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Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model

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HIGHLIGHTS

- The L-THIA-LID 2.1 model was developed for simulating BMP and LID practice impacts.
- Grass strips were the most cost-efficient practice to reduce runoff and pollutants.
- The L-THIA-LID 2.1 model is valid to help users identify cost effective plans.

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ABSTRACT

The adverse influence of urban development on hydrology and water quality can be reduced by applying best management practices (BMPs) and low impact development (LID) practices. This study applied green roof, rain barrel/cistern, bioretention system, porous pavement, permeable patio, grass strip, grassed swale, wetland channel, retention pond, detention basin, and wetland basin, on Crooked Creek watershed. The model was calibrated and validated for annual runoff volume. A framework for simulating BMPs and LID practices at watershed scales was created, and the impacts of BMPs and LID practices on water quantity and water quality were evaluated with the Long-Term Hydrologic Impact Assessment-Low Impact Development 2.1 (L-THIA-LID 2.1) model for 16 scenarios. The various levels and combinations of BMPs/LID practices reduced runoff volume by 0 to 26.47%, Total Nitrogen (TN) by 0.30 to 34.20%, Total Phosphorus (TP) by 0.27 to 47.41%, Total Suspended Solids (TSS) by 0.33 to 53.59%, Lead (Pb) by 0.30 to 60.98%, Biochemical Oxygen Demand (BOD) by 0 to 26.70%, and Chemical Oxygen Demand (COD) by 0 to 27.52%. The implementation of grass strips in 25% of the watershed where this practice could be applied was the most cost-efficient scenario, with cost per unit reduction of \$1 m^3/yr for runoff, while cost for reductions of two pollutants of concern was \$445 kg/yr for Total Nitrogen (TN) and \$4871 kg/yr for Total Phosphorous (TP). The scenario with very high levels of BMP and LID practice adoption (scenario 15) reduced runoff volume and pollutant loads from 26.47% to 60.98%, and provided the greatest reduction in runoff volume and pollutant loads among all scenarios. However, this scenario was not as cost-efficient as most other scenarios. The L-THIA-LID 2.1 model is a valid tool that can be applied to various locations to help identify cost effective BMP/LID practice plans at watershed scales.

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1. Introduction

With more people shifting to live in urban areas (Paul and Meyer, 2001; Grimm et al., 2008), urbanization has become a global trend. Urbanization changes natural or agricultural land uses to residential, commercial, and industrial areas, which increases imperviousness. The increased imperviousness of the area and urban activities lead to increased runoff, decreased baseflow, reduced groundwater recharge, and water quality deterioration (Brun and Band, 2000; Rose and Peters, 2001; Lee and Heaney, 2003; Randhir, 2003; Tang et al., 2005; Olang and Furst, 2010; Newcomer et al., 2014). Although combined sewer systems are used in urban areas to treat polluted water, combined sewer overflows (CSOs) may occur during some rainfall periods. CSOs may discharge directly to lakes, streams, rivers, and even oceans, which result in severe water pollution problems (Hatt et al., 2004; Gunderson et al., 2011; Hata et al., 2014).

Best management practices (BMPs) and low impact development (LID) practices are two effective control measures to reduce runoff and control the movement of pollutants (Urbonas, 1994; USEPA, 2008). BMPs, including retention pond, detention basin, and wetland basin, are large scaled, centralized approaches that treat stormwater runoff at the end of a drainage area (USEPA, 2008; Gilroy and McCuen, 2009). LID practices, such as green roof, rain barrel/cistern, bioretention system, porous pavement, permeable patio, grass strip, grassed swale, and wetland channel, are small-scale on-site practices to preserve pre-

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development site features or reduce the impact of development activities at the source (Prince George's County, 1999; Dietz, 2007).

Numerous studies have shown the capabilities of BMPs and LID practices in reducing water quantity and improving water quality (e.g., Barbosa and Hvitved-Jacobsen, 1999. Wright et al., 1999; Bhaduri et al., 2000; Pagotto et al., 2000; Brattebo and Derek, 2003; Hunt et al., 2006; Bean et al., 2007; NPRPD, 2007; Dietz and Clausen, 2008; Damodaram et al., 2010; Zhang and Zhang, 2011; Vezzaro et al., 2011; Vijayaraghavan et al., 2012; Ahiablame et al., 2013; Kok et al., 2013; Autixier et al., 2014; Newcomer et al., 2014). For example, Dietz and Clausen (2008) measured stormwater runoff and pollutant concentrations for both traditional development and development utilizing LID practices; the results showed that traditional development increased runoff and pollutant loads, while implementation of LID practices greatly reduced runoff and pollutants compared to traditional development conditions. Ahiablame et al. (2013) used the L-THIA-LID model to simulate six levels and combinations of porous pavement and rain barrel/cistern in two watersheds that were highly urbanized, which showed that the implementation of different LID scenarios resulted in 2% to 12% reductions in runoff and pollutant loads. Newcomer et al. (2014) conducted a field and model-based (HYDRUS-2D) study in San Francisco, CA, which demonstrated the benefits of BMPs/LID practices on groundwater recharge. Comings et al. (2000) studied two wet ponds at a commercial and residential area in Bellevue, WA, and found 61% to 81% reduction of TSS, 19% to 46% reduction of TP, and 37% to 76% reduction of metals.

