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Evaluating the Impact of Low Impact Development (LID) Practices on Water Quantity and Quality under Different Development Designs Using SWAT

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Abstract: The effects of Low Impact Development (LID) practices on urban runoff and pollutants have proven to be positive in many studies. However, the effectiveness of LID practices can vary depending on different urban patterns. In the present study, the performance of LID practices was explored under three land uses with different urban forms: (1) a compact high-density urban form; (2) a conventional medium-density urban form; and (3) a conservational medium-density urban form. The Soil and Water Assessment Tool (SWAT) was used and model development was performed to reflect hydrologic behavior by the application of LID practices. Rain gardens, permeable pavements, and rainwater harvesting tanks were considered for simulations, and a modeling procedure for the representation of LID practices in SWAT was specifically illustrated in this context. Simulations were done for each land use, and the results were compared and evaluated. The application of LID practices demonstrated a decrease in surface runoff and pollutant loadings for all land uses, and different reductions were represented in response to the land uses with different urban forms on a watershed scale. In addition, the results among post-LIDs scenarios generally showed lower values for surface runoff and nitrate in the compact high-density urban land use and for total phosphorus in the conventional medium-density urban land use compared to the other land uses. We suggest effective strategies for implementing LID practices.

Keywords: effectiveness of LID practices; different urban designs; SWAT; model development; LID modeling

1. Introduction

Urbanization has caused many problems for runoff and pollutants due to the increase in impervious surfaces. This increase in impervious surfaces changes natural flow characteristics, causing increased runoff volume and peak flow rate, decreased groundwater recharge due to interrupted infiltration to soil layers, and a lowered water table, consequentially causing decreased base flow [1,2]. In addition, urban runoff from impervious surfaces is a main transport mechanism for many pollutants, such as sediment, heavy metals, and nutrients to nearby water bodies. These pollutants contribute to the deterioration of water quality. New methods of stormwater management are therefore required to mitigate the impact of urbanization on runoff and pollutants from an environmental perspective. One alternative strategy is the implementation of Low Impact Development (LID) practices (or urban Best Management Practices; urban BMPs), designed to treat water at the source where it is generated. LID practices can reverse the deteriorated conditions back to a pre-development state or even better [3].

Many studies of hydrology and water quality treatment through LID practices have been conducted. LID practices have been deemed effective through positive results from experiments and modeling. For instance, the installation of bioretention cells or permeable pavements has resulted in large reductions in runoff volumes, peak flow rates, and pollutants [4–8]. For a modeling approach, Abi Aad et al. [9] modeled rain tanks and rain gardens using Storm Water Management Model 5 (SWMM 5), and demonstrated that runoff was delayed and reduced by them. Ackerman and Stein [10] indicated reductions of flow, sediment, and copper by a bioretention cell, a grassed swale, a planter box, and a planter box with a grassed swale in their study that evaluated the effectiveness of BMPs by using Hydrologic Simulation Program-Fortran (HSPF) coupled with a BMP module. Carter and Jackson's [11] study investigated the effects of green roofs on hydrology at four spatial scales using a StormNet Builder model, which they showed significantly reduced peak runoff rates.

The effectiveness of LID practices, however, can vary depending on a variety of conditions. Some studies have demonstrated that LID practices are reliant on watershed characteristics such as soils, topography, and precipitation. Holman-Dodds et al. [12] reported large runoff on a low infiltration type D soil despite the existence of LID practices and also indicated the decreased effectiveness of LID practices under large precipitation. Brander et al. [13] revealed that the performance of LID practices was effective on soil type A and small storms. The effectiveness of LID practices for small storms was also presented in Ackerman and Stein [10], Carter and Jackson [11], Schneider and McCuen [14], etc. In addition, the effects of LID practices were evaluated differently according to locations, numbers, and types of LID practices [15,16].

Other than these watershed characteristics and LID practice conditions, there could be other factors that influence the effectiveness of LID practices. One thing we could consider is the impact of urban patterns. Some studies have determined the positive impacts of high-density urban pattern on water volumes and pollutant loadings. Seo [17] investigated how the amount of runoff and pollutant loadings were generated differently under three different urban planning designs and presented the compact high-density urban type as the most effective urban type. Jacob and Lopez [18] also evaluated the benefits of high density development for the reduction of water quality loadings in comparison with standard suburban developments, mentioning it as an effective approach more than traditional BMPs under their study conditions. Such studies imply that the effects of the application of LID practices could vary with different urban patterns. However, a limited number of studies have been performed on the effectiveness of LID practices under different urban design patterns. For example, Brander et al. [13] analyzed the effects of infiltration practices on urban runoff under their four development types (conventional curvilinear, urban cluster, coving, and new urbanism) using a spreadsheet model, the Infiltration Patch (IP). They showed runoff reduction to be different for the four types of development designs, and the smallest runoff was obtained for the urban clustered design in most scenarios because of the large natural land area. Williams and Wise [19] simulated the hydrologic responses from traditional and clustered developments with BMPs and LID practices using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), and they indicated very similar results to the results of the pre-development condition in the clustered development with LID practices. Gilroy and McCuen [20] studied the three land uses: "single family", "townhome", and "commercial lot" to identify the impact of location and volume capacity of urban BMPs (cisterns and bioretention cells) on runoff volumes and peak discharge rates. They represented different percentages of reduction in the three land uses under every scenario for location and volume. However, very few studies have attempted to simulate LID practices and land use with different urban patterns, especially for rain gardens (RGs), permeable pavements (PPs), and rainwater harvesting tanks (RWHs) (which were considered in the present study), using the Soil and Water Assessment Tool (SWAT).

In this regard, we focused on the application of the LID practices in SWAT and on the evaluation of the watershed-wide effectiveness of the LID practices under given different urban designs. The SWAT model was developed to simulate three LID practices. The hydrologic and water quality results were analyzed and compared with and without LID practices within the same land use and among different land uses. The results of the post-development states from the Seo [17] study were utilized as baseline data to evaluate the post-development states with LID practices. In the text, the terms "pre-LIDs" and "post-LIDs" are used to designate the post-development state before and after constructing LID practices, respectively.

2. Materials and Methodology

2.1. Study Area Description

Runoff and pollutant problems caused by stormwater have been a crucial issue in coastal areas because these areas receive pollutants from upstream sources [21,22] and are simultaneously affected by the tide. In particular, urban areas usually face more serious threats because increased impervious surfaces can discharge water and pollutants without natural handling. The study area, situated to the north of League City, Texas, within the Clear Creek watershed, meets the described characteristics. It is located downstream of Clear Creek near Galveston Bay, and is planned for regional development (Figure 1).

