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Marginal-cost-based greedy strategy (MCGS): Fast and reliable optimization of low impact development (LID) layout

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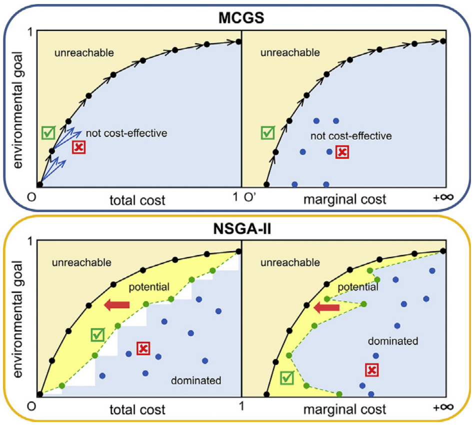
HIGHLIGHTS

- A fast and reliable method, MCGS, is developed for LID layout optimization.
- MCGS is based on the law of increasing marginal costs and rational choice theory.
- Three case studies with different settings prove broad applicability of MCGS.
- MCGS is superior to NSGA-II in five prominent advantages.
- MCGS addresses concerns of multi-stage LID layout planning.

GRAPHICAL ABSTRACT



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ABSTRACT

Cost effectiveness is a major concern when implementing low impact development (LID) practices for urban stormwater management (USWM). To optimize LID layout, an efficient and more reliable method, namely, the Marginal-Cost-based Greedy Strategy (MCGS) was developed based on the economic law of increasing marginal costs (MCs) and the stepwise minimization of MCs. To verify its broad applicability, MCGS was applied in three case studies in China with different system settings and environmental goals. Both Cases I and II were watershed-scale studies in Suzhou City urban districts, but in Case II, the impact of future uncertainties (i.e., climate change, urban expansion, and LID performance degradation) on USWM system performance was considered. Case III was a block-scale study of the Xixian New District (a pilot "Sponge City" in China), which involved a rainwater pipe network and a complicated environmental goal. Compared with the extensively used but complicated NSGA-II, the MCGS performed better in terms of yielding more converged performance trade-offs, providing more choices for city planners, and requiring much less computational resources in all three cases. Meanwhile, MCGS established an optimal pathway for multi-stage LID layout planning. The success of MCGS indicated that the MC of a LID practice determined its favorability in an USWM system.

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1. Introduction

Recent decades witness a rapid urbanization worldwide. In China, for example, its urban population has grown to 52.4% in 2015 from 42.5% in 2005, and the build-up areas have increased by 17,252 km^2 over the past decade (Jia et al., 2017). Rapid urbanization has caused severe a “city syndrome,” including urban flooding, non-point source (NPS) pollution, water shortage, and landscape and ecological degradation, which is threatening public health (Larsen et al., 2016; Versini et al., 2018). This situation is worsening with continuing population growth and economic development, rapidly growing impervious ratios in urban areas, frequent occurrence of extreme weather conditions, and an increased resident demand for amenity and access to urban landscape (Ferguson et al., 2013; Urich and Rauch, 2014; He et al., 2015; Wang et al., 2017). Therefore, urban stormwater management (USWM) has become a significant action item for city planners and government leaders.

The worldwide recognized concept of low impact development (LID), i.e., decentralized measures (e.g., green roof, porous pavement, and bioretention), which treat in-situ stormwater runoff along the flow path (Prince George's County, 1999; USEPA, 2008), are proven effective and environmentally friendly for USWM (e.g., urban flooding control, peak flow reduction, NPS pollution removal, and rainwater utilization) (Clausen and Bedan, 2009; Fletcher et al., 2014; Askarizadeh et al. 2015; Liu et al., 2015a). LID practices also provide multi-functional (e.g., environmental, ecological, and socio-economic) services and strengthen urban resilience to deal with the uncertainties of future developments (Marlow et al., 2013; Meerow and Newell, 2017; Wang et al., 2018). Inspired by this eco-environmentally sound concept, a national program, namely, “Sponge Cities” has been initiated in China since 2013, targeting at solving or alleviating the “city syndrome” (Gaines, 2016). Annually, this program is devoting an enormous amount of resources to pilot cities for LID practice planning/implementation for stormwater runoff control, as an indispensable component to the grey infrastructure that has typically been used in USWM (Jia et al., 2017). How to select proper LID practices, determine their suitable size, and place them in right locations are essential when drafting LID layout schemes within the constraint of the given investment. The officials and the public are all concerned about getting a positive multi-functional return, especially for the environmental aspects. A balance between competing environmental and economic concerns is urgently required (Xu et al., 2017). Previous studies (Bark et al. 2015; Cano and Barkdoll 2017; Liu et al., 2016a) have indicated that a multi-objective LID layout optimization can address these concerns.

