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Research article

Integrated hydro-environmental impact assessment and alternative selection of low impact development practices in small urban catchments

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ABSTRACT

Attention is increasingly being paid to low impact development (LID) practices in urban stormwater management. Because LID practices offer a wide variety of hydro-environmental benefits, it is often necessary to account for these benefits collectively in cost-benefit analysis and LID alternative selection. The conventional methods of quantifying these benefits, however, can hardly incorporate the preferences of decision makers, and commonly involve tedious parameter estimations. To address these shortcomings, this study adopts a relative performance evaluation method to assess the various hydro-environmental impacts of LID alternatives in small urban catchments. This study considers several categories of hydro-environmental impacts, including water balance impact, surface pollutant load abatement, and combined sewer overflow and flood risk mitigation. Several performance indicators are used for each impact category. The system-wide effectiveness of an LID alternative is then derived by the weighted aggregation of its indicator scores, which are obtained by comparing its performance with that of all of the other alternatives. The hydro-environmental impact of green roofs and bioretention cells of varying areas in New York City, U.S. are investigated in detail. The results suggest that a green roof that covers the whole catchment is as effective as a bioretention cell that covers 3%–5% of the catchment in terms of stormwater management, and that the effectiveness of a bioretention cell doubles when its surface area increases from 2% to 10% of the catchment area. These assessment results are influenced by catchment-specific assessment criteria (e.g., the high flow threshold) and management interests, which suggests that design guidelines for different catchments should be tailored to their natural and drainage characteristics. The framework used in this study allows stakeholders' interests to be reflected in LID alternative selections and the implications of different design guidelines to be thoroughly investigated.

1. Introduction

Low impact development (LID) practices (also known as sustainable drainage systems and green infrastructure, among other terms) are decentralized semi-natural hydrological controls and connections that aim to restore the pre-development hydrologic regimes (Dietz, 2007; Ahiablame et al., 2012). In urban stormwater management, LID practices have been found to be effective in mitigating flood risk (Qin et al., 2013; Chui et al., 2016), replenishing groundwater (Trinh and Chui, 2013), and reducing surface pollutant loads (Dietz and Clausen, 2008; Lucke and Nichols, 2015). They also provide other environmental benefits, such as mitigating the urban heat island effect (Takebayashi and Moriyama, 2007) and promoting the health of ecosystems and human (Tzoulas et al., 2007).

LID practices are often implemented as retrofits to existing drainage systems to manage the quality and quantity of stormwater runoff (Goncalves et al., 2018). However, unlike conventional stormwater drainage infrastructure (such as drainage pipes and storage units), LID practices are able to provide multiple hydro-environmental benefits in various impact categories (Jose et al., 2015; Jaffe, 2010). These benefits are often characterized using a range of performance indicators; for instance, the effectiveness of flood risk mitigation can be assessed by reductions in the peak flow rate, and performance in restoring pre-development hydrology can be characterized by changes in the long-term surface runoff volume (Koop and van Leeuwen, 2015).

Naturally, integrated assessments that involve multiple performance indicators are necessary to take account of the multiple hydro-environmental benefits provided by LID practices. For example, runoff ratio and flashiness indicators are used in Bell et al. (2016) to examine the changes in hydrological responses due to stormwater control measures, and peak discharge rate and runoff volume are used in Petrucci et al. (2013) to investigate the hydrological impact of different stormwater management policies. Although individual indicators can provide meaningful information on hydro-environmental impacts, their values

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often need to be aggregated into a single performance score (e.g., a monetary value) for cost-benefit analysis and comparison and selection of alternatives (Gogate et al., 2017).

The most commonly used techniques for deriving integrated performance scores can be categorized into two groups: independent evaluation methods and relative performance evaluation (RPE) methods. In independent evaluation methods, all of the hydro-environmental benefits being considered are first quantified using a common unit (such as monetary value or equivalent), and an integrated score is then obtained by aggregating these values (Foster et al., 2011; Wise et al., 2010). The performance of an alternative solution can be evaluated independently without taking account of the performance of other alternatives. In RPE methods, the relative performance scores of an alternative are derived by comparing its performance with that of all other alternatives (Kouvelis and Yu, 2013).

The commonly used independent evaluation methods, however, present some difficulties in practice. First, it can be difficult to convert intangible hydro-environmental benefits to monetary values (or equivalent) where subjective evaluations and expert judgments are involved (Vandermeulen et al., 2011; Wild et al., 2017). This problem becomes more obvious when the performance indicators are associated with each other (Burkhard et al., 2012), e.g., when both the volume and the duration of combined sewer overflows (CSO) are of interest and each has its own performance indicator. As these correlated performance indicators are often used to characterize different facets of the same entity, double counting can easily occur (Burkhard et al., 2012). Second, almost all of the required parameters are determined based on their physical meanings (e.g., the market value) in the modeling phase, and the evaluation results are then given to the decision makers. This means that the management interests of the decision makers are not reflected in the assessment results unless they are explicitly valued in the modeling phase (Londono Cadavid and Ando, 2013).