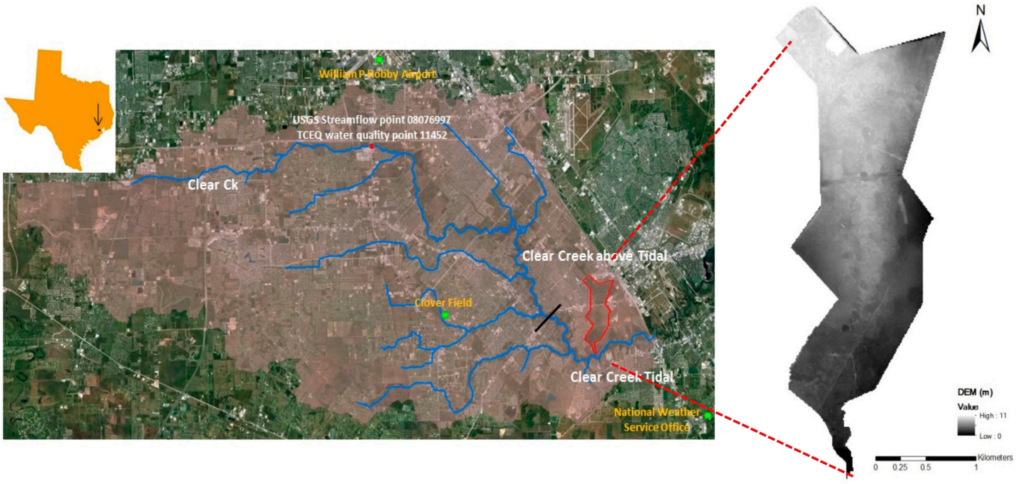


Figure 1. The location of the study area (**right**) included in the Clear Creek watershed (**left**).

It is desirable to scale up the analysis of LID practices to a large watershed after observing detectable water quantity and quality changes at a small level [23]. This is because modeling LID practices at a large scale can make the noticeable effectiveness of LID practices difficult to assess, so that it cannot provide information for changes that should be conducted at small-scale levels [23]. Thus, within the boundary of a pre-developed area, a roughly 3.5 km^2 (350 ha) small area was considered as the study area.

The topography ranges from 0 m to 11 m in elevation, with roughly 90% of the area within 6 m to 8 m in elevation, so the slope of the area is mild. Typical characteristics of this area are high runoff and low permeability. Four kinds of soils are present in this area. Addicks (loam) is the most predominant, comprising about 61% of the soil, followed by Bernard (clay loam), comprising about 27% of the soil. Lake Charles (clay) and Aris (silt loam) cover the remainder. All soil properties are represented as poorly drained hydrologic soil group (HSG) D. Wetland and hay are dominant, making up about 60% of current pre-developed land use. The weather is generally typified by hot summers and clement winters, indicating monthly mean temperatures of around 84 °F (29 °C) in August and around 53 °F (12 °C) in January. The average annual temperature is around 70 °F (21 °C). The impact of the oceanic climate decreases the difference between the low and high temperatures. The monthly average precipitation ranges from about 50 mm to 165 mm, and the average annual precipitation is about 1270 mm. A high probability of extreme storms exists in this area. The study area is located in Harris County [24].

2.2. Description of Input Data

Spatial and temporal input data, projected as an Albers Equal-Area Conic projection with North American 1983 datum, were used for setting up the model. A 10 m squared resolution Digital Elevation Model (DEM) was used to sufficiently express details, obtained from the Natural Resources Conservation Service (NRCS) Geospatial Data Gateway.

For land uses, three different types of land use data, derived from potential urban layouts typical of League City, were considered. These included: (1) a compact high-density urban land use (termed as UHD); (2) a conventional medium-density urban land use (termed as UMD); and (3) a conservational medium-density urban land use (termed as UMC) (Figure 2). The urban area of each land use consists of residential and commercial areas. In the figure, parts of the residential and commercial areas are enlarged from the entire urban areas representing those patterns. The same population applied to all residential areas of land uses. UHD land use includes the smallest portion of residential area and is urbanized, the most among the three urban designs, but also allows for most of the area to remain as natural space. It has a larger roof area in the residential area than the other two designs in order to accommodate an identical population. Thus, it represents a high percentage of imperviousness in the residential area. UMD land use has a pervasive urban pattern in the United States. The residential part of the urban area is composed of conventional neighborhoods consisting of single family units. A UMC residential area includes conservational areas that have to be kept as green space under the same base format with the conventional neighborhoods of the UMD residential area. Thus, it represents less imperviousness than the UMD residential area. The UMD and UMC land uses have the same size of residential area, and the residential area makes up more area than that of the UHD land use. The commercial area of all urban areas is the same in size. In total, urban area occupied about 21% and 56% in the UHD and UMD/UMC land uses, respectively. The residential and commercial areas represent different impervious and pervious ratios for each urban area (Table 1). For the remaining land areas, excluding urban areas, land use data obtained from the USDA NRCS Geospatial Data Gateway were represented to a pre-development state. The same land use data from Seo [17] were used to assess the effectiveness of LID practices under these different urban land uses, and more detailed design specifications can be found in Seo [17].

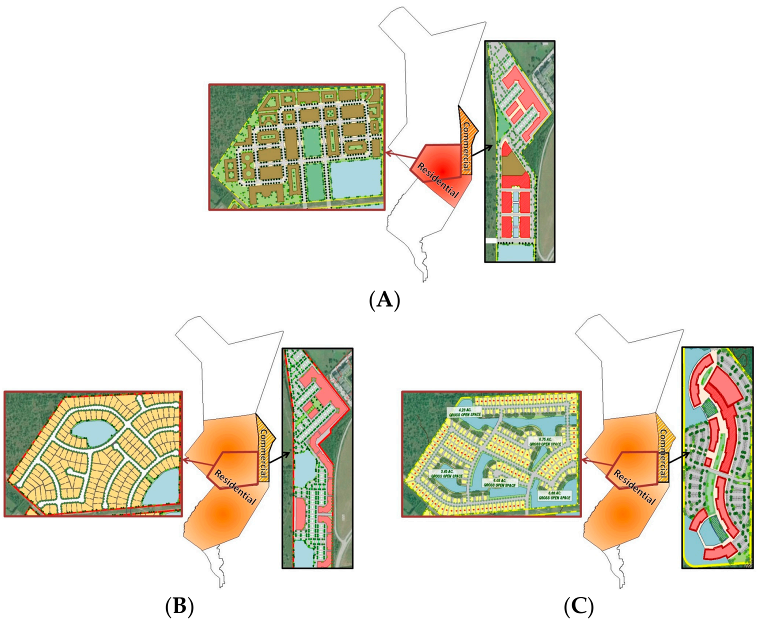


Figure 2. Three land use data with different urban forms (Parts of the residential and commercial areas are enlarged): (**A**) Compact high-density urban land use (UHD); (**B**) Conventional medium-density urban land use (UMD); and (**C**) Conservational medium-density urban land use (UMC).

