified by participants (from: planning, design, maintenance, social, and economic factors).

Challenges Statements	Repeated time	Category
Lack of adequate funding/ budget planning	18	Economic factors
Insufficient maintenance	13	Maintenance
Lack of knowledge in design and maintenance	12	Design, maintenance
Poor/improper design and installation	11	Design
Lack of communication/ consensus among multi-stakeholders	10	Policy, design, maintenance
Customize plan and standards for design and maintenance	9	Policy, design, maintenance
High cost of maintenance	8	Maintenance
Lack of considering specific needs of a location/ climate	7	Design
Concern on physical issues	7	Maintenance
Public knowledge, education and outreach	7	Social factors
Policy change or lack of will in making impactful change	5	Policy

Policy Challenges: Stakeholders reflected that the important policy challenges are lack of consensus and communication among multi-stakeholders and lack of political will in making impactful changes (Table 1). As there are always multiple stakeholders involved in GI projects, conflicts in views and goals are extremely likely. Cooperative implementation practices may be one means to get past conflicts that can be achieved by starting extensive outreach and increasing inter-sectoral cooperation (Schiappacasse and Müller 2015). However, there is usually a lack of sufficient collaboration among stakeholders in many cities that may hinder such cooperative approaches (Cettner et al. 2013; Dhakal and Chevalier 2017). To help promote consensus and better communication among stakeholders, local regulations and laws affecting the land-use implementation and decisions may need to be altered or adapted to address current policy issues and values to promote cooperation (Schiappacasse and Müller 2015). Lack of political will in making impactful changes may also affect the ability to change regulations for multi-stakeholder challenges. For climate change issues, policy makers and planners need to be engaged with wide range of stakeholders and sectors to continuously be prepared for anticipated changes and update action and risk management plans as situations and environments change from current conditions. (Matthews et al. 2015).

As stated by stakeholders in our focus group, one way to foster collaboration between multiple stakeholders is to get credit for multiple benefits of GI that can address the diverse needs of multiple stakeholders. However, getting credit for co-benefits was also discussed during the focus group as one of the key policy challenges (Table 11-Appendix 2). One of the main reasons for GI implementation is managing stormwater and preventing combined sewer overflows (CSOs). For example, Maryland Department of the Environment's GI program is designed to promote the city's compliance with Clean Water Act regulation, controlled by the requirements of the Chesapeake Bay total maximum daily load (TMDL), and Municipal Separate Storm Sewer Systems (MS4s) (Maryland Department of the Environment Water Management

Administration 2015). Based upon the conversation with practitioners, “the stronger budget only comes out of the stormwater budget due to regulatory obligations and other benefits such as community redevelopment for safety or improving air quality for community health are not considered”. Practitioners stated, “if social benefits, or real estate value is taken into the account, consequently those projects might turn out to be the most cost-effective versus siloed program”. Stakeholders suggested that it is important to revise and update policy by regulatory agencies to consider co-benefits or and to allow credits for TMDL that are comparable to what originally was considered for combined sewer overflow. The reason for not addressing the multi-functionality of GI is a traditional individual management perspective (Schiappacasse and Müller 2015). As a result, additional benefits, such as the social effects of GI that may be a ‘catalyst’ to financial development, have been ignored (Schiappacasse and Müller 2015). GI needs to be considered in similar way as other infrastructures and be designed and implemented to function as a whole not as a unrelated pieces and elements (Schäffler and Swilling 2013).

Design Challenges: Stakeholders reported that lack of knowledge about specific designs, lack of design standards, and insufficient communication between designers and maintenance workers were among the most important design challenges (Table 1). Stakeholders expressed a general lack of knowledge in horticulture and landscape design such as plant selection, plant type and size, and connection between the type of soil and plants, and a lack of considering design for commercial vs. residential settings as important challenges. Other studies have also shown the lack of knowledge and technical skills in different project phases, and lack of connections between multi-stakeholders are among the significant barriers for GI implementation (Naumann et al. 2011; Vail and Meyer 2012). Stakeholders mentioned a lack of specific design guidelines and standards is another challenge they faced. For example, one stakeholder expressed that “we don’t have a guideline for how long the media should sit before it can be planted, standards for aesthetic values, or site assessment for invasive species”.

Lack of considering specific needs of a location was also discussed as one of the main design challenges which also relates to lack of technical skills and understanding of the specific needs by the design team as discussed during the focus group. This result was also aligned by other studies that show lack of/ insufficient national standards and code and lack of considering climate change in design which can be also a policy-related challenge (Dhakal and Chevalier 2017; Thorne et al. 2018). In addition, stakeholders mentioned that every single site needs a specific survey and test to specify the needs but usually the high associated cost prevents sufficient analysis. One of the reasons could be the lack of data on the cost and performance of specific GI (Copeland 2014).

Maintenance Challenges: Stakeholders stated insufficient maintenance and high cost of maintenance as one the most important challenges of GI (Table 1). Local experience with GI shows a different set of operation and maintenance protocols is required for a decentralized system like GI compared to a traditional water system (Keeley et al. 2013). Stakeholders in our focus group discussed using and archiving design documents to consider needs for local settings as an approach for efficient maintenance. In addition, stakeholders reflected that monitoring a system over time will help determine causes of GI failure and that having a customized maintenance plan for each site could have a significant effect on enhancing the GI resilience.

Stakeholders stated the cost and lack of adequate funding as the number one challenge in maintenance. While stormwater GI is cost-effective (Montalto et al. 2007), the amount of maintenance costs are still being determined (Keeley et al. 2013) due to high uncertainty around the cost of maintenance (both in private and public sectors) and considerations of who would be responsible for long-term maintenance costs (Sharma et al. 2012; Thorne et al. 2018). Maintenance costs is also a factor that has been found to have a negative effect on the willingness of residents to adopt GI (Hammitt 2004; Zuniga-Teran et al. 2020). Taking into account costs that include maintenance as well as a wide range of benefits beyond stormwater management, such as energy-savings, pollution mitigation, habitat provision (Dunn 2010; Tzoulas et al. 2007), would help determine total GI cost-effectiveness.

Economic challenges: Stakeholders stated that the lack of funding and budget prioritization as the main economic challenges (Tables 1 and 2). Stakeholders also expressed insufficient allocation of funds for maintenance. One of the focus group participants stated that “the higher cost is needed where people live compared to facilities that are not close to the residents’ home because maintenance is sometimes not needed much especially when a facility is still functioning”. One way to overcome the budget issue could be through combined sources of public and private sources. Prince George's County, MD is one of the pioneers to join the innovative 30-year Community-Based Public-Private Partnerships agreement (CBP3), referred to as the Clean Water Partnership. The Public-Private Partnership is a partnership between the county and a private entity (such as Designgreen, LLC). The goal of the partnership is to provide services in a cost-effective way. The CBP3 agreement aims to meet the requirements of the Chesapeake Bay TMDL. In accordance with Prince George’s County’s Municipal Separate Storm Sewer System, the county is required to retrofit about 15,000 acres of uncontrolled impervious surfaces by 2025. Thus, through this partnership the county looks to finance, design, build, operate, and maintain stormwater GI. Through the initial three years of the agreement, the county has invested $100 million for planning and implementation of GI to retrofit 2,000 acres. The private parties fund 30-40 percent, enabling the project to start sooner and this funding is also responsible for long-term maintenance. Besides sharing financial and legal risk, the CBP3 provides economic development by generating new local business opportunities, jobs, and building community wealth (USEPA 2020). Currently, GI is more easily implemented in new development compared to retrofitting existing developed areas. Despite these challenges, the pressure on city budgets and urgency of maintenance makes it hard to alter traditional budget lines (Dunn 2010). There are also cost challenges with regards to design for larger storm events. However, there are strategies to move to the type of GI that are more cost-effective and could better handle peak flow reductions, such as porous pavement. In addition, modification in design of other type of GI, such as increasing the depth of green roofs and the area of bioretention, could be also helpful for meeting future precipitation challenges (Chui and Zhang 2016).

Social challenges: Stakeholders expressed the lack of knowledge and education on GI as one of the main factors that can affect public attitude and acceptance of GI (Table 1). Stakeholders stated the importance of education and outreach to convey the importance of GI, to expand the idea into peoples’ normal life routines, and to dispel misconceptions about GI promoting nuisance organisms. One of the approaches for community engagement discussed during the focus group was initiating GI projects through the outreach activities followed by workshops targeted at bringing residents together with practitioners. Participatory workshop approaches that integrate scenario planning can help residents to have a vision of their community that includes GI (Semenza et al. 2007). This can be combined with various visualization techniques for better communication with residents (Lovell and Taylor 2013; Shearer 2005; Tress and Tress 2003).

Based upon the stakeholders’ input, we were able to identify that certain challenges were mentioned within certain categories. We grouped the challenges to find any patterns with representatives from various sectors that touch upon policy, design, maintenance, social, and economic factors (Table 2). Remarkably, we observed that stakeholders representing financial and institutional approaches do not consider connections with social factors (Table 2). The discussion of economic factors was on factors that are directly related to financial aspects such as budget planning and institutional aspects. These did not take into account how economic factors need to be discussed for social outcomes and society perception and knowledge. Looking into financial group and budget planning, the social factors is the only category that was not considered during the discussion for its financial needs (Table 2). That could be also linked into the resources that is allocated for public awareness. If there are more awareness in the society, people may ask for more resources to overcome their challenges. We can see that there is no relation between challenges related to social factors to any of institutional group showing that there is disconnection between policy needed to be in place for improving society perceptions and awareness.

Table 2 Common challenges among categories- We identified 5 categories and asked stakeholders to identify the challenges related to each category. We grouped the common challenges into institutional, social outcomes, perception and knowledge, physical, and financial. Each cell with + shows the category includes the named challenges.

Stakeholder Group	Identified Challenges	Challenge Categories				
		Policy	Design	Maintenance	Economic factors	Social factors
Institutional	Policy change/ Political will	+			+	
	Lack of Standard or evaluation system	+	+	+		
	Lack of considering sectors' connection			+	+	
	Lack of consensus and communication	+	+	+		
Social Outcomes	Lack of considering specific needs of a society	+	+			
	Environmental justice					+
Perception and Knowledge	Public attitude			+		+
	Lack of knowledge	+	+	+		+
	Lack of outreach					+
Physical	Biophysical limitations		+	+		
	Lack of considering specific site features		+	+		+
Financial	Budget planning issue	+	+	+	+	

3-2- Resilience Assessment Framework

The GI resilience challenge discussion during the focus group, under the defined categories of policy, design, maintenance, economic factors, and social factors was used to co-develop the indicators for GI resilience assessment framework. We assume that a practical framework for GI resilience assessment needs to emerge from exploration of GI challenges. Thus, the development of resilience assessment indicators and the connection of those indicators to resilience dimensions was done in the context of the challenges described above.

3-2-1- Resilience Indicators

A holistic approach for assessing the GI resilience is to select the indicators that enable us to find out the GI's ability to absorb risks, efficiently respond and recover, and capacity to adapt to a new state (Rus et al. 2018). Indicators can help with highlighting the key factors needed to evaluate a system. Resilience assessment is a growing field and the aim of studies elaborating on different indicators to be incorporated into a resilience assessment framework is to convert the resilience into a measurable concept. An integrated assessment framework could help to better understand the complexities of working with GI as socio-ecological systems (Sharifi and Yamagata 2016). Resilience indicators and metrics could recognize and prioritize requirements, screen development, and allocate resources (NRC 2012). As resilience is a multi-faceted concept, a comprehensive assessment framework should address the dimensions of policy, design, maintenance, economic factors, and social factors (Mosleh, 2020, chapter 4).

Policy: Policy indicators can be used to evaluate policies in terms of their capacity to encompass climate change impacts, their effectiveness for collaboration with other entities and stakeholders, and how they support cost-sharing and other integrated approaches (Table 3). Policy is not a stand-alone dimension but interconnected with the other categories considered in this study. Policy helps to define activities and communication among sectors and identify the mechanisms that exist for possible mitigation plans and authority for implementation. Strong policy plays a key role in enhancing the resilience by binding other elements of the GI system and strengthening associated social networks (Frankenberger et al. 2013). Policy describes how diverse actions are linked, what mechanisms available to make the possibility of mitigation plans and guarantee that they are applied (Sharifi and Yamagata 2016). Here, the policy and institutional factors are connected to almost all the categories (Table 2), highlighting the significance of policy for various aspects affecting the climate resilience of GI.

