Which parameter really drives green infrastructure performance? a sensitivity-based guide for robust modeling under climate extremes

Quels paramètres déterminent la performance des infrastructures vertes ? Un guide de modélisation robuste fondé sur l'analyse de sensibilité sous extrêmes climatiques

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RÉSUMÉ

Les infrastructures vertes (GI) sont de plus en plus mises en avant comme une approche flexible pour atténuer les inondations urbaines et améliorer la qualité de l'eau, cependant leur conception et leur évaluation reposent souvent sur des choix de paramètres très simplifiés ou hétérogènes. Cette étude développe un cadre intégré qui combine la paramétrisation, l'analyse de sensibilité, l'évaluation de l'incertitude et l'analyse coût-efficacité afin de fournir une base plus transparente pour la planification des GI dans les villes disposant de données limitées. Une base de données issue de travaux publiés a été utilisée pour établir des plages de paramètres représentatives pour les bassins de bio-rétention, les toitures végétalisées et les chaussées perméables. L'analyse de Sobol montre que seuls quelques paramètres dominent les réponses hydrologiques et de qualité de l'eau, ce qui indique que le comportement du modèle est gouverné par un ensemble restreint de contrôles plutôt que par l'ensemble complet de l'espace paramétrique. Ces paramètres influents ont ensuite été propagés dans le modèle pour quantifier l'incertitude de performance à travers un ensemble de scénarios climatiques, produisant des distributions de résultats qui reflètent la variabilité inhérente aux systèmes de GI. L'évaluation coût-efficacité montre en outre que certaines configurations peuvent offrir des bénéfices hydrologiques stables au regard de leur coût sur le cycle de vie, même sous une intensification des pluies dans les scénarios futurs. Le cadre proposé offre ainsi une voie pratique pour évaluer les stratégies de GI dans les régions où les données observées sont limitées, et souligne la nécessité d'intégrer l'incertitude des paramètres lors de l'évaluation de la résilience pluviale à long terme. L'approche est généralisable et peut soutenir la conception d'interventions robustes et économiquement viables dans des environnements urbains en forte croissance.

ABSTRACT

Green infrastructure (GI) is increasingly promoted as a flexible approach for mitigating urban flooding and improving water quality, yet its design and evaluation often rely on highly simplified or inconsistent parameter choices. This study develops an integrated framework that combines parameterization, sensitivity analysis, uncertainty assessment, and cost-effectiveness evaluation to provide a more transparent basis for GI planning in data limited cities. A database derived from published studies was used to establish representative parameter ranges for bio-retention cells, green roofs, and permeable pavements. The Sobol analysis revealed that only a few parameters dominate hydrological and water quality responses, indicating that model behaviour is governed by a concentrated set of controls rather than the full parameter space. These influential parameters were then distributed through the model to quantify performance uncertainty across a set of climate scenarios, producing output distributions that reflect the variability inherent in GI systems. The cost-effectiveness assessment further shows that some configurations can offer stable hydrological benefits relative to their life cycle cost, even when rainfall intensifies under future scenarios. The framework therefore provides a practical path for evaluating GI strategies in regions where observed data are limited, and it highlights the need to incorporate parameter uncertainty when assessing long-term stormwater resilience. The approach is generalizable and can support the design of robust and economically viable interventions in rapidly growing urban environments.

KEYWORDS

Green infrastructure, Urban stormwater modelling, Sobol sensitivity analysis, Cost-effectiveness analysis, SWMM

1.INTRODUCTION

Urban areas are facing growing pressure to manage stormwater under increasingly extreme rainfall conditions (Güneralp et al., 2015). Traditional grey drainage systems often struggle with short-duration, high-intensity storms, prompting growing interest in green infrastructure (GI) such as bioretention cells (BRC), permeable pavements (PP), and green roofs (GR) (Green et al., 2021). Even when decentralized storage and infiltration are included, modelled performance remains highly sensitive to the parameterization of hydrological and soil processes (Johannessen et al., 2019). Many studies rely on default values from manuals or experimental reports, yet these values may not reflect the climatic and hydro-environmental characteristics of a specific site (Kumar et al., 2022, Yang et al., 2015). As a result, parameter uncertainty becomes a major barrier to accurately assessing GI performance and long-term cost-effectiveness under future climate conditions.

