Published in final edited form as:

J Clean Prod. 2021 March 20; 289: . doi:10.1016/j.jclepro.2020.125146.

Assessment of green infrastructure performance through an urban resilience lens

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Abstract

Green infrastructure (GI) is widely recognized for reducing risk of flooding, improving water quality, and harvesting stormwater for potential future use. GI can be an important part of a strategy used in urban planning to enhance sustainable development and urban resilience. However, existing literature lacks a comprehensive assessment framework to evaluate GI performance in terms of promoting ecosystem functions and services for social-ecological system resilience. We propose a robust indicator set consisting of quantitative and qualitative measurements for a scenario-based planning support system to assess the capacity of urban resilience. Green Infrastructure in Urban Resilience Planning Support System (GIUR-PSS) supports decision-making for GI planning through scenario comparisons with the urban resilience capacity index. To demonstrate GIUR-PSS, we developed five scenarios for the Congress Run sub-watershed (Mill Creek watershed, Ohio, USA) to test common types of GI (rain barrels, rain gardens, detention basins, porous pavement, and open space). Results show the open space scenario achieves the overall highest performance (GI Urban Resilience Index = 4.27/5). To implement the open space scenario in our urban demonstration site, suitable vacant lots could be converted to greenspace (e.g., forest, detention basins, and low-impact recreation areas). GIUR-PSS is easy to replicate, customize, and apply to cities of different sizes to assess environmental, economic, and social benefits provided by different types of GI installations.

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CRediT authorship contribution statement

Xin Fu: Conceptualization, Methodology, Software, Investigation, Validation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Matthew E. Hopton:** Conceptualization, Resources, Supervision, Project administration, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Xinhao Wang:** Conceptualization, Validation, Writing - original draft, Writing - review & editing, Visualization.

Declaration of competing interest

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

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125146.

Keywords

Stormwater management; Green infrastructure; Assessment; Urban resilience; Planning support system

1. Introduction

Against the backdrop of global environmental change and rapid urbanization, building urban resilience has attracted increased attention from both practitioners and researchers in urban planning (Calderón-Contreras and Quiroz-Rosas, 2017; Deal et al., 2017; Kim and Lim, 2016). Making cities and human settlements inclusive, safe, resilient, and sustainable has been identified as UN sustainable development goals in recent years (United Nations, 2016, 2017, 2018). Over the past several years, Resilient Cities Network organization (https://resilientcitiesnetwork.org) has received about 330 membership applications from 94 countries—applicants present their strategies to become more resilient to the physical, social, and economic challenges. Cities, as complex socio-ecological systems, are facing increasing threats posed by resource depletion or different natural or human-induced disasters which may occur suddenly like extreme weather, or slowly such as gradual economic decline or climate change (Bennett, 2017; Fu and Wang, 2018; Kremer et al., 2015). Because of incomplete prediction (i.e., cannot fully predict failure) of technological and vulnerability of social systems, cities should protect their people and property, and foster positive changes or adaptations (Comfort, 2005; Foster, 1997; Meerow and Newell, 2016; https://unhabitat.org/resilience/). Therefore, a city needs to assess and build capacity for resilience to absorb, mitigate, and adapt to many kinds of disturbances while maintaining its organization and social, ecological, and economic functions. The generalized concept of resilience was used in physics, material science, and engineering (Hoffman, 1948), and Holling (1973) was the first to introduce resilience to describe the character of an ecosystem. It has evolved to an umbrella concept in multiple fields, such as engineering (Folke, 2006; Larkin et al., 2015), socio-ecology (Leichenko, 2011; Pelling, 2003), climate change (Dieleman, 2013), economic recovery (Pendall et al., 2010; Simmie and Martin, 2010), disaster recovery (Colten et al., 2008; Vale and Campanella, 2005), and others. The notion of resilience appeared in urban planning in the 1990s (Mileti, 1999). Urban resilience refers to the ability of a social-ecological system to absorb, mitigate, and adapt to changes (Desouza and Flanery, 2013), and to withstand an extreme event without undergoing considerable change, or the system quickly recovers to the pre-disturbance state, all without a large amount of assistance from outside the community or system (Mileti, 1999). Resilience capacity of an urban system can be strengthened by robust infrastructure, high biodiversity, redundant resources, tight feedbacks, rich social capital, integrated modularity, effective innovations, and so on (Ahern, 2011; Chelleri et al., 2015).

The idea of resilience has been applied to many types of infrastructure systems to characterize the ability to handle the magnitude and duration of negative effects from disturbances (Kim et al., 2017; Shafieezadeh and Burden, 2014). One frequently proposed technology to help build resilience capacity is green infrastructure (GI) as part of a stormwater management plan, and is considered an important strategy of urban planning aimed at enhancing sustainable development (Meerow and Newell, 2017; Simić et al., 2017). Urban greenspace and GI can provide a number of benefits in addition to stormwater benefits (e.g., Hoover and Hopton 2019) and may increase urban resilience. A focus of urban resilience thinking in GI development is to understand, leverage, and value its ecological, social, and economic functions (Barthel et al., 2010; Ernstson et al., 2010). As a decentralized and autonomous infrastructure to supplement current stormwater drainage networks (i.e., gray infrastructure) in urban systems, GI (e.g., rain gardens, detention basins, greenspace, etc.) is widely recognized as effective in reducing risk of flooding and harvesting water for potential future use as part of stormwater management (Fletcher et al., 2015; Nordman et al., 2018). Beyond that, GI also provides and maintains a variety of social, economic, and ecological services to enhance the quality of life for urban residents (Jim et al., 2015; Kim et al., 2017). Many studies have found evidence that GI enhances economic conditions of a city to cope with negative effects from globalization and economic declines, such as reducing existing infrastructure costs (Vineyard et al., 2015), increasing property values (but see Hoover et al., 2020), providing new green jobs, and reducing the amount of energy and unrenewable materials used in managing stormwater (Ferreira et al., 2013).

