MODELING LOW IMPACT DEVELOPMENT AT THE SMALL-WATERSHED SCALE: IMPLICATIONS FOR THE DECISION MAKING PROCESS

A Dissertation

by

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ABSTRACT

Negative effects of urban stormwater runoff on water environment have been a growing concern in the United States. Drastic change in land uses to urban communities with pavements from natural land uses can destroy the already established eco-hydrologic system prior to the land conversion. Low Impact Development practices (LIDs) have been used as an alternative stormwater management approach in urban areas. The effects of LIDs on hydrology and water quality have been widely accepted to be positive through research that generally indicates decrease in surface runoff volume and pollutant loads. However, LIDs can have varying effectiveness under different conditions. In this research, the effectiveness of LIDs was assessed under three urban development plans (compact high-density (UHD), conventional medium-density (UMD), and conservational medium-density (UMC)) and under various configurations of LIDs factors (types, locations, and percent allocations) for surface runoff, nitrate, and total phosphorus in order to identify their performance on improving stormwater runoff and water quality under such conditions.

Rain gardens, rainwater harvesting systems, and permeable pavements, commonly used in urban areas, were selected. The Soil and Water Assessment Tool (SWAT) was modified to implement the LIDs simulations at a watershed scale. A manual optimization was attempted to identify the LIDs configurations that meet targeted reduction amounts in a cost-effective manner. Then the effectiveness of LIDs was evaluated for the three urban plans and for the optimized LIDs configurations.

The research indicates that the effectiveness of LIDs varies under various conditions examined. Under urban development plans, the efficiency of LIDs was measured in the order of the following land uses for all variables: UMD > UMC > UHD. Among post-LIDs scenarios, the UHD scenario resulted in low amounts in surface runoff and nitrate while the UMD scenario predicted low TP yields. Under LIDs factors through the optimization, the various configurations of type, location, and percent allocation changed the effectiveness of LIDs and/or caused the same effectiveness of LIDs for each variable. This research is useful in that it can ultimately suggest proper strategies in urban watersheds to effectively control stormwater and help regulators establish effective LID policies based on the results.

DEDICATION

To my mom, dad and brother

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NOMENCLATURE

BMPs	Best Management Practices
LIDs	Low Impact Development practices
NCDC	National Climate Data Center
NO_3	Nitrate
NRCS	Natural Resources Conservation Service
post-LIDs	Post-development state with LIDs (indicates all of UHDLIDs, UMCLIDs, and UMCLIDs)
PPs	Permeable pavements
pre-LIDs	Post-development state without LIDs (indicates all of UHD, UMC, and UMC)
prestate	Pre-development state
RGs	Rain gardens
RWHs	Rainwater harvesting systems
SURQ	Surface runoff
TCEQ	Texas Commission on Environmental Quality
TP	Total phosphorus
UHD	Post-development state with a compact high-density urban form
UHDLIDs	Post-development state of a compact high-density urban form with LIDs

UMC	Post-development state with a conservational medium-density urban form
UMCLIDs	Post-development state of a conservational medium-density urban form with LIDs
UMD	Post-development state with a conventional medium-density urban form
UMDLIDs	Post-development state of a conventional medium-density urban form with LIDs
USGS	United States Geological Survey
USDA	United States Department of Agriculture

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CHAPTER I

INTRODUCTION

Overview

Problems from stormwater have been on the rise in recent years in the United States. During precipitation events, surface runoff and pollutants from nonpoint pollution sources flow over land surfaces and arrive and accumulate in final water bodies such as rivers and lakes. The increase of impervious surfaces by urbanization and population growth can accelerate such a situation and thus can make stormwater problems by the surface runoff and pollutants serious. For example, urban impervious surfaces exacerbate stormwater problems by generating runoff during rainfall without any natural handling. They change runoff patterns by increasing flows in wet weather and making low flows dry up during drought periods (Jeong et al., 2011). The changed runoff patterns make streams or rivers fluctuate dramatically. Impervious surfaces decrease the amount of infiltration into soil layers and increase the amount of runoff from surfaces. Increased surface runoff makes flow velocity much faster and results in high peaks during a short time. In addition, urban impervious surfaces can lead to deteriorated water quality in water bodies because water deterioration is closely associated with the amount of impervious surfaces (Schueler, 1992; Schueler, 1994; Arnold and Gibbons, 1996). The increased and accelerated runoff by urban surfaces increases sediment transporting capacity and accordingly increase sediment and sediment attached pollutant yields. Excessive nitrogen and phosphorus in streams can be attributed to the use of fertilizer in urban regions for managing land such as lawns in residential areas, parks, and golf courses. These problems should be necessarily dealt with from an environmental perspective.

However, it is difficult to restrict fast development leading to urbanization because of these problems. Therefore, with development, a new approach to preserve the water environment is needed. As an alternative stormwater management approach, Low Impact Development practices (LIDs, equivalent to urban Best Management Practices; urban BMPs) have received much attention and have been installed as adequate tools for controlling stormwater quantity and quality in many urban areas. The effects of LIDs on hydrology and water quality have been studied through much research. The positive effects of LIDs have been proven by showing reductions of surface runoff volumes and pollutant loadings through many field experiments (e.g., Bean et al., 2007; Collins et al., 2008; Dietz and Clausen, 2008; Hunt et al., 2006 and 2008; Jaber and Guzik, 2009) and through modeling approaches (e.g., Abi Aad et al., 2009; Ackerman and Stein, 2008; Carter and Jackson, 2007; Damodaram et al., 2010; Jeon et al., 2010; Jeong et al., 2013). However, it is necessary to study the implementation of LIDs with respect to urban patterns and types, locations, and percent allocations of LIDs. A limited number of previous studies have evaluated the effects of LIDs under those kinds of conditions (e.g., Brander et al., 2004; Gilroy and McCuen, 2009). The simulation of LIDs has seldom been performed at a watershed scale. In addition, there have been no studies for a manual optimization method to determine optimal LIDs conditions for the analysis of the effectiveness of LIDs. Such studies are needed as they can ultimately provide information for establishing proper watershed-wide strategies to effectively manage watersheds.

The Clear Creek watershed including the study area is a highly developed region in which a large portion of lands is impervious cover. Large amounts of surface runoff and pollutants are generated from the impervious areas and flow to the main stream, Clear Creek, thus aggravating its natural condition. Such a circumstance has a negative influence, especially, on the study area which is located downstream near the bay because coastal zones are the final repository from upper regions (Culliton, 1998; Howarth et al., 2002). The study area is characterized by slow flow on mild slopes and high water volume by tidal currents because of its geographical location such that more water problems are generated in this region than in other regions including flooding and eutrophication caused by stratification. Many pollutants such as bacteria, sediment, nitrogen, and phosphorus have been of great concern in the estuarine area (USEPA, 2007). Moreover, the study area is in the midst of planning for regional development. This area has been planned for installation of LIDs to minimize negative impacts of stormwater runoff on to water bodies.

Objectives of the Research

The overall objective of this research is to evaluate the effectiveness of LIDs on water quantity and quality under various conditions such as different urban patterns and various LID design practices including types, locations, and percent allocations in order to ultimately suggest proper planning and design of LIDs projects at a watershed scale. To achieve this goal, three specific goals are addressed in the study.

- Evaluate the effect of urban designs on runoff volume and quality
- Evaluate the effect of LIDs implementation on three urban designs
- Optimize type, location, and percent allocation of LID practices at a watershed scale for decision making guidelines

The study is organized into five chapters. Chapter I and Chapter V provide, respectively, a general introduction to the problems and the objectives addressed herein and overall conclusions and recommendations which summarize the results of each chapter and suggest future research. Each of the tasks is specifically addressed in the rest of the chapters as follows:

- In Chapter II, the impact of land use change in different patterns of urban development on hydrology and water quality is first examined. This study is ultimately for the purpose of employing the results of post-development states as baseline data for the next step, the application of LIDs. In this chapter, a pre-development state and post-development states based on three different urban designs are addressed to identify how different urban designs affect hydrology and water quality. The results are evaluated for each urban land use and the effective urban designs that can minimize the impact of urbanization are determined.

- In Chapter III, the application of LIDs to three types of urban design is addressed to evaluate the effectiveness of LIDs on water quantity and quality under different urban types and to determine optimal urban patterns that result in the greatest improvement. In this chapter, post-development states without LIDs (pre-LIDs scenarios) and post-development states with LIDs (post-LIDs scenarios) are addressed, and a hydrologic model development is attempted for simulating LIDs.
- Chapter IV addresses evaluation of the effectiveness of LIDs under various combinations of LIDs design guidelines for types, locations, and percent allocations, based on typical urban land use. In this chapter, LIDs conditions are considered along with the economic aspect which covers initial installation, management, and maintenance of LIDs, and a manual optimization is addressed to identify the optimal LIDs conditions that reduce stormwater runoff and pollutant loadings in a cost-effective manner. The effectiveness of LIDs is evaluated based on the optimized results.

For these studies, three types of urban design are employed, which were obtained from League City, Texas: a compact high-density urban form, a conventional medium-density urban form, and a conservational medium-density urban form. Three types of LIDs, rain gardens, permeable pavements, and rainwater harvesting systems, are applied to urban designs. The SWAT model is used because it has sufficient capability to simulate the impact of land use change and to represent hydrologic behavior by the application of LIDs. The effectiveness of LIDs is evaluated for surface runoff, nitrate, and total phosphorus.

CHAPTER II

MODELING THE IMPACT OF LAND USE CHANGE USING DIFFERENT URBAN DEVELOPMENTS ON WATER QUANTITY AND QUALITY USING SWAT

Introduction

Urbanization has been a main cause of stormwater problems. Urban development alters hydrologic patterns and aggravates water quality by not exerting a natural ability to attenuate runoff and water quality pollution. A runoff volume is accordingly elevated even if the total amount of water is the same as for the natural state. Flow velocity becomes much faster and the quickened flow velocity engenders high erosion and excessive nutrient loading.

The impact of land use change to urban areas on hydrology and water quality has been observed in many studies through modeling work. For example, Pisinaras et al. (2010) tested water volumes and nitrate and soluble phosphorus loadings according to the impact of the three types of land use changes (conversion to deforestation, urbanization, and agricultural land) using a Soil and Water Assessment Tool (SWAT) model. Bhattarai et al. (2011) investigated water yields and sediment, organic-N, and organic-P loadings under two land use data for the increase of developed and agricultural areas corresponding to the decrease of forest areas using a Better Assessment Science Integrating Point and Non-point Sources (BASINS) model. The studies revealed that the more impervious surfaces were increased, the more runoff and pollutant loadings were generated.

However, most studies have considered a small portion of land use changes to urban areas and focused mainly on changes to agricultural lands. The land use changes to a large proportion of developed areas were just performed in the limited number of studies. For instance, Parker (2010) simulated the impact of two similar types of mixed-use urban developments on stormwater runoff and pollutant loadings in two different regions of North Texas using SWAT. He proved the capabilities of SWAT in modeling urban watersheds and demonstrated similar results of runoff exceeding 50% of precipitation and the consequential nutrient loads in both regions. He additionally pointed out through the results that differences in water quantity and quality could exist depending on how urban areas are designed. However, few studies have addressed variations of hydrologic and water quality responses depending on different urban designs. Girling and Kellett (2002) compared three urban designs which have different dwellings and impervious/pervious areas by using CITYgreen and the Simplified Urban Nutrient Output Model: a conventional low density plan, a neighborhood village plan (denser than the conventional low density plan), and an open space plan (similar to the neighborhood village plan with more open space). They documented that the neighborhood village plan showed higher peak flow and nitrogen and phosphorus loads than the other two designs because of high impervious surfaces and low open space and urban forests. Yang and Li (2011) evaluated the impact of two different urban planning types (high-density and low-density residential) on streamflow in the Panther Creek watershed in Houston, TX using SWAT and concluded that lower amounts of runoff were generated in high-density scenarios compared to low-density scenarios under the same percentage of imperviousness in both scenarios. A similar result was included in Jacob et al.'s (2009) study that assessed high-density development through comparison with standard suburban developments under a constant population using a simple spreadsheet model. No studies were found that have conducted watershed-wide modeling according to different urban development using SWAT.

The city of League City, TX, within the Clear Creek watershed, has experienced urbanization and has further future plans for regional development. Studies of hydrologic and water quality impact under various types of urban development are needed before performing construction because such studies could elucidate which urban designs could minimize the negative impact of new development on the environment.

In this regard, the presented study examined the impact of land use change using different urban design concepts on water quantity and quality at a watershed scale. To achieve the objective, calibration for a current pre-development state was first performed in order to obtain baseline data that adequately represented the characteristics of a study area. Simulations were conducted for a total of 8 years from 2004 to 2011 to specifically investigate streamflow, total oxidized nitrogen (TON, equal to the sum of nitrite (NO_2) and nitrate (NO_3) nitrogen), and total phosphorus (TP) both on a monthly and daily basis, using SWAT. A Sequential uncertainty fitting 2 (SUFI2) program was used for the purpose of calibrating model results and quantifying model uncertainties. After simulation, new land uses with different urban patterns were applied to the study area to identify hydrologic and water quality responses between pre- and post-development states. The post-development states under different urban patterns were analyzed and compared to one another.

Methodology

Simulation Background and Study Area

The water quantity and quality for the pre-development state of the study area should have been first predicted to identify the impact of urbanization. However, there was not enough data to calibrate and validate the current water quantity and quality in the study area. In particular, this area is included within an area which is influenced by tidal currents because it is located near an estuary of Clear Creek (Fig. 2.1). The Clear Creek watershed including the study area is divided into two stream segments, 1101 and 1102, by the Texas Commission on Environmental Quality (TCEQ). Segment 1101 (Clear Creek Tidal) is a tidal-affected region, and segment 1102 (Clear Creek Above Tidal) is a non-tidal region (TCEQ, 2014). The study area is located within tidal segment 1101, and there exist large uncertainties in calibrating the area by using very little observed data affected by the tidal currents. Thus, the entire Clear Creek watershed was considered for the purpose of calibration, and the calibration was only performed at an upstream gauging station (Site number: 08076997) that is not tidally affected and has observed data both regarding streamflow and water quality. The same parameters from the upstream calibration were then extended to the study area for simulating the current pre-development state. This approach was judged as applicable and reasonable in this situation because general watershed characteristics such as topography, hydrology, and climate are very similar over the entire watershed.

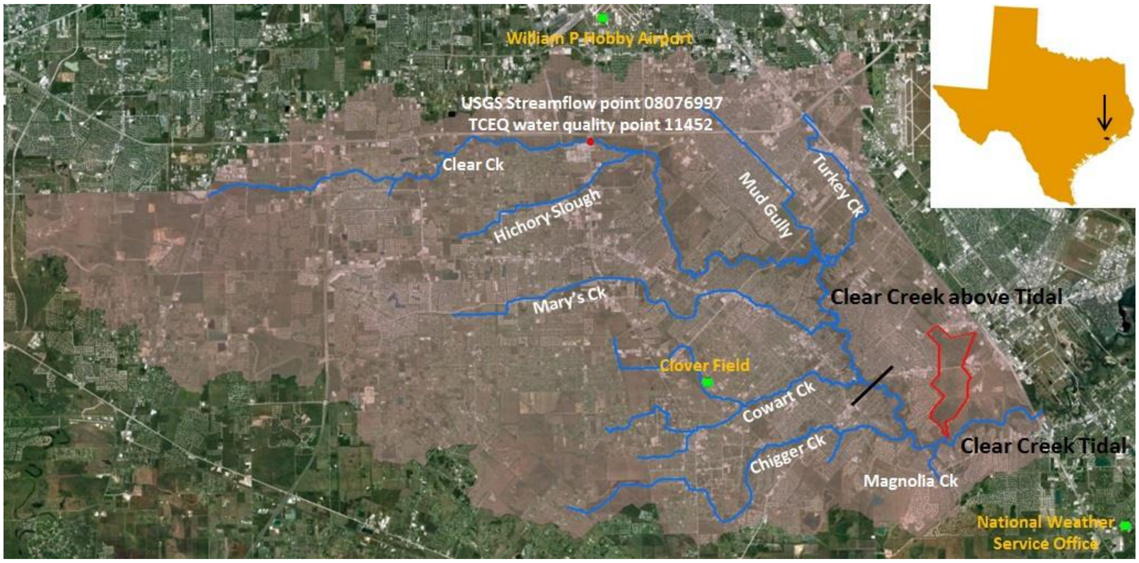


Figure 2.1 The Clear Creek watershed and the study area (red boundary)

The Clear Creek watershed is located to the south of Houston and nestled within West Galveston Bay (Hydrologic Unit Code: 12040204). It is contiguous to the Buffalo Bayou watershed of Buffalo-San Jacinto (Hydrologic Unit Code: 12040104) upward and the Dickinson Bayou watershed of West Galveston Bay downward. It is a medium-sized watershed which covers approximately 424 km^2. Clear Creek stretches northwestward and extends eastward until it meets Galveston Bay. Some tributaries flow into Clear Creek including: Chigger Creek, Cowart Creek, Mary's Creek/North Fork Mary's Creek, Turkey Creek, and Magnolia Creek. Clear Creek, including the tributaries, runs through Galveston, Harris, Brazoria, and Fort Bend counties. The elevation of this watershed ranges from 0 m downstream near Clear Lake to 39 m upstream, but around 85% of the area is between elevations from 8 m to 19 m. Most areas generally tend to have a gentle slope. This watershed is also characterized as having topography with low infiltration and high surface runoff potential, representing the predominant settings of urban land uses (63.23%) and hydrologic soil group (HSG) D (99.66%). In addition, the meteorological characteristics are very similar over the entire watershed. The climate of the watershed includes mild winters and hot summers. When cold air comes down from the northwest and meets the Gulf air, it can cause very powerful thunderstorms that occasionally form tornadoes. A comparison of the monthly precipitation and mean temperatures at three stations shows very similar patterns (Fig. 2.2). The yearly rainfall varies from 567.6 mm to 1,819.5 mm for the three stations, but annual average rainfall shows a slight difference within 8% based on the William P Hobby Airport station, which is located near the calibration point.

The study area is a small area of around 3.5 km^2 (350 ha). It encompasses some parts of Friendswood, Webster, and League City in Harris County. The topography is characterized as a gently rolling slope with an elevation ranging from 6 to 8 meters for approximately 90% of the area. Loam (Addicks) and clay loam (Bernard) constitute the predominant soil types, which take up around 61% and 27%, respectively. All the soils are low permeability of HSG D. As it is in a currently pre-developed state, forests, wetlands, hay, and rangeland comprise the land use of this area and wetland and hay are taking up around 60% of the total land use. However, some of the lands are scheduled to be changed to urban areas. A description for future land use is contained in the "Description of Land Use Change and Scenarios" section.

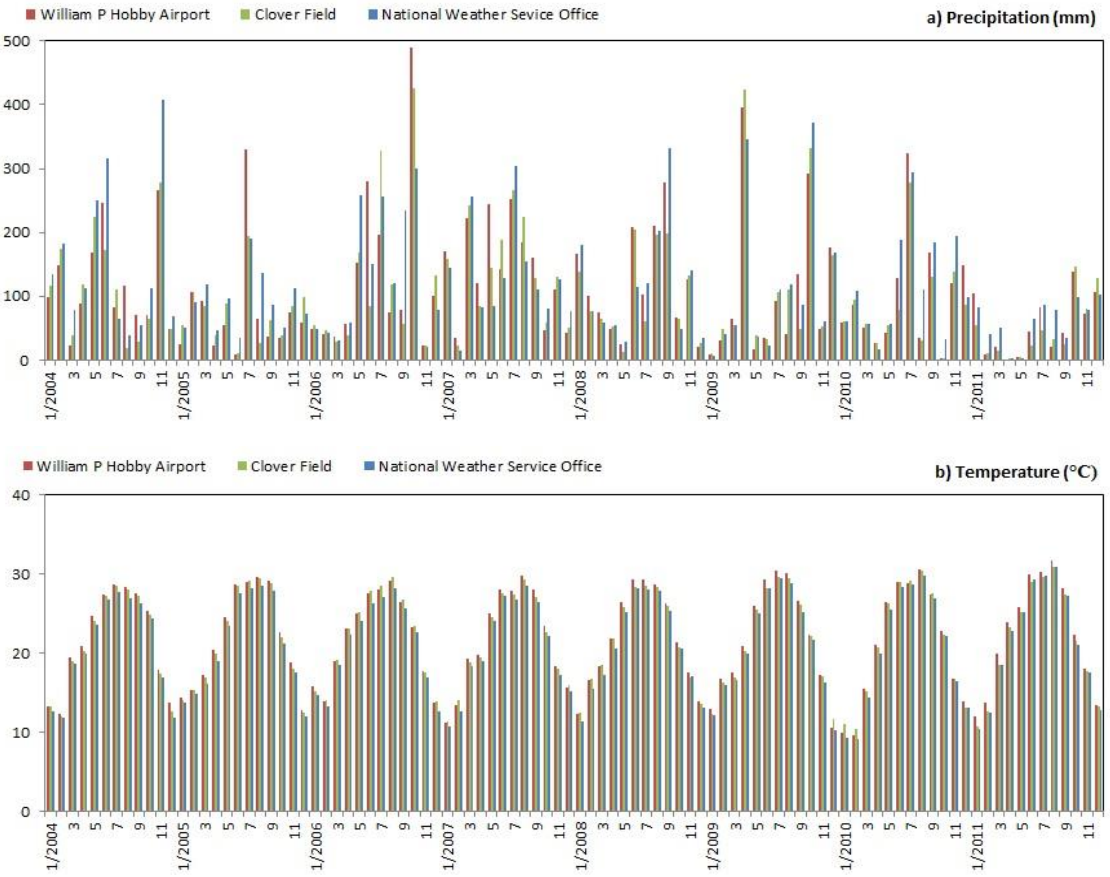


Figure 2.2 Comparison of precipitation and temperature at three weather stations

Model Description

SWAT, developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), is a model which has been widely used for simulating hydrologic processes and water quality trends according to land management scenarios. It possesses effective water quantity and quality components, and there are various pre- and post-processing tools such as SWAT-CUP (for model calibration), VIZSWAT (for model visualization and analysis), and SWAT-Check (for check of input parameter errors). It has been applied to a variety of conditions of simulation. Diverse scales of watersheds were simulated in investigating flow and pollutant loadings, including a small scale (Kannan et al., 2007), a medium scale (Pisinaras et al., 2010), and a large scale (Santhi et al., 2001). Sub-daily, daily, monthly, or yearly basis simulations have been performed, and Jeong et al. (2010) studied sub-hourly modeling capability. In addition, various watersheds have been applied to SWAT to simulate water quantity and quality, including a mountainous area (Lee et al., 2011; Rostamian et al., 2008), a karst-influenced area (Echegaray, 2009), and a coastal area (Bosch et al., 2004; Francos et al., 2001; Kannan, 2012; Lee et al., 2011). In particular, the capability to simulate urban settings has been verified (Parker, 2010; Yang and Li, 2011). SWAT is a very flexible model and is being constantly improved for better simulation.

