Uncertainty Considerations in Green Infrastructure Optimization: A Review

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Abstract: Urban landscape planners and policymakers aim to find robust/optimal green infrastructure (GI) placement solutions that can perform well over a wide range of plausible futures and meet different objectives. While some studies on the spatial allocation of GI embraced multi-objective optimization to inform multi-functional GI placement decisions, many GI optimization studies are silent on potentially important questions raised by the deep uncertainties surrounding GI models, decision levers, and success metrics. This review paper provides an overview of this research gap, potentially relevant uncertainties for GI placement, and suggested research directions.

Keywords: Green infrastructure, decision making, uncertainty, optimization, spatial allocation

1 Introduction

Green infrastructure (GI) placement, a recurrent subject in urban landscape planning and design, is a complex task involving evaluating several functions and objectives of GI and uncertain factors that affect GI efficacy. EPA defines Green Infrastructure (GI) as "the range of measures that use plant or soil systems, permeable surfaces or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters" (US-EPA 2015). However, GI benefits aren't limited to water quantity and quality regulation, and it encompasses many other benefits including microclimate, biodiversity, and cultural benefits (LOVELL & TAYLOR 2013).

Climate change is projected to lead to increased frequency, intensity, and/or duration of extreme weather events in many places (REVI et al. 2014), driving unprecedented GI placement challenges for urban landscape planners and designers. Green infrastructure is considered an ecosystem-based climate adaptation approach as opposed to hard, engineering adaptation approaches such as grey infrastructure. Ecosystem-based climate adaptation approaches provide more "flexible, cost-effective and broadly applicable alternatives for buffering the impacts of climate change while overcoming many drawbacks of hard infrastructure." (JONES et al. 2012). There is a growing body of literature on the contributions of GI to flood control and resilience, suggesting the effectiveness of GI practices for mitigating urban flooding (FENNER et al. 2019, LENNON et al. 2014, MEI et al. 2018).

Climate change and other processes such as rapid urbanization, make the context for green infrastructure planning deeply uncertain. *Deep* uncertainty refers to a situation "where the system model and the input parameters to the system model are not known or widely agreed on by the stakeholders to the decision" (LEMPERT 2002). These uncertainties are also *dynamic* "because decisions often play out over a considerable length of time during which new research and observations have the potential to change the uncertainties" (KELLER et al. 2021). Within this context, decision-makers are concerned, more than ever, about robustness to un-

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certainties (HERMAN et al. 2015). *Robustness* broadly refers to "the insensitivity of system design to errors, random or otherwise, in the estimates of those parameters affecting design choice" (HERMAN et al. 2015). "A robust strategy is one that performs well, compared to the alternatives, over a wide range of plausible futures" (LEMPERT 2019). Robustness analysis can help to identify the deeply uncertain factors responsible for system vulnerabilities (HERMAN et al. 2015).

While some studies on the spatial allocation of GI embraced multi-objective optimization to inform multi-functional GI placement decisions, many studies are silent on potentially important questions raised by the deep uncertainties (ASHLEY et al. 2018, BARAH et al. 2021). These deep uncertainties surround the exogenous model inputs such as precipitation projections and model parameters (MERESA et al. 2021, SHARMA et al. 2021), the system models (FRENI et al. 2010, KNIGHTON et al. 2016), the considered and feasible decision-levers (ZEVENBERGEN et al. 2008, LEMPERT et al. 2013), as well as the considered and relevant metrics of success (EVERS et al. 2012, LEMPERT et al. 2013). Different choices on whether and how to represent deep uncertainties can drastically influence what analysts and decision-makers consider an optimal and/or robust strategy (ELLSBERG 1961, HUNG & HOBBS 2019, ZAREKARIZI et al. 2020). While this influence has been acknowledged, GI optimization studies rarely integrate uncertainty considerations into their research (GU et al. 2018). One hypothesis to explain this apparent gap is a lack of clear guidance and accessible tools to improve the characterization of uncertainties and their effects on GI planning (BARAH et al. 2021).

This review paper provides an overview of this research gap, potentially relevant uncertainties for GI placement, and suggested research directions. This paper especially focuses on GI decision support studies that address a formal optimization problem for spatial allocation of GI. Optimization allows for the efficient search of optimal green infrastructure placement when considering multiple possibly conflicting objectives of GI. The scope of this paper also doesn't allow us to expand the review by discussing studies that did not formulate an optimization problem but considered uncertainty in green infrastructure planning and assessment. Examples of these studies are FISCHBACH et al. (2020) which looked at the effect of deep rainfall uncertainty in GI policy evaluation, and HEIDARI et al. (2022) that studied several uncertain factors related to GI design and cost affecting the cost-benefit assessment of GI policies.