Multi-objective evolution algorithm (MOEA) is a powerful tool with general applicability for solving multi-objective problems (MOPs) with several contradictory objectives. Oraei Zare et al. (2012) and Xu et al. (2017) successfully achieved a trade-off between the environmental and economic indicators by coupling the Non-Sorting Genetic Algorithm (NSGA-II) with the Storm Water Management Model (SWMM). NSGA-II was also a built-in module in the System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN) (Shoemaker et al., 2009), which is useful for city planners to seek for a cost-effective planning scheme (Lee et al., 2012; Jia et al., 2015). However, its expensive computational cost and premature convergence are significant concerns, particularly when the system complexity increases dramatically, such as when multiple sites and LID practices need to be considered in a large planning area (Liu et al., 2016a) or when future uncertainties, such as climate change and urban development, need to be considered (Urich and Rauch, 2014; Liu et al., 2016b). To address “the curse of dimensionality” of decision variables, Liu et al. (2016a) applied a dynamic planning strategy, that is, multi-level spatial optimization to conduct LID layout optimization in a watershed-scale area. However, this strategy largely relies on the hypothesis of independent hydrologic response units (HRUs) (Cibin and Chaubey 2015), which may not be true in many real cases. In addition, a MOEA is a “black-box” approach. The underlying mechanism of selection and placement of suitable LID practices is too complicated and unclear for city planners to understand (Cano and Barkdoll 2017) thereby lowering their confidence in the optimization results.

The above shortcomings of MOEAs lead many researchers to turn to scenario analysis methods for an optimal USWM system design (Cano and Barkdoll 2017), especially for robust decision making under uncertain conditions (Urich and Rauch, 2014; Zischg et al., 2017). Compared to MOEAs, which are objective driven methods, scenario analysis methods are driven by a set of influencing factors. That is, each planning scenario is often designed on the basis of certain prerequisites. For example, Dong et al. (2017) designed three system configurations with green roofs, permeable pavement and storage tanks from the perspective of flooding, environmental and technical severity, and compared their resilience to future rainfall extremes and urban land use change. Similarly, Casal-Campos et al. (2015) studied more planning scenarios by integrating a regret-based approach. However, the reliability of the scenario analysis results is highly dependent on the quality of scenario assumption (Urich and Rauch, 2014; Zischg et al., 2017). Moreover, scenario analysis methods give up seeking the most cost-effective planning schemes and often result in solutions far from Pareto optimality (Roach et al., 2016; Xu et al., 2017) because identifying the performance of many potential scenarios through exhaustive attack is impossible (Liu et al., 2016a).

Moreover, LID layout planning within the entire planning area to achieve a given control target is a gradual (i.e., with several stage goals) rather than a single-stage process (Zischg et al., 2017). However, many of the aforementioned studies (Oraei Zare et al., 2012; Casal-Campos et al. 2015; Liu et al., 2016a; Cano and Barkdoll 2017; Dong et al., 2017; Xu et al., 2017) just drew a final-stage blueprint and did not point out the pathway to realization. Besides, when the control target becomes stricter (e.g., increase NPS pollution removal rate from 50% to 70%) in the future, the traditional MOEAs or scenario analysis methods do not have a proper answer where to place additional LID practices to achieve the new control target, based on the previously implemented LID layout, which may have lock-in effects (Haasnoot et al., 2013). In summary, the performance deficits during LID implementation cannot be disregarded and Pareto optimality should be guaranteed always (Creaco et al. 2013). That is, an optimal pathway of multi-stage planning should be established by solving the LID layout optimization problem instead of just throwing out a single-stage static planning scheme.

Inspired by Liu et al. (2016a) and Mao et al. (2017) who pointed out that cost effectiveness (i.e., average cost per unit control target achieved) determines the favorability of LID practice, this study proposes a new optimization method based on the economic law of increasing marginal costs (MCs) (Fisher, 1961) and rational choice theory (Blume and Easley 2008), namely, Marginal-Cost-based Greedy Strategy (MCGS) for LID layout planning. This method takes the essence and discards the weaknesses of MOEAs and scenario analysis methods, and can generate a more reliable performance trade-off with markedly low computational costs. No peer-reviewed literature that applies a greedy strategy to plan an USWM system optimally has yet been found. Moreover, the MCGS process of generating the optimal planning schemes exactly blazes an optimal pathway of multi-stage LID layout planning.

MCGS is applied to the following three case studies in China to verify the above statements using the popular NSGA-II for comparison:

- Case I: independent HRUs and a simple objective;
- Case II: independent HRUs and a complicated objective;
- Case III: dependent HRUs and a complicated objective.

2. Material and methods

2.1. Definition of a MOP

Before introducing the development of MCGS, a general LID layout optimization problem is described, which comprises contradictory objective functions and decision variables.