Stakeholders ranked cost-share policy (especially for retrofits), policy to recognize and prioritize co-benefits, and policy for a more integrated management and planning system as the most important policy indicators for GI resilience (Table 3). This could be connected to the importance of considering GI multi-functionality to address the multiple demands of stakeholders. Considering co-benefits of GI could enhance the involvement of multi-stakeholder and as a result, can provide platform for more collaboration and move toward the cost-share activities. Consequently, cost-share policy can identify the mechanism and assure the implementation. These top indicators are basically connected to the real needs of the policy that has identified earlier as significant policy challenges from stakeholders' perspectives (Table 2). For example, if we improve the sector's connection and communication, that have identified as policy challenges, we could eventually move toward a more integrated system and cost-share policy that has identified as top-ranked GI resilience indicators.

Design: The design category of GI resilience comprises the indicators related to the climate change capacity of designed features (i.e. planting, soil design, and hydrologic capacity) for flooding, drought, salt, and wildlife pressure (Table 3). There are also indicators related to biophysical features that need to be designed considering the specific needs of a site and checking the linkage of site features to the intended design after the implementation. In addition, some of the indicators are related to the existence of specific standards for soil and plant selection and monitoring. These indicators are connected to identified challenges that include lack of knowledge in design, improper design, and lack of consideration of specific needs of a location/climate (Table 2). Improving the knowledge of the design team and checking for the indicators that are related to climate and specific needs of a location can enhance the resilience of GI.

One of the design indicators that were ranked as important was checking for the linkage of site features to the intended design. Although checking GI if functioning as designed is important, inspections show that many of GI installations need maintenance to fulfill their design intention (Lindsey et al. 1992). Also, the presence of a design checklist (i.e. location hierarchy, soil, management of invasive, etc.) was perceived as an important indicator to ensure GI is designed in a way to withstand the external stressors on site. Design standards and guidelines that are adapted to local conditions and specific stressors are crucial for successful GI design and implementation (Hui Li et al. 2017). Although the design standards are important, there is significant uncertainty about how to plan, design, and implement GI in an ideal way (Baptiste et al. 2015; Campbell et al. 2016; Sinnett et al. 2018). One reason is insufficient data about performance features of GI, as well as lack of knowledge and experience of the design team (NRC 2009).

Maintenance: The maintenance category of GI resilience mostly included auditing plant cover and soil permeability over time, and consideration of specific site changes in time (such as, invasive species, sedimentation, soil compaction). Custom maintenance plans, proper documentation, and updating maintenance checklists based on the needs of each specific site are among the indicators selected by stakeholders (Table 3). Connecting the challenges identified by stakeholders and the indicators shows that, despite the obvious needs for maintenance in many sites, insufficient maintenance is one of the big challenges (Table 2). One of the reasons is the high cost of the maintenance and insufficient budget allocated for the maintenance (Table 2).

The top-ranked indicators were checking for biophysical features such as plant health, plant cover, and sedimentation (Table 3). Sediment accumulations and consequent clogging have found to be challenges seen in urban areas. This will affect the hydraulic connectivity and can cause overflow during rainfall events (Asleson et al. 2009; Brown and Hunt 2011). Soil function is a main issue in urban GI that may need pretreatment, or continued maintenance, such as replacement of soil media as necessary (Hatt et al. 2008; Li and Davis 2008). Checking for plant health and plant cover can indicate clogging as well as plants can provide macropore flow around roots and decrease the moisture through evapotranspiration of water in the soil between storm events (Hatt et al. 2008; Li et al. 2009).

Economic Factors: The economic category of GI resilience was comprised of indicators related to the security and prioritization of budgets, especially overlooked aspects of GI such as allocating sufficient funding for maintenance (Table 3). Economic factors, similar to policy, are interconnected with the other four categories considered in this study. As a sufficient budget not only helps with better design and implementation, it can also help with planning for community engagement. As discussed during the focus group, sufficient funding is important but prioritization of how to allocate limited funding to where it is needed is a high priority. One of the issues with funding allocation and prioritization is the need to reliably evaluate the cost and benefits of GI and to build these cost and benefits into funding models to support implementation and maintenance of GI (Zuniga-Teran et al. 2020). Connecting the indicators selected by stakeholders and identified challenges shows a close connection between the real financial challenges and indicators of GI resilience (Table 2 and Table 3).

The top ranked economic indicator for resilience was a sufficient budget for frequent maintenance, followed by the need to understanding the funding needs of maintenance. Regulations and policy may have a great impact on the economic factors especially when the design parameters have not been established in policy. As discussed during the focus group, if maintenance is considered during the design stages, the subsequent cost may be significantly reduced. However, most of the time maintenance is not included during the design stage. In Europe, regulations for GI design such as constructed wetlands are included as established design parameter and subsequently, the monitoring is minimal as it has been shown that efficient design results in treatment efficacy (Levy et al. 2014).

Although economic factors are important for design and maintenance, the cost is one of the important factors found to be affected other aspects of GI such as the willingness of people to implement GI (Baptiste et al. 2015). In the United States, many cities have allocated economic incentives for encouraging GI projects (Vogel et al. 2015). But, the policy behind it is mostly water quality mandates that may hinder other benefits of GI (Levy et al. 2014). Including other co-benefits in policy may help to better recognize the co-benefits and subsequent cost-share among stakeholders.

Social Factors: The social category of GI resilience is connected to indicators such as public knowledge, acceptance, and level of outreach, as well as equity and affordability of GI (Table 3). Society has been highlighted as a critical factor in urban resilience: “the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience” (100 Resilient Cities 2018). This shows that considering biophysical and engineering components alone will not be sufficient to plan for resilience of and through GI (Sharifi and Yamagata 2016). Social equity and affordability are important factors for resilience building because they are connected to the risks populations have to the impacts of climate change (Urban Land Institute 2018). For example, vulnerability to storm events is usually greater in low-income regions compare to wealthy neighborhoods (Hoang and Fenner 2016). Low-income neighborhoods have less access to ecosystem services they need and disproportional access to GI, both important environmental justice issues for GI planning (Fernández-Álvarez 2017; Smiley et al. 2016).

We found that the top ranked priority indicators (Table 3) in the social factor category included public acceptance, knowledge, and level of outreach prior to the design, during the construction, and during the maintenance. These top indicators were also reflected as important current challenges by stakeholders during the focus group discussions that identified community contributions and enhancing resident's knowledge. The city of Los Angeles is an example of a community partnership and local government in GI projects (Sadeghi et al. 2016). This example shows the support of the local community through continuous engagement activities to facilitate local government management of GI. Although public outreach and engagement are important as indicators to check for, it may be more difficult to persuade low-income communities as they might not willing to spend time on GI projects or have negative views of green spaces and vegetation (Furlong et al. 2018). This issue also makes it difficult to improve equity and subsequent resilience in those areas.

3-2-2- Resilience Dimensions

With a set of indicators now co-developed with stakeholders, we used the resilience matrix approach (Linkov, Eisenberg, Bates, et al. 2013) to relate each indicator to three dimensions of resilience: absorb, recover, and adapt (following NRC, 2012). Here, resilience is known as a complementary feature to improve risk management by providing strategies for mitigation and adaptation. Conceptually, risk analysis "helps the system prepare and plan for adverse events", while resilience management considers integrating the temporal capacity of a system "to absorb and recover from adverse events, and then adapt" (Linkov et al. 2014). Relating each indicator to these resilience dimensions could help GI planners and decision-makers to prioritize resource provision to enhance the climate resilience of GI, depending on local priorities with respect to absorbing, recovering, or adapting to shocks. This prioritization may be related to the temporality of responses – absorbing and recovery capacity of the system happens relatively quicker in response to adverse events, whereas adaptation results from learning from disturbance in order to manage future shocks.

Absorb: The absorb dimension of resilience is defined as, maintaining the most essential functions and service accessibility while preventing disturbance or malfunctions. The absorbing capacity of GI is dependent on planning effective arrangements to enable GI to maintain its basic function. For example, making sure that the current site features are linked to the intended design or that the right plants are selected for specific site conditions, ensures that GI is able to maintain its function and to continuously deliver ecosystem services. In maintenance, if the plant cover is regularly audited and we make sure to have healthy vegetation, or if soils are monitored for permeability, we are preparing GI to be able to maintain its main functionality during storm events. Even in less tangible categories such as social factors, outreach prior to design, during construction, and during maintenance could educate personnel to be able to act in a way to allow GI to maintain its functionality (Table 3).

Recover: The recovery dimension of resilience management is defined as, restoring all critical functions and services to their pre-event function, and also to ensure accessibility to functions. The recovery capacity of GI is dependent on the preparations to help GI to return to its pre-disaster function. For example, sedimentation is one of the challenges urban GI face during a storm event. Removing sediment accumulation after storm events that cause clogging of the feature helps the recovery of GI to return to pre-event functions. Having a standard for soil replacement in the design category helps with the recovery of GI, especially when facing compaction and permeability impacts that do not fulfill the intended goals of GI design.

From the social factor perspective, volunteerism is one of the indicators that can help with recovery of GI after an adverse event through public engagement to restore functions to deliver ecosystem services (Table 3).

Adapt: The adapt dimension in resilience management is defined as learning from an adverse event or anticipating shocks to modify procedure, the arrangement of the system, personnel training, or other features to develop more resilient. Managers can learn over time how to select more resilient arrangements to respond to external pressures. One of the examples in the design category is identifying a resilient plant palette over time for altered climate conditions, drought, increases in salinity, and shifting wildlife pressures. For example, in the maintenance category, a customized maintenance plan for individual GI features that is developed over time by learning and observing feedbacks from the system can foster resilience through adaptation. Stakeholders expressed the need for dedicated funding to develop more resilient GI after learning from an adverse event as a critical economic factor (Table 3).

Policy and economic factors mostly included indicators that stakeholders identified to be important for all dimensions of resilience (Table 3), suggesting their centrality in managing GI for resilience. These two categories seem to be more holistic as they are interconnected with the other three categories considered in this study. For example, policy for a more integrated planning and management system and policy to enhance communication among agencies was identified by participants as not only important for the preparation of absorbing for an adverse event, but the more connected the agencies and part of a system are also the more helpful to recognize approaches for recovery and adaptation after an adverse event. Urban areas regularly include multiple administrative sectors which might entangle the administration of ecological systems. If the institutions and organizations are not connected, as there might be objectives in common, they provide a variety of responses after an adverse events which might complicate management and cause conflicts (Schiappacasse and Müller 2015). Also, sufficient funding for frequent maintenance and understanding the maintenance funding requirement would be helpful in all stages of confronting and addressing an adverse event as indicated by participants during the focus group. Sufficient funding to target priorities would maximize the efficiency of GI and promote the development and maintenance of GI as needed (Naumann et al. 2011).

We found a sequential pattern in resilience management by looking at the indicators selected under the maintenance category. This sequential pattern can show us the prioritization for planning for maintenance. We realized that maintenance includes indicators that are allocated to checking for plant health and plant cover. These indicators identified to be important for absorbing an adverse event which should be considered in the first place. Followed by that there have been indicators identified for recovery dimension of resilience such as actively updating plant lists by maintenance staff to identify plants that are not suitable for an individual GI. Afterward, there are indicators that addressing the adaptation such as a customized maintenance plan for individual features (Table 3). This pattern shows how this category included integrating the capacity of a system to absorb, recover from adverse events and then adapt as defined in the resilience management by NAS.

3-2-3- GI Resilience Assessment Framework Development

The resilience matrix was first described by Linkov et al. (Linkov, Eisenberg, Bates, et al. 2013) as a generalized method for resilience assessment. This framework is a 4 by 4 matrix including 4 major subcomponents (including physical, information, cognitive, and social) of each system management and four dimensions of resilience and disaster management as described by NAS 2012). This framework has been applied to the cyber, coastal community, energy, engineering, and ecological system (Eisenberg et al. 2014; Fox-Lent et al. 2015; Linkov, Eisenberg, Plourde, et al. 2013; Roege et al. 2014) was an important step in identifying aspects of the resilience of each system, this framework needs to be investigated within the specifics of each case system if the goal is to build real assessment tools. For example, Fox-Lent et al. (2015) expanded the framework by providing detailed indicators for coastal community resilience under the general subcomponents. Their work to apply the framework to a specific setting demonstrated the potential for the need to weight the importance of indicators based on stakeholder perceptions (Fox-Lent et al. 2015). As in our focus group, stakeholders stated the importance of some of the indicators over others (Table 3). Without engagement with the stakeholder community, this critical information needed for application of the resilience assessment approach would be missing.

