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# Representation and Evaluation of Low Impact Development Practices with L-THIA-LID: An Example for Site Planning

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**Abstract**

A computational framework was developed to represent, evaluate, and report the effectiveness of low impact development practices using the Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) model. This framework consists of a four-step methodology to characterize the impacts of LID practices on runoff and pollutant loading using modified Curve Number (CN) values. The methodology was demonstrated in a case study of a residential subdivision in Lafayette, Indiana. The LID practices represented in this study are commonly used to mitigate hydrologic impacts of urbanization. Simulation results showed that water sensitive design principles could bring post-developed hydrology to a level comparable to that of pre-development. Implementation of LID practices should be carefully planned with preliminary studies and optimization techniques to attain intended goals. The methodology outlined in this study can be utilized within other computational models that support simulation of LID practices with the CN approach to assess the beneficial uses of these practices.

**Keywords:** runoff, urbanization, stormwater, urban hydrology, modeling, watershed management

## 1. Introduction

The world population is increasingly living in cities and metropolises since the industrial revolution. This increasing urbanization requires conversion of agricultural lands, forests, and wetlands into urban land uses. Urbanization adversely alters watershed hydrology, contributing to the deterioration of water resources and water quality (USEPA, 2001). Examples of this alteration include increased runoff volumes and peaks, decreased time of concentration, decreased base flow recharge (Moscrip & Montgomery, 1997; Burns et al., 2005), and increases in nonpoint source (NPS) pollution in runoff (Schueler, 1995; Ying & Sansalone, 2010a & 2010b). Urban NPS pollutants include suspended and dissolved solids, nutrients, oxygen-demanding organisms, bacteria, pesticides, metals, oil and grease among others. Transport of pollutants in runoff from land areas into water bodies is a natural process; however, urban NPS pollution is intensified by activities associated with urbanization. The most prevalent of these activities include increased impervious surfaces (e.g., roads, parking lots, sidewalks, roofs, compacted areas), increased application of fertilizers and pesticides on municipal lawns and gardens, erosion from land disturbance due to construction activities, increasing use of vehicles that causes pollutant inputs into the air and subsequent atmospheric deposition transferred to nearby aquatic systems by runoff (Lin et al., 1993; Baird et al., 1996). Hydraulically connected impervious surfaces can produce high volumes of runoff (Lee & Heaney, 2003), causing changes in runoff water chemistry constituents (Ying & Sansalone, 2010a). For example, Sansalone et al. (1998) and Ying & Sansalone (2010a) showed that the accumulation and washoff of pollutants from dry deposition on impervious surfaces can increase contaminant loads in runoff during rainfall events.

Although urban NPS pollution has been a research topic in environmental studies and water resources engineering for many years (Lazaro, 1990; Harbor, 1994; Moscrip & Montgomery, 1997; Tang et al., 2005), it is essential to re-examine the topic in this era of newly emerging stormwater management methods and computer models (Grove et al., 2001; Tang et al., 2005; Lim et al., 2010). Ranging from computationally intense to simple algorithms, computer models have been used at multiple scales to understand processes that govern urban stormwater runoff, and to evaluate the effects of land use changes on hydrology and water quality (Im et al., 2003; Lim et al., 2010).

Emerging stormwater management techniques such as low impact development (LID) practices are often utilized in urban environments as best management practices to mitigate influences of urbanization on water resources and water quality (Coffman, 2002). Evaluation of LID practices is typically conducted through field monitoring and simulation modeling. While the former is necessary for characterizing and identifying changes or trends in the efficiency of the practices; it is generally limited in providing extensive information due to variability in topographic, soil and weather conditions across scales. Simulation modeling provides a means to generalize this information. In recent years, there has been a growing interest in modeling LID practices due to high costs required to evaluate their effectiveness using field monitoring conventions (NRC, 2008). However, the techniques to model LID practices are as numerous as the computer models due to the lack of a standard procedure to represent them within model environments.