To address these challenges, this study examines three interrelated questions. The first is to clarify realistic parameter ranges for commonly used GI by synthesizing existing work and assembling a more representative parameter dataset. The second examines which parameters most strongly influence hydrological and water-quality outcomes and whether these sensitivities change under different rainfall conditions. The third assesses the effects of climate change on the performance and cost-effectiveness of alternative GI layouts and explores ways investment decisions could be optimized under future rainfall conditions.

These topics were originally explored in detail in our published journal article (Liu et al., 2025). In this paper, we focus on presenting the core methodological elements and several key insights that are most relevant to practical planning and engineering applications. This research contributes practical guidance for data-scarce urban regions, where GI design must balance hydrological performance with economic feasibility. By identifying the most influential parameters and clarifying the distribution of uncertainty within design evaluations, the study provides a clear framework for allocating monitoring resources, selecting robust configurations, and supporting climate-adaptive planning.

2.METHODOLOGY

A structured modeling framework was developed to examine the influence of parameter uncertainty and climate variability on the performance and cost-effectiveness of GI in Phnom Penh City. The framework integrates parameterization, hydrological modeling, climate scenario generation, global sensitivity analysis, and uncertainty evaluation within a unified workflow.

First, parameter ranges for BRC, PP, and GR were compiled through an extensive literature review, resulting in a database of representative hydraulic and structural properties. These ranges provided the basis for defining realistic variability in infiltration capacity, media characteristics, depression storage, and surface conditions.

Second, these parameters were incorporated into a Personal Computer Storm Water Management Model (PCSWMM). Seven GI scenarios, including single and combined configurations, were then developed to evaluate alternative design strategies for the study area.

Third, rainfall inputs were constructed for 1-, 3-, and 10-year return periods using historical observations and projected intensity shifts under RCP4.5 and RCP8.5. The Chicago design storm method was applied to generate short-duration, high-intensity events that represent critical stress conditions for the drainage system.

Fourth, the modeling environment was automated using Python to support Sobol global sensitivity analysis. This analysis quantified the influence of each GI parameter on hydrological and environmental outputs, including the reduction rate of peak flow, runoff volume, and pollutant loads.

Finally, the interquartile ranges of the most sensitive parameters were used to construct uncertainty bounds for performance and cost-effectiveness evaluations. This step made it possible to assess the extent to which parameter variability reshapes expected hydrological outcomes and the economic competitiveness of different green-infrastructure configurations.

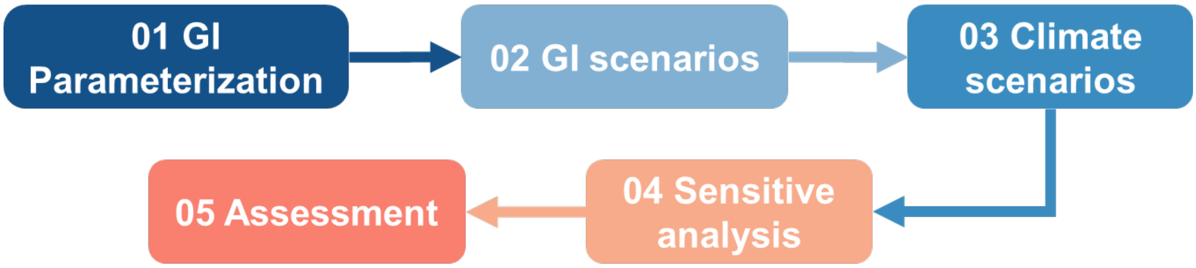

Figure 1 Research framework

3. REULTS AND DISCUSSION

3.1 Investigation on GI parameterization

The literature review incorporated 180 parameter sets and produced a consolidated parameter database covering BRC, PP, and GR across diverse climatic and design conditions. The compiled dataset revealed substantial variability in hydraulic conductivity, media porosity, storage depth, and surface roughness, with interquartile ranges often differing by an order of magnitude across studies. This broad variation confirms that default parameter values from manuals cannot fully represent local hydro-environmental conditions. The synthesized ranges therefore provided a solid basis for defining realistic parameter uncertainty for the subsequent modeling and scenario analyses.