The review addresses two research questions:

1. How is uncertainty currently considered in GI optimization literature? What are the main research gaps?
2. What uncertainty sources and methods of uncertainty considerations are relevant to GI optimization?

2 Methods

The two questions are addressed through bibliometric (analytical) and full-text (narrative) literature analyses. The combination of the methods helps to answer the research questions in two different scales. The bibliometric analyses perform a science mapping exercise revealing the broader patterns in the literature. The full-text analysis allows for a more granular investigation of the literature.

The analytical part analyses the bibliometric information and abstracts of peer-reviewed publications to understand general trends and gaps in the uncertainty considerations in GI optimization literature. More specifically, we used two bibliometric and text mining R-packages, i. e., *bibliometrix* (ARIA & CUCCURULLO 2017) and *topicmodels* (GRÜN & HORNIK 2011), to analyze BibTex files from the Web of Science (WoS) platform. The *bibliometrix* package uses a systematic, transparent, and reproducible review process to synthesize literature findings, whereas *topicmodels* clusters the abstracts of the articles into groups.

The keywords for the two search inquiries in WoS were: 1) TS=optimi* AND "green infrastructure," 2) TS=uncertain* AND "green infrastructure." TS stands for the topic. When searching references (Dec 9, 2021) that have optimi* (e. g., optimize, optimise, optimization, etc.) and green infrastructure in their topic, the results included 260 papers from 2007 to 2022. The papers that had uncertain* (e. g., uncertain, uncertainty) and green infrastructure in their topic included 140 results from 2009 to 2022. Articles in both inquiries are growing over time. We acknowledge that the keyword "uncertainty" doesn't have an agreed-upon definition between different disciplines and it might not be the only term used in the literature, but we chose to focus on this term based on the definitions provided in the introduction.

We examined the keyword co-occurrence network generated by *bibliometrix* and topic clusters generated by both *bibliometrix* and *topicmodels*. The keyword co-occurrence network is based on the number of publications in which both keywords occur together in the title, abstract, or keyword list. Regarding the topic clusters, the Louvain method for community detection (BLONDEL et al. 2008) is used to create clusters among the nodes. The Fruchterman-Reingold layout is used to visualize the clusters (FRUCHTERMAN & REINGOLD 1991).

The narrative part includes a full-text review of articles. With two sets of search terms: 1) "green infrastructure" and "optimi*" and 2) "green infrastructure" and "uncertain*, we used Google Scholar, Scopus, and WoS to download relevant literature. After removing redundancies, we screened the abstracts based on two inclusion criteria: 1) to be relevant to a general definition of GI (e. g., those referring to agriculture as GI were omitted) and 2) to address a GI spatial allocation optimization problem. We included 45 papers that met both criteria.

For the full-text review of each article, we recorded the GI type, GI objective(s), uncertainty source(s), uncertainty quantification or characterization method, and optimization method. Next, because GI multi-objective optimization problems share many qualities of climate risk management problems, we used KELLER et al. (2021) categorization of methods relevant to climate risk decision analyses to visualize where the reviewed GI optimization studies are located in this spectrum. KELLER et al. (2021) categorized the methods based on: 1) how the objectives are considered by the analysis, i. e., from only a single objective to multiple objectives with considerations of robustness to uncertainty (y-axis) and 2) "different levels of epistemic uncertainty representation, ranging from none to deep and dynamic uncertainties." (x-axis) (KELLER et al. 2021).

3 Results and Discussion

The clustering of topics in GI optimization literature revealed by the bibliometric analysis shows that uncertainty is not a dominant keyword, especially in the non-stormwater-focused literature. Figure 1 shows the results of keyword co-occurrence network analysis and community detection for GI optimization literature. The results of topic clusters from both *bible-*

ometrix and *topicmodels* confirm a similar pattern (refer to the paper's GitHub repository for extended analyses). These analyses show the two main parts of green infrastructure optimization literature. The first part is the stormwater-focused literature which is represented in the two clusters at the top of Fig.1. The two top clusters' domains overlap mostly on water quantity and quality management. The second part is the non-stormwater-focused literature which is represented with the two clusters at the bottom with a focus on domains such as energy, microclimate, air pollution (bottom left) and biodiversity, conservation, restoration (bottom right). The two bottom clusters overlap in the thermal comfort domain. Uncertainty when appearing, tends to relate closely to the stormwater side of green infrastructure and optimization studies.