The differences in the representation of LID in simulation models may be explained by the fact that modeling hydrologic and water quality processes in urban catchments is particularly challenging due to the inherent complexity of natural features cohabiting with anthropogenic structures such as sewage and stormwater drainage systems that must be taken into account during evaluations (Ellis et al., 2004a; Ellis et al., 2004b). An array of techniques, ranging from simple to complex equations, is generally utilized to characterize the impacts of LID practices on urban hydrologic processes in watershed models (Abi Aad et al., 2010; Jeon et al., 2010). However, the use of multiple and complex techniques may be challenging and time consuming for planners or decision-makers who often need a quick screening tool for summarizing information about the performance of LID practices. Standardizing the representation of LID practices with numerical guidelines in simulation modeling is needed to reduce modeler's biases and provide consistency across models and studies for comparing, sharing, and distributing modeling results to a wider community, thus promoting wide applicability of these practices. Results for modeling LID practices are as valuable as monitoring studies for environmental planning and management. Therefore, this paper proposes a standard methodology for the representation, evaluation and reporting the effectiveness of LID practices with watershed models. This methodology was developed within the Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID) model.

## 2. The L-THIA-LID Model

L-THIA-LID was developed in response to growing demands for understanding hydrologic and water quality benefits of LID development compared to conventional development. L-THIA-LID is an enhanced version of the L-THIA model (Engel, 2001) which uses the United States Department of Agriculture, Soil Conservation Service curve number (SCS-CN) and event mean concentration (EMC) methods to simulate runoff and NPS pollutant loads based on local daily rainfall, land use, and soil data (NRCS, 1986; Baird et al., 1996). The CN method is a two-parameter (CN and the initial abstraction, S) empirically-based procedure widely used in simple stormwater management methods as well as in complex watershed models to determine how much of a given rainfall event becomes direct runoff (Mockus, 1972; Garen & Moore, 2005). The initial abstraction, which describes all losses of precipitation before runoff begins (interception, infiltration, surface storage, and evaporation), is a function of the CN and is calculated as (NRCS, 1986):

$$S = \frac{25400}{CN} - 254 \tag{1}$$

Under the condition that precipitation, $P_h$ (mm) > 0.2S, direct runoff depth, $Q_h$ (mm) is estimated as:

$$Q_h = \frac{(P_h - 0.2S)^2}{(P_h + 0.8S)}$$

$$Q_h = 0 \text{ when } P_h \leqslant 0.2S \tag{2}$$

The volume of runoff from an area is determined by:

$$Q_v = Q_h \times A \tag{3}$$

where $Q_v$ is the volume of water; and A is the area of interest. Water quality is determined with calculated EMC values embedded in the model. Pollutant loads are estimated by multiplying simulated runoff and EMCs for land use types. The EMC values used in the model were proposed by Baird et al. (1996).

The use of the CN equation in L-THIA-LID is a simple alternative to more complicated hydrological models that require inputs of intensive datasets, often not available for most areas of interest or that would be difficult to obtain. The L-THIA-LID model presented in this study can be used to simulate runoff and NPS pollution associated with LID practices at lot to watershed scales, allowing comparison between LID development and conventional development. This model is a quick screening and easy to use environmental assessment tool developed to assist decision making for planners and natural resource managers. The L-THIA-LID model currently supports a group of LID practices, including bioretention/rain garden, grass swale, open wooded space, porous pavement, permeable patio, rain barrel/cistern, and green roof. Both lot and watershed level simulations are based on modified CN values which describe the effects of these practices on hydrology and water quality. The model calculates runoff and pollutant loads on daily, monthly, or annual basis.

## 3. Methods

### *3.1 Theoretical Framework*

The framework presented in this study to standardize modeling of LID practices relies on the use of CN method, design considerations, performance measures, and readily available datasets. The modeling procedure consists of four steps: (1) representation of LID practices; (2) consideration of design guidelines; (3) computation of runoff; and (4) computation of LID effectiveness index.

#### 3.1.1 Representation of LID Practices

Evaluating the effectiveness of LID practices with the L-THIA-LID model involves the use of SCS-CN values to estimate runoff. The simulated runoff is then used to compute pollutant loads for the area of interest. The CN is a key parameter common to all LID practices used for this study. Seven LID practices including porous pavement, permeable patio, rain barrel/cistern, grass swale, bioretention systems, green roof, and open wooded space, are represented with CN values suggested by Sample et al. (2001) in accordance to runoff mitigation capacity of the practices. These recommended CN values were used to adjust default values in the model to characterize the effects of the LID practices on runoff and pollutant loading, allowing comparison between hydrologic and water quality conditions before and after implementation of the practices.

The alteration of CN values within the L-THIA model is a common approach. Previously, Lim et al. (2006a) replaced default CN values to improve runoff and pollutant estimation for their study area. Thus, the representation of LID practices with recommended values of runoff CN takes into account the impacts of LID practices on water resources and standardizes LID modeling. The LID practices considered in this study are described below.