The hydrologic cycle simulated in SWAT consists of land and water phases based on a water balance. The land phase deals with flow, sediment, nutrients, and pesticides on land in subbasins, while the movement of these constituents through channels to a final outlet is controlled by the water phase. SWAT can predict surface runoff volume by one of two methods: a modified Natural Resources Conservation Service (NRCS) curve number method (SCS, 1972) based on antecedent soil moisture condition, soil property, and land use or a Green & Ampt infiltration method (Green and Ampt, 1911) based on effective hydraulic conductivity and wetting front matric potential. This study used the curve number method. An amount of infiltration is estimated by the difference between precipitation and surface runoff under the curve number method, or it is directly calculated under the Green & Ampt infiltration method.

The movement of water into a soil layer occurs continuously until the soil layer has uniform water content. Percolation is caused when the soil layer is above the field capacity water content, and it ultimately contributes to groundwater recharge. Channel flow routing is modeled by the variable storage method (Williams, 1969) or the Muskingum method. Evaporation is separately computed from plants and soils. Plant transpiration is governed by potential evapotranspiration and leaf area index. From soils, potential evapotranspiration and soil cover index by biomass and residues estimate maximum soil water evaporation, and then water content and soil depth determine actual soil water evaporation. Potential evapotranspiration (PET) is estimated by use of three options: Penman-Monteith (Monteith, 1965; Allen, 1986; Allen et al., 1989), Priestley-Taylor (Priestley and Taylor, 1972), and Hargreaves (Hargreaves et al., 1985). The Penman-Monteith method was used in the present study.

Computation of sediment yield is performed under a Modified Universal Soil Loss Equation (MUSLE; Williams, 1975), which replaces the rainfall energy factor of a Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965 and 1978) with a runoff factor. SWAT provides four stream power models for estimating sediment routing for deposition and degradation in stream channels: a simplified Bagnold model (Bagnold, 1977; Williams, 1980), a Kodatie model (Kodoatie, 2000), a Molinas and Wu model (Molinas and Wu, 2001), and a Yang sand and gravel model (Yang, 1996).

The processes for nitrogen and phosphorus are also modeled by SWAT. Nitrogen entering soil layers through sources such as fertilizer, plant residue, and rain is transformed into five different forms (fresh, stable, and active organic forms and inorganic forms of NO_3 and NH_4) in the soil. The processes of plant uptake, denitrification, volatilization, leaching, and erosion eliminate nitrogen from the soil. For phosphorus, six different pools are monitored by SWAT: fresh (plant residue and microbial biomass), active (soil humus), and stable (soil humus) organic forms and solution, active, and stable inorganic forms. Plant uptake and erosion affect phosphorus removal from the soil. The kinetics of QUAL2E (Brown and Barnwell, 1987) controls in-stream nutrient routing. More detailed hydrologic and water quality processes are explained in Theoretical Documentation Version 2009 (Neitsch et al., 2011).

Description of Input Data

Specific spatial and temporal data, such as topography, land uses, soils, point sources, and meteorological data, were collected to run SWAT. Since stream network and watershed creation are affected by the spatial scale of topography, a 10 m × 10 m resolution Digital Elevation Model (DEM) was selected from USDA NRCS Geospatial Data Gateway for accurate simulation. SWAT already includes State Soil Geographic Database (STATSGO) and can directly use it for an application of soils. However, it is not adequate for a small study area because of its low resolution of 1:250,000. Thus, the Soil Survey Geographic Database (SSURGO), with a high resolution of 1:24,000, was used in this study. The data was obtained from USDA NRCS Soil Data Mart and processed as a SWAT format using a SSURGO data processor. A total of three weather stations were considered: Houston Clover Field, Houston William P Hobby Airport, and the Weather Service Office. The weather data of each station were collected for precipitation and maximum and minimum temperature from the National Climate Data

Center (NCDC) on a daily basis. Other weather data generated by weather generator were used for relative humidity, wind speed, and solar radiation. Each subbasin was given an impact from a weather station that is the nearest from the center of a subbasin. Fifteen waste water treatment plants (WWTPs) were considered as point sources for the simulation of the entire Clear Creek watershed. The data was obtained from TCEQ and the Environmental Protection Agency (EPA) Permit Compliance System (PCS), and daily average loading data were used. Typical Pollutant Concentrations (TPCs) data were also used to supplement the missing data of each facility. Seven WWTPs are included in Clear Creek, and the rest of them are included in each tributary. The loadings of WWTPs that exist at the same subbasin were all combined together and used as one dataset for the subbasin. No WWTPs are located within the study area. Considering these point sources is important because, even though discharges from each WWTP are small, the impact of the total amounts from several WWTPs can be great on streams. Streamflow data was obtained from the United States Geological Survey (USGS) Water Data on a monthly and daily basis at the station within the Clear Creek Above Tidal segment (Site number: 08076997). The water quality dataset was obtained from the TCEQ Surface Water Quality Monitoring Web Reporting Tool at the same location as the USGS streamflow station (Station ID: 11452). However, only a limited number of grab samples were reported because of the lack of water quality data. Thus, a USGS Load Estimator (LOADEST) program (Runkel et al., 2004) was used to calculate monthly loads. This is a program that calculates monthly constituent loads by using daily water quality and streamflow data based on statistical approaches. Detailed information can be found in the LOADEST document. Land use data was acquired from the USDA NRCS Geospatial Data Gateway, and the recent 2006 Land Cover dataset was used to represent the current state. The land use of the whole watershed is organized under 5 classes: urban area (63.23%), forest (1.82%), rangeland (1.73%), wetland (7.27%), and agricultural land (25.95%). The study area includes forest (25.71%), rangeland (15.35%), wetland (30.71%), and hay (28.23%). Urban designs for post-development simulations in the study area were obtained from the city of League City. The detailed post-development designs and land uses based on the designs are illustrated below. All data were projected using the same projection and datum, the Albers Equal-Area Conic projection with the North American 1983 datum, before using the data.

Description of Land Use Change and Scenarios

Three types of urban design with noticeable differences were introduced to parts of the study area: a compact high-density urban form, a conventional medium-density urban form, and a conservational medium-density urban form. The designs were developed by Edminster, Hinshaw, Russ and Associates, Inc. (EHRA) for the city of League City. For simulations, three land uses were created based on the different urban patterns from each design. They represent spatially different distributions of urban layouts and different percentages of urban areas under the same population in order for scenarios to be comparable. The urban areas of all land uses include residential and commercial areas. According to the proposed urban designs, hypothetical scenarios were constructed to identify how land use changes to different urban types would affect hydrologic and water quality processes.

The pre-development state was first simulated as a baseline scenario for evaluating the impact of the land use changes (designated as prestate). In this step, calibration, validation, and uncertainty analyses were processed. As previously described, the entire Clear Creek watershed was considered for the processes because of insufficient observed data and the influence of the tidal currents in the study area. The calibrated parameters held constant to the study area to better reflect the current watershed characteristics.

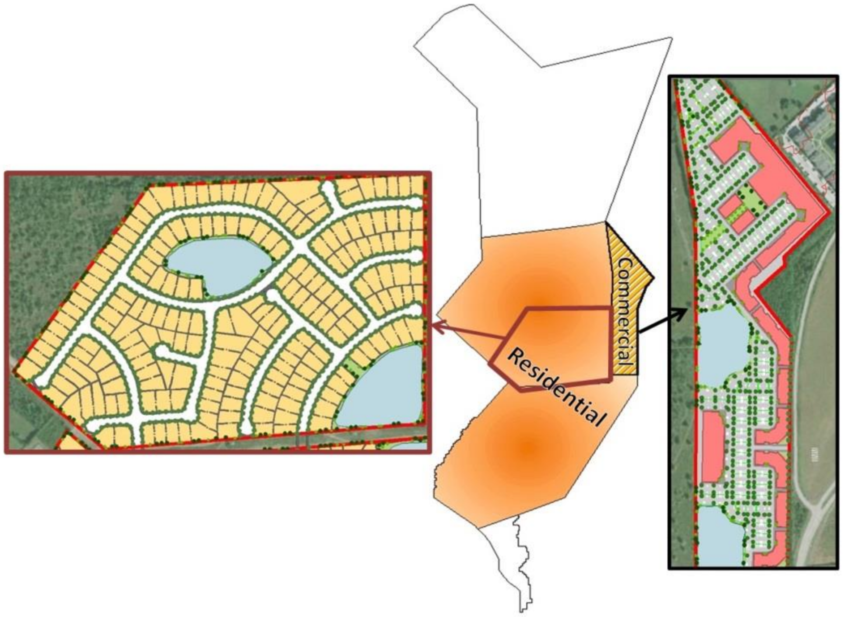
The land use with the compact high-density urban form (Dwelling Units per Acre (DUA):10 units/ac; > 8 units/ac is considered as residential high-density (Neitsch et al., 2011)) was considered as a first scenario (designated as UHD). It is characterized as a heavily developed area and maximized site perviousness. Thus, it is more distinctly divided into developed and undeveloped areas than the other two land uses. The urban area, constructed in the middle of the study area, takes around 21% of the total area which was changed from around 16% hay and 5% rangeland in the pre-development state. The urban area consists of 61% imperviousness and 39% perviousness in the residential area and 68% imperviousness and 32% perviousness in the commercial area, respectively. This urban design includes wide right-of-way and roof areas in the residential area and a large building area (Floor Area Ratio (FAR): 0.28) in the commercial area in proportion to the other two urban designs.

The land use with the conventional medium-density neighborhood form (DUA: 3 units/ac; 1-4 units/ac is considered as residential medium-density (Neitsch et al., 2011)) was taken into account as the second scenario (designated as UMD). This urban design is a typical pattern in the United States and is built with single family houses meeting a minimum lot size of 7,000 square feet (League City, 2014). It is a dispersed urban pattern so that it has a larger urbanized area than the compact high-density urban form. However, it has lower imperviousness and higher perviousness. On the whole, the land use represents about 56% urbanization, comprising 44% and 75% impervious covers in the residential and commercial areas, respectively. The urban area, constructed on the south part of the study area, was created by reduction of about 15% rangeland, 14% wetland, and 27% hay from the original land. The commercial area includes higher imperviousness than that of the high-density design even though it represents a lower floor area ratio (FAR: 0.23) than that of the high-density design. This is because it is composed of only one story buildings and has large outside parking areas. On the other hand, two-story parking garages are utilized with smaller-spaced outside parking lots in the high-density commercial area so that it can save the impervious area.

In the third scenario, the land use with the conservational medium-density neighborhood form (DUA: 3 units/ac; 1-4 units/ac is considered as residential medium-density (Neitsch et al., 2011)) was applied to the study area (designated as UMC). The base format of this urban design is similar to the second design, but it has restrictive requirements to conserve the existing area. The residential lots are separated into lots with and without deed-restricted green space. The lots with deed-restricted green space are limited with a maximum building coverage of 45% and a minimum green space of 40% for conservation. The urban area is the same as for the second land use, but is designed to have more open space. Impervious areas of 41% and 68% respectively are covered in the residential and commercial areas, which are that 3% and 7% impervious covers are decreased from the second design. The commercial area is characterized as a mixture of the two previous designs in that it has one- and two-story buildings and decreased outside parking areas. It has the same floor area ratio (FAR: 0.23) with the second design and has more open space than the second design, but its imperviousness is the same as for the commercial area of the high-density design because the walkable areas are more increased than in the other two designs.

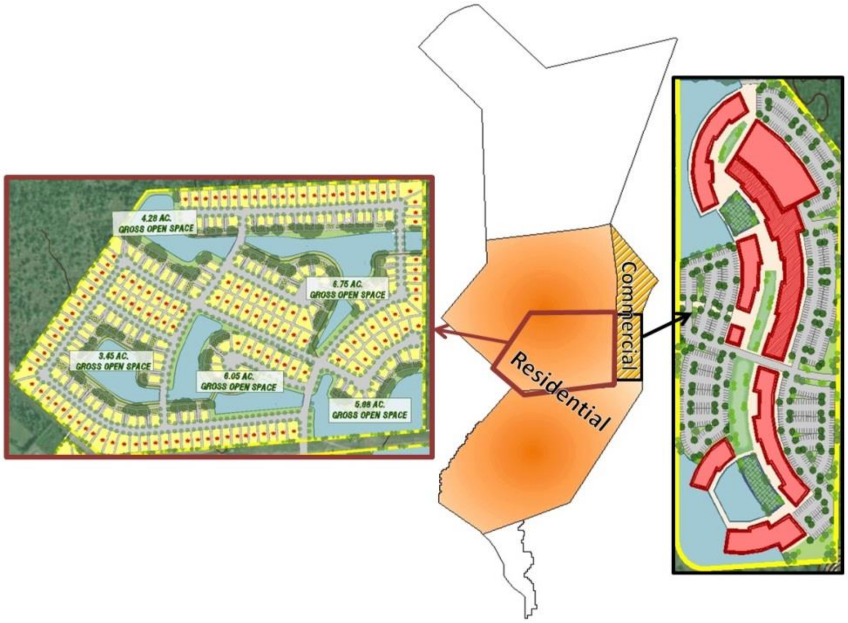
Overall, the residential areas are characterized differently for each urban land use, but the commercial areas are illustrated similarly. The rest of the area, with the exception of the urban area, is left in an undisturbed state in all land uses. The three urban layouts and detailed plans are presented in Fig. 2.3. Blowups show sections in the residential and commercial areas and those patterns are applied to entire urban areas. The percentage of land use changes to urban areas and the impervious/pervious fractions in the urban areas are summarized in Table 2.1. Simulations were performed based on the three land uses with the different urban types, and the changes of water quantity and quality were compared to one another and analyzed.

(A) UHD



(B) UMD

Figure 2.3 The urban layouts and detailed plans (Blowups are sections of the urban areas); (A) Compact high-density urban land use (UHD) (B) Conventional medium-density urban land use (UMD) (C) Conservational medium-density urban land use (UMC)



(C) UMC

Figure 2.3 Continued

Table 2.1 Percentage of land use change to urban areas for three scenarios

Scenario name	Land use description (based on each design)	Forest	Rangeland	Wetland	Hay	Urban	Impervious/pervious fraction (%)	
							Residential	Commercial
UHD	compact high-density urban development	0%	-5%*	0%	-16%	+21%*	61/39	68/32
UMD	conventional medium-density urban development	0%	-15%	-14%	-27%	+56%	44/56	75/25
UMC	conservational medium-density urban development	0%	-15%	-14%	-27%	+56%	41/59	68/32

*Negative and positive percentages respectively mean decrease and increase from the pre-development state

Calibration and Evaluation Approach

The calibration process for the pre-development state was performed by SUFI2, a tool that makes possible analyses of sensitivity, calibration, and uncertainty under Bayesian inference methods simultaneously. In SUFI2, sensitive and influential parameters are identified by a method of one-factor-at-a-time (OAT) sensitivity analysis for Latin Hypercube (LH) sampling, developed by Van Griensven et al. (2006). This LH-OAT method uniformly divides parameter ranges into N intervals and randomly samples only one value within the interval by changing parameters one at a time (Van Griensven et al., 2006). A degree of uncertainty is represented as a p-factor, which is a percentage of observed data bracketed by 95% prediction uncertainty (95PPU), and as an r-factor, which is the average thickness of the 95PPU band divided by a standard deviation of the observed data (Abbaspour, 2011). If most of the observed data are bracketed within the 95PPU of the most narrow uncertainty band, it means that its simulation is very good. The range of the p-factor is 0 to 1, and a p-factor of 1 indicates an exact match of simulated data with the observed data. Contrary to the p-factor, an r-factor of 0 represents a perfect match with the observed data, and the range is 0 to infinity. It is difficult to get these ideal values because of many errors and uncertainties. There is no specific standard that is considered satisfactory for these factors, but, generally, the r-factor is considered satisfactory when its value is less than 1. For the p-factor, it is considered desirable when it is greater than 0.5. A more detailed description for SUFI2 can be found in Abbaspour (2011).

Further goodness-of-fit measures were used to evaluate the performance of SWAT: the Nash-Sutcliffe efficiency (NSE), a coefficient of determination (R^2), and mean absolute error (MAE). The NSE and R^2 methods have been very commonly used in the evaluation of streamflow, sediment, and nutrients (Bosch et al., 2004; Du et al., 2009; Jha et al., 2007; Lee et al., 2011; Pisinaras et al., 2010; Santhi et al., 2001; White et al., 2005). The NSE represents how accurate simulations are against observations, and R^2 shows a degree of correlation for how dispersed simulations are against observations. Moriasi et al. (2007) explained model evaluation measures and satisfactory standards in detail. Legates and McCabe (1999) also recommended that absolute error measures with observed and simulated means and standard deviations should be represented with relative error measures such as NSE and R^2 for proper evaluation. They identified high evaluation values, which can occur as a result of squared differences in relative error measures. Willmott and Matsuura (2005) suggested the mean absolute error (MAE) as the most appropriate measure to account for evaluation of absolute error measures. Therefore, MAE was added with the mean and the standard deviation to properly measure the model performance. MAE describes mean model performance error for observed data, and it is regarded as low when it is below 50% of the standard deviation for the observations and the value of 0 represents an exact match with the observed data (Moriasi et al., 2007; Singh et al. 2005).

Model Processing Procedure

The entire watershed and multiple subbasins were first delineated through the process of creating stream networks by using 10m resolution topography data. From the auto-delineated watershed, the subbasin for the study area was manually modified to fit with a boundary of the pre-developed space where three land uses would be applied. Various land uses and soil properties were then overlaid and single slope was considered on each subbasin. The subbasins were discretized into Hydrologic Response Units (HRUs), minimal units which have homogeneous land use, soil property, and management. As a result, a total of 28 subbasins and 313 HRUs were finally created within the whole watershed. The calibration process was conducted by controlling parameters sensitive to hydrology and water quality within their acceptable range. Somewhat large parameter ranges were considered for the first calibration within which many observed data could be bracketed, and then the ranges were gradually narrowed down according to suggested ranges. Several calibration processes were carried out until the differences between the simulated and the observed were minimized so that the best goodness-of-fit values, such as the p- and r-factors, were met. Streamflow was calibrated as the first step of modeling before water quality constituents were calibrated. Nutrients are greatly affected by sediment transport, but sediment could not be calibrated because of the lack of observed data. Thus, sediment balance in the watershed was checked by the SWAT-Check program which checks potential model errors, identifies unusual predictions, and helps not to recalibrate a model which has problems. In the following, TP and NO_2 plus NO_3 were calibrated under the proper simulation of sediment. For nutrients, particular calibration needs were required because of low evaluation values from the auto-calibration. The manual calibration approach was attempted to fine-tune the parameters from SUFI2 for improving the evaluation values (Arnold et al., 2012). A total of 34 parameters were considered for the calibration. A list of final parameter values is represented in Table 2.2. For the validation, the same parameter values from the calibration were applied to different time periods. The simulation was conducted from Oct. 2006 to Sep. 2009 for the calibration and from Oct. 2009 to Dec. 2011 for the validation both on a monthly and daily basis.

Table 2.2 Considered parameters and their final values for the calibration

Variable	Parameter	Description	Final value
Flow	r*__SOL_AWC(1).sol	Available water capacity of the soil layer (mm H_2O/mm soil)	0.17 ~ 0.31
	r__SOL_BD(1).sol	Moist bulk density (Mg/m^3)	1.32 ~ 1.67
	r__SOL_K(1).sol	Saturated hydraulic conductivity (mm/hr)	0.18 ~ 150.15
	v*__ESCO.hru	Soil evaporation compensation factor	0.970
	v__EPCO.hru	Plant uptake compensation factor	0.902
	r__OV_N.hru	Manning's "n" value for overland flow	0.04 ~ 0.23
	v__SURLAG.bsn	Surface runoff lag time	0.248
	v__GW_REVAP.gw	Groundwater "revap" coefficient	0.08
	v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm H_2O)	167
	v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	103
	v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.034
	v__GW_DELAY.gw	Groundwater delay time (days)	153.75
	v__ALPHA_BF.gw	Baseflow alpha factor (1/days)	0.192
	r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	57 ~ 82

Table 2.2 Continued

Variable	Parameter	Description	Final value
Nutrients	r__USLE_K(1).sol	USLE equation soil erodibility (K) factor	0.247 ~ 0.332
	r__USLE_C.crop.dat	Min value of USLE C factor applicable to the land cover/plant	0.001 ~ 0.200
	v__SOL_ORGP(1).chm	Initial organic P concentration in surface soil layer (mg/kg)	52.20
	v__SOL_SOLP(1).chm	Initial labile (soluble) P concentration in surface soil layer (mg/kg)	34.74
	v__BIOMIX.mgt	Biological mixing efficiency	0.18
	v__PPERCO.bsn	Phosphorus percolation coefficient (10 m^3/Mg)	16.9
	v__PHOSKD.bsn	Phosphorus soil partitioning coefficient (m^3/Mg)	100.5
	v__PSP.bsn	Phosphorus sorption coefficient	0.051
	v__P_UPDIS.bsn	Phosphorus uptake distribution parameter	15
	v__CMN.bsn	Rate factor for humus mineralization of active organic nitrogen	0.0029
	v__GWSOLP.gw	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin (mg/L)	1.561
	v__ERORGP.hru	Organic P enrichment ratio	0.062
	v__SOL_ORGN(1).chm	Initial organic N concentration in the soil layer (mg/kg)	29.98
	v__SOL_NO3(1).chm	Initial NO_3 concentration in the soil layer (mg/kg)	66.5
	v__NPERCO.bsn	Nitrogen percolation coefficient	0.10
	v__RCN.bsn	Concentration of nitrogen in rainfall (mg/L)	1.656
	v__N_UPDIS.bsn	Nitrogen uptake distribution parameter	59.95
	v__SDNCO.bsn	Denitrification threshold water content	0.012
	v__SHALLST_N.gw	Concentration of nitrate in groundwater contribution to streamflow from subbasin (mg/L)	180.24
	v__ERORGN.hru	Organic N enrichment ratio	0.49

[*] Description of each qualifier; “v” means that parameter value is replaced by a value from the given range and “r” denotes the multiplication by one plus a given value (Abbaspour et al., 2007)

After the calibration and validation processes, the study area was extracted from the entire watershed to address the post-development state. The modeling setup for the post-development state was achieved as all inputs and parameters remained the same except for land use data. The three land use data were made by applying different urban areas and impervious/pervious fractions based on the future urban designs of League City and keeping the remaining land use as it is in the original state. The fractions of imperviousness and perviousness in the urban areas were obtained through each design CAD file. In cases in which there was no information in the designs, similar types of neighborhoods were sampled through the Google Earth program (Google Inc., Mountain View, CA) to obtain the impervious fractions. The connected and disconnected impervious fractions were determined by using the ratio from average values represented in the SWAT theoretical documentation. For urban sizes, the same commercial areas were kept for all land uses. For the residential areas, three times less area was reflected in the high-density residential area compared to the medium-density residential area in order to keep the same population. The subbasins of the study area were manually delineated based on the urban district of each land use data. The residential and commercial areas were individually defined as different subbasins in all land use data. The subbasins and each land use were then applied to the study area to evaluate the post-development states. New simulations were set up each time to represent different scenarios. From the process, 4 subbasins and 18 HRUs were treated for the UHD scenario and 5 subbasins and 18 HRUs for the UMD and UMC scenarios. Average monthly and yearly data for surface runoff, nitrate, and TP were analyzed to compare the pre- and post-development scenarios. Statistical analysis using t-test was also performed through a comparison of means for a 95% confidence level. For the t-test, the daily

SWAT data for surface runoff, nitrate, and total phosphorus from rainfall greater than 0.5 inches were used for comparing pre-development to post-development. The impact of urban development (UHD, UMD, and UMC) was compared to the pre-development state as well as to each other.