Table 1. Information for each urban area for the three land uses (in %).

Land Use	Urban Area [1]	Impervious/Pervious Fraction [2]	
		Residential	Commercial
UHD	21	61/39	68/32
UMD	56	44/56	75/25
UMC	56	41/59	68/32

Notes: [1] The proportion of an urban area for total land use area; [2] The fraction of impervious and pervious parts in an urban area.

Soil data, the high-resolution Soil Survey Geographic Database (SSURGO), were obtained from the NRCS Soil Data Mart (https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Daily precipitation and temperature were collected from the National Climate Data Center (NCDC) at Houston Clover Field and at the National Weather Service Office stations, considered as representative stations for the study area. A weather generator was used for the rest of the weather dataset of the simulation.

2.3. Model Selection

A watershed-wide evaluation for the effectiveness of LID practices is needed because stormwater eventually has an influence on the final water body of a watershed [25]. It is cumbersome to calculate reduction rates from all LID practice sites within a watershed for a watershed-wide evaluation. Moreover, since the reductions of runoff and pollutant loads by LID practices can be affected by various watershed characteristics such as topography, land use, soil property, precipitation, and so forth, in this regard, a modeling approach is required to take into account all of these factors. It is important to select an optimal model that properly reflects the hydrologic responses with the application of LID practices. In the present study, SWAT was selected because it has an ability to simulate the process of hydrology and water quality in a variety of studies for long periods [26–28]. SWAT has effective components for the simulation of water quantity and quality. It applies a modified NRCS curve number (CN) method [29] to estimate surface runoff and a Modified Universal Soil Loss Equation (MUSLE) [30] to calculate sediment yields. Different forms of nutrients which are transformed into several pools (e.g., organic and inorganic pools) are also simulated. A comprehensive description of the processes is provided in Neitsch et al. [31].

The model was initially developed for the purpose of simulating water quantity and quality from agricultural and rural environments. However, it is gradually showing its capacity to simulate mixed land uses, which have a large proportion of urban areas or urban settings [32–35]. In addition, the suitability of SWAT in the simulation of agricultural BMPs has been proven. The benefits of many agricultural practices have been examined and evaluated using SWAT [36,37]. This implies that SWAT has the potential to predict water quantity and quality for urban watershed management systems [38]. Existing BMP tools have been upgraded and modified, and new tools for urban BMP modeling are being added in SWAT. For example, Jeong et al. [39] reported a development of algorithms for urban BMPs in SWAT such as Sedimentation-Filtration Basins, Retention-Irrigation Basins, Detention Ponds, and Wet Ponds. Jeong et al. [32] also tested the Sedimentation-Filtration basins (SedFil) algorithm to validate the capability of its components in SWAT. Additionally, the recently updated new version, SWAT 2012, allows many conservation practices, which were not included in other existing models, for modeling water quality by entering pollutant removal efficiencies. As the development of improved tools is encouraged for LID modeling in SWAT, processes through updates and modifications are continuously in progress to adequately represent LID practices.

2.4. Previous SWAT Simulation

The pre- and post-development simulations from the Seo [17] study were used as baseline simulations in order to investigate the effectiveness of LID practices under the same land uses with her study. In the previous work, the influence of land use change on water quantity and quality was identified under three different land uses. To do this, the following stepwise procedures were conducted. The pre-development condition (termed as 'prestate' was first taken into account to assess the impact of urban development. The process was focused on calibration and validation to obtain parameters that could stand for characteristics of the study area. The study area was difficult to calibrate because of sparse and tidal-affected data. Thus, the upstream gauging station (United States Geological Survey (USGS) site number: 08076997 with sufficient data and outside the impact of tidal currents) was considered for calibration, and the SWAT simulation was carried out over the entire Clear Creek watershed (424 km^2), including the study area. The calibration process was performed by using both an auto-calibration tool (sequential uncertainty fitting 2; SUFI2) and a manual approach. The performance of SWAT was evaluated by a *p*-value, an *r*-factor, the Nash-Sutcliffe efficiency (*NSE*), a coefficient of determination (R^2), and mean absolute error (*MAE*). The validation process was conducted with the same parameter values from the calibration. The uncertainty analysis for the streamflow represented 56% and 54% of the observed data bracketed by the 95% prediction uncertainty (95PPU in SWAT) with values of 0.54 and 0.42 for the r-factor, respectively, in the calibration and validation processes. The streamflow showed good correlation to the observation based on the performance indicator values of 0.79/0.94 (R^2), 0.77/0.92 (*NSE*), and 0.59/0.26 (*MAE*) for calibration/validation. The results of nutrient loadings also indicated good correlation to the observed data, showing satisfactory indicator values. This calibration process assumed that watershed properties are similar only across the entire watershed.

After finishing the calibration process, the study area was separated from the Clear Creek watershed and treated as one watershed data to consider post-development scenarios. The three land uses with different urban designs (illustrated in the Description of Input Data section) were applied to the study area. Initial conditions for the post-development simulations were set based on the calibrated parameters from the pre-development simulation. Each land use was divided into different sub-basins and Hydrologic Response Units (HRUs) based on land uses and soil properties. A total of 4 sub-basins and 18 HRUs were produced in the UHD land use, and the UMD and UMC land uses were delineated as 5 sub-basins and 18 HRUs apiece. Each post-development simulation was individually run and investigated for surface runoff, nitrate, and total phosphorus (TP). Overall, the results showed an increase of runoff and pollutant loadings due to the effect of the urbanization rate of the post-development scenarios. The UMD land use represented a large increase, and a slightly lower increase was indicated in the UMC land use compared to the UMD land use. The UHD land use was the effective urban land use showing a minimal increase from the pre-development state. The final result values were used for comparison with the results of the post-LIDs scenarios in the "Results" section.