##### 3.1.1.1 Bioretention Systems

Bioretention systems consist of shallow depressions designed for holding stormwater runoff from impervious surfaces such as parking lots, rooftops, sidewalks, and drive ways. They promote infiltration by allowing rain water to soak into the ground, thus reducing runoff that can potentially enter stormwater systems (Davis et al., 2006; Dietz, 2007; Roy-Poirier et al., 2010). Bioretention systems also support runoff filtration for water quality improvement with planted non-invasive vegetation (Davis et al., 2006; Dietz, 2007; Roy-Poirier et al., 2010). In urban communities using combined sewer systems, the use of bioretention reduces the overflow frequency of these combined sewer systems. During winter, bioretention systems may capture the majority of runoff produced by melting snow from impervious surfaces. The values of runoff CN used to represent hydrologic benefits of bioretention systems are 15, 20, 35, and 40 for HSG A, B, C, and D, respectively (Sample et al., 2001).

##### 3.1.1.2 Rain Barrel and Cistern

Installation of rain barrels and cisterns in residential subdivisions allows harvest of rainfall water for potential reuse. In many countries with water scarcity problems, especially in developing countries, the use of vertical storage systems, tanks, and underground storage structures is a common practice and serves as good water supply reservoirs. The value of runoff CN used to represent rain barrels and cisterns is 85 for the 4 HSGs (Sample et al., 2001).

##### 3.1.1.3 Green Roof

Green roofs have been used for many years, especially in Europe, to retain precipitation, provide insulation, and create habitats for wildlife (Miller, 1998; Rowe, 2011). Green roofs have also been credited for lowering urban air temperature and help reduce heat island effects (Miller, 1998; Rowe, 2011). Depending on the thickness of the layers used and the extent of required maintenance, green roofs can be portrayed as extensive or intensive (GRRP, 2010). Green roof was represented using the value of 85 for runoff CN for the 4 HSGs (Sample et al., 2001).

#### 3.1.1.4 Permeable Pavement and Permeable Patio

Permeable pavements or asphalts are generally used to capture and filter runoff from impervious parking lots, driveways, streets, roads, and patios, thus controlling NPS pollution loading (Dietz, 2007). While traditional pavements turn almost all rainfall into runoff, permeable pavements encourage infiltration of rainfall by creating extra moisture in the soil profile. The original CN value of 98 for conventional asphalt was changed to 70, 80, 85, and 87 for driveways and sidewalks with porous materials as suggested by Sample et al. (2001).

#### 3.1.1.5 Open Wooded Space

Open wooded spaces are nature preserves with natural landscape features. These natural conditions play a major role in the protection of flora and fauna. Open wooded spaces offer various sites for natural hydrologic and water quality processes to take place by preserving the integrity of the environment. The values of 68, 79, 86, and 89 were used for poor condition open space, 49, 69, 79, and 84 for fair condition open space, and 39, 61, 74, and 80 for good condition open space (Sample et al., 2001), respectively.

### 3.1.2 Considerations of Design Guidelines

To achieve maximum stormwater management through LID practices, design guidelines recommend that criteria for practice sizing, materials to be used for practice construction, size and shape of the site of interest should be taken into account (Atchison et al., 2006; ACo, 2010). To generalize these design guidelines, the methodology proposed in this study focuses on the footprint of the LID practice area for optimum performance. Modeling efforts should determine the area of the practice to model using the contributing impervious area of the project site multiplied by a sizing factor as follows:

$$Size_{LID\ practice} = Cs \times AIS \qquad (4)$$

where Cs is the sizing factor constant; and AIS is the area of hydraulically connected impervious surfaces at the site to be treated. For example, the footprint of an effective bioretention area should be 15 % of the area of the contributing impervious surface in the watershed (Atchison et al., 2006). This means that, for appropriate application of the reported CN values, a factor of 0.15 must be used to determine the size of the practice. In this study the Cs values used for the sizing of LID practices are listed in Table 1. The underlying assumption that supports the use the reported CN values is that the watershed is divided into multiple hydrologic response units (HRUs) and each HRU is associated with only one practice for modeling purposes during a scenario analysis. An HRU is a portion of the watershed with the same soil type, land use and treatment, and characterized by a single CN value, giving a homogeneous hydrologic response.

The size of rain barrels and cisterns was determined using the following equation (SEMCOG, 2008):

$$V = Cs \times C_{VR} \times P \times A \qquad (5)$$

where V is the volume of water to detain (L); $C_{VR}$ is the volumetric runoff coefficient (0.9 to 0.95 recommended); P is the precipitation amount (mm); and A is the drainage area (roof) to the cistern ($m^2$).