Results

Results of Calibration and Validation

The calibration result set up on a monthly basis for flow is represented in Fig. 2.4. The uncertainty analysis represented 56% of the observed data bracketed by the 95PPU with the value of 0.54 for the r-factor. The performance also verified strong agreements between the observed and the simulated data by representing the high values of 0.79 (R^2) and 0.77 (NSE) and the low value of 0.59 (MAE) based on the range of the values suggested by Moriasi et al. (2007) and Singh et al. (2005). The large error on July 2007 does not seem to be associated with the influence of precipitation because the observation for the month shows a large difference with other observations representing similar amounts of precipitation. This is assumed to be due to other unknown reasons such as incorrectly reported measured data or other contributing sources of water (e.g. swimming pools). In the validation, 54% of the observations were included within the narrow uncertainty band (r-factor = 0.42), and very good values of R^2 (0.94), NSE (0.92), and MAE (0.26) were achieved.

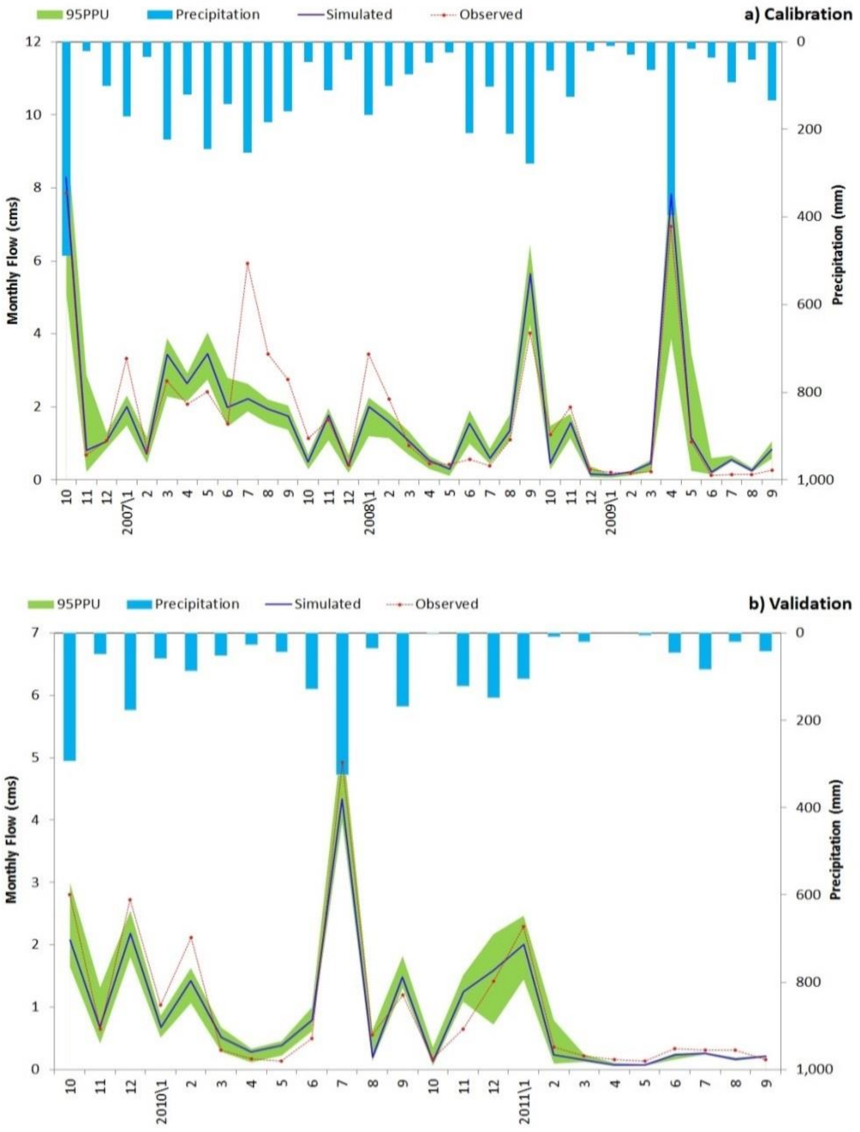


Figure 2.4 Calibration and validation results for monthly streamflow at the Clear Creek watershed (95PPU: 95% prediction uncertainty)

The daily simulated and observed flow pair also fit well both for the calibration and the validation (Fig. 2.5). Values for a p-factor of 0.72 and an r-factor of 0.47 were reached through the calibration process, and the narrow uncertainty band (0.43) bracketed 62% of the observed data through the validation process. A strong correlation between the observed and the simulated data was revealed, as indicated in Table 2.3 for both processes. Overall, the model results for flow tend to be underestimated, but they tracked the observed flow trends fairly well.

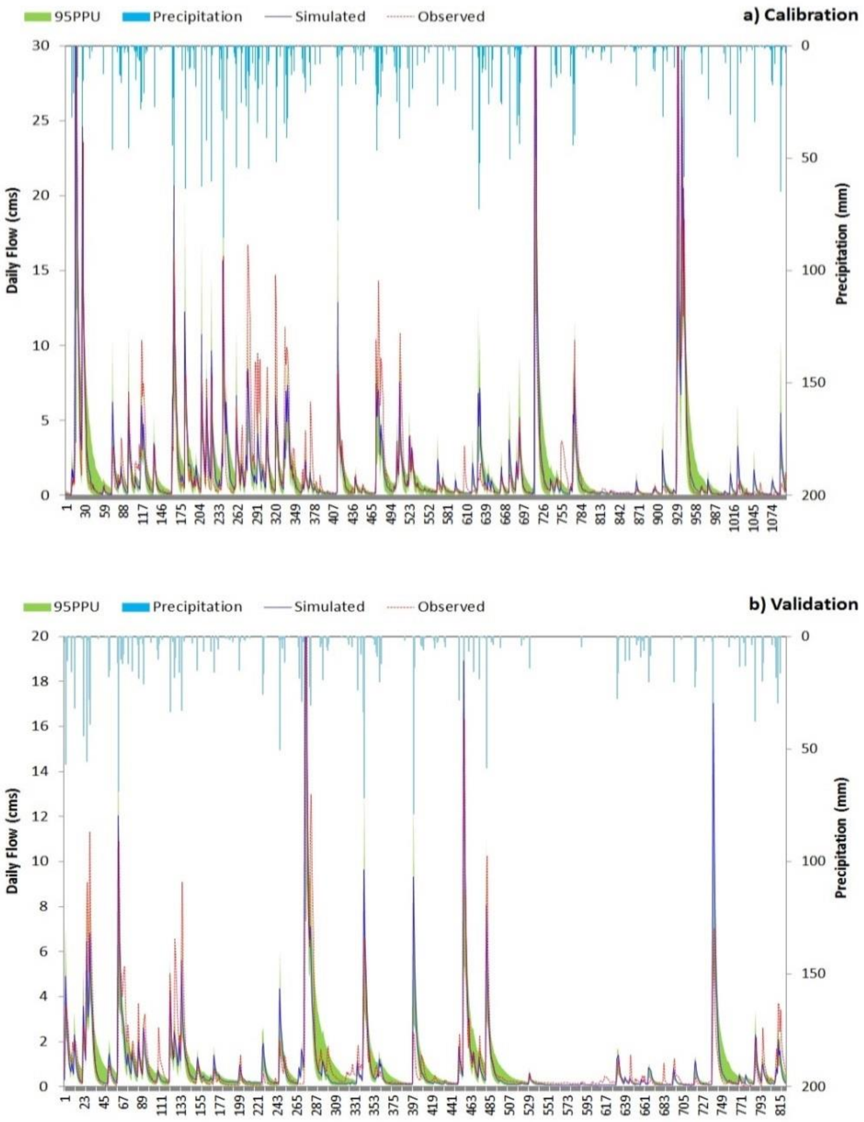


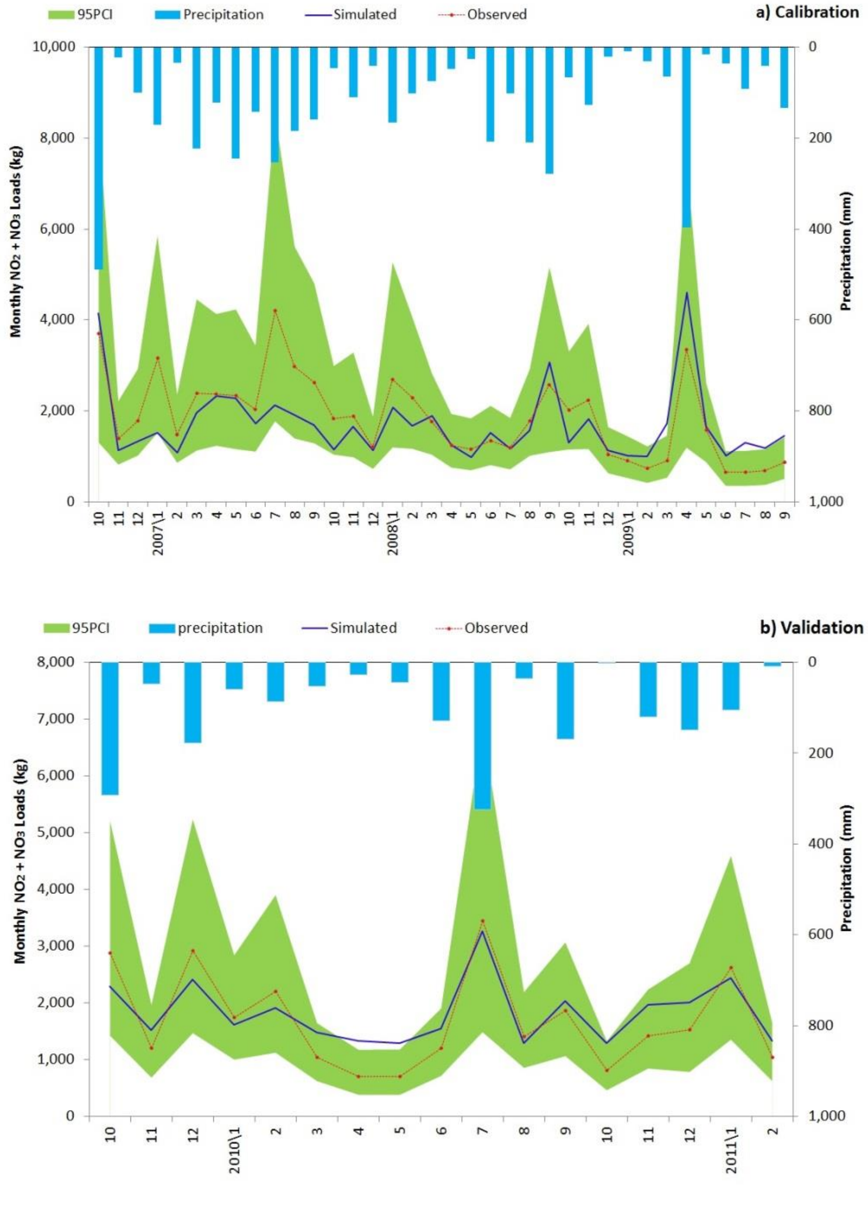
Figure 2.5 Calibration and validation results for daily streamflow at the Clear Creek watershed (95PPU: 95% prediction uncertainty)

Table 2.3 Model evaluation of the streamflow

		p-factor	r-factor	R^2	NSE	MAE (cms)	Mean (cms)		Standard deviation (cms)	
							Obs.	Sim.	Obs.	Sim.
Monthly	Calibration	0.56	0.54	0.79	0.77	0.59	1.78	1.70	1.90	1.91
	Validation	0.54	0.42	0.94	0.92	0.26	0.99	0.89	1.17	0.99
Daily	Calibration	0.72	0.47	0.75	0.74	0.85	1.79	1.71	3.92	3.86
	Validation	0.62	0.43	0.68	0.62	0.49	0.96	0.90	2.08	2.19

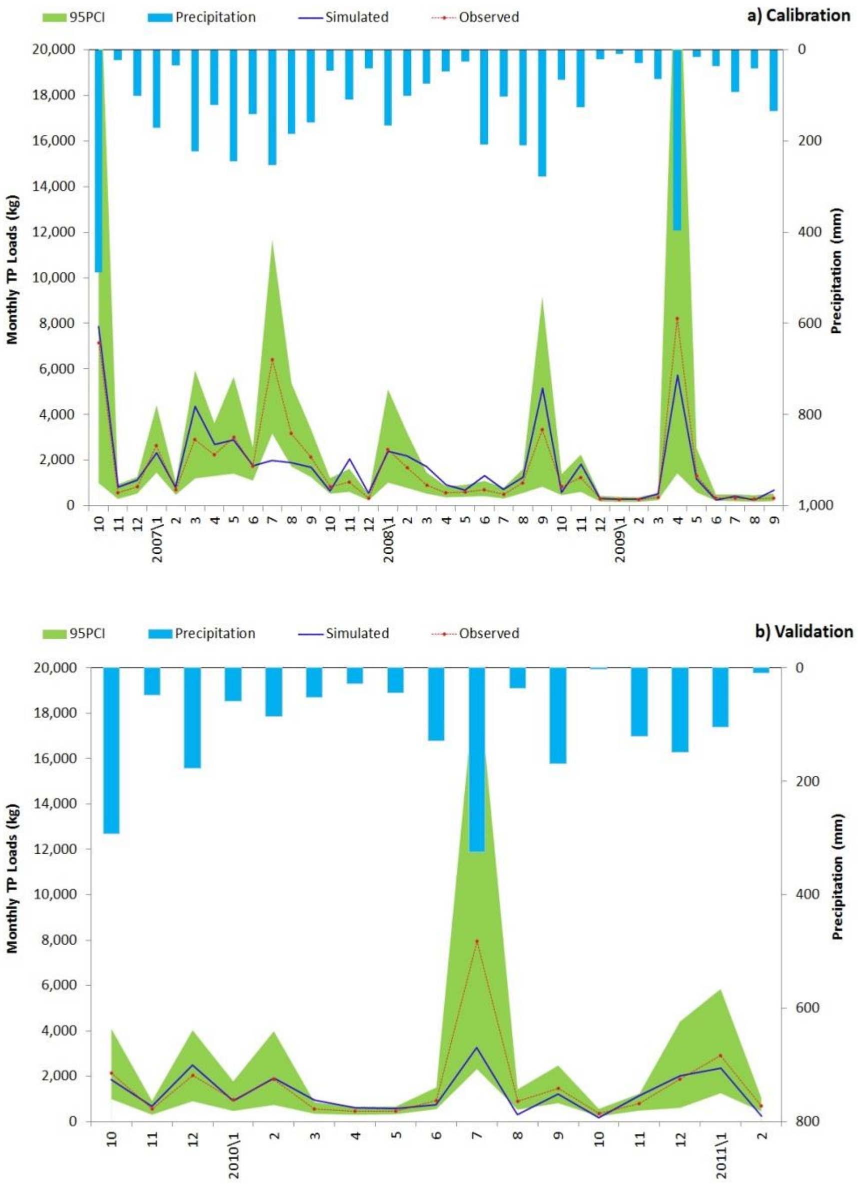
For monthly nutrients, since the manual calibration was performed after the auto-calibration, uncertainties of the simulations were not estimated. Instead, a 95% confidence interval for the observations was represented to provide reliability for the simulations. The comparisons of the simulated and observed monthly TP and NO_2 plus NO_3 were given in Fig. 2.6. As seen, almost all simulated values were included within the 95% confidence interval of the observations, and they generally followed the trends of the observations well during the calibration and validation periods (Table 2.4). The simulations of TP represented very similar patterns with the flow simulation. This may be because it is closely associated with the transportation of sediment by the influence of flow. The predicted results indicated satisfactory values for the goodness of the calibration. In the validation, relatively lower evaluation values than the calibration were obtained due to the inadequately simulated peak flow even though very close simulation was achieved at low flows. The calibration for NO_2 plus NO_3 tends to be skewed high rearward. That is, underestimation was shown in the fore simulation and overestimation was seen in the rear simulation. The difference between the simulated and the observed is presumed due to unaccountable factors such as unknown activities, incorrectly reported observed data, and so forth. A somewhat low NSE and high MAE values were obtained for the calibration, but the model simulated it with reasonable accuracy.

The daily process could not be thoroughly implemented because of limitations in the monitoring data so that the same parameter values from the monthly process were applied and simulated.



(A) Nitrite plus nitrate

Figure 2.6 Calibration and validation results for monthly nutrient loadings at the Clear Creek watershed (95PCI: 95% confidence interval for observations) (A) Nitrite plus nitrate (B) Total phosphorus



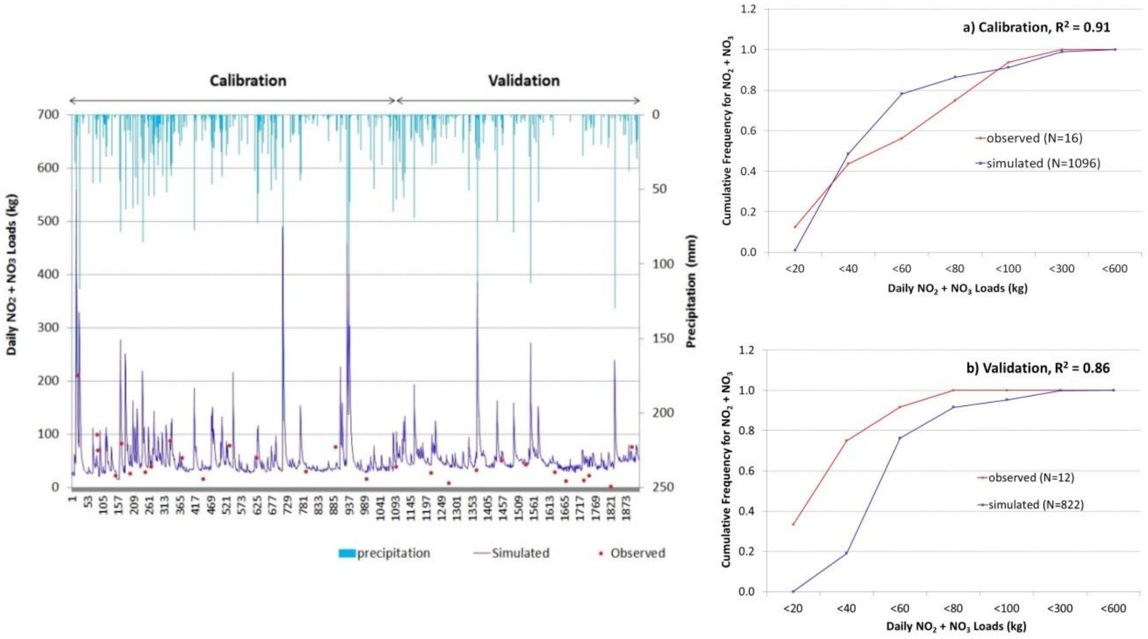
(B) Total phosphorus

Figure 2.6 Continued

Table 2.4 Model evaluation of the monthly nutrients

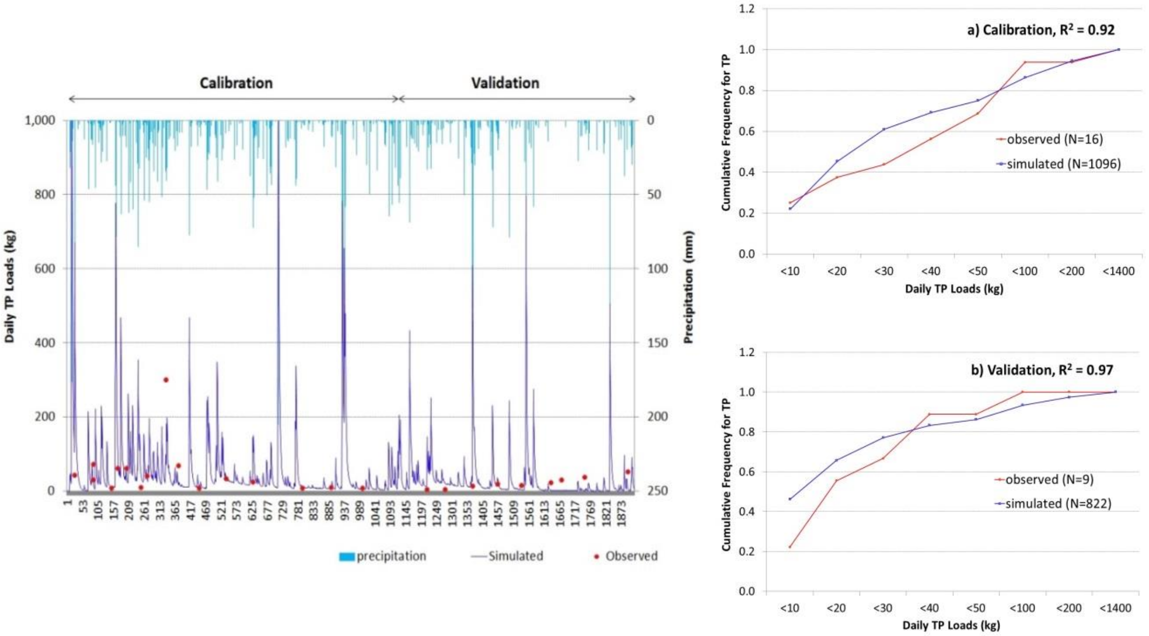
Variable		R^2	NSE	MAE (kg)	Mean (kg)		Standard deviation (kg)	
					Obs.	Sim.	Obs.	Sim.
TP	Calibration	0.72	0.72	560.48	1,709.88	1,724.72	1,919.75	1,664.81
	Validation	0.68	0.54	532.41	1,584.93	1,257.10	1,747.91	874.74
NO_2 plus NO_3	Calibration	0.51	0.45	483.10	1,861.99	1,711.36	890.04	789.43
	Validation	0.86	0.75	369.56	1,688.58	1,821.65	818.68	530.75

The results were evaluated not only as quantitative statistics, but also as cumulative frequency curve. The frequency curve was used in order to make up for poor evaluation results with few grab samples (Baffaut and Benson, 2009; Bougeard et al., 2011). Fig. 2.7 shows the daily nutrient simulation results. The discrepancies between the observed and the simulated data were large (Table 2.5). Nevertheless, the simulations moderately tracked the tendency of the observations by showing very good linear relationships between them (Fig. 2.7). These results can overcome the poor daily evaluation such as in Baffaut and Benson (2009) and Bougeard et al. (2011).



