MODELING THE EFFECTS OF LOW IMPACT DEVELOPMENT PRACTICES ON STREAMS AT THE WATERSHED SCALE

A Dissertation

by

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ABSTRACT

Urban growth contributes to increasing stormwater runoff which in turn causes an increase in the frequency and severity of flooding. Moreover, increased stormwater runoff contributes to changing the character and volume of energy inputs to the stream. Traditionally, stormwater management controls such as detention pond had been extensively studied and evaluated with respect to reducing and controlling peak flows. Nonpoint source pollutants due to urbanization and expanding of agricultural fields have become a big burden on municipalities and states.

Low Impact Development practices were developed to negate the negative impacts of urbanization on water resources by reducing the runoff volume and peak flows as well as improving outflow water quality. Though these practices have the capability of reducing runoff volumes and enhancing outflow water quality, they can be costly. Therefore, understanding the impact of installing LID practices on a watershed scale is becoming increasingly important.

In this study, field experiment and model study were applied to evaluate the effectiveness of LID practices on a watershed scale in the Blunn Creek Watershed located in Austin, Texas. The three LID practices which were evaluated in this study are permeable pavements, a bioretention area, and a detention pond. The main objective of this study was to investigate the influences of these practices at a watershed scale on: potential reduction on channel bank erosion, potential reduction on flood, and potential impact on aquatic life.

This study was one of very few studies that take place in the Blackland clay soil in Texas. A combination of different levels of LID practices such as permeable pavement and bioretention area resulted with achieving the main goal of this study of reducing stream bank erosion, bankfull exceedance, and maintaining acceptable flows for the integrity of aquatic life habitat. All LID practices have shown significant difference with respect to a control treatment at 95% confidence ratio. Performance of the modeled LID practices was validated by showing acceptable agreement in the percentage of reductions in total runoff between field experiments and model data.

DEDICATION

I dedicate this thesis to my wife Rawan Najjar and my family

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My first and most earnest gratitude goes to the Almighty Allah for materializing my dream. I would like to acknowledge my research advisor Dr. Fouad Jaber, and my research committee members for their inspiring, helpful suggestions and persistent encouragements as well as close and consistent supervision throughout the period of my Doctoral program. Dr. Jaber has provided insightful discussions about the research. I am also very grateful for his scientific advice and knowledge and many insightful discussions and suggestions.

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Most of all, I thank my parents, my wife, and kids for their loving support through my life.

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CHAPTER I

INTRODUCTION

Urban areas are expanding rapidly in the United States, resulting in an increase in impervious cover (EPA, 2012).Urban growth contributes to increasing stormwater runoff which in turn causes an increase in the frequency and severity of flooding. Moreover, increased stormwater runoff contributes to changing the character and volume of energy inputs to the stream. As a result, infiltration and base flow, as a proportion of total flow, will decrease and urban runoff volumes, frequency of flooding and peak runoff flow rates will increase (EPA, 2012). The consequences of urbanization will be reflected not only in the hydrological cycle and infrastructure, but also in human health and environment. Urban runoff has a significant role in transporting pollutants such as chemicals, sediments, pesticides, fertilizers, and oils into water bodies, where they harmfully affect water quality (Kim et al., 2007; Davis, 2007).

Low Impact Development (LID) practices were developed to reduce the negative impacts of urbanization on water resources by reducing runoff volumes and peak flows as well as improving outflow water quality (Villarreal et al., 2004). LID practices include the installation of any of the following structural measures to retrofit existing infrastructure and to reduce runoff volumes and peak flows; bioretention, green roofs, rainwater harvesting, and permeable pavements (Damodaram, 2010). LID practices has gained popularity because of their role in maintaining post development hydrograph close to the natural condition present before development occurs (Coffman 2002). The installation of these practices contributes to decreasing the need for paving, gutters, curbs, and inlet structures that eventually reduce the infrastructure construction and maintenance costs (Sample et al., 2002). Previous studies confirmed the beneficial uses of LID practices at the micro-scale such as plot or small field experiment in comparison to developed scenario without any consideration to LID structures (Selbig and Bannerman 2008; Bedan and Clausen 2009; Wang et al. 2010; Zimmerman et al. 2010). However, there is still many discussions and debates about many of these practices and their benefits on larger scales such as watershed scale. Therefore, understanding the impact of installing LID practices on a watershed scale is becoming increasingly important.

Literature Review

Increasing impervious cover through urbanization will lead to an increase in runoff volumes, and eventually this will increase flooding. Stream channels adjust by widening and eroding stream banks which can impact downstream properties negatively (Chin and Gregory, 2001). Also, urban runoff drains through sediment bank areas, known as riparian zones, and constricts stream channels (Walsh, 2009). Physical and chemical factors associated with urbanization such as high peak flows and low water quality stress aquatic life and contribute to the overall biological condition of urban streams (Maxted et al., 1995). While LID practices have been mentioned and studied in literature for stormwater management, they have not been studied in respect to reducing potential impact on flooding, stream bank and bed erosion and aquatic life.

To better evaluate the performance and the effectiveness of LID practices at a watershed scale, three practices were introduced (sustainable detention pond, bioretention, and permeable pavement). These practices capture the storm and base flow over a longer period of time, and are recommended as new metrics to characterize the magnitude of urban development influence, stream bank and bed erosion, aquatic life, and flood. These measures will create a linkage between urban watershed development and stream conditions in particular biological health.

Channel Response to Development-Induced Watershed Changes

Changing land uses due to urbanization can have harmful effects on urban and suburban streams, both hydrologically and biologically. Impervious surfaces generate higher peak flows which cause stream enlargement through bed and bank erosion (Ludwig et al., 2005; Sovern and Washington, 1997). The channel erosion observed in streams surrounded by urbanized areas is due to the increased frequency of the bankfull discharge (Pizzuto et al., 2000). Bankfull discharge reflects a state of maximum velocity in the channel, and therefore maximum competence for the transport of the load. It is generally accepted to be the dominant discharge that is close to steady- state conditions (Carling, 1988). Bankfull flows occur only every one to two years in a pristine stream (Leopold, 1994). Though, with the impact of urban development these flows can occur three to five (Klein, 1979, Booth, 1991) times per year, causing bank erosion, movement of large woody debris, and infilling of pools (Booth, 1991). Streams continue to enlarge until water velocity drops to a stable level which is defined as stream equilibrium and reaching this stable level might be delayed for several decades based on the additional volumes of flows received (Morisawa and LaFlure, 1979).

Numerous studies link the influence of urbanization and stream health and enlargement due to bank and bed erosion (Goodwin et al., 1997). Hession et al., (2003) studied the influence of varying riparian vegetation on channel morphology in rural and urban watersheds. They found that channel width and cross-sectional area are larger in urban watersheds and documented a significant difference of ($p<0.001$). Also, bankfull channels in forested streams are wider and have greater cross-sectional areas, while there are no significant differences between forested and non-forested bankfull depth, sinuosity, slope, or median bed particle size (Hession et al., 2003). Trimble (1997) conducted a study to evaluate the contribution of stream channel erosion to sediment yield from an urbanizing watershed. The study considered San Diego Creek in southern California, and measurements from 1983 to 1993. Results showed that stream channel erosion provided 10^5 Mg/yr of sediment, or about two-thirds of the total sediment yield. Another study conducted by Bledsoe and Watson (2001) found that even low levels of imperviousness 10 to 20 % have the potential to destabilize urban streams. On the other hand, Wolman and Schick (1976) found that some morphological changes and adjustments in urban streams are not strictly responses to altered stream flow patterns. For instance, banks that have been defrosted or artificially stabilized can have narrower channels and this change was not inherited from alteration in stream flow.

Konrad et al., (2005) studied the impact of urban development on stream flow and streambed stability. They examined 16 streams in the Puget Lowland, Washington, using three stream flow metrics that integrate storm-scale effects of urban development over annual to decadal timescale. They concluded that the increase in the magnitude of frequent high flows due to urban development but not their cumulative duration has important consequences for channel form and bed stability in gravel bed streams. That can be explained by the geomorphic equilibrium which depends on moderate duration. Streams with low values of T_{Qmean} (fraction of time that stream flow exceeds the mean stream flow) and $T_{0.5}$ (fraction of time that stream flow exceeds the 0.5-year flood) are narrower than expected from hydraulic geometry (Konrad et al., 2005). At this point, creating different development scenarios and applying several levels of LID practices is becoming increasingly important to better evaluate the performance of LID practice at a watershed scale. The available literature concluded that urbanization increases the magnitude of frequent high flows and all the negative impact associated with it, but none of the available literature projected the effect of future urban development scenarios (with LID practices with respect to human health and environment).

Urbanization and Aquatic-System Degradation

Stream ecosystems are the most fragile, degraded, and threatened ecosystems because of the strong interactions between aquatic and terrestrial environments and human disturbances that can affect either system (Nature Conservancy, 1996). Changes in demographic and land use due to urbanization have brought about profound changes to the physical, chemical, and biological integrity of streams (Hollis, 1975). Variation in flow over a day and a season can affect aquatic life (May, 1997). Low base flows during summer and dry periods can cause fish mortalities due to reduced velocity, cross-sectional area, and water depth (Williamson et al., 1993). Also, high flows can wash salmonid eggs from reeds (Vronskii and Leman, 1991). While high flows can be essential to help in the migration of all fish when water velocity exceeds their swimming speed, juveniles are more vulnerable to high flows (Chilibeck et al., 1993). Moreover, high water velocity due to urbanization can be extremely harmful to the stream environment if there is a lack of boulders and large woody debris, which provide eddies where fish can rest and have shelter. Rood and Hamilton (1994) found out that Salmon habitat had a significant degradation over the past one hundred years due to altering flow regimes and removal of riparian vegetation. Klein (1979) concluded that when watershed imperviousness exceeds 10 percent, a rapid decline in biotic diversity might result. Sovern and Washington (1997) concluded that urbanization causes an increase in sediment load due to stream enlargement through bed and bank erosion. These additional volumes of sediment loads contribute to clogging and degrade salmonid spawning gravel quality by reducing the gravel porosity, hence hindering the resupply of dissolved oxygen to fish eggs. Reed (1978) conducted a study in the state of Pennsylvania where he looked at the effectiveness of sediment-control techniques during highway construction in respect to aquatic life. Results showed that suspended sediments coming from construction activities can harmfully affect aquatic life by habitat elimination under heavy loading or by interference with feeding under lighter stress. Whipple et al. (1981) concluded in their study that the decrease in low flow discharges eliminates the available stream habitat, increases the probability that the streams may go dry, may increase temperature fluctuations and increase the concentration of pollutants due to lack of dilution which in its turn negatively reflects on aquatic life health. DeGaspari et al. (2009) utilized hydrologic modeling to emulate hydrologic metrics for different development scenarios. The aim of the study was to determine which development scenario best met management plans with respect to aquatic life. Though this was found to be a suitable method, hydrologic metrics which can be reliably predicted by the model should be selected over other metrics that cannot be predicted well.

All previous literature studied the influence of urbanization, landuse, variability of flow, and suspended solids due to bed and bank erosion on aquatic life, there is a great need for modeling the effect of LID practices at a watershed scale on aquatic life. Most of the available research considered metrics that were poorly suited to characterize the magnitude of hydrological changes and their impact on biological stream health. Modeling the impact of change in hydrology due to urbanization based on field data on aquatic life is becoming very important.

Urbanization and Flood Frequency

Urban development contributes to modify hydrological processes when vegetation cover and soil are cleared from the land surface (Jones and Clark, 1987). The more the impervious cover the higher the flood frequencies that may result (Moscrip and Montgomery, 1997). Poff and Ward (1989) studied daily flow records for seventy eight USGS stations across the United States for variability and the pattern of the flood regime. They characterized streams into different classes by their hydrologic characteristics and these that could theoretically have an impact on the biological community and flood frequencies. They were unable to quantitatively relate stream biology to hydrology due to the lack of consistent data. Another study by Scoggins (2000) proved that hydrologic parameters proposed by both Poff and Ward (1989) might be used to characterize streams in central Texas and that these parameters might be related to stream biology and flood frequency. Olden and Poff (2003) tested the redundancy in proposed hydrologic indices using the same sites used by Poff and Ward (1989). They concluded that many of the 171 hydrologic indices tested were correlated and redundancy could be reduced by using principal component analysis to reduce collinearity. Moscrip and Montgomery (1997) studied six low-order streams in the Puget Lowlands, Washington, for the period between the 1940-1950 and the 1980-1990. They utilized USGS station records and each basin was separated into periods prior to and after urban expansion. Results showed that each basin that experienced a significant increase in urbanized areas showed increased flood frequency. The pre-urbanization 10-year recurrence interval flows correspond to 1 to 4-year recurrence interval events in post-urbanization records. On the other hand, no apparent shift in flood frequency was observed in either of the control basins that represent a limited change in the urbanized area. Schueler (1992) concluded that urbanization alters stream hydrology and increases stream velocity, flooding magnitude, and flooding frequency. Also, flood duration typically declines as the time from peak to base flow discharge is reduced (Paul and Meyer, 2001). Hirsch et al., (1990) showed that flood duration depends on the degree of urbanization, spatial management and location of impervious cover within the basin.

Although the effects of urbanization on watershed hydrology and river-channel morphology have been studied for decades as literature mentioned above showed, previous studies focused on a limited number of morphologic variables and ignored the complicating influence of varying LID practices types and designs. There is still a great need to evaluate these controls in the field and to collect quantitative data to evaluate their performance, especially in the Southern part of the United States. There is also very little data on the potential impact of the adoption of LID practices at a watershed level. Sample and Heaney (2006) stated that the lack of such research is caused by the difficulty of modeling processes at the small scale required by low impact development (LID) management options without field data. There are very few research that studied the effectiveness of LID practices and their performance based on field data with respect to reducing potential impact on flooding, stream bank and bed erosion and aquatic life. None of the available research studied the correlation between changing in the hydrology on a watershed scale due to urbanization after the installation of LID practices (sustainable detention pond, bioretention and permeable pavement) and potential impact on flooding, stream bank and bed erosion, and aquatic life.

Most of the available studies evaluate the effectiveness of LID practices on a site scale using field experiments, modeling or by developing algorithms based on design storms or average rainfall Graham et al., 2004). Several efforts contribute to analyze the effectiveness of these practices based on pollutant removal such as nitrogen, phosphorus and total fecal (Hunt et al., 2008). Other studies focused on the cost effectiveness incentives of LID practices solely (EPA, 2014). Bracmort et al. (2006) studied the effectiveness of LID practices over the long term in respect to enhancing water quality. They ran several scenarios using Soil and Water Assessment Tool (SWAT) to determine the long term (20 years) impact of LID practices on water quality for two watersheds. Results showed that LID practices that were in a good condition (regularly maintained) reduced the average annual sediment yield by 16% to 32% and the average annual phosphorus yield by 10% to 24%. On the other hand, LID practices in their current condition reduced sediment yield by 7% to 10% only and phosphorus yield by 7% to 17%.

There are very few studies that address the effectiveness of LID practices at a watershed scale. There is a great need to understand the functionality of these practices, their ability to adjust the changes in land uses, and return peak flows to the pre-development scenario.

The hypothesis of this research study is that the integration of LID practices at watershed scale improves stream health and conditions. Specifically:

1) LID practices reduce potential bed stream erosion in urban areas
2) LID practices provide healthy environment for aquatic life habitat
3) LID practices reduce potential flooding in urban streams

This study is one of very few studies that took place in the Blackland clay soil in Texas. Blackland clay soil consists of about 12.6 million acres of east-central Texas extending southwesterly from the Red River to Bexar County, which covers mostly the biggest cities in Texas; Austin, Dallas, San Antonio, and Houston (Texas Almanac, 2013).

Goal and Objectives

The main goal of this study is to evaluate and model the effects of LID practices /green building infrastructure on streams at a watershed scale. The three LID practices targeted in this study are permeable pavements, a bioretention area, and a detention pond. The specific objectives of this research are to investigate the influences of LID practices at a watershed scale on:

- Potential reduction on channel bank erosion ,
- Potential reduction on flood and
- Potential impact on aquatic life.

CHAPTER II

CALIBRATION AND EVALUATION OF SWAT FOR SUB-HOURLY TIME STEPS

Synopsis

SWAT is a semi-distributed, lumped parameter, river basin scale, continuous time model that was developed to simulate hydrology and water quality in watersheds. Traditionally, the model operated at a daily time step and it estimated the influence of landuse and management practices on water, agricultural chemical yields in a watershed. The daily time step format provided by SWAT may not be sufficient to capture the impact of flashy storms where peak flows last for minutes only and are not reflected in daily average flows. It might also miss important processes such as the first flush of urban runoff. A sub-hourly model for urban applications was developed by Jeong and Srinivasan (Jeong et al., 2010) but is currently not widely used. SWAT-CUP is a calibration program that is interfaced with SWAT. The main goal of this study was to apply sub-hourly time steps using SWAT and SWAT CUP to calibrate these sub-hourly models. The model was tested using data from the Blunn creek watershed in Austin, TX.

This study presents the calibration and evaluation process and examines uncertainty using the sequential uncertainty fitting (SUFI-2) method in SWAT-CUP for a sub-hourly 15-minute time step model. The model was calibrated and evaluated for a 2- year period. Results show that the sub-hourly SWAT model provides reasonable estimates of stream flow for multiple storm events. Calibrated stream flows for a 2 year period using the 15- minute time step had an R^2 of 0.78 and a Nash-Sutcliff coefficient

(NS) of 0.78. The P-factor and R-factor calculated using SUFI-2 procedures have provided good agreement by bracketing around 54- 56% observed data on a sub-hourly basis. The 2 year validation period had an R2 of 0.70 and a NS of 0.67. It was concluded that the sub-hourly SWAT in conjunction with SWAT-CUP have the capabilities to simulate and estimate parameter uncertainty for complex hydrological processes and their interactions.

Introduction

Most hydrological models must be calibrated so their outputs can be used for tasks ranging from regulation to research (EPA, 2002). Distributed hydrological models often account for several variables that include data from numerous fields; weather, soil, land use, surface and ground water and management practices. Manual calibration is difficult due to the complexity of large scale models with many objectives and the numerous interactions between these objectives (Abbaspour et al. 2007). The process of calibration accounts for testing a model using known inputs and outputs data to closely match the behavior of the real system (EPA, 2002). These parameters can be estimated through direct measurement conducted in real scenarios Or in some cases, these input parameters are unknown and must be determined through a trial and error process or by literature to match the model response to observed data.

In today’s complex models there are a plethora of parameters; narrowing those to the primary ones controlling the natural processes being modeled makes optimization of calibration parameters more feasible. Sensitivity analysis is one tool that is used prior to the calibration process in order to study the uncertainty level in the model output with respect to different changes in model inputs. This type of analysis is considered essential in order to determine the parameters that should be included in the calibration process (Ma et al., 2000).

It is important that each model user makes every possible effort to minimize the differences between simulated and measured field data. Also, to make proper decisions concerning remedial action or environmental compliance, there should be a clear demonstration that simulated data coming out of models are reasonably representative onsite. (Oliver et al., 1997).

SUFI-2 is a multi-site semi-automated inverse modeling routine (Abbaspour et al., 2007) within SWAT-CUP (Calibration and Uncertainty Program) for calibration and uncertainty analysis. SWAT-CUP is a calibration program that is interfaced with SWAT. In SUFI-2, parameter uncertainties are represented by a multivariate uniform distribution in a parameter hypercube. In this method, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables such as rainfall, the conceptual model, parameters and measured data (Abbaspour et al., 2007). There are two measures that account for uncertainty quantification; P-factor and R-factor. The P-factor is the percentage of measured data bracketed by the 95% Prediction Uncertainty (95PPU). The R-factor is the average thickness of the 95PPU band divided by the standard deviation of the measured data. A Latin Hypercube sampling scheme for propagating uncertainty is integrated within SWAT-CUP, and the uncertainty (referred to as 95PPU) is calculated at the 2.5% and 97.5% levels for each simulated variable (Abbaspour et al., 2007). The success of calibration and uncertainty prediction is judged on the basis of closeness of the P-factor to 100% and the R-factor to 1 (Zhou, 2012). A perfect match between observed and simulated flows are indicated by Nash-Sutcliff (NS) and coefficient of determination, R^2, values of 1. This would reflect a simulation where, based on parameter uncertainty, 100% of the observed data fell within the 95PPU, but due to measurement errors, and conceptual model uncertainty this is a rare occurrence. SUFI-2 starts by assuming a large parameter uncertainty that is within a physically meaningful range, to ensure the measured data fall within the 95PPU (Abbaspour et al., 2007). Later, the model decreases this uncertainty range gradually while monitoring the goal factors such as the NS coefficient and the R^2 values between the measured and simulated data. The NS coefficient can be expressed as follows (Nash & Sutcliffe, 1970):

$$NS = 1 - \frac{\sum(Qo - Qm)^2}{\sum(Qo - \overline{Qo})^2} \qquad \text{(Equation 2.1)}$$

Where: Q_o is observed discharge (m^3/s)
Q_m is modeled discharge (m^3/s)
$\overline{Qo}$ is average observed discharge (m^3/s)

Generally, model simulation can be considered satisfactory if NS value > 0.50 (Moriasi et al. 2007). SUFI-2 allows running several iterations, and in each iteration previous parameter ranges are updated by calculating the sensitivity matrix and the equivalent of a Hessian matrix (Neudecker & Magnus, 1988), followed by the calculation of a covariance matrix, 95% confidence intervals of the parameters, and a correlation matrix. Parameters are updated so the new ranges are always smaller than the previous and continue until centered around the best simulation (for more details, see Abbaspour et al., 2007).

Several efforts have been carried out over the last decades to develop automated methods for the estimation of model parameters by fitting them to historical data. These methods also assist in facilitating model evaluation in terms of the accuracy of the simulated data to measured or historical data using several combinations of input parameters. Nash & Sutcliffe (1970), Sorooshian and Gupta (1992), Sefe and Boughton, (1982), Beven (2002), and Moriasi et al. (2007) focused mainly on the search for an optimization technique that can tackle the parameter estimation problem, the determination of the most appropriate quantity and kind of data, the efficient representation of the uncertainty of the calibrated model, and the determination of kinds of errors present in the measured or historical data. One common problem in the available calibration techniques is stability and convergence (Yeh, 1986). Abbaspour et al. (1996) developed an algorithm called the Bayesian uncertainty development algorithm (BUDA) in order to achieve a higher reduction in uncertainty in hydrological models. The development of several mathematical methods, helps optimizing calibrations that can evaluate more factors such as uncertainty for highly complex models with high-speed computers. Generalized Likelihood Uncertainty Estimation (GLUE) is one commonly used method that has been developed to quantify the uncertainty of hydrological models in rainfall-runoff modeling. This method is different from other methods because it rejects the concept of an optimum model and parameter set. GLUE assumes all model structures and parameter sets have an equal likelihood of being acceptable prior to input of data into a model (Beven and Binley 1992).

Model validation is the next step after calibration; the validation process involves analyzing the goodness-of-fit and checking whether the calibrated model's predictive performance is in accordance with observed/ measured data. The definition of sufficient accuracy of the validation process can vary based on the use and model's goals (Refsgaard ,1997). The wider use of SWAT using sub-hourly data for more accurate hydrologic modeling depends on a demonstrated successful calibration and validation of SWAT and uncertainty analysis.