### 3.1.3 Computation of Runoff

The total amount of runoff is runoff generated from all HRUs in the watershed, which can potentially reach downstream receiving waters. Runoff in the watershed is calculated using the distributed CN approach (Peters, 2010). In a watershed, the generation of runoff varies widely across land uses, and the distributed CN approach calculates runoff volume separately for each HRU as described in equation 3. The total runoff is the sum of individual runoff generated from all HRUs. The distributed CN method addresses more appropriately water quality impacts of urbanization, especially during small storm events, by estimating the effective contribution of each land use to runoff in the watershed (Peters, 2010). This method reduces the risk of runoff overestimation or underestimation that may occur by averaging the runoff depth over the entire watershed. Water quality in the watershed is estimated as:

$$WQ_m = \sum_{i}^{N} \left( Q_{HRU} \times A_i \times EMC_{HRU} \right) \qquad (6)$$

Where $WQ_m$ is the total water quality pollutant mass in the watershed; N is the number of HRUs; $Q_{HRU}$ is the runoff from an HRU; $A_i$ is the area of the HRU; and $EMC_{HRU}$ is the concentration of a pollutant from an HRU.

### 3.1.4 Computation of LID Effectiveness Index

The impact of LID practices on water quantity and quality for a study area can be evaluated with LID practice effectiveness index ($EI_{LID}$). The $EI_{LID}$ standardizes comparison between pre-development and post-development with and without LID for average annual runoff and pollutant loading. The $EI_{LID}$ is calculated as:

$$EI_{LID} = 100\left[\frac{\left(Y_{NoLID} - Y_{LID}\right)}{Y_{NoLID}}\right] \quad (7)$$

where Y is the average runoff or pollutant load for a time period; NoLID is the description of a land use scenario without LID practices implemented; and LID is the description of a land use scenario with LID practices implemented. The average overall effect of a group of LID practices may be estimated using the cumulative index (CI) for LID effectiveness as:

$$CI_{LID} = \frac{\sum_{i}^{n}\left(EI_{LID}\right)}{n} \quad (8)$$

where n is the number of LID practices being evaluated.

Table 1. Factors (Cs) Used for Sizing LID Practices

| Low impact development practice | Cs-factor |
|---|---|
| Bioretention systems | 0.15 |
| Rain barrel/Cistern[a] | 1 |
| Green roof | 1 |
| Open wooded space | 0.15 |
| Porous pavement | 1 |
| Permeable patio | 1 |

[a]This factor computes the volume of the barrel/cistern (See Equation 5).

### *3.2 Application*

The proposed modeling procedure was applied to Brookfield Heights (BH), a residential subdivision in Lafayette, Indiana (Figure 1) to evaluate the long-term effects of LID practices in "what if scenarios" using the L-THIA-LID model without calibration. The uncalibrated L-THIA-LID was used in this study to provide theoretical impacts of the development of the subdivision, as would be the case in preliminary studies presented by developers to decision-makers. The BH subdivision is located approximately 10 km east of Purdue University campus and was built in 1990 in accordance with the Tippecanoe County Drainage and Sediment and Subdivision ordinances. The BH subdivision drains into Wildcat Creek which drains into the Wabash River. Both Wildcat Creek and the Wabash River are subject to elevated amounts of nonpoint source pollutants and sediments (Karns et al., 2006). Eroded sediments carry nutrients, pathogens, chemicals, and various substances that significantly contribute to the deterioration of downstream waters. Although transport of sediment into water bodies is a natural process (Wachal et al., 2009), soil loss to the Wabash River is magnified by the contribution of land disturbance activities such as agriculture and urbanization in this area.

The Greater Lafayette area is home to Purdue University, various industrial and other commercial enterprises facilitate rapid urbanization with more than 1000 persons per $km^2$. This rapid urbanization is translated into the construction of new residential subdivisions to accommodate the growing community. The topography in Lafayette is characterized by flat plains with elevations ranging approximately from 150 m to 220 m. The average air temperature generally ranges from -8 ℃ in January to 30 ℃ in July (http://climate.agry.purdue.edu/climate/facts.asp). Average monthly precipitation varies between 30 mm in February and 130 mm in May (http://climate.agry.purdue.edu/climate/narrative.asp).