(A) Nitrite plus nitrate

Figure 2.7 Calibration and validation results for daily nutrient loadings along with cumulative frequency curves at the Clear Creek watershed (A) Nitrite plus nitrate (B) Total phosphorus



(B) Total phosphorus

Figure 2.7 Continued

Table 2.5 Statistics for evaluation of the daily nutrients

Variable		No. of Observations	Mean (kg)		Standard deviation (kg)	
			Obs.	Sim.	Obs.	Sim.
TP	Calibration	16	50.30	41.25	68.36	37.99
	Validation	9	23.11	11.06	15.15	8.56
NO_2 plus NO_3	Calibration	16	61.60	47.10	46.66	15.37
	Validation	12	29.08	46.76	19.73	7.25

Results of Land Use Change

As expected, the land use change in the study area affected both runoff and nutrient loadings. Overall, surface runoff amounts were increased and water qualities were degraded due to urban developments, and the degree of hydrologic and water quality modification was noticed differently under the different future build-out plans. For surface runoff, the impact of urbanization was smallest in the UHD scenario, a maximum increase was predicted in the UMD scenario, and the UMC scenario was slightly lower than the UMD scenario, as seen in Fig. 2.8 and Table 2.6. For nitrate, noticeable differences were shown between pre- and post-development scenarios, following the trend of surface runoff. The smallest increase was generated in the order of the UHD scenario followed by the UMC scenario and then the UMD scenario. For total phosphorus, the land use change resulted in an increase of TP in the same order with surface runoff and nitrate.

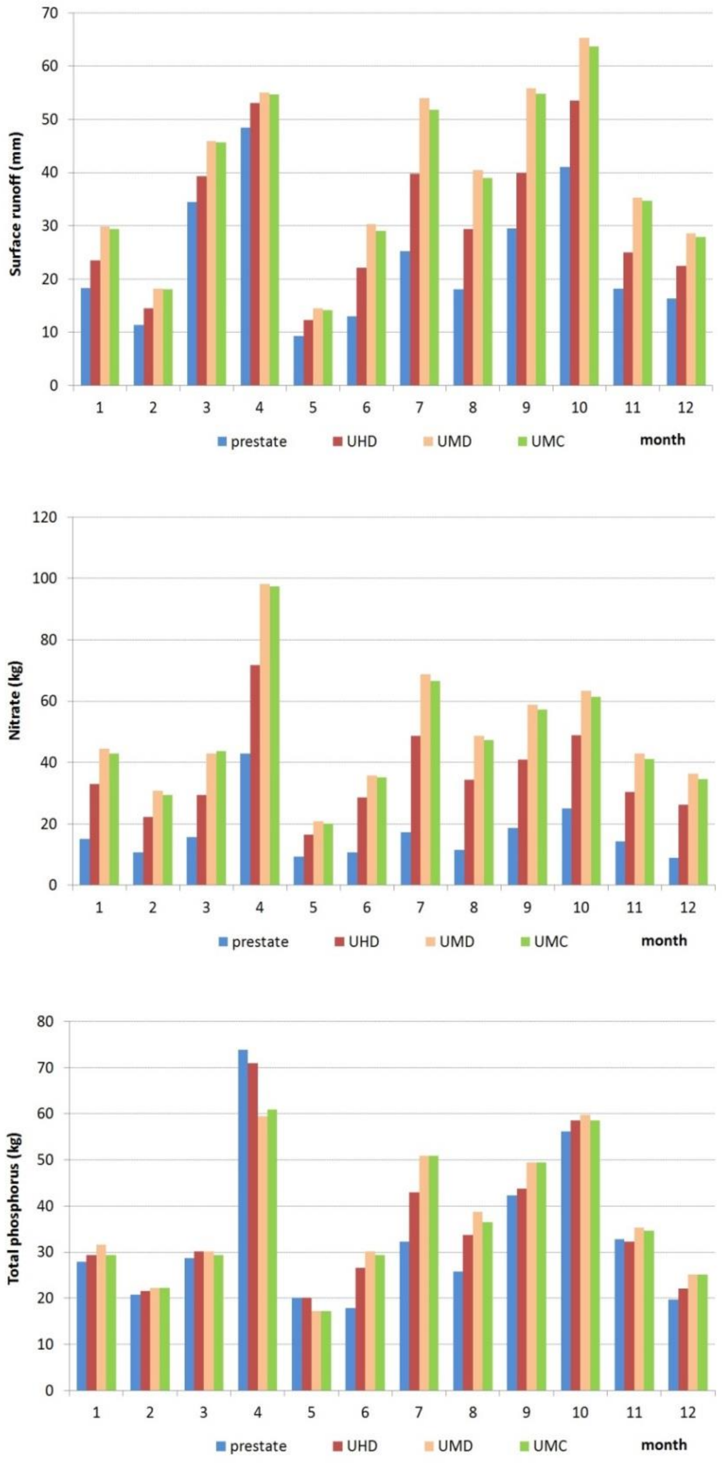


Figure 2.8 Comparison of surface runoff, nitrate, and total phosphorus under the three land uses with different urban types

Table 2.6 Average annual results and the difference between the pre- and post-development scenarios on a watershed scale

Scenario	SURQ (mm)	NO_3 (kg/ha)	TP (kg/ha)	Impact of urban developments		
prestate	282.97	0.56 (200.24)*	1.11 (398.08)	SURQ (mm)	NO_3 (kg/ha)	TP (kg/ha)
UHD	374.66	1.20 (430.92)	1.21 (431.64)	91.69	0.64 (230.68)	0.10 (33.55)
UMD	473.32	1.65 (591.87)	1.26 (449.55)	190.35	1.09 (391.64)	0.15 (51.46)
UMC	462.73	1.61 (577.19)	1.24 (443.46)	179.76	1.05 (376.95)	0.13 (45.37)

* Parenthesis means pollutant loadings (in kg)

First, for the results of the comparison between pre-development and each urban scenario, p-values are shown in Table 2.7. The results indicated that the UMD and UMC scenarios were significantly higher than pre-development for surface runoff and all urban scenarios (UHD, UMD, and UMC) for nitrate transport. However, the UHD scenario was not significantly different from pre-development in surface runoff (p-value = 0.21 > 0.05) and all urban scenarios in TP (p-value > 0.05). This means that the UHD land use does not affect surface runoff volume and TP yields even after urban development. On the other hand, in comparing the urban scenarios to each other using the impact of urban development only, it was found that the impact of the UHD scenario was significantly lower for surface runoff and nitrate transport than both the UMD and UMC scenarios (Table 2.8). However, there was no significant difference between the UMD and UMC scenarios for both surface runoff and nitrate. For total phosphorus, no significant difference was found among urban developments.

Table 2.7 Statistical analysis (p-values of t-test) between pre-development and each urban scenario

Scenario	Pre-development		
	Surface runoff	Nitrate	TP
UHD	0.209	9.00E-08*	0.97
UMC	0.018*	4.80E-14*	0.92
UMD	0.013*	1.50E-14*	0.81

* means a statistically significant difference

Table 2.8 Statistical analysis (p-values of t-test) among urban scenarios

Scenario	Surface runoff		Nitrate		TP	
	UHD	UMC	UHD	UMC	UHD	UMC
UMC	1.10E-06*	-	3.40E-07*	-	0.60698	-
UMD	1.60E-07*	0.67	8.30E-08*	0.86313	0.31091	0.6773

* means a statistically significant difference

Meanwhile, in the result of total phosphorus, overestimations of the prestate scenario were observed in several months unlike surface runoff and nitrate (Fig. 2.8). Obvious over-prediction was detected, especially, in April. This is presumably due to the indirect influence of large runoff for the month. Large runoff increases sediment transporting capacity, and thus it can contribute to the results of the large amount of phosphorus. In addition, since the difference of surface runoff between the pre- and post-developments is not large, if a concentration of TP discharged from the pre-development state is larger than those from the post-development states, a larger load can be generated in the prestate scenario than under the urban scenarios. In this study, large parts of the agricultural land were changed to urban areas. Tong and Chen (2002) indicated that a larger amount of TP in agricultural lands was generated than in urban areas. The minor differences of TP loads between the pre- and post-development scenarios signify that the pre-development state discharges a significant amount of TP. This could explain the reason why a higher amount of TP was represented in the UHD scenario which has more pre-developed land than the UMD and UMC scenarios for the month.

Across the board, better results were demonstrated in the land use with the compact high-density pattern than in the other two design patterns for all variables. In this regard, the results are consistent with several research findings mentioned in Introduction of the present study. The differences in results among the urban scenarios can be attributed to the size and impervious/pervious ratio of urban areas. Many researchers have stated that water degradation is closely correlated with imperviousness (Schueler, 1992; Schueler, 1994; Arnold and Gibbons, 1996). The high-density design represents the greatest intensity of impervious fraction among the urban designs so that the impact of the urban part on surface runoff and pollutant loadings is largest as seen Table 2.9. However, the urban development is concentrated on almost one third of the medium-density urban size and the rest of the land use remains as open space. Thus, overall impervious surface is smallest in the land use with the high-density design. Accordingly, the results showed the smallest increase of surface runoff and pollutant loadings on a watershed scale. Jacob et al. (2009) indicated that high reductions were represented in high-density development because of a reduced runoff-generating area. In the case of the UMD and UMC scenarios that have the same urban areas, results showing lower increases of surface runoff and pollutant loadings in the UMC scenario could also be accounted for as a result of the smaller impervious fraction even though the differences between them are minor.

Table 2.9 Impact of only urban parts on surface runoff and nutrients

Scenario	SURQ (mm)	NO_3 (kg/ha)	TP (kg/ha)
UHD	445.29	3.13	0.45
UMD	340.97	1.96	0.26
UMC	322.01	1.89	0.23

Conclusion

The present study was intended to identify how land use change using different urban designs has an impact on water quantity and quality. The results of the post-development states demonstrated different increases in runoff and nutrients through the relative comparison with the pre-development state. It is true that as urbanization gradually increases in the near future, it will result in existing water quantity and quality problems becoming even worse. The study could not only help people understand and realize the seriousness of water problems, but also provide an insight into how to manage the region to minimize the hydrologic and water quality impacts of urbanization. It would consequentially help decision makers to prepare proper actions for the future on the scale of development. Meanwhile, an effective urban design for water quantity and quality can vary with different watershed characteristics, conditions of urban areas, and so forth, unlike the results of this study. It is suggested that modeling work, therefore, be performed prior to urbanization.

The model showed that the least amount of increase was found in the UHD scenario. However, even though the impacts of the urban design were close to those of the pre-development state, the differences between them were obvious. In Harris County including the study area, a minimum detention rate, 0.55 ac-ft per acre, is required by the Harris County Public Infrastructure Department Architecture & Engineering Division (HCPID-AED) and the Harris County Flood Control District (HCFCD) to control outflow for a new development. This suggests that consideration of facilities that can buffer stormwater impacts by post-development is needed to reflect such a requirement. In this study, the content for the facilities is not addressed because it is out of the scope of the study. The present study, in this regard, could play an important role in laying a foundation for future research.

CHAPTER III

EVALUATING THE EFFECTIVENESS OF LOW IMPACT DEVELOPMENT PRACTICES (LIDS) UNDER DIFFERENT URBAN PLANNING DESIGNS USING SWAT

Introduction

Fast-paced urbanization has raised many stormwater problems due to the increase in impervious surfaces. The increase in impervious surfaces changes natural flow characteristics; runoff is increased, groundwater recharge is decreased as infiltration to soil layers is interrupted, and the water table is lowered, resulting in decreased base flows (Leopold, 1968; Shaw et al., 2010). Additionally, urban runoff from impervious surfaces is a major source of pollutants because stormwater runoff transports many pollutants, such as sediment, heavy metals, and nutrients, to nearby water bodies. These pollutants contribute to deteriorated water qualities. New stormwater management is, therefore, required to mitigate the impact of urbanization on runoff and pollutants from an environmental perspective. One alternative strategy is Low Impact Development practices (LIDs), designed to treat water at the source where it is generated. LIDs can restore deteriorated conditions to their original levels before development or even lower (Prince George's County, 1999).

Because LID techniques (or urban Best Management Practices; urban BMPs) have been deemed effective, they have gradually drawn much attention and many studies have analyzed the effects of LIDs on hydrologic processes and water quality. The positive performance of LIDs has been demonstrated through many experiments in the field and through modeling works in watersheds. For instance, the installation of bioretention areas or permeable pavements has resulted in large reductions for runoff volumes, peak flow rates, and pollutants (e.g., Bean et al., 2007; Collins et al., 2008; Hunt et al., 2006 and 2008; Jaber and Guzik, 2009). For a modeling approach, Abi Aad et al. (2009) 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 (2008) indicated reductions of flow, sediment, and copper by bioretention, grassed swale, planter box, and planter box with grassed swale in their study in which they evaluated the effectiveness of BMPs using Hydrologic Simulation Program-Fortran (HSPF) coupled with a developed BMP module. In Carter and Jackson's (2007) study that investigated the effects of green roofs on hydrology at four spatial scales using a StormNet Builder model, they showed significantly reduced peak runoff rates.

The effectiveness of LIDs, however, can vary depending on a variety of conditions. Some studies have demonstrated that it is reliant on watershed characteristics such as soils, topography, and precipitation. Holman-Dodds et al. (2003) reported large runoff on a low infiltration type D soil despite the existence of LIDs and indicated the decrease of the effectiveness of LIDs in large precipitation. Brander et al. (2004) revealed that small storm and soil type A are effective factors in assessing the performance of LIDs. The effectiveness of LIDs for small storms was also presented in

Ackerman and Stein (2008), Carter and Jackson (2007), Schneider and McCuen (2006), etc.

Besides watershed characteristics, there could be other factors that have an influence on the effectiveness of LIDs. Some studies have determined the impact of urban patterns on water volumes and pollutant loadings. The present author investigated how the amount of runoff and pollutant loadings were generated differently under three different urban planning designs in Chapter II and presented the compact high-density urban type as the most effective urban type. Such studies imply that the effectiveness of LIDs could also vary with different urban patterns. However, a limited number of studies have been performed for the effectiveness of LIDs under urban design conditions. For example, Brander et al. (2004) analyzed the effects of infiltration practices on urban runoff under four development types (e.g., 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 with the urban clustered design in most scenarios because of the large natural land area. Williams and Wise (2006) simulated the hydrologic responses from traditional and clustered developments with BMPs and LIDs using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), and indicated very similar results with the results of pre-development condition in the clustered development with LIDs. Gilroy and McCuen (2009) studied three land uses consisting of single family, townhome, and commercial lot uses in identifying the impact of location and volume capacity of urban BMPs (cisterns and bioretentions) 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. Furthermore, very few studies have attempted to simulate LIDs, especially, rain gardens, permeable pavements, and rainwater harvesting systems which were considered in the present study, by using the Soil and Water Assessment Tool (SWAT) even though SWAT has enough capability to reflect the behavior by these LIDs through surface and subsurface hydrologic and water quality modules.

In this regard, we focused on the application of the LIDs in SWAT and on the evaluation of the watershed-wide effectiveness of the LIDs under different given urban designs. The results of the post-developments (pre-LIDs scenarios) from Chapter II were utilized as baseline data to evaluate the post-development states with LIDs (post-LIDs scenarios). A model was developed to simulate the LIDs considered. The hydrologic and water quality results were analyzed and compared with and without LIDs within the same land use and among land uses. In the text, the terms “pre-LIDs” and “post-LIDs” are used to designate the post-development state before and after constructing LIDs, respectively.

Materials and Methodology

Study Area Description

Stormwater problems have been a serious concern in coastal areas because coastal areas are the depot for pollutants from upstream (Culliton, 1998; Howarth et al., 2002) while downstream is affected by tidal currents. In particular, urban areas usually face more serious threats because increased impervious surfaces can exacerbate stormwater problems by generating runoff without natural handling. The study area, located to the north of League City, Texas, within the Clear Creek watershed, meets the described characteristics (Fig. 3.1). It is located downstream of Clear Creek near Galveston Bay and is planned for regional development.

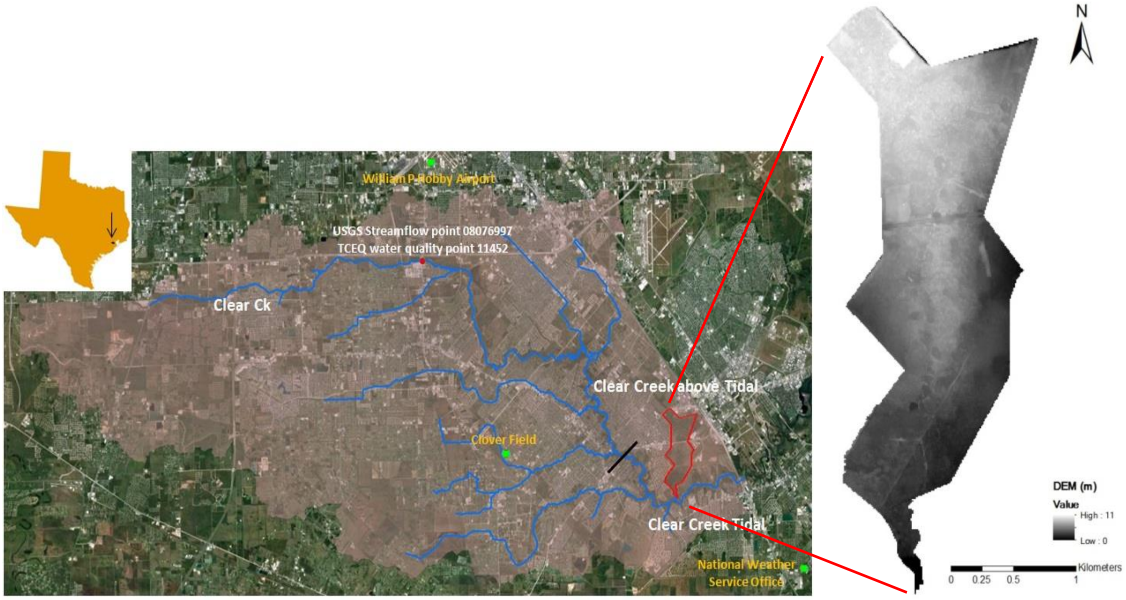


Figure 3.1 The Clear Creek watershed (left) and the study area (right) within the Clear Creek watershed

As the study area is small in size, it is desirable to scale up the analysis of LIDs to a large watershed after apprehending tangible changes of water quantity and quality at a small level (Dougall et al., 2003). This is because LID modeling at a large scale can make the noticeable effectiveness of LIDs difficult to figure out so that it cannot provide information for changes that should be conducted at a small-scaled level (Dougall et al., 2003). Within the boundary of a pre-developed area, a roughly 3.5 km^2 (350 ha) area was considered as a study area.

The topography ranges from 0 m to 11 m in elevation, and approximately 90% of the area is within 6 m to 8 m so that the slope of the area is generally gentle. Low infiltration and high surface runoff are represented as typical characteristics of topography of this area. Soils are composed of heterogeneous mixtures. Addicks (loam) covering about 61% of the soils is the most predominant soil, and Bernard (clay loam) comprises approximately 27% of the soil types. Lake Charles (clay) and Aris (silt loam) occupy the remainder. All soil properties are represented as poorly drained hydrologic soil group (HSG) D. Wetland and hay are predominant making up about 60% of current pre-developed land use. The weather is generally typified by clement winters and hot summers. The average annual temperature is around 21°C (70°F), indicating a low monthly average temperature of around 12°C (53°F) and a high monthly average temperature of around 29°C (84°F). The difference between the low and high temperatures is not large due to the influence of the oceanic climate. There is a high probability of powerful thunderstorms in this area. The annual precipitation is around

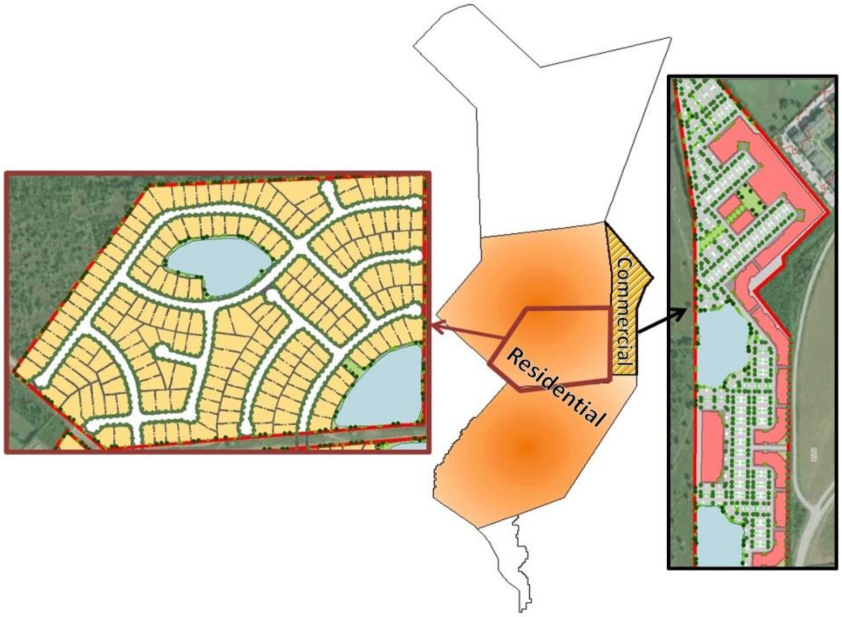
1,270 mm on average, and monthly values vary from approximately 50 mm to 165 mm. The study area is located in Harris County (USGS, 2014).