To understand the abovementioned effects GI has on urban resilience, it is necessary to assess GI performance in terms of urban resilience thinking. And to evaluate how GI can help maintain or transform an urban system to a preferred state in response to a changed environment (more impervious surface, higher population density, more stormwater runoff, or higher waterlogging risk). For this study, we assume a system is in a preferred state and resilience of the system is sought after. Existing urban resilience assessments have started to address the comprehensive capacity of a social-ecological system in dealing with multiple risks (Meerow et al., 2016; Pendall et al., 2010). GI technologies are typically implemented with assessments that create persuasive arguments for implementing GI from the perspective of different goals (Vandermeulen et al., 2011). For example, one's interests may include assessment of ecosystem services (delivery of benefits classified as provisioning, regulating, supporting, and cultural; Millennium Ecosystem Assessment, 2005; Koc et al., 2017; Tiwary and Kumar, 2014), valuation or assessment of economic conditions (Kousky et al., 2013; Nordman et al., 2018), environmental impact assessments (O'Sullivan et al., 2015; Zawadzka et al., 2017), or an assessment of sustainability (Lafortezza et al., 2013; Makropoulos et al., 2008). However, current assessments of GI generally inspect a single or a few factors of interest that are a subset of factors important to building urban resilience. It lacks a comprehensive assessment framework to evaluate GI performance in providing effective ecosystem services, and promoting desirable economic, environmental, and social conditions in a social-ecological system. Because of the complexity of social-ecological systems, lack of available data, and limited modeling methods, some measurements needed for assessing GI in terms of resilience are difficult to quantify. Usually they are measured qualitatively with grades or categories based on perceptions (Makropoulos et al., 2008). It can be difficult, but necessary, to combine quantitative and qualitative measurements in a comprehensive indicator system and, therefore, complicates assessing urban resilience.

To address this challenge, we developed a comprehensive indicator system integrating environmental, economic, social, and cultural dimensions of resilience (Bibri and Krogstie, 2017), and combined quantitative and qualitative indicators using the fuzzy comprehensive evaluation (FCE) method. By using FCE, some qualitative factors, which are difficult to obtain with conventional analytical techniques, can be evaluated quantitatively (Rajak et al., 2016; Shi, 2012). We also embedded the assessment process into a scenario-based planning support system (Green Infrastructure performance in Urban Resilience Planning Support System; GIUR-PSS). A planning support system (PSS) combines geospatial data, methods, and technologies with expert knowledge into a system to support tasks and decisions associated with planning (Boulange et al., 2018; Pettit et al., 2018), in this case to facilitate public participation and to support decision-making for GI planning and investment. GIUR-PSS enables the user to identify the planning challenge, incorporates models, and applies data processes to assist public and community leaders to participate in developing, visualizing, assessing, and comparing scenarios, and allows for informed decisions on the assessment of urban resilience (Fu et al., 2016; Pettit et al., 2018). Some newer trends of PSS are incorporated into GIUR-PSS, such as involving the interests of various stakeholders (Hawken et al., 2020), considering of public benefit beyond an immediate fulfilment (Kuller et al., 2017), addressing spatial impacts on environmental and societal components (Bach et al., 2015), and facilitating discussions around scenarios (Pettit et al., 2019; Sample et al., 2001). In GIUR-PSS, the public with multiple interests and preferences can participate in selecting types of GI to install, scoring qualitative indicators, and weighing all indicators to assign relative importance. An index of urban resilience capacity index is calculated to compare scenarios for discussion and decision of desired scenario, and unsatisfied results can be feedbacked to develop new alternatives.

2. Methods

2.1. The GIUR-PSS architecture

The architecture of GIUR-PSS includes scenario generation, fuzzy comprehensive evaluation (indicator set, indicator modeling or survey, grading and weighting, and fuzzy algorithm), and decision-making modules (Fig. 1). GIUR-PSS starts with scenario generation that works together with plans and strategies relevant to GI installation practices. Scenarios allow users to develop and clarify practical choices, policies, actions, and preferences for using GI (Coates, 2016). Users can experiment with scenarios based on their preferred type, amount, location, and sequence of GI installation (Fu et al., 2019).

The first step incorporating fuzzy comprehensive evaluation is to establish a set of indicators relevant to resilience capacity provided by GI according to specific indicator selection rules and characteristics of the study area. The indicator set is based on literature review and an understanding of how they relate to urban resilience, and indicator values are collected through different mechanisms. For example, some selected indicators are modeled with local data and scenario assumptions, whereas some indicators' values are collected from user (e.g., expert) input through surveys. Ultimately, each indicator is provided a level of importance and contribution to resilience, and stakeholder preference through a number of steps described below. In brief, a grading system is utilized to define standards or rules corresponding to a given value of each indicator and to present its contribution to the evaluation objective and conduct fuzzy membership matrix. Analytic Hierarchy Process

(AHP) is used to make an indicator weight vector to present the relative importance of different indicators to the evaluation objective. The fuzzy algorithm combines fuzzy membership matrix and weights to establish the index for GI performance in building urban resilience capacity. Additional information is provided below.

Another important feature of GIUR-PSS is that it analyzes and compares scenarios to help make decisions for GI planning. GIUR-PSS conducts "what-if" analyses by comparing the effects or consequences of different scenarios, and helps build consensus among stakeholders on a preferred alternative (Waddell and Vanegas 2011). The "optimal" forecasting outcome will be explored through alternative scenarios based on FCE resulting indices, until a desired or best outcome (in all tested scenarios) is reached (Deal et al., 2017; FHWA, 2012). Different scenarios are compared with their FCE results in order to find one scenario that is satisfied for implementation. If no satisfactory scenario is found, a feedback mechanism (e.g., Hendry, 1988) is initiated to generate additional alternative scenarios.