In RPE methods, the hydro-environmental benefits of an alternative are evaluated by its relative effectiveness compared to other alternatives. This procedure does not require converting the various environmental impacts into a common unit. The relative performance scores are dimensionless quantities, allowing different weights to be assigned to them to reflect the preference of the decision makers or the scores' relative importance (Kamali et al., 2018). As the weights do not carry physical meanings, the weight associated with a specific entity can be divided into multiple smaller weights. The smaller weights can then be assigned to the relevant performance indicators according to their relative importance to that entity. In recent years, RPE methods have received increasing attention in the stormwater management field. For example, Casal-Campos et al. (2015) used an RPE method (i.e., the regret-based approach) to evaluate the robustness of various city-scale stormwater management strategies (such as the do-nothing alternative and the rooftop disconnection alternative) in eight impact categories (e.g., river flood risk, costs, and acceptability). The regret scores of each alternative are obtained by evaluating the performance deficiency compared to the best-performing alternative. These scores can be interpreted as the opportunity missed (e.g., Ellis et al., 2006). Jayasooriya et al. (2016) used an RPE method to evaluate the effectiveness of the candidate solutions of an optimization problem because it can effectively convert different performance measurements into a single comparable unit without tedious parameter estimations.

The RPE methods provide an effective way to collectively account for multiple hydro-environmental benefits and incorporate the preferences of decision makers; however, there have been few applications in LID-related studies. This could be due to the absence of an established framework that combines integrated hydro-environmental assessments with RPE methods, and the limited number of studies that investigate the implications of adopting RPE method in the context of decision making and alternative selection. This study therefore proposes a framework that uses RPE methods to aggregate the results from the integrated hydro-environmental assessment of LID practices. Some modifications have been made to conventional RPE methods to more effectively account for multiple performance indicators and to involve decision makers. For example, a two-level structure is presented in which multiple performance indicators are used for each impact category and different weights can be independently assigned to the indicators and the impact categories.

This study also aims to investigate the implications of adopting RPE methods in integrated performance assessment and alternative selection, including the effects of decision makers' preferences on the assessment results. Some common issues in performance assessment that deserve the attention of modelers and decision makers are highlighted, such as the uncertainties introduced by ambiguities in the definitions of performance indicators (e.g., the threshold of high flows) and by the assumptions used in the hydrological models.

A case study in New York City, U.S. is presented as an application example, in which the hydro-environmental benefits of bioretention cells (BCs) with varying areas and a green roof (GR) are evaluated and compared. Several impact categories are considered, including water balance impact, surface pollutant load abatement, and CSO and flood risk mitigation. Multiple performance indicators are used in each category. Finally, the effectiveness scores of the LID alternatives are derived by taking into account the hydro-environmental performance and the weights assigned to each performance indicator.

2. Methods

The proposed framework uses a hydrological model to simulate the long-term hydro-environmental performance of various LID alternatives and uses an RPE method to assess the system-wide effectiveness of these alternatives.

2.1. SWMM modeling

The Storm Water Management Model (SWMM; Rossman, 2015) is used for hydrological simulation in this study. SWMM has widespread applications in urban stormwater management and is currently used as the computation engine in several established LID design tools, including the National Storm Water Calculator (SWC; EPA, 2015a) and the California Phase II LID Sizing Tool (California State University Sacramento Office of Water Programs, 2016).

The key hydrological processes in both subcatchments and LID practices can be simulated by SWMM. LID practices in SWMM are represented as combinations of different horizontal layers. The water level in each layer of the LID practices at each computational time step is updated by solving water balance equations. The model representations of the considered alternatives and the key hydrological processes are shown in Fig. 1. Detailed hydrological simulation methods and computation steps were described in Rossman and Huber (2016). The SWMM toolbox in the R programming language developed in Yang and Chui (2018) was extended in this study for data analysis. The source code of this toolbox is freely available upon request from the authors.

This study adopts a continuous simulation strategy such that the initial water content in the LID practices before each storm event can be effectively modeled. In previous studies, such as that by Lucas and Sample (2015), the hydro-environmental impacts are assessed using the climatic condition in several representative years, i.e., the “design year”. Similarly, in the proposed method, the long-term time series is first split into multiple annual time series, and hydrological simulation and analysis are then performed using each annual time series. The long-term mean performance, as well as the annual performance variations can be derived using this assessment method.

In some cases, independent storm events must be identified from the continuous time series, such as when calculating the runoff volume reduction for each storm event. Two storm events are considered to be independent if they are separated by a dry spell that is equal to or longer than a certain time threshold, i.e., the inter-event time definition