2.5. Specification of Used LID Practices and Scenarios

Three types of LID practices were chosen to be used in this study: rainwater harvesting tanks (RWHs), rain gardens (RGs), and permeable pavements (PPs). They are effective land management practices that are commonly used in urban watersheds. These LID practices have specific locations, taking up small areas or replacing existing impervious surfaces. It was assumed that RWHs are placed above ground for every house unit in the UMD and UMC residential areas and underground in the UHD residential area due to space restrictions. It was assumed that RGs are randomly installed in individual yards or neighborhood units along the street system in the residential areas, and PPs are taken into account only in the parking lots of commercial areas. Each LID practice was designed to capture the runoff and runoff-borne pollutants generated only from specific sites: that is, RWHs from roofs, PPs from parking lots, and RGs from residential areas, excluding roofs such as backyards, driveways, and sidewalks. Table 2 provides the percentages of roofs and parking lots in the residential and commercial areas for each land use, acquired from each design data and by sampling similar types of neighborhoods in Google Earth. These are the percentages of the areas covered by RWHs and PPs. The percentages of the areas covered by RGs are 6.6% and 8.0% of the UHD and UMD/UMC residential areas, respectively, and they were obtained by multiplying the rest of the percentages excluding roofs in the residential areas by a size factor of RGs based on Mechell and Lesikar [40]. In this study, it was assumed that the areas covered by each type of LID practice in each urban area were considered as full LID implementation. That is, each house has a rainwater harvesting tank, all parking lots in the commercial area are replaced by permeable pavements, and rain gardens are installed as much as the estimated percentages in the backyards of houses and public areas such as sidewalk patios. Also, 100% efficiency without consideration of seasonal impacts was assumed for all types of LID practices. These extreme conditions are ideal situations for new developments and we recognize that they might not be practical in a retrofit, but this is for the purpose of evaluating the benefit based on the LID practices that could be fully accommodated in the given LID areas for each urban design. No LID practices are assumed to be in non-urban areas.

Table 2. Fractions of roofs and parking lots in the urban area of each land use (in %).

Land Use	Roofs [1]	Parking Lots [2]
UHD	34	34
UMD	20	47
UMC	20	31

Notes: [1] Percentages of roofs occupied in the residential areas; [2] Percentages of parking lots occupied in the commercial areas.

In the present study, we focused on simulating the existence of LID practices under three types of land use with different urban patterns in order to evaluate the effectiveness of LID practices and to identify an optimal development plan. Three post-LIDs scenarios were created based on the land uses, and each was tested. They were assessed through comparison with pre-LIDs scenarios, already performed in previous work. The results among the post-LIDs scenarios were also compared and analyzed. Table 3 provides a summary of the scenarios addressed in the study.

Table 3. Summary of scenarios.

Land Use	Urban Design	Name of Scenario	
		Pre-LIDs	Post-LIDs
UHD	Compact urban type with high density	UHD	UHDLIDs
UMD	Conventional type with medium density	UMD	UMDLIDs
UMC	Conservational type with medium density	UMC	UMCLIDs

2.6. Representation of LID Practices in SWAT

2.6.1. Model Development

LID practices capture runoff to the extent of their capacities, and then once their capacities are exceeded, the LID practices discharge flows untreated. The SWAT model was developed to account for the hydrological behavior of LID practices in urban areas. A simple modification and addition of codes was conducted in the surface runoff subroutine.

The surface runoff in urban areas is estimated as the sum of surface runoff from the connected impervious area and disconnected impervious/pervious areas. Surface runoff from the connected impervious area is calculated by an impervious curve number. Surface runoff from the disconnected impervious/pervious areas is computed by a composite curve number under a surface runoff equation

(Equation (1)). Each surface runoff is multiplied by fractions of each area and then summed to obtain the final urban surface runoff (Equation (2)).

$$Q \text{ or } Q_{imp} = \frac{(P - 0.2S)^2}{(P + 0.2S)} \quad (1)$$

$$Q_{tot} = Q \cdot (1 - fcimp) + Q_{imp} \cdot fcimp \quad (2)$$

where Q and Q_{imp} are the surface runoff depths (mm) in the disconnected impervious/pervious areas and in the connected impervious area, respectively, Q_{tot} is the total surface runoff depth in urban areas (mm), P is precipitation (mm), S is a potential maximum retention (mm), and fcimp is the fraction of the connected impervious area.

To consider the amount of surface runoff captured by LID practices, a modified surface runoff equation (Equation (3)) was added in the existing codes.

$$Q_{LIDs} = Q_{tot} - LID_{val} \quad (3)$$

where Q_{LIDs} is the surface runoff depth (mm) in which the impact of LID practices is considered, and LID_{val} is the surface runoff depth (mm) stored by each LID practice. This method was determined based on McCuen's study that subtracted the amount of water captured by infiltration practices from urban surface runoff [41].

This is a suitable approach because SWAT has critical hydrologic algorithms that can best illustrate the flow characteristics of the LID practices being considered. In the case of RGs and PPs that have a natural infiltration system via soil layers, the amount of water exceeding storage capacity is generated as surface runoff by the developed equation (Equation (3)), and the amount of water stored is reflected as infiltration into the soil layers in SWAT. The difference between the amount of rainfall and the amount of surface runoff influences the amount of infiltration into the soil layers such that if precipitation is, for example, 110 mm and surface runoff is 100 mm, the amount of infiltration is 10 mm. However, if 20 mm of water is captured by RGs or PPs, 80 mm of surface runoff is finally discharged by the modified equation (Equation (3)) and the infiltrated water becomes 30 mm. That is, the 20 mm of water is to be added for soil water routing. If the capacities of the RGs or PPs are larger than the urban surface runoff, the amount of precipitation becomes the amount of infiltration. It is possible to simulate these LID practices for not only single events but also for consecutive rainfall. When rainy days are continuous, the daily subtraction from total surface runoff and its addition to the soil layers occurs by Equation (3). However, consecutive rainfall is mostly from small storms, and it is less frequent that large rainfall will occur continuously. In addition, the infiltration of the stored water affects the soil moisture condition, and cases in which all soil layers are completely saturated are not common. Even if that were the case, SWAT can model excess water as surface runoff.

In the case of RWHs, surface runoff is also released after rain tanks reach their volume capacity. However, the water captured by rain tanks is not infiltrated, unlike RGs and PPs. Therefore, the algorithm was additionally coded with relevance to its function. That is, codes were added such that the water from roofs is accumulated in the rain tanks and the maximum storage depth of the rain tanks is used in cases where the water accumulated exceeds the maximum storage depth of the rain tanks. The intentional drainage of the rain tanks was then taken into account for the purpose of reuse of the rain tanks. In this study, it was assumed that if there is no rainfall during a period of at least seven days after cessation of rainfall, the stored water in the rain tanks is intentionally emptied within the days between rainfall events. The stored water might be utilized for various purposes such as watering lawns and gardens, but this is explained as a water loss in SWAT. The description was mainly focused on the hydrologic components of SWAT related to the behavior of LID practices, and the schematic flow chart of the subroutines of the SWAT codes related to the hydrologic behavior by LID practices was added (Figure 3).