2.2. Study area

Congress Run is a sub-watershed of the Mill Creek watershed, and is located at the boundary of 3 municipalities; City of Cincinnati, City of Wyoming, and Springfield Township in Hamilton County, Ohio, United States (Fig. S1). The drainage area of Congress Run sub-watershed is 9.83 km^2 and has 3262 parcels. Most data used in this study are publicly available and obtained from government databases or websites. For example, we created impervious areas by merging multiple layers, including buildings, driveways, roads, paved parking lots, and sidewalks. Pervious area was identified by subtracting impervious area from the land cover data (Dewitz 2019; www.mrlc.gov). Soil survey data, slope, and parcel layers were from Cincinnati Area Geographic Information System (http://cagismaps.hamilton-co.org/cagisportal) and used for the runoff quantity modeling. All data processing and preparation were conducted using ArcGIS 10.5 (ESRI, Redlands, CA).

2.3. Fuzzy comprehensive evaluation

The assessment of GI performance in urban resilience capacity is characterized by a complicated social-ecological system under imprecise conditions, fuzziness, and uncertainty, and determined by multiple criteria from both quantitative estimation and qualitative judgments. Therefore, FCE is an effective means to address these problems and facilitate multiple layers and multiple criteria for comprehensive decision making (Gharibi et al., 2012; Pislaru et al., 2019). Fuzzy logic is a tool for transforming human knowledge and its decision-making ability into a mathematical formula to define membership functions in order to decrease the fuzziness (Han et al., 2015). FCE has been applied in various fields, including evaluation of urban planning implementation (Tong and Zhang, 2016), urban water management with PSS (Makropoulos et al., 2003), flood vulnerability assessment (Yang et al., 2018), sustainability evaluation (Bai et al., 2017), transportation system performance (Rajak et al., 2016), and so on. The basic procedure of the FCE method is: (1) establishing the indicator set and grading or ranking system for a specific objective; (2) creating the fuzzy membership matrix by assigning values to indicators and membership functions; (3) determining weights (or importance) for indicators; and (4) defining the

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objective of the assessment being performed based on the fuzzy arithmetic of the fuzzy membership matrix and weight vector of indicators.

2.3.1. Indicator set and grading system of FCE in GIUR-PSS—

There are many factors that influence the performance of GI and its resulting urban resilience capacity (Gordon et al., 2018). Following scientific, systematic, spatial, and representative principles and based on literature review (Wang et al., 2015, 2017), an indictor set is designed for assessment of GI performance in building urban resilience capacity with three levels (Table A1). The indicator set considers GI performance in building urban resilience capacity as the goal (the first level); the goal is determined by the three system dimensions (the second level; i.e., environmental, economic, and social dimensions). Indicators (the third level) in the environmental dimension focus on ecological services provided by GI, such as, runoff abatement, water quality improvement, biodiversity, and so on (Allen et al., 2016; Ling and Chiang, 2018; Venturelli and Galli 2006). Examples of indicators in the economic dimension represent economic benefits and costs, such as, GI construction and maintenance costs, creation of green employment, etc. (Campanella, 2006; Pakzad and Osmond, 2016; Thornbush et al., 2013). Indicators in the social dimension address social capital and public issues, such as, increase of recreational areas, public health improvement, and cultural contributions, and so on (Campbell et al., 2016; Ling and Chiang, 2018; Sierra et al., 2018). Most indicators have one directional desirability (polarity) and range in value from 0 to 1. For example, higher runoff abatement leads to higher desirability and improves urban resilience capacity (positive polarity), and lower GI construction cost is transformed to higher desirability and improves urban resilience capacity (negative polarity; i.e., values further from zero correspond to higher resilience). Generally, the levels and elements in the assessment indicator set can be assumed as Eq. (1) and Eq. (2):

$$O = \{D_1,\ D_2,\ D_3\} \tag{1}$$

$$D_{ij} = \{D_{i1},\ D_{i2},\ \ldots D_{ij}, \ldots D_n\}\ (i = 1,\ 2,\ 3;\ j = 1,\ 2,\ \ldots,\ n) \tag{2}$$

where, O is the objective level of the indicator set; D_i is the dimension level, D_{ij} is the jth indictor in the ith dimension; n is the number of the indicator in each dimension.

Each indicator represents single or combined pathways of absorption, mitigation, and adaptation for achieving urban resilience. The definitions of absorption, mitigation, and adaptation follow Fu and Wang (2018). Absorption and mitigation abilities relate to the resilient capacity of an infrastructure system, and adaptation addresses the ability of self-organization and learning of a living system (Desouza and Flanery, 2013). For example, if a rain garden is installed in the lawn of a residential parcel, its infiltration ability is corresponding to the lawn’s infiltration ability and represents the absorption ability of the GI. However, the increased detention ability designed for the rain garden could provide mitigation for the negative influence of stormwater runoff. The indicator for community socialization addresses the adaptation pathway–if GI can provide useable space (e.g., community park), or an opportunity for communication, gathering, or connection between people in the community, it results in an increase in social capital and is helpful for recovery after disturbance (Cox and Hamlen, 2015).

Indicators can be quantitative or qualitative in format. In our study, values of quantitative indicators were calculated through modeling, whereas values for qualitative indicators were obtained by querying experts. Quantitative indicators are divided into one of five ranks, corresponding to the level of GI performance in terms of building capacity of urban resilience: ‘very low’, ‘low’, ‘medium’, ‘high’, and ‘very high’ (Eq. (3)). Standards for ranking quantitative indicators were based on relevant literature (Wang et al., 2015), existing values (Zhao et al., 2014), expert recommendations (Sun and Xue, 2019), or even common sense (Phillis et al., 2017). In this study, possible minimum and maximum values of the indicator are used for ‘very low’ or ‘very high’ standards, their lower and higher quartiles are used for ‘low’ and ‘high’ standards, and their mean value is used for the ‘medium’ standard (Table 1). Developing and modeling extreme scenarios are helpful to find possible minimum and maximum values. For example, a business as usual scenario (Varum and Melo, 2010), which presents status quo with existing land use, is used to provide modeling values for the ‘very low’ categories in runoff and water quality improvement, decrease of gray infrastructure cost, and increase of recreational areas indicators, and for ‘very high’ category in GI construction cost indicator. According to the non-development extreme scenario (e.g., grassland), we used its modeled values as references for ‘very high’ categories in runoff and water quality improvement indicators. Another extreme scenario assumes equal areas for different land use types providing the value for ‘very high’ category in land use diversity, and “1” is used as the minimum value for this indicator. The third extreme scenario converts all vacant lots to recreational area that provides a reference for ‘very high’ category in increase recreational area indicator. The modeling value of Sce4 (porous pavement; see section 2.4 for further description) scenario in GI construction cost indicator represents the ‘very high’ category in this indicator. And the modeling value of Sce4 in green employment indicator represents the ‘very low’ category in this indicator.