Description of Input Data

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

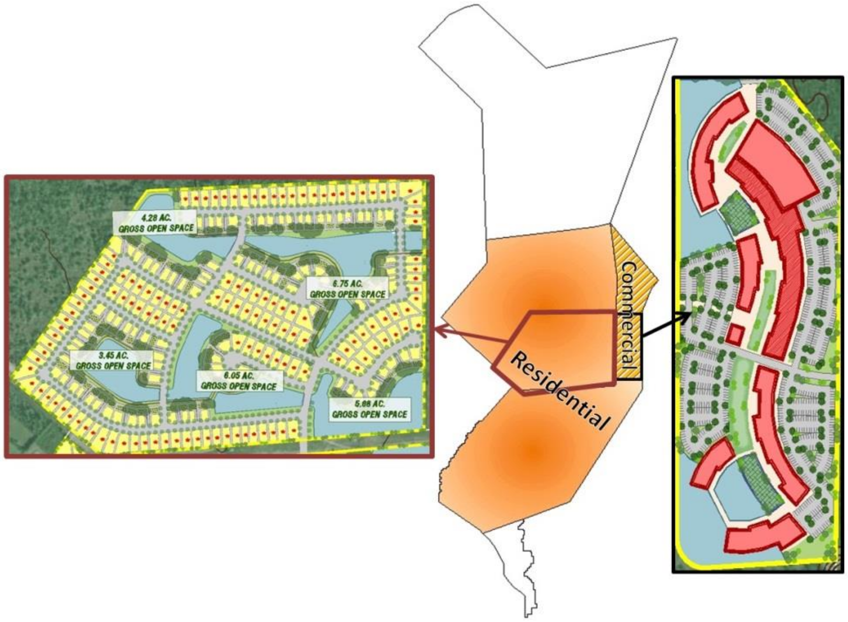
For land uses, three different types of land use data, derived from potential urban layouts of the city of League City, were considered; they are land uses with 1) a compact high-density urban form (termed as UHD), 2) a conventional medium-density urban form (termed as UMD), and 3) a conservational medium-density urban form (termed as UMC) (Fig. 3.2). The urban area of each land use consists of residential and commercial areas, and, in the figures, blowups are parts of the residential and commercial areas and the entire urban areas represent those patterns. The same population is applied to all residential areas of land uses.

(A) UHD



(B) UMD

Figure 3.2 Three land use data with different urban types (Each blowup is a section of the residential and commercial areas); (A) Compact high-density urban land use (UHD) (B) Conventional medium-density urban land use (UMD) (C) Conservational medium-density urban land use (UMC)



(C) UMC

Figure 3.2 Continued

UHD land use includes the smallest portion of residential area, highly converted to an urbanized system, among the three urban designs and 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 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 areas, and they are a more expanded area than that of the UHD land use. The commercial area of all urban areas is the same in size. In total, an urban part occupied about 21% and 56% areas 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 3.1). For the remaining land areas excluding the urban areas, land use data obtained from the USDA NRCS Geospatial Data Gateway was kept as a pre-development state. The same land use data from Chapter II were used to evaluate the effectiveness of LIDs under these different urban land uses. More detailed design specification can be found in Chapter II.

Table 3.1 Information for each urban area in 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

[1] The proportion of an urban area for total land use area

[2] The fraction of impervious and pervious parts in an urban area

For soil data, the high-resolution Soil Survey Geographic Database (SSURGO), suitable for a small-scaled study area, was used. It is available from the NRCS Soil Data Mart. For the weather dataset from 2004 to 2011, daily precipitation and temperature were collected from the National Climate Data Center (NCDC) at Houston Clover Field and at National Weather Service Office stations, considered as representative stations for the study area (Fig. 3.1). Weather generator was used for the rest of the weather dataset of the simulation. Wastewater treatment plants (WWTPs) were not considered because they do not exist within the study area.

Model Selection

A watershed-wide evaluation for the effectiveness of LIDs is needed because stormwater eventually has an influence on the final water body of a watershed (Emerson et al., 2005). It is cumbersome to calculate reduction rates from all LIDs sites within a watershed for a watershed-wide evaluation. Moreover, since the reductions of runoff and pollutant loads by LIDs 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 hydrologic responses with the application of LIDs. In the present study, SWAT was selected because it has proved an ability to simulate the process of hydrology and water quality in a variety of studies for a long period of time (e.g., Abbaspour et al., 2007; Jha et al., 2007; Santhi et al., 2001). SWAT has effective components for the simulation of water quantity and quality. It applies a modified NRCS curve number (CN) method (SCS, 1972) to estimate surface runoff and a Modified Universal Soil Loss Equation (MUSLE; Williams, 1975) 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 for the processes is provided in Neitsch et al. (2011).

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 (e.g., Jeong et al., 2013; Parker, 2010; Yang et al., 2009; Yang and Li, 2011). In addition, the suitability of SWAT in the simulation of BMPs has been proven. The benefits of many agricultural practices have been examined and evaluated using SWAT (e.g., Bracmort et al., 2006; Santhi et al., 2006). This implies that SWAT has the potential for predicting water quantity and quality for urban watershed management systems (Hunt et al., 2009). 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. (2011) 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. (2013) 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, has modules to allow many conservation practices which are not included in other existing models by entering removal efficiency of pollutants. As development of improved tools is encouraged for LIDs modeling in SWAT, processes through updates and modifications are continuously in progress to adequately represent LIDs.

Description of SWAT Previous Simulation

In the previous work, the simulations for pre- and post-developments were preceded by baseline simulations. 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 the prestate scenario) was first taken into account to assess the impact from post-developments. The process was concentrated 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 (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. This calibration process is possible as a result of very similar watershed properties across the entire watershed.

After finishing the process, the study area was simply separated from the Clear Creek watershed and treated as one watershed for the next steps in the post-development process. The three land uses with different urban designs (illustrated in the section on Description of Input Data) 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 subbasins and HRUs based on land uses and soil properties. A total of 4 subbasins and 18 HRUs were produced in the UHD land use, and the UMD and UMC land uses were delineated as 5 subbasins and 18 HRUs. Each post-development simulation was individually run and investigated for surface runoff, nitrite, and total phosphorus. Overall, the results showed an increase of runoff and pollutant loadings by the post-developments. 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 represented and used for comparison with the results of post-LIDs scenarios in the Results section. Additional details for the processing procedures and the results are given in Chapter II.

Specification of Used LIDs and Scenarios

Three types of LIDs were chosen to be used in this study: rainwater harvesting systems (RWHs), rain gardens (RGs), and permeable pavements (PPs). They are effective land management practices that are commonly used in urban watersheds. These LIDs have specific locations, taking up small areas or replacing existing impervious surfaces. It was hypothesized that RWHs would be 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 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 3.2 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 neighborhood on Google Earth. These are the percentages of the areas covered by RWHs and PPs, respectively. The percentages of the areas covered by RGs are respectively 6.6% and 8.0% of the UHD and UMD/UMC residential areas, 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 (2008).

Table 3.2 Fractions of roofs and parking lots in the urban areas of each land use (%)

Land use	Roofs[1]	Parking lots[2]
UHD	34	34
UMD	20	47
UMC	20	31

[1] Percentages of roofs occupied in the residential areas
[2] Percentages of parking lots occupied in the commercial areas

In this study, it was assumed that the areas covered by each type of LIDs in each urban area are considered for full LIDs installation. 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 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 LIDs. 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 LIDs that could be fully accommodated in the given LIDs areas for each urban design. No LIDs exist in other areas except for the urban areas.

In the present study, we focused on simulating the existence of LIDs under three types of land use with different urban patterns in order to evaluate the effectiveness of LIDs and to identify an optimal development plan. Three post-LIDs scenarios based on the land uses were created and 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 3.3 provides a summary of the scenarios addressed in the study.

Table 3.3 Summary of scenarios

Land use	Urban design	Name of scenario	
		pre-LIDs	post-LIDs
UHD	Compact urban form with high density	UHD	UHDLIDs
UMD	Conventional form with medium density	UMD	UMDLIDs
UMC	Conservational form with medium density	UMC	UMCLIDs

Representation of LIDs in SWAT

Model Development

As previously mentioned, LIDs capture runoff to the extent of their capacities and discharge it beyond them. The SWAT model was developed to account for the hydrological behavior by LIDs in urban areas. A simple modification and addition of codes were conducted in surface runoff subroutine.

The surface runoff in urban areas is estimated as the sum of surface runoff from a connected impervious area and from a disconnected impervious/pervious area. Surface runoff from the connected impervious area is calculated by an impervious curve number and surface runoff from the disconnected impervious/pervious area is computed by a composite curve number under a surface runoff equation (Eq. 3.1). Each surface runoff is multiplied by fractions of each area and then summated to obtain the final urban surface runoff (Eq. 3.2).

$$Q \text{ or } Q_{imp} = \frac{(P - 0.2S)^2}{(P + 0.2S)} \tag{3.1}$$

$$Q_{tot} = Q \cdot \left(1 - fcimp\right) + Q_{imp} \cdot fcimp \tag{3.2}$$

where Q and Q_{imp} are the surface runoff depths (mm) in the disconnected impervious/pervious area 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.

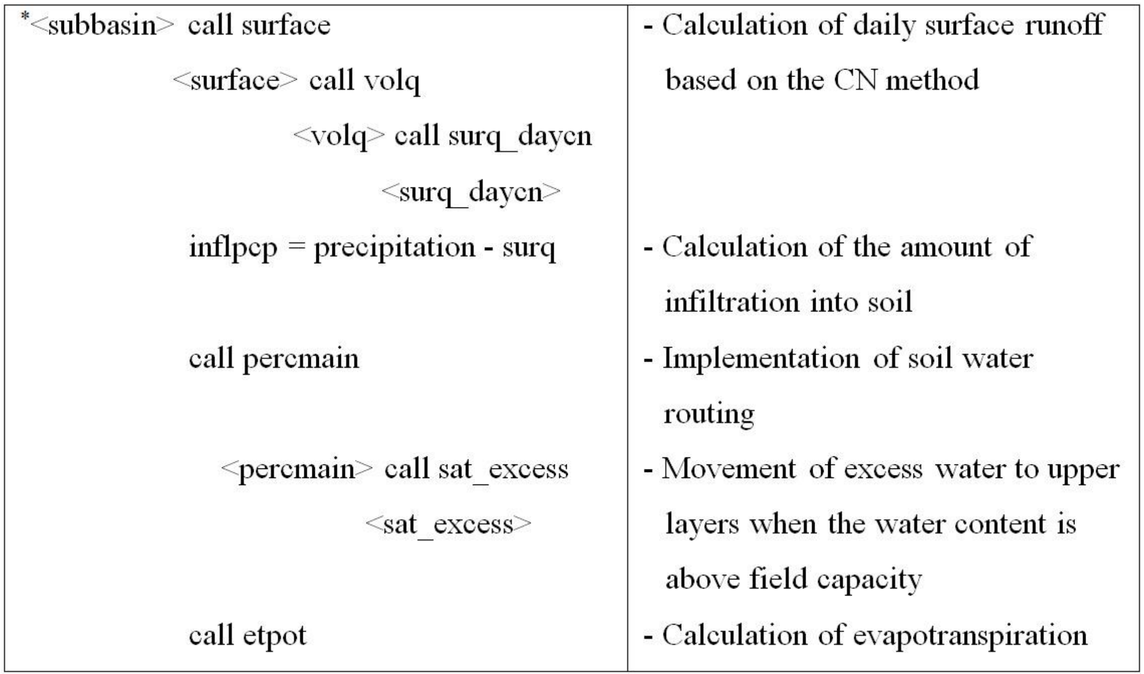
To consider the amount of surface runoff captured by LIDs, a modified surface runoff equation (Eq. 3.3) was added in the existing codes.

$$Q_{LIDs} = Q_{tot} - LIDval \tag{3.3}$$

where Q_{LIDs} is the surface runoff depth (mm) in which the impact of LIDs is considered, and LIDval is the surface runoff depth (mm) stored by each LID. This method was determined based on McCuen's study that subtracted the amount of water captured by infiltration practices from urban surface runoff (MDE, 1983).

This is a suitable approach because SWAT has critical hydrologic algorithms that can best illustrate the flow characteristics of the LID practices being considered. That is, 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 (Eq. 3.3), 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 (Eq. 3.3) 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 LIDs 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 occur by Equation 3.3. However, consecutive rainfall is mostly from small storms and there is less frequency that large rainfall will occur continuously. In addition, infiltration of the stored water affects soil moisture condition, and cases in which the all soil layers are completely saturated are not common. Even if that were the case, SWAT can make 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 cannot be naturally infiltrated unlike RGs and PPs. Therefore, the algorithm was additionally coded with relevance to its function. That is, codes were added such that 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 LIDs, and the schematic flow chart of the subroutines of the SWAT codes related to the behavior of LIDs was added (Fig. 3.3).



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

*<> means subroutines of SWAT codes

Figure 3.3 Schematic flow chart of the hydrologic subroutines and description of functions

Design Storage Depth

Each LID allows for holding 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. They 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 from the rainfall is a volume for water quality protection in this region (Technical Manual of iSWM: http://iswm.nctcog.org/technical_manual.asp) (NCTCOG, 2014). For CN, 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. 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 1,000 gallon capacity rain tank was assumed to be a standard in the medium-density residential area (Shannak et al., 2014), and the runoff depth was inversely calculated by Equation 3.4:

$$\text{a capacity of rain tank (gal)} =$$
$$\text{runoff depth (in)} \cdot 0.623 \cdot \text{roof area (ft}^2\text{)} \cdot \text{runoff coefficient} \tag{3.4}$$

where 0.623 is the unit conversion factor, 0.9 of a 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. Proportional volumes of rain tanks are 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 3.4). The information for the maximum storage depths and types of LIDs was provided as a text file in SWAT, and the subroutine that can read the information was added in the SWAT algorithm.

Table 3.4 Maximum storage depth retained by each LID (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

Model Configuration

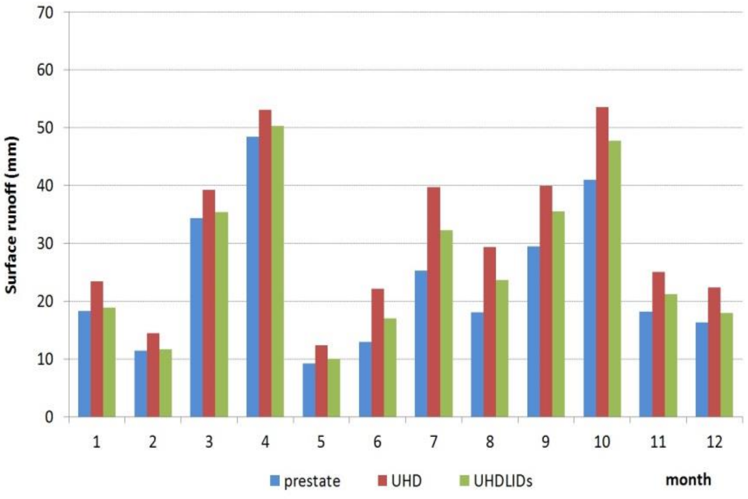
The model processing procedure was very similar to the steps of the previous work except for the urban land use to treat specific management practices. Other parameter values and input data were unaffected, and the current urban land use data was more detailed to facilitate the application of LIDs to 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 3.2). New urban data for the roofs and parking lots were added in the current urban data, and 100% impervious fractions were applied to their properties. For the existing urban data, impervious fractions in which the roofs and parking lots were excluded were applied to the current 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 LIDs numbers that represent each type in the text file were entered in the designated HRUs.

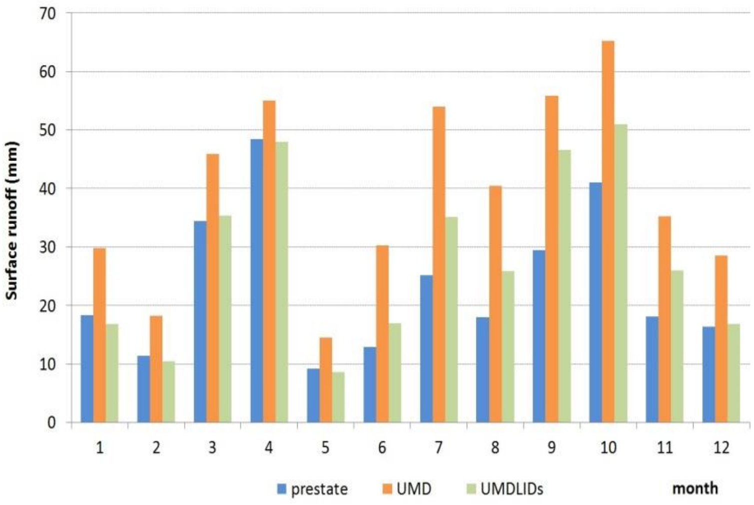
Through this process, a single type of LIDs was assigned to each HRU. That is, PPs were considered in the HRUs of the parking lots, RWHs in the HRUs of the roofs, and RGs in the HRUs of the residential urban areas. The same process was individually implemented for the three land uses. The simulation was conducted from Oct., 2006 to Dec., 2011. Average monthly and yearly results over the continuous periods were analyzed for scenarios along with statistical analysis (t-test) to evaluate the watershed-wide effectiveness of LIDs on surface runoff, nitrate, and total phosphorus for each land use. For statistical analysis, t-test was conducted among scenarios for a 95% confidence level comparing daily surface runoff, nitrate, and total phosphorus data from precipitation events above 0.5 inches.

Results

The performance of LIDs modeling positively affected all variables for all land uses. Figure 3.4 and Table 3.5 respectively represent the average monthly and yearly responses of LIDs for each land use. Because part of surface runoff was detained by LIDs, 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 (Fig. 3.4). The differences between the pre- and post-LIDs scenarios were extracted differently for each land use. For the UHD land use, 14% of surface runoff was reduced, and 29% and 25% reductions respectively were obtained in the UMD and UMC land uses on an average annual basis (Table 3.5). The results between pre- and post-LIDs scenarios showed a statistically significant difference in all land uses ($p\text{-value} < 0.05$).

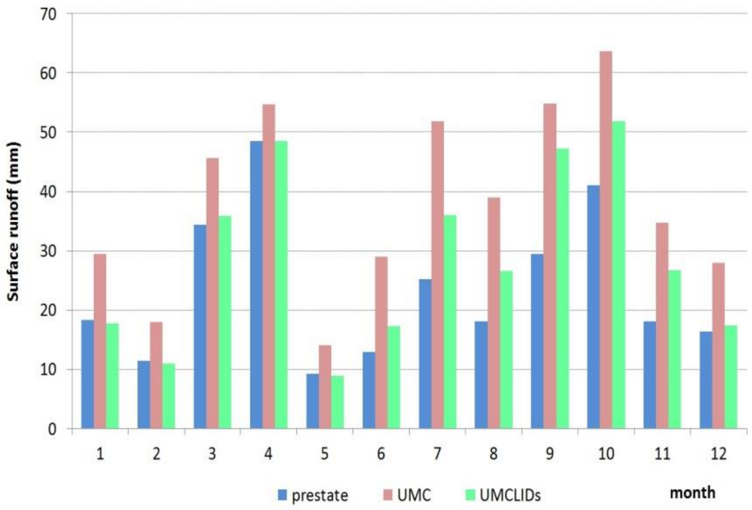


(A) UHD



(B) UMD

Figure 3.4 Average monthly response of LIDs for surface runoff in each land use (A) Compact high-density urban land use (UHD) (B) Conventional medium-density urban land use (UMD) (C) Conservational medium-density urban land use (UMC)



(C) UMC

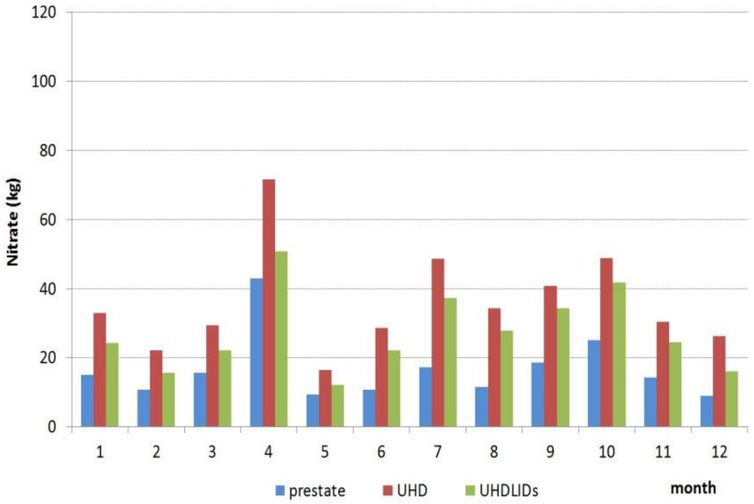
Figure 3.4 Continued

Table 3.5 Average annual response of LIDs under each land use

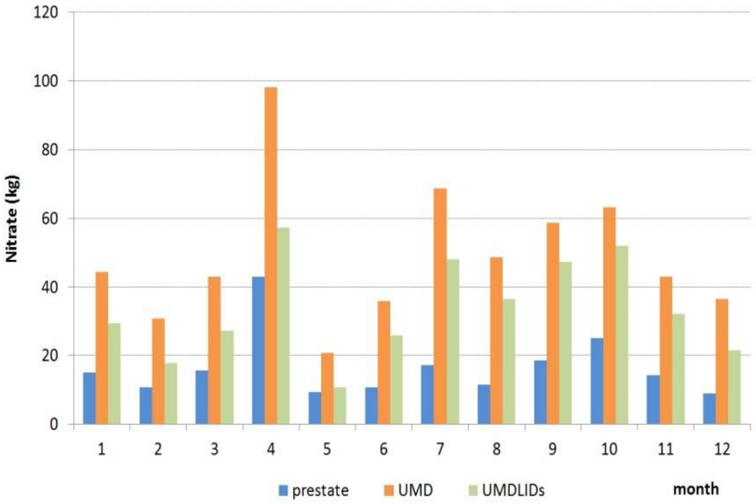
Scenario	SURQ (mm)	GWQ (mm)	ET (mm)	NO_3 (kg)	TP (kg)	Difference (% reduction)		
						SURQ (mm)	NO_3 (kg)	TP (kg)
UHD	374.66	45.76	855.66	430.92	431.64	52.97 (14%)	101.37 (24%)	46.45 (11%)
UHDLIDs	321.69	63.19	893.13	329.55	385.19			
UMD	473.32	15.78	797.02	591.87	449.55	135.51 (29%)	186.03 (31%)	110.69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

The application of LIDs had an influence on subsurface hydrology. As the water detained by LIDs was infiltrated to 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 3.5). The amount of evaporation in a soil layer is determined by soil water content. Because the greatest effect of LIDs on surface runoff was in UMD land use, the amount of infiltration in that land use reached the greatest amount. It increased soil water the most and led to the largest increase of ET in the UMD land use. In the UMDLIDs scenario, 10% more was evapotranspired than under the UMD scenario. Then, 8% of ET was increased in the UMC land use. The smallest increase of ET (4%) was shown for the UHD land use. 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 can be seen from these results, the decrease of surface runoff by LIDs is closely related to the increase of ET and GW, and the results prove that the hydrologic behavior by LIDs is properly performed in SWAT.