*<subbasin> call surface	- Calculation of daily surface runoff based on the CN method
<surface> call volq	
<volq> call surq_daycn	
<surq_daycn>	
inflpcp = precipitation - surq	- Calculation of the amount of infiltration into soil
call percmain	- Implementation of soil water routing
<percmain> call sat_excess	- Movement of excess water to upper layers when the water content is above field capacity
<sat_excess>	
call etpot	- Calculation of evapotranspiration

Figure 3. Schematic flow chart of the hydrologic subroutines related to the behavior of LID practices and description for the functions of each subroutine.

2.6.2. Design Storage Depth

Each LID practice holds different storage depths. In the case of RGs and PPs, the maximum runoff depths that could be treated by them were determined based on the amount of rainfall that is given to them and CN according to the degree of impervious and pervious fractions on each site. RGs and PPs were assumed to be designed to capture the runoff generated from 1.5 inches (38.1 mm) of rainfall. As 1.5 inches of rainfall is the 85th percentile storm event of the north central Texas region, the runoff amount from the rainfall is a volume for water quality protection in this region (Technical Manual of iSWM: http://iswm.nctcog.org/technical_manual.asp) [42]. An impervious CN (98) was used for PPs in all land uses because they deal with only the water from parking lots. For RGs, both impervious CN for the connected impervious covers and composite CN for the disconnected impervious/pervious covers were utilized to calculate the runoff depths that RGs can store. The CN for RGs was estimated differently for each land use because each land use has different urban patterns, comprised of different percentages of impervious and pervious fractions.

In the case of RWHs, the 1000 gallon capacity rain tank was assumed to be a standard in the medium-density residential area [43], and the storage depth was inversely calculated by Equation (4):

$$\text{Capacity of rain tank (gal)} = \text{Storage depth (in)} \times 0.623 \times \text{Roof area } (\text{ft}^2) \times \text{Runoff coefficient} \quad (4)$$

where 0.623 is the unit conversion factor, 0.9 runoff coefficient was used for roofs, and an average roof area per unit was determined through the design data and sampling of similar neighborhoods in Google Earth. A proportional volume of rain tanks was employed according to the roof area of each land use. The same runoff depth was consequently used for RWHs in all land uses.

Overall, the same storage depths for PPs and RWHs and different storage depths for RGs were applied for each land use (Table 4). The information for the maximum storage depths and types of LID practices was provided as a text file in SWAT, and the subroutine that can read the information was added in the SWAT algorithm.

Table 4. Maximum storage depth detained by each LID practice for each land use (in mm).

Land Use	Rain Gardens	Permeable Pavements	Rainwater Harvesting Tanks
UHD	22.45	32.52	12.94
UMD	19.11	32.52	12.94
UMC	17.83	32.52	12.94

2.7. Model Configuration

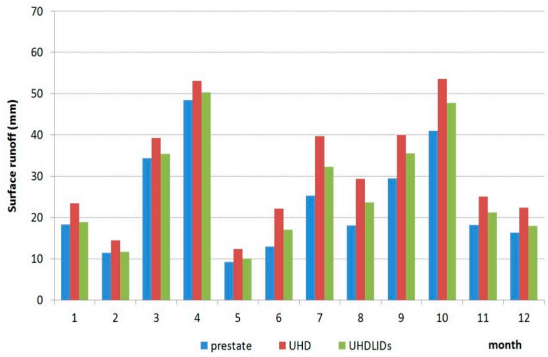
The model processing procedure was very similar to the steps of the previous work except for the urban land use to treat specific management practices. Other parameter values and input data were unaffected, and the current urban land use data was more detailed, to facilitate the application of LID practices to SWAT.

In order for RWHs and PPs to handle runoff only from roofs and parking lots, the roofs and the parking lots were separately allocated as different HRUs. They were manually partitioned from the existing HRUs of the residential and commercial areas by multiplying the current HRUs by percentages of the areas for the roofs and parking lots (Table 2). New urban data for the roofs and parking lots were added into the current urban data, and 100% impervious fractions were applied to their properties. Impervious fractions in which the roofs and parking lots were excluded were applied to the existing residential and commercial data. The urban type of the separated HRUs was replaced by new individual urban numbers for the roofs and parking lots, and the values that represent each type of LID practice were entered in the designated HRUs.

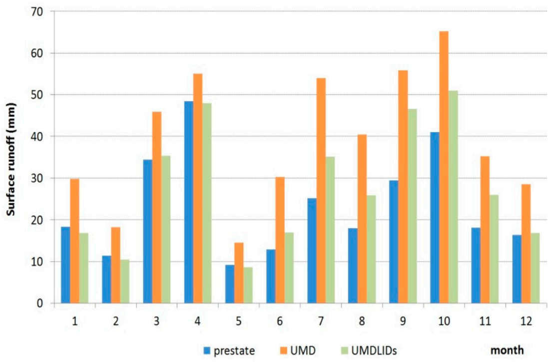
Through this process, a single type of LID practice was assigned to each HRU. That is, PPs were considered in the HRUs of the parking lots, RWHs in the HRUs of the roofs, and RGs in the HRUs of the residential urban areas. The same process was individually implemented for the three land uses. The simulation was conducted from October 2006 to December 2011. Average monthly and yearly results over the continuous periods were analyzed for all scenarios along with statistical analysis in order to evaluate the watershed-wide effectiveness of LID practices on surface runoff, nitrate, and TP. For the statistical analysis, a *t*-test was conducted for daily surface runoff, nitrate, and total phosphorus data from precipitation events above 0.5 inches among scenarios to a 95% confidence level. All *t*-tests conducted had more than 150 data points (n).