$$V = \{v_1, v_2, v_3, v_4, v_5\} = \{1, 2, 3, 4, 5\} \tag{3}$$

where, V is the set of indicator’s ranking; v_1, v_2, v_3, v_4, and v_5 are ranks representing levels in building capacity of urban resilience—’very low’, ‘low’, ‘medium, ‘high’, and ‘very high’; the score of ranks are 1, 2, 3, 4, and 5, respectively. Additional details on the calculation or modeling methods are provided in Supplementary Material.

To obtain original values for the qualitative indicators, we invited 70 experts to rank importance of indicators through an unstructured opinion survey. Experts were employees within the Agency and represented different expertise such as, ecology, hydrology, green infrastructure, economics, and sociology, and they were asked to assign scores to each qualitative indicator in terms of its performance in building capacity of urban resilience for all types of GI or scenarios. The range of scores is consistent with the evaluation ranks used in the quantitative indicators. The questionnaire (see Supplementary Material) was designed for five types of GI (e.g., rain barrel, rain garden, porous pavement, detention basin, and open space). For each GI type, the questionnaire provided design variables for a specific type of GI as a reference for the expert to help assign scores to indicators. The design variables include GI function (e.g., detention or infiltration runoff, recreation, etc.), vegetation and types (e.g., grass, tree, etc.), land area required (e.g., large or small), spatial distribution (e.g., centralized or scattered), maintenance required (e.g., yes or no), and construction costs (e.g., expensive or inexpensive). Additional details are in Supplementary Material.

2.3.2. Fuzzy membership function—Fuzzy membership function (R) is used to project any given value (x) of an indicator to the membership degree ([0, 1]) for each evaluation rank, represented as $R(x)$. Fuzzy membership function can be expressed in various forms such as triangular, trapezoidal, Gaussian, etc. (Yang et al., 2013). Considering most quantitative indicators are continuous variables (Wu et al., 2010), triangular form was selected in this study. The single factor fuzzy membership triangular functions for positive and negative polarities are in Li et al. (2019). The fuzzy membership triangular functions work on En1, En2, En4, Ec1, Ec2, Ec3, Ec7, and So1 indicators (Table A1) to conduct membership degrees $rt_{i,j}$ ($rt_{i,j}$ is a fuzzy membership degree matrix for quantitative indictor i corresponding to jth evaluation rank in V).

Valid questionnaires (i.e., no missing data) from the survey of experts are used to conduct fuzzy membership matrix for qualitative indicators. The total responses from the questionnaires are summed for each indicator, and the membership degree of the indicator is calculated by Eq. 4

$$rl_{i,j} = \frac{C_{i,j}}{\sum_{j=1}^{5} C_{i,j}} \quad (4)$$

where, $rl_{i,j}$ is fuzzy membership degree matrix for qualitative indictor i corresponding to jth evaluation rank in V, $i \in$ { En3, En5, En6, En7, En8, Ec4, Ec5, Ec6, So2, So3, So4, So5, So6, So7} and $j \in \{1,2, 3, 4, 5\}$; $C_{i,j}$ is total counts of experts selected indicator i belonging to jth comment.

Next, two fuzzy membership matrixes ($rt_{i,j}$, $rl_{i,j}$) for quantitative and qualitative indicators are combined to construct a fuzzy evaluation matrix R (Eq. (5)):

$$R = (r_{ij})_{n \times 5} = \begin{pmatrix} r_{11} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{n5} \end{pmatrix} \quad (5)$$

where, R is the fuzzy evaluation matrix; r_{ij} is the fuzzy membership degree of indicator i corresponding to jth evaluation rank; n is the number of indicators.

2.3.3. Weight of indicators—The weight vector of FCE is obtained by the AHP method to represent relative importance of indicators to contribute to urban resilience capacity (Mu and Pereyra-Rojas, 2017). Each element within a specific level (e.g., dimension or indicator level) is pair-wise compared in a nine-point scale and a relative importance matrix is determined by experts' recommendations. The consistency ratio (CR) is calculated to guarantee consistency of judgment through different dimensions or indicators, by dividing the consistency index by the random index. Saaty (2012) has shown that a CR ≤ 0.10 is acceptable to continue the AHP analysis. The weight vector in FCE for different indicators is shown in Eq. (6):

$$W = (w_1, \dots, w_i, \dots, w_n), \sum_{i=1}^{n} w_i = 1 \quad (6)$$

where, W is the weight vector; w_i is the weight for indicator i; n is the number of indicators.

2.3.4. Fuzzy comprehensive evaluation model—

Fuzzy membership of the comprehensive evaluation can be calculated by the fuzzy membership matrix and weight vector (Eq. (7)),

$$F = W \times R = (w_1, \dots, w_i, \dots, w_n) \times \begin{pmatrix} r_{11} & \cdots & r_{15} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{n5} \end{pmatrix} = (f_1, f_2, f_3, f_4, f_5) \quad (7)$$

where F is the fuzzy comprehensive evaluation set; f_j is the comprehensive fuzzy membership degree to jth evaluation rank for a specific scenario; n is the number of indicators.

2.3.5. Defuzzification to a fuzzy index—

To get the final evaluation result of the GI performance in building urban resilience capacity, the comprehensive evaluation set (F) is defuzzified by using a weighted average method (Eq. (8)) (Li et al., 2015; Loh et al., 2017).

$$GIURI = \sum_{j=1}^{5} f_j^2 \times j \Big/ \sum_{j=1}^{5} f_j^2 \quad (8)$$

$GIURI$ is GI performance in building Urban Resilience Index; $j \in \{1, 2, 3, 4, 5\}$ corresponding to evaluation ranks in V.