The 426 houses in the BH subdivision were built on small lots with 10 m wide streets, 1 m wide sidewalks with curb and gutter systems. The average lot size in this subdivision varies between 1000 to 4000 $m^2$. Construction of this subdivision replaced 71 hectares of agricultural and forested land uses on poorly drained to well drained soils. The current land use of the study area currently consists of 10 % forest, 41 % grass, 3 % water, and 46 % impervious surface (Table 2). This study examined hydrology and water quality in pre-developed and post-developed conditions, and a group of LID implementation scenarios in the BH subdivision (Table 3).


Figure 1. Brookfield Heights Subdivision in Lafayette, Indiana

Table 2. Pre-Developed and Post-Developed Land Use Areas and Hydrologic Soil Groups (HSGs) in the Brookfield Heights Subdivision

| Land use | HSG | Pre-development | | Post-development | |
|---|---|---|---|---|---|
| | | Area (ha) | % | Area (ha) | % |
| Agricultural | B | 32.5 | 46 | | |
| | C | 13.2 | 19 | | |
| Forest | B | 10.0 | 14 | 7.3 | 10 |
| Grass | B | 8.4 | 12 | 20.3 | 28 |
| | C | 5.6 | 8 | 8.7 | 12 |
| Water | B | 0.9 | 1 | 1.2 | 3 |
| | C | | | 0.5 | 1 |
| Impervious | B | | | 22.9 | 32 |
| | C | | | 9.6 | 14 |

Table 3. Low Impact Development (LID) Practices and Associated Land Areas Used for Simulation Scenarios

| Simulation Scenarios | ID | Area (ha) | Percent of total area |
|---|---|---|---|
| Post-development w/o LID | Post | 71 | 100 |
| Bioretention systems | BS | 4.9 | 7 |
| Open wooded space | OWS | 4.9 | 7 |
| Green roof | GR | 8.4 | 12 |
| Rain barrel/Cistern | RBC | 8.4 | 12 |
| Porous pavement | PP | 24.1 | 33 |
| Permeable patio | PPat | 6 | 8 |
| Combined LID practices | AP | 56 | 79 |

3.2.1 Low Impact Development Scenarios

The effectiveness of LID practices in the study area was examined in 8 simulation scenarios using 6 practices which include bioretention, rain barrels and cisterns, green roof, open wooded space, porous pavement, and permeable patio (Table 3). The basic underlying assumption used for the simulations is that anthropogenic activities during construction of the subdivision influence the integrity of hydrologic properties of the local soils, causing a shift of all HSGs to HSG D in the developed subdivision (Lim et al., 2006b). The study also assumed that all impervious surfaces are hydraulically connected in the subdivision. Scenario 1 considered the subdivision in its current state, i.e. without implementation of any LID practices. Scenario 1 serves as a baseline. Scenarios 2 through 7 placed LID practices in the subdivision one at a time based on Cs-factors as depicted in Table 1. For example, in scenario 6, all driveways and streets within the subdivision were replaced by porous pavements. In scenario 2, grass areas corresponding to 15 % of impervious surfaces within the subdivision were converted into bioretention systems. Scenario 8 placed all LID practices combined in appropriate areas within the subdivision using the respective Cs-factors. Note that scenarios 2, 3, and 5 are used in a retrofitting manner in this study (Table 3). In other words, grass areas corresponding to 15 % of impervious surfaces were converted into bioretention systems, conventional streets were converted into porous pavements, conventional roofs were converted into green roofs, grass areas corresponding to 15 % of impervious surfaces were converted into open wooded spaces, all driveways were considered as permeable patios, and all rooftops were assumed connected to rain barrels or cisterns.

3.2.2 Data

Twenty years of daily rainfall data (1990 - 2009) obtained from the West Lafayette 6 NW (129430) observation station were used in this study. This station is located approximately 10 km west of the BH subdivision and the data is available at the National Climatic Data Center (NCDC: http://www.ncdc.noaa.gov/oa/ncdc.html). Pre-development land use themes were created in a previous study using a paper copy of a 1957 aerial map (Gunn, 2001; Table 2; Figure 1). Post-developed land uses were created using manual digitization in ArcGIS 9.3 by overlying an aerial photo of 2008 obtained from Indiana Spatial Data Portal (http://www.indiana.edu/~gisdata) on the subdivision outline. Impervious surfaces consist of driveways, streets, and building footprints (Table 2).