In urban areas, pollutants are generally dependent on surface runoff. According to the decrease of surface runoff, the runoff-borne pollutants, nitrate (NO_3) and total phosphorus (TP), also showed decreases in the post-LIDs scenarios of all land uses (Fig. 3.5 and 3.6 and Table 3.5). 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 pre- and post-LIDs scenarios in all land uses ($p\text{-value} < 0.05$). TP loadings decreased respectively 11%, 25%, and 22% in the UHD, UMD, and UMC land uses on an average annual basis, and the results also showed significant differences between pre- and post-LIDs scenarios ($p\text{-value} < 0.05$) except for the UHD land use.

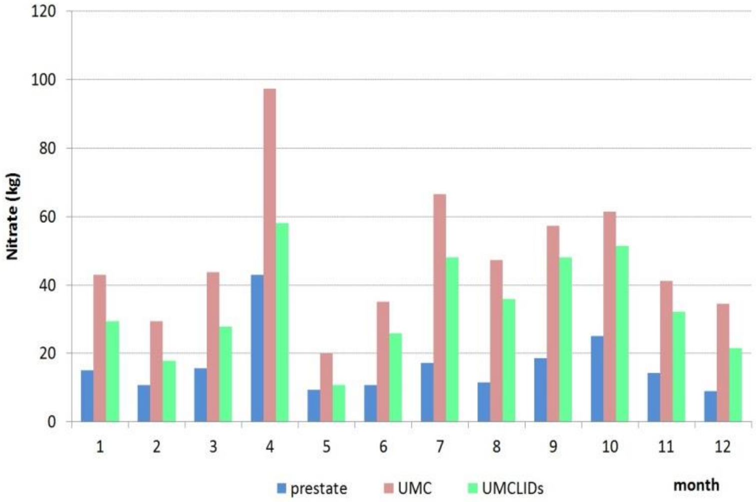


(A) UHD



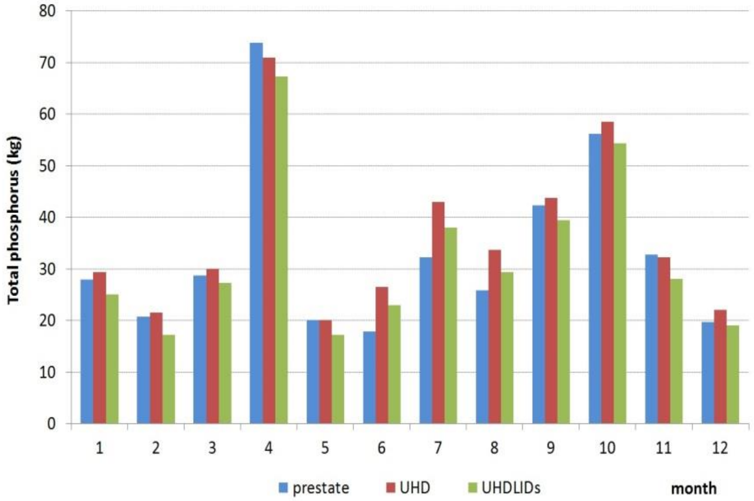
(B) UMD

Figure 3.5 Average monthly response of LIDs for nitrate in each land use (A) Compact high-density urban land use (UHD) (B) Conventional medium-density urban land use (UMD) (C) Conservational medium-density urban land use (UMC)



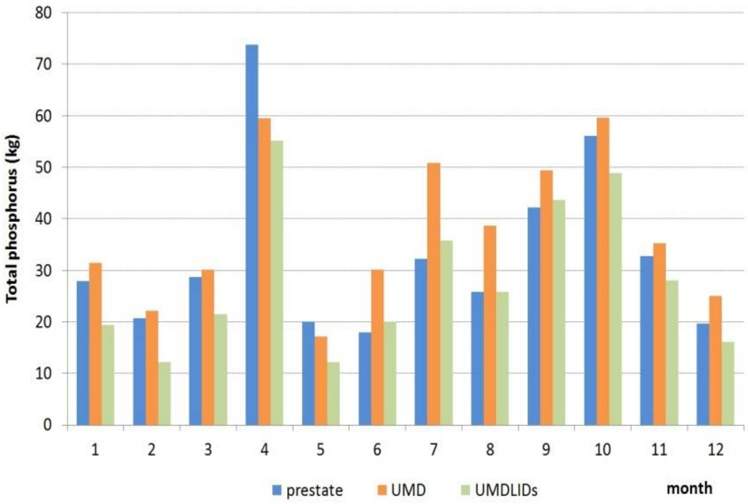
(C) UMC

Figure 3.5 Continued

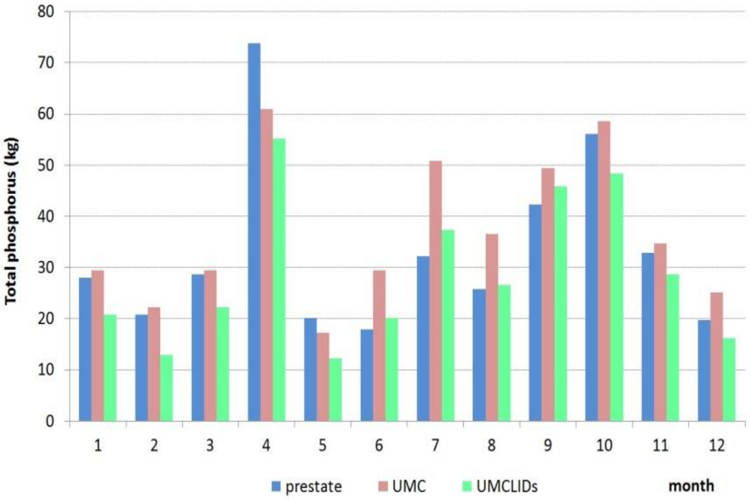


(A) UHD

Figure 3.6 Average monthly response of LIDs for total phosphorus in each land use (A) Compact high-density urban land use (UHD) (B) Conventional medium-density urban land use (UMD) (C) Conservational medium-density urban land use (UMC)



(B) UMD



(C) UMC

Figure 3.6 Continued

Overall, the degree of contribution of LIDs 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 can be attributed to the difference in the area covered by LIDs among land uses. The amounts reduced by LIDs only in each urban area are largest in the UHD land use for all variables as seen in Table 3.6. However, the UHD land use has the smallest urban area and thus the area covered by LIDs is smallest among land uses so that the smallest effectiveness of LIDs was represented. The pre-development scenario of the previous work was plotted with the pre-and post-LIDs scenarios, and it was statistically analyzed with post-LIDs scenarios for the purpose of observing the effect of LIDs. P-values were provided in Table 3.7. 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 for UHD, UMD, and UMC to pre-development conditions. However, with regard to nitrate, all post-LIDs scenarios were significantly higher than pre-development conditions. That is, the application of LIDs could not improve the negative effect of development on nitrate when compared to pre-development conditions.

Table 3.6 Reduction by LIDs only in urban areas

Land use	SURQ (mm)	NO_3 (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 3.7 Statistical analysis (p-values of t-test) between pre-development and each post-LIDs scenario

Scenario	Pre-development		
	Surface runoff	Nitrate	TP
UHDLIDs	0.577	0.0025*	0.72
UMCLIDs	0.382	1.00E-06*	0.32
UMDLIDs	0.439	1.60E-06*	0.34

* means a statistically significant difference

Meanwhile, despite the largest reduction under the UMD land use, it was observed that the results among post-LIDs scenarios showed low surface runoff and pollutant amounts under different urban land uses (Table 3.5). In the case of surface runoff and nitrate, a low value was achieved under the UHDLIDs scenario among the post-LIDs scenarios. This is because the reduction by LIDs is smallest under the UHD land use, but the impact of the land use is relatively smallest among the land uses, indicating a statistically significant difference from both UMD and UMC land uses (p-value < 0.05). In addition, since high soil water could be kept by the saved pre-developed area, the highest ET value was obtained in the UHDLIDs scenario. On the contrary, it was noticed that GW was lowest in the UHDLIDs scenario. This could be explained that recharge to groundwater occurs less because of the large amount of evaporation in the soil. For surface runoff and nitrate, 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 has more pervious fraction than the UMD land use, but after applying LIDs, less surface runoff and nitrate were shown in the UMD land use. This could be because while the area covered by RGs and RWHs is same under the two land uses, the area covered by PPs is larger, as much as the difference of parking lot area (16%), in the UMD land use compared to that in the UMC land use (Table 3.2). Contrary to surface runoff and nitrate, the high value of TP was shown in the UHDLIDs scenario. This result is in contrast with the result from the pre-LIDs scenarios which represented a low TP value in the UHD scenario. This is seen because even though the UHD scenario indicated a low value in TP, the value was not a relatively lower value compared to those of the UMD and UMC scenarios (a statistically significant difference was not indicated among urban developments, showing p-value above 0.05) and the effect by LIDs was also insignificant between the UHD and UHDLIDs scenarios, showing p-value 0.066 (> 0.05). Table 3.8 provides the results of statistical analysis for all pre- and post-LIDs scenarios for all variables.

Table 3.8 Statistical analysis (p-values of t-test) for all pre- and post-LIDs scenarios

Surface runoff

Scenario	UHD	UHDLIDs	UMC	UMCLIDs	UMD
UHDLIDs	2.00E-10*	-	-	-	-
UMC	1.10E-06*	5.30E-14*	-	-	-
UMCLIDs	0.11	0.1	5.20E-07*	-	-
UMD	1.60E-07*	7.70E-15*	0.67	9.10E-08*	-
UMDLIDs	0.04*	0.26	9.00E-08*	0.71	1.50E-08*

Table 3.8 Continued

Nitrate

Scenario	UHD	UHDLIDs	UMC	UMCLIDs	UMD
UHDLIDs	1.40E-05*	-	-	-	-
UMC	3.40E-07*	2.00E-16*	-	-	-
UMCLIDs	0.85649	8.20E-05*	1.00E-05*	-	-
UMD	8.30E-08*	2.00E-16*	0.86313	3.70E-06*	-
UMDLIDs	0.77799	0.00028*	7.20E-07*	0.67591	2.10E-07*

Total phosphorus

Scenario	UHD	UHDLIDs	UMC	UMCLIDs	UMD
UHDLIDs	0.06615	-	-	-	-
UMC	0.60698	0.07087	-	-	-
UMCLIDs	0.00061*	0.02572*	0.00116*	-	-
UMD	0.31091	0.02236*	0.6773	0.0003*	-
UMDLIDs	0.00074*	0.03136*	0.00141*	0.91933	0.00036*

* means a statistically significant difference

From these results, it is worth noting that, without LIDs, UHD land use can be the best choice which can minimize the impact of urbanization on surface runoff and pollutant loadings. However, when LIDs are applied to urban developments, UHD land use cannot be the only perfect choice in reducing runoff and pollutants. As seen in Table 3.8, 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. That is, post-LIDs scenarios were better than the UHD scenario in some cases. In addition, surface runoff showed very similar results among the post-LID scenarios, not representing statistically significant differences (p-value > 0.05). This might be because UHD land use used in this study had a less urban density than the ones usually used in other studies and thus LIDs could make the impact of urban development more or less equal altogether.

Conclusion

The present study provided an opportunity to examine the impacts of LIDs on flow and pollutant loadings under three land uses with the different urban patterns given and to develop a model for simulating the examined LIDs in SWAT. The method in representing LIDs in SWAT was flexible and easily applicable. There is no model that completely incorporates all requirements to simulate various LIDs. 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 LIDs in SWAT.

The application of LIDs contributed to the reduction of surface runoff and pollutants under all land uses, and the LIDs effectiveness 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-value < 0.05) just except for TP between the UHD and UHDLIDs scenarios (p-value = 0.066 > 0.05). However, despite the significant contribution of LIDs in most cases, a large amount of surface runoff can be generated by heavy precipitation because LIDs 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 the requirement, it is necessary to study other alternatives that can cover the rest of the volume besides the volume of the LIDs. It is beyond the scope of the present study and thus was not treated.

The results among the post-LIDs scenarios showed that 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 LIDs under different designs could provide useful information on an optimal design. The result would help regulator develop effective LID policies on a development scale which could enhance the solutions for stormwater problems for their watersheds. Meanwhile, it should be noted that the results can be changed if considering different watersheds with different soils, slopes, and land use properties, different conditions such as types and allocations of LIDs, or a budget of LIDs implementation. Therefore, it is recommended that simulations be performed in advance under the development policy at a region prior to constructing LIDs.

CHAPTER IV

EVALUATING VARIOUS LOW IMPACT DEVELOPMENT SCENARIOS USING SWAT FOR OPTIMAL DESIGN CRITERIA DEVELOPMENT

Introduction

Development goes with increased impervious cover (Freeman et al., 2008). Urban impervious surfaces have aggregated stormwater problems. Specifically, surface runoff volume is significantly increased as infiltration is hindered. It decreases groundwater recharge and accordingly reduces the amount of base flow (Paul and Meyer, 2001). Significant water-bound pollutants are conveyed to nearby water bodies by the increased urban runoff flowing over the impervious surfaces. It is necessary to take corrective action in response to those stormwater problems. Installation of Low Impact Development practices (LIDs) is one method to offset the adverse impact caused by urbanization. LIDs help to achieve both development and environmental protection by imitating the hydrology of a pre-developed state. Research on the effects of LIDs has been active and has comprehensively been addressed in a variety of studies. Most studies have demonstrated the benefits of LIDs by showing reductions in runoff volume and pollutant loadings (e.g., Dietz and Clausen, 2008; Damodaram et al., 2010; Jeon et al., 2010; Jeong et al., 2013).

However, the degree of effectiveness of LIDs can be affected by various factors. Some studies, for example, have reported the different effects of LIDs on water quantity and quality under different types of soil (e.g., Brander et al., 2004; Holman-Dodds et al.,

2003) and under various rainfall patterns (e.g., Ackerman and Stein, 2008; Carter and Jackson, 2007; Schneider and McCuen, 2006). A few studies have pointed out that different effects of LIDs could exist depending on how urban areas are designed (Brander et al., 2004; Gilroy and McCuen, 2009; Williams and Wise, 2006). The present author also evaluated the effectiveness of LIDs on hydrology and water quality under three land uses with different types of urban pattern (compact high-density, conventional medium-density, and conservational medium-density) using the Soil and Water Assessment Tool (SWAT) and presented the optimal land use.

In addition to these external conditions, the effectiveness can also be expected to vary as a result of various LIDs planning and design factors such as types, locations, percent allocations, and so forth. Gilroy and McCuen (2009) simulated the spatial and quantitative effects of cisterns and bioretention areas using a developed spatio-temporal model and provided information on the spatial arrangements and volumes needed to achieve effective results in reduction of runoff volumes and peak discharge rates. Endreny and Collins (2009) examined groundwater recharge and mounding by adjusting the spatial arrangements of bioretention areas as distributed, clustered, and single units using a MODFLOW model in an urban residential area of New York, USA. They determined that groundwater mounding was the highest when bioretention areas were arrayed as single units and lowest when they were fully distributed. Holman-Dodds et al. (2003) stated the importance of LIDs placement from differences in runoff volumes depending on the soil types. Brander et al. (2004) identified the impact of the number of infiltration practices by demonstrating that runoff differences among different urban types could be overcome by implementing a number of infiltration practices. Bracmort et al. (2006) and Santhi et al. (2006) also represented higher reductions in accordance with numerous best management practices (BMPs, conventional stormwater treatment systems akin to LIDs).

In this regard, the establishment of proper watershed-scaled strategies for LIDs conditions is required to obtain optimal results. Cost is an essential factor that must be considered along with the strategies because a restricted budget is usually given for performing the strategies (Arabi et al., 2006). To establish effective conditions for LIDs based on minimal cost (refer to cost-effective conditions), many what-if scenarios would have to be considered. The more conditions are increased, the more scenarios are created. Gilroy and McCuen (2009) simply followed common trends in determining scenarios for placing cisterns and bioretention areas, and Chaubey et al. (2008) stated that random placement is normally used. However, such methods can make an effective scenario which may result in better outcomes along with the reduction in cost missed among other unconsidered scenarios. For this reason, optimization is necessary. Many researchers have performed optimizations to accomplish optimal effects close to a required target value based upon minimal cost within their criteria (e.g., Arabi et al., 2006; Gitau et al., 2004 and 2006; Maringanti et al., 2009 and 2011; Rodriguez et al., 2011). However, most studies have been for BMPs optimization in agricultural watersheds and have drawn the optimal scenario (or the best solution) by utilizing various optimization tools such as genetic algorithm (GA) through model development. While the use of the tools enables evaluation of a myriad of probable options for various

LIDs conditions, it makes the process complex and increases the simulation time (Maringanti et al., 2009). In particular, it becomes an inefficient way when considering just a few conditions or small watersheds. In this regard, a manual technique for optimization is demanded which can simplify the complexity and which can easily provide information on the cost-effective conditions at any watershed.

The ultimate goal of the present study is to evaluate the effectiveness of LIDs under various LIDs conditions at a watershed scale. To attain this goal, a manual optimization was first conducted for the various conditions of LIDs, using a Microsoft Excel spreadsheet. Targeted reduction amounts were arbitrarily set, and the conditions of LIDs were optimized to meet them based on minimal cost. Subsequently, how the effectiveness of LIDs varies with certain conditions was analyzed. Three LIDs conditions were taken into account: types of LIDs, locations of LIDs, and percent allocations of LIDs at each location. The process was performed for surface runoff, nitrate (NO_3), and total phosphorus (TP).

Methodology

Case Study Area

The study was carried out in a small-scaled area of approximately 350 ha (3.5 km^2), comprised of some portions of League City, Webster, and Friendswood in Harris County, Texas. The area is nested within the Clear Creek watershed and is situated downstream of Clear Creek which belongs to an area under the influence of tidal currents (Fig. 4.1). Estuarine areas have generally had more water problems, such as flooding and accumulation of untreated pollutants, than other regions because of their geographical characteristics. In that regard, this is an area that should be managed.

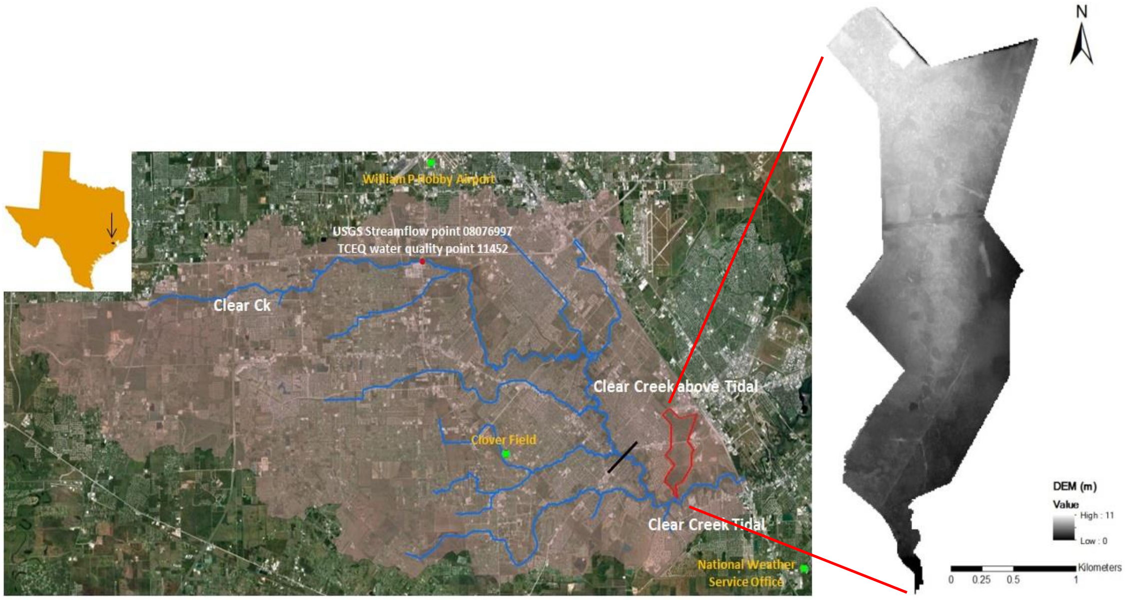


Figure 4.1 The study area within the Clear Creek watershed

The topography of the area tends to be flat with an elevation of almost 6 to 8 meters. While current land use is in a pre-development state consisting of hay (28.23%), rangeland (15.35%), wetland (30.71%), and forest (25.71%), new urban land use is adopted for future development in this area. It is a land use with a conventional urban form of medium density (Fig. 4.2). This is an urban pattern that is commonly encountered in the United States, with single family neighborhoods and a commercial district. It is one of the urban strategies by the city of League City (League City, 2013). The soil of the study area is classified into four types: Addicks (61.4%), Bernard (27.3%), Lake Charles (3.2%), and Aris (8.1%). The textures of the soils are mainly clay and clay loam, and they all belong to hydrologic soil group (HSG) D, very low permeable. Mild winters and hot summers are typical weather patterns for this region. The temperature averages about 12°C (53°F) in January and about 29°C (84°F) in August. The average annual rainfall is approximately 1,270 mm with an average monthly range of about 50 mm to 165 mm. Intense rainfall is typical of this region because of its oceanic climate.

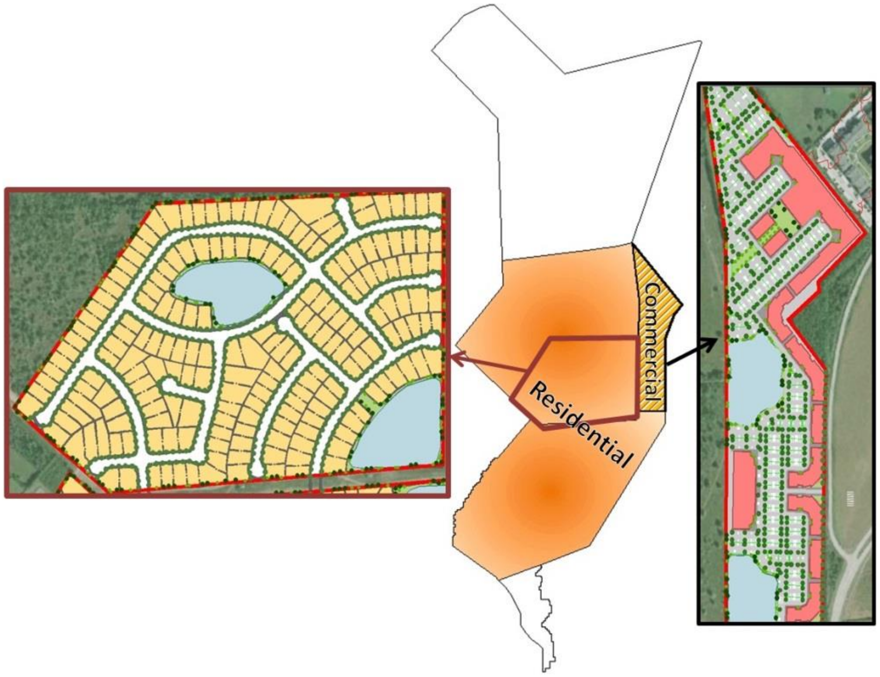


Figure 4.2 New land use with the conventional urban form of medium density (Blowups are sections of the urban area)

Model Description and Development

Soil and Water Assessment Tool (SWAT) is a model developed by the United States Department of Agriculture - Agricultural Research Service (USDA - ARS). It has been extensively used to deal with various water quantity and quality problems from many watersheds, and its capability has been verified through results. It is applicable to simulations of various sizes of watersheds from small and medium watersheds to large watersheds (e.g., Spruill et al., 2000; Francos et al., 2001; Lee et al., 2011). It can also simulate long and short terms and even sub-daily and sub-hourly time steps (e.g., Bracmort et al., 2006; Qi and Grunwald, 2005; Jeong et al., 2010). As SWAT is a distributed model, it can discretize a watershed as subbasins and Hydrologic Response

Units (HRUs), minimal response units. It has essential model components such as surface runoff, infiltration, groundwater, evapotranspiration, nutrient cycling, etc. All components are operated at an HRU level.

