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Research article

Small scale green infrastructure design to meet different urban hydrological criteria

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ABSTRACT

As small scale green infrastructures, rain gardens have been widely advocated for urban stormwater management in the contemporary low impact development (LID) era. This paper presents a simple method that consists of hydrological models and the matching plots of nomographs to provide an informative and practical tool for rain garden sizing and hydrological evaluation. The proposed method considers design storms, infiltration rates and the runoff contribution area ratio of the rain garden, allowing users to size a rain garden for a specific site with hydrological reference and predict overflow of the rain garden under different storms. The nomographs provide a visual presentation on the sensitivity of different design parameters. Subsequent application of the proposed method to a case study conducted in a sub-humid region in China showed that, the method accurately predicted the design storms for the existing rain garden, the predicted overflows under large storm events were within 13–50% of the measured volumes. The results suggest that the nomographs approach is a practical tool for quick selection or assessment of design options that incorporate key hydrological parameters of rain gardens or other infiltration type green infrastructure. The graphic approach as displayed by the nomographs allow urban planners to demonstrate the hydrological effect of small scale green infrastructure and gain more support for promoting low impact development.

1. Introduction

The widespread impermeable land surfaces in the ever expanding urban landscape prevent the groundwater recharge from rainfall infiltration and have caused a series of environmental problems (Demuzere et al., 2014). Low impact development (LID) concepts has been widely advocated in recent years to mitigate the negative impact of urban development on stormwater runoff; various LID practices, including many small scale green infrastructures have been found effective in reducing stormwater runoff through in-situ retention and infiltration processes (Dietz, 2007; Balascio and Lucas, 2009; Valinski and Chandler, 2015). Rain gardens that reduce stormwater runoff through focused recharge to groundwater have been recognized as a functional small scale green infrastructure. The definition given by the USEPA states that 'A rain garden is a depressed area in the landscape that collects rain water from a roof, driveway or street and allows it to soak into the ground' (http://www2.epa.gov/soakuptherain/rain-gardens). Existing studies have shown that rain gardens are very effective in reducing peak flow rates and total volume of stormwater runoff via retaining and re-routing processes (Hunt et al., 2006; Davis, 2008; Ahiablame et al., 2013). Because their natural integration with the urban landscape, rain gardens hold special appeal to urban stormwater management, and have become a widely accepted LID practice (Davis et al., 2009, 2012; Roy-Poirier et al., 2010). Rain gardens are normally sized to retain a pre-defined volume of stormwater runoff that is either from the first flush or a design storm; additional runoff entering the rain garden is discharged into urban stormwater drainage systems via an overflow device (NCCES, 2008). As flow reduction devices, rain garden design should accommodate retention/storage capacity for design storms and the potential outflows under larger storms. With effective rain gardens, the conventional city stormwater drainage systems can be built with a reduced capacity and consequently the reduced cost (Burns et al., 2012).

The existing rain garden design guidelines lack of consistency in

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defining a few design parameters, such as the design storm and the infiltration during storms etc. As an engineering structure, the rain garden design storm may be defined as the storm that generates just enough runoff that can be fully retained in the rain garden. As the multiple functions of rain gardens get recognized in recent years, there have been suggestions to refining the design procedure to target specific storms (Lucas, 2010; Palhegyi, 2010; He and Davis, 2011). The design manuals in the U. S. generally state that rain gardens should target the first flush of storm, or the first inch (2.54 cm) of rainfall (USEPA, 1999; NCCES, 2008; WIDNR, 2010; MNPCA, 2007). The existing rain garden studies applied different methods of hydrological analysis. For example, Brown et al. (2013) and Hathaway et al. (2014) examined rain garden hydrological processes with the field hydrology model- DRAINMOD based on long-term daily rainfall record; while Christensen and Schmidt (2008) used historical rainfall records with different intensities in their rain garden study. To investigate hydrological effect of a roadside bioretention device, Kurtz (2008) applied two design storm concepts: one was a theoretical 6-hr storm for combined sewer system pipe sizing, and the other was an actual event from record for sizing tunnels for sewer overflow. From the perspective of practical design, the event based approach is generally consistent with the design procedure for urban storm drainage systems. For instance, many cities in China use storms of 3–5-yr recurrence interval for separate sewage and storm drainage system design (MOC, 2000). If rain gardens or similar small scale green infrastructures are designed with the same or similar approach as the city storm drainage system, their hydrological effect can be assessed more easily to make them an integrated part of the city drainage system. Unfortunately, such design concept has not been adopted in urban stormwater management.