## 4. Results and Discussion

### *4.1 Comparison of Pre- and Post-Development Annual Runoff Quantity and Quality*

A comparison of simulated annual runoff between pre-development and post-development in the BH subdivision from 1990 to 2009 indicated that construction of this subdivision impacted hydrology throughout the 20 years of the study period (Figure 2). Although increase in runoff varies widely from year to year, simulated average annual runoff for the post-developed condition was 6 fold higher than runoff for pre-development (Table 4). The increase of runoff increase in post-development could be directly related to increase in impervious surfaces (> 40 %) in the BH subdivision (Table 2). Tang et al. (2005) also observed similar runoff impacts of urbanization on surface runoff due to increase in impervious surfaces. Hamdi et al. (2011) argued that more than 35 % of imperviousness could cause change in annual time series runoff and high flows, and increase frequency of flood events. These results have major implications for local flood control managers, suggesting the need for innovative flood control systems such as onsite bioretention systems, swales, porous pavements, porous patios, and open wooded spaces to manage potential increase in runoff due to urbanization.

Average annual simulated TSS, TP, TN, Pb, Cu, and Zn loads also increases as a result of development activities (Table 4). Winter and Duthie (2000) showed that increase in urban areas was correlated to TP loading. Yin and Li (2008) published similar findings when they investigated suspended solids sources in Wuhan City, China. The authors reported that 40 % of suspended solids in urban runoff originated from road-deposited sediments. Nelson and Booth (2002) linked 15 % of sediment in an urban catchment to road surface washoff. Yard work causing soil disturbance may also result in increased TSS and turbidity (Kayhanian et al., 2001). Runoff from driveways and parking areas in the subdivision could contribute important amounts of pollutant loadings. Generally, these pollutants are bound to sediment particles during rainfall events. For example, Furumai et al. (2002) found greater fractions of heavy metals (Zn, Pb, and Cu) in particulate form than in soluble form in highway runoff. Loading of heavy metals in urban runoff is reportedly related to automobile use (Pitt et al., 1995; Sansalone et al., 2001), especially during the starting of vehicles. It should also be noted that fertilizers and chemicals are often used on urban lawns, gardens, golf courses, and public parks. Sometimes urban dwellers tend to use relatively more fertilizers and pesticides per unit area of lawn than what a farmer would use. The application of elevated chemicals may result in higher nonpoint source (NPS) pollution in urban streams compared to agricultural streams (USGS, 1999).

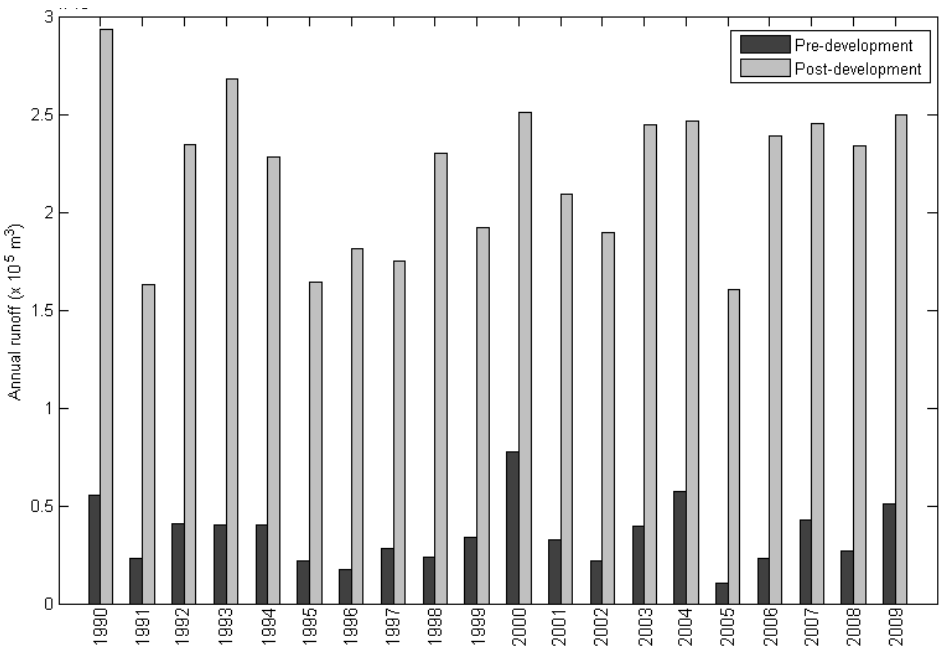


Figure 2. Simulated Annual Runoff for Pre-Development and Post-Development

Table 4. Simulated Average Annual Runoff and Pollutant Loads for Pre-Development and Post-Development

| | Pre-development | Post-development |
|---|---|---|
| Runoff ($m^3$/yr) | 35,000 | 220,000 |
| TSS (kg/yr) | 3,600 | 9,200 |
| TP (kg/yr) | 40 | 100 |
| TN (kg/yr) | 100 | 400 |
| Pb (kg/yr) | 0.10 | 2.0 |
| Cu (kg/yr) | 0.10 | 3.0 |
| Zn (kg/yr) | 1.0 | 17 |

