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Research article

Optimizing surface and contributing areas of bioretention cells for stormwater runoff quality and quantity management

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ABSTRACT

Bioretention cells (BCs) have received increasing attention in stormwater quality and quantity management. Selecting a suitable implementation level of BCs to concurrently achieve multiple performance targets (e.g., first flush reduction, peak flow reduction, and runoff volume reduction) is essential and often challenging. This study proposes a method for formulating suitable sizing criteria for multi-objective stormwater management. The performance of BCs of different areas is assessed first using the Storm Water Management Model (SWMM) and then look-up curves (i.e., the performance target versus the required area of BCs) for each of the performance targets and the multi-objective cases are derived. In some cases, the available area of BCs is limited; to account for the multi-objective management interests and maximize the system-wide benefits, an optimal contributing drainage area for BCs should be selected. A method is therefore developed to solve this optimization problem. A case study of Hong Kong shows that the required area of BCs increases non-linearly with increased performance targets. With a limited area of BCs, larger contributing areas are favorable if no special emphasis is placed on the intensive control of peak flow reduction. Design standards (e.g., the intensity of the design storm), evaluation methods (e.g., depth threshold of the initial portion of runoff), and management preference all exert some influence on the resultant sizing criteria and optimization results. Carefully selecting these catchment-specific evaluation methods should lead to more appropriate sizing criteria and thus promote more efficient BC adoption.

1. Introduction

A bioretention system is defined as a landscape depression that consists of a surface ponding layer, vegetation, a soil layer, a storage layer, overflow structures, and an optional underdrain system (Liu et al., 2014). It is designed to capture stormwater runoff from external impervious catchments to reduce surface pollutant loads (Dietz and Clausen, 2008; McIntyre et al., 2016; Rycewicz-Borecki et al., 2017), runoff volumes (Liu and Fassman-Beck, 2017), and peak flow rates (Davis et al., 2009). Bioretention cells (BCs) are small-scale shallow depressions (Passeport et al., 2009) that are used to treat runoffs from small external contributing areas (e.g., catchments less than 2 ha). BCs are one type of commonly used low impact development (LID) practice (also known as sustainable drainage systems or green infrastructure) that aim to mimic natural hydrological processes by prompting depression storage, evapotranspiration, and infiltration (Dietz, 2007). Through decades of research and application, the effectiveness of BCs in stormwater management has generally been recognized, and the implementation of BCs is becoming more prevalent (Ahiablame et al., 2012). BCs can also provide other benefits (Demuzere et al., 2014), such as aesthetic enhancement (Liu et al., 2014) and ecological restoration (Houdeshel et al., 2012).

In urban stormwater management practices, in some countries (e.g., U.S., U.K.), LID guidelines, handbooks, and design codes covering the planning, design, construction, and maintenance of BCs are available (e.g., DoE Prince George's County, 2009; Ballard et al., 2007). In these guidelines, different sizing criteria are given mostly to account for the different purposes of BC adoption, e.g., surface pollutant and flood risk mitigation. BCs are commonly implemented with a primary focus on surface pollutant mitigation. In these cases, a BC is usually sized to have a void volume that stores a certain depth of runoff from the contributing drainage area (CDA) which includes the external catchment that drains to the BC and the area of BC. This required void volume is often termed water

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quantity volume (WQV) (Sage et al., 2015). By providing WQV, small and frequent runoff events can be eliminated (Winston et al., 2016), and the initial portion of large runoff events can be captured (Davis et al., 2009). The first flush effect (FFE) is a phenomenon where a higher concentration of pollutants exists in the initial portion of runoffs (Sansalone and Cristina, 2004). Therefore, intercepting the initial portion of surface runoff may lead to considerable reductions in pollutant loads. Baek et al. (2015) reported that FFE could be effectively mitigated by BCs with adequate storage volume. They also showed that the concentration of pollutants in the outflow of BC was highly sensitive to the size of the BC and thus that selecting an optimal surface area of BCs was necessary.

WQV may vary significantly in different catchments. Sage et al. (2015) showed that the target stormwater storage volumes (i.e., storage depth provided to the catchment) ranged from 2 to 43 mm in different catchments around the world. Generally, WQV should be determined according to catchment-specific management needs and required design levels. For example, larger WQVs are preferred for pollutant hotspots where intensive mitigation is required. However, the actual reduction volumes may differ from the designed WQV. For example, the Department of Environmental Protection of New York (NYC DEP, 2016) reported higher reduction volumes than the designed ones, likely due to the hydrological processes other than storage (e.g., evapotranspiration, exfiltration, and underdrain outflow) in BCs. The actual performance of BCs may also vary from event to event (Baek et al., 2015). Therefore, to better estimate the actual runoff reduction, either onsite monitoring or numerical modeling is required.