2.4. Scenario development

In dense urban areas, decentralized GI (e.g., LIDs) and large-scale GI (e.g., BMPs) are used to help increase infiltration and retention of stormwater and therefore reduce the stormwater runoff (Fu et al., 2019). Although many GI scenarios or preferences could be generated and tested with the proposed methodology, in this study we developed five scenarios as a demonstration to test GIUR-PSS and assess resilience. We selected common types of GI and tested scenarios that included rain barrels (Sce1), rain gardens (Sce2), detention basins (Sce3), porous pavement (Sce4), and open space (e.g., community park; Sce5). Our descriptions of rain barrels, rain gardens, detention basins, and porous pavement can be found in Fu et al., 2019. Open space provides temporary storage of stormwater runoff and can provide publicly-accessible recreation areas (e.g., picnic areas, playgrounds, etc.). For each type of GI, if the volume of runoff entering GI is more than the storage capacity or infiltration rate (for porous pavements), the excess water becomes part of the runoff.

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A suitability analysis using ArcGIS 10.5 was used to allocate different types of GI within the study area. Criteria for the suitability analysis include key design parameters for each type of GI (e.g., surface area, depth, and costs of construction and maintenance) are presented in Table 2 (Center for Neighborhood Technology, 2009; National Stormwater Calculator (v1.2.0.1); Schueler et al., 2007; USEPA, 2004).

3. Results and discussion

3.1. Urban resilience assessment framework for GI

We developed a novel GIUR-PSS framework that imbeds the FCE method into a GIS-based planning support system. We improved the data loop through scenario development, modeling or surveying, fuzzy algorithm, and decision-making. The unique feature is GIUR-PSS facilitates and evaluates different scenarios as a comparable index (i.e., GIURI) for building urban resilience capacity and an “optimal” scenario will be recommended for implementation. A robust indicator system is built to assess GI performance based on indicators currently used in the literature. Indicators are organized to represent benefits (e.g., improve water quality) or costs (e.g., construction cost) for building urban resilience capacity. Single or multiple pathways for each indicator are assigned to help planners understand and track its effect (e.g., absorption, mitigation, or adaptation) and timing (e.g., before or during disturbance) in building urban resilience capacity. We also provided guidance to assist in determining grading standards for evaluation ranks of quantitative indicators using local data and extreme scenario assumptions to provide more accurate and possible values for inclusion. Valid responses from the query of experts were obtained from 34 (49%) respondents who scored the 14 qualitative indicators. Finally, GIUR-PSS incorporated two parts of fuzzy membership matrixes from quantitative and qualitative indicators into an index to compare scenario’s performance and assist decision-making.

3.2. Fuzzy membership matrix

Seven quantitative indicators are simulated for the difference scenarios. According to the ranking standards (Table 1), the fuzzy membership degree of quantitative indicators for each evaluation rank are calculated (Fig. 2). Frequencies of scores assigned by experts for qualitative indicators are summarized to assign evaluation rankings (Fig. 2). In open space scenario (Sce5), for example, quantitative indicators (e.g., create green employment (Ec2), runoff (En1)) are ranked very high and high, respectively, although qualitative indicators (e.g., enhance aesthetics (So2)) generally had higher rankings (Fig. 2). Nine indicators predominately were ranked ‘very high’ (left side of line a) meaning the probability of ‘very high’ is more common than other assigned rankings in open space scenario (Fig. 2). There are six indicators dominated by ‘high’ rank, and three indicators are dominated by ‘medium’ rank (Fig. 2). Only three indicators were ranked ‘low’ rank and there is no indictor ranked ‘very low’ (Fig. 2). Fuzzy membership distribution of each indicator for other scenarios can be found in Supplementary Materials (Figs. S2-5).

To compare the distribution of ratings between the different scenarios, we count the number of indicators in each dimension and rank the evaluation (Fig. 3). In the environmental dimension, most of indicators for rain barrels scenario (Sce1) are rated ‘very low.’ Indicator ratings of rain gardens (Sce2), detention basins (Sce3), and porous pavement (Sce4) scenarios, are concentrated in 'low' and 'medium' rankings. Open space scenario has land use diversity (En4) in 'low' ranking and two indicators (En3, En8) in 'very high' ranking. In the economic dimension, rain barrels scenario has most of indicators in 'very low' ranking. Porous pavement scenario performs poorly in the economic dimension; three indicators (Ec1, Ec2, and Ec6) are ranked 'very low.' Four indicators (Ec2, Ec3, Ec5, and Ec6) are ranked 'low' for rain gardens scenario. Decreasing gray infrastructure (Ec3) is ranked 'very high' in detention basins scenario. Three indicators (Ec2, Ec4, and Ec6) ranked 'very high' result in the open space scenario being the best in this dimension. In the social dimension, indicator ratings of detention basins scenario or porous pavement scenario are concentrated in 'very low' ranking (e.g., So1, So3, and So4). The ranges of the indicator rating for rain barrels scenario and rain gardens scenario are around 'medium' ranking. Open space scenario is the best performance scenario again with four indicators (So2, So4, So5, and So6) in 'very high' ranking. In total dimensions, the 'very low' ranking dominates rain barrels and porous pavement, the 'low' ranking dominates rain gardens and detention basins scenarios, and 'very high' ranking dominates open space scenario.

We collected pair-comparison scorings for all indicators from a small group of experts and calculated AHP weights. The average weights were used as final weights for the fuzzy comprehensive evaluation, W = {0.0795, 0.0732, 0.0794, 0.0196, 0.0123, 0.0217, 0.0389, 0.1047, 0.0205, 0.0528, 0.0469, 0.0166, 0.0098, 0.0316, 0.0728, 0.0277, 0.0228, 0.0438, 0.0536, 0.1457, 0.0263}.

