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Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement

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ABSTRACT

The impacts of urbanization on hydrology and water quality can be minimized with the use of low impact development (LID) practices in urban areas. This study assessed the performance of rain barrel/cistern and porous pavement as retrofitting technologies in two urbanized watersheds of 70 and 40 km^2 near Indianapolis, Indiana. Six scenarios consisting of the watershed existing condition, 25% and 50% implementation of rain barrel/cistern and porous pavement, and 25% rain barrel/cistern combined with 25% porous pavement were evaluated using a proposed LID modeling framework and the Long-Term Hydrologic Impact Assessment (L-THIA)–LID model. The model was calibrated for annual runoff from 1991 to 2000, and validated from 2001 to 2010 for the two watersheds. For the calibration period, R^2 and NSE values were greater than 0.60 and 0.50 for annual runoff and streamflow. Baseflow was not calibrated in this study. During the validation period, R^2 and NSE values were greater than 0.50 for runoff and streamflow, and 0.30 for baseflow in the two watersheds. The various application levels of barrel/cistern and porous pavement resulted in 2–12% reduction in runoff and pollutant loads for the two watersheds. Baseflow loads slightly increased with increase in baseflow by more than 1%. However, reduction in runoff led to reduction in total streamflow and associated pollutant loads by 1–9% in the watersheds. The results also indicate that the application of 50% rain barrel/cistern, 50% porous pavement and 25% rain barrel/cistern combined with 25% porous pavement are good retrofitting options in these watersheds. The L-THIA–LID model can be used to inform management and decision-making for implementation of LID practices at the watershed scale.

1. Introduction

Urbanization has important hydrologic and environmental implications (O'Driscoll et al., 2010; Gunn et al., 2012). Hydrologic impacts of urban expansion are generally reflected in increasing runoff rate and volume, decreasing soil-water that would normally support infiltration, decreasing groundwater recharge and baseflow, decreasing interception and evapotranspiration (Harbor, 1994; Moscrip and Montgomery, 1997; Tang et al., 2005), and degradation of water quality in both streams and shallow groundwater due to urban waste discharge, industrial discharge, leakage from waste disposal grounds, and nonpoint source pollutant losses (USEPA, 2000a, 2000b).

Adverse impacts of urbanization on watershed hydrology and water quality can be minimized by implementing water sensitive designs, sustainable drainage systems, or low impact development technologies (USEPA, 2000c; Lloyd, 2001; France, 2002; Scholz and Grabowiecki, 2007; Ahiablame et al., 2012a). Low impact development practices (LIDs) are micro-scale control practices used to bring the natural hydrology of a site close to that of its pre-development conditions (i.e., before development occurs) (Coffman, 2002; HUD, 2003). The implementation of LID practices is driven by four fundamental hydrologic considerations: control of runoff volume, control of peak runoff rate, control of flow frequency/duration, and control of water quality (PGCo, 1999a, 1999b). LID practices combine planning and design to restore initial abstraction (interception, infiltration, depression storage) lost during site development, thus preserving pre-development hydrology (PGCo, 1999a, 1999b).

LID practices have been utilized to mitigate hydrologic and water quality impacts of urbanization. For example, the Jordan Cove Urban Watershed Project in Waterford, Connecticut is a study, among

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others, which comparatively assessed the quality and quantity of residential stormwater runoff between a traditional watershed and a LID watershed (Bedan and Clausen, 2009). Results indicated that post-development runoff was reduced by 42% in the LID watershed and peak discharge was similar to that of pre-development conditions. In the present study, LID practices considered include rain barrels, cisterns, and porous pavements due to their potential implementation in existing urbanized areas. Harvesting rain water using large storage systems such as barrels or cisterns is not a new technology and practice. It can be traced back to ancient civilizations several thousand years ago in Europe, Middle East, Asia, Africa, and South America, where durable storage units and cisterns were used to collect water for agricultural, domestic (including drinking water and air conditioning), and touristic purposes (Roebuck, 2007; Leung, 2008). Research has shown that harvesting rain water with appropriate tank sizes, can be used to control stormwater runoff (Aad et al., 2010; Damodaram et al., 2010) and meet at least 50% of non-potable water demand for human uses such as WC flushing, garden irrigation, and washing machines (Roebuck, 2007). With climate change and drought effects, rain water harvesting is being considered as a new strategy to optimize the use of available water sources (Pandey et al., 2003; Kaspersen, 2012).