Table 3 Indicators selected by stakeholders for policy, design, maintenance, economic factors and social factors, their connection to the resilience concept, and their measurement techniques. Ranking was determined using a consensus ranking approach (Cook and Seiford 1978).

Rank	Indicator	Resilience dimension		
		Absorb	Recover	Adapt
	Policy			
1	Cost-share policy for retrofit (rebates, subsidy, grant)	×		×
2	Policy to recognize and prioritize co-benefits	×	×	×
3	Policy for more integrated system	×	×	×
4	Coordination on regulation for co-benefits (holism)	×	×	×
5	Policy in place to coordinate with other agencies	×	×	×
6	Policy for consideration of climate change related criteria in design			×

7	Policy for considering stormwater as a resource (Recycle, reuse, restore)	×		
8	Policy for considering the carbon footprint (e.g. maintenance schedule, soil mix, etc.)			×
*	Policy on local sourcing, plants, and soils	×	×	×
	Design			
1	Check for the linkage of site features to intended design	×	×	×
2	Presence of a design checklist (location hierarchy, soil, landscape architecture, invasive treat, etc.)	×	×	×
3	Resilient plant pallet for drought/salt/wildlife tolerance			×
4	Standard for soil replacement		×	
5	Codify design criteria based on current and future needs	×	×	×
6	Check for soil profile change (to get to the reference soil condition)			×
7	Consider right balance of plant diversity	×		
8	Planting/soil design developed with anticipation of climate change	×	×	×
9	Measure co-benefits	×	×	×
10	Check for being in/out of the flow path or online in the context of resiliency	×		
11	Hydrologic capacity of features (how they may handle large events)	×	×	×
*	Design for maintenance standards	×		
	Maintenance			
1	Plant are healthy/alive	×		
2	Sedimentation		×	
3	Consider plant cover	×		
4	Customize maintenance plan for individual feature			×
5	Dewatering/permeability	×		
6	Invasive presence		×	
7	Documents are readily available in field to allow maintenance staff response	×	×	
8	Plant lists are updated with maintenance staff actively		×	
9	Planting plans are on record and updated			×
10	Consider appropriate condition of GI for maintenance (maintain, replace, restore)	×	×	×
11	Check for appropriate lag time between installation and initiation of maintenance	×	×	×
12	Maintenance capacity (funding, personnel, training)	×	×	×
*****	Management of change over time (i.e. the need for species change due to increased shade or sun)			×
	Economic Factors			
1	Sufficient budget for frequent maintenance	×	×	×
2	Understanding of maintenance funding requirements	×	×	×
3	Dedicated funding			×
4	Cost per area for life cycle	×		
*	Targeted planning and funds for BMP implementation to address the most vulnerable areas (flooding, heat stress)	×		
*	Include Life cycle costs in planning	×	×	×
	Social Factors			
1	Public acceptance and preference	×	×	×
2	Level of outreach (prior to design, during construction, during maintenance)	×		
3	Public knowledge/Education	×	×	×
4	Equitable distribution of GI	×		
5	Affordability of GI	×		
6	Curriculum building/existence	×	×	
7	Student Knowledge/ curriculum effectiveness	×	×	
8	Volunteerism		×	
9	Signage	×	×	
10	Job development			×
*	Impact of GI on property values	×		

× shows if the cell has the connection to the resilience dimension

*shows the indicators identified by participants after focus group via post survey

Specific cases might not be able to easily place all identified indicators under the 4 subcomponents of physical, information, cognitive, and social initially defined by Linkov, Eisenberg, Bates, et al. (2013). For example, we found categories that are related to the resilience of GI such as economic and policy factors that were not part of the Linkov, Eisenberg, Bates, et al.'s (2013) framework. Other researchers have considered adding more categories including, infrastructure, economic, social, environmental, community, political, institutional, and engineering factors to better describe the resilience of their specific system (Cutter et al. 2014; Karamouz et al. 2014; Longstaff et al. 2010). Each particular case needs to consider its own subcomponent/categories because there may not be overlap in relevant topics and subjects. For example, categories that were considered for resilience to coastal flood events focused on hydrological aspects (Karamouz et al. 2014) and were different than a case focusing on community resilience to disasters in general, which were focused on social and demographic aspects (Cutter et al. 2014). Here, we identified challenges that are specific to GI systems and selected our categories and specific indicators under those categories. This could help us identifying and targeting sectors that are crucial for the resilience of the defined system and not overlooking factors that might affect some aspects of defined system resilience.

We found that relating stakeholder-defined indicators to literature-defined resilience dimensions also helps to develop an applicable tool from a more generalize framework. We can start to see how local managers prioritize system elements and processes within general categories. This is an important step to move beyond using the resilience literature in order to develop a framework for local applications. Sharifi and Yamagata (2016) identified an extensive list of indicators for urban resilience and provide a matrix that needs to be completed by either using expert opinions to relate each indicator to resilience for a specific system and specific case study. Similarly, we used stakeholder engagement approaches to extract stakeholders' perceptions and to involve them in the framework development process. In this study, diverse actors in policy, design, maintenance, economic and social aspects of GI collectively first recognized the challenges for GI and then co-produced indicators that link to these challenges for resilience in a way that built off the generic framework. The result is a more detailed framework that could guide development of a practical tool. This approach overcomes the context-specificity issues reported in Sharifi and Yamagata (2016).

The process of working with stakeholders to co-produce a resilience framework can also lead to learning process among stakeholders and ultimately produce reliable and robust knowledge (Borquez et al. 2017). Dialogue among various stakeholders is beneficial for mutual learning and helps to recognize the challenges among sectors that may have neglected in more general discussions (Borquez et al. 2017; Muñoz-Erickson et al. 2017). For example, in our focus group, there was a discussion on the lack of connection between the design and maintenance sectors that may cause challenges for resilience if the design process proceeds without considerations of maintenance in mind. Thus, the diversity of the focus group reveals connections and processes that are critical for resilience, and can provide a path for including them in solutions. This framework encourages networks of communication for clear dialogue on multiple aspects of resilience management that are important for reaching holistic goals of urban resilience. Participants in the workshop indicated the need and effectiveness of the workshop for facilitating transparent dialogue among various stakeholders and for developing new professional connections. Participants found the workshop gave an opportunity to discuss challenges among various stakeholders that rarely get the chance to communicate together about their concerns. The co-produced knowledge was found to be practical and necessary; stakeholders reported that there is a need for such a resilience framework and further assessment tools.

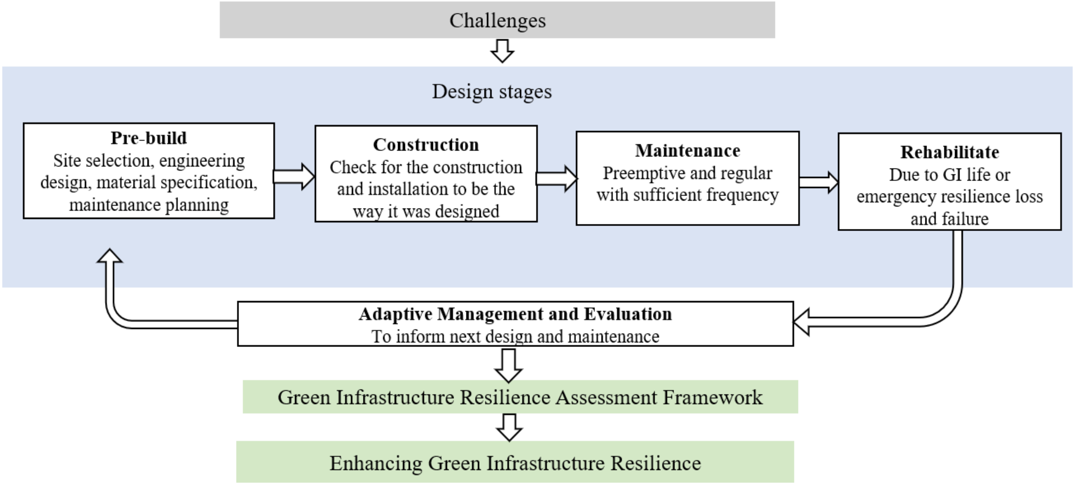


Figure 3 Conceptual model of green infrastructure (GI) design as related to resilience. GI resilience challenges affect all the stages of design.

The focus group revealed that working with GI provides some unique challenges for assessing and managing for resilience. GI is an *object* in the built environment – a set of features that are constructed and installed in the landscape. However, discussions among the stakeholders revealed that GI also can be thought of as a set of *processes* that span a set of stages from conception to implementation to maintenance (Felson et al. 2013). The focus group identified a set of challenges (Table 1 and 2) for GI that was discussed in general for GI; however, these challenges likely affect the different design stages of GI in unique ways as well. Both our review of the literature and discussions during the focus group revealed that these different stages and their relevance to resilience if often ignored. Working with a representative from the UMD Environmental Finance Center after the focus group, we identified that for each of the stages in design (Figure 3), there might be different policy, design, maintenance, economic factors and social factors that need to be considered for resilience as people doing the planning and actual implementation for each of those stages. Before the workshop and from reviewing the literature, we had identified maintenance as an overlooked stage and tried to consider it as a separate category to emphasize its importance. Discussions with stakeholders reveals that explicit consideration of the unique aspects of the pre-build, construction, maintenance, and rehabilitation phases will also be critical for the resilience of GI (Philips 2013). Consideration of these distinct phases, and their connection to aspects of resilience should help to further guide and enhance resilience planning.

4- Conclusion

We argued that if GI is to convey resilience to cities that GI itself must be resilient, so we worked with stakeholders to co-develop a GI resilience assessment framework. Building off a literature review, we used a focus group approach to co-produce indicators that could be used to assess GI resilience and linked these indicators to different dimensions of resilience. Specifying these indicators and dimensions, as well as the challenges that influence them can help planners and decision-makers prioritize resources to enhance the climate resilience of GI. A collaborative co-production approach for resilience frameworks is critical because it can reveal how knowledge links to practice and also specific aspects of local cases that can affect resilience. For example, stakeholders saw that financial and institutional approaches were linked, but did not necessarily connect them to social outcomes, despite the importance of social well-being for climate resilience. Furthermore, stakeholders revealed the different design stages of GI pose unique challenges for resilience that are often ignored. A co-produced resilience framework also encourages networks of communication for clear dialogue on resilience management that can integrate diverse opinions within a broader holistic resilience response. This GI resilience framework can be implemented to guide planning and assessment to link GI resilience goals in policy, design, planning, and implementation.

5- Acknowledgments

This project was funded by an NSF CHN-L (# 1518376) grant and Babbitt Dissertation Fellowship from the Lincoln Institute of Land Policy.

6- Supplementary Data

Supplementary data associated with this chapter can be found in appendix 2.

Chapter 6: Conclusion

Stormwater management, and more specifically green infrastructure (GI), plays an important role in integrated urban water management (IUWM). The goal of using GI as part of sustainable urban water management is the use of the urban landscape for transforming a linear approach of conventional urban water management to a cyclic approach mimicking the water cycle in the natural environment. To optimize the role of GI, decision-makers and urban water managers need to select the best options according to the specific needs and demands of their region. One of the ways is to familiarize them with available tools such as models that facilitate moving toward a more integrated system and selection of the best sustainable alternatives such as GI. In chapter 2, I looked at the role of models in decision-making in IUWM and the detailed application of the most commonly used models. However, one of the deficiencies of these models is not considering the needs of local region governance and its connection to the ecosystem services supply. Thus, to effectively managed GI especially in the semi-arid environment with water sustainability crisis, in chapter 3, I studied the supply and demand of ecosystem services using stakeholders' perceptions. This would inform the stakeholders and decision-makers to select the appropriate types of GI according to local needs. To maintain the optimized role of GI and receive sustainable ecosystem services, I need to have an evaluation framework to assess all the aspects affecting the resilience of GI. In chapter 4, I developed a generalized framework by identifying GI challenges and indicators through literature to ultimately find the gaps in GI resilience and inform urban planners to enhance resilience in response to those gaps. Finally, in chapter 5, I engaged stakeholders and professionals to provide their input for co-producing a more specific GI resilience assessment framework that links to perceived barriers.