The objective of this paper is to detail the procedures to successfully do an uncertainty analysis and calibrate and validate SWAT for sub-hourly time steps using SWAT-CUP.

Model Description

SWAT

The hydrologic model used for this study was the SWAT model, a semi-distributed, lumped parameter, river basin scale, continuous time step model developed to assess and predict hydrological processes and changes in large basins (Abbaspour et al. 2007). This model was developed to operate on a daily time step and it is often used to estimate the impact of landuse and management on water, agricultural chemical yields in a watershed. The major components of the model include hydrology, soil, land management, plant growth, pesticides, nutrient, weather, reservoir routing, and erosion. Several versions and releases have been developed and the latest version of SWAT that this study utilized and available at http://swat.tamu.edu was SWAT 2012. SWAT works on dividing the watershed into several subbasins that are later divided into Hydrological Response Units (HRU). These units have homogenous characteristics such as soil, land use, and land management. SWAT model components have been put together and originated from several USDA- ARS field scale models (Abbaspour et al. 2007). For instance, the groundwater component was incorporated into the first version of SWAT through the use of the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987). In the latest version of SWAT, the contribution of groundwater to total stream flow is estimated by creating shallow aquifer storage (Arnold & Allen, 1996). Percolation from the bottom of the root zone is considered as recharge to the shallow aquifer. SWAT consists of two methods to estimate water runoff; the Soil Conservation Service curve number method when daily time step applied and the Green Ampt infiltration method when sub daily time step applied. In SWAT, peak runoff rate is estimated by applying the rational method, time of concentration is estimated using Manning's equation and sediment transport is estimated using the Modified Universal Soil Loss Equation (Neitsch et al. 2005). In the sub-hourly model, the excess rainfall from each HRU in each subbasin at every time interval is calculated by the Green and Ampt Mein Larson equation (Mein and Larson 1973).

$$f(t) = Ke(1 + \frac{\Psi\Delta\theta}{F(t)}) \qquad \text{(Equation 2.2)}$$

where: f(t) is the infiltration rate at time t

Ke is the effective hydraulic conductivity

Ψ is the wetting front matric potential

Δθ is the change in moisture content,

F(t)is the cumulative infiltration at time t

Water balance is what governs SWAT processes because it directly impacts plant growth, nutrients transport, pesticides, runoff and pathogens, this water balance relationship can be expressed as follows (Arnold et al. 1998):

$$SW_{t=} SW_0 + \sum_{i=1}^{n}(R + Q_{sur} + E_a + W_{seep} + Q_{gw}) \qquad \text{(Equation 2.3)}$$

Where: SW_t= final soil water content

SW_o= initial soil water content

t= time

R = amount of precipitation on time step i

Q_{surf} = amount of surface run-off on time step i

E_a = amount of evapotranspiration on time step i

W_{seep} = amount of percolation and bypass exiting the soil profile bottom on time step i

Q_{gw} = amount of return flow on time step i

SWAT_CUP

SWAT Calibration and Uncertainty Procedures (SWAT-CUP) is a program that is interfaced with SWAT. This program is designed to integrate various calibration/uncertainty analysis programs such as: SUFI2 (Abbaspour et al., 2007), GLUE (Beven and Binley, 1992), and ParaSol (Van Griensven and Meixner, 2006). The program allows the user to run the procedure several times until convergence is reached (Abbaspour et al., 2004). This study utilized a multi-site semi-automated inverse modeling routine SUFI-2 for calibration and uncertainty analysis for the Blunn Creek Watershed. The general concept how the SWAT-CUP works can be seen in the following figure (Figure 2-1) (Abbaspour et al., 2007).

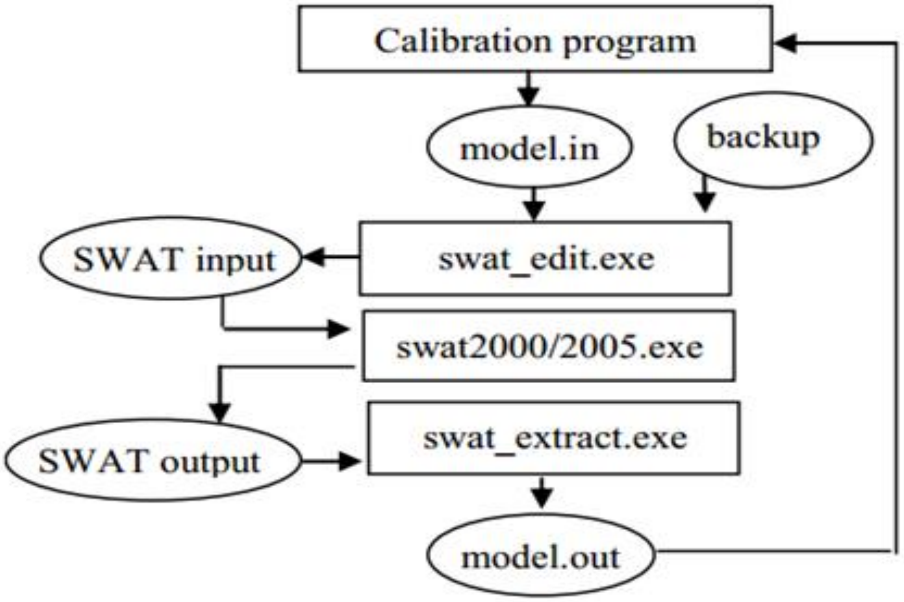


Figure 2-1. Interaction between calibration program and SWAT in SWAT-CUP (Abbaspour, 2007).

SWAT-CUP program writes the model parameters in model.in. Then, swat_edit.exe edits the SWAT text files, inserting the new parameter values. After that, SWAT simulator is run. Finally, the swat_extract.exe program extracts the desired variables from the SWAT output files and writes them to model.out. The procedure continues as required by the calibration program (Abbaspour, 2007).

This study utilized a multi-site semi-automated inverse modeling routine SUFI-2 for calibration and uncertainty analysis for the Blunn Creek Watershed in Austin, TX.

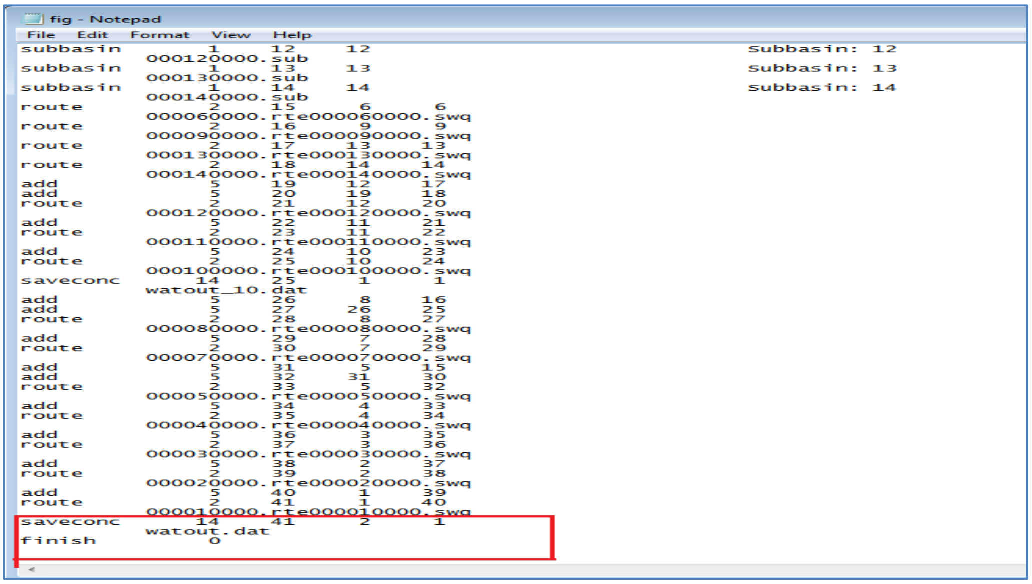
Methodology

SWAT-CUP Setup

Three main steps were taken in order to run SWAT-CUP. First of all, observed historical data were downloaded from USGS website for calibration purposes. Second, input parameters were converted into sub-hourly format through SWAT. Finally, inputs were entered and the SWAT-CUP program was run.

Observed stream discharges at USGS Station 08157700, operated by City of Austin (COA) after the year 2001, were retrieved in 15 min format from USGS (USGS, 2014) for the period between 1998 and 1999 for calibration purposes between 2001 and 2002 for validation purposes. Flow data were modeled and compared to observed data for calibration purposes.

It should be noted at this point that SWAT-CUP version 5.1.4.2 that was used in this study is designed for daily, monthly and yearly time steps though it can read and accept hourly or sub-daily format because it calls data from the TXINOUT folder that is already exported from and formatted by SWAT. The following steps were followed to convert the daily model to a sub-hourly time step model: 1) subdaily weather data for precipitation and temperature were used to do an initial run of SWAT; 2) the *fig.fig* file located in the TXINOUT folder in a SWAT project was changed by including a new *saveconc* command for sub-hourly output. This command saves flow, sediment and water quality data from a specified point to a file (Figure 2-2). The first input number of the command which appears in the red box in Figure 2 represents the command code (14). The second input (41) represents the hydrograph storage location number of the data to be printed to the file. The third number (2) is the unique sequential file number for the *saveconc* command and the fourth input number (1) represents the printing frequency and value of 1 represents the sub-hourly printing frequency. The default printing value (0) given by SWAT is for daily averages unless another printing frequency is input. The last row before the finish command is the name of file where data will be saved and printed (watout.dat) (Neitsch et al., 2005).



```
subbasin        1     12      12                                         subbasin: 12
          000120000.sub
subbasin        1     13      13                                         subbasin: 13
          000130000.sub
subbasin        1     14      14                                         subbasin: 14
          000140000.sub
route           2     15       6       6
          000060000.rte000060000.swq
route           2     16       9       9
          000090000.rte000090000.swq
route           2     17      13      13
          000130000.rte000130000.swq
route           2     18      14      14
          000140000.rte000140000.swq
add             5     19      12      17
add             5     20      19      18
route           2     21      12      20
          000120000.rte000120000.swq
add             5     22      11      21
route           2     23      11      22
          000110000.rte000110000.swq
add             5     24      10      23
route           2     25      10      24
          000100000.rte000100000.swq
saveconc       14     25       1       1
          watout_10.dat
add             5     26       8      16
add             5     27      26      25
route           2     28       8      27
          000080000.rte000080000.swq
add             5     29       7      28
route           2     30       7      29
          000070000.rte000070000.swq
add             5     31       5      15
add             5     32      31      30
route           2     33       5      32
          000050000.rte000050000.swq
add             5     34       4      33
route           2     35       4      34
          000040000.rte000040000.swq
add             5     36       3      35
route           2     37       3      36
          000030000.rte000030000.swq
add             5     38       2      37
route           2     39       2      38
          000020000.rte000020000.swq
add             5     40       1      39
route           2     41       1      40
          000010000.rte000010000.swq
saveconc       14     41       2       1
          watout.dat
finish          0
```

Figure 2-2. Screen shot of Sub-hourly saveconc command

Calibration Parameters

The parameters responsible for stream-flow assessment for the Blunn creek watershed were defined in the SWAT-CUP program under the calibration input parameters tab and under the Par_inf.txt file (Table 1) in order to be optimized. Since SWAT is a distributed hydrological model, there are potentially many parameters that can affect the stream flow assessment. Investigating the potential impact of all these parameters can be a very difficult task due to the high number of parameters and the complex interaction between them. Furthermore, looking at a sub-hourly time step format would result in a more complex model since it accounts for more details than daily or monthly time step. Therefore, utilizing an automated model such as SWAT-CUP rather than manual calibration becomes very important to save time and achieve higher accuracy. An Initial run that accounts for all available parameters (Table 2-1) was conducted.

Table 2-1. Initial calibration parameters given by SWAT-CUP

Parameter name	Description
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II
v__ALPHA_BF.gw	Baseflow alpha factor (1/day)
v__GW_DELAY.gw	Groundwater delay (days)
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
v__GW_REVAP.gw	Threshold depth of water in the shallow aquifer for "revap" to occur
v__ESCO.hru	Soil evaporation compensation factor
v__CH_N2.rte	Manning roughness for main channel
v__CH_K2.rte	Effective hydraulic conductivity
v__ALPHA_BNK.rte	Baseflow alpha factor for bank storage
r__SOL_AWC(1).sol	Available water capacity of the soil layer (mm H2O/ mm soil)
r__SOL_K(1).sol	Saturated hydraulic conductivity (mm/hr)
r__SOL_BD(1).sol	Moist bulk density (g/cm^3)
v__SFTMP.bsn	Snowfall temperature (^{o}c)

The duration of the simulation (beginning and ending) is defined under *SUFI2_swEdit.def*. The number of years to be simulated, beginning and end of the simulation, and the number of warm up periods are defined under the *File.Cio* file, which is a SWAT file. All the parameters to be fitted plus their minimum and maximum ranges are defined under *Absolute_SWAT_Values.txt*. Default values for the fitted parameters and their ranges given by SWAT-CUP were used. Observed values that correspond to the variables in *output.rch* file were edited after converting it into sub-hourly format under *observed_rch .txt*. The name of variables to be extracted from the *output.rch.txt* files were defined under *Var_file_rch_txt* which is in this case only flow.

Uncertainty Analysis

Five objective functions were selected to analyze model efficiency of stream flow calibration for the Blunn creek watershed; P-factor (ranges between 0% and 100%), R-factor (ranges between 0 and infinity), R^2, NS and bR^2 (which is the coefficient of determination multiplied by the coefficient of regression). The best-fit of the model can be quantified by the coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NS) between the observations and the final best simulations. Default values and ranges given by SWAT-CUP for other variables (soil, HRU, groundwater, basin, subbasin, .etc.) were selected. The objective function type was selected to be NS coefficient with 0.5 minimum value of objective function threshold for the behavioral solutions. The output of the initial run that can be found in the *watout* file within the TXINOUT folder was printed in 15 minutes time steps. The main outcome variable in SWAT-CUP was defined to be flow with 14 reaches/subbasins and to account for one reach in each subbasin. The preprocessing procedures, which include running the Latin hypercube sampling program was executed followed by running SUFI-2_execute.exe program that runs the *SWAT_Edit.exe* extraction file as well as *SWAT.exe*. *SUFI2_post.bat* file in order to estimate objective function, 95 PPU calculation, 95 PPU for behavioral simulation and 95 for the variables with no observations. An integrated sensitivity analysis for all parameters utilized in the initial run was printed out in conjunction to calibration outputs. Only the most sensitive parameters based on t-statistic and p-value were selected for a second run of calibration.

Case Study

This case study is based on research conducted in Austin, Texas and specifically the Blunn Creek Watershed (Figure 2-3). The watershed was estimated to have 34.8% impervious cover in 2003 and the total catchment area is 1 square mile. The creek has a length of three miles. The total population estimated to be living in the watershed area in 2013 is 6,000 and the projected to be 6810 by 2030 might (COAa, 2013).

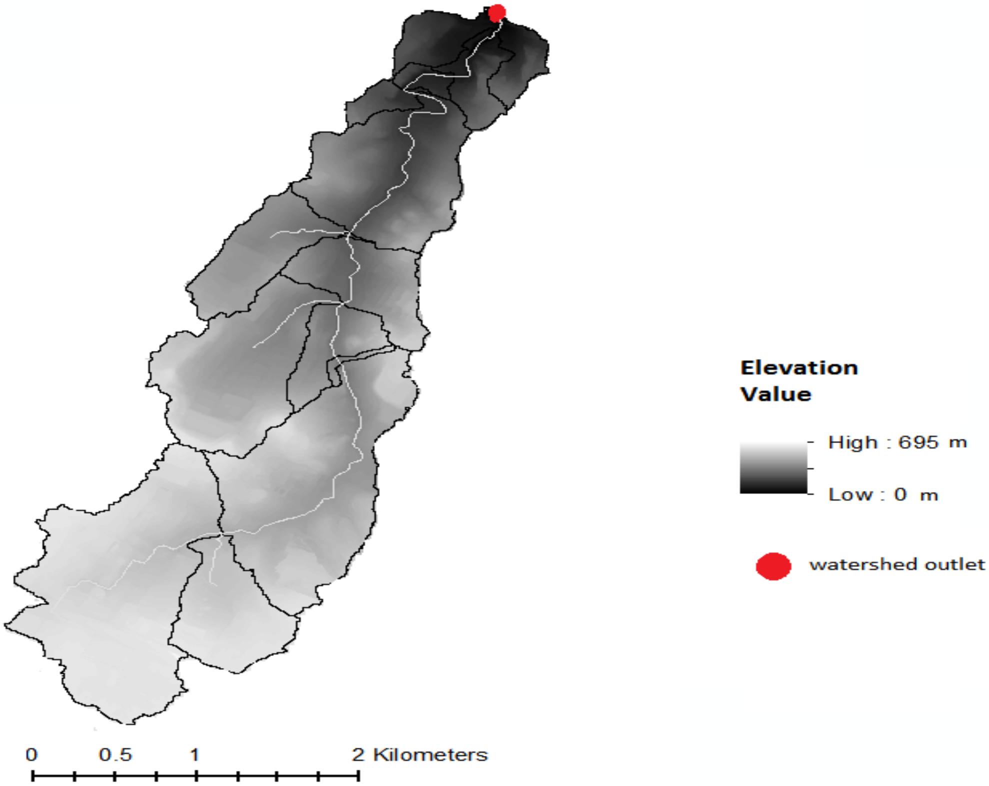


Figure 2-3. Blunn Creek Watershed in Austin, Texas.

The selection of the SWAT model was mainly because it is an integrated model that accounts for most hydrological components is easily accessible, in the public domain, and much of the input data are readily available. Also, the integration of the model with GIS environment allows the user to utilize all GIS tools to modify, add and edit layers to SWAT maps. SWAT 2012.10.4 was used and modified to run on a sub-hourly time step. Models were run using 15 minute rainfall data from the Flood Early

Warning System (FEWS) and Water Quality Monitoring (WQM) sections at COA, sub-hourly temperature data from the Austin and Austin-Bergstrom NOAA weather stations (WGEN_US_COOP_1960_2010), a 10-ft integer Digital Elevation Model (DEM) developed by COA based on 2003 LIDAR data and SSURGO soils data from NRCS. Geometry of the channels for each sub-basin was modified after conducting a cross-section analysis for the DEM layer. The cross-section analysis was done by converting the DEM layer using an interpolation line tool under 3D Analyst menu in ArcGIS and creating a profile graph (Figure 2-4) and calculating the dimensions of an equivalent trapezoidal cross-section.

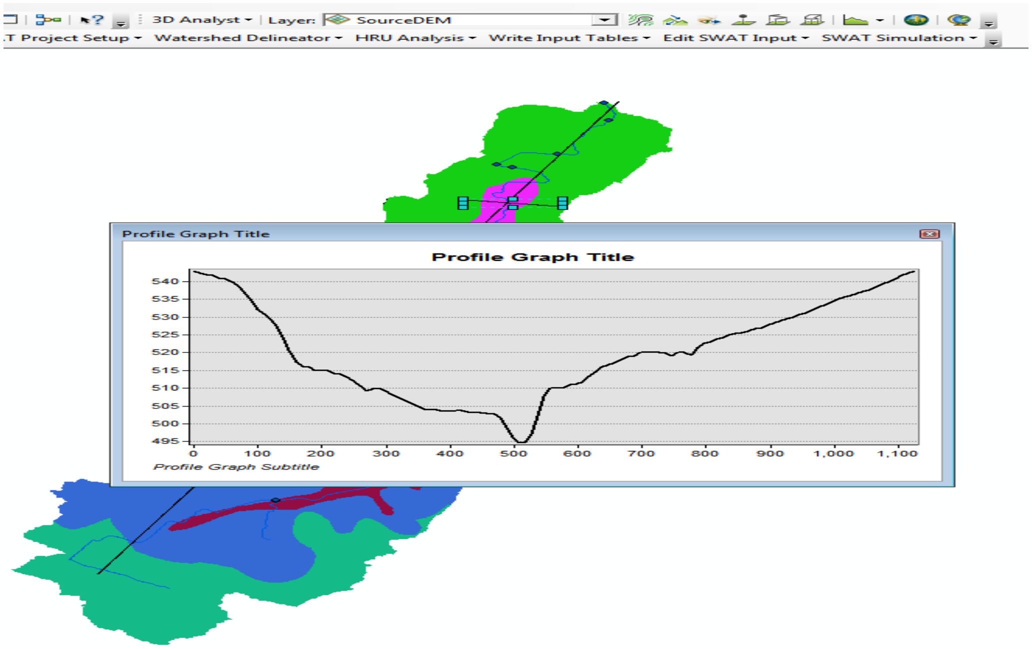


Figure 2-4.Cross section analysis for the DEM layer using 3D Analyst tool.

The specific objectives of the case study are to model the hydrology of the Blunn Creek Watershed using SWAT program and the calibration and validation of this model using SWAT-CUP.

Results

The results of a global sensitivity analysis of stream-flow parameters using Latin hypercube regression systems is shown in Figure 2-5. Eight parameters were selected for calibration based on the results of sensitivity analyses that varied all parameters simultaneously, (Table 2-2).

Table 2-2. Stream flow parameters selected for calibration

Stream flow parameters selected for calibration*	Description
v__ALPHA_BF.gw	Base flow alpha factor
v__GW_DELAY.gw	Groundwater delay
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur
v__CH_N2.rte	Manning roughness for main channel
v__CH_K2.rte	Effective hydraulic conductivity
r__SOL_AWC	Available water capacity of the soil layer
V_ESCO.hru	Soil evaporation compensation factor
r__SOL_K(1).sol	Saturated hydraulic conductivity

*** Description of each qualifier: “v” means that parameter value is replaced by a value from the given range and “r” means that parameter value is multiplied by (1 + a given value) (Abbaspour et al., 2007)**

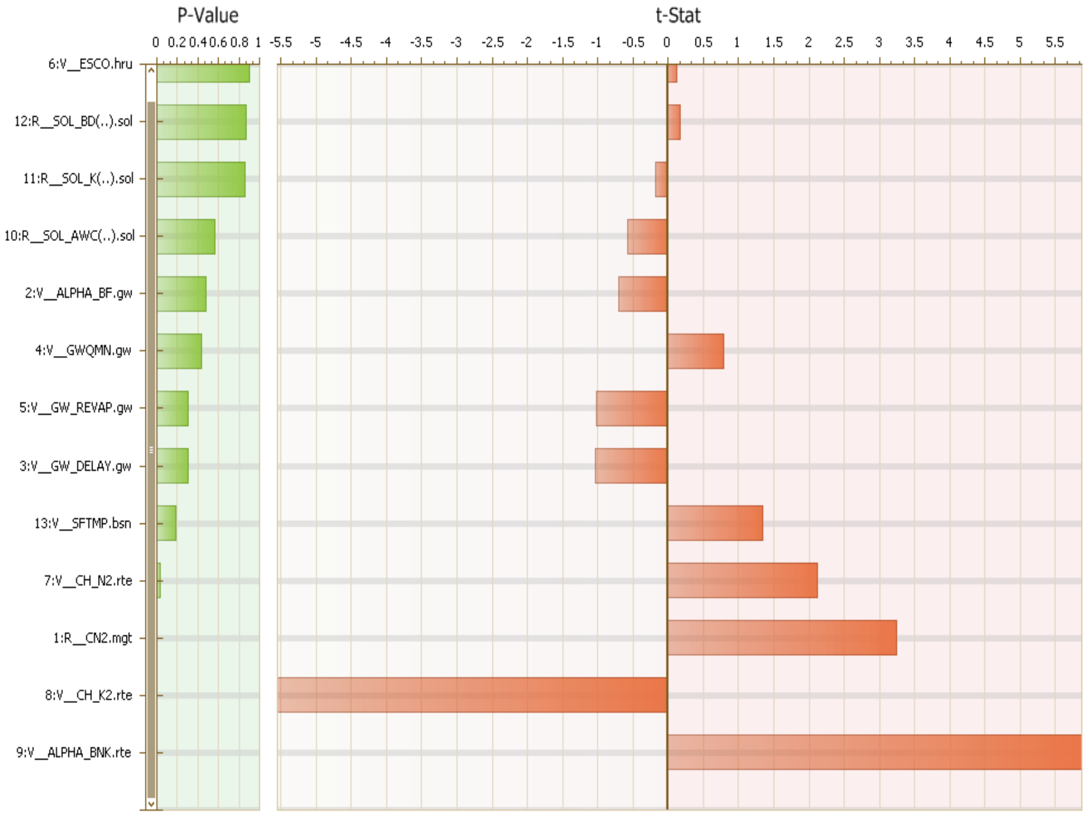


Figure 2-5. Global sensitivity analysis for an initial run that accounts for all uncertainty parameters

The parameters have given ranks for their sensitivity to the model calibration (Table 2-3).