3.3. Scenario comparison

We used common GI types to develop five scenarios as case studies for the urban resilience assessment. Through a suitability analysis, locations and amounts of different types of GI were identified, according to established constraints and criteria (Fig. S6). Total suitable area and amount of GI installed for rain barrels (Sce1), rain gardens (Sce2), detention basins (Sce3), and porous pavement (Sce4) scenarios in the study area can be found in Fu et al., 2019. The open space scenario (Sce5) used the same locations and half the surface area as detention basins (Sce3; i.e., open space is installed instead of detention basins) in Fu et al., 2019.

Fuzzy membership matrix and weights are combined to conduct the index of GI performance in urban resilience (Fig. 4). The open space scenario (Sce5) has the highest overall score in building urban resilience capacity (GIURI = 4.2675). The rain garden scenario (Sce2) ranks second (GIURI = 2.5395). The remaining three scenarios, in decreasing order, are detention basin, porous pavement, and rain barrel scenarios.

3.4. Implication and further application

The urban resilience assessment for GI helps to understand the abstract and multi-dimensional nature of resilience in a social-ecological system (Cumming et al., 2005; Fu and Wang, 2018) and recognizes and explores essential factors for better preparedness for resilience (Burton 2014). Using FCE enables one to incorporate quantitative and qualitative indicators for building a comprehensive assessment that integrates environmental, economic, and social dimensions. GIUR-PSS framework imbeds the FCE method into a GIS-based planning support system to facilitate and evaluate different scenarios as a comparable index (i.e., GIURI) for building urban resilience capacity and presents the “optimal” scenario. Our methodology enables multiple types of data input to the feedback loop through scenario development, modeling or surveys, fuzzy algorithm, and decision-making. And it allows stakeholder input and testing of alternate scenarios that can reflect their preferences and interests to aid in decision making.

In the assessment process, a robust indicator system is developed firstly to represent benefits (positive direction) or costs (negative direction) contributing to urban resilience capacity. We address pathways to help readers to relate and track indicator’s effects (e.g., absorption, mitigation, or adaptation) and timing (e.g., before or during disturbance) in building urban resilience capacity. Our trials of simulating extreme scenarios provided additional values for grading standards of evaluation ranks for quantitative indicators, not just depending on existing values in the literature, and may return more accurate results (Sun and Xue, 2019). This method can be applied in different geographic areas using local data along with the assumptions and modeling methods used here for the quantitative indicators. Our valid responses received for 14 qualitative indicators compare favorably with the literature (e.g., Loh et al., 2017; Wang et al., 2017).

Creating a chart of membership distribution helps compare the results from converting the indicator’s original value (from modeling or experts’ selection) to fuzzy membership in the different evaluation ranks. For the open space scenario, there is more variation in the expert selections than the modeled results, probably because experts have individual opinions about the ranking an indicator should receive. Having many indicators with a high probability with higher evaluation ranks will result in higher values of GIURI in the defuzzification process. We used radar maps to compare how many indicators with the highest rankings were distributed in different dimensions. Defuzzification is an important process to create an index for scenario comparison. In our five scenarios tested, we show open space had the highest GIURI score indicating it is the best option for building urban resilience capacity. Our calculated results align with the opinion of our experts who thought open space contributes the most to different dimensions for urban resilience. The literature also supports the idea that community parks are popular infrastructure in building an adaptive and resilient urban area (e.g., Campbell et al., 2016; Flouri et al., 2014; Lin et al., 2013).

Our methodology uses a customizable GIUR-PSS and indicators that are readily available from the literature and can be applied to other locations for assessing environmental, economic, and social influence on urban resilience capacity from different types of GI. For example, scenarios could be developed for new or additional GI technologies or modified parameters (e.g., depth of detention basin), or climate change could be included by setting scenario assumptions that alter precipitation pattern or quantity. The availability of data will vary from place to place, but missing data can be modeled and the ability to include stakeholder participation can account for local conditions and preferences.

This study has some limitations to be addressed in future research. First, an indicator’s value is normalized by the fuzzy membership functions with standards of evaluation ranks or selection frequency from a survey. An indicator can have influence on building urban resilience capacity, but they are all positive rankings (e.g., from ‘very low’ to ‘very high’ are assigned 1 to 5)—negative rankings are not included in the FCE method. Second, to keep our demonstration simple, we assume each scenario installs a single type of GI on all suitable parcels in the study area. We do not simulate scenarios with less than 100% installation, or mixed use of GI types such as a scenario installing 50% rain barrels and 50% rain gardens on suitable parcels. It is possible to model processes for quantitative indicators and calculate GIURI values, but scoring qualitative indicators requires expert input for a specific type of GI and their relative rankings were not evaluated. For example, experts scored enhance aesthetics as 1 for rain barrels and 4 for rain gardens, but we did not seek input on adopting using 50% of each and using 4 or 2.5 (=1*0.5 + 4*0.5) as a final score. In addition, we examined only one component (i.e., GI) of an urban system and its contribution to urban resilience. Ideally, the urban system would be examined from a much more extensive perspective to include all components identified as vital to operation and function of the system. Perhaps future work could build on our methodology to include a more exhaustive framework. However, we consider our analysis of GI in building urban resilience to be a first step in understanding better how to assess these systems and make management decisions to build resilient urban areas.

4. Conclusion

In this study, we proposed a planning support system to assess GI performance for building urban resilience capacity. GIUR-PSS provides a framework and methodology to facilitate FCE by combining scenario generation, scenario modeling or scoring, fuzzy algorithm, and decision-making. It also provides a robust indicator system for assessing GI performance according to indicators used in urban resilience assessment. We linked potential pathways (absorption, mitigation, and adaptation) to each indicator as a reference for connecting each indicator to urban resilience. In order to overcome a lack of quantitative data, GIUR-PSS incorporates modeling and survey results to obtain an indicator’s value. To demonstrate and test GIUR-PSS, we developed five scenarios for Congress Run watershed. Our results indicate an open space scenario achieved the highest GIURI (4.2675). If one tracks changes in indicator’s pathways, fuzzy membership distribution, and dominated rank across scenarios and incorporates the concerns or priorities of the stakeholder community (e.g., improving air quality or creating more employment), GIUR-PSS can help decision makers select a preferred or optimal scenario. In our example, to implement the open space scenario would require reclaiming or purchasing vacant lots and creating forested land, detention basins, and useable open-space facilities (e.g., soccer fields or picnic areas). Because GIUR-PSS incorporates stakeholder preferences, decision makers can conduct ‘what-if’ analyses to compare scenarios to identify the optimal scenario.