3.2 Which parameters influence GI performance the most?

Sobol global sensitivity analysis identified a small subset of parameters that dominated model outputs. Among all types of GI, deployment area, initial soil moisture, and saturated hydraulic conductivity emerged as the three most influential parameters governing system performance. These parameters accounted for more than 65% of the total variance in the model outputs. This result suggests that these parameters should be specified with sufficient accuracy during both design and simulation stages to support reliable performance prediction.

3.3 Quantifying uncertainty in GI performance

After identifying the key sensitive parameters, the analysis examined the influence of their variability on the reliability of GI performance. Non-sensitive parameters were fixed at representative values, while sensitive parameters were allowed to vary within their interquartile ranges. This sampling strategy generated a broad set of simulations that reflect a realistic envelope of possible outcomes rather than a single deterministic estimate.

The results showed that performance variability increased notably when parameter uncertainty was propagated through the model. The reduction rate of runoff volume, peak flow, and pollutant loads exhibited substantial spread across simulations, indicating that system behavior is highly dependent on a small number of influential parameters. The magnitude of variability also increased with storm intensity, suggesting reduced reliability of performance estimates under more extreme rainfall conditions. Combined GI configurations generally produced narrower ranges of outcomes compared to single systems, highlighting their potential to deliver more stable performance under uncertain conditions.

These findings demonstrate the necessity of integrating parameter uncertainty into GI assessments, as neglecting variability can lead to overconfident expectations and suboptimal planning decisions, especially under future climate scenarios.

3.4 Cost-benefit tradeoffs revealed under parameter variability

Cost-effectiveness analysis revealed marked differences in performance under parameter variability. Although combined GI scenarios generally achieved higher hydrological benefits, their cost–benefit ratios varied significantly once uncertainty was incorporated. For some parameter combinations, lower-cost single systems overlapped in performance with more expensive hybrid configurations, indicating that uncertainty can shift the relative ranking of GI options. The marginal benefit curves showed clear diminishing returns at higher investment levels. Accounting for parameter uncertainty is therefore essential for identifying economically robust GI strategies.

4. CONCLUSION

This paper summarizes the key methodological elements and insights from our published journal article (Liu et al., 2025), with a focus on the practical implications for urban drainage planning. The integrated framework to quantify the parameterization, sensitivity, uncertainty, and cost-effectiveness of GI under varying climate conditions in a data limited urban environment. The results demonstrate that a transparent and transferable parameterization process provides a solid basis for reproducible GI modeling. The Sobol analysis revealed that a small subset of parameters governs most hydrological and pollutant removal responses, suggesting that calibration can be streamlined by prioritizing the variables with the strongest influence. Once these sensitive parameters were used to generate the model ensemble, the resulting output distributions showed that GI performance is not a single deterministic value but spans a broad range that reflects the underlying variability of the system. This variability carries practical implications, since GI types with narrow uncertainty bands offer more predictable performance across multiple rainfall scenarios.

The cost-effectiveness analysis further indicates that combined GI configurations generally perform better and more consistently than single-type designs, although their feasibility still depends on available budgets. These findings provide a more evidence based foundation for selecting GI combinations that remain robust under parameter uncertainty and shifting rainfall intensities. For rapidly developing cities with limited-data availability, the framework also offers a tractable path for integrating parameter variability into planning decisions without greatly increasing modeling complexity.

Overall, the framework strengthens the methodological foundation for GI performance assessment in data-scarce regions and provides practical guidance for system planning by demonstrating that locally calibrated GI combinations can enhance design, investment, and long-term resilience decisions under diverse hydrological and budgetary conditions.

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