Surface runoff can be calculated based on a modified Natural Resources Conservation Service (NRCS) curve number method (SCS, 1972) on a daily basis. Surface runoff calculation in urban areas is respectively processed for the disconnected impervious/pervious area and for the connected impervious area, and urban surface runoff is finally estimated by adding each surface runoff from each area. The amount of infiltration depends on the amounts of precipitation and surface runoff. That is, it is estimated by excluding surface runoff from rainfall. The infiltrated water is uniformly distributed in a soil layer through a redistribution process. The soil water is percolated at water content above field capacity in the soil layer, and groundwater is recharged by percolation. The amount of actual evaporation from soil is affected by the water content of a soil layer. The evaporation is decreased below the soil water content at the field capacity of the layer. Sediment and nutrient processes interrelate with the water process. A Modified Universal Soil Loss Equation (MUSLE; Williams, 1975) predicts sediment yield, which is a function based on a runoff factor. The transportation of nitrate is influenced by surface runoff, lateral subsurface flow, or percolation. Soil attached nutrients such as organic and mineral phosphorus and organic nitrogen are governed by sediment yield transported by surface runoff under a loading function (McElroy et al., 1976; Williams and Hann, 1978).

Model Development

The SWAT processes can sufficiently explain the hydrologic behavior by LIDs on a watershed scale. Therefore, SWAT was determined to be a suitable model, and model development was performed for the simulation of LIDs by adding new codes and modifying existing codes.

In this study, three LID practices including permeable pavements (PPs), rain gardens (RGs), and rainwater harvesting systems (RWHs) were factored into an urban area. They partially store surface runoff generated from an urban area up to their capacities and discharge water exceeding their capacities as surface runoff. Surface runoff process was modified to reflect the hydrologic behavior by LIDs based on McCuen's method (MDE, 1983). He used the amount that runoff depth stored by infiltration practices is excluded from the runoff depth of post-development in order to calculate the modified curve number that reflects the infiltration practices. The idea for the method was incorporated into the surface runoff process as Equation 4.1.

$$Q_{LIDs} = Q_{tot} - LIDval \tag{4.1}$$

where Q_{tot} is the surface runoff depth (mm) before the application of LIDs, Q_{LIDs} is the surface runoff depth (mm) after LIDs are reflected, and LIDval is the storage depth (mm) of each LID.

SWAT effectively represents hydrologic behaviors by PPs and RGs under the developed equation. As can be seen in the equation, surface runoff, excluding stored water by PPs and RGs, is computed, and the water stored by PPs and RGs is added to the amount of infiltration without disappearance. On the other hand, RWHs are simply storage facilities that cannot directly infiltrate the stored water into soil layers, unlike RGs and PPs. Thus, codes were additionally included that water accrues in the rain barrels and that the accumulated water is deliberately drained to reuse them. The rain barrels were defined to be vacated when at least 7 consecutive dry days between rainfall events lasted. A text file that allows for entrance of the storage depths for each LID was included in a SWAT folder, and an algorithm that could read the text file was coded. The lack of description for the representation of LIDs in SWAT was detailed in Chapter III.

LID Practices Conditions for Optimization

The three LIDs under consideration are building-scaled facilities frequently practiced in urbanized areas which have very little space for installation. Each LID is site-specific. In this study, they are assumed to address stormwater and the consequential pollutant loadings only from each specific site: that is, RWHs are installed below roofs and harvest runoff and pollutants only from rooftops during rainfall, PPs are considered only in the parking lots of a commercial area and collect runoff and pollutants generated only from parking lots, and RGs are integrated in the backyards of each house or street systems such as sidewalks at random and treat runoff and pollutants generated from a residential area.

Each LID occupies different areas. In the case of RWHs, areas of roofs were substituted to represent their areas since RWHs deal with runoff only from roofs. The design data from the city of League City offers no information for roof areas. Therefore, an average roof area was acquired from similar neighborhoods with a conventional medium-density urban design through sampling in Google Earth, and total roof area was determined by multiplying the average roof area by the number of lots presented from the design data. The total area of RGs was estimated by multiplying a catchment area by a size factor based on soil properties and depths of RGs (Mechell and Lesikar, 2008). The catchment area was applied for each residential subbasin area in which the total roof area was excluded. This process was for the purpose of ruling out runoff addressed by RWHs. The size factor, 0.1, was used based on data from Bannerman and Considine (2003). The total area of PPs was dependent on the percentage of parking lot area presented in the commercial area of the design data. Consequently, 20% (36.37 ha) and 8% (14.55 ha) of the residential area were considered respectively as the areas for RWHs and RGs, and 47% (8.57 ha) of the commercial area was taken into account as the area for PPs.

Each LID was designed to detain different runoff depths. The maximum storage depths of PPs and RGs were limited to a rainfall size. They were calculated by 1.5 inches (38.1 mm) of precipitation on each site based on the CN method. The runoff from the 1.5 inches of rainfall is the amount for protecting water quality in the north central Texas region as the 85th percentile storm, which is referenced in Technical Manual of iSWM (http://iswm.nctcog.org/technical_manual.asp). Calculations show this number is not much different in the Houston area and thus would be used in this study. For RWHs, the 1,000 gallon rain barrel was assumed to be used to treat runoff and pollutants from a roof (Shannak et al., 2014). The volume was reversely divided by the average roof area to estimate maximum storage depth. As a result, PPs, RGs, and RWHs were sized to capture 32.52 mm, 19.11 mm, and 12.94 mm runoff depths from each area, respectively.

The information for the maximum areas and storage depths of LIDs is summarized in Table 4.1.

Table 4.1 Specific information for maximum areas and storage depths of LIDs

	Area (ha)			Storage depth (mm)
	Commercial area (subbasin 2)	Residential area (subbasin 3)	Residential area (subbasin 4)	
Subbasin area	18.22	83.28	98.55	-
RGs	-	6.66	7.88	19.11
RWHs	-	16.66	19.71	12.94
PPs	8.57	-	-	32.52

Modeling Work

In the context of this study, “pre-LIDs” and “post-LIDs” mean the post-development state without and with LIDs, respectively. Simulations for pre- and post-LIDs scenarios were performed for the purpose of identifying the maximum benefits of LIDs which would be ultimately used to set targeted reduction amounts in order to evaluate the effectiveness of LIDs. The targeted reduction amounts are illustrated in the subsection of Manual optimization.

The simulation for the pre-LIDs scenario was first configured by using several input data. It is desirable to use high resolution data for the simulation of a small study area for producing accurate outputs. The ten by ten meter Digital Elevation Model (DEM), obtained from USDA NRCS Geospatial Data Gateway, was used to describe topography in detail. For soils, the Soil Survey Geographic Database (SSURGO) from the NRCS Soil Data Mart was applied. The daily rainfall and temperature data of two stations, the National Weather Service Office and Houston Clover Field, were employed which were acquired from the National Climate Data Center (NCDC). For humidity, wind speed, and solar radiation, the generated data from a weather generator were used. These weather data from each station have an impact on the nearby subbasins. The new land use with a conventional medium-density urban form was applied to obtain results in the post-development state. The urban area of the land use takes up about 56% of the total area and is separated as residential and commercial areas which have 44% and 75% impervious fractions, respectively. The remaining area (44%) remains unchanged as a pre-developed area. The land use was represented as 5 subbasins, including 2 subbasins for the residential area and 1 subbasin for the commercial area, and 18 HRUs in total. The parameters acquired from the calibration process of pre-development state were kept fixed (the content for the calibration process can be found in Chapter II). SWAT was tested for surface runoff, nitrate, and total phosphorus from Oct., 2006 to Dec., 2011. The results of the pre-LIDs scenario indicated 473.32 mm for surface runoff, 591.87 kg for nitrate, and 449.55 kg for TP on an average annual basis.

The simulation for the post-LIDs scenario was performed under the same conditions as for the pre-LIDs scenario. In order to test the post-LIDs scenario, the three LID facilities were applied in SWAT. RWHs and RGs were considered in the same residential area and PPs were only in the commercial area. The LIDs were assumed to be fully placed and implemented, and seasonal impacts of LIDs were not reflected. The application of LIDs was performed at an HRU level. The existing HRUs of the residential and commercial areas were divided to represent the separate HRUs of the roofs and parking lots in order to treat RWHs and PPs. The RGs were dealt with in the rest of the HRUs of the residential area. In order to divide the HRUs, the percentages for the areas of the roofs (20%) and the parking lots (47%) were multiplied to the existing HRUs. The roofs and parking lots were included as new urban types in the existing urban data, and each urban type was applied to the separated specific HRUs. The number representing each LID given in the text file was also applied to all HRUs that have LIDs. The post-LIDs scenario was run by using the modified SWAT, and the effects by LIDs were measured for runoff, nitrate, and TP on a watershed scale. The LIDs controlled surface runoff and the consequential pollutants well in urban areas as shown in decreased values from the pre-LIDs scenario. The results represented 337.81 mm for runoff, 405.85 kg for nitrate, and 338.86 kg for TP. The differences between the pre- and post-LIDs scenarios (equivalent to the reduction amounts according to the impact of LIDs) were calculated for each variable.

Cost Estimation

Cost functions as an important measure for optimization. An annual total cost for each LID was estimated as the sum of construction and maintenance costs, based on the following equation by Arabi et al. (2006) (Eq. 4.2).

$$C_{td} = \left[C_0 \cdot (1+s)^{td} + C_0 \cdot rm \cdot \left(\frac{(1+s)^{td} - 1}{s}\right)\right] / \, td \qquad (4.2)$$

where C_{td} is the annual cost per unit area during a design life ($/ft^2/yr), C_0 is the construction cost per unit area ($/ft^2), rm is the proportion of maintenance to construction cost, s is the interest rate, and td is the intended life of LIDs based on routine maintenance.

Data for the construction costs per unit area ($/ft^2) were acquired from experimental field data of the Texas A&M AgriLife Research and Extension Center in Dallas. The cost of $6 per square feet was used for RGs, $14 per square feet for PPs, and $1 per gallon for RWHs. In the case of RWHs, the cost per gallon was converted by replacing the 1,000 gallon rain barrel with the average roof area. The functions of LIDs are decreased as time passes so that maintenance is continuously required to keep the same effectiveness during the life time of each LID. For the computation of maintenance costs, 5% was used as the proportion of maintenance of RGs to construction cost. This value was referenced by the US Environmental Protection Agency 1999 (USEPA, 1999). In the case of PPs and RWHs that have no reference data, 5%, the same as for RGs, was used for PPs because similar maintenance cost was incurred to maintain PPs in the experimental field of the AgriLife center, and a 1% ratio was determined for RWHs due to the low maintenance requirements. For all LIDs considered, the same interest rate of

4.5% was considered and the same lifespan of 20 years was applied to the cost calculation. As a result, the annual costs per unit area were estimated as 1.19 ($\$/ft^2/yr$) for RGs, 2.79 ($\$/ft^2/yr$) for PPs, and 0.04 ($\$/ft^2/yr$) for RWHs.

Manual Optimization

Setting Targeted Reductions

The USEPA has conducted a water quality standards program which presents a threshold level to protect water bodies (USEPA, 1986). Under the policy, states and local authorities have individual criteria to be handled for pollutants that are an issue in their region. However, there currently exists no recommended criteria for reduction in this study area and accordingly no given budget limitation. Therefore, it was arbitrarily determined that five cases would be used as targeted reduction amounts to be controlled for all variables. The targeted reduction amounts for each case include the following values: 25%, 35%, 45%, 55%, and 65% of the maximum reduction amount. In the modeling work, the maximum reduction amounts were obtained by 100% occupation of LIDs in the urban area, and those amounts were 135.51 mm for runoff, 186.03 kg for nitrate, and 110.69 kg for TP as average annual values in the watershed. For Case 1, 25% of the maximum reduction amounts (33.88 mm for runoff, 46.51 kg for nitrate, and 27.67 kg for TP) were targeted as reduction amounts to be managed. Likewise, Cases 2, 3, 4, and 5, respectively, targeted 35%, 45%, 55%, and 65% of the maximum reduction amounts. The constant difference among cases is for facilitating evaluation of the effectiveness of LIDs from the LIDs conditions considered. The targeted reduction amounts for each case are summarized in Table 4.2.

Table 4.2 Hypothetical cases for the targeted reduction amounts

	Targeted reduction amount				
	Case 1	Case 2	Case 3	Case 4	Case 5
Surface runoff (mm)	33.88	47.43	60.98	74.53	88.08
Nitrate (kg)	46.51	65.11	83.71	102.32	120.92
Total phosphorus (kg)	27.67	38.74	49.81	60.88	71.95

Optimization Procedure

For the purpose of identifying the conditions of LIDs that achieve both the targeted reduction amounts and minimal cost, a stepwise manual operation for optimization was attempted for all variables. The LIDs conditions considered were the type, location, and percent allocation. Each type and location (subbasin) of LIDs under 100% allocation were first taken into account to determine a ranking for cost in handling unit reduction in order to ultimately minimize the total cost for reducing a targeted amount. In this study, RGs and RWHs were distributed only in the residential area that is composed of two subbasins (subbasin 3 and subbasin 4), and PPs were placed only in the commercial area which takes one subbasin (subbasin 2). Because one type of LIDs was considered for each designated subbasin, five cases for the conditions were generated: that is, RGs in subbasin 3, RGs in subbasin 4, RWHs in subbasin 3, RWHs in subbasin 4, and PPs in subbasin 2. The SWAT model was run for each case and average annual reduction amounts for all variables were investigated through the difference from the pre-LIDs scenario. The annual cost for the implementation of LIDs was estimated for every case by multiplying the annual cost per unit area calculated under the cost equation (Eq. 4.2) by the LIDs area of each case (given in Table 4.1). The cost per unit reduction was then calculated by dividing the annual cost into the average annual reduction amounts for every case. Different values were obtained for every case for each variable, and they were ranked in the order of least costly to most costly. The reduction amounts treated per unit area of LIDs were also computed for each case in order to optimize the percent occupation which met targeted reduction amounts. These amounts were obtained by dividing the average annual reduction amounts into the LIDs area of each case. By following this procedure, a database for optimization was prepared. Optimization was achieved - in the order of type and location for the ranking of the cost per unit reduction - as reduction amounts according to the percent occupation of LIDs were accumulated up to the point that targeted reduction amounts were met.

With regard to optimization of percent occupation, three constraint conditions were applied to explore the behavior of LIDs effectiveness for the LIDs conditions: 1) ultimate adoption, 2) maximum adoption, and 3) minimum adoption. Ultimate adoption means to allow full occupation in given LIDs areas even if it is not feasible in reality. Maximum adoption means to restrict the potential occupation of LIDs up to a maximum of 75% for RGs and RWHs and 50% for PPs. Minimum adoption is to require at least 20% occupation of LIDs but not to exceed 75% for RGs and RWHs and 50% for PPs.

The optimization was performed in the same way for each targeted reduction amount for all variables. After optimization, the cost of each case was estimated through the product of the reduction amount and the cost per unit reduction, and the final total cost was obtained as the sum of the cost of each case. The final cost per unit reduction was also obtained by dividing the total cost into the targeted reduction amount. The same process of cost calculation was conducted for optimized conditions for all variables.

Figure 4.3 provides a stepwise procedure for a manual optimization.

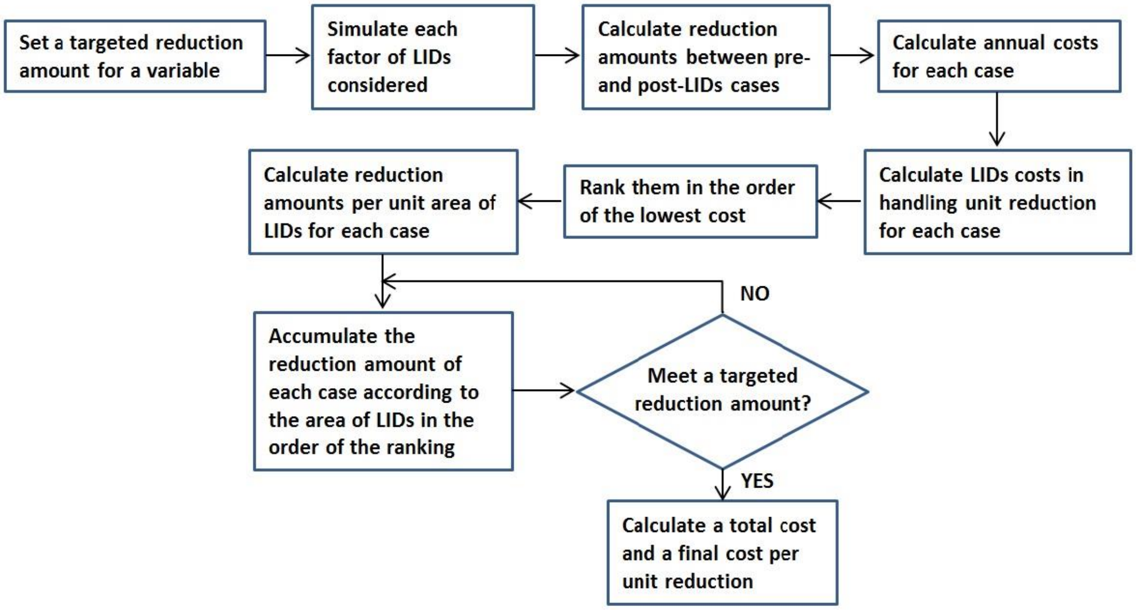


Figure 4.3 Flow chart for a manual optimization procedure

Results

The cost-effective conditions for controlling each targeted reduction amount were determined for all variables through the optimization process. A variety of configurations were drawn for each variable. For surface runoff, the optimal conditions were ranked in the order of RWHs (4)[1], RWHs (3), RGs (4), RGs (3), and PPs (2). For nitrate, they were arranged in the order of RWHs (3), RWHs (4), RGs (4), RGs (3), and PPs (2). In the case of TP, since the amount of TP reduced by RWHs was tiny compared to the cost for implementation of RWHs, the cost-effective conditions were prioritized in the sequence of RGs (3), RGs (4), RWHs (4), RWHs (3), and PPs (2) unlike runoff and nitrate. Under these rankings, different percentages of occupation were assigned, which met the given targeted reduction amounts (Table 4.3 to 4.5).

As can be seen through these results, various combinations of conditions affected the effectiveness of LIDs. For example, with regard to the result of the surface runoff of the ultimate adoption (Table 4.3A), the effectiveness of LIDs in the watershed increased as much as 13.55 mm in Case 2 by considering 22.62% RGs (4) more than in Case 1.

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[1] Parenthesis means a location (subbasin) of LIDs

Table 4.3 Results of the optimization for surface runoff

(A) Ultimate adoption			Case 1	Case 2	Case 3	Case 4	Case 5
Targeted reduction amount			33.88	47.43	60.98	74.53	88.08
Ranking	Type	Location	% allocation				
1	RWHs	Sub 4	100.00	100.00	100.00	100.00	100.00
2	RWHs	Sub 3	100.00	100.00	100.00	100.00	100.00
3	RGs	Sub 4	40.14	62.76	85.38	100.00	100.00
4	RGs	Sub 3	0.00	0.00	0.00	9.99	38.28
5	PPs	Sub 2	0.00	0.00	0.00	0.00	0.00
(B) Maximum adoption							
Ranking	Type	Location	% allocation				
1	RWHs	Sub 4	75.00	75.00	75.00	75.00	75.00
2	RWHs	Sub 3	75.00	75.00	75.00	75.00	75.00
3	RGs	Sub 4	44.24	66.86	75.00	75.00	75.00
4	RGs	Sub 3	0.00	0.00	18.10	46.39	74.68
5	PPs	Sub 2	0.00	0.00	0.00	0.00	0.00
(C) Minimum adoption							
Ranking	Type	Location	% allocation				
1	RWHs	Sub 4	75.00	75.00	75.00	75.00	75.00
2	RWHs	Sub 3	75.00	75.00	75.00	75.00	75.00
3	RGs	Sub 4	22.28	44.90	67.52	75.00	75.00
4	RGs	Sub 3	20.00	20.00	20.00	38.93	67.21
5	PPs	Sub 2	20.00	20.00	20.00	20.00	20.00

Table 4.4 Results of the optimization for nitrate

(A) Ultimate adoption			Case 1	Case 2	Case 3	Case 4	Case 5
Targeted reduction amount			46.51	65.11	83.71	102.32	120.92
Ranking	Type	Location	% allocation				
1	RWHs	Sub 3	100.00	100.00	100.00	100.00	100.00
2	RWHs	Sub 4	100.00	100.00	100.00	100.00	100.00
3	RGs	Sub 4	29.87	59.04	88.21	100.00	100.00
4	RGs	Sub 3	0.00	0.00	0.00	21.41	57.30
5	PPs	Sub 2	0.00	0.00	0.00	0.00	0.00
(B) Maximum adoption							
Ranking	Type	Location	% allocation				
1	RWHs	Sub 3	75.00	75.00	75.00	75.00	75.00
2	RWHs	Sub 4	75.00	75.00	75.00	75.00	75.00
3	RGs	Sub 4	40.64	69.81	75.00	75.00	75.00
4	RGs	Sub 3	0.00	0.00	29.51	65.42	75.00
5	PPs	Sub 2	0.00	0.00	0.00	0.00	29.06
(C) Minimum adoption							
Ranking	Type	Location	% allocation				
1	RWHs	Sub 3	75.00	75.00	75.00	75.00	75.00
2	RWHs	Sub 4	28.21	75.00	75.00	75.00	75.00
3	RGs	Sub 4	20.00	38.84	68.01	75.00	75.00
4	RGs	Sub 3	20.00	20.00	20.00	47.31	75.00
5	PPs	Sub 2	20.00	20.00	20.00	20.00	29.06

Table 4.5 Results of the optimization for total phosphorus

(A) Ultimate adoption			Case 1	Case 2	Case 3	Case 4	Case 5
Targeted reduction amount			27.67	38.74	49.81	60.88	71.95
Ranking	Type	Location	% allocation				
1	RGs	Sub 3	68.96	96.57	100.00	100.00	100.00
2	RGs	Sub 4	0.00	0.00	20.76	44.47	68.18
3	RWHs	Sub 4	0.00	0.00	0.00	0.00	0.00
4	RWHs	Sub 3	0.00	0.00	0.00	0.00	0.00
5	PPs	Sub 2	0.00	0.00	0.00	0.00	0.00
(B) Maximum adoption							
Ranking	Type	Location	% allocation				
1	RGs	Sub 3	68.96	75.00	75.00	75.00	75.00
2	RGs	Sub 4	0.00	18.53	42.24	65.95	75.00
3	RWHs	Sub 4	0.00	0.00	0.00	0.00	75.00
4	RWHs	Sub 3	0.00	0.00	0.00	0.00	75.00
5	PPs	Sub 2	0.00	0.00	0.00	0.00	36.30
(C) Minimum adoption							
Ranking	Type	Location	% allocation				
1	RGs	Sub 3	38.07	65.68	75.00	75.00	75.00
2	RGs	Sub 4	20.00	20.00	35.70	59.40	75.00
3	RWHs	Sub 4	20.00	20.00	20.00	20.00	75.00
4	RWHs	Sub 3	20.00	20.00	20.00	20.00	75.00
5	PPs	Sub 2	20.00	20.00	20.00	20.00	36.30

The effect increased 100% in Case 3 by extending RGs occupation as much as 45.24% and 200% in Case 4 as 59.86% RGs (4) and 9.99% RGs (3) were added from Case 1. In addition, an increase of 300% was shown in Case 5 as 59.86% RGs (4) and 38.28% RGs (3) more were considered than for Case 1. When nitrate is a focused variable (Table 4.4A), 29.17% more adoption of RGs (4) than in Case 1 improved the effectiveness of LIDs of 18.6 kg in Case 2. The effect rose 100% in Case 3 as 58.34% RGs (4) more was added than in Case 1. Also, increases of 200% and 300% of the effect appeared in Cases 4 and 5 respectively by further considering 70.13% RGs (4) and 21.41% RGs (3) and expanding 70.13% RGs (4) and 57.30% RGs (3) more than in Case 1. In the case of TP, RGs were only included in the optimal conditions because the amount handled by RGs was as large as covering all targeted reduction amounts. As seen in Table 4.5A, the effectiveness of LIDs grew by 11.07 kg in Case 2 as 27.61% RGs (3) more was factored than in Case 1 and the effect increased 100% in Case 3 as 31.04% RGs (3) and 20.76% RGs (4) more were adopted than in Case 1. In addition, improvements of 200% and 300% occurred in Cases 4 and 5 by adoption of 31.04% RGs (3) and 44.47% RGs (4) more and of 31.04% RGs (3) and 68.18% RGs (4) more than in Case 1, respectively. These phenomena, that is, the variation of the effectiveness of LIDs by the different combinations of the conditions, were represented under the maximum and minimum adoptions as well (Table 4.3BC to 4.5BC).