It would be worthwhile to explore if the fuzzy algorithm can use negative evaluation ranks for quantitative indicators or negative scores for qualitative indicators. That would better capture negative influences on urban resilience capacity resulting from different types of GI. It is not clear if multiple types of GI would interact with each other, and if the final score would adopt the highest score among different types of GI. A better understanding of how different types of GI interact to build urban resilience capacity is needed. For example, what happens if one type of GI has a positive score for a specific indicator, but another type of GI has negative score for the same indicator from survey, do they offset one another? Clearly additional research is warranted.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

We thank A. Garmestani, X. Ma, and P. Jordan for helpful comments in earlier drafts of the manuscript. Part of this research was performed while X. Fu held a National Academies of Science, Engineering, and Medicine Postdoctoral Associateship at United States Environmental Protection Agency. Opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use. The authors declare no conflict of interest.

Appendix A. Indicator set

Table A1

Indicators for GI performance in urban resilience capacity with pathway and source.

Goal	Dimension	Code	Indicator	Polarity	Pathway			Source
					Absorption	Mitigation	Adaptation	
GI performance in urban resilience capacity	Environmental	En1	Runoff	−	*	*		Modeling
		En2	Improve water quality	+	*	*		Modeling
		En3	Increase groundwater recharge	+	*	*	*	Survey
		En4	Land use diversity	+	*		*	Modeling
		En5	Noise Reduction	+				Survey
		En6	Improve air quality	+	*			Survey
		En7	Decrease microclimate temperatures	+	*		*	Survey
		En8	Improve wildlife habitats	+	*		*	Survey
	Economic	Ec1	Green infrastructure construction cost	−		*		Modeling
		Ec2	Create green employment (GI maintenance)	+		*	*	Modeling
		Ec3	Decrease gray infrastructure cost (abating same amount runoff)	+		*		Modeling

Goal	Dimension	Code	Indicator	Polarity	Pathway			Source
					Absorption	Mitigation	Adaptation	
		Ec4	Increase property values	+	*			Survey
		Ec5	Increase city revenue	+	*			Survey
		Ec6	Increase local development (inducing tourism)	+	*		*	Survey
		So1	Increase recreational area	+		*		Modeling
		So2	Enhance aesthetics	+	*		*	Survey
		So3	Produce food or crops	+	*	*		Survey
		So4	Increase community interaction (social capital)	+			*	Survey
	Social	So5	Strengthen sense of place and culture	+			*	Survey
		So6	Increase human Health and wellbeing	+	*	*	*	Survey
		So7	Increase understanding of environment (education)	+			*	Survey

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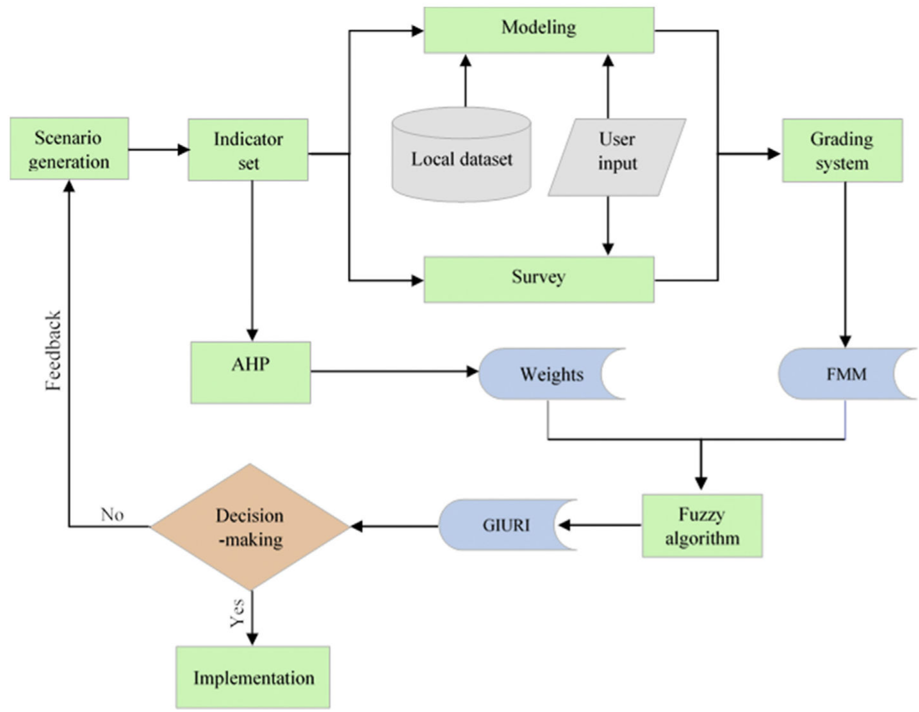

Fig. 1.

GIUR-PSS structure. AHP: Analytic Hierarchy Process; FMM: Fuzzy Membership Matrix; GIURI: GI performance in building Urban Resilience Index.

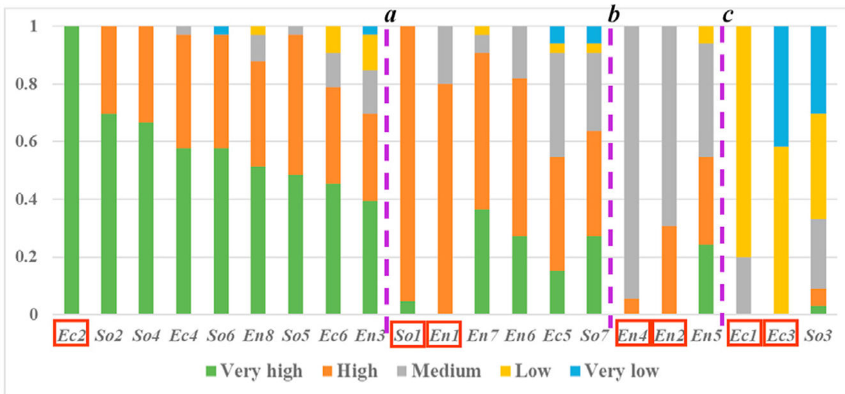

Fig. 2.