Table 2-3. Parameter sensitivities for SUFI-2

Parameter_Name	Ranking	t-stat	P-value	Si
V__ESCO.hru	8	0.12	0.91	0.95
R__SOL_K(..).sol	7	-0.18	0.86	43.4
R__SOL_AWC(..).sol	6	-0.58	0.57	0.48
V__ALPHA_BF.gw	5	-0.70	0.48	0.69
V__GWQMN.gw	4	0.79	0.43	0.5
V__GW_DELAY.gw	3	-1.03	0.31	51
V__CH_N2.rte	2	2.12	0.04	0.189
V__CH_K2.rte	1	-5.55	0.00	31.25

Table 2-4 below shows the minimum and maximum ranges of the parameters fitted for the sub-hourly calibration in the SUFI-2.

Table 2-4. Stream flow calibration parameter uncertainties

Parameter Name	Fitted Value	File name	Minimum value	Maximum value
V__ALPHA_BF.gw	0.25	.gw	0	1
V__GW_DELAY.gw	350.25	.gw	30	450
V__GWQMN.gw	1.95	.gw	0	2
V__ESCO.hru	0.88	.hru	0.8	1
V__CH_N2.rte	0.23	.sub	0	0.3
V__CH_K2.rte	30.52	.sub	5	130
R__SOL_AWC(..).sol	0.0025	.sol	-0.2	0.4
R__SOL_K(..).sol	0.31	.sol	-0.8	0.8

The manning coefficient (Ch_N2) fitted value suggested by SWAT-CUP was far from expectation. One possible explanation that baseflow was not being well simulated in SWAT due to lack of input in precipitation during non-rainy days. This resulted in water balance errors and that was compensated by SWAT-CUP by increasing the manning roughness coefficient. We expect that if analysis was made with manning coefficient = 0.035 only, baseflow would be affected then the results of this study should be valid for the calibration run produced by SWAT-CUP. The remaining default uncertainty parameters given by SWAT-CUP were tested as a double check test and they had no significant effect on stream-flow simulations. Updating the values of the remaining parameters did not result in significant changes in the model output.

The distribution of the number of simulations in the parameter sensitivity analysis was plotted after comparing the parameter values with the objective functions for the sub-hourly calibrations (Figure 2-6). The x-axis in this figure is the paramter value and the y-axis is the objective function value (NS).

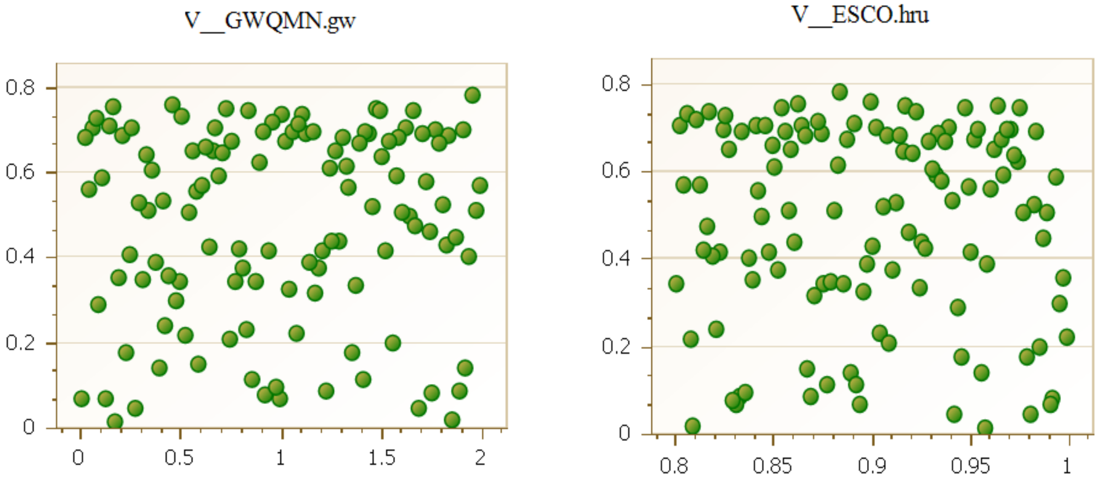


Figure 2-6a

Figure 2-6b

Figure 2-6 Sensitive parameters during sub-hourly calibration for the Blunn Creek Watershed vs. objective function. a: Threshold depth of water in the shallow aquifer required for return flow to occur, b: Soil evaporation compensation factor, c:Available water capacity of the soil layer, d: Saturated hydraulic conductivity, e: Groundwater delay, f: Base flow alpha factor, g: Manning roughness for main channel, h: Effective hydraulic conductivity

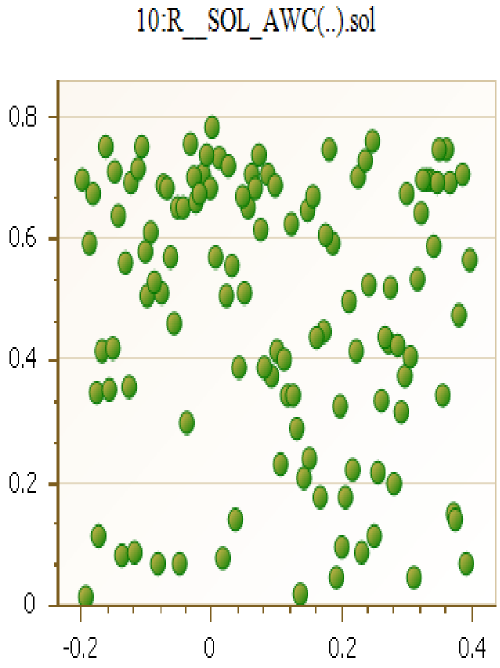


Figure 2-6c

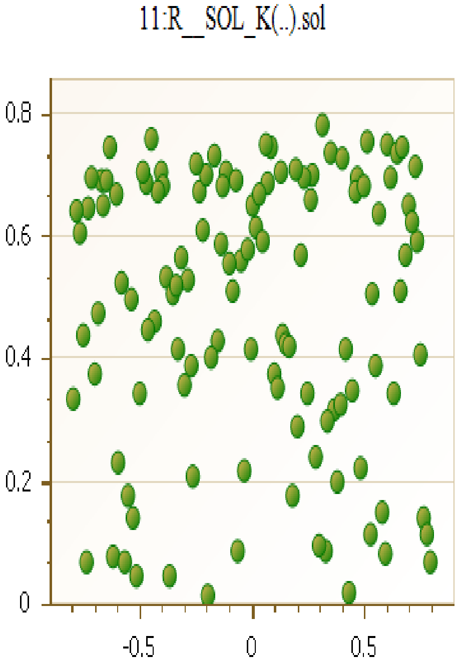


Figure 2-6d

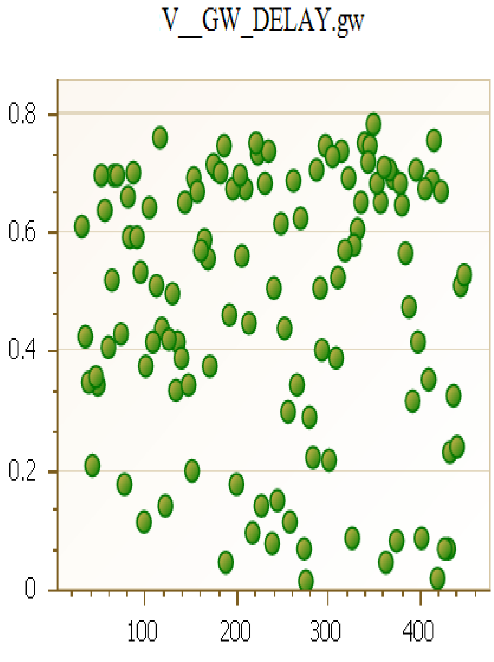


Figure 2-6e

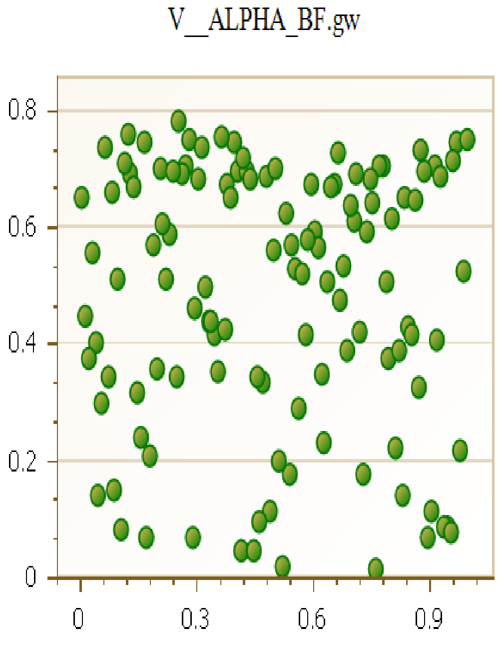


Figure 2-6f

Figure 2-6 Continued

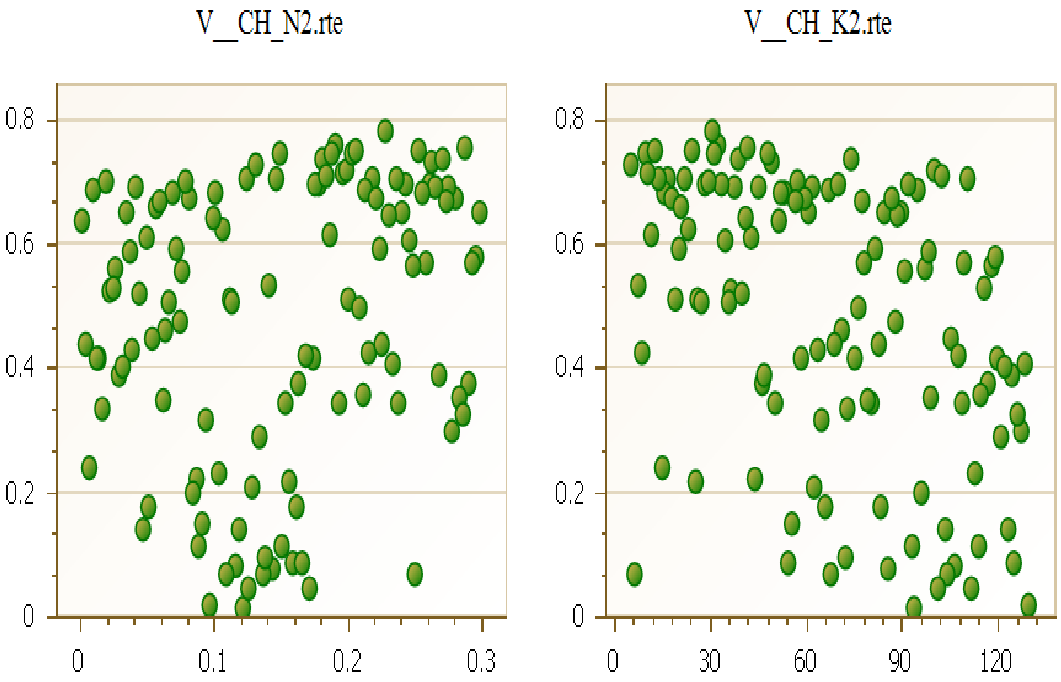


Figure 2-6g

Figure 2-6h

Figure 2-6 Continued

Results from SUFI-2, for the sub-hourly calibration showed that the alpha base flow factor (Alpha_BF), the soil evaporation compensation factor (ESCO), the threshold depth of water in the shallow aquifer required for return flow to occur factor (GWQMN) and the ground water delay factor (GW_DELAY) had a wide range in their values (Figure 2-6a,b,e), whereas, the soil effective hydraulic conductivity and Manning roughness for the main channel show large variation in their values (Figure 2-6 h,g). The goodness-of-fit and efficiency of the model were tested using the main objective functions listed above. These five objective functions were analyzed on a sub-hourly basis correspondingly for SUFI-2 uncertainty technique (Table 2-5) for the best-fit model

Table 2-5. Stream flow calibration results for sub-hourly model

Variable	**Value**
p-factor	56%
r-factor	0.54
$\mathbf{R}^2$	0.78
NS	0.78
b $\mathbf{R}^2$	0.6423
MSE	0.0035
SSQR	0.0005

After observing model performance and running initial iterations using SWAT-CUP with all input parameters to be optimized (Figure 2-7) , the baseflow was systematically overestimated at the outlet of the watershed (in subbasin 1), and there is a late shift in the flow peak.

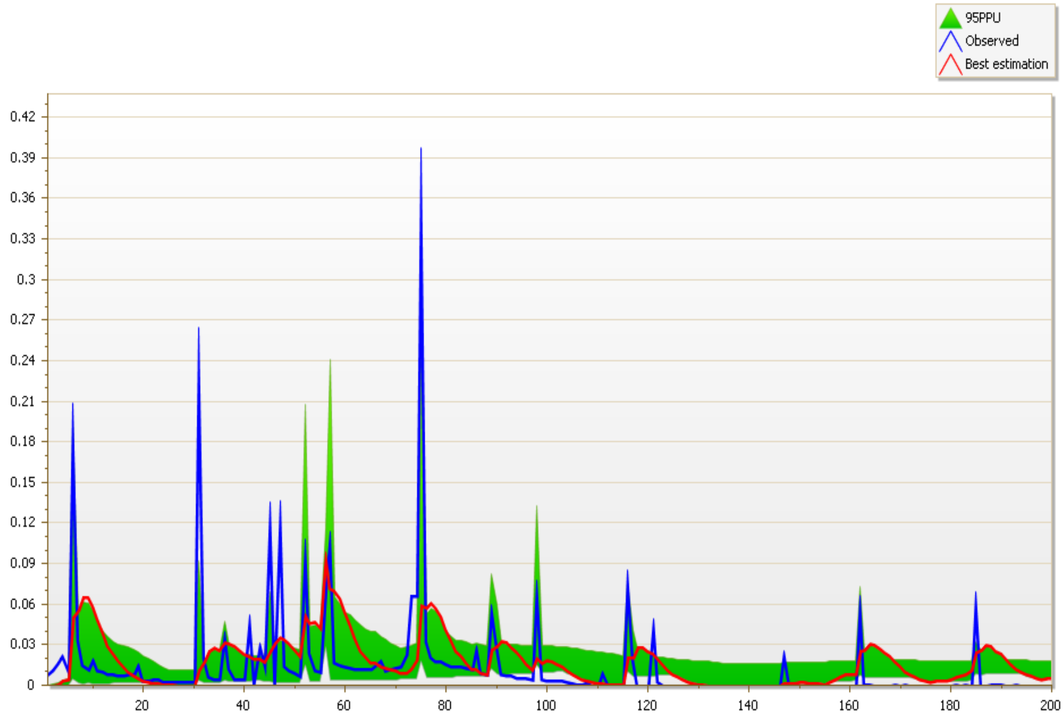


Figure 2-7. Initial iteration with all available parameters

The following steps were taken to fix this problem; baseflow factor was decreased, deep percolation (GWQMN) was increased, the groundwater revap coefficient (GW_REVAP) was increased, and the threshold depth of water in shallow aquifer (REVAPMN) was decreased. To correct the peak flow delay, the slope (HRU_SLP) was increased, Manning’s roughness coefficient (OV_N) was decreased, the value of overland flow rate (SLSUBBSN) was decreased, and snow melt parameters (SMTMP) were decrease. Figure 2-8 shows the result after applying these steps as well as considering only the eight parameters included in the calibration (Table 2-2). Clearly, adjusting the previous parameters resulted in simulated data that match the observed data better with respect to peak flow and time to peak.

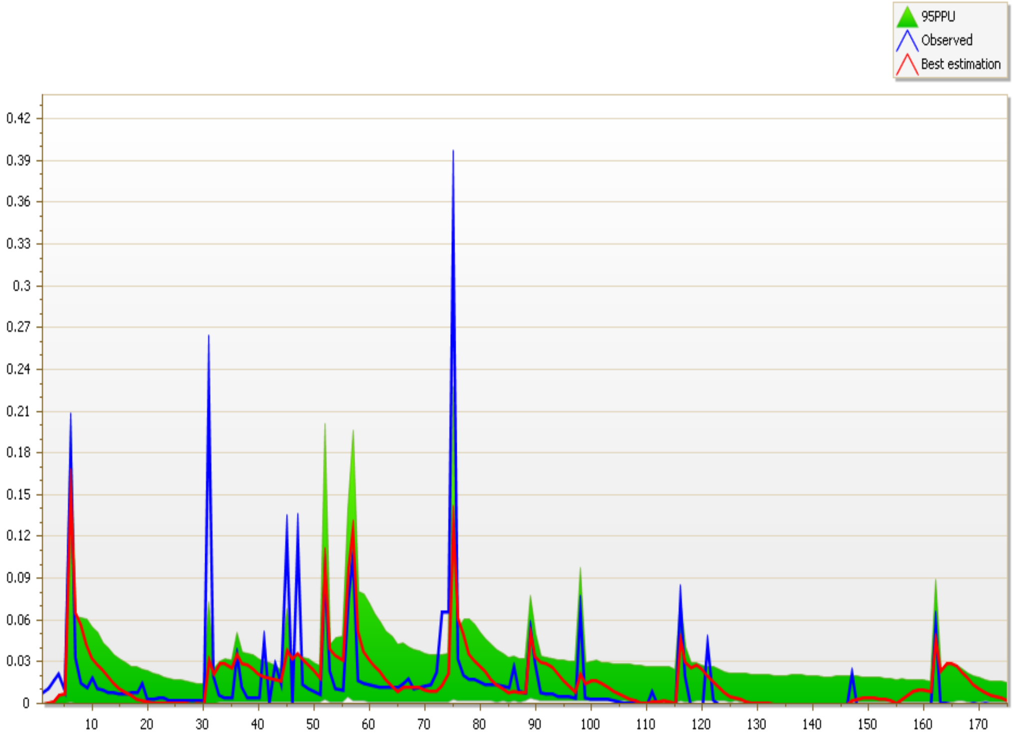


Figure 2-8. Iteration accounts for parameters with the highest sensitivity level

The water balance of the model results for the calibration periods was performed in order to assess the validity of the calibrated and validated model (Table 2-6). The inflow of the water balance (Eq. 4) is precipitation and the return flow originated by groundwater as it is descried in SWAT 2012 manual. The outflow/losses are represented by surface runoff, evapotranspiration and percolation. It should be noted that irrigation application was applied with a frequency of nine applications for each HRU and with a total volume of 227.84 mm as SWAT output file showed for the 24 simulation period. The following land uses were excluded from irrigation application: parks, undeveloped lands, open spaces, transportation and infrastructure, and camp ground. The error percentage was calculated by dividing losses by inflow.

Table 2-6. Average annual water balance components and error percentages for the calibration period at the Blunn Creek Watershed

Component	**Calibration/Depth (mm)** (1998 and 1999)	**Validation/ Depth (mm)** (2001 and 2002)
Precipitation	1484.1	1878
Surface Runoff	466.29	575
Lateral Flow contribution to stream flow	73.06	96.69
Groundwater contribution to stream flow	3.28	6.91
Water percolation	32.94	72.79
Drainage Tile	0	0
Amount of water stored in soil	192.83	315.41
Actual ET	1262.17	1406.36
Error %	18	9

The validation period was the years 2001 and 2002.. NS value for validation was 0.67 and R^2 value equals to 0.70 for sub-hourly time step model. It should be noted that both calibration and validation procedures were run for the entire two year period in addition to another two year warming up period. These results show that SWAT-CUP can be used to calibrate and validate SWAT when used for sub-hourly time steps. Accordingly SWAT can be used to estimate peak flow times during a storm and can be used for applications that occur at a sub-hourly scale such as low impact development hydrology.

Conclusions

Sub-hourly simulation model has been optimized successfully using SWAT 2012 and calibrating using SWAT-CUP, SUFI2 procedures. SWAT-CUP presented an effective graphical interface in order to visualize calibration components such as observed data, simulated data, 95 PPU and the best fit model. The sensitivity analysis adopted for stream flow calibration was very successful and contributed to optimizing the total number of uncertainty parameters and accordingly more efficient calibration procedures. SUFI-2 gave good results in minimizing the differences between simulated and observed data for the sub-hourly time step model. The P-factor and R-factor calculated using SUFI-2 procedures have provided good agreement by bracketing around 54- 56% observed data on a sub-hourly basis. Results showed acceptable matching between simulated and observed flows for the Blunn Creek Watershed for the simulation period. The presented study showed that the sub-hourly SWAT model results in a reasonable stream flow hydrograph under multiple storm events. Calibrated stream flows for a 2 year period with 15- min simulation had (R^2= 0.78) and (NS =0.78). Validation procedures for a 2 year period showed acceptable correlation between simulated and observed data, NS value is 0.67 and R^2 value equals to 0.70. This study showed how a sub-hourly model can be run using SWAT and calibrated using SWAT-CUP for a long simulation period. Calibrating and validating a sub-hourly model for a long duration instead of single storm was attained. The ability to optimize the best set of parameters to minimize the uncertainty for a complex system is an important tool with a complex watershed model, enhancing the ability to select the "best" model from a multitude of models with varying parameter sets which may provide similar results.

CHAPTER III

MODELING STREAM BANK EROSION AT A WATERSHED SCALE IN THE BLACKLAND PRAIRIE ECOSYSTEM

Synopsis

Stream bank erosion is a naturally occurring process that includes the removal of soil particles due to change in stream flow, and the discharge of runoff from other sources. The goal of this study was to investigate the capability and performance of sub-hourly time steps SWAT models in predicting of stream flow in the Blackland Prairie ecosystem and to estimate potential stream bank erosion. The major steps carried out to achieve this objective include; sensitivity analysis for sub-hourly time step SWAT models, development of two methodologies to represent bioretention and permeable pavement into SWAT, analysis of shear stress and excess shear stress for stream flows under different development scenarios and in conjunction with different levels of LID practices, and estimating potential stream bank erosion for different median soil particle sizes using real and design storms.