3. Results and Discussion

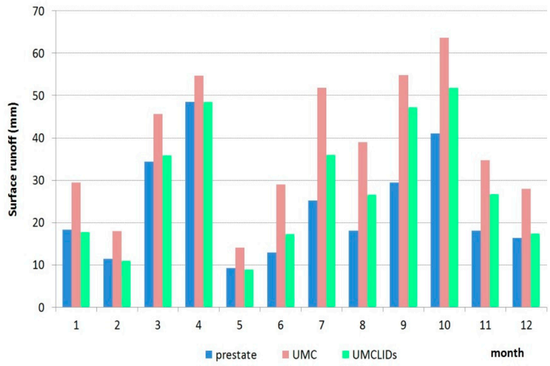
The performance of simulated LID practices positively affected all variables for all land uses. Figures 4–6 and Table 5 represent the average monthly and yearly responses of LID practices for each land use. As part of the surface runoff was detained by LID practices, the decreased surface runoff was denoted in the post-LIDs scenarios of all land uses, showing a tendency to follow the behavior of the pre-development state (Figure 4). The differences between the pre- and post-LIDs scenarios were extracted differently for each land use. For the UHD land use, 14% of the surface runoff was reduced, and 29% and 25% reductions were obtained in the UMD and UMC land uses, respectively, on an average annual basis (Table 5). The results showed statistically significant differences between the pre- and post-LIDs scenarios in all land uses (p-values < 0.05). The application of LID practices also had an influence on subsurface hydrology. Since the water detained by LID practices infiltrated into the soil layers, it increased the soil water content and, consequently, contributed to the increase of both evapotranspiration (ET) and groundwater (GW) for all land uses (Table 5). The amount of evaporation in a soil layer is determined by soil water content. Since the greatest effect of LID practices on surface runoff was in the UMD land use, the amount of infiltration in that land use was greatest. It increased soil water the most and led to the largest increase of ET. That is, ET was 10% greater under the UMDLIDs scenario than the UMD scenario, 8% greater under the UMCLIDs scenario than the UMC scenario, and 4% greater under the UHDLIDs scenario than the UHD scenario. In addition, increased soil water affected the increase of groundwater, representing the same order of increase with ET: that is, UMD land use > UMC land use > UHD land use. As seen from these results, the decrease of surface runoff by LID practices was closely related to the increase of ET and GW, indicating that the hydrologic behavior by LID practices was adequately simulated in SWAT.



(**A**)



(**B**)



(**C**)

Figure 4. Average monthly response of LID practices for surface runoff (SURQ) in each land use: (**A**) Compact high-density urban land use (UHD); (**B**) Conventional medium-density urban land use (UMD); and (**C**) Conservational medium-density urban land use (UMC). The term 'prestate' in the chart means pre-development condition.

Table 5. Average annual response of LID practices under each land use (GWQ: Flow to groundwater; ET: Evapotranspiration; NO_3: Nitrate Loading; TP: Total phosphorus loading.

Scenario	SURQ (mm)	GWQ (mm)	ET (mm)	NO_3 (kg)	TP (kg)	Difference (% Reduction)		
						SURQ (mm)	NO_3 (kg)	TP (kg)
UHD UHDLIDs	374.66 321.69	45.76 63.19	855.66 893.13	430.92 329.55	431.64 385.19	52.97 (14%)	101.37 (24%)	46.45 (11%)
UMD UMDLIDs	473.32 337.81	15.78 79.17	797.02 874.85	591.87 405.85	449.55 338.86	135.51 (29%)	186.03 (31%)	110.69 (25%)
UMC UMCLIDs	462.73 344.93	15.80 74.74	808.16 872.13	577.19 406.68	443.46 346.03	117.80 (25%)	170.51 (30%)	97.43 (22%)

In urban areas, pollutants are generally dependent on surface runoff. According to the decrease of surface runoff by LID practices, the runoff-borne pollutants, nitrate (NO_3) and total phosphorus (TP), also showed decreases in the post-LIDs scenarios of all land uses (Figures 5 and 6 and Table 5). Nitrate loadings were reduced by 24%, 31%, and 30% in the UHD, UMD, and UMC land uses, respectively, and the results represented significant differences between the pre- and post-LIDs scenarios in all land uses (p-values < 0.05). TP loadings decreased 11%, 25%, and 22% in the UHD, UMD, and UMC land uses, respectively, on an average annual basis, and the results also showed statistically significant differences between the pre- and post-LIDs scenarios (p-values < 0.05), except for the UHD land use.

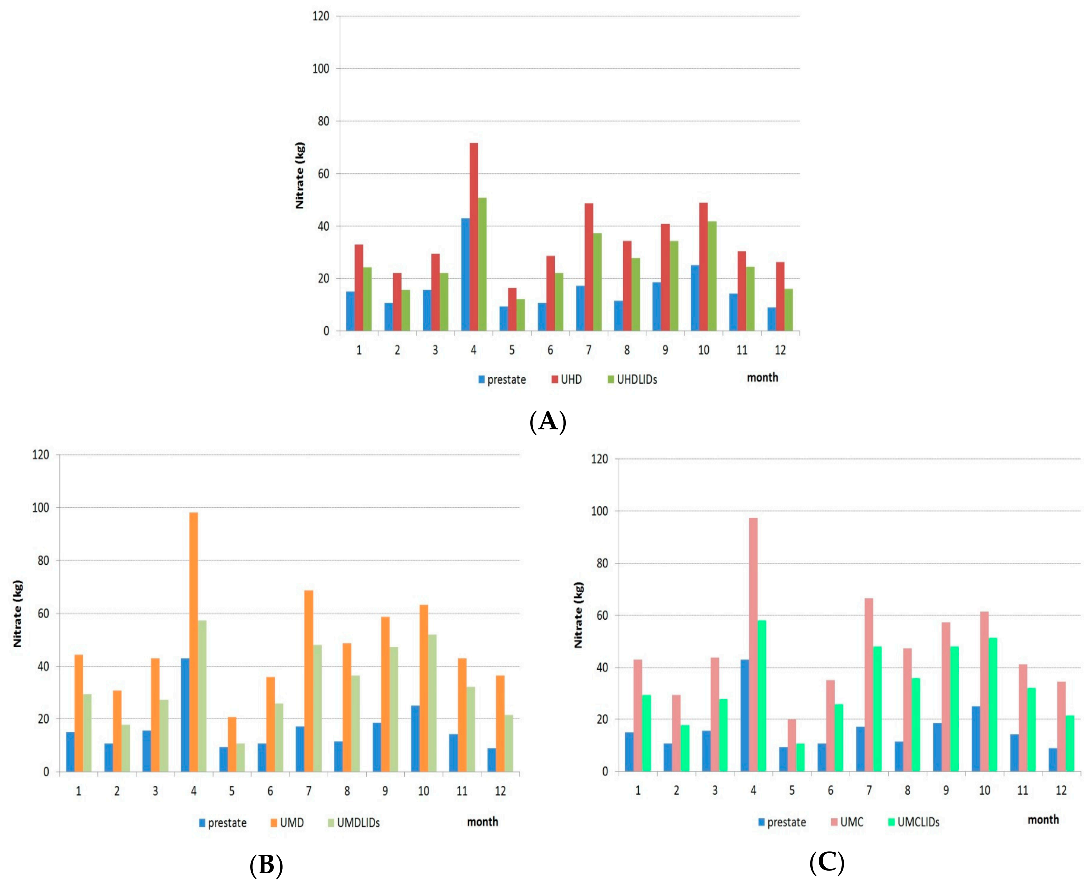


Figure 5. Average monthly response of LID practices for nitrate (NO_3) in each land use: (**A**) Compact high-density urban land use (UHD); (**B**) Conventional medium-density urban land use (UMD); and (**C**) Conservational medium-density urban land use (UMC). The term 'prestate' in the chart means pre-development condition.