Fuzzy membership distribution for open space scenario (Sce5; vertical axis shows fuzzy membership degree; indicator labels with red rectangle are quantitative indicators; purple dashed lines show ranking standards' boundaries).

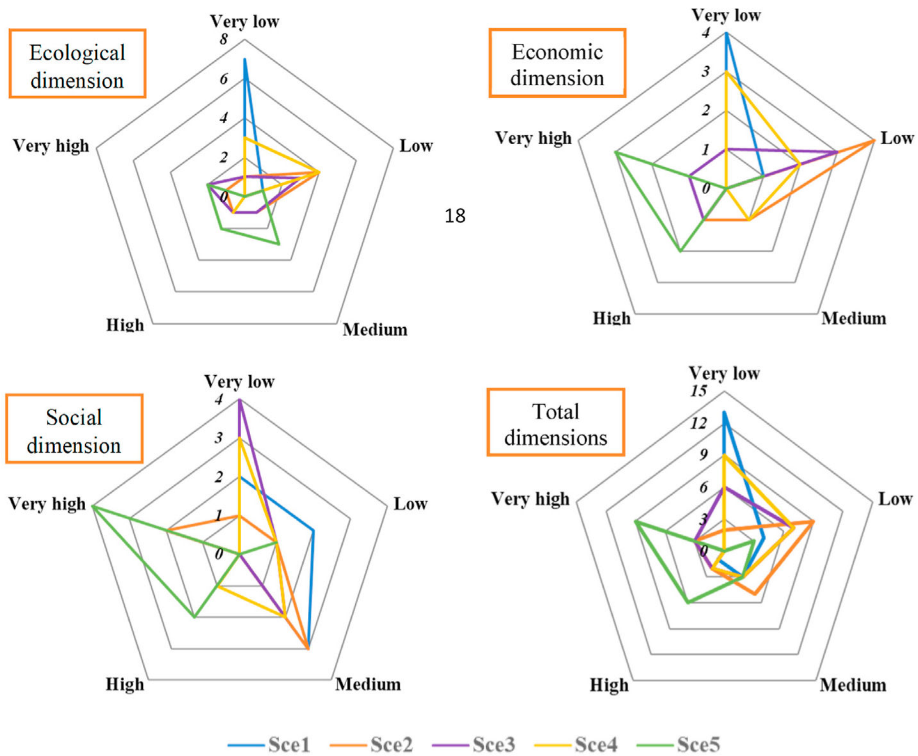

Fig. 3.

The number of indicator's and their evaluation ranking for single and total dimensions (i.e., addition of the three dimensions).

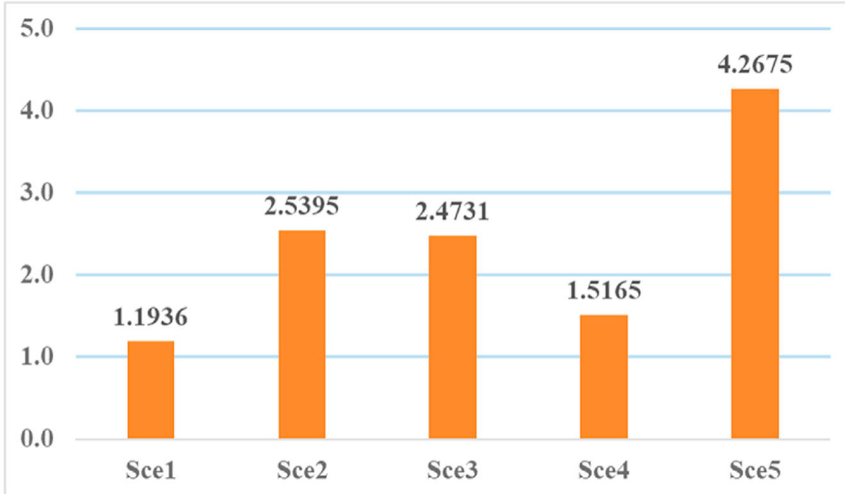

Fig. 4.

GI performance in urban resilience index for different scenarios (horizonal axis shows difference scenarios, vertical axis shows the GIURI).

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Table 1

Ranking standards for quantitative indicators (the code corresponds to the indicator in Table A1).

Dimension	Code	Indicator	Unit	Ranking standards				
				Very low	Low	Medium	High	Very high
Environ-mental	En1	Runoff	inch	1.42	1.32	1.26	1.13	1.03
	En2	Water quality improvement	kg	0	331	662	992	1323
	En4	Land use diversity	-	1	1.2	1.4	1.6	1.8
Economic	Ec1	Green infrastructure construction cost	$\$/m^3$	1295	1043	791	549	288
	Ec2	Creating green employment	hundred hours	0	46.79	93.57	140.35	187.13
	Ec3	Decreasing gray infrastructure cost (abating same amount of runoff)	million $	1.33	8.14	14.95	21.75	28.57
Social	So1	Increase recreational area	ac	0	81.89	163.77	245.68	327.57

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Table 2

GI design on suitable parcels.

GI	Drainage area (km^2)	Slope (%)	Hydrologic soil groups	Surface area (m^2) or capacity	Depth (m)	Construction cost ($\$/m^2$)	Maintenance cost ($\$/m^2$)
Rain barrel	–	–	–	0.76 m^3 (4 barrels per building)	–	218.84	0.00
Rain garden				impervious area * 20%	0.15	75.35	3.66
Shared detention basin	<0.080	<15	A, B, C, or D	Vacant lot area *80%	0.15	139.93	3.66
Porous pavement	<0.012	<15	A or B	Driveway area or paved parking area	–	76.42	0.39
Open space	<1 ac	<15	A, B, C, or D	Vacant lot area *50%	0.15		