### *4.2 What if Brookfield Heights Subdivision Was Developed With LID Approach?*

The goal of this section is to examine which LID practice would have the potential to help mitigate hydrologic effects induced by the construction of the BH subdivision. Modeling studies have demonstrated that urban runoff quantity and quality can be managed with the use of LID strategies (Park et al., 2008; Jeon et al., 2010; Wang et al., 2010). Simulation scenarios in this study focused on assessing the effectiveness of the different practices based on LID design considerations (Table 1). Thus, LID design was simulated with 6 practices in 8 scenarios and the effectiveness of these practices were evaluated for runoff, TSS, TP, TP, Pb, Cu, and Zn as shown in Table 5. Comparisons of model simulations with no practices (baseline scenario) to model simulations with LID practices hypothetically implemented in the subdivision were conducted using equation 7 for the 20 year study period. Simulated runoff was reduced by 2 %, 11 %, 6 %, 52 %, and 10 %, with the use of bioretention systems, green roofs, rain barrel or cisterns, porous pavements, and permeable patios, respectively (Table 5).

Simulated pollutant loads were also reduced similarly by more than 50 % for all pollutants under porous pavements (Table 5). These results are consistent with monitoring studies which credited permeable pavements as a major urban best management practice for runoff and associated pollutant load reduction when building new subdivisions or retrofitting existing residential dwellings (Dietz, 2007; Collins et al., 2008; Collins et al., 2010; Fassman & Blackbourn, 2010). The simulated permeable pavements and patios indicate that urban runoff management can be achieved using permeable materials in place of conventional asphalt and concrete. Although all HSGs have been shifted to HSG D, the representation of permeable materials with a CN value of 87 (instead of 98) in this study (Table 1) explains the reduction observed in runoff and pollutant loads. The simulated porous pavements consist of 74 % of the contributing impervious surface (33 % of the total area; Table 3), suggesting that reduction in runoff is mainly due to reduction in impervious surfaces.

Detention of sediment and nutrients in bioretention systems was reported to be 70 % for TSS (Line & Hunt, 2009), and more than 20 % for nutrients (Davis et al., 2006; Dietz, 2007; Line & Hunt, 2009; Roy-Poirier et al., 2010). The performance level of the simulated bioretention in this study for runoff and pollutant reduction was relatively lower (1-2 %, Table 5) compared to reported reduction values (Dietz, 2007; Davis et al., 2006; Line & Hunt, 2009). However, results indicate that bioretention practices have a potential to mitigate stormwater impacts of land development (Table 5).

The open wooded space did not significantly impact runoff and pollutant loads compared to other practices. This is due to the nature of this study in which LID practices were explored as retrofitting technologies. Open wooded spaces are typically recommended when an area is being developed to preserve sensitive areas. Open wooded spaces promote natural hydrology by reducing the amount of pollutants entering streams and supporting ground water recharge. Placing open wooded spaces in grassed areas that have low runoff potential provided little additional benefit as a retrofit LID practice.

Green roofs and rain barrels/cisterns show similar effectiveness in reducing runoff and pollutant loads (Table 5). Retention of rainwater in green roofs and rain barrels resulted in 10 % reduction of the effective rainfall that will be converted into surface runoff, especially during small storm events. The limitation in detention capacity of these two practices could be explained by the fact that during the long-term simulation, nearly 100 % of large storm events were lost in the form of surface runoff since water detention capacity of green roof and rain barrel systems were relatively limited in reducing runoff.

When all the practices were simulated with the corresponding Cs-factors, higher reduction for both runoff and pollutant loads were observed compared to individual practices (Table 5). The application of the Cs-factors of the LID practices translated into the alteration of more than 70 % of the total study site with the impact of at least one LID practice (Table 3). This greatly influenced the hydrologic response of the constructed subdivision. Throughout the simulation scenarios, it appears that a reduction in impervious surface leads to a reduction in runoff, indicating that the presence of impervious surface in a watershed would facilitate runoff processes as reported by previous studies (Shuster et al., 2005; Tang et al., 2005). These results also imply that the combination of a group of LID practices at strategic points in the area of interest using optimization techniques and preliminary studies could result in improved site hydrology and water quality.