Summary of Results

Chapter 2 is a review of the most common models in IUWM, as models are tools that allow decision-makers to deal with conflicts in managing urban water systems. The objective was to provide a comparative study of IUWM models aimed at assisting the users to select the most appropriate model according to any specific needs. My results showed that in the drinking water section, the majority of models are focused on water supply and demand and less in leakage analysis in the distribution system while leakage contributes to a great loss in urban water resources. Wastewater and graywater reuse are the capabilities of many models which are very beneficial in IUWM but the extension design of the wastewater network which is needed in further wastewater development is only covered by one of the models. Also, in stormwater management, the focus of models is largely on hard engineering and other important considerations such as the impact of GI on water balance are less reflected. One of the features that can be added to these models is ecosystem services evaluation and consideration of its supply and demand in the selection of types of GI. Providing options to selecting various ecosystem services could be beneficial for comparing different water management scenarios when a decision-maker wants to decide among various options.

Chapter 3 looks at linking the stakeholder perceptions of ecosystem services supply and demand to GI practice in Tucson, AZ. I aimed at studying the stakeholders' knowledge, perception, and practice of GI ecosystem services to improve urban planning as such information in local cases is less explicit. The results indicated the stakeholders’ high level of knowledge reflecting unique environmental conditions and urban design in this semi-arid environment. This led the stakeholder’s prioritization to be exclusive to the region, focusing on water sustainability and urban heat mitigation. I found strong agreement in environmental perceptions between different management sectors; however, there were some mismatches between the priority of stakeholders and their perceptions of important environmental. Furthermore, I found ecosystem services prioritized by stakeholders revealed a unique classification of ecosystem services and that generalized classification schemes for ecosystem services might not be useful for management and planning of various climate with unique specification, as one typology might not fit all purposes and cases. This chapter also indicated the study of ecosystem services supply and demand, as well as ecosystem disservices on various types of GI, can help the selection of effective forms of GI to address the priorities of stakeholders. This study, therefore, provides critical information for GI management, planning, and policymaking in urbanized semi-arid regions and shows the necessity of understanding the stakeholder knowledge, perceptions, and priorities for other regions where GI is being implemented.

Chapter 4 develops a social-ecological framework for the resilience of urban stormwater management. This framework builds from a general resilience matrix by defining critical functionality for GI and specific factors controlling its viability and resilience. I identified five categories that are challenges for the resilience of GI: policy, design, maintenance, economic factors, and social factors. Unlike other GI assessment frameworks that are focused on design and final ecosystem services, I work from a social-ecological perspective and included aspects of design and planning, but also socio-economic and policy factors that may affect the resilience of GI for sustainability of receiving ecosystem services (as a process not a final outcome). In addition, I developed indicators under each category by reviewing the literature and suggested relating each indicator to three dimensions of resilience (i.e. absorb, recover, and adapt) by expert input to build a more informative framework and identify which indicators need to be prioritized in planning and resource allocation.

Chapter 5 describes co-producing a social-ecological framework for stormwater GI resilience with stakeholders, and builds off the resilience assessment framework from Chapter 4. I engaged a diverse group of stakeholder's representatives from managers, planners, designers, and maintenance using a focus group and interviews. The most important challenges of GI discussed by stakeholders are lack of or insufficient maintenance, poor design and installation, lack of knowledge and education, and insufficient funding, especially for maintenance. I found that stakeholders did not connect financial and institutional aspects to social outcomes and perceptions. Stakeholders refined an extensive list of indicators (from Chapter 4) and related them to the resilience dimensions of absorbing, recovering from, or adapting to stresses in order to assist GI planning. Furthermore, my results highlight that for GI to be resilient it is necessary to consider design phases of GI; that is, to think of GI as a process rather than as an object. Finally, this framework could inform the management of adverse events by decision-makers in various sectors related to GI plan, design, and implementation. Most importantly, this framework can be helpful to evaluate the level of resilience in GI and can be used to allocate resources to enhance resilience to meet stakeholder priorities.

The GI resilience assessment framework developed from the literature (Chapter 4) and refined with stakeholder input (Chapter 5) reveals the importance of stakeholders' involvement in developing such assessment frameworks. Stakeholders selected more detailed indicators compared to what was found in the literature. Indicators mentioned in the literature (i.e. redundancy, biodiversity, multi-functionality, etc.) were more general and difficult to measure, while indicators selected by stakeholders were more specific to GI and more operational (i.e. a resilient plant pallet for drought/salt/wildlife tolerance). Moreover, indicators selected by stakeholders connected to existing challenges that threaten the resilience of GI. Having stakeholders ranked the indicators is also important to identify priorities for the best resource allocation and prioritization to meet resilience needs.

Final Thoughts

GI and ecosystem services concepts are aimed to improve sustainability, resilience, and environmental planning issues in urban areas. Investigating and understanding the complex interconnections of social-ecological systems and elements that affect GI resilience can lead sustainable cities through desired ecosystem services. However, planning with ecosystem services needs a comprehensive and holistic view that considers all the subsystems of the social-ecological system. This dissertation aimed to tackle different subsystems of social-ecological system, including, institutional aspects of decision-making, ecosystem services, and resilience. As decision-making in the urban environment is often complex and multi-disciplinary, we need to study and consider different pieces to help us come up with a comprehensive solution. Therefore, conventional approaches such as considering cost as the only factor for the selection of alternatives in urban water management or considering the government as an individual decision-maker are no longer viable and effective. Often, qualitative decision factors are not considered as a part of the decision process, and decisions are made mostly based upon the available quantitative decision factors or single decision maker's opinion. However, making a decision in complex social-ecological systems requires a holistic view and multidisciplinary knowledge of social-ecological aspects.

To facilitate decision-making in urban areas incorporating a wide range of stakeholders' perceptions, along with other quantitative data, is needed. For instance, considering the demand of stakeholders and specific needs of a region and connection of that with ecosystem services supply is one way to fulfill the needs and come up with the best alternatives especially for selecting GI. However, none of the IUWM models studied in this dissertation considered that critical component. Thus, the results of this study (i.e., ecosystem services supply, demand, and disservices rankings) can be used as an input of decision-support systems (i.e. multi-criteria decision analysis). These results are semi-quantitative data on preferences that can be easily used as an input of such framework. The GI resilience assessment framework can be used to inform urban water managers and decision-makers about the level of resilience in GI. This evaluation framework is not only helpful after implementation for auditing the resilience of GI, but it can also be used to inform decision-makers on the selection of GI as well. This framework can be further developed with managers to allow it to inform decision-makers on the types of GI that are more resilient in the urban environment; information that can also be used as an input of decision support systems. These are all pieces of information that can be used along with quantitative data (i.e. costs, capacity for runoff reduction, spatial limitation, etc.) to better inform decision-making for urban water management.

There is a trend toward using IUWMMs more in decision making. Finding and studying the deficiencies of the current water management system can help to move toward better implementation of IUWM in the urban environment. Involvement of stakeholders plays an important role to facilitate moving toward a more collaborative and integrated system in urban water management to meet holistic goals of resilience and the IUWM concept. The ultimate outcome of this dissertation is to inform decision-making frameworks to support the inclusion of both quantitative and qualitative decision criteria and to involve stakeholder opinions in the decision-making process through a more comprehensive assessment approach compared to single command-and-control value judgments.

Planning for any GI practice needs the knowledge of the broader social-ecological system because just the social system and ecological system alone cannot adequately inform decisions. For GI planning and implementation various components needs to be considered, such as: (1) scientific and engineering feasibility, (2) economic and institutional feasibility, (3) environmental feasibility, (4) public feasibility and issues of equity, and (5) political feasibility. Thus, diverse groups of stakeholders such as ecologists, engineers, hydrologists, economists, policy makers, and the public have to work together to address various aspects of social-ecological system. To achieve resilience goals for GI, all of the above components need to be involved to prevent the failure of the whole integrated system. Lack of required funding and community support are examples of potential failures to implement and maintain GI in urban environment that lead to failures in stormwater management system and ultimately the resilience of cities. To implement resilience frameworks for any given zone within the US and across the globe, an expert should bring these social-ecological components together. In cities that are struggling for basic needs, educational approaches and awareness for the basic services that can received by implementing GI locally and at the city level, combined with an incentive program should be helpful to foster implementation.

Gaps and Future Research Needs

One of the current gaps in GI planning and stormwater management is lack of application-oriented tools that can help enhance urban resilience. This dissertation identified the need for integration of qualitative data as well as quantitative data for GI selection and decision-making in cities. In addition, this study introduced a framework that involved a diverse group of stakeholders both for urban resilience and for connecting ecosystem services supply and demand of GI for planning. However, the focus was mainly on the practitioners, managers, and decision-makers rather than residents. In some cases, implementing rain barrels, cisterns, and rain gardens the final decision-makers are homeowners and their perceptions, beliefs, and attitudes need to be integrated with those of managers and practitioners for planning urban environments. In addition, this dissertation suggests that consideration of GI ecosystem services supply and demand as well as an applicable resilience framework for GI need to be developed for the specific needs, goals, and climates of regions. Therefore, similar studies, or comparative studies, need to be performed for various cities across climates to identify patterns of similarity and differences before making any generalized recommendations for GI selection and planning. Another limitation of this study was limited sample sizes as I was interested in stakeholders who were involved in planning and decision-making environment. This limited my ability to draw on quantitative inferences, and larger sample sizes would enable the researcher to find clearer distinctions between the views of practitioners with different professional backgrounds. Nevertheless, this study did highlight the application of mixed qualitative and quantitative approaches to explore frameworks to inform the management of GI by decision-makers and multi-stakeholders in various sectors to address sustainability and resilience through planning, design, and implementation.

Appendices

Appendix 1

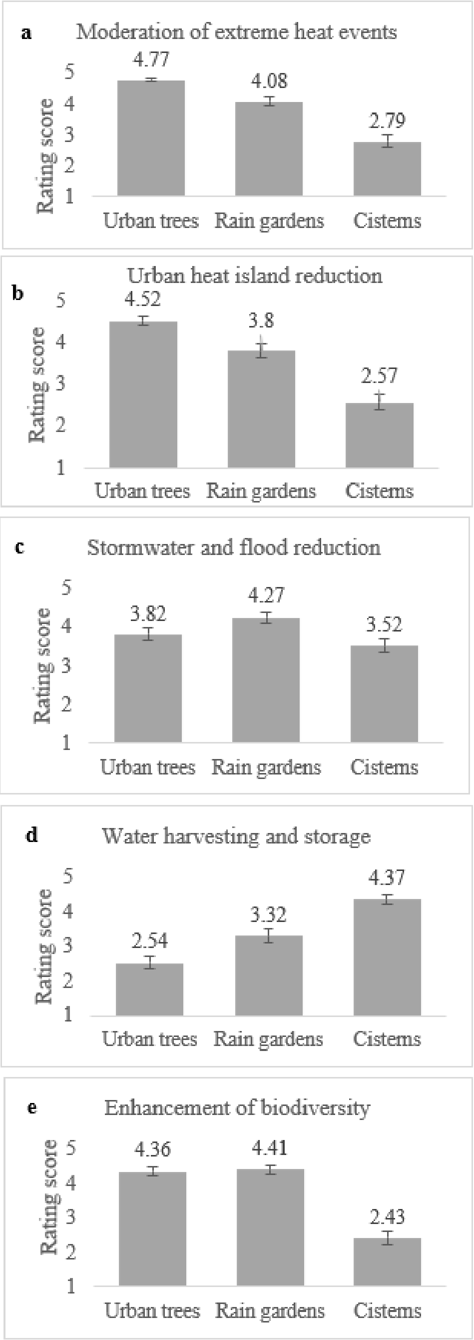
There were 63 respondents including 1.11% (n=7) from city level government, 15.87% (n=10) engineering and design firms, 3.17% (n=2) environmental authority or utility, 15.87% (n=10) local and county level government, 19.05% (n=12) neighborhood association, 22.22%(n=14) non-profit organization and there were 7 people who didn't specify their positions.