Although many BCs are designed to mitigate surface pollutant, their benefits in flood risk mitigation should not be ignored (Ahiablame and Shakya, 2016). For example, Hunt et al. (2008) demonstrated that BCs were effective at reducing peak flow rates in different storm events. Selecting suitable sizing criteria for BCs explicitly for flood risk mitigation is essential, yet the sizing criteria are defined in various ways in different catchments and therefore deserve additional study (Sage et al., 2015). Currently, both flow rate and volume-based regulations have been used to size BCs with the primary function of flood mitigation. Although flow rate regulations are directly linked with flood risk, there are difficulties in application. For example, it is hardly possible to design a BC to achieve a particular peak flow reduction for all storm events because the performance of BC decreases with large storms (Li et al., 2009). Strictly abiding by the flow rate regulations may result in significant oversizing, as sufficient storage volume must be provided for extremely large storms. Petrucci et al. (2013) further showed that flow-rate based regulations were generally less preferred, as BCs may not able to deliver the desired hydrologic outcomes at a catchment scale.

Using volume-based regulations for flood risk mitigation requires additional modeling or monitoring efforts, as the link between the implemented BC area (or provided storage volume) and resultant flood risk reduction is not immediately apparent. For example, in New York City, bioretention systems (e.g., right-of-way bioswales and on-site bioretentions) were implemented to mitigate flooding and reduce combined sewer overflow (CSO) (NYC DEP, 2016). Volume-based design criteria were used, in which bioretention systems were sized to capture the first inch (2.5 cm) of rainfall. Their effectiveness in sewer flooding and CSO control was then accessed through on-site monitoring and computer modeling.

Aside from mitigating the initial portion of runoff and flood risk, other benefits of BC in water balance restoration may be of management interest. For example, BCs can reduce the long-term runoff volume of the catchment (Liu et al., 2014) because of enhanced infiltration (Chui and Trinh, 2016) and evapotranspiration (Wadzuk et al., 2014). Minimizing the long-term runoff volume in a catchment with a combined drainage system reduces the workload of wastewater treatment plants and detention facilities. In a catchment with a separate drainage system, it reduces the impact on downstream water quality and quantity.

In practice, numerical models have frequently been applied to assess the performance of BCs in stormwater management and to investigate the effectiveness of different sizing criteria. Reviews of the commonly used models were provided in Elliott and Trowsdale (2007) and Liu et al. (2014). The choice of model generally depends on the scale and scope of the study and the requirements of the design guidelines. For example, SUSTAIN (Lee et al., 2012) is applicable for determining the optimal layout of BCs and other practices at a watershed scale for water quality management (Chen et al., 2014), and i-Tree Hydro (USDA Forest Service, 2016) is commonly used to assess the effects of BCs on the urban hydrological cycle. New models are constantly being developed for different applications. For example, Jia et al. (2016) proposed a simple water balance based hydrologic model to estimate the surface bypass volume of BCs during large storms. Gülbaz and Kazezyılmaz-Alhan (2017a) developed a hydrological model to match the experimental results and to explain the hydrological behavior of BCs. The United States Environmental Protection Agency (US EPA)'s Storm Water Management Model (SWMM) (Rossman, 2015), an open-source hydrologic/hydraulic model, has received wide attention and has been successfully adopted in various BC studies to simulate the hydrological performance of BCs (Gülbaz and Kazezyilmaz-Alhan, 2017b). As SWMM can simulate the hydrological processes of urban catchments, it can also be used to predict the peak flow and runoff volume of the catchments with BC adoptions (Rosa et al., 2015; Chui et al., 2016) and to study the annual water budget alterations caused by the implementation of BCs (Avellaneda et al., 2017). SWMM has also been used as the simulation engine for several practical BC design tools, including the National Storm Water Calculator (EPA, 2013) and the California Phase II LID Sizing Tool (California State University Sacramento Office of Water Programs, 2016).

As discussed previously, BCs can simultaneously provide multiple hydro-environmental benefits, such as water quality improvement, flood risk mitigation, and water balance restoration, and the current sizing criteria are commonly formulated to fulfill specific management targets. In cases where multiple hydro-environmental benefits are of interest, it is necessary to derive suitable sizing criteria to account for these management interests and to maximize the system-wide benefits provided by BCs (Chin, 2017). Additionally, under conditions of limited resources (e.g., only a certain area of BCs can be built due to economic or other constraints), the CDA of BCs that maximizes the system-wide benefits should be determined. Moreover, different evaluation methods may result in different evaluation results of BC performance and may consequently lead to different sizing criteria. For example, in evaluating the effectiveness of BCs in peak flow reduction, design storms of different intensities can be used, and the resultant peak flow reduction percentages can differ. Thus, the implications of using different evaluation methods in performance evaluation and sizing criteria formulation should be explicitly investigated.

Therefore, this study aims to answer the following questions.

1. How large is the area of BCs needed to meet different interests in stormwater management, including first flush control, peak flow, and runoff volume reduction?
2. How can suitable sizing criteria that simultaneously account for multiple management interests be formulated? How can CDA be