For the same retention requirements, infiltration during a storm process will increase flow retention capacity in addition to the static storage space in a rain garden. The USEPA (1999) bioretention factsheet lists options for rain garden sizing; it states that a facility with sand bed requires less retention area, e.g., 5% of the contributing area with sand bed vs. 7% without. But the available design methods generally neglect infiltration in rain gardens during storm events; the retention space of a rain garden is sized for holding all runoff from the design storm. The soil infiltration parameter is only used for estimating the time required for draining a rain garden after a storm (MNPCA, 2007; WIDNR, 2010). The existing rain garden studies applied different methods while investigating the infiltration processes during storms, including the infiltration in unsaturated media (Brown et al., 2013; Hathaway et al., 2014; Liu et al., 2015) and the lateral exfiltration (Lucas, 2010; and He and Davis, 2011). Considering the complex process of the soil infiltration during storms, whether and how to include infiltration during a storm process should be determined according to its relative importance (or percentage) in the stormwater retention.

The lack of consistency in design procedure as discussed above may result in rain gardens designed or constructed on the basis of different hydrological criteria, making it difficult to assess rain garden performance or transfer valuable research findings from one site to another. Rain gardens are mostly community-based local stormwater treatment facilities that receive runoff from contributing areas of limited sizes. So it is feasible to develop a simple design or evaluation approach that includes basic design parameters as considered in more comprehensive rain garden studies. Because rain garden planning needs to consider different soil and geomorphologic conditions, as well as the hydrological relationships (Ahiablame et al., 2013), an intuitive graphic approach may be desirable to present the hydrological benefits of rain gardens to stakeholders in the planning stage (Bosch et al., 2012).

In order to develop a practical tool for planning green infrastructures to reduce the adverse impact of urban development, this paper presents a simple method for design or hydrological evaluation of rain gardens and other similar infiltration-type small scale green infrastructures. The method consists of analytical models and the matching nomographs in graphic forms. The proposed method was aimed for 1) sizing a rain garden to meet specified design criteria, 2) estimating overflow processes under large storms, and 3) evaluating hydrological performance of existing rain gardens.

2. Methods

2.1. *The case study site description and data collection*

A pilot scale rain garden was built on campus of the Xi'an University of Technology in Xi'an, China in spring 2011, and flow measurement was conducted between 2011 and 2013. As shown in Fig. 1, the garden has a surface area of 26.7 m^2 and storage depth of 15 cm; it receives runoff from a nearby laboratory roof that is about 605 m^2 in area. On-situ measurements showed that the groundwater table is generally below 3 m. Inflow and outflow/overflow of the rain garden was measured with pressure transducers mounted on V-notch weirs installed at the inlet and outlet of the rain garden (Tang, 2013). The city Xi'an is in central China (E107°40′~109°49′ and N33°39′~34°45′) with a temperate continental climate. The annual average temperature in Xi'an is 13 °C, the average annual rainfall is 551 mm and the average annual evaporation is 990 mm. More than 80% rainfall occurs in the months from May to October. The city is situated on widely distributed loess soil that generally has deep profile of more than 50 m. The soil bulk density of is generally 1.35 g/cm^3, composing of 9% clay, 80% silt, and 10% sand. The reported infiltration rate of the loess soil varies from 0.4 m/d to 2 m/d and higher. The low values are normally obtained in laboratory with disturbed soil samples, while the field measurements often yield much greater infiltration rates due to well developed soil structure. Over-pumping of groundwater in Xi'an has caused great depression of ground water table depth in the city range. Considering the moderate rainfall, deep soil profile and low water table, there is a great potential to treat stormwater runoff with rain gardens to encourage focused recharge in Xi'an.

2.2. *The rain garden hydrological model and the derived nomographs*

For a specific storm, a rain garden design aims to 1) determine the appropriate size of a rain garden to retain the design storm runoff, and 2) estimate the potential overflow volume produced by more intense storms. Suppose a candidate site has been located for rain garden construction, and the equivalent surface area ratio (s) has been determined with Eq. (1), the major design goal is to determine the rain garden depth for flow retention.

2.2.1. *Assumptions for the rain garden hydrological model*

For a typical rain garden as illustrated in Fig. 1, the inflow consists of storm runoff from the contributing area and the rainfall over the garden surface; outflow consists of infiltration in the garden and overflow from the garden during large storm events. To develop the hydrological model, we made the following assumptions:

1) A storm is represented by its intensity, duration, and frequency (IDF) relationship; the storm intensity is the average of its entire duration;