Fig. 1: Conceptual clustering of the analyzed GI optimization literature showing uncertainty as a marginal keyword closely related to stormwater GI. The domain-specific keywords are shown in black. Other keywords are in grey.

Out of 45 papers that addressed optimization of spatial allocation of green infrastructure, 19 considered some level of uncertainty. Most studies that considered uncertainty are focused on water quality, quantity, and cost objectives. Based on KELLER et al.'s (2021) categorization of climate risk decision analyses, many reviewed studies incorporated multiple objectives but little consideration of deep or deep/dynamic uncertainties (Fig. 2). The two papers (HUNG & HOBBS 2019, XU et al. 2019) that considered deep or deep/dynamic uncertainties only focused on a single objective. Additionally, robustness analysis is lacking in most GI optimization studies. Four out of 45 papers considered robustness (HUNG & HOBBS 2019, LIU et al. 2019, PISCOPO et al. 2021, XU et al. 2019). Two studies considered deep and dynamic uncertainties in the context of single objective function optimization, but both considered robustness which could not be captured in the visualization (HUNG & HOBBS 2019, XU et al. 2019).

When considering no uncertainty, five studies considered single objective optimization (HUANG et al. 2015, JAYASOORIYA et al. 2016, JIA et al. 2020, QIU et al. 2020, TORRES et al. 2021), 17 studies considered multiple objective optimization, and one study considered multi-objective with robustness (LIU et al. 2019). When considering shallow uncertainty, two studies considered single objective optimization (GU et al. 2018, KAZAK et al. 2018), 14 studies considered multiple objectives (DONG et al. 2021, ECKART et al. 2018, GALLO et al. 2020, GIACOMONI & JOSEPH 2017, JAYASOORIYA et al. 2018, LANZAS et al. 2019, LENG et al. 2021, LIU et al. 2016, LIU et al. 2017, LIU et al. 2021, RAEI et al. 2019, REINWALD et al. 2019, SINGH et al. 2019, ZENG et al. 2021), and one study considered multiple objectives with robustness (PISCOPO et al. 2021). There were no studies that considered deep uncertainties.

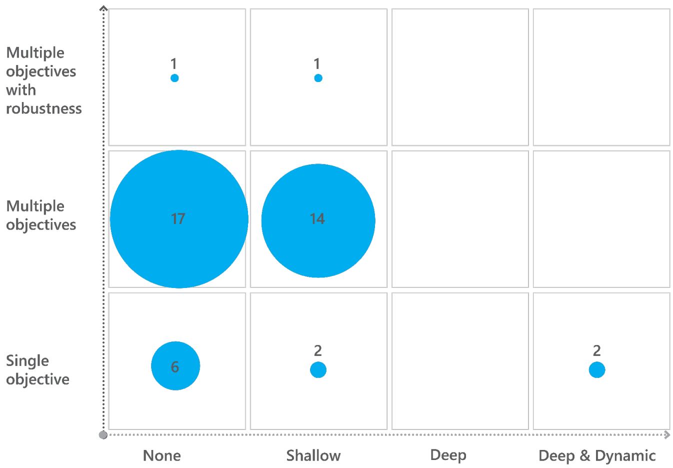

Fig. 2: Locating the reviewed studies based on their objective(s) (y-axis) and uncertainty consideration (x-axis) shows a major gap in investigating deep and dynamic uncertainties as well as robustness analysis. The numbers and size of the circles represent the number of studies in each combination of objectives and uncertainties considered.

The source of the uncertain parameters addressed in reviewed literature can be categorized into seven categories: 1) Hydrologic, 2) Hydraulic, 3) Water quality, 4) Cost, 5) Stakeholder preferences, 6) GI adoption and implementation, 7) GI design, and 8) Data resolution. Table 1 provides examples of parameters studied in each category. Rainfall uncertainty is the most frequent parameter studied. The second place belongs to land use/imperviousness parameters. The uncertain parameters listed here reflect the parameters related to the aforementioned objectives of water quality, quantity, and cost. The list could significantly expand if we consider uncertainty with a focus on other benefits such as enhancing thermal comfort and biodiversity.