Table 5. Estimated Effectiveness Index ($EI_{LID}$) Used for the Evaluation of LID Practices

| LID practice | ID | Runoff | TSS | TP | TN | Pb | Cu | Zn |
|---|---|---|---|---|---|---|---|---|
| Bioretention systems | BS | 2 | 2 | 1 | 2 | 2 | 2 | 1 |
| Open wooded space | OWS | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Green roof | GR | 11 | 10 | 11 | 11 | 11 | 11 | 12 |
| Rain barrel/cistern | RBC | 11 | 10 | 11 | 11 | 11 | 11 | 12 |
| Porous pavement | PP | 52 | 50 | 54 | 55 | 52 | 53 | 56 |
| Permeable patio | PPat | 10 | 10 | 11 | 12 | 11 | 11 | 11 |
| Combined LID practices | CP | 59 | 59 | 59 | 64 | 59 | 59 | 59 |

*4.3 Model Limitations*

The L-THIA-LID model computes pollutant loads as products of runoff and pollutant concentrations. This methodology relies on the assumption that a decrease in runoff would cause a decrease in pollutant loads, without taking into account detailed transport and cycling mechanisms of pollutants before they are delivered to nearby surface waters.

Wilson & Weng (2010) reported that the concentration of most NPS pollutants within residential land uses could increase with increase in urban land use spatial extent and population. These are complex relationships that may vary by urban location but are represented by averages in the L-THIA-LID model. For example, activities such as automobile uses could result in increased concentrations of heavy metals compared to that of nutrients. Some homeowner associations may also have incentives to support reduced use of fertilizers and chemicals on properties. For example, the BH homeowner association encourages residents to apply no more than 0.5 kg fast-release N per 100 $m^2$ in a single application on their lawns (BHH, 2006). These types of resolutions, if followed, could reduce nutrient loading in runoff.

For modeling purposes, this study also assumed that only one practice is applied to a specific land use area one at a time during a simulation scenario. In reality, each land use area can have more than one practice. Further investigation is needed to simultaneously apply multiple practices to an area during a scenario run to improve agreement between modeling and field conditions. The practices were assumed to be installed at a suitable level to reduce runoff by the volumes modeled. Field experimental work and in-depth assessment with monitoring data would be required to determine the strengths and the deficiencies of the predictive capabilities of the model.

## 5. Conclusions

This study proposed a framework within the L-THIA-LID model to standardize modeling of LID practices to support decision making in water resources planning and management. The L-THIA-LID model is a quick screening tool for evaluation of hydrologic and water quality impacts of LID practices, and for identifying the need for more detailed modeling. The effects of LID practices on hydrology and water quality were characterized using modified CN values based on previously published work. The proposed modeling method allows evaluation of the extent to which a development can potentially disrupt pre-development hydrology, and assess “what if” a site was developed with LID principles. This proposed procedure was applied to a residential subdivision in Lafayette, Indiana, using 20 years of rainfall data for long-term simulation. The present study leads to the following conclusions:

- Average annual runoff and pollutant loads increased for post-developed conditions compared to pre-developed conditions, indicating that the construction of the BH subdivision influenced pre-development hydrology and water quality.
- Simulations of LID scenarios, by reducing the amount of runoff and pollutant loading after the construction of the BH subdivision, showed that LID design principles such as porous pavement, permeable patio, and rain barrel could be used to bring post-developed hydrology to a level comparable to that of pre-development. This study showed that reduction in runoff is greatly influenced by reduction in impervious surfaces. To this effect, considerations should be given to LID practices in water resources planning and management for the preservation of natural hydrology.
- Simulation results showed that not all practices were effective for the subdivision used in the analysis. This suggests that implementation of LID practices should be carefully planned with preliminary studies and optimization techniques to attain intended goals. The choice of which practices to use should be based on the needs and the history of the site of interest to ensure maximum performance of these practices.
- The present framework can be adopted in other models using the SCS-CN method or similar underlying equations to represent LID practices, obtain information about the effectiveness of these practices, and support development of decision making tools for water resources planning and management.
- Results from this study provide theoretical impacts of the developments with and without LID design approaches, as would be the case in preliminary studies at the planning stage, and should be used with caution. Future research should take into account site specific conditions to calibrate and validate model parameters with observed data.

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