A sub-hourly SWAT model was successfully calibrated and validated for stream flows. Calibrated stream flows for a 2-year period using the 15-minute time step had an R^2 of 0.78 and an NS of 0.78. The 2 year validation period had an R^2 of 0.70 and a Nash Sutcliffe (NS) of 0.67. Results showed that combining permeable pavement and bioretention area resulted with the greatest reduction percentages in runoff volumes, peak flows, and excess shear stress under both real and design storms. Adding bioretention only resulted with the second greatest reduction percentage and adding

detention pond only had the least reduction percentages. Results showed agreement between modeling data and field experiments' findings. The soil particle with median diameter equals to 64 mm had the least excess shear stress among all design storms, while 0.5 mm soil particle size had the largest magnitude of excess shear stress. The larger the value of excess shear stresses, the higher the potential of erosion to happen.

Introduction

Changing land due to urbanization increases the amount of stormwater runoff which in turn can have harmful effects on urban and suburban streams, both hydrologically and biologically. As streams meander across the surface of the earth, they erode their beds and banks in a dynamic natural way (Staley et al., 2006). Several research studies have demonstrated the significant contribution of stream bank erosion to total sediment loading (Simon and Darby, 1999; Sekely et al., 2002; Evans et al., 2006). Konrad et al., (2005) studied the impact of urban development on stream flow and stream bed stability. They examined 16 streams in the Puget Lowland, Washington, using three stream flow metrics that integrate storm-scale effects of urban development over annual to decadal timescales. They concluded that the increase in the magnitude of frequent high flows due to urban development but not their cumulative duration has important consequences on channel form and bed stability in gravel bed streams.

In order to restore or maintain channel stability, the incision of the channel bed and erosion of the stream banks must be prevented. Stability of a streambed can be attained by acquiring the balance between sediment supply and sediment transport capacity, while stream bank stability can be attained by maintaining the applied shear stress to be below erosive thresholds (Lawler, 1995). These thresholds can be estimated by defining the critical shear stress at which soil detachment begins. The erosion rate will remain zero as long as the critical shear stresses are higher than the applied shear stress (Hanson et al., 2002; Nearinget al., 1989). Sediments resulting from stream bank erosion can account for 85% of watershed sediment yields and bank retreat rates of 1.5 to 1100 m/year have been documented in several studies (Prosser et al., 2000; Simon et al., 2000; Wallbrink et al., 1998) .The total damage to natural resources and human health due to water pollution by sediment costs an estimated $16 billion annually in North America (Osterkamp et al., 1998).

Erosion control and management of urban streams is becoming increasingly important because of the economic damage that stream bank erosion can cause along urban streams and impairment of water quality. Low Impact Development (LID) was developed to mimic the natural water cycle of the land by reducing the negative impact of stormwater runoff on water bodies and eventually human health. LID practices are structural or non-structural management practices that aim to decrease the impacts of urbanization and sediments on water quality. LIDs include the installation of any of the following structural measures to retrofit existing infrastructure and reduce runoff volumes and peak flows: bioretention, green roofs, rainwater harvesting, and permeable pavements (Damodaram, 2010). Regulatory enforcement of LID implementation results in an urgent need for quantitative information on LID effectiveness for sediment and stream erosion (Lee and Jones-Lee, 2002). While LID practices have been mentioned in literature for stormwater management (Dietz and Clausen, 2008; Elliott and Trowsdale, 2007; Hood et al., 2007; Bedan et al., 2009) there is little research that studied LID practice impact with respect to reducing stream bank erosion in urban areas.

Jeong et al. (2011) developed a sub-daily algorithm which was integrated into SWAT to simulate LIDs such as detention basins, wet ponds, sedimentation filtration ponds, and retention irrigation systems. The algorithm was tested for predicting sediment yield and total runoff but not for potential stream bank erosion. Krishnappan and Marsalek (2002) conducted an experiment in a rotating circular flume to test for transport characteristics of sediment from an on-stream stormwater pond in Kingston, Ont., Canada. The main findings of this experiment were that the sediments from the pond exhibited cohesive behavior and formed particle aggregates when subjected to a flow field. The experiment provided data on the sediment fraction which would deposit under specific shear stress and the deposited sediment fraction which would be eroded. Bledsoe (2002) designed a detention pond based on time-integrated sediment-transport capacity. They examined the impact of the detention pond in reducing stream channel erosion for two bed material sizes (8mm and 0.5 mm). They concluded that the followed methodology of design resulted in channel instability and substrate changes and they recommended developers to account for the frequency distribution of sub-bankfull flows, the capacity to transport heterogeneous bed and bank materials, and potential shifts in inflowing sediment loads before conducting a design. Furthermore, other studies addressed LID practices effectiveness through field experiments, but not through computer simulations that are capable of covering wider scales. Field experiments are costly and difficult to duplicate, though computer simulation can be run several times with a numerous number of variables. McCuen and Moglen (1988) suggested a multi-criterion approach to mitigate channel instability. This approach requires the cumulative, post-development bed load transport volume not to exceed the predevelopment amount for the 2-year recurrence interval. This approach did not account for an evaluation of LIDs and shear stresses.

Erosion and Hydrological Modeling

Erosion occurs in three main processes: fluvial entrainment, subaerial processes, and mass wasting (Hooke, 1979; Couper and Maddock, 2001; and Wynn and Mostaghimi, 2006). The general definition of erosion is the detachment and removal of particles or aggregates from the soil surface. This study has a specific focus on potential erosion that might occur for the surface of urban stream banks. Local climate changes that include wetting and drying or freezing and thawing of the soil surface, result in weakening the bonding between aggregates, and detaching soil particles from their places and this process is defined as subaerial (Couper and Maddock, 2001). As a result of hydraulic forces applied directly to the stream bank by flowing water, fluvial erosion occurs. Mass failure of a stream bank occurs when geotechnical instability causes stream banks to collapse. Stream bank retreat is the collective loss of bank material from subaerial processes, fluvial entrainment, and mass failure (Lawler et al., 1997).

Numerous models were developed that include a stream bank erosion component including: The Système Hydrologique Européen (SHE) (Abbott et al., 1986), Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002), Watershed Erosion Prediction Project (WEPP) (Flanagan et al., 2001) and Conservation Channel Evolution and Pollutant Transport System (CONCEPTS) (Langendoen, 2000). Mostly, these models use the excess shear stress equation for determining rates of erosion. This study utilized SWAT to estimate stream flows for long periods of time for the Blunn Creek Watershed located in Austin, Texas, and investigated the influence of these flows on potential stream bank erosion.

Modeling LIDs effectiveness with respect to stream bank erosion at a watershed scale is a challenging issue that requires robust algorithms to simulate not only stream flow, but also water balance, and volumes of water runoff. SWAT is one of the very few tools that meet such requirements (Arabi et al., 2008; Gassman et al., 2007). SWAT is a physically based watershed model designed to predict the impacts of management practices on water quantity and quality in large complex watersheds and yields of agricultural chemicals over long periods of time (Neitsch et al., 2002). The major components of SWAT include nutrient and pesticide fate, weather, erosion and hydrology.

Stream bank stability is modeled by calculating the ratio of driving to resistive forces in order to determine potential failure or collapse (Thorne and Abt, 1993; Osman and Thorne, 1988). The role of saturated and unsaturated pore water pressure has been included in estimating stream bank erosion. Stream bank erosion of fine grained soils due to overland flow or channel scour is commonly modeled with an excess shear stress equation relating erosion rate (ε) to applied shear stress (τa) once a critical shear stress (τc) has been exceeded (Hanson and Cook, 1997; Hanson, 1990; Partheniades, 1965):

$$\varepsilon = k_d (\tau_a - \tau_c)^a \qquad \text{(Equation 3.1)}$$

where,

ε = erosion rate (m/s)

k_d = erodibility coefficient (m^3/N-s)

a= power term, commonly assumed to be unity (Hanson and Cook, 1997)

τ_a = applied shear stress on the soil boundary (Pa)

τ_c = critical shear stress (Pa)

The erodibility coefficient and critical shear stress are considered properties inherent to a given soil. The applied shear stress is the hydraulic force applied on the soil boundary of the stream bank per unit area. Fox et al. (2006) and Wilson et al. (2007) conducted lysimeter experiments to model stream bank undercutting by seepage flow and bank collapse. They compared flow rates and sediment concentrations from the lysimeter experiments to seepage flow. They concluded that a detailed characterization of the soil profile is highly dependent on accurate seepage erosion estimation, but the measurements were not correlated to stream stage, stream bank soil pore water pressure, or precipitation.

Stream Stability

Stream bank stability is enhanced when stream banks are unsaturated (Rinaldi and Casagli, 1999; Simon and Curini, 1998). A pre-wetting condition resulting from prolonged high flows, groundwater rise, and infiltration of precipitation incorporates mechanisms that increase the stream bank soil moisture content. Large changes in soil moisture content for stream banks have a negative result on stream stability (Lawler et al., 1997).

Several studies have been conducted to investigate the influence of different physical and biological factors on stream stability. Hession et al. (2003) studied the influence of varying riparian vegetation on channel morphology in rural and urban watersheds. They found that channel width and cross-sectional areas are larger in urban watersheds and documented a significant difference in p-value ($p<0.001$). Also, bankfull channels in forested streams are wider and have greater cross-sectional areas, while there are no significant differences between forested and non-forested bankfull depth, sinuosity, slope, or median bed particle size. Trimble (1997) conducted a study to evaluate the contribution of stream channel erosion to sediment yield from an urbanizing watershed. The study considered the San Diego Creek in southern California, and measurements from 1983 to 1993. Results showed that stream channel erosion provided 105 Mg/yr of sediment, or about two-thirds of the total sediment yield. Another study conducted by Bledsoe and Watson (2001) found that increased high flows due to urbanization have the potential to destabilize urban streams by assuming fixed channel dimensions and size of bed material, though morphologic adjustments to increased high flows can be expected in alluvial channels. Wolman and Schick (1967) found that morphological adjustments in urban streams are not strictly responses to altered stream flow patterns. These adjustments may confound the morphological responses of channel stream flow patterns. For instance, banks that have been defrosted or artificially stabilized can have narrower channels.

Smerdon and Beasley (1961) conducted a flume study on eleven cohesive soil samples to investigate the relationship between soil properties and critical shear stress. All the samples were leveled after placement in the flume without compaction. Soil samples continued to be observed under increasing flow rates, and the shear stress corresponding to bed failure was considered τ_c. The following empirical correlations were developed between τ_c and soil properties (plasticity index, dispersion ratio, mean particle size, and percent clay):

$$\tau_c = 0.16 \text{ X } I_w^{0.84} \qquad \text{(Equation 3.2)}$$

$$\tau_c = 10.2 \text{ X } D_r^{-0.63} \qquad \text{(Equation 3.3)}$$

$$\tau_c = 3.54\text{X } 10^{-28.1\ D50} \qquad \text{(Equation 3.4)}$$

$$\tau_c = 0.493 \text{ X } 10^{0.0182\ Pc} \qquad \text{(Equation 3.5)}$$

where; τ_c = critical shear stress (Pa)

Iw = plasticity index

Dr = dispersion ratio (%)

D50 = mean particle size (mm)

Pc = percent clay by weight (%)

The overall goal of this study was to predict stream flows for long periods of time using SWAT for the Blunn Creek Watershed located in Austin, Texas and investigate the influence of these flows on potential stream bank erosion by incorporating several levels of LID practices.

The objectives of this study are: 1) develop a sub-hourly time step SWAT model, 2) develop a simple way to represent bioretention and permeable pavement in SWAT model, 3) investigate the influence of LID practices on reducing total volumes of stormwater runoff, peak flows, excess shear stress and eventually potential stream bank erosion.

Methodology

Model Development

This study used the ArcSWAT modeling package, which runs the 2012 version of the SWAT model (SWAT 2012.10.4) within the ESRI ArcGIS 10.1 environment (DiLuzio et al., 2004). The preprocessing of the GIS data was facilitated through the interface; elevation, soil, land use, and weather as basic model inputs. SWAT was applied and outputs format were modified to sub-hourly time steps. The watershed was divided into 14 sub basins and each subbasin is parameterized using a series of HRUs (hydrologic response units) which are a particular combination of land cover, soil and management. At each HRU the following are simulated and then aggregated for the subbasin by a weighted average method; soil water content, nutrient cycles, crop growth, and management practices. Each subbasin had physical and climatic data such as reach geometry, slope and climatic data. Estimated flow was calculated for each subbasin and routed through the stream system. SWAT considers evapotranspiration, surface runoff, percolation, groundwater return flow, lateral subsurface flow, and channel transmission losses. Runoff is simulated and estimated with the Green Ampt Infiltration method (Mein and Larson, 1973). Stream flow and volumes of runoff were evaluated at the watershed outlet and at the end of each subbasin.

Data used in the modelling are the following: 15-min rainfall data downloaded from the Flood Early Warning System and Water Quality Monitoring sections at City of Austin (COA) station, daily temperature data from the Austin and Austin-Bergstrom NOAA weather stations were used, weather zone from (WGEN_US_COOP_1960_2010), 3m integer Digital Elevation Model (DEM) developed by COA based on 2003 LIDAR data and SSURGO soils data NRCS. Several land use scenarios were developed to account for future development in the watershed and compare it to different development plans. These scenarios reflect three different development patterns; low density, medium density, and high density and they were developed by adjusting Curve Number (CN) for residential areas by average lot size. The values of CN were 92 for High density scenario, 87 for medium density scenario and 85 for low density scenario.

Calibration and Validation

The model was calibrated and validated at the watershed outlet for a period of two years. Sub-daily flow measurements were available at station 08157700 and retrieved from USGS website for the period between 1998 and 1999 for calibration purposes. Validation procedures for the period between 2001 and 2002 were conducted to ensure the validity of the selected uncertainty parameters through the calibration process. The performance of each simulation was assessed by coefficient of determination R^2 and Nash–Sutcliffe coefficient of efficiency, NS (Nash and Sutcliffe, 1970), computed as follows:

$$NS = 1 - \frac{\sum(Qo - Qm)^2}{\sum(Qo - \overline{Qo})^2} \qquad \text{(Equation 3.6)}$$

Where: Q_o : observed discharge (m^3/s)

Q_m : modeled discharge (m^3/s)

$\overline{Qo}$: average observed discharge (m^3/s)

When computing the NS value the first year of simulation was always skipped; to avoid the influence of initial conditions such as soil water content and eventually runoff estimates.

Sensitivity Analysis

Sensitivity analysis is the study and investigation of how uncertainty in the output of a model can be influenced by different sources of uncertainties in the model input (Saltelli et al. 2009). In this study, a sensitivity analysis was conducted to investigate the impact of input parameters in estimating flow at a 15-min time interval. The sensitivity of thirteen parameters related to stream flow and SWAT was indexed and those highly ranked parameters were selected for calibrating the model. The evaluation was based on the Latin hypercube sampling method that is incorporated with the one-factor-at-a-time analysis technique (LH-OAT) (Wang et al. 2005) (Equation 7). LH-OAT is a screening method which is incorporated in SWAT. The method works best when the number of intervals used for the Latin-Hypercube sampling is high enough to obtain converged parameter (Van Griensven et al., 2006).

$$S_{ij} = \frac{\dfrac{\left| M(x_1, \ldots, x_i + \Delta x_i, \ldots, x_K) - M(x_1, \ldots, x_i, \ldots, x_K) \right|}{M(x_1, \ldots, x_i + \Delta x_i, \ldots, x_K) + M(x_1, \ldots, x_i, \ldots, x_K)}}{\left| \Delta x_i \right| / x_i} \qquad \text{(Equation 3.7)}$$

where: Sij : the relative partial effect of parameter xi around LH point j

K : the number of parameters

M : the model output (time series result of stream flow at every time step at the watershed outlet)

SWAT Calibration and Uncertainty Procedures (SWAT-CUP) which is a program that is interfaced with SWAT and developed by (Abbaspour et al., 2007) was adopted for this sensitivity analysis. This program includes three calibration procedures that are capable of calibrating and evaluating SWAT outputs. These procedures include: Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (ParaSol) (Van Griensven and Meixner, 2006), and Sequential Uncertainty FItting (SUFI-2) (Abbaspour et al., 2007).

Channel Geometry and Hydraulic Properties

The following steps were followed to update the geometry of the channel in each subbasin of the watershed. First of all, FEMA floodplain maps for the watershed were retrieved in order to apply cross sectional analysis for the channels. Second, HEC-RAS 4.1.0 software developed by the United States Army Corps of Engineers was installed and put into work. HEC-RAS has been applied broadly in estimating the hydraulic characteristics of rivers (Carson, 2006; Pappenberger et al., 2005). It is an integrated software that was developed to estimate water surface profiles using the following energy equation (Brunner, 2002):

$$\mathrm{Y2} + \mathrm{Z2} + \frac{\alpha_2\, \mathrm{V2}^2}{2\mathrm{g}} = \mathrm{Y1} + \mathrm{Z1} + \frac{\alpha_1\, \mathrm{V1}^2}{2\mathrm{g}} + \mathrm{h_e} \qquad \text{(Equation 3.8)}$$

Where: Y : water depth (m)

Z : channel elevation (m)

V : average velocity (m/2)

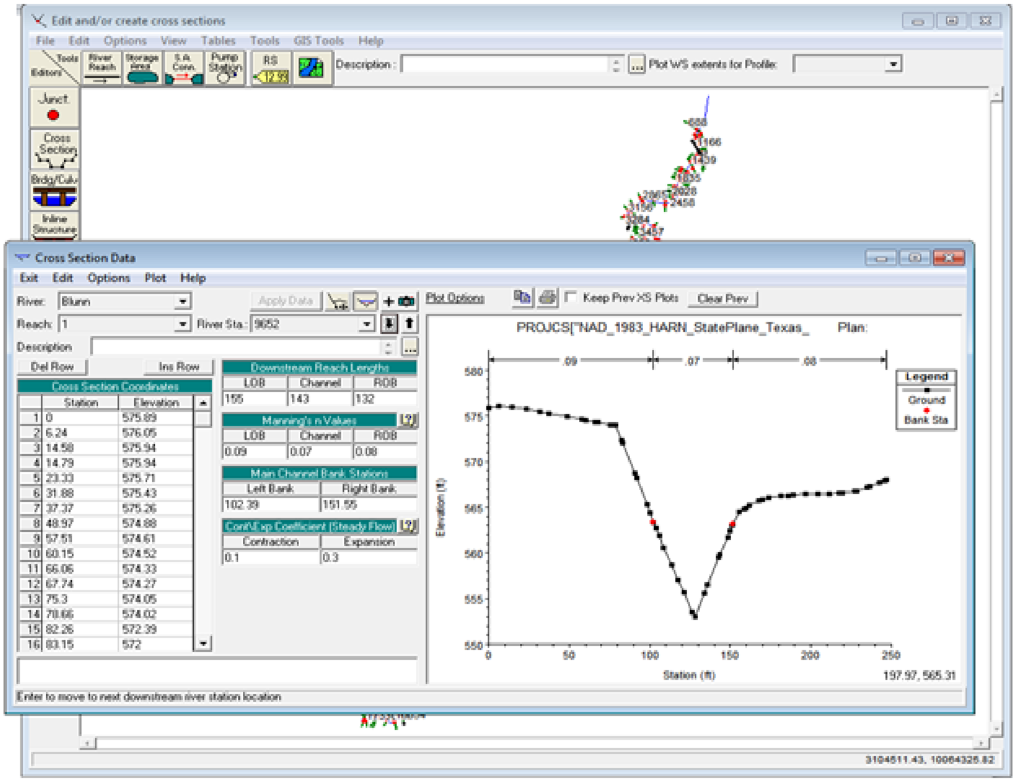
α :velocity weighting coefficient

he : energy head loss (m)

g : gravitational acceleration (m/s^2)

subscripts 1 and 2 : cross sections 1 and 2 respectively.

Third, a project was created into HEC-RAS program and FEMA floodplain map was imported for cross section analysis (Figure 3-1).



River: Blunn

Reach: 1

River Sta.: 9652

Description:

Cross Section Coordinates

	Station	Elevation
1	0	575.89
2	6.24	576.05
3	14.58	575.94
4	14.79	575.94
5	23.33	575.71
6	31.88	575.43
7	37.37	575.26
8	48.97	574.88
9	57.51	574.61
10	60.15	574.52
11	66.06	574.33
12	67.74	574.27
13	75.3	574.05
14	78.66	574.02
15	82.26	572.39
16	83.15	572

Downstream Reach Lengths

LOB	Channel	ROB
155	143	132

Manning's n Values

LOB	Channel	ROB
0.09	0.07	0.08

Main Channel Bank Stations

Left Bank	Right Bank
102.39	151.55

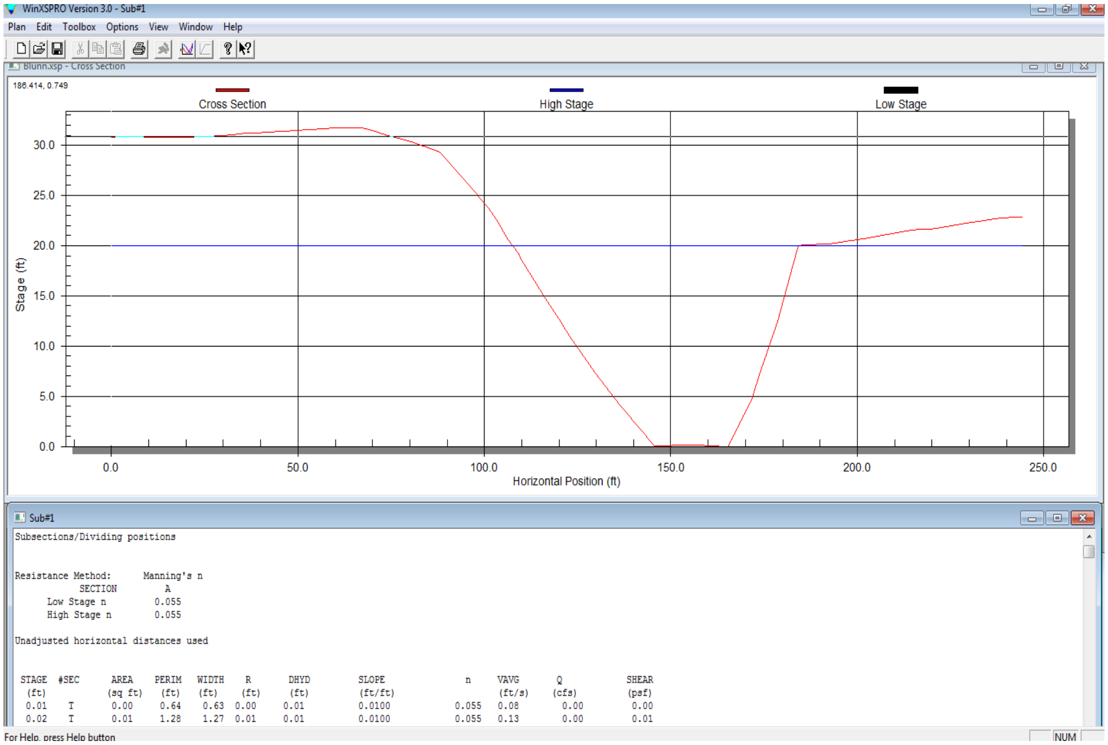
Cont\Exp Coefficient (Steady Flow)

Contraction	Expansion
0.1	0.3

Enter to move to next downstream river station location

Figure 3-1. Example of HEC-RAS analysis

Fourth, each subbasin was divided in mutli-river stations and each station had a unique cross section. Fifth, average cross section analysis was developed for each subbasin, exported to MS Excel format, and utilized as an input for WinXSPRO program. Sixth, the WinXSPRO 3.0 program that was created by the National Forest Service was utilized to estimate the channel hydraulic properties for each subbasin (Hardy et al., 2005). The program developed a stage-discharge relationship based on cross-section and slope along with velocity and shear stress (Figure 3-2). The stage-discharge relationship was based on Manning's equation using the channel slope calculated by SWAT program and cross section data developed by HEC-RAS.



```
Subsections/Dividing positions


Resistance Method:      Manning's n
          SECTION          A
     Low Stage n         0.055
     High Stage n        0.055

Unadjusted horizontal distances used


 STAGE  #SEC     AREA   PERIM   WIDTH    R      DHYD        SLOPE           n     VAVG     Q          SHEAR
  (ft)          (sq ft)  (ft)    (ft)   (ft)    (ft)       (ft/ft)               (ft/s)   (cfs)       (psf)
  0.01    T      0.00    0.64    0.63  0.00     0.01       0.0100           0.055  0.08      0.00       0.00
  0.02    T      0.01    1.28    1.27  0.01     0.01       0.0100           0.055  0.13      0.00       0.01
```

Figure 3-2 Example of WinXSPRO analysis

LIDs Development and Representation

LIDs capture the storm and base flow patterns over a long time period, and they are recommended as new metrics to characterize the magnitude of urban development influence, and stream bank erosion. Several levels of LIDs were applied and represented the different development scenarios including detention pond (DP) only, bioretention/raingarden (RG) only, permeable pavement (PP), and a combination of RG and DP. They were selected based on their ease of adoption by developers, their potential effectiveness, and the viability of associated processes in the SWAT model.