Table 1: Uncertain sources and parameters considered in the reviewed articles

Uncertainty source category	Uncertain parameter(s)	# of articles	References
Hydrologic model parameters	Rainfall	13	(DONG et al. 2021, ECKART et al. 2018, GU et al. 2018, KAZAK et al. 2018, LIU et al. 2017, LIU et al. 2016, LENG et al. 2021, PISCOPO et al. 2021, RAEI et al. 2019, REINWALD et al. 2019, WANG et al. 2019, XU et al. 2019, ZENG et al. 2021)
	Land use (imperviousness)	6	(DONG et al. 2021, GIACOMONI & JOSEPH 2017, LIU et al. 2017, LIU et al. 2016, LENG et al. 2021, RAEI et al. 2019)
	Soil moisture	1	(KAZAK et al. 2018)
	Subcatchment features (area, width, slope)	2	(GIACOMONI & JOSEPH 2017, RAEI et al. 2019)
Hydraulic model parameters	Channel/pipe features (size, slope, Manning's roughness, etc.)	1	(GIACOMONI & JOSEPH 2017)
Water quality model parameters	BOD build-up and wash-off coefficients	1	(RAEI et al. 2019)
	TSS build-up and wash-off coefficients	1	(RAEI et al. 2019)
Cost	Installation cost	2	(GU et al. 2018, LIU et al. 2021)
	Operation and maintenance cost	2	(GU et al. 2018, LIU et al. 2021)
Stakeholder preferences	Weights of performance measures	2	(JAYASOORIYA et al. 2018, GALLO et al. 2020)
	Constraints for performance measures	1	(GALLO et al. 2020)
GI adoption/implementation	GI adoption rate	1	(ECKART et al. 2018)
	GI efficacy	1	(HUNG & HOBBS 2019)
GI design	GI design parameters (e. g., release coefficient, infiltration rate)	1	(GU et al. 2018)
Data resolution	Data resolution	1	(SINGH et al. 2019)

Uncertainty assessment can be in form of quantification or characterization or a combination of both. Uncertainty quantification describes "uncertainties using one or more probability distributions, while uncertainty characterization typically represents uncertainties through the use of scenarios that are designed to capture relevant ranges" (KELLER et al. 2021). Out of 19 of the papers that considered a level of uncertainty, eight took a quantification and 11 a characterization approach. The quantification methods included two-stage stochastic programming and Bayesian learning, Monte Carlo Simulations, fuzzy α-cut technique, and uncertainty linear optimization combined with chance constraint programming (CCP). Examples of parameters handled with uncertainty quantification were GI efficacy, rainfall, imperviousness, water quality coefficients, biophysical parameters, and stakeholders' preferences. A uniform probability distribution is assumed in most cases. The uncertainty characterization was used to evaluate the GI solutions in multiple but limited scenarios of the future. Examples of parameters handled with uncertainty characterization were rainfall, imperviousness, pipe/channel characteristics, biophysical parameters, and stakeholders' preferences.

The results of the full-text analysis are limited by the number of reviewed papers which might not include all GI spatial allocation optimization literature. The scope of the paper also doesn't allow for discussion of the effect of specific green infrastructure models and optimization methods on uncertain factors considered.

4 Conclusion and Future Research Directions

We identify a considerable gap in uncertainty considerations in the analyzed GI optimization literature. Specifically, in this literature, 1) uncertainty is a marginal keyword and it is not embraced in non-stormwater-focused GI optimization (e. g., GI optimization focused on biodiversity and thermal comfort); 2) deep and dynamic uncertainty and robustness analysis are rarely considered; 3) uncertainty characterization is restricted to a limited number of scenarios and uncertainty quantification is mostly performed with the assumption of uniform distribution for many uncertain factors; 4) while rainfall and to some extent, land use uncertainties have been considered in GI spatial allocation optimization, the uncertainty in cost, GI design, and stakeholder values are less studied.

Based on the observed gaps, we identify four immediate areas of future research: 1) understanding how uncertainty considerations change recommendations in GI spatial allocation optimization problems; 2) developing frameworks for incorporating relevant uncertainty sources to the GI objectives considered; 3) understanding stakeholder values and how they affect the GI objectives and uncertainty analysis; 4) incorporating deep and dynamic uncertainties and adding robustness analysis to GI decision-making research through relevant approaches such as Many Objective Robust Decision Making that combines many objective evolutionary optimization, robust decision making (RDM), and interactive visual analytics (HADKA et al. 2015, KASPRZYK et al. 2013).

The contributions of this review are twofold. This paper provides an overview of uncertainty considerations in GI optimization and informs future research questions in this less explored area. Beyond green infrastructure planning, this review highlights the importance of uncertainty considerations in urban landscape planning and design in a deeply uncertain world. As urban landscape planners and researchers aim to actively contribute to climate change adaptation solutions, the need for integration of robustness analysis to urban landscape planning and design process is more paramount than ever.

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Data and Code Availability

The data, code for bibliometric analysis and additional tables (list of all 45 papers and an extended table of review) are available at:
https://github.com/NastaranT/uncertainty_in_GI_optimization_literature_review.

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