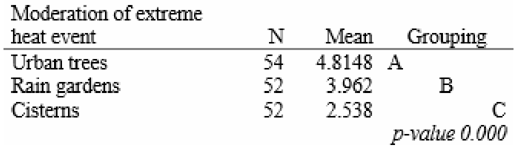
Table 1 Sample demographics

Variable		**Total**
Type of stakeholder	City level government	7
	Local and county level government	10
	Environmental utility	5
	Non-profit organization	14
	Engineering and design	12
	Neighborhood association	12
Role in the office	Head of the department	15
	Not the head	41
Employment duration	Less than 2 years	13
	2-5 years	13
	5-10 years	12
	More than 10 years	17
Main office field of work* (one office may have more than 1 field)	Design	21
	Plan	38
	Install	11
	Maintain	16
Office requirement for MS4s	Yes	12
	No	37
Period of time living in Tucson region	Less than a year	6
	1-5 years	6
	5-10 years	7
	10-15 years	5
	15-20 years	6
	More than 20 years	26
Period of time living in Southwest	Less than a year	5
	1-5 years	2
	5-10 years	6
	10-15 years	5
	15-20 years	5
	More than 20 years	33
Degree	Bachelor's	15
	Master's	26
	PhD	12
Major	Ecology	6
	Biology	2
	Agriculture	3
	Landscape architecture	9
	Engineering	6
	Hydrology	14
Participation in LID conference	Yes	25
	No	32
Member of Pima County LID working group	Currently member	21
	Member in the past	10
	Not a member	20

Gender	Male	21
	Female	31

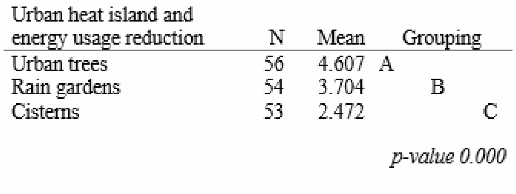
MS4 stormwater discharges from small municipal separate stormwater system, LID low impact development





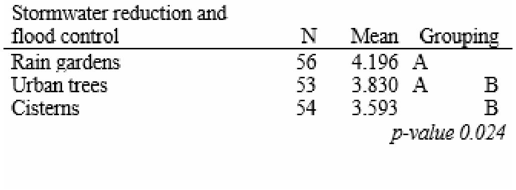
Moderation of extreme heat event	N	Mean	Grouping
Urban trees	54	4.8148	A
Rain gardens	52	3.962	B
Cisterns	52	2.538	C

p-value 0.000



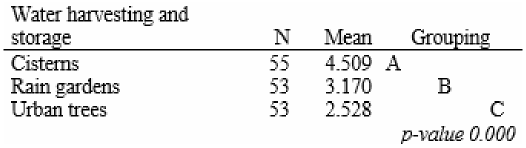
Urban heat island and energy usage reduction	N	Mean	Grouping
Urban trees	56	4.607	A
Rain gardens	54	3.704	B
Cisterns	53	2.472	C

p-value 0.000



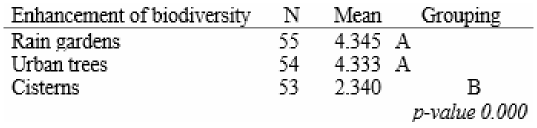
Stormwater reduction and flood control	N	Mean	Grouping
Rain gardens	56	4.196	A
Urban trees	53	3.830	A B
Cisterns	54	3.593	B

p-value 0.024



Water harvesting and storage	N	Mean	Grouping
Cisterns	55	4.509	A
Rain gardens	53	3.170	B
Urban trees	53	2.528	C

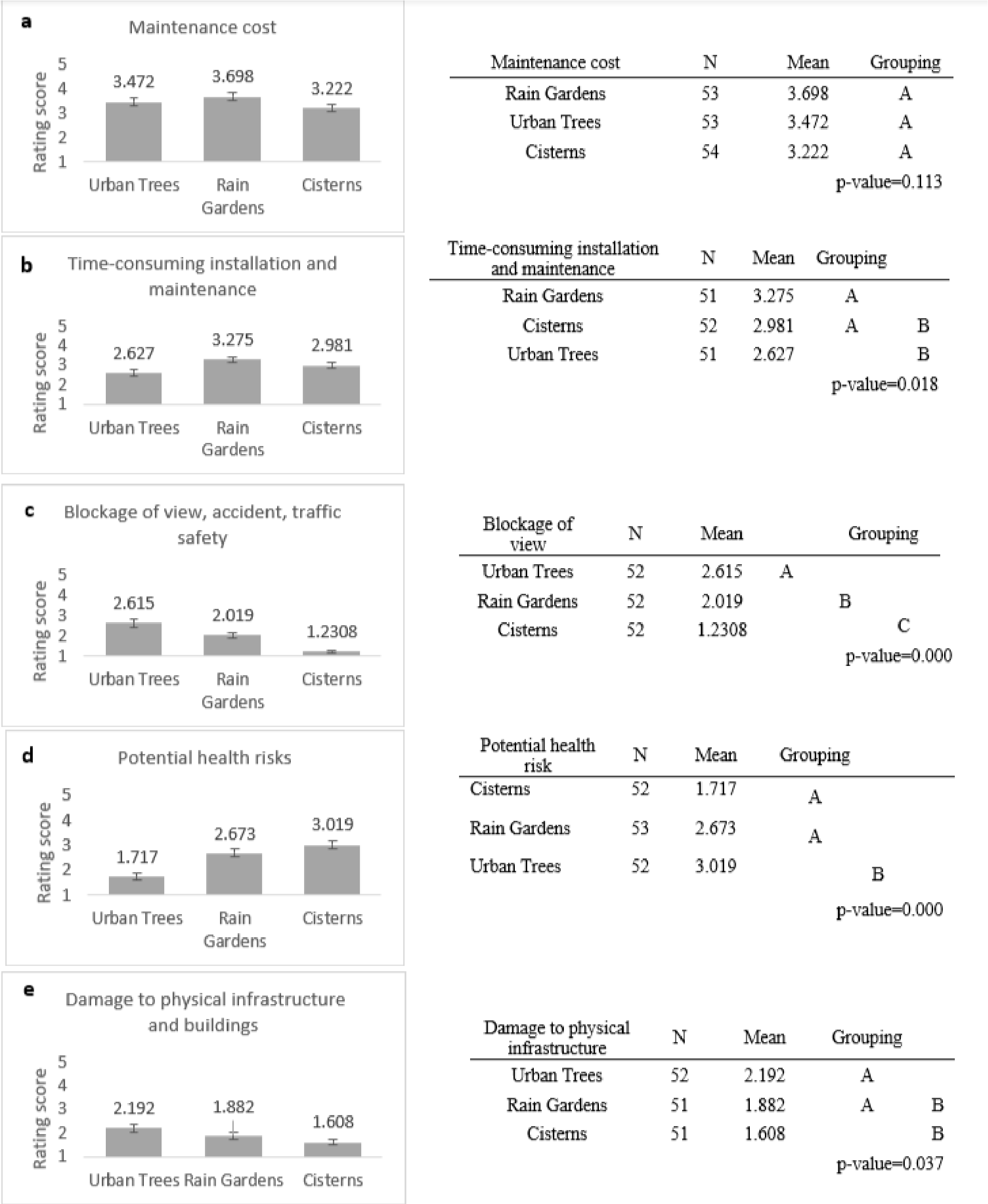
p-value 0.000



Enhancement of biodiversity	N	Mean	Grouping
Rain gardens	55	4.345	A
Urban trees	54	4.333	A
Cisterns	53	2.340	B

p-value 0.000

Figure 1 Column charts showing ecosystem services supply by urban trees, rain gardens, and cisterns as rated by stakeholders in Tucson, AZ. (a) moderation of extreme heat events, (b) urban heat island reduction, (c) stormwater reduction, (d) water harvesting and storage (e) enhancement of biodiversity—Five top ecosystem services supply by stakeholder selected to compare and group green infrastructure. Tukey pairwise comparison is done to compare green infrastructure



Maintenance cost	N	Mean	Grouping
Rain Gardens	53	3.698	A
Urban Trees	53	3.472	A
Cisterns	54	3.222	A

p-value=0.113

Time-consuming installation and maintenance	N	Mean	Grouping	
Rain Gardens	51	3.275	A	
Cisterns	52	2.981	A	B
Urban Trees	51	2.627		B

p-value=0.018

Blockage of view	N	Mean	Grouping		
Urban Trees	52	2.615	A		
Rain Gardens	52	2.019		B	
Cisterns	52	1.2308			C

p-value=0.000

Potential health risk	N	Mean	Grouping	
Cisterns	52	1.717	A	
Rain Gardens	53	2.673	A	
Urban Trees	52	3.019		B

p-value=0.000

Damage to physical infrastructure	N	Mean	Grouping	
Urban Trees	52	2.192	A	
Rain Gardens	51	1.882	A	B
Cisterns	51	1.608		B

p-value=0.037

Figure 2 Column charts showing environmental concerns of urban trees, rain gardens, and cisterns as rated by stakeholders in Tucson, AZ. (a) maintenance cost, (b) time consuming installation and maintenance, (c) blockage of view, accident, and traffic safety, (d) tree leaves as litter, and (e) damage to physical infrastructure and buildings—Five top concerns by stakeholder selected to compare and group green infrastructure. Tukey pairwise comparison is done to compare green infrastructure.

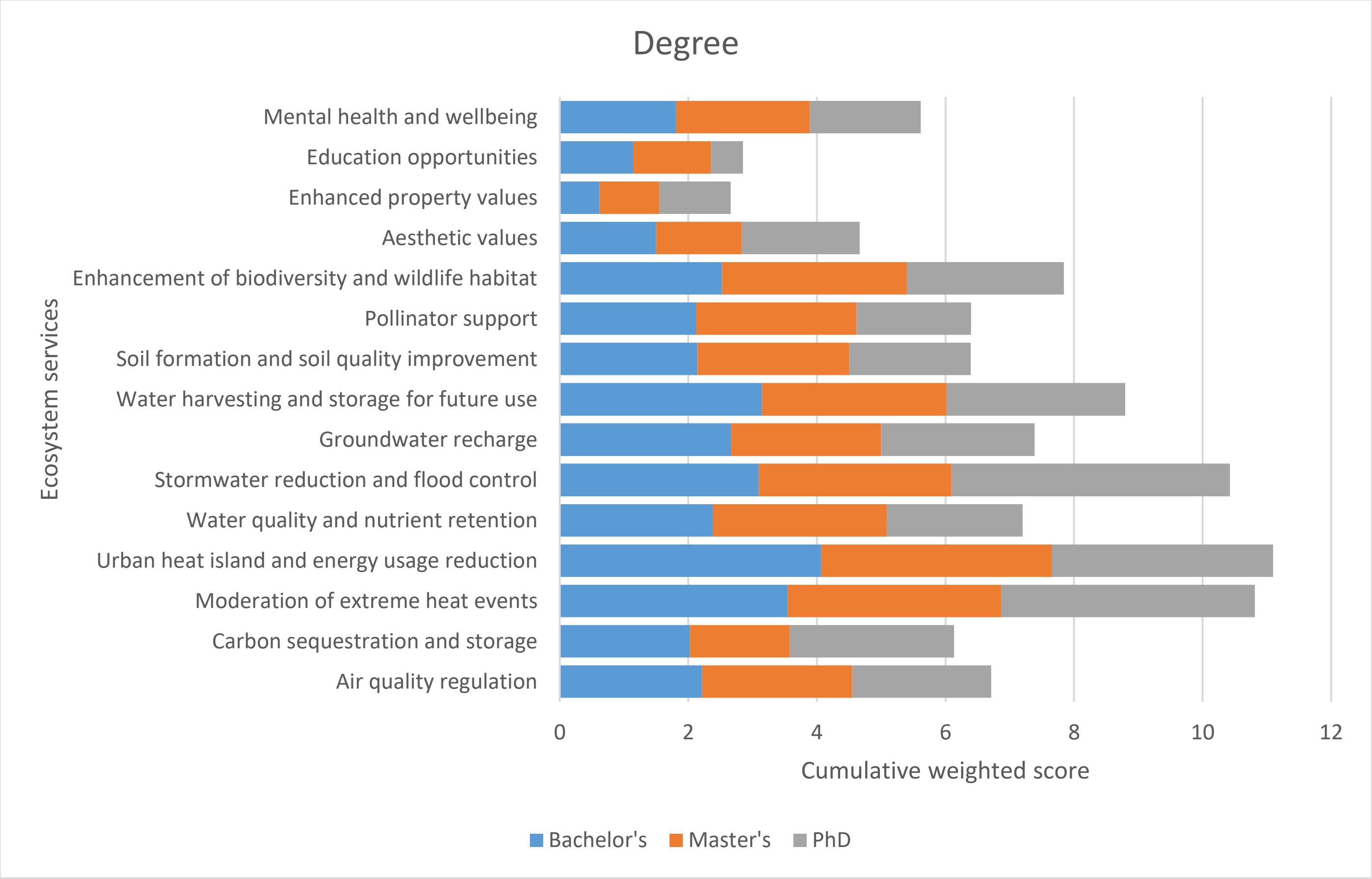


Figure 3 Ecosystem services priorities from green infrastructure ranked by stakeholders and its connection to their degree. A cumulative weighted score was used to compare ranking ecosystem services perceived by stakeholders with various demographics and background. Cumulative weighted average is the average of a set of scores where each set carries a different amount of importance regarding the score each stakeholder allocated to ecosystem services (from 1-15).

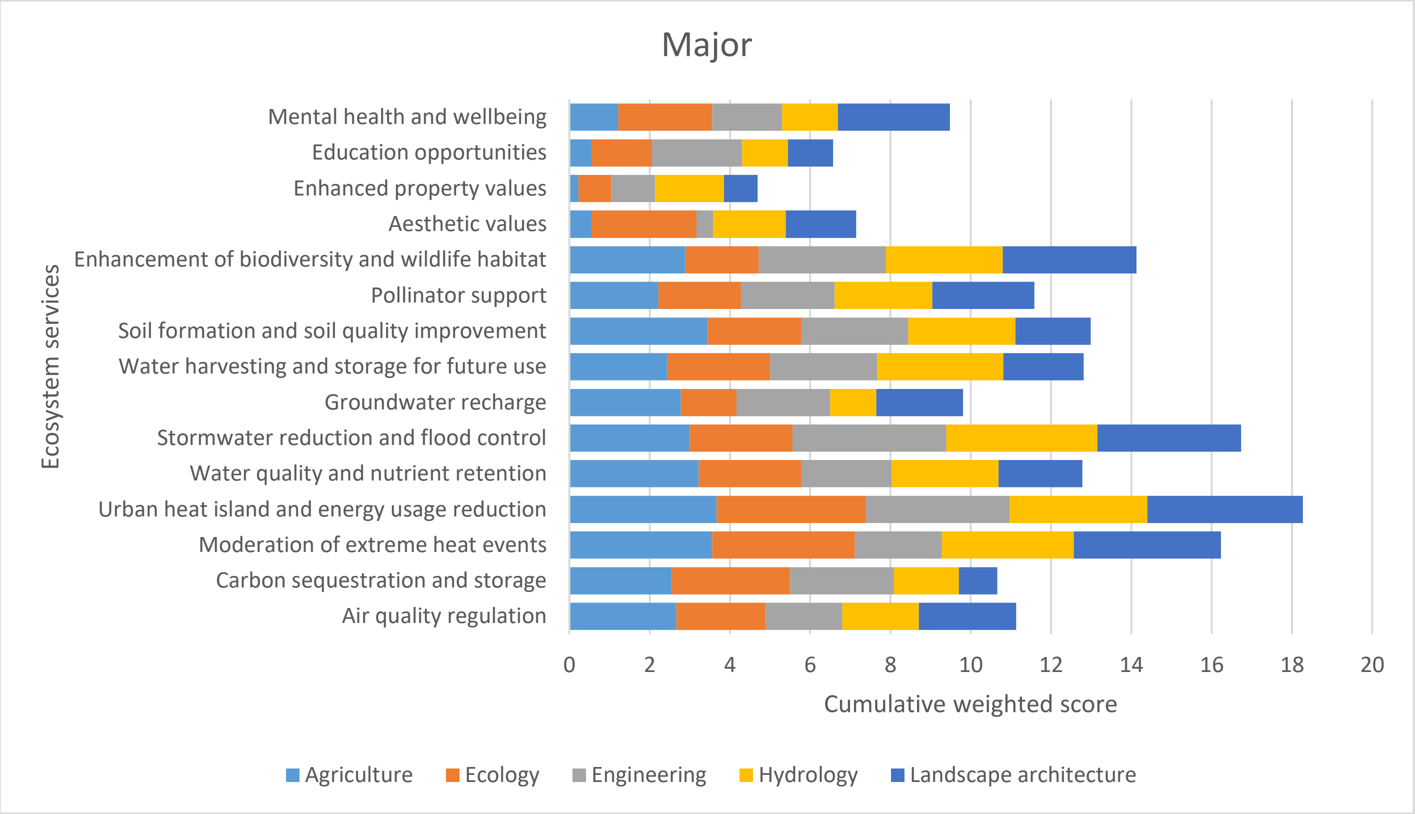


Figure 4 Ecosystem services priorities from green infrastructure ranked by stakeholders and its connection to their Major. A cumulative weighted score was used to compare ranking ecosystem services perceived by stakeholders with various demographics and background. Cumulative weighted average is the average of a set of scores where each set carries a different amount of importance regarding the score each stakeholder allocated to ecosystem services (from 1-15).

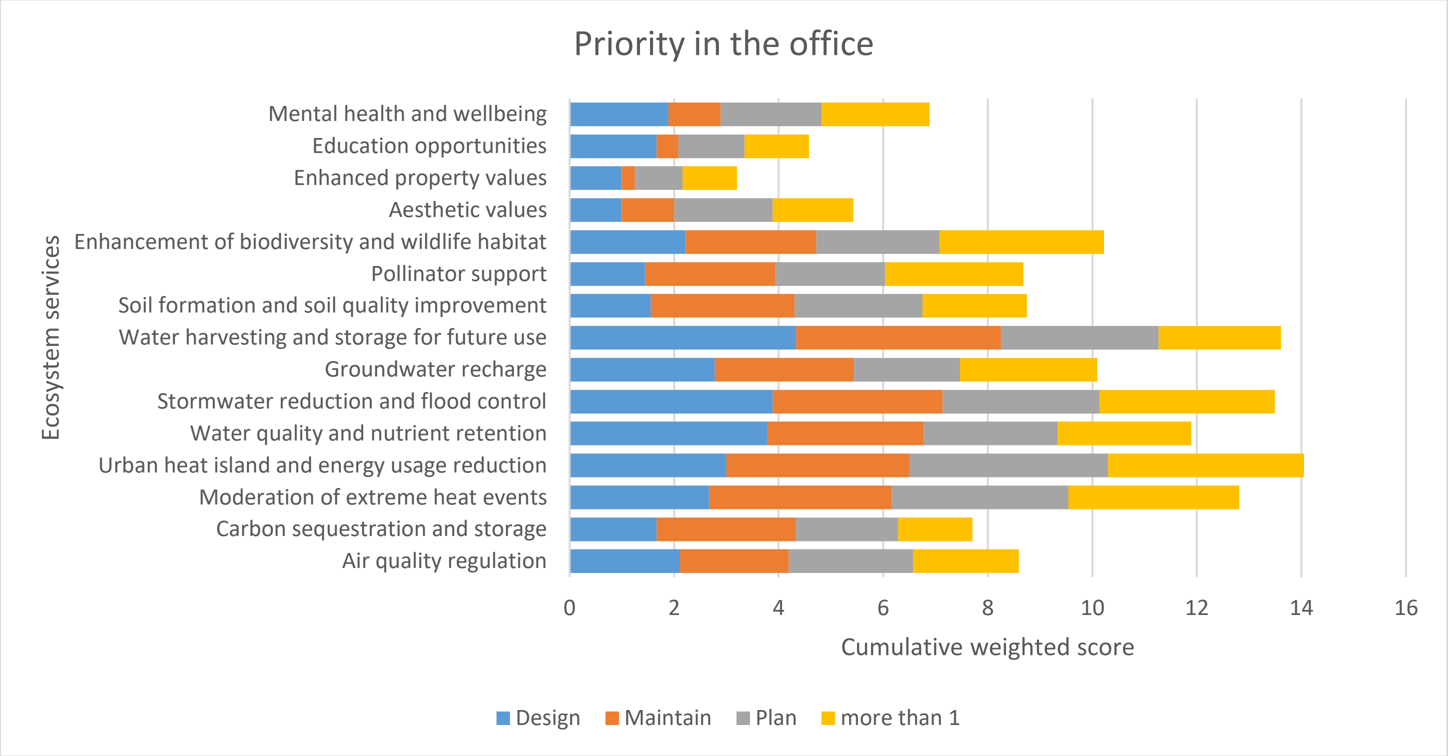


Figure 5 Ecosystem services priorities from green infrastructure ranked by stakeholders and its connection to their profession. A cumulative weighted score was used to compare ranking ecosystem services perceived by stakeholders with various demographics and background. Cumulative weighted average is the average of a set of scores where each set carries a different amount of importance regarding the score each stakeholder allocated to ecosystem services (from 1-15).

Table 2 Non-parametric statistical tests to assess relationships between demographic variables stakeholder and environmental and water issues knowledge

		There is a need to substitute other sources for fresh water	There is a need to control stormwater	Groundwater extraction and water table depletion is a	There is a need to recharge groundwater	There is a need to enhance the water quality of	Delivery of water from the Colorado River by the Central	There are already enough ways to handle water-related issues in Tucson	Rainfall harvesting can be used as a supplementary or	Population growth and increasing demand will be a challenge in	Climate change will have significant effect on water supply and water	Green infrastructures can help for future challenges
	df	P-value										
Sector	5	0.678	0.780	0.732	0.835	0.385	0.474	0.064	0.283	0.554	0.896	0.469
Major	6	0.764	0.837	0.663	0.342	0.689	0.501	0.454	0.286	0.866	0.589	0.825
Degree	3	0.279	0.916	0.127	0.947	0.628	0.219	0.835	0.229	0.465	0.129	0.900
Role in the office	1	0.576	0.850	0.117	0.764	0.303	0.226	0.793	0.449	0.133	0.982	0.982
Duration of employment	3	0.773	0.850	0.965	0.872	0.782	0.542	0.714	0.945	0.408	0.518	0.766
Duration/Tucson	5	0.916	0.984	0.393	0.689	0.465	0.427	0.872	0.637	0.890	0.888	0.938
Duration/ Southwest	5	0.951	0.851	0.214	0.761	0.870	0.847	0.976	0.901	0.884	0.753	0.982
LID Member	2	0.212	0.259	0.803	0.119	0.448	0.500	0.190	0.403	0.129	0.555	0.273
LID Conference	1	0.181	0.298	0.912	0.609	0.810	0.384	0.758	0.733	0.019	0.320	0.539
Gender	3	0.946	0.675	0.971	0.893	0.710	0.538	0.669	0.662	0.682	0.868	0.884

Green cells show statistically significant level $p < 0.05$

Table 3 Non-parametric statistical tests to assess relationships between demographic variables and ecosystem services supply of rain gardens

		Air Quality regulation	Carbon sequestration and storage	Moderation of extreme heat events	Urban heat island and energy usage reduction	Water quality and nutrient retention	Stormwater reduction and flood control	Groundwater recharge	Water harvesting and storage for future use	Soil formation and soil quality improvement	Pollinator support	Enhancement of biodiversity and wildlife habitat	Aesthetic values	Enhanced property values	Education opportunities	Mental health and wellbeing
Rain Garden	df	P-Value														
Sector	5	0.035	0.256	0.074	0.009	0.189	0.071	0.007	0.250	0.074	0.252	0.120	0.369	0.063	0.012	0.527
Major	6	0.694	0.163	0.678	0.710	0.903	0.747	0.609	0.388	0.532	0.772	0.546	0.655	0.415	0.820	0.268
Degree	3	0.849	0.936	0.808	0.547	0.768	0.218	0.198	0.961	0.840	0.135	0.558	0.566	0.340	0.917	0.438
Role in the office	1	0.851	0.708	0.398	0.556	0.607	0.451	0.380	0.500	0.964	0.386	0.315	0.392	0.170	0.344	0.576
Duration of employment	3	0.074	0.023	0.025	0.115	0.363	0.568	0.003	0.316	0.887	0.794	0.720	0.721	0.967	0.452	0.557
Duration/Tucson	5	0.525	0.532	0.848	0.796	0.658	0.944	0.789	0.809	0.477	0.929	0.557	0.833	0.705	0.856	0.442
Duration/ Southwest	5	0.501	0.907	0.955	0.750	0.455	0.607	0.939	0.127	0.853	0.402	0.739	0.778	0.239	0.413	0.992
LID Member	2	0.404	0.358	0.698	0.588	0.383	0.304	0.573	0.960	0.062	0.461	0.080	0.191	0.081	0.220	0.514
LID Conference	1	0.283	0.611	0.827	0.690	0.505	0.930	0.018	0.783	0.903	0.536	0.986	0.420	0.934	0.576	0.950
Gender	1	0.379	0.619	0.482	0.684	0.760	0.710	0.473	0.519	0.681	0.945	0.889	0.811	0.790	0.935	0.586

Green cells show statistically significant level $p < 0.05$

Table 4 Non-parametric statistical tests to assess relationships between demographic variables and ecosystem services supply of cisterns