The DP was placed in the middle of the watershed on the stream network (Figure 4). RGs were represented in each subbasin and PP was represented in 27% of the total watershed area. This representation for the PP was based on typical average parking lots in Dallas, TX downtown that has the same watershed area of Blunn Creek Watershed (City of Dallas, 2011). The various scenarios were run using the same calibration parameters and weather as the base model.

Detention Pond Development

There are two types of DP employed in the Austin area; on-site detention (off-line) and regional detention (on-line). The current version of SWAT considers only the regional detention which is placed on-line or in other words, on-stream. According to the COA code of development, small storms are allowed to pass through virtually uncontrolled and there is only ponding during the larger runoff events that drain out in less than 24-hours. A hypothetical detention pond was designed according to the COA standards. Pond sizes were calculated as follows. A raster surface was converted to contour lines with 1 foot (0.3 m) contour intervals. A 12 m line segment was placed at the end of subbasin 10 shown in Figure 3-3 to represent the width of the detention pond across the creek. This width was based on the current geometry of the channel and could not be wider than a channel due to current development and residential areas adjusting to the channel. Following the contour line, an area of 3608 m^2 was delineated which is the extended lines from the two ends of the 12 m segment line. The average operation depth along the pond is 3 m which was calculated directly from the geometry of the channel. A stepped weir was used and the height of it was based on the required storage volumes for the following design storms: (2 year, 25 year, and 100 year).

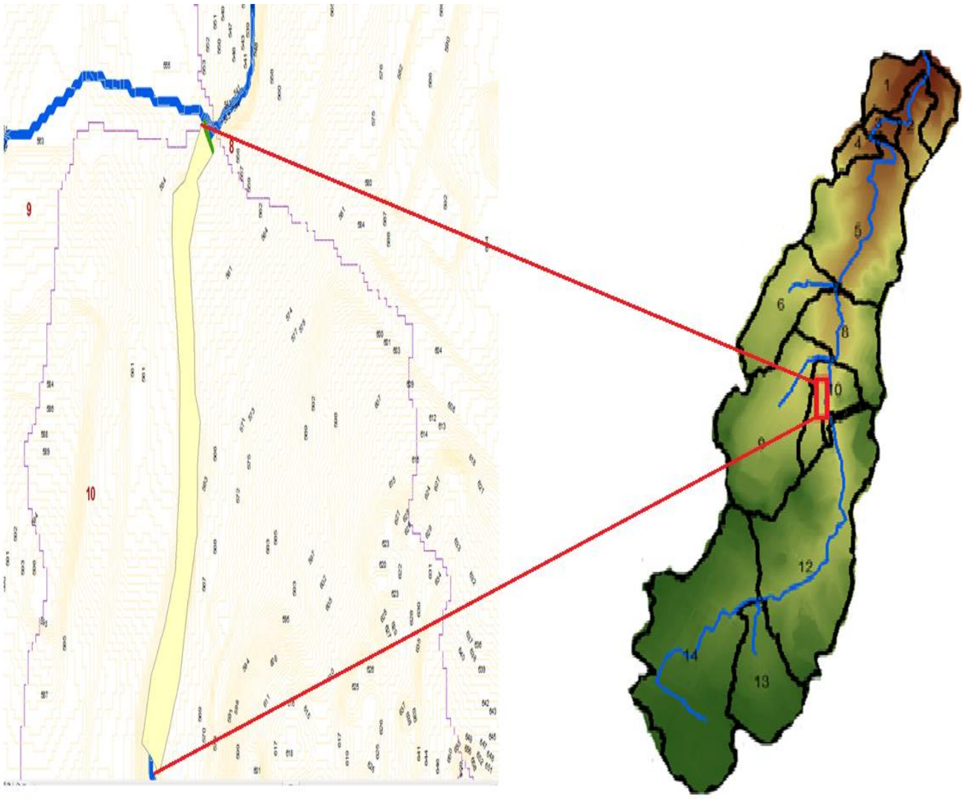


Figure 3-3. Location of a Detention Pond at subbasin 10

The pond was designed after modeling the SCS 24 hour rainfall distribution for type III region (Travis county) (Asquith and Roussel, 2004) (Figure 3-4).

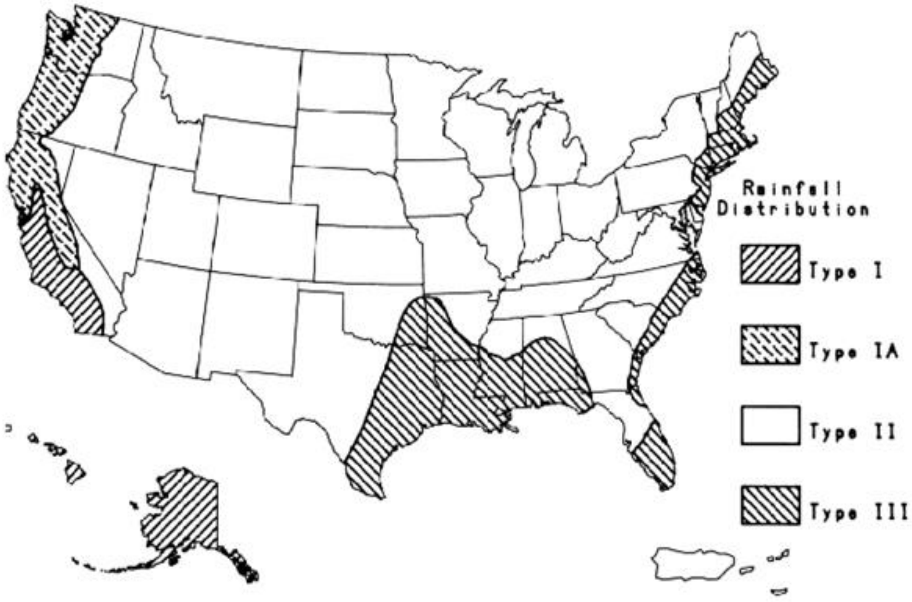


Figure 3-4. Geographic boundaries for SCS rainfall distribution (Asquith and Roussel, 2004)

Bioretention/Raingarden and Permeable Pavement Development and Representation

The methodology was followed accounts for modifying existing Best Management Practices (BMPs) within SWAT program to serve as RG and PP. The current version of SWAT does not incorporate RG or PP within the BMP package. For the purpose of this study, the Sedimentation Filtration (Sedfil) was modified to act as bioretention and permeable pavement. There are three designs of Sedfil offered by SWAT; full scale, partial scale, and sedimentation pond only. The full scale design allows the entire water quality volume (Equation 9) to be held in the sedimentation basin and later discharge slowly to the filtration basin via a perforated riser pipe. The second design “partial sedfil” distributes the water quality volume between the filtration and sedimentation champers after foregoing the perforated riser pipe (COA, 2011). The main difference between the two designs is the sedimentation basin, the full design should receive the full water quality volume, while the sedimentation and filtration basin in the partial-sedfil design account for the water quality volume only (Figure 3-5).

$$V_{wq} = 0.07 \times \left\langle 0.5 + \left| \frac{Impervious\ area}{Total\ drainage\ area} - 0.2 \right| \times 1 \right\rangle \times A_d \qquad \text{(Equation 3.9)}$$

Where; V_{wq}: water quality volume (m^3)

A_d : drainage area of the LID (m^2)

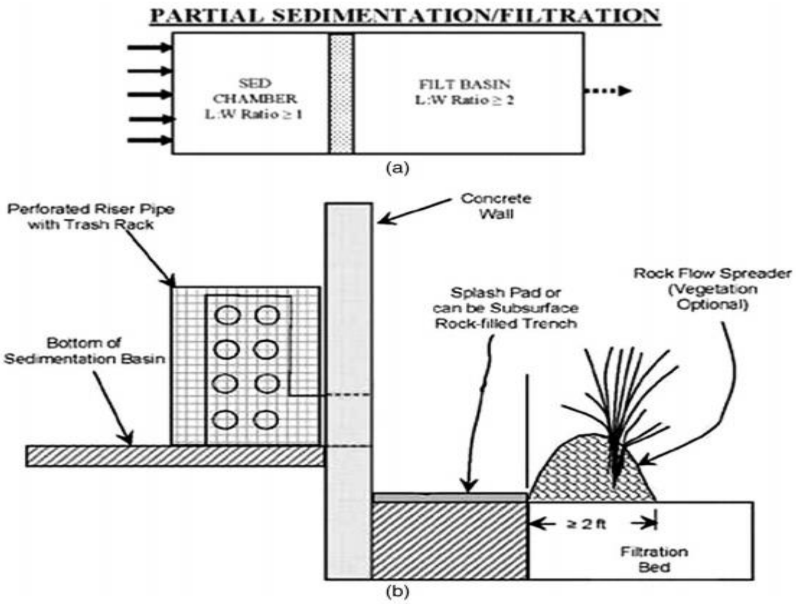
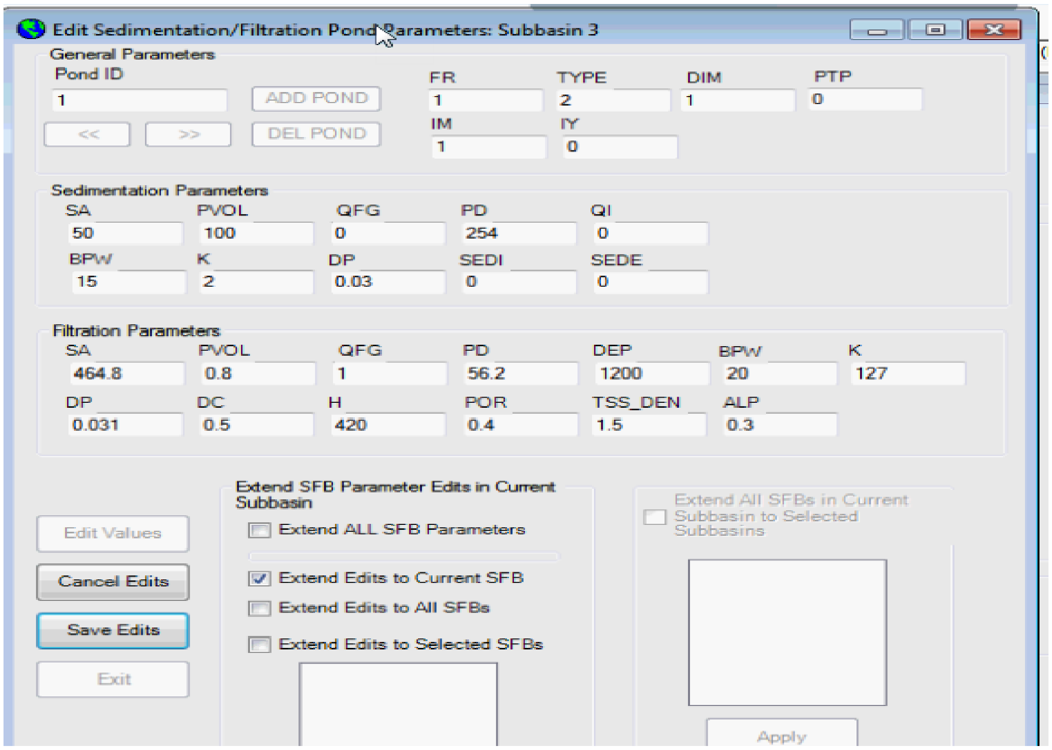


Figure 3-5. Schematic of Austin sedimentation/filtration basins [Courtesy of City of Austin (2011)]: (a) configuration of full/partial sedimentation filtration basins; (b) riser pipe outlet system and flow spreader in full type systems

The partial scale design was used in this study to simulate bioretention and permeable pavement. Two parameters were considered in adjusting the Sedfil design; water ponding and depth of filtration media. A typical standard of a bioretention and a permeable pavement surface area that is 3 to 10 % of the total catchment area was followed (Jaber et al., 2012). Initial run was executed with an automatic sizing function in order to size the pipes required to release runoff inside and outside the system. In order to minimize the function of the sedimentation basin and concentrate on a filtration basin only which represent the bioretention and permeable pavement, the following steps were followed: the surface area of the sedimentation area was selected to represent a forebay area that might be installed before a bioretention area and in case of the permeable pavement that was totally ignored by selecting a minimum number that the system would allow in order to minimize this effect, the outlet orifice pipe was selected to be bigger than the one for the filtration in order to divert most of the runoff to the filtration basin where it will be treated, the depth of the filtration media for the bioretention was selected to be 1200 mm and maximum ponding depth of the water to be 420 mm, the depth of the filtration media for the permeable pavement was 356 mm and maximum ponding depth of the water of 10 mm (Figure 3-6). It is worth noting that ponding and filtration depths for both bioretention and permeable pavement were selected to represent field experiments for similar LID practices studied at the Texas AgriLife Research and Extension Center located in Dallas, TX. The field experiment LID practices at the center were utilized later to judge the performance of modeled LIDs in SWAT.



Edit Sedimentation/Filtration Pond Parameters: Subbasin 3

General Parameters

Pond ID: 1

FR: 1
TYPE: 2
DIM: 1
PTP: 0
IM: 1
IY: 0

Sedimentation Parameters

SA: 50
PVOL: 100
QFG: 0
PD: 254
QI: 0
BPW: 15
K: 2
DP: 0.03
SEDI: 0
SEDE: 0

Filtration Parameters

SA: 464.8
PVOL: 0.8
QFG: 1
PD: 56.2
DEP: 1200
BPW: 20
K: 127
DP: 0.031
DC: 0.5
H: 420
POR: 0.4
TSS_DEN: 1.5
ALP: 0.3

Extend SFB Parameter Edits in Current Subbasin

☐ Extend ALL SFB Parameters
☑ Extend Edits to Current SFB
☐ Extend Edits to All SFBs
☐ Extend Edits to Selected SFBs

☐ Extend All SFBs in Current Subbasin to Selected Subbasins

Figure 3-6. Example of a bioretention/raingarden sizing

Potential Erosion Estimates

The model outputs for the various scenarios were compared using the methodology developed by Glick and Gosselink (2011). The potential impact of urban development on stream bank erosion potentials was evaluated using annual excess stream flow. This study investigates the potential bank erosion in the main channel and does not account for flows that exceed bankfull and spills into the floodplain. The rate of energy dissipation against the bed and banks of a stream was estimated. Shear and critical shear were computed using the following equations:

$$\tau = \gamma_W \times D_H \times S_W \qquad \text{(Equation 3.10)}$$

$$\tau_c = \theta_c \times (S_g - 1) \times \gamma_w \times d_{50}$$ (Equation 3.11)

where,

γ_w = density of water (kg/m^3)

D_H = depth of water (m)

S_w = channel slope

S_g = specific gravity of soil, 2.65 g/cm^3

d_{50} = median particle diameter, (50mm and 0.5 mm)

θ_c = critical Shield's parameter

The critical Shield parameter is a non-dimensional number used to calculate the initiation of motion of sediment in a fluid flow. The critical Shield parameter was determined by using shield parameter curves for different soil types (Julien, 1995), after determining average soil particle diameter size, the corresponded Shield parameter value can be selected. The median particle sizes considered in this study are listed in Table 3-1.

Table 3-1. Median soil particle sizes and classification used in potential erosion estimates (Julien, 1995)

Particle size classification	Particle size diameter (mm)
Medium sand	0.5
Medium gravel	10
Coarse gravel	20
Very coarse gravel	32
Small cobbles	64

After calculating critical and shear stresses, flows for different urban development scenarios on annual basis were monitored and evaluated based on the exceedance of critical shear stress and average cumulative exceedance of critical shear stress. Cumulative excess shear (CE) was calculated using the following relationship (Glick and Gosselink, 2011):

$$CE = \Sigma (\tau - \tau c), \text{ for all } \tau > \tau c \qquad (Pa) \qquad \text{(Equation 3.12)}$$

Cost Analysis

The costs incurred to all types of LIDs this research study investigated are evaluated based on a research work at Texas AgriLife Research Urban Solutions Center in Dallas. Several LIDs were designed and constructed to evaluate their effectiveness in reducing stormwater runoff and improving outflow water quality. Bioretention, permeable pavement, and detention pond are the LIDs constructed and evaluated. The total costs of these LIDs were found to be as follows:

Bioretention = \$6 / sq ft

Permeable Pavement = \$12/ sq ft

The cost of detention pond was based on Brown and Schueler (1997) equation to estimate the cost of wet ponds which was modified to estimate the cost of stormwater wetlands using the following equation:

$$C = 30.6 \times V^{0.705} \qquad \text{(Equation 3.13)}$$

where:

C = Construction, design and permitting cost;

V = Volume in the pond to include the 10-year storm (ft^3).

Statistical Analysis

The main type of statistical analysis conducted in this study was comparison between mean differences. First: a statistical test for $\mu1 - \mu2$ was conducted to test a hypothesis about the difference between two population means (one current scenario without LID practices and another current scenario combined with different levels of LID practices). The differences in sample means were judged statistically as significant or not, by comparing them to the variation within samples.

The null and alternative hypotheses are:

H0: $\mu1 = \mu2$

Ha: At least one of the population means differs from the rest.

A significant level of $\alpha < 0.05$ was selected to ensure the probability of being wrong concluding in favor of research hypothesis is small. This way, if the research hypothesis is true, there is a chance of 5% of being wrong and 95% of being correct. In other words, the type I error which could be committed if we reject the null hypothesis when it is true will be controlled and the alternative hypothesis is going to prove beyond a reasonable doubt (Ott and Longnecker, 2008).

Performance Validation of LIDs

Each type of LID practice can have a unique design and accordingly different responses to stormwater runoff and amounts of reductions desired. Modeling LIDs at a watershed scale requires field data that have been tested in every location to confirm the validity and high performance of LIDs (Gallo et al., 2012). Therefore, a field experiment at the Texas A&M AgriLife Research Center located in Dallas, Texas was conducted to help in designing LID practices and integrating them into SWAT model. The permeable pavement experiment had three treatments and a control. The three treatments represent five types of material (interlocking permeable concrete pavement blocks, grassed pavement, and impermeable concrete “control”). Placing the three treatments onsite was based on average parking traffic, ease of data collection, and as recommended by literature. The bioretention area was designed in a way that allows for runoff to drain to a collection point within the median for automatic sampling and flow measurement. An overflow box was placed on surface to drain water through an underground pipe to help in soil infiltration. Overflow was measured by a flow measuring device (ISCO). To measure soil water storage, a pressure transducer was installed. Selecting plants for the bioretention area was based on optimal performance of the rain garden, including treatment of the stormwater. Input and output flows were monitored and reported to determine the effectiveness of the system. Data for one year was documented and used to ensure validity of the developed LIDs. The table below (Table 3-2) shows each LID, water quality and quantity data to be monitored and the equipment needed.

Table 3-2. Monitoring system and equipment used to report LIDs performance at the Texas A&M Agrilfe Extension Services Center in Dallas Texas.

LID Type	Water Monitoring		Equipment
Permeable pavement	Inflow	Rain gauge	Automatic sampler
	Perforated pipe	Flow meter	
	Overflow	Flow meter	
Bioretention	Inflow	Rain gauge	Automatic sampler
	Water storage	Pressure transducer	
	Overflow	Flow meter	
Detention Pond	Inflow	Rain gauge	Water storage container & manual sampling
	Water storage	Pressure transducer	
	Outflow	Flow meter	

A detention pond was designed to retain 1 ½ inch of rain. It had two inlets and one outlet. ISCO samplers were placed at the inlets and outlet to monitor runoff volumes entering and leaving out the pond.

Results

The main objective of this study was to investigate the capability and performance of sub-hourly time step SWAT models for the prediction of stream flow in the Blunn Creek Watershed and the estimation of potential stream bank erosion. The major steps carried out to achieve this objective; analysis of sub-hourly time step SWAT models sensitivity, development of an easy way to represent PP and RG in the Blunn Creek Watershed, analysis of shear stress and cumulative excess shear stress for stream flows under different development scenarios and in conjunction with different levels of LIDs, and the estimation of potential stream bank erosion for different median soil particle sizes.

Sensitivity Analysis

This study utilized a multi-site semi-automated inverse modeling routine (SUFI-2) that is integrated in SWAT-CUP for calibration and uncertainty analysis for the Blunn Creek Watershed. A global sensitivity analysis of stream-flow parameters was calculated using Latin hypercube regression systems. Based on initial run, knowledge of the problem and software, and a relative sensitivity analyses; (varying all parameters simultaneously), a decision was made on eight parameters to be included in the calibration (Table 3-3).

Table 3-3. Stream flow parameters selected for calibration

Stream flow parameters selected for calibration	Description
ALPHA_BF	Base flow alpha factor (1/days)
GW_DELAY	Groundwater delay (days)
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (m)
CH_N2	Manning roughness for main channel
CH_K2	Effective hydraulic conductivity (mm/hr)
SOL_AWC	Available water capacity of the soil layer (mm water /mm soil)
ESCO	Soil evaporation compensation factor
SOL_K(1)	Saturated hydraulic conductivity (mm/hr)

The parameters have given ranks for their sensitivity to the model calibration (Table 3-4).