Overall, the degree of contribution of LID practices for all variables was smallest in the UHD land use followed by the UMC land use, and it was largest under the UMD land use. This could be attributed to the difference in the area covered by LID practices among land uses. The unit reduction amounts by LID practices only in each urban area were largest in the UHD land use for all variables, as seen in Table 6. However, the UHD land use had the smallest urban area and the smallest area covered by LID practices among land uses, and thus the percent reduction by LID practices was smallest in the UHD land use. The pre-development scenario was plotted along with the pre- and post-LIDs scenarios (Figures 4–6), and was statistically analyzed with post-LIDs scenarios for the purpose of observing the effect of LID practices (Table 7). From the results, it was observed that the post-LIDs scenarios were statistically similar to pre-development conditions for surface runoff and total phosphorus. In other words, LID practices reduced the increases in surface runoff and total phosphorus from the development to pre-development state. However, with regards to nitrate, all post-LIDs scenarios were significantly higher than the pre-development condition. That is, the application of LID practices could not bring the negative effect of nitrate back to the pre-development condition.

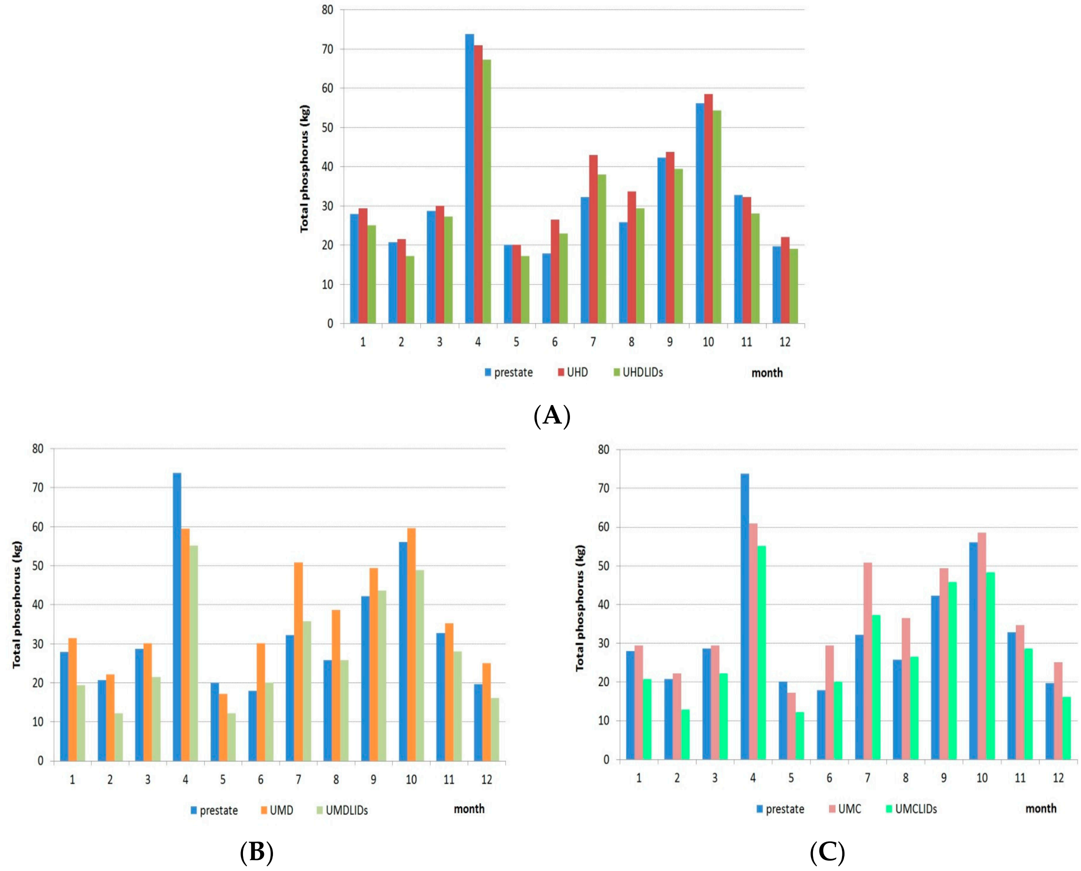


Figure 6. Average monthly response of LID practices for total phosphorus (TP) in each land use: (**A**) Compact high-density urban land use (UHD); (**B**) Conventional medium-density urban land use (UMD); and (**C**) Conservational medium-density urban land use (UMC). The term 'prestate' in the chart means pre-development condition.

Table 6. Unit reduction amounts of surface runoff and nutrients by LID practices only in the urban area for each land use.

Land Use	Surface Runoff (mm)	Nitrate (kg/ha)	TP (kg/ha)
UHD	257.23	1.37	0.63
UMD	242.73	0.93	0.55
UMC	211.01	0.85	0.49

Table 7. Statistical results (p-values) from the t-test between pre-development and each post-LIDs scenario for all variables.

Scenario	Pre-Development		
	Surface Runoff	Nitrate	TP
UHDLIDs	0.577	0.0025 *	0.72
UMCLIDs	0.382	1.00×10^{-6} *	0.32
UMDLIDs	0.439	1.60×10^{-6} *	0.34

Note: * indicates a statistically significant difference.