		Air Quality regulation	Carbon sequestration and storage	Moderation of extreme heat events	Urban heat island and energy usage reduction	Water quality and nutrient retention	Stormwater reduction and flood control	Groundwater recharge	Water harvesting and storage for future use	Soil formation and soil quality improvement	Pollinator support	Enhancement of biodiversity and wildlife habitat	Aesthetic values	Enhanced property values	Education opportunities	Mental health and wellbeing
Cistern	df	P-Value														
Sector	5	0.146	0.618	0.070	0.019	0.060	0.007	0.047	0.163	0.644	0.214	0.383	0.039	0.018	0.455	0.021
Major	6	0.355	0.166	0.713	0.768	0.526	0.208	0.282	0.764	0.243	0.492	0.526	0.593	0.066	0.222	0.347
Degree	3	0.597	0.273	0.796	0.575	0.882	0.945	0.622	0.568	0.252	0.320	0.219	0.531	0.489	0.291	0.698
Role in the office	1	0.801	0.857	0.876	0.345	0.526	0.015	0.673	0.178	0.303	0.797	0.433	0.686	0.500	0.056	0.527
Duration of employment	3	0.651	0.384	0.313	0.292	0.891	0.703	0.585	0.520	0.535	0.689	0.716	0.033	0.709	0.178	0.190
Duration/Tucson	5	0.706	0.550	0.500	0.093	0.768	0.350	0.867	0.718	0.542	0.107	0.368	0.878	0.593	0.377	0.818
Duration/ Southwest	5	0.415	0.613	0.592	0.245	0.264	0.392	0.521	0.571	0.493	0.355	0.352	0.942	0.344	0.567	0.533
LID Member	2	0.600	0.451	0.628	0.866	0.510	0.330	0.570	0.942	0.539	0.967	0.508	0.761	0.119	0.274	0.545
LID Conference	1	0.799	0.815	0.379	0.992	0.486	0.781	0.135	0.291	0.482	0.956	0.592	0.752	0.581	0.247	0.505
Gender	2	0.531	0.452	0.160	0.267	0.571	0.319	0.469	0.650	0.333	0.321	0.271	0.237	0.671	0.805	0.541

Green cells show statistically significant level $p < 0.05$

Table 5 Non-parametric statistical tests to assess relationships between demographic variables and ecosystem services supply of urban trees

		Air Quality regulation	Carbon sequestration and storage	Moderation of extreme heat events	Urban heat island and energy usage reduction	Water quality and nutrient retention	Stormwater reduction and flood control	Groundwater recharge	Water harvesting and storage for future use	Soil formation and soil quality improvement	Pollinator support	Enhancement of biodiversity	Aesthetic values	Enhanced property values	Education opportunities	Mental health and wellbeing
Urban tree	df	P-Value														
Sector	5	0.577	0.690	0.751	0.711	0.801	0.511	0.019	0.113	0.139	0.181	0.165	0.727	0.829	0.424	0.563
Major	6	0.203	0.605	0.141	0.608	0.318	0.291	0.239	0.718	0.950	0.403	0.566	0.949	0.610	0.227	0.191
Degree	3	0.514	0.653	0.440	0.628	0.876	0.583	0.853	0.633	0.402	0.171	0.818	0.877	0.705	0.588	0.603
Role in the office	1	0.073	0.028	0.166	0.583	0.305	0.434	0.360	0.800	0.925	0.206	0.630	0.235	0.039	0.219	0.137
Duration of employment	3	0.825	0.981	0.822	0.954	0.579	0.583	0.707	0.172	0.616	0.706	0.941	0.881	0.752	0.720	0.869
Duration/Tucson	5	0.413	0.384	0.773	0.725	0.605	0.272	0.391	0.498	0.190	0.376	0.995	0.843	0.792	0.617	0.681
Duration/ Southwest	5	0.576	0.457	0.756	0.886	0.615	0.672	0.819	0.225	0.650	0.227	0.783	0.909	0.949	0.454	0.901
LID Member	2	0.651	0.568	0.841	0.623	0.322	0.131	0.406	0.455	0.274	0.444	0.026	0.363	0.408	0.158	0.450
LID Conference	1	0.153	0.143	0.669	0.606	0.343	0.886	0.015	0.535	0.732	0.760	0.441	0.337	0.170	0.547	0.211
Gender	2	0.595	0.758	0.886	0.975	0.798	0.114	0.144	0.878	0.311	0.556	0.470	0.828	0.965	0.668	0.971

Green cells show statistically significant level $p < 0.05$

Table 6 Non-parametric statistical tests to assess relationships between demographic variables and environmental concerns perceived by stakeholders

		Maintenance costs	Potential health risks-mosquitos and allergens	Presence of disturbing wildlife	Tree leaves and fruits as litter	Security issues	Time-consuming installation and maintenance	Groundwater contamination due to pollution build-up	Damage to physical infrastructure and buildings	Blockage of view, accidents, traffic safety	Blockage of sunlight
Rain Garden	df	P-value									
Sector	5	0.213	0.658	0.405	0.222	0.562	0.279	0.148	0.135	0.276	0.268
Major	6	0.198	0.552	0.598	0.165	0.468	0.351	0.775	0.728	0.086	0.187
Degree	3	0.546	0.201	0.660	0.504	0.641	0.263	0.550	0.477	0.345	0.090
Role in the office	1	0.046	0.650	0.886	0.989	0.451	0.207	0.859	0.787	0.746	0.341
Duration of employment	3	0.590	0.632	0.373	0.656	0.575	0.692	0.829	0.759	0.343	0.463
Duration/Tucson	5	0.843	0.396	0.669	0.431	0.228	0.318	0.335	0.110	0.334	0.531
Duration/ Southwest	5	0.972	0.177	0.131	0.094	0.947	0.947	0.659	0.378	0.675	0.840
LID Member	2	0.238	0.538	0.580	0.959	0.266	0.784	0.970	0.317	0.014	0.510
LID Conference	1	0.446	0.460	0.970	0.798	0.157	0.596	0.741	0.027	0.008	0.480
Gender	1	0.497	0.318	0.304	0.413	0.273	0.299	0.419	0.777	0.100	0.712

Green cells show statistically significant level $p < 0.05$

Appendix 2

Methods: Ranking and priorities

In this study we have a group of stakeholders that rank the indicators under each category (Table 1-5 each table represents one category). To find out the level of importance in each category, we asked experts to rank those indicators. As the ranking of each expert is different, we used the Cook and Seiford (1978) method to come up with a consensus ranking. We have a group of experts selecting among various alternatives (indicators).

Table 1 Experts ranking on the indicators related to policy category

	Experts ranking						
Indicator	E1	E2	E3	E4	E5	E6	E7
Q1_1	3	1	2	1	3	6	2
Q1_2	4	3	4	3	4	1	3
Q1_3	2	2	1	7	2	3	4
Q1_4	5	4	3	8	5	4	7
Q1_5	1	5	7	5	1	7	6
Q1_6	6	6	6	2	6	5	5
Q1_7	7	7	8	6	7	8	8
Q1_8	8	8	5	4	8	2	1

E= Expert
Q1= Indicators related to policy category
Q1_1= Cost-share policy for retrofit
Q1_2= Policy for more integrated system
Q1_3= Policy to recognize and prioritize co-benefits
Q1_4= Coordination on regulation for co-benefits
Q1_5= Policy for consideration of climate change in design
Q1_6= Policy for considering stormwater as a resource
Q1_7= Policy for considering carbon footprint in the life cycle
Q1_8= Policy in place to coordinate with other agencies

Table 2 -Experts ranking on the indicators related to design category

	Experts ranking					
Indicator	E1	E2	E3	E4	E5	E6
Q2_1	11	5	6	11	9	3
Q2_2	4	6	5	4	8	7
Q2_3	10	7	8	10	7	8
Q2_4	7	2	4	7	2	6
Q2_5	9	3	9	9	10	9
Q2_6	8	8	7	8	5	5
Q2_7	3	4	3	3	3	4
Q2_8	1	1	2	1	4	1
Q2_9	5	9	10	5	11	10
Q2_10	6	10	11	6	6	11
Q2_11	2	11	1	2	1	2

E= Expert
Q2= Indicators related to design category
Q2_1= Plant/soil design for climate change
Q2_2= Consider right balance of plant diversity
Q2_3= Standard for soil replacement
Q2_4= Presence of a design checklist (i.e. location hierarchy, soil, management of invasive, etc.)
Q2_5= Check for soil profile change (to get to the reference soil condition)
Q2_6= Resilient plant pallet for drought/salt/wildlife tolerance
Q2_7= Check GI for being in/out of the flow path
Q2_8= Codify design criteria based on current and future needs
Q2_9= Measure co-benefits
Q2_10= Check for the linkage of site features to intended design
Q2_11= hydrologic capacity of features (how they will handle large events)

Table 3 Experts ranking on the indicators related to maintenance category

	Experts ranking					
Indicator	E1	E2	E3	E4	E5	E6
Q3_1	1	8	6	1	4	6
Q3_2	2	9	7	2	5	7
Q3_3	3	10	4	3	2	4
Q3_4	4	11	8	4	6	8
Q3_5	5	12	5	5	3	5
Q3_6	6	4	1	6	7	9
Q3_7	7	6	9	7	12	10
Q3_8	8	7	11	8	9	11
Q3_9	9	5	10	9	10	12
Q3_10	10	2	2	10	8	2
Q3_11	11	1	12	11	11	3
Q3_12	12	3	3	12	1	1

E= Expert
Q3= Indicators related to maintenance category
Q3_1= Plants are healthy/alive
Q3_2= consistent plant cover
Q3_3= Dewatering/permeability
Q3_4= Invasive presence
Q3_5= Sedimentation
Q3_6= Customize maintenance plan for individual feature
Q3_7= Documents are readily available in field to allow maintenance staff response
Q3_8= Plant lists are updated with maintenance staff actively
Q3_9= Planting plans are on record and updated
Q3_10= Appropriate lag time between installation and initiation of maintenance
Q3_11= Consider appropriate condition of green infrastructure for maintenance
Q3_12= Maintenance capacity (funding, personnel, training)

Table 4 Experts ranking on the indicators related to economic factors category

	Experts ranking					
Indicator	E1	E2	E3	E4	E5	E6
Q4_1	3	4	3	3	3	1
Q4_2	4	3	4	4	1	4
Q4_3	2	2	2	2	2	2
Q4_4	1	1	1	1	4	3

E= Expert
Q4= Indicators related to economic factors category
Q4_1= Cost per area for life cycle
Q4_2= Dedicated funding
Q4_3= Sufficient budget for frequent maintenance
Q4_4= Understating of maintenance funding requirement

Table 5 Experts ranking on the indicators related to social factors category

	Experts ranking					
Indicator	E1	E2	E3	E4	E5	E6
Q5_1	6	6	5	6	5	2
Q5_2	4	1	4	4	3	1
Q5_3	7	5	2	7	4	5
Q5_4	1	4	1	1	2	3
Q5_5	3	2	3	3	1	4
Q5_6	8	7	6	8	6	7
Q5_7	10	8	7	10	7	8
Q5_8	2	10	10	2	8	9
Q5_9	9	9	9	9	9	10
Q5_10	5	3	8	5	10	6

E= Expert
Q5= Indicators related to social factors category
Q5_1=Equitable distribution of green infrastructure
Q5_2= Affordability (installation for residents)
Q5_3= Level of outreach (prior to the design, during the construction, and during the maintenance)
Q5_4= Public knowledge
Q5_5= Public acceptance and preference
Q5_6= Curriculum building/ check for existence of curriculum
Q5_7= Student knowledge/ curriculum effectiveness
Q5_8= Signage
Q5_9= Volunteerism
Q5_10= Job development

Cook and Seiford used the median ranking, which minimizes the total ordinal distance measure between the group of experts and individual expert preference ranking. The group result is highly in agreement with the expert's individual view. In the next step, we created a m×m matrix (m=the number of indicators) (Table 6-10). If n is the number of experts, the ranking of i toward an indicator is $r_{ij.}$ In that matrix, r_{ij} is the distance of ith indicator from the jth rank. To calculate r_{ij}, we used the formula shown as follow:

$$d = \sum_{i=1}^{n} \sum_{j=1}^{m} \left| r_{ij} - r_j^c \right|.$$

In the former formula, r_j^c is a ranking number k (k = 1, 2, …, m) if we let $r_j^c = K$. Then d_{jk} is the total distance of n experts when the consensus ranking of indicator j is k,

$$d_k = \sum_{i=1}^{n} \left| r_{ij} - d_k \right|$$

thus,

$$d_k = \sum_{j=1}^{m} d_{ji}\,, \qquad k = 1,2,\dots,m.$$

In the m*m matrix, columns indicate ranks and rows indicate indicators. In each column we selected the minimum number and assign the rows number to that rank. Thus, we could determine indicator’s rank (Tzeng and Huang 2011). For example, in the table 6, number 13 is the minimum of first column which is the distance of Q1-1 indicator from the first rank. As 13 is located in the top of the column, the Q1-1 has the first rank. For the second column there are two minimums (number 9). However, as Q1-1 already placed in the first rank, we should consider the second 9 in the column. Therefore, Q1_3 has the second minimum number and is considered as the second rank. The red cells represent the minimum distance of each indicator from the corresponding priority which determine rank of each indicator.

Table 6 Distance matrix- Selecting the best rank in policy category using the assignment algorithm

Indicator	Priority							
	1	2	3	4	5	6	7	8
Q1_1	13	9	9	15	21	27	35	43
Q1_2	18	12	6	6	14	22	30	38
Q1_3	15	9	11	15	21	27	33	41
Q1_4	33	25	17	11	9	13	17	23
Q1_5	25	23	21	19	17	19	23	31
Q1_6	34	26	20	14	8	6	14	22
Q1_7	50	42	34	26	18	10	4	6
Q1_8	36	30	26	22	20	20	20	20

Q1= Indicators related to policy category

(1) Q1_1= Cost-share policy for retrofit
(2) Q1_3= Policy to recognize and prioritize co-benefits
(3) Q1_2= Policy for more integrated system
(4) Q1_4= Coordination on regulation for co-benefits
(5) Q1_8= Policy in place to coordinate with other agencies
(6) Q1_5= Policy for consideration of climate change in design
(7) Q1_6= Policy for considering stormwater as a resource
(8) Q1_7= Policy for considering carbon footprint in the life cycle

Table 7 Distance matrix- Selecting the best rank in design category using the assignment algorithm

Indicator	Priority										
	1	2	3	4	5	6	7	8	9	10	11
Q2_1	39	33	27	23	19	17	17	17	17	19	21
Q2_2	28	22	16	10	8	8	10	14	20	26	32
Q2_3	44	38	32	26	20	14	8	6	8	10	16
Q2_4	22	16	14	12	12	12	14	20	26	32	38
Q2_5	43	37	31	27	23	19	15	11	7	11	17
Q2_6	35	29	23	17	11	9	7	7	13	19	25
Q2_7	14	8	2	4	10	16	22	28	34	40	46
Q2_8	4	6	10	14	20	26	32	38	44	50	56
Q2_9	44	38	32	26	20	18	16	14	12	12	16
Q2_10	44	38	32	26	20	14	14	14	14	14	16
Q2_11	13	11	15	19	23	27	31	35	39	43	47

Q2= Indicators related to design category
(1) Q2_10= Check for the linkage of site features to intended design
(2) Q2_4= Presence of a design checklist (i.e. location hierarchy, soil, management of invasive, etc.)
(3) Q2_6= Resilient plant pallet for drought/salt/wildlife tolerance
(4) Q2_3= Standard for soil replacement
(5) Q2_8= Codify design criteria based on current and future needs
(6) Q2_5= Check for soil profile change (to get to the reference soil condition)
(7) Q2_2= Consider right balance of plant diversity
(8) Q2_1= Plant/soil design for climate change
(9) Q2_9= Measure co-benefits
(10) Q2_7= Check GI for being in/out of the flow path
(11) Q2_11= hydrologic capacity of features (how they will handle large events)

Table 8 Distance matrix- Selecting the best rank in maintenance category using the assignment algorithm

Indicator	Priority											
	1	2	3	4	5	6	7	8	9	10	11	12
Q3_1	20	18	16	14	14	14	18	22	28	34	40	46
Q3_2	26	20	18	16	14	14	14	18	22	28	34	40
Q3_3	20	14	10	10	14	18	22	26	30	34	40	46
Q3_4	35	29	23	17	15	13	13	13	17	21	25	31
Q3_5	29	23	17	13	9	13	17	21	25	29	33	37
Q3_6	27	23	19	15	13	11	13	17	21	27	33	39
Q3_7	45	39	33	27	21	15	11	11	11	13	17	21
Q3_8	48	42	36	30	24	18	12	8	8	10	12	18
Q3_9	49	43	37	31	25	21	17	13	9	9	13	17
Q3_10	28	22	22	22	22	22	22	22	24	26	32	38
Q3_11	43	39	35	33	31	29	27	25	23	21	19	23
Q3_12	26	24	22	24	26	28	30	32	34	36	38	40

Q3= Indicators related to maintenance category
(1) Q3_1= Plants are healthy/alive
(2) Q3_5= Sedimentation
(3) Q3_2= Consistent plant cover
(4) Q3_6= Customize maintenance plan for individual feature
(5) Q3_3= Dewatering/permeability
(6) Q3_4= Invasive presence
(7) Q3_7= Documents are readily available in field to allow maintenance staff response
(8) Q3_8= Plant lists are updated with maintenance staff actively
(9) Q3_9= Planting plans are on record and updated
(10) Q3_11= Consider appropriate condition of green infrastructure for maintenance
(11) Q3_10= Appropriate lag time between installation and initiation of maintenance
(12) Q3_12= Maintenance capacity (funding, personnel, training)

Table 9 Distance matrix- Selecting the best rank in economic factors using the assignment algorithm

Indicator	Priority			
	1	2	3	4
Q4_1	11	7	3	7
Q4_2	14	10	6	4
Q4_3	6	0	6	12
Q4_4	5	7	9	13

Q4= Economic factors
(1) Q4_3= Sufficient budget for enough frequent maintenance
(2) Q4_4= Understating of maintenance funding requirement
(3) Q4_2= Dedicated funding
(4) Q4_1= Cost per area for life cycle

Table 10 Distance matrix- Selecting the best rank in social factors category using the assignment algorithm

Indicator	Priority									
	1	2	3	4	5	6	7	8	9	10
Q5_1	24	18	14	10	6	6	12	18	24	30
Q5_2	11	9	7	7	13	19	25	31	37	43
Q5_3	24	18	14	10	8	10	12	18	24	30
Q5_4	6	6	8	12	18	24	30	36	42	48
Q5_5	10	6	4	8	14	20	26	32	38	44
Q5_6	36	30	24	18	12	6	4	6	12	18
Q5_7	44	38	32	26	20	14	8	6	8	10
Q5_8	35	29	27	25	23	21	19	17	17	19
Q5_9	49	43	37	31	25	19	13	7	1	5
Q5_10	31	25	19	15	11	11	13	15	19	23

Q5= Indicators related to social factors category
Q5_5= Public acceptance and preference
Q5_3= Level of outreach (prior to the design, during the construction, and during the maintenance)
Q5_4= Public knowledge/ education
Q5_1=Equitable distribution of green infrastructure
Q5_2= Affordability (installation for residents)
Q5_6= Curriculum building/ check for existence of curriculum
Q5_7= Student knowledge/ curriculum effectiveness
Q5_9= Volunteerism
Q5_8= Signage
Q5_10= Job development

Table 11 All challenges to green infrastructure (GI) resilience expressed by stakeholders for policy, design, maintenance, economic factors, and social factors.

Categories	Main Challenges
Policy	Policy change
	• Policies change frequently
	Lack of consensus, communication, and institutional challenges
	• Challenges on making a long-term decision that could correspond with climate change adaption and uncertainty
	• Proliferation of acronyms/ Lack of standard language from location to location
	• Institutions are sometimes slow in making impactful changes
	• Apathy or resistance to change
	• Challenges with multi-stakeholder
	a. Lack of collaboration with designers- what is necessary or not to be included in the policy
	b. Collaboration with other agencies/utilities
	• Lack of jurisdiction coordination
	• Lack of developed consensus between stakeholders: owners/ design team/ builders/ maintenance crew
	Lack of consideration on multiple co-benefits
	• Stronger budget only comes out of stormwater budget and other benefits such as safety or improving air quality not considered
	Lack of a comprehensive evaluation system
	• Lack of policy to support research on evaluating how green infrastructure (plants, soil, etc.) will respond to climate change
	• Needs for better definition of standards
	• Lack of approved nutrient and sediment credit
	Lack of sufficient budget planning
	• Considering pollinators corridors, to prioritize those in funding allocation
	• Lack of/ insufficient incentives for retrofitting existing property
	Lack of considering research and innovation in policy
	• Lack of policy to involve research in decision making
	• Difficulty getting credit for innovative stormwater designs and strategies
	• Credit for developing researched tools (e.g. landscape conservation)
	Lack of policy for specific needs of society
	• Lack of consideration of climate change urgency in policy
	• Lack of policy for private-public distribution of practices
Design	Lack of design knowledge
	• General lack of horticulture and landscape design knowledge in plant selection, size, spacing, grade, and type considering the different volume of water, commercial vs. residential.
	• Lack of considering the connection between the type of soil and plants (knowledge transfer)
	• Lack of research on the use of in-situ soil vs. extracted/ delivered soil media
	Lack of consensus and communication
	• Lack of consensus of stakeholders at the design table
	• Connection of design and maintenance for plant replacement with a description of why those new plants have selected
	• Lack of communication of maintenance crew with designers on issues on site
	• Competing interest- stormwater management is afterthoughts both for new design and retrofits
	Biophysical limits
	• Lack of plant supply and find the best substitution when things are not available. Especially finding substitution when plants are not favorable for a place (i.e. deer, salt, and sediment pressure)
	• Lack of space- There is a lot of places needed green infrastructure but there is lack of space
	• One size does not fill all
	Specific needs of a location

	• Lack of understanding site specific needs by design team • Cost prohibition to do a survey for each site, or test for every single site • Consider regional specificity Anacostia vs Arizona GI • Consideration of forebay/ cheek dams/ sediment sump to capture first flush sediments • Maximizing drainage area to facilities • Design considering public acceptance Lack of specific guideline or willing to change • No guideline for how long the media should sit before you plant on it • Wide range of design standards • Lack of aesthetic standards • Site assessment/ invasive species before the design • Permitting process difficulty- once permit is approved, no appetite for updating- even if additional funding is available Cost and timing • Cost of plant supply and cost of design and construction • Sometimes design process for new capital projects need to be very fast paced, the design could be improved if additional time available
Maintenance	Lack of Knowledge • Find documentation for old facilities on intended design- Understanding the design set and needs • Understanding the failure of the system either by when it retains water and draining well or when water bypassing or the media drain to quickly • Lack of considering the difference in cleaning different sites • Expertise and knowledge of maintenance crew (3) o Limited plant knowledge o Not understanding the needs and function of GI • Lack of personnel and trained inspectors Lack of communication • Communication with maintenance crew if they are doing the right thing • Private owners may not have access to engineering Biophysical limits o Concerns on physical issues (i.e. sedimentation, weeds, pollutant build-up, salt, deer pressure Specific maintenance needs for individual feature • Lack of customizing a maintenance plan for the type of GI that you're building (example more needs of permeable pavers in DC compared to a parking lot in Fredrick) Lack of specific guideline • Lack of standard for performing regular maintenance • Lack of guideline for replacement scheduling Cost • Cost is the number one- Expensive to maintain- Lack of adequate funding especially for retrofit • Considering rapid response capacity, potential maintenance budget for a catastrophic storm event Public attitude • Maintenance is sometimes not needed much especially when the facility is still functioning, but it also ties to public acceptance. Especially, for one that is publicly visible requires more maintenance. • Considering the dynamics of adjacent development
Economic Factors	Budget prioritization • Lack of the prioritization of money- Less money allocated to maintenance • Consideration of more expenses needed per multiple small structures than one large in construction- design might be similar and needs less cost but construction costs are going to be higher • Higher cost needed where people live compared to facilities in the city and county that needs cut once a year vs weekly on people's home • Budget for redevelopment/ new development Budget allocation for maintenance

	• Upfront budget for practices to reduce maintenance
Social Factors	Lack of knowledge and education • Lack of education/ acceptance of GI • Outreach a. Workshops for stakeholders (designers, residents (4), utilities, and agencies) • Education of K-12 into later years Public attitude and acceptance • People afraid of falling into GI, mosquito problems, snakes, bees, cricket • Some communities won't accept wildlife • Convey the importance of GI and expand the idea into people's normal life routines • Lack of interest in installing • Lack of will to modify behaviors and ignorance Environmental justice • Out of site facilities receive little or no attention Specific needs of a feature • Community design specific to their needs

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