Table 3-4. Parameter sensitivities for SUFI-2

Parameter_Name	Ranking	t-stat	P-value
ESCO.hru	8	0.12	0.91
SOL_K(..).sol	7	-0.18	0.86
SOL_AWC(..).sol	6	-0.58	0.57
ALPHA_BF.gw	5	-0.70	0.48
GWQMN.gw	4	0.79	0.43
GW_DELAY.gw	3	-1.03	0.31
CH_N2.rte	2	2.12	0.04
CH_K2.rte	1	-5.55	0.00

Model Calibration and Validation

Calibrated stream flows for a 2 year period with 15- min simulation had (R^2= 0.78) and (NS =0.78). The goodness-of-fit and efficiency of the model were tested using the main objective functions mentioned in Table 3-5. These five objective functions were analyzed on a sub-hourly basis correspondingly for SUFI-2 uncertainty technique for the best-fit model.

Table 3-5. Stream flow calibration results for sub-hourly model

Variable	Value
p-factor	56%
r-factor	0.54
R^2	0.78
NS	0.78
b R^2	0.6423
MSE	0.0035
SSQR	0.0005

Validation procedures for the period between 2001 and 2002 were conducted to ensure the validity of the calibration process. NS value for validation was 0.67 and R^2 value equals to 0.70 for the sub-hourly time step model. All in all, the comparison between observed and simulated stream flow showed that there is a good agreement between the observed and simulated discharge which was verified by higher values of R^2 and NS. Results also showed that the p-factor which is the percentage of observations bracketed by the 95 % prediction uncertainty (95PPU), brackets 56 % of the observation and r-factor (average number of measured variables divided by the standard deviation of these measured variables) equals to 0.54.

Channel Geometry and Hydraulic Properties

The geometry of the channel, hydraulic radius, and slopes were estimated after running WinXSPRO 3.0 and HEC-RAS programs. Critical shear stress for the following median soil particle sizes was calculated using Equation 11 and 12; 0.5 mm, 10mm, 20mm, 32mm, and 64mm (Table 3-6).

Table 3-6. Median soil particle sizes and corresponding critical shear stress at each subbasin in the Blunn Creek Watershed

			critical shear stress (lbs./square feet)				
Subbasin	Channel Slope	Hydraulic Radius (ft)	d_{50}=0.5 mm	d_{50}= 10mm	d_{50}=20 mm	d_{50}=32 mm	d_{50}=64 mm
1	0.018	11.06	0.0069	0.15	0.32	0.54	1.12
2	0.020	15.09	0.0069	0.15	0.32	0.54	1.12
3	0.010	6.3	0.0069	0.15	0.32	0.54	1.12
4	0.018	5.19	0.0069	0.15	0.32	0.54	1.12
5	0.012	3.93	0.0069	0.15	0.32	0.54	1.12
6	0.045	4.79	0.0069	0.15	0.32	0.54	1.12
7	0.011	5.37	0.0069	0.15	0.32	0.54	1.12
8	0.013	5.79	0.0069	0.15	0.32	0.54	1.12
9	0.025	5.12	0.0069	0.15	0.32	0.54	1.12
10	0.014	5.03	0.0069	0.15	0.32	0.54	1.12
11	0.032	3.05	0.0069	0.15	0.32	0.54	1.12
12	0.010	2.37	0.0069	0.15	0.32	0.54	1.12

Table 3-6 Continued

			critical shear stress (lbs./square feet)				
Subbasin	Channel Slope	Hydraulic Radius (ft)	d_{50}=0.5 mm	d_{50}= 10mm	d_{50}=20 mm	d_{50}=32 mm	d_{50}=64 mm
13	0.023	1.7	0.0069	0.15	0.32	0.54	1.12
14	0.012	0.88	0.0069	0.15	0.32	0.54	1.12

Potential Erosion Estimates

Excess shear was calculated and evaluated for design and real storms. The 2-year storm was found to be equivalent to 3.5 inch,10 year storm equivalent to 6.1 inches, 25 year storm equivalent to 7.6 inches, and 100 year storm was equivalent to 10 inches. Excess shear was calculated using the modeled SWAT flow output for each 15-minute interval and summed to obtain cumulative excess shear for all the study's scenarios. All the models were run for twenty-five years 1987-2012, the first two years were used as a warm up period and not for analyses. The LIDs considered in this study include detention pond (DP), bioretention area/ raingarden (RG), and permeable pavement (PP). The results, illustrated in Figure 3-7, show the potential shear stress for a selected one day storm event by integrating different levels of LIDs and a current scenario without LIDs.

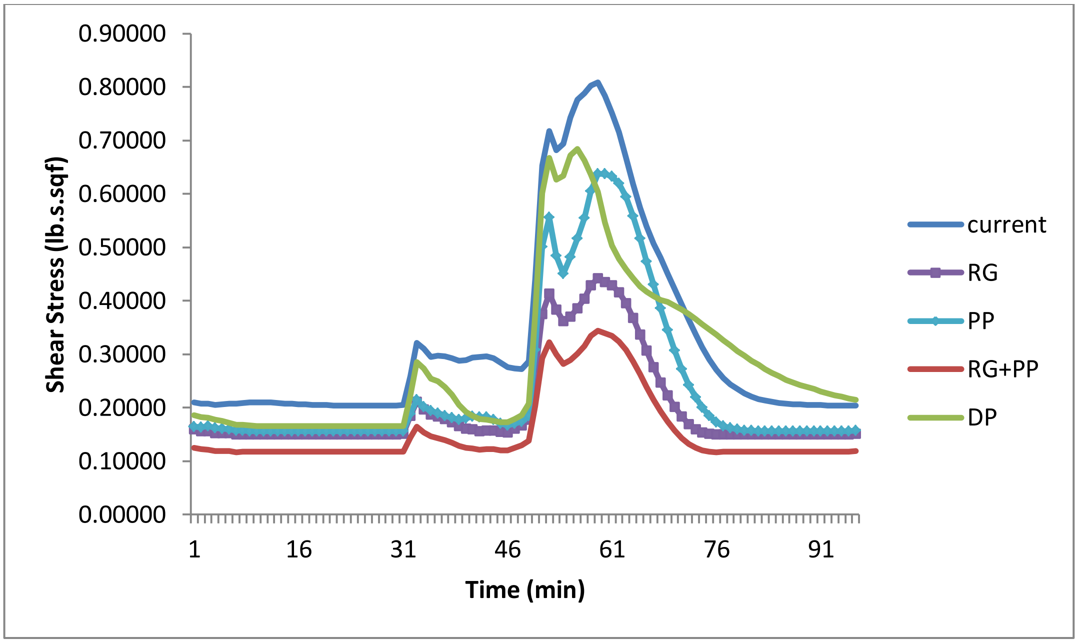


Figure 3-7. Shear stresses (lbs. square feet) for current scenario and different levels of LIDs based on Sedfil modification.

The scenario that accounts for a combination of RG and PP based on sedfil modifications resulted in the greatest reductions in shear stress. RG modified by sedfil came in the second order with respect to greatest reductions in shear stresses. The DP contributed to lowering shear stresses and peak flow especially at the beginning of the storm. In general, the Sedfil accounts for a ponding area where runoff will be captured and released after 24 hours. This functionality of the Sedfil contributed to reducing peak flows, volumes and slightly delaying the peak flows. The excess shear stress was also evaluated for several median particle diameters and in combination with different levels of LIDs (Figure 3-8).

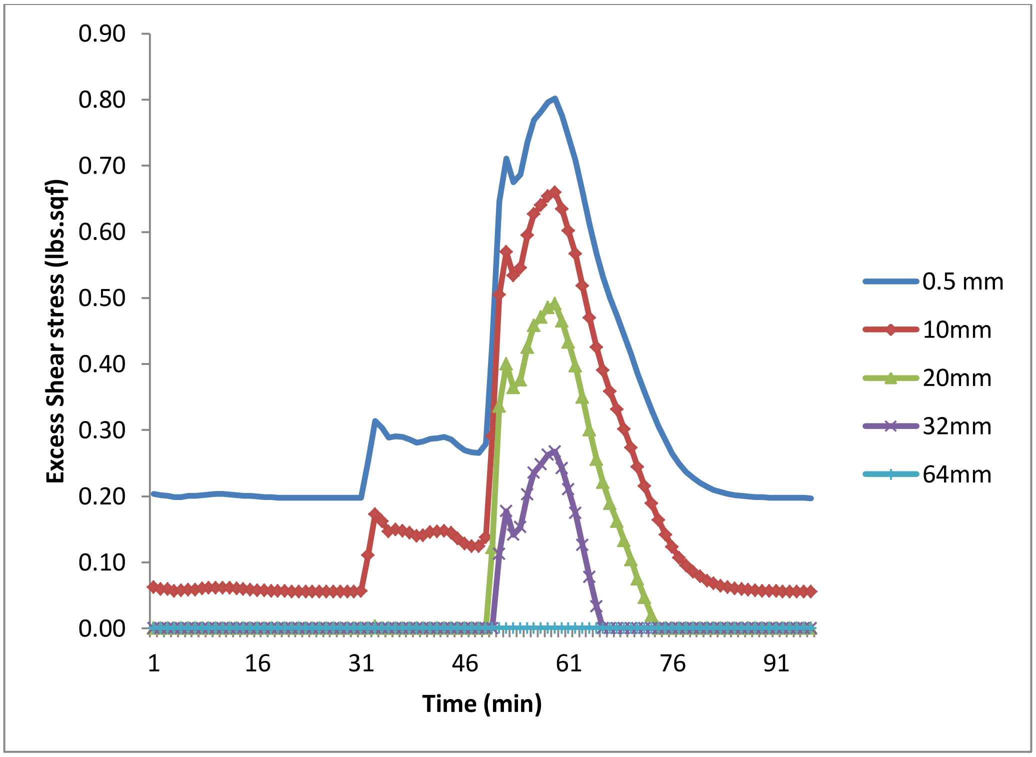


Figure 3-8. Excess shear for the current scenario without LIDs

Figure 3-8. shows that the 0.5mm soil particle diameter had the highest excess shear and potential erosion while the 64 mm had zero excess shear stress for the current scenario without any LID practices. The impact of LID practices on reducing excess shear stress for different soil particle diameter is shown in Table 3-7.

Table 3-7. Reduction percentages in excess shear stress for different soil particle diameters and by utilizing different types of LID practices.

	Particle Diameter (mm)	Reduction (%)
Current+DP	0.5	13.44
	10	24.06
	20	34.67
	32	65.16
	Average	34.33
(PP+RG)-Sedfil	0.5	40.07
	10	71.74
	20	87.55
	32	100.00
	Average	74.84
Current+ RG-Sedfil	0.5	39.82
	10	71.29
	20	83.33
	32	100.00
	Average	73.61
Current+ PP-Sedfil	0.5	26.86
	10	48.09
	20	44.28
	32	80.06
	Average	49.82

The same trend continued to hold and combining PP and RG based on Sedfil modifications resulted with the greatest reduction in excess shear stress for all soil particle diameters. Adding RG only based on Sedfil modification resulted with the second greatest reduction in excess shear stress. The DP had less reduction percentages than RG-Sedfil due to the fact that the design of the pond accounted for flows above the flow associated with critical shear stress for longer period of time such as 100 year storm.

To ensure the validity of performance for the designed LIDs on a longer period of time, analysis of performance for the following recurrence intervals was conducted, 2-yr, 10-yr, 25-yr, and 100-yr. Percentage of annual reductions for volumes and peak flows are shown in Table 3-8.

Table 3-8. Reduction percentages in runoff volumes and peak flows for different recurrence intervals and by utilizing different types of LID practices.

	Recurrence Interval (Year)	Volume Reduction (%)	Peak Flow Reduction (%)
Current+DP	2	46.64	23.17
	10	25.53	15.30
	25	17.95	25.37
	100	15.26	22.07
	Average Reduction (%)	26.34	21.48
Current +RG-Sedfil	2	79.71	78.73
	10	48.12	10.85
	25	40.75	31.09
	100	30.71	16.55
	Average Reduction (%)	49.82	34.31

Table 3-8 Continued

	Recurrence Interval (Year)	**Volume Reduction (%)**	**Peak Flow Reduction (%)**
Current+(PP and RG)-Sedfil	2	81.96	79.81
	10	58.70	29.72
	25	49.71	43.66
	100	38.58	28.97
	Average Reduction (%)	57.24	45.54
Current+PP-Sedfill	2	57.09	50.16
	10	36.55	12.10
	25	28.82	15.31
	100	21.72	8.28
	Average Reduction (%)	36.05	21.46

Combining RR and RG based on sedfil modification continued to result with the greatest reduction percentages for both runoff volumes and peak flows for all recurrence intervals. RG based on Sedfil modification had the second greatest reduction in runoff volumes and peak flows followed by PP- Sedfil and the DP scenario had the least reduction percentages.

Excess shear analysis for both design storms and real storm in the Blunn Creek showed agreement with findings. The impacts of development density on potential erosion were assessed using annual excess shear for the year 2002 for median soil particle size equivalent to 20 mm (Figure 3-9).

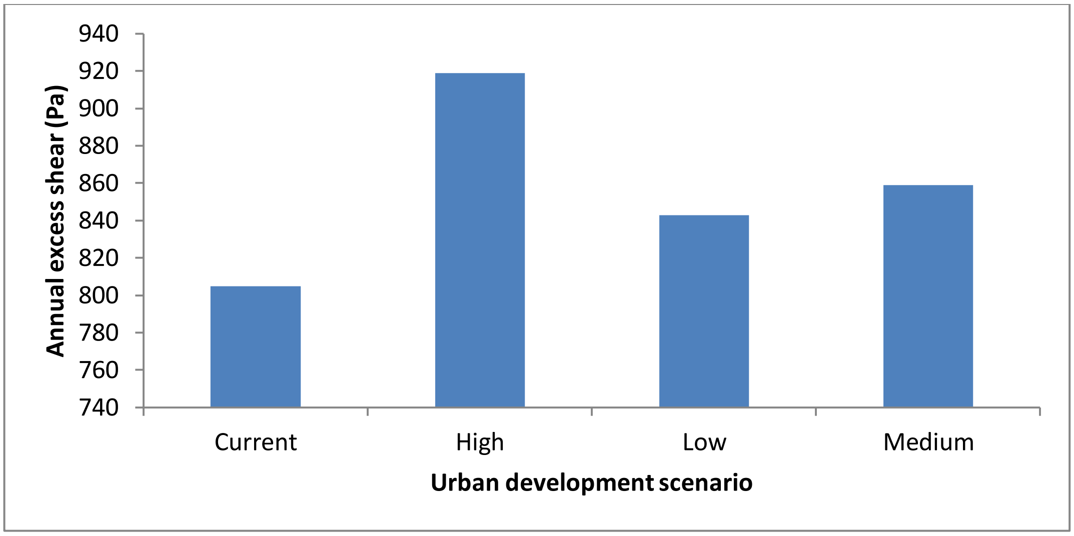


Figure 3-9. Annual excess shear (Pa) for different development densities and median soil particle size equivalent to 20 mm

Clearly, the development scenario that reflects high density with CN equals to 92 for residential areas resulted with the greatest magnitude of excess shear stress. The low density development scenario was 85, which placed it in the second order after the current development scenario, with respect to least excess shear stress,.

Cost Analysis

The total cost and reduction percentages of the studied LIDs are as follows (Table 3-9):

Table 3-9. Total cost of the studied LIDs

LID type	Total Surface area (m^2)	Cost ($)
Bioretention*	61217	3,950,004
Bioretention and Permeable Pavement	96743	8,538,780
Detention pond	2624	213,122.61
Permeable Pavement*	35526	4,588,776

***The cost of Permeable Pavement and Bioretention analyzed here is based on the design accounts for Sedfil modifications**

As we can clearly notice from the previous analysis, detention pond system is the most economic option. Combining bioretention with permeable pavement doubled the cost but the runoff reduction in volumes and peak flows were not increased with the same amount.

Statistical Analysis

Table 3-10. Summary t-Test: Paired Two Sample for Means Current and LID practices

Scenario	Mean	Variance	Observations	Pearson Correlation	Hypothesized Mean Difference	df	t Stat	P(T<=t) one-tail	t Critical one-tail	P(T<=t) two-tail	t Critical two-tail
Current	0.83	0.81	96								
DP	0.62	0.44	96	0.93	0.0	95	5.66	0.0	1.66	0.0	1.985

Table 3-10 Continued

Scenario	Mean	Variance	Observations	Pearson Correlation	Hypothesized Mean Difference	df	t Stat	P(T<=t) one-tail	t Critical one-tail	P(T<=t) two-tail	t Critical two-tail
Current	0.83	0.81	96								
PP+RG(Sedfill)	0.26	0.11	96	0.96	0.0	95	9.56	0.0	1.66	0.0	1.985
RG-Sedfil	0.26	0.13	96	0.98	0.0	95	10.17	0.0	1.66	0.0	1.980
PP-Sedfil	0.44	0.42	96	0.97	0.0	95	12.36	0.0	1.66	0.0	1.985
PP+RG-Sedfil	0.25	0.10	96	0.96	0.0	95	9.56	0.0	1.66	0.0	1.980

The first comparison was between a current scenario and a scenario that accounts for DP only. Since our t-value (t = 5.66) is larger than the tabled t-value (t = 1.66) this means that there is a small chance that the population means are the same, and so with 95% confidence we conclude that the means are different. The second comparison was between a current scenario and a scenario that accounts for PP+RG-Sedfil. Table 3-10. shows that the t-value (t = 9.56) which is larger than the tabled t-value (t = 1.66) this means that there is a small chance that the population means are the same, and so with 95% confidence we conclude that the means are different. RG based on Sedfil modifications were analyzed with respect to current scenario without LIDs. Table 3-10. shows that the t-value (t = 10.17) which is larger than the tabled t-value (t = 1.66) this means that there is a small chance that the population means are the same, and so with

95% confidence we conclude that the means are different. The next analysis was for PP-Sedfil and current scenario without LID practices. Table 3-10. shows that the t-value (t = 12.36) which is larger than the tabled t-value (t = 1.66) and this means that there is a small chance that the population means are the same, and so with 95% confidence we conclude that the means are different.

Finally, the last analysis was between RG and PP based on Sedfil modification with respect to current scenario without LID practices. Table 3-10. shows that the t-value (t = 9.56) which is larger than the tabled t-value (t = 1.66) this means that there is a small chance that the population means are the same, and so with 95% confidence we conclude that the means are different.

Performance Validation of LIDs

Modeling results with respect to LID practices' performance were compared to experimental studies that took place at The Texas AgriLife Research and Extension Center at Dallas and which have the same designs. The results were compared with respect to reduction in runoff volumes.

The permeable parking experiment resulted with average reduction equal to 65% for both grass paver and interlocking concrete paver treatments. It is worth noting that this amount of reduction was reported for four rainfall events and the maximum event was 1.96 in and minimum was 0.67 inches. The bioretention data showed that runoff was reduced by 51% for the same reporting period and same rainfall events (Jaber, 2014). Modelling data showed reduction percentages equal to almost 80% for the raingarden scenario and 57% for the permeable pavement for the 2 year storm equivalent to 3.5

inch. All in all, modelling data and experimental data showed acceptable agreement with respect to total volumes reduction.

Conclusions

Sub-hourly time step SWAT models were developed and integrated with different levels of LID practices to study the potential stream bank erosion in Blackland Prairie ecosystem. LID practices studied are: detention pond, bioretention /raingarden, and permeable pavement. The presented study showed that the sub-hourly SWAT model resulted with reasonable stream flow hydrograph under multiple storm events. The SWAT models were tested and validated before applying the study's scenarios. Calibrated stream flows for a 2-year period using the 15- minute time step had an R^2 of 0.78 and an NS of 0.78. The 2-year validation period had an R^2 of 0.70 and a NS of 0.67.

The bioretention and permeable pavement were represented in SWAT model based on Sedfil modifications. The scenario that combines permeable pavement with raingarden resulted with the greatest reduction in runoff volumes, peak flows, and excess shear stress under both real and design storms. Adding raingarden only resulted with the second greatest reduction and adding detention pond only had the least reduction percentages. Results showed agreement between modeling data and field experiments' findings. Cost analysis was conducted and the scenario which accounts for detention pond only was the most economical solution while combing bioretention and permeable pavements was the least economic. All study scenarios showed significant difference at 95% confidence rate.

CHAPTER IV

LOW IMPACT DEVELOPMENT RESPONSE TO URBANIZATION AND FLOODING SIMULATED BY SUB-HOURLY SWAT MODEL IN THE BLUNN CREEK WATERSHED

Synopsis

The main objective of this study is to understand and quantify the performance of Low Impact Development (LID) practices with respect to potential flooding. The Blunn Creek Watershed located in Austin, Texas has 54 % impervious cover and based on census‘s projection it will reach 65% by 2040. A sub-hourly 15-min time step SWAT model to increase the accuracy of simulations was applied to estimate flows and evaluate flooding in the Blunn Creek Watershed. Bioretention and permeable pavement were represented in the SWAT model by modifying the routine of a current sedimentation filtration design. Field experiment at the Texas AgriLife Research and Extension Center located in Dallas, TX was constructed and monitored for one year to evaluate and validate the performance of the modeled LID practices. The evaluation of flooding was based on percentage of flow exceedance over bank-full flow.

Results showed that combining bioretention and permeable pavement had the greatest reduction in peak discharges for all recurrence intervals (2-year, 10-year, 25-year, and 100-year). Permeable pavement had the least percentage of reductions for all recurrence intervals. All LID practices had 100% reduction in percentage of exceedance for bankfull flows for the 2-year recurrence intervals. The same trend continued to hold and combining bioretention and permeable pavement resulted with the greatest

reductions in percentage of exceedance of bankfull flows. Performance of modeled LID practices was validated by showing acceptable agreement in percentage of reductions in total runoff between field experiments and model data.

Introduction

Urban development contributes to modifying hydrological processes when vegetation cover and soil are cleared from the land surface (Jones and Clark, 1987). The more the imperviousness cover is, the higher the flood frequencies that may result (Moscrip, and Montgomery,1997). The expansion of urban areas results in decreasing infiltration of precipitation, increasing runoff, higher peak discharge, volume, and frequency of floods increase in nearby streams. During urban development, many stream channels alter their geomorphological characteristics which in turn can limit their capacity to convey floodwater. The severity and peak discharge of a flood are influenced by the intensity and duration of a storm, hydrological conditions preceding the storm, vegetation, topography and geology of stream basins (Hollis, 1975).

There has been a considerable research concerning the relationship between stream hydrology and fluvial geomorphology and vegetation cover (Shafroth et al., 1998; Stromberg, 2001). Plants that are established near suitable conditions for germination and sufficient nutrient can survive during flood events and at the same time provide additional support for soil profile protecting it from collapse (Hupp and Osterkamp, 1996; Scott et al., 1996).

Poff and Ward (1989) studied daily flow records for seventy eight USGS stations across the United States for variability and the pattern of the flood regime. They characterized streams into different classes by their hydrologic characteristics and that these could theoretically have an impact on the biological community and flood frequencies. They were unable to quantitatively relate stream biology to hydrology due to the lack of consistent data. Another study by Scoggins (2000) proved that hydrologic parameters proposed by both Poff and Ward (1989) might be used to characterize streams in central Texas and that these parameters might be related to stream biology and flood frequency. Olden and Poff (2003) tested the redundancy in proposed hydrologic indices using the same sites used by Poff and Ward (1989). They concluded that many of the 171 hydrologic indices tested were correlated and redundancy could be reduced by using principal component analyses to reduce collinearity. Moscrip and Montgomery (1997) studied six low-order streams in the Puget Lowlands, Washington, for the period between 1940-1950 and 1980-1990. They utilized USGS station records and each basin was separated into periods prior to and after urban expansion. Results showed that each basin that experienced a significant increase in urbanized area showed increased flood frequency. The pre-urbanization 10-year recurrence interval flows correspond to 1 to 4-year recurrence interval events in post-urbanization records. On the other hand, no apparent shift in flood frequency was observed in either of the control basins that represent a limited change in urbanized area.

Schueler(1992) concluded that urbanization alters stream hydrology and increases stream velocity, flooding magnitude, and flooding frequency. Also, flood duration typically declines as the time from peak to base flow discharge is reduced (Paul and Meyer, 2001). Hirsch el al., (1990) showed that flood duration depends on the degree of urbanization, spatial management and location of impervious cover within the basin.

Low impact development (LID) is a group of practices that was developed to mitigate the negative impact of urbanization that includes increasing impervious cover by utilizing onsite practices to reduce stormwater runoff and enhance outflow water quality. These practices have been recommended as an alternative approach to better mimic the natural flow through using decentralized stormwater controls to reduce runoff at the source. These practices include bioretention, green roofs, rainwater harvesting, and permeable pavements (Davis, 2007, and Bean et al., 2007). Hunt et al., (2008) showed through a study they conducted in North Carolina that the use of Bioretention area resulted in 96.5 % reduction in peak outflow for 16 storms with less than 42 mm of rainfall. They concluded that bioretention can effectively reduce peak flows for small to midsize storm events.

Although the effects of urbanization on watershed hydrology and river-channel morphology have been studied for decades as mentioned above, previous studies focused on a limited number of morphologic variables and ignored the complicating influence of varying LID practices and designs (Paul and Meyer, 2001). There is still a great need to evaluate these practices and there is very little data on the potential impact of the adoption of LID practices at a watershed level. The recent available research evaluates the effectiveness of LID practices on a site scale using; field experiment, modeling or by developing certain algorithm based on designed storms or average rainfall (Elliott and Trowsdale, 2007; Dietz, 2007; Dietz and Clausen, 2008; Graham, 2004). Several efforts contribute to analyze the effectiveness of these practices based on pollutant removal such as nitrogen, phosphorus and total fecal. Other studies focused on the cost effectiveness incentives of LID practices solely. However, there has been little research published on the influence of LID practices on a watershed scale. Bracmort et al. (2006) studied the effectiveness of LID practices on the long run in respect to enhancing water quality. They ran several models using Soil and Water Assessment Tool (SWAT) to determine the long term (20 years) impact of LIDs on water quality for two watersheds. Results showed that LIDs that were in a good condition (regularly maintained) reduced the average annual sediment yield by 16% to 32% and the average annual phosphorus yield by 10% to 24%. On the other hand, LIDs in their current condition reduced sediment yield by 7% to 10% and phosphorus yield by 7% to 17%.

The overall goal of this research study is to evaluate the potential effects of urbanization on stream flood and to address the effectiveness of LID practices at a watershed scale. There is a great need to understand the functionality of LID practices, their ability to adjust the changes in land uses, and return peak flows to pre-development scenario. This study is one of very few studies that took place in the Blackland clay soil in Texas. Blackland clay soil consists of about 12.6 million acres of east-central Texas extending southwesterly from the Red River to Bexar County, which covers mostly the biggest cities in Texas; Austin, Dallas, San Antonio, and Houston (Texas Almanac, 2013).

Methodology

Model Setup

Soil Water and Assessment Tool (SWAT) is a continuous and spatially distributed model designed to predict the impact of land management practices on water, sediment and agricultural chemical yields over long periods of time (Neitsch et al., 2002). This study utilized the SWAT 2012.10.4 version to run sub-hourly time step models. Traditionally, the model operated at a daily time step and it estimated the influence of landuse and management practices on water, agricultural chemical yields in a watershed. The daily time step format provided by SWAT may not be sufficient to capture the impact of flashy storms where peak flows last for minutes only and are not reflected in daily average flows. It might also miss important processes such as the first flush of urban runoff. A sub-hourly model for urban applications was developed by Jeong and Srinivassan (Jeong et al., 2010) but is currently not widely used.

The Blunn Creek Watershed was first subdivided into subbasins based on Digital Elevation Model (DEM) and channel network, and later parameterized by a series of smaller modeling units, known as hydrologic response units (HRUs) according to topography, types of land use and soil.

There are two methods to calculate surface runoff using SWAT based on a time step of the model. Daily time step model estimates surface runoff by the SCS curve number CN method (SCS 1972) (Equation 4.1).

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad \text{(Equation 4.1)}$$

where

Q is runoff (in)

P is rainfall (in)

S is the potential maximum soil moisture retention after runoff begins (in)

I_a is the initial abstraction (in)

The sub-daily time step model uses the Green and Ampt Mein Larson (GAML) excess rainfall method (Mein and Larson 1973).

$$f(t) = Ke\left(1 + \frac{\Psi \Delta\theta}{F(t)}\right) \qquad \text{(Equation 4.2)}$$

where: f(t) is the infiltration rate at time t (hr)

Ke is the effective hydraulic conductivity (cm/hr)

Ψ is the wetting front matric potential (cm)

Δθ is the change in moisture content,

F(t)is the cumulative infiltration at time t (cm)

The underground water storage can be estimated in different ways in SWAT based on travelling distance; shallow aquifer and deep aquifer. In this study, surface runoff was predicted based on GAML method since sub-hourly time step model is used. The Muskingum method was used for channel flow routing, and the Penman-Monteith method was selected to calculate potential evapotranspiration. The watershed was delineated into 14 subbasins and total stream flow volumes of runoff were evaluated at the outlet of the watershed (Figure 4-1).

Data Acquisition

The following types of data were required to run a sub-hourly time step SWAT model; DEM layer, soil types and properties data, land use and land cover map and observed data for calibration and validation purposes.

Models ran using 15 min rainfall data that were retrieved from a local weather station at the City of Austin. Daily temperature data from the Austin and Austin-Bergstrom NOAA weather stations were used, weather zone from (WGEN_US_COOP_1960_2010). The DEM for the watershed was 3m integer which was developed by COA based on 2003 LIDAR data. Land cover map was acquired from COA and reclassified into five categories including residential, commercial, industrial, utilities and roads, and open space (Figure 4-1).Soil properties including; texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each layer were obtained from the Soil Survey Geographic database (SSURGO) that is distributed by the Natural Resources Conservation Service (NRCS). The HRU thresholds were defined by setting a percentage of 5% for the followings; Land use percentage over subbasin area, soil class percentage over land use area, and slop class percentage over soil area. The following types of landuse were within the Land use threshold exemptions and they did not receive any supplemental water by irrigation; parks and recreation, golf course, campgrounds, open space, and undeveloped areas.

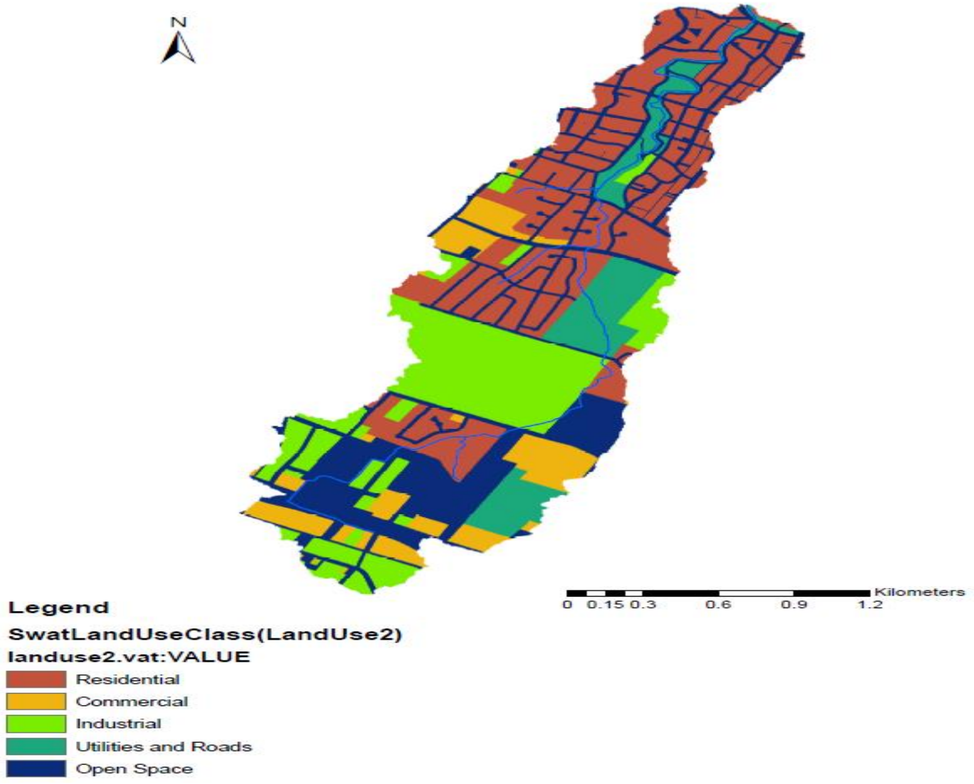


Figure 4-1. Land use map for Blunn Creek Watershed (current scenario)

Model Calibration and Validation

Hydrological data of 1998-1999 and 2001-2002 were obtained from USGS website for station number 08157700 and used to calibrate and validate model parameters. An automatic calibration program interfaced with SWAT called SWAT-

CUP was used to calibrate this study's models. This program is designed to integrate various calibration/uncertainty analysis programs such as multi-site semi-automated inverse modeling routine SUFI2 (Abbaspour et al., 2007) which was used in this study. The global sensitivity analysis procedure embedded in SWAT model through One-factor-At-a-Time (LH-OAT) (Griensven and Meixner,2006) was applied and eight most sensitive parameters of the SWAT model were identified including ALPHA_BF (Base flow alpha factor), GW_DELAY (Groundwater delay), GWQMN (Threshold depth of water in the shallow aquifer required for return flow to occur), CH_N2 (Manning roughness for main channel), CH_K2 (Effective hydraulic conductivity), SOL_AWC (Available water capacity of the soil layer), ESCO (soil evaporation compensation factor, and CH_K1 (Saturated hydraulic conductivity).The performance of each simulation was assessed by the Nash–Sutcliffe coefficient of efficiency, NS (Nash and Sutcliffe, 1970), computed as follows:

$$NS = 1 - \frac{\sum(Qo - Qm)^2}{\sum(Qo - \overline{Qo})^2} \qquad \text{(Equation 4.3)}$$

Where: Q_o : observed discharge

Q_m : modeled discharge

$\overline{Qo}$: average observed discharge

When computing the NS value, the first two years of simulation were always skipped, to avoid the influence of the initial conditions such as soil water content and eventually runoff estimates.

LID Representation in SWAT

Field experiments of two LID practices (bioretention area, and permeable pavement) were constructed at the Texas AgriLife Research and Extension Center located in Dallas, TX. Practices were installed and evaluated for one year with respect to reducing total runoff volumes. The integration of LID practices into SWAT model was based on these field experiments and to reflect real scenarios so that the performance of the modeled practices can be validated later as well.

A parking lot was designed to include two different types of pavements and a control. Three parking stalls of each type, forming one monitoring unit, are connected to an automatic sampler that collects runoff from all stalls. Each parking stall is 18ft x10ft. The three treatments are grass pavers, permeable interlocking concrete pavers, and impervious concrete (control). Runoff quantity is measured, and storage estimated. Rainfall is measured from a weather station (Campbell Scientific) on the property. A perforated drain runs the length of the stalls in the parking median.

A bioretention area was also constructed and curbs were cut to allow for runoff to drain to a forebay, which is a hundred square feet in area and about 1 foot deep on average for automatic sampling (ISCO 3700) and flow measurement (flume). Runoff was directed into the bioretention area (100ft x 20 ft). All runoff in the rain garden watershed was routed through the inlet flume. A surface overflow box drains water to an underground pipe to the first inlet of the detention pond. Moreover, the drainage layer of the rain garden had house a perforated pipe that assists in soil infiltration. An ISCO flow meter was used to measure the overflow and perforated pipe flow and samples were collected with an ISCO 3700 automatic sampler.

It should be noted at this point that the current SWAT version SWAT2012 does not include bioretention or permeable pavement. One of the objectives of this study was to develop a methodology to account for these practices into SWAT model.

The partial scale design was used in this study to simulate bioretention and permeable pavement. Two parameters were considered in adjusting the sedimentation filtration design; water ponding and depth of filtration media. A typical standard of a bioretention and a permeable pavement surface area that is 3 to 10 % of the total catchment area was followed (Jaber et al .2012). Initial run was executed with an automatic sizing function in order to size the pipes required to release runoff inside and outside the system. In order to minimize the function of the sedimentation basin and concentrate on a filtration basin only which represent the bioretention and permeable pavement, the following steps were followed: the surface area of the sedimentation area was selected to represent a forebay area that might be installed before a bioretention area and in case of the permeable pavement that was totally ignored by selecting a minimum number that the system would allow in order to minimize this effect, the outlet orifice pipe was selected to be bigger than the one for the filtration in order to divert most of the runoff to the filtration basin where it will be treated there, the depth of the filtration media for the bioretention was selected to be 1200 mm and maximum ponding depth of the water to be

420 mm, the depth of the filtration media for the permeable pavement was 356 mm and maximum ponding depth of the water was 10 mm (Figure 7). It is worth noting that ponding and filtration depths for both bioretention and permeable pavement were selected to represent field experiments for similar LID practices studied at the Texas AgriLife Research and Extension Center located in Dallas, TX. The field experiment of LID practices at the center were utilized later to judge the performance of modeled LIDs in SWAT.

A bioretention area was installed in each subbasin and permeable pavements were considered to represent 27% of the total watershed. This representation for the permeable pavement was based on typical average parking lots in Dallas, TX downtown that has the same watershed area of Blunn Creek Watershed (City of Dallas, 2011).
A hypothetical detention pond was designed according to the City of Austin standards. Pond sizes were calculated as follows; a raster surface was converted to contour lines with 1 foot (0.3 m) contour interval. The second step was to place a 12 m line segment at the end of subbasin 10 to represent the width of the detention pond across the creek. This width was based on the current geometry of the channel and could not be wider than a channel due to current development and residential areas adjacent to the channel. Following the contour line, an area of 3608 m^2 was delineated which is the extended lines from the two ends of the 12 m segment line. The average operation depth along the pond is 3 m which was calculated directly from the geometry of the channel. A stepped weir was used and the height of it was based on the required storage volumes for the following design storms: (2 year, 25 year, and 100 year).

Flood Impacts

The first task associated with evaluating flooding in the Blunn Creek Watershed was to calculate the geometry of the channels for each subbasin. A cross section analysis was conducted using HEC-RAS 4.1.0. FEMA floodplain map for the Blunn Creek Watershed was obtained from City of Austin and imported into HEC-RAS for cross section analysis. Multi river stations with cross section for each were developed by the software and exported for analysis. Total area of each channel was calculated directly in the cross section view of HEC-RAS for several design storms (Figure 4-2).

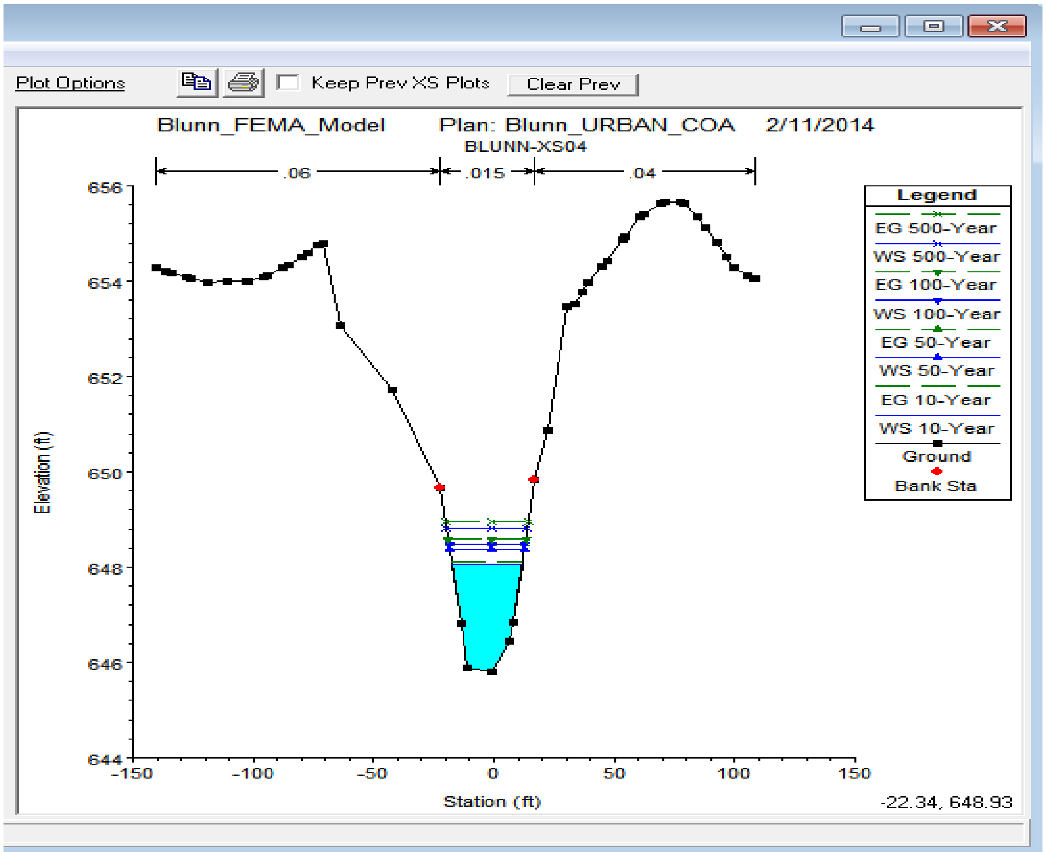
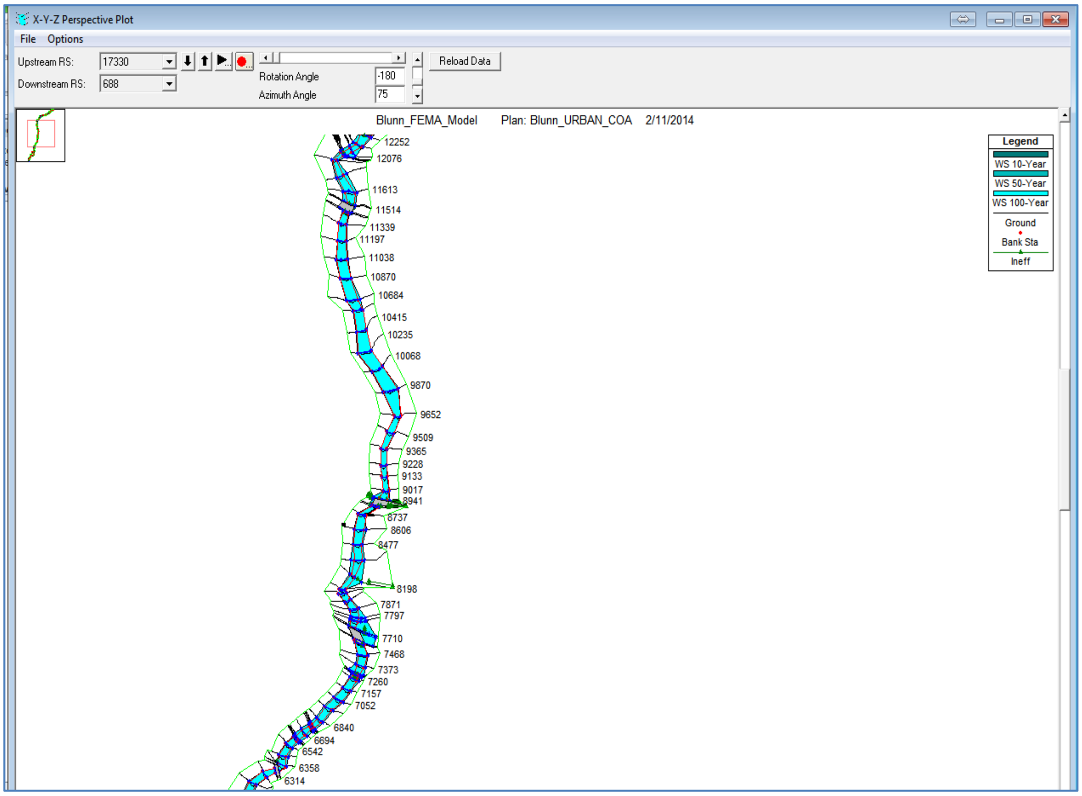


Figure 4-2. Cross section analysis of Blunn Creek Watershed using HEC-RAS software

Stage discharge analysis helped in determining areas that have narrow geometry and higher potential of flooding (Figure 4-5). The next task was to determine bankfull discharges for each subbasin. It is worth noting that most Blunn Creek channels are incised and do not represent the natural stream channels. Therefore, evaluating flooding based on exceedance of flows to floodplain is not feasible due to the fact that even the 100-year storm would not over flow channel geometry (Figure 4-3).



Upstream RS: 17330

Downstream RS: 688

Rotation Angle: -180

Azimuth Angle: 75

Blunn_FEMA_Model Plan: Blunn_URBAN_COA 2/11/2014

Figure 4-3. Stage discharge analysis for Blunn Creek using HEC-RAS software

The general rule of thumb regarding bankfull discharges for natural channels is the peak for the 1.1-1.5-year storm (Cinotto, 2003 and Craynon, 2013). For the purpose of this study and since Blunn Creek Watershed is considered highly urbanized, a 1.5-year storm was selected to represent bankfull discharges for each subbasin. Design storms for the following recurrence intervals (1.5-year, 2-year, 10-year, 25-year, and 100-year) were modeled for the SCS 24 hour rainfall distribution for type III region (Travis county) (Asquith and Roussel, 2004).

The evaluation subbasins differed in physical and geological characteristics such as slope, soil type, and channel dimensions. These characteristics are listed in (Table 4-1), showing drainage area, hydraulic radius, slope and bankfull flow rate values at each subbasin. SWAT was run using 15-min time step precipitation for different design storms and flooding was evaluated based on the frequency of flow exceedance over bankfull flow rates and reduction in peak flows.

Table 4-1. Hydrological characteristics of Blunn Creek Watershed

Subbasin	Channel Manning (n)	Channel Slope	Hydraulic Radius (m)	Drainage area (Sq.KM)	Bankfull flow (m^3/s)
1	0.055	0.018	3.37	3.51	3.09
2	0.055	0.020	4.60	3.35	3.06
3	0.055	0.010	1.92	3.25	3.04
4	0.055	0.018	1.58	3.22	3.04
5	0.055	0.012	1.20	3.18	3.03
6	0.055	0.045	1.46	2.74	0.76
7	0.055	0.011	1.64	0.0053	2.55
8	0.050	0.013	1.76	2.53	2.57
9	0.080	0.025	1.56	2.32	1.69
10	0.080	0.014	1.53	1.88	1.84

Table 4-1 Continued

Subbasin	Channel Manning (n)	Channel Slope	Hydraulic Radius (m)	Drainage area (Sq.KM)	Bankfull flow (m^3/s)
11	0.060	0.032	0.93	0.01	1.71
12	0.055	0.010	0.72	1.74	1.72
13	0.055	0.023	0.52	1.05	0.46
14	0.010	0.012	0.27	0.80	0.99

Results and Discussion

A Sub-hourly time step model was developed through SWAT 2012 and used to evaluate potential flooding for different recurrence intervals (2-year, 10-year, 25-year, and 100-year) for each subbasin in the Blunn Creek Watershed. Table 4-2. below shows the equivalent inches of rain for each recurrence interval.

Table 4-2. Recurrence intervals and equivalent rainfall amounts

Recurrence interval (year)	Rainfall (inches)
2	3.5
10	6.1
24	7.6
100	10

The model was calibrated for a 2 year period with 15- min and (R^2= 0.78) and (NS =0.78). P-value and R^2 were analyzed on a sub-hourly basis correspondingly for SUFI-2 uncertainty technique for the best-fit model. Validation procedures for the period between 2001 and 2002 were conducted to ensure the validity of the calibration process. NS value for validation was 0.67 and R^2 value equals to 0.70 for the sub-hourly time step model. All in all, the comparison between observed and simulated stream flow showed that there is a good agreement between the observed and simulated discharge which was verified by higher values of R^2 and NS.

The impact of LID practices was evaluated for the following scenarios; installing Detention Pond (DP) only, bioretention/raingarden (RG) only, Permeable Pavement (PP) and a combination of PP and RG. Peak flows reduction percentages were calculated by comparing flows leaving out each subbasin with LID practices to a scenario where no LID practices were considered (control). Adding RG only contributed to reduce on average peak discharges for all subbasin by 73%, 20%, 24%,13% for the following recurrence intervals, 2-year, 10 –year, 25-year, and 100-year respectively (Figure 4-4) .

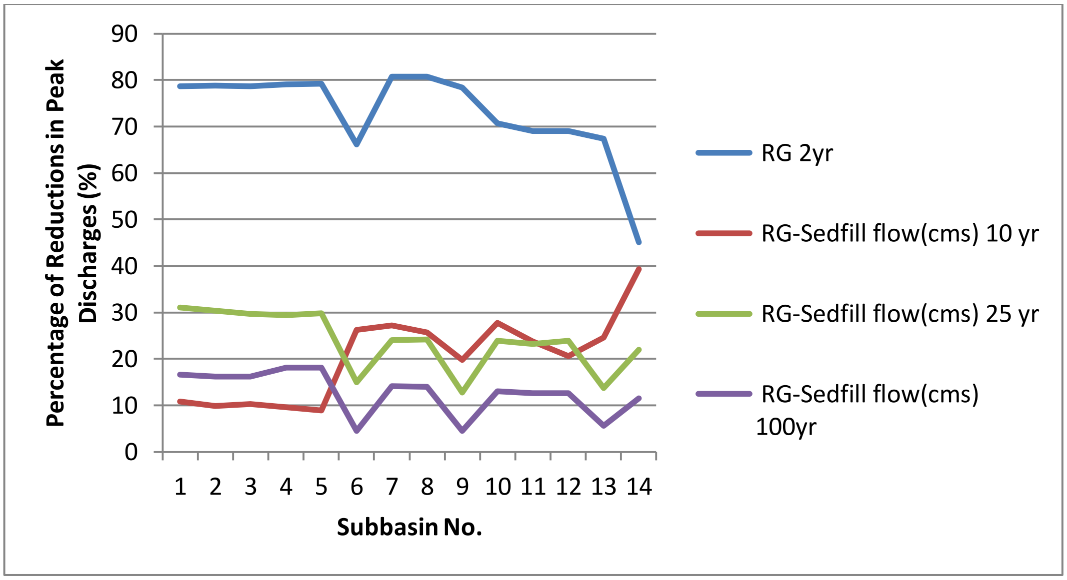


Figure 4-4. Peak discharges reduction (%) by adding RG only for different design storms

While combining RG and PP resulted with average reduction in peak discharges for all subbasins by 77%, 37%,24%, 19% for the following recurrence intervals, 2-year, 10 –year, 25-year, and 100-year respectively (Figure 4-5).

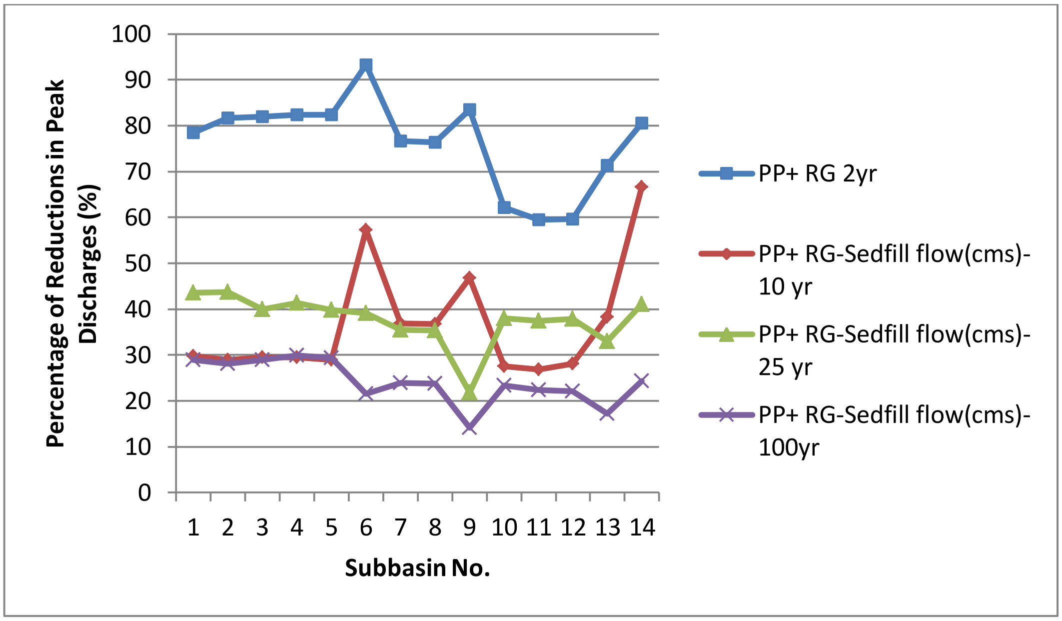


Figure 4-5. Peak discharges reduction (%) by adding RG and PP for different design storms

A detention pond was also evaluated in reducing peak discharges for all subbasins in the watershed and reduction percentages resulted are: 19%, 16%, 20%, and 18% for 2-year, 10 –year, 25-year, and 100-year recurrence intervals respectively (Figure 4-6). Clearly, the impact of DP installation was very obvious in subbasin 10 where it was installed and in the subbasins that followed.

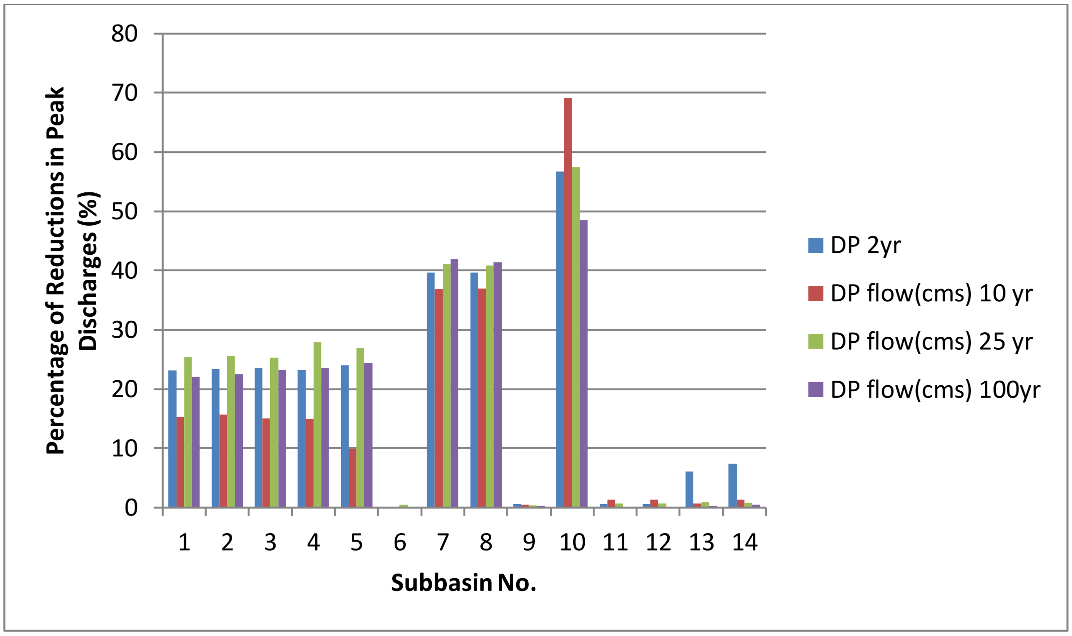


Figure 4-6. Peak discharges reduction (%) by adding RG and PP for different design storms

Adding PP also contributed to reduce peak discharges by 40%, 15%, 13%, and 11% for the following recurrence intervals, 2-year, 10 –year, 25-year, and 100-year respectively (Figure 4-7).

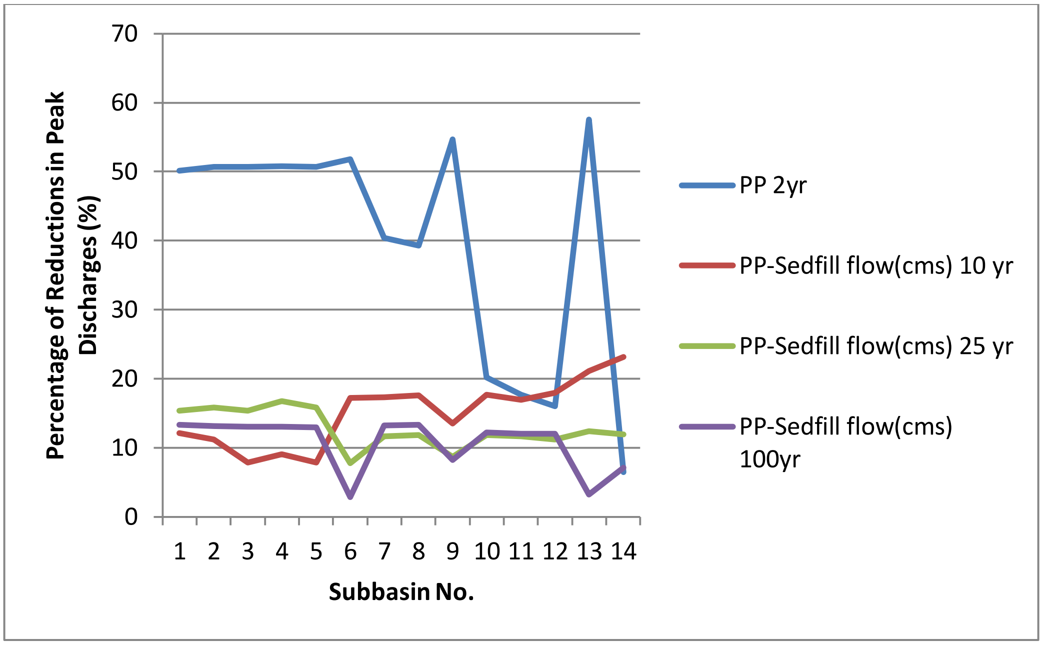


Figure 4-7. Peak discharges reduction (%) by adding PP only for different design storms

The next level of evaluation of LID practices in reducing potential flooding for different recurrence intervals was based on exceedance of bankfull discharges. The exceedance percentage for the current scenario was calculated and compared other scenarios where LID practices were included (Table 4-3)

Table 4-3. Eceedance percentages of the current scenarios without LIDs

Subbasin	**Current scenario exceedance rates (%)**			
	2-year	10-year	25-year	100-year
1	1.90	45.02	64.69	78.69
2	1.92	43.96	64.25	78.45
3	1.94	44.32	64.11	78.59
4	1.62	43.91	64.24	78.89
5	1.62	43.47	63.93	78.81
6	0.00	47.59	60.82	73.61
7	1.92	57.50	71.70	82.04
8	1.91	57.38	71.60	82.03
9	1.17	59.28	70.04	79.90
10	2.13	61.34	76.65	85.85
11	2.29	62.33	77.71	86.54
12	1.71	62.77	77.43	86.46
13	20.73	67.68	78.94	86.38
14	8.90	66.68	78.87	86.80

The effectiveness of LIDs' placement with respect to reduction in exceedance of bankfull discharges was studied for each subbasin and for different recurrence intervals. For almost all scenarios and for all subbasins, exceedance percentages dropped for zero percent when including any of the studied LIDs. Though, PP had almost 100% reduction in percentage of exceedance of bankfull discharges for the 2-year storm it had the least reductions percentages for the other recurrence intervals

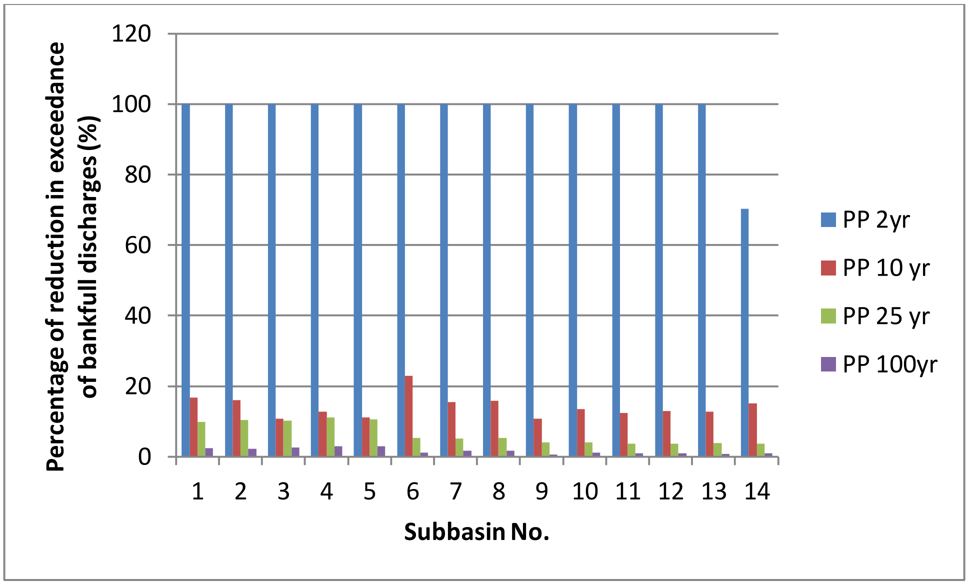


Figure 4-8. Percentage of exceedance reduction (%) of bankfull discharge by adding PP only for different design storms and for all subbasins

Adding RG only for each subbasin in the Blunn Creek Watershed contributed to reduce average percentage of exceedance of bankfull discharges by 100%, 20%, 14%, and 3% for the following recurrence intervals, 2-year, 10-year, 25-year, and 100-year respectively.

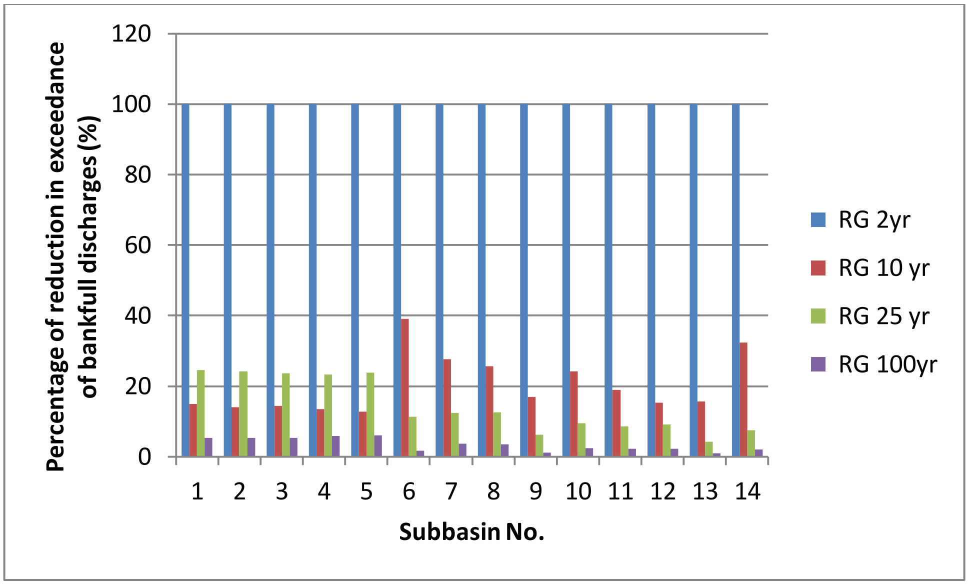


Figure 4-9. Percentage of exceedance reduction (%) of bankfull discharge by adding RG only for different design storms and for all subbasins

The DP was placed at subbasin number 10 and it contributed to reduce percentage of exccedance of bankfull discharges by 80%, 21%, 14%, and 6% for the following recurrence intervals, 2-year, 10-year, 25-year, and 100-year respectively (Figure 4-10).

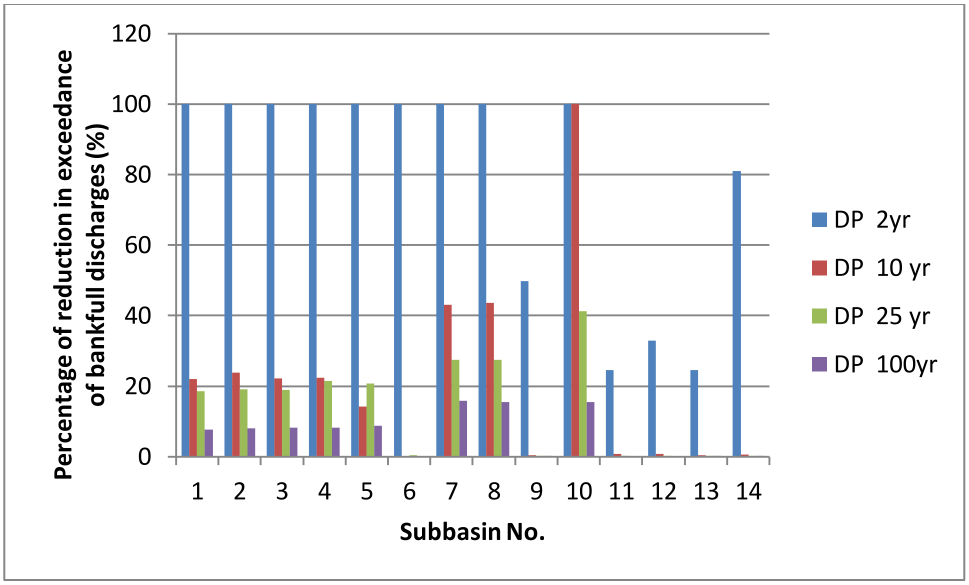


Figure 4-10. Percentage of exceedance reduction (%) of bankfull discharge by adding DP only for different design storms and for all subbasins

Combining PP and RG resulted with the greatest reduction in exceedance percentages for all design storms and subbasins among the other scenarios. On average, the percentage of reduction for the 2-year storm was 100%, 10-year storm was 51%, 25-year storm was 27%, and 8% for the 100-year storm (Figure 4-11).

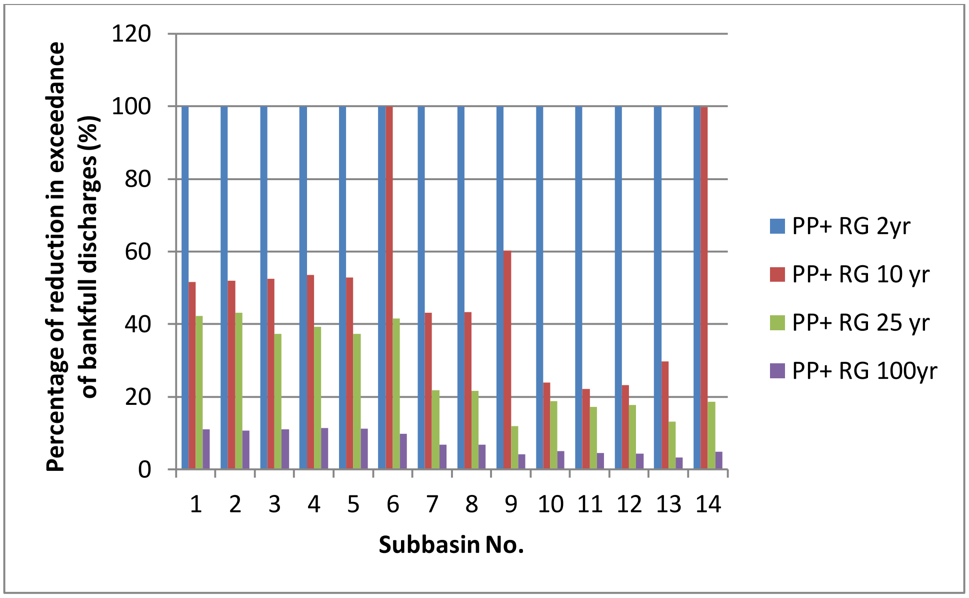


Figure 4-11. Percentage of exceedance reduction (%) of bankfull discharge by combining PP and RG for different design storms and for all subbasins

Performance Validation

The performance of studied LID practices was evaluated with respect to field experiment for same type of LIDs which were constructed at the Texas AgriLife Research and Extension Center located in Dallas, TX and monitored for one year. The evaluation was based on runoff volume reductions (Table 4-4).

Table 4-4. Comparison of LID performance between field experiment and model data

Type of LID	Reduction % for experiment	Average Rainfall (in)	Reduction % for model	Average Rainfall (in)
Bioretention	51	0.96	80	3.5
Permeable Pavement	65	0.96	57	3.5
Detention Pond	100	0.96	47	3.5

As Table 4-4 shown, model data showed acceptable ranges of reduction with field experiment results except for the detention pond where the performance for the field experiment was two times the model. This can be justified on the unique design of the detention pond places in the field. It was designed to retain 1.5 inches of runoff and the pond was designed to resemble a meandering river with two inflow points, planted with associated vegetation to reduce erosion as well as act as filter strips, to serve as a demonstration tool for stream restoration. All these features contribute to enhance the performance of the detention pond and increase percentage of reductions.

Conclusions

A sub-hourly 15-min time step SWAT model to increase the accuracy of simulations was applied to estimate flows and evaluate flooding in the Blunn Creek Watershed. Bioretention , permeable pavement, and detention pond were the LID practices applied in this study. The current version of SWAT does not incorporate bioretention of permeable pavement in the pond file. These two practices were represented by modifying the routine of a sedimentation filtration design. Field experiment at the Texas AgriLife Research and Extension Center located in Dallas, TX was constructed and monitored for one year to evaluate and validate the performance of the modeled LID practices. The evaluation of flooding was based on percentage of flow exceedance over bank-full flow. Results showed that combining bioretention and permeable pavement had the greatest reduction in peak discharges for all recurrence intervals (2-year, 10-year, 25-year, and 100-year). Permeable pavement had the least percentage of reductions for all recurrence intervals. All LID practices had 100% reduction in percentage of exceedance for bankfull flows for the 2-year recurrence intervals. The same trend continued to hold and combining bioretention and permeable pavement resulted with the greatest reductions in percentage of exceedance of bankfull flows. Performance of modeled