On the other hand, it was also observed that various combinations of the conditions could cause the same effectiveness of LIDs through the comparisons among the ultimate, maximum, and minimum adoptions. Under maximum adoption, reduction amounts which are not addressed by the difference in percent occupation from the ultimate adoption are passed on to the next rankings. In the case of minimum adoption, after 20% adoption for all rankings, the same process with the maximum adoption is conducted for the remaining amounts which are expected to be reduced. The result in Case 3 of surface runoff, for example, showed fully occupied LIDs up to the point of ranking 3 and 18.1% RGs (3) under the condition of maximum adoption in meeting the same reduction amount with the ultimate adoption (Table 4.3B). Under the condition of minimum adoption, 67.52% RGs (4) was applied for ranking 3 and the highest and lowest constraint values were applied for the rest of the rankings (Table 4.3C). The different percent adoption was represented for not only Case 3 but also for four cases among the three constraint conditions, but the same LIDs effects with the ultimate condition were achieved. These phenomena were also found in all cases of nitrate and total phosphorus.

In regard to the aspect of cost, final total costs and costs per unit reductions generated from the optimized conditions were compared and analyzed (Table 4.6). All results displayed are the minimal costs that treated the given targeted reduction amounts. In the comparison of each case among the conditions of constraint adoption, the ultimate condition appeared to be the most cost-effective for all cases and for all variables. This is because more adoption of LIDs for cost-effective conditions is possible in controlling the same targeted reduction amount. Among five cases in each constraint condition, the smallest total cost and the cost in handling unit reduction were indicated in Case 1 for all variables under the ultimate and maximum adoption conditions. This is due to the fact that the more a targeted reduction amount is increased, the more the total cost is increased and the consequential cost per unit reduction is therefore increased. On the other hand, the minimum adoption presented the most cost-effective result in Case 5 for runoff and in Case 4 for nitrate and TP, and the most cost-inefficient result was represented in Case 1 for all variables. This can be seen because relatively expensive PPs compared to the reduction amount are considered in all cases. With regard to nitrate and TP, the reason why Case 4 is more cost-effective than Case 5 is also attributable to more percent occupation of PPs in Case 5. That is, the increase of the total cost is significant compared to the increase of the targeted reduction amount.

Table 4.6 Total cost and the consequential cost per unit reduction

Case	Variable	Ultimate adoption		Maximum adoption		Minimum adoption	
		Cost ($)	Cost per unit reduction*	Cost ($)	Cost per unit reduction	Cost ($)	Cost per unit reduction
5	Runoff	1,493,527.83	16,956.54	1,513,759.76	17,186.24	1,963,588.64	**22,293.30**
4		1,251,284.14	16,789.22	1,271,516.07	17,060.68	1,721,430.57	23,097.45
3		1,017,591.16	16,687.76	1,029,336.60	16,880.38	1,483,537.77	24,328.95
2		788,374.34	16,622.70	791,769.48	16,694.29	1,254,320.94	26,447.09
1		559,157.51	**16,505.60**	562,628.65	**16,608.06**	1,025,104.12	30,259.74
5	NO_3	1,656,393.69	13,698.51	2,263,032.20	18,715.45	2,263,032.20	18,715.45
4		1,349,072.15	13,185.47	1,434,446.15	14,019.89	1,793,187.45	**17,526.13**
3		1,046,268.60	12,498.38	1,126,953.36	13,462.21	1,488,503.12	17,781.17
2		750,678.20	11,529.45	821,713.58	12,620.47	1,192,912.72	18,321.61
1		455,087.80	**9,785.39**	526,072.52	**11,311.72**	963,350.07	20,714.15
5	TP	1,547,180.52	21,504.95	2,449,017.71	34,039.98	2,449,017.71	34,039.98
4		1,306,918.32	21,468.24	1,310,485.93	21,526.85	1,788,390.63	**29,377.20**
3		1,066,656.12	21,415.22	1,070,249.06	21,487.36	1,548,229.76	31,083.77
2		826,916.70	21,345.41	829,936.20	21,423.35	1,309,329.87	33,798.06
1		590,495.76	**21,339.66**	590,517.17	**21,340.43**	1,072,908.94	38,773.37

*Unit is $/mm for runoff and $/kg for nitrate and total phosphorus

Recommendation

Various combinations of LIDs conditions have been analyzed to evaluate the effectiveness of LIDs. However, the water volumes detained by LIDs under the conditions meeting each targeted reduction amount with minimal cost are small as indicated in Table 4.7 because the maximum capacities and allowable areas of LIDs are limited. For heavy rainfall, a considerable amount of water that is not addressed by LIDs is generated as surface runoff, directly entering channels. In that context, large such amounts need to be taken into account for controlling stormwater in new urban development.

Table 4.7 Volumes detained by detention ponds and the consequential costs

(A) Ultimate adoption

Case	Variable	Volume detained by LIDs (ac-ft/ac)	Volume detained by detention ponds (ac-ft/ac)	Cost ($/yr)	Savings ($/yr)
5	Runoff	0.0110	0.1429	243,339.92	13,050.24
4		0.0104	0.1434	244,048.85	12,341.31
3		0.0098	0.1440	244,731.94	11,658.22
2		0.0093	0.1446	245,401.17	10,988.99
1		0.0087	0.1451	246,069.64	10,320.51
5	NO_3	0.0114	0.1425	242,862.80	13,527.36
4		0.0106	0.1432	243,762.77	12,627.39
3		0.0099	0.1439	244,648.16	11,742.00
2		0.0092	0.1447	245,511.16	10,879.00
1		0.0085	0.1454	246,372.89	10,017.26
5	TP	0.0038	0.1501	251,941.30	4,448.86
4		0.0032	0.1507	252,634.31	3,755.85
3		0.0026	0.1512	253,326.52	3,063.63
2		0.0020	0.1518	254,016.45	2,373.71
1		0.0014	0.1524	254,696.05	1,694.11

Table 4.7 Continued

(B) Maximum adoption

Case	Variable	Volume detained by LIDs (ac-ft/ac)	Volume detained by detention ponds (ac-ft/ac)	Cost ($/yr)	Savings[*] ($/yr)
5	Runoff	0.0092	0.1446	245,482.09	10,908.07
4		0.0086	0.1452	246,188.43	10,201.73
3		0.0080	0.1458	246,893.92	9,496.23
2		0.0074	0.1464	247,584.71	8,805.45
1		0.0069	0.1470	248,250.71	8,139.45
5	NO_3	0.0105	0.1433	243,883.47	12,506.69
4		0.0090	0.1448	245,713.38	10,676.77
3		0.0083	0.1456	246,609.48	9,780.67
2		0.0075	0.1463	247,497.80	8,892.36
1		0.0068	0.1470	248,356.64	8,033.52
5	TP	0.0109	0.1430	243,486.50	12,903.66
4		0.0032	0.1506	252,623.95	3,766.21
3		0.0026	0.1512	253,316.18	3,073.98
2		0.0020	0.1518	254,007.62	2,382.54
1		0.0014	0.1524	254,696.05	1,694.11

(C) Minimum adoption

5	Runoff	0.0100	0.1439	244,574.79	11,815.37
4		0.0094	0.1445	245,281.97	11,108.18
3		0.0088	0.1451	245,975.87	10,414.29
2		0.0082	0.1456	246,643.69	9,746.47
1		0.0077	0.1462	247,310.75	9,079.40
5	NO_3	0.0105	0.1433	243,883.47	12,506.69
4		0.0095	0.1443	245,072.51	11,317.65
3		0.0088	0.1450	245,961.40	10,428.76
2		0.0081	0.1458	246,822.47	9,567.68
1		0.0057	0.1482	249,707.61	6,682.55
5	TP	0.0109	0.1430	243,486.50	12,903.66
4		0.0055	0.1483	249,904.20	6,485.96
3		0.0049	0.1489	250,599.27	5,790.89
2		0.0043	0.1495	251,289.89	5,100.27
1		0.0037	0.1501	251,972.56	4,417.59

[*] The savings occurred because of reduced detention pond volumes for the amounts controlled by LIDs

For this study, detention ponds were incorporated as an interconnected area between the channel and the urban area to reflect the amount, and 100-year 24 hour rainfall (13 inches) for this region was determined as the standard amount of rainfall for the purpose of calculating the volumes that should be captured by detention ponds. First, the required detention volume was estimated by the difference in surface runoff between pre- and post-developments. The volumes that should be captured by detention ponds were then calculated by subtracting the volumes detained by LIDs from the required detention volume. The costs of the detention ponds for the calculated volume capacities were calculated using the following equation developed by Brown and Schueler (1997) (Eq. 4.3).

$$C = 24.5 \cdot V^{0.705} \tag{4.3}$$

where C is the establishment cost including construction, design, and authorization ($) and V is the pond volume (ft^3). For the calculation of the annual cost, a 5% ratio (rm) for maintenance and a design life of 20 years (td), obtained from the USEPA website, were considered and the same interest rate of 4.5% was applied. Additionally, the cost savings for the detention ponds were computed which occurred because of the amounts controlled by LIDs. These savings were obtained as a result of the difference between the costs for the calculated detention volumes and the required detention volume. Table 4.7 presents the volumes detained by the detention ponds and the consequential costs in each case for all variables and constraint conditions.

Conclusion

The present study has described the variability of the effectiveness of LIDs under various combinations of LIDs conditions on a watershed scale and has analyzed the consequential costs. To attain this goal, five targeted reduction amounts were set and the conditions considered that meet them were optimized. As accounted for in the Manual Optimization section, the optimization method employed is very simple and practical in providing cost-effective conditions. It is likely that this method would be applicable in many studies. Also, it can easily assist watershed managers in determining the best solution for the establishment of LIDs for their watershed management.

What could be learned by analyzing the results of this study is that the results for the effectiveness of LIDs and the associated costs, different from the results of the present study, might also be generated by other conditions such as different types of LIDs besides RGs, PPs and RWHs, different values of limitation for the occupation of LIDs, different treatment goals, watershed characteristics, and so forth. Therefore, adequate studies for a variety of conditions should be done in advance to achieve effective results within a given budget before the installation of LIDs. The results of such studies would likely suggest planning and design of LIDs projects that accomplish a balance between environmental and economic aspects on a development or watershed scale.

This study has been based on modeling work and simple calculations. However, if field work is performed along with the study, it is possible to validate the results from the study. Such additional study will be a very meaningful work in that it can prepare the ground for studies on other watersheds.

CHAPTER V

CONCLUSIONS

Summary

The research overall focused on an evaluation of the effectiveness of LIDs on surface runoff, nitrate, and total phosphorus under two dominant conditions: urban land uses (including three different urban designs: compact high-density urban form, conventional medium-density urban form, and conservational medium-density urban form) and LIDs design guidelines (including types, locations, and percent allocations). To perform this research, a pre-development state was first calibrated and evaluated to obtain parameter values which were reflective of the watershed characteristics of the study area. Under the same parameter values and watershed conditions, post-development simulations for the three different urban land uses were performed and the impact of land use change was evaluated for each land use. Rain gardens, rainwater harvesting systems, and permeable pavements were taken into account in the urban areas of residential and commercial areas for all land uses. These LIDs were simulated under each urban land use by using a modified SWAT model which was developed to reflect the hydrologic behavior of LIDs. Average monthly and yearly results for the simulation period were utilized to assess the watershed-scaled effectiveness of LIDs for the urban design conditions. For the LIDs conditions, after a manual optimization was performed which met both targeted reduction amounts generated from the results of simulation under conventional urban design and minimal cost, the effectiveness of LIDs was evaluated under the optimized LIDs conditions. The following results were achieved through the procedure:

- Land use change resulted in an increase of surface runoff and the degradation of water qualities and there were different degrees of hydrologic and water quality changes under the three urban land uses examined. For all variables considered, the UHD scenario generated the smallest increase followed by the UMC scenario and then the UMD scenario. From a comparison between a pre-development state and each urban scenario, high-density urban land use was not significantly different from a pre-development state in surface runoff and TP. From a comparison between urban scenarios, high-density urban land use showed a statistical difference from other urban land uses for surface runoff and nitrate while no statistical difference was obtained among urban scenarios for TP. The hydrologic and water quality differences among the urban land uses could be due to differences in the size of urban areas and in impervious/pervious fractions in urban areas.
- The performance of LIDs modeling contributed to a decrease of surface runoff volumes and pollutant loadings for all land uses, but the reductions were represented differently under the three urban land uses. For all variables, the reduction produced by LIDs was greatest in the UMD land use followed by the UMC land use and then the UHD land use, showing significant differences between pre- and post-LIDs scenarios under all land uses except for the UHD land use in TP. This could be due to the fact that the UMD land use has the

largest urban area and thus the area covered by LIDs is the largest among all land uses. Through a comparison between a pre-development state and each post-LIDs scenario, post-LIDs scenarios were statistically comparable to a pre-development state for surface runoff and TP, but not for nitrate. Meanwhile, the results among post-LIDs scenarios showed low surface runoff and nitrate amounts in the following: the UHDLIDs scenario < the UMDLIDs scenario < the UMCLIDs scenario. For TP, the order was as follows: the UMDLIDs scenario < the UMCLIDs scenario < the UHDLIDs scenario. For surface runoff and nitrate, the lowest value in the UHDLIDs scenario could be attributed to the fact that the UHD land use has the smallest urban area among the three land uses and, accordingly, the impact of the urban area is the smallest. Thus, even though the percent reduction by LIDs is smallest under the UHD land use, the lowest value can be generated. The lower value in the UMDLIDs scenario compared to the UMCLIDs scenario could be because the UMD land use has more parking lots and thus the area covered by PPs is larger than under the UMC land use. For TP, the reason why the UHDLIDs scenario showed the largest value could be explained by the fact that the impact of the urban area for the UHD land use is smallest among the three land uses but the difference is rather slight compared to the other land uses, unlike the trends of surface runoff and nitrate, and the impact by LIDs is smallest. The post-LIDs scenarios were statistically similar and were better than the UHD scenario in general. From these results, it is worth noting that the application of LIDs made the difference in runoff volume and pollutant loads greatly narrowed among the urban land uses.

- The various combinations of LIDs conditions affected the effectiveness of LIDs and the associated costs. As different percentages of allocation were assigned in the order of RWHs[1] (4), RWHs (3), RGs[2] (4), RGs (3), and PPs[3] (2)[4] for surface runoff, in the order of RWHs (3), RWHs (4), RGs (4), RGs (3), and PPs (2) for nitrate, and in the order of RGs (3), RGs (4), RWHs (4), RWHs (3), and PPs (2) for TP in order to meet the given targeted reduction amounts, it was identified that these various combinations of conditions could result in differing effectiveness of LIDs. In addition, it was observed that the same effectiveness of LIDs could be caused by simply controlling the percentages of allocation under constraint conditions in the same order of types and locations of LIDs for each variable. For the consequential costs, all results were those for minimal costs, but the ultimate adoption was the most cost-effective among the constraint conditions for all cases and all variables because of more adoption of cost-effective conditions than the other constraint adoptions. Among the five cases for given targeted reduction amounts under the ultimate and maximum adoptions, every Case 1 showed the smallest cost per unit reduction for all variables. On the

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[1] Rainwater harvesting systems

[2] Rain gardens

[3] Permeable pavements

[4] Parenthesis means a location (subbasin) of LIDs

other hand, Case 1 represented the largest cost per unit reduction for all variables under the minimum adoption because of the consideration of permeable pavements, which are expensive compared to the reduction amount, for all cases.

Overall, the research demonstrated varying effectiveness of LIDs on hydrology and water quality under various conditions. It is worthwhile to investigate how the effectiveness of LIDs can differ under certain conditions. This is because such studies can provide useful information on proper actions for effectively controlling stormwater and pollutants and help policy makers establish effective LID policies for environmentally sustainable development for the future by suggesting guidelines for LIDs planning and design in a watershed.

Recommendations for Future Studies

Research for some of the issues that could not be pursued could provide additional valuable information. Based on the present research, several suggestions are recommended for future research.

- The results for the effectiveness of LIDs can be changed if a study is performed under varied conditions including: different watersheds with different soils, slopes, and land use properties, different types of LIDs other than RGs, PPs and RWHs, different constraint conditions for the occupation of LIDs, different treatment goals and budget limitations, and so forth. Therefore, it is suggested that simulations under a variety of conditions be done in advance prior to the installation of LIDs to attain effective stormwater control.

- This research showed that UHD land use might not be enough to improve the surface runoff volumes and pollutant loadings as compared to LIDs applied to urban developments, with statistically significant differences in the performance between the post-LIDs scenarios and the UHD scenario in some cases. While this result is valid for the density used in this study (10 units/acre), denser developments might provide different results. In this regards, a study researching the effect of various high densities could be a future research project to determine the density that would result in no need for LIDs.
- Modeling tasks for LIDs were conducted and worked well for surface and subsurface hydrology and the consequential water quality, showing decreased surface runoff and pollutant loadings along with increased evapotranspiration and groundwater. However, it is necessary to do field experiments on a watershed scale along with modeling tasks because such a study can provide an opportunity to verify modeling results. Field work could not be performed in the present research because the goal of the research was to predict a future situation, but a future study involving field work would likely be a useful sequel to the present research.
- The research reported herein focused on the effects of LIDs on water quantity and quality on a watershed scale. In order to control stormwater from new urban developments, counties require minimum detention rates to be met. However, as previously indicated herein, only small amounts of water were detained by LIDs. For the amounts of water that could not be treated by LIDs, therefore, it is

necessary to study other alternatives such as detention ponds in order to meet requirements set by counties.

- In the research, an evaluation of the effectiveness of LIDs on hydrology and water quality under a variety of conditions was performed in a small-scaled study area within the Clear Creek watershed. However, an investigation in a large-scaled study area is recommended in order to identify effective conditions and the corresponding impact of LIDs at a large watershed-scaled level.

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APPENDIX A

LOW IMPACT DEVELOPMENT PRACTICES

Source: http://www.centralohioraingardens.org/wp-content/uploads/2011/12/rain-garden-filling-up-cell-31.jpg

A.1 Example of a rain garden placed in a right of way

A.2 Example of a 1,000 gallon rainwater harvesting tank (61 inch diameter) at the Harris County Extension Office in Houston (Courtesy: Fouad Jaber)

A.3 Example of a permeable pavement (pervious concrete paver (above) and permeable interlocking concrete paver (below) at the Texas A&M AgriLife Research and Extension Center in Dallas) (Courtesy: Fouad Jaber)

APPENDIX B

HOUSE PLAN FOR LIDS INSTALLATION

Estimation of sizes for a rain garden and a rainwater harvesting tank at a house scale as an example in the medium-density urban area were developed. Each house has a 1,000 gallon (6-ft diameter) rainwater harvesting tank, and the rainwater harvesting tank is only intended to capture the runoff and runoff-borne pollutants generated from a roof. Rain gardens take 8% of the residential area, and they are installed in the backyards of houses and public areas such as sidewalk patios and are only intended to treat the runoff and runoff-borne pollutants generated from backyards, driveways, and sidewalks. In the case of rain gardens, to identify the size of a rain garden in the backyard of a house, one subbasin of a residential part was selected and the area of rain gardens was calculated. Then, the area of rain gardens in public areas was estimated, and the area of rain gardens in backyards was also calculated by subtracting the area of rain gardens in public areas from the area of rain gardens. The size of a rain garden in the backyard of a house was obtained by dividing the area of rain gardens in backyards into the number of houses. As a result, a rain garden of an approximately 25-ft diameter was obtained. A 6-ft rainwater harvesting tank and a 25-ft rain garden were illustrated at a house scale.

B.1 Size of a rain garden

Area of subbasin (sub3) (ft^2)	Area of RGs (ft^2)	RGs in public areas (ft^2)	RGs in backyards (ft^2)	# of house	Diameter of a RG (ft)
8,963,840.15	717,107.21	408,751.11	308,356.10	618	**25**

B.2 Example of LIDs installation at a house level