Although there are numerous modeling, field, and laboratory studies evaluating the effectiveness of BMPs and LID practices on water quantity and quality, presently, there are few studies estimating the possible impacts of BMPs and LID practices at watershed scales when implementing various levels and combinations of these practices in series. Further, scientific papers evaluating the cost of implementing BMPs and LID practices at watershed scales are sparse. Research searching for cost-effective scenarios (levels and combinations) to implement BMPs and LID practices at watershed scales is also relatively rare.

The primary goal of the study was to evaluate the impacts of BMPs and LID practices on hydrology and water quality at a watershed scale with the L-THIA-LID 2.1 model. The model was calibrated and validated for runoff volume. A framework for simulating BMPs and LID practices at watershed scales was created. BMPs and LID practices, including green roof, rain barrel/cistern, bioretention system, porous pavement, permeable patio, grass strip, grassed swale, wetland channel, retention pond, detention basin, and wetland basin, were simulated for various levels of adoption and combinations. The total cost of implementing BMPs and LID practices was estimated for each scenario, and the more cost-effective scenarios were identified.

2. Background and enhancement of L-THIA-LID model

2.1. Background of L-THIA-LID model

Based on the previous L-THIA-LID model (Ahiablame et al., 2012), the L-THIA-LID 2.0 model (Liu et al., 2015) was developed to better simulate the impacts of BMPs and LID practices on hydrology and water quality. Similar to other versions of the L-THIA model (Harbor, 1994; Engel et al., 2003; Ahiablame et al., 2012), input data for long term daily precipitation, hydrologic soil group, and land use types are needed. In the same way, the L-THIA-LID 2.0 model evaluates runoff volume based on the Curve Number (CN) method and estimates nonpoint source pollutant loads with runoff volume and event mean concentration (EMC) of specific land uses. To represent BMPs and LID practices, the L-THIA-LID 2.0 model computes runoff volume for land uses that include BMPs and LID practices based on both the CN method and percent runoff reduction method; estimates water quality changes with the runoff volume reduction method, pollutant concentration reduction method, and irreducible concentration method based on International Stormwater Best Management Practices (BMP) Database; and simulates BMPs and LID practices in series (Ahiablame et al., 2012; Liu et al., 2015).

2.2. L-THIA-LID 2.1 model

In this study, to evaluate the performance of BMPs and LID practices at watershed scales, the L-THIA-LID 2.1 model was developed with the consideration of being applied in various locations.

2.2.1. Framework for simulating BMPs and LID practices at watershed scales

BMPs and LID practices were selected and implemented both individually and in series starting at the hydrologic response unit (HRU) level based on the conditions of the area, suitable locations for LID practices, and percent implementation of BMPs and LID practices. Based on the site characteristics (Table A.1), which included drainage area (ha), drainage slope (%), imperviousness (%), hydrologic soil group (A-D), road buffer (m), stream buffer (m), and building buffer (m), together with other logistical concerns, suitable locations for implementing BMPs and LID practices were selected. After obtaining suitable locations for LID practices, the unique combinations of land use, soil type, and LID practices were obtained.

The drainage area of each practice was based on features of the practices: (1) Rain barrel/cistern and green roof only treated runoff from roof tops (same as building footprints). It was assumed that rain barrels can only be implemented in residential areas, cisterns can only be implemented in commercial/industrial area, and green roof can be applied in commercial and industrial areas only. (2) Porous pavement and permeable patio only treated runoff from the surface of the pavement or patio. (3) Bioretention, represented with the Curve Number (CN) method, treated 15% of the remaining runoff after being treated by green roof, rain barrel/cistern, porous pavement, and permeable patio. (4) Biofilter-grass swale, biofilter-grass strip, and wetland channel, which were suitable for small drainage areas, only treated remaining runoff after being treated by green roof, rain barrel/cistern, porous pavement, permeable patio, and bioretention. Areas with different combinations of land use, soil type, and LID practices were assumed to be independent to each other when implementing LID practices. (5) A portion of runoff treated by the LID practices was then treated by BMPs (including detention basin, retention pond, and wetland basin).

To implement BMPs and LID practices in series, the following framework was followed. When there was more than one LID practice suitable to be implemented in an HRU: situation (1) (green roof and rain barrel/cistern, which can be implemented in series) and situation (2) (porous pavement and permeable patio) were parallel to each other; all other situations were applied in series. Grassed swale and wetland channel were parallel to each other. All LID practices can be applied in series with BMPs; however, BMPs were parallel to each other.

2.2.2. Cost of implementing BMPs and LID practices

Total cost (Tc) to implement BMPs and LID practices and cost per unit reduction per year were combined in the L-THIA-LID 2.1 model to evaluate the cost of implementing BMPs and LID practices. The total cost (Tc) to implement BMPs and LID practices was estimated by construction cost, maintenance cost, and opportunity cost (Arabi et al., 2006). Construction cost (Cc), ratio of annual maintenance cost to construction cost (Rmc), interest rate (s), and BMP/LID practice design life (dl) were used to calculate Tc:

$$Tc = Cc \times (1+s)^{dl} + Cc \times Rmc \times \left[\sum_{i=1}^{dl} (1+s)^{(i-1)}\right]. \tag{1}$$

Construction costs and annual maintenance costs of BMPs and LID practices are shown in Table 1. All costs were converted to 2014 US dollars (http://www.usinflationcalculator.com/).

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