Porous pavements are generally utilized to collect, treat and infiltrate surface runoff, allowing groundwater recharge, water saving through recycling, and pollution prevention (Pratt et al., 1999; Scholz and Grabowiecki, 2007). The scientific literature showed that porous pavement systems have an ability to significantly reduce runoff (that would normally enter downstream water bodies) and improve water quality (Scholz and Grabowiecki, 2007; Dietz, 2007; Ahiablame et al., 2012a), even in soils with relatively slow infiltration rates (Dreelin et al., 2006) and under varying environmental conditions (Tota-Maharaj and Scholz, 2010). Porous pavements, like other LID practices, are increasingly gaining interest from many developers and public policy makers seeking to find solutions for moving cities toward sustainability. Efforts to investigate the effectiveness of LID practices have largely been directed toward micro-scale evaluation of bioretention systems, green roofs, swales, permeable pavements, and other LID practices (e.g., Scholz and Grabowiecki, 2007; Davis et al., 2009; Roy-Poirier et al., 2010; Dietz, 2007; Berndtsson, 2010; Rowe, 2011; Ahiablame et al., 2012a). These studies credited LID techniques as best management practices capable of reducing runoff and improving water quality (e.g., Davis, 2005; Fach and Geiger, 2005; Hunt et al., 2006; Collins et al., 2008; Fassman and Blackbourn, 2010; Gregoire and Clausen, 2011; Myers et al., 2011).

Even though the literature on the effectiveness of LID practices is relatively rich, there is currently little quantitative information describing potential impacts of these practices at the watershed scale, increasing less interest for their widespread implementation in many urban areas. Further, previous research has mainly focused on runoff management, without much consideration given to baseflow. Because of the potential impacts of many of the LID practices on baseflow, the impacts of LID practices on baseflow at the watershed scale need to be investigated. Little information is also available for exploring LID practices as retrofitting technologies at the watershed scale.

The objective of this study was to document the effectiveness of LID practices in managing urban water at the watershed scale by simulating watershed level impacts of rain water harvesting systems (specifically, rain barrel, cistern) and porous pavement on runoff, baseflow, and total streamflow. Effectiveness is defined in this study as percent change in runoff, baseflow, total streamflow, and pollutant loads with the implementation of LID practices. Various levels of rain barrel/cistern and porous pavement scenarios were evaluated in two urbanized watersheds.

2. L-THIA–LID model description

The L-THIA–LID model was developed as an enhanced version of the original L-THIA model to incorporate modeling capabilities of LID practices (Engel and Hunter, 2009). Similar to the L-THIA model, the L-THIA–LID model estimates direct runoff using the Curve Number (CN) method from daily rainfall depth, land use, and hydrologic soil group data (Harbor, 1994). The CN method was empirically developed as a simple procedure for estimating runoff volume (without baseflow component) at the watershed scale (NRCS, 1986; Garen and Moore, 2005). The relationship between rainfall, runoff and CN is not linear, indicating that small changes in land use or rainfall can produce large changes in runoff. The CN technique is widely used in simple stormwater management methods, as well as in complex models for more sophisticated analyzes. The use of the CN method in L-THIA–LID is a simple alternative to more complicated hydrological models that require extensive data inputs which are often not readily available for most areas, or too complex. L-THIA–LID allows the user to evaluate the effects of LID strategies on water quantity and quality. The CN method allows characterization of the relationship between watershed storage and initial abstraction, Ia (i.e., interception, infiltration, surface storage, and evaporation) as (USDA-SCS, 1972):

$$\mathrm{Ia} = 0.2S \tag{1}$$

where S is the watershed storage. The CN and storage, S, are related by (USDA-SCS, 1972):

$$\mathrm{CN} = \frac{25,400}{254 + S} \tag{2}$$

The model estimates direct runoff (Q, mm) for a given precipitation depth (P, mm) as:

$$Q = \frac{(P - \mathrm{Ia})^2}{(P - \mathrm{Ia}) + S} \quad \text{for } P > \mathrm{Ia} \tag{3}$$

$$Q = 0 \quad \text{for } P \le \mathrm{Ia} \tag{4}$$

To evaluate the impacts of LID practices on streamflow at the watershed scale, an empirical equation, developed for the study region with watershed characteristics (known to influence baseflow) to estimate the baseflow component of the total streamflow, was implemented in L-THIA–LID. A description of the development of the baseflow model is provided in Ahiablame et al. (2013). The baseflow equation is formulated as:

$$Q_b = 29.896\mathrm{BDA}^{0.953}\mathrm{APCP}^{1.424}\mathrm{BFI}^{1.260} \tag{5}$$

where Q_b is the annual baseflow (m^3); BDA is the watershed drainage area (km^2); APCP is the annual precipitation (mm); and BFI is the baseflow index. BFI is related to CN by:

$$\mathrm{BFI} = -0.00726\mathrm{CN} + 1.142 \tag{6}$$

The coefficients in Equation (6) were obtained by calibration using data for 18 Indiana watersheds (Ahiablame et al., 2013). It should be noted that Equation (6) was developed with data having a CN range of 70–90 which gives BFI values between 0.48 and 0.63. The estimated baseflow and runoff are used to determine pollutant loads from various land uses by multiplying them with Baseflow Pollutant Coefficients (BPCs) and Event Mean Concentration (EMC) values, respectively. The EMCs are pollutant loading coefficients developed by the U.S. Environmental Protection Agency's Nationwide Urban Runoff