For the comparison among the final results of post-LIDs scenarios, low surface runoff and pollutant amounts were observed under different urban land uses (Table 5). In the case of surface runoff and nitrate, low values were achieved under the UHDLIDs scenario among the post-LIDs scenarios. This was because the impact of the UHD land use itself was the smallest among the land uses because of its small proportion of urban area, indicating statistically significant differences from both UMD and UMC land uses (Table 8). Thus, although the reduction caused by the application of LID practices was smallest under the UHD land use, it exhibited the lowest surface runoff and nitrate values achieved. In sequence, the UMDLIDs scenario showed a low value in comparison to the UMCLIDs scenario. The result was opposite that of the UMD and UMC scenarios. That is, less surface runoff and nitrate were generated under the UMC land use because it had a higher pervious fraction than the UMD land use, but after applying LID practices, less surface runoff and nitrate were shown in the UMD land use. This could be because while the area covered by RGs and RWHs was the same under the two land uses, the area covered by PPs was larger, as much as the difference of the parking lot area (16%), in the UMD land use compared to that in the UMC land use (Table 2). Contrary to the surface runoff and nitrate, the high value of TP was shown in the UHDLIDs scenario. This result was in contrast with the result from the pre-LIDs scenarios which represented a low TP value in the UHD scenario. This was seen because although the UHD scenario indicated a low value for TP, this was not a relatively lower TP value than those of the UMD and UMC scenarios (statistically significant differences were not indicated, showing *p*-values above 0.05) and the effect of the LID practices was also insignificant between the UHD and UHDLIDs scenarios (the *p*-value between the two scenarios was 0.0662). Table 8 provides the results of the statistical analysis for all pre- and post-LIDs scenarios for all variables.

Table 8. Statistical results (*p*-values) from the *t*-test for all pre- and post-LIDs scenarios.

		Surface Runoff			
Scenario	**UHD**	**UHDLIDs**	**UMC**	**UMCLIDs**	**UMD**
UHDLIDs	2.00×10^{-10} *	-	-	-	-
UMC	1.10×10^{-6} *	5.30×10^{-14} *	-	-	-
UMCLIDs	0.11	0.10	5.20×10^{-7} *	-	-
UMD	1.60×10^{-7} *	7.70×10^{-15} *	0.67	9.10×10^{-8} *	-
UMDLIDs	0.04 *	0.26	9.00×10^{-8} *	0.71	1.50×10^{-8} *
		Nitrate			
Scenario	**UHD**	**UHDLIDs**	**UMC**	**UMCLIDs**	**UMD**
UHDLIDs	1.40×10^{-5} *	-	-	-	-
UMC	3.40×10^{-7} *	2.00×10^{-16} *	-	-	-
UMCLIDs	0.8565	8.20×10^{-5} *	1.00×10^{-5} *	-	-
UMD	8.30×10^{-8} *	2.00×10^{-16} *	0.8631	3.70×10^{-6} *	-
UMDLIDs	0.7780	0.0003 *	7.20×10^{-7} *	0.6759	2.10×10^{-7} *
		Total Phosphorus			
Scenario	**UHD**	**UHDLIDs**	**UMC**	**UMCLIDs**	**UMD**
UHDLIDs	0.0662	-	-	-	-
UMC	0.6070	0.0709	-	-	-
UMCLIDs	0.0006 *	0.0257 *	0.0012 *	-	-
UMD	0.3109	0.0224 *	0.6773	0.0003 *	-
UMDLIDs	0.0007 *	0.0314 *	0.0014 *	0.9193	0.0004 *

Note: * means a statistically significant difference.

Before applying LID practices to urban developments, UHD land use might be the best choice for minimizing the impact of urbanization on surface runoff and pollutant loadings, as shown in other studies [17,18,35]. Jacob and Lopez [18] mentioned the advantage of higher density development outperforming traditional stormwater BMPs in pollutant reductions, due to the decrease of a runoff-generating area. However, after the application of LID practices to urban developments, all post-LIDs scenarios performed better than the UHD scenario (Table 5). Statistically, the UHD scenario represented significant differences from the UHDLIDs and UMDLIDs scenarios in surface runoff, from the UHDLIDs scenario in nitrate, and from the UMCLIDs and UMDLIDs scenarios in TP (Table 8). In addition, when LID practices were applied to urban developments, the advantage of the UHD land use decreased. For example, in the case of surface runoff, although the UHDLIDs scenario showed the lowest value among post-LIDs scenarios, the results of all post-LIDs scenarios were very similar, not representing statistically significant differences (p-values > 0.05). This was seen because the UHD land use used in this study had a lower urban density than the ones usually used in other studies, and thus LID practices could make the impact of urban development more or less equal altogether. On the contrary, in the case of TP, the highest value was obtained in the UHDLIDs scenario, and statistically significant differences among post-LIDs scenarios existed (p-values < 0.05). From these results, the UHD land use should not be considered as the perfect choice in reducing runoff and pollutants when LID practices are applied to urban developments.

4. Conclusions

The present study provided an opportunity to examine the impacts of LID practices on flow and pollutant loadings under three land uses with different urban patterns and to develop a model for simulating the examined LID practices in SWAT. The method of representing LID practices in SWAT was flexible and easily applicable. There is no model that completely incorporates all the requirements to simulate various LID practices, but the developed model performed well for the simulations of surface and subsurface hydrology and the consequential water quality. The results demonstrated an applicability of the examined LID practices in SWAT. It is worth noting that the model only addressed three of the four main LID practices (Green roofs were excluded due to cost of construction). For proprietary and site specific LID practices, the model would need to be modified on a case by case basis. In addition, reduction rates from field studies in Texas were used in this paper. The use of data from local projects would enhance the model results when used in other regions.

The application of LID practices contributed to the reduction of surface runoff and pollutants under all land uses, and the effectiveness of LID practices was demonstrated differently for each land use in the watershed. The reductions were statistically significant in terms of the differences between pre- and post-LIDs scenarios under all land uses for all variables (p-values < 0.05), except for TP between the UHD and UHDLIDs scenarios (p-value = 0.0662 > 0.05). However, despite the significant contribution of the LID practices in most cases, a large amount of surface runoff could still be generated by heavy precipitation because LID practices are limited in capacity and area in land use. The Harris County Flood Control District (HCFCD) and the Harris County Public Infrastructure Department Architecture & Engineering Division (HCPID-AED) require new urban areas to follow a minimum detention rate of 0.55 ac-ft per acre in order to control flooding. In considering this requirement, it is necessary to study other alternatives that can cover the rest of the volume besides the volume of the LID practices. This is beyond the scope of the present study and thus was not examined.

The results among post-LIDs scenarios showed that the UHD land use performed better in achieving the low values for surface runoff and nitrate than the other land uses, and UMD land use led to obtaining the low value for TP. Testing of the effectiveness of LID practices under different designs could provide useful information on an optimal design. Such results would help regulators develop effective LID policies on a city scale which could enhance the solutions for runoff and pollutant problems for their watersheds. In addition, it should be noted that the results can be changed if considering different watersheds with different soils, slopes, and land use properties, and different conditions such as types and allocations of LID practices, or a budget of LID implementation. Therefore, it is recommended that simulations be performed in advance under the development policy of a region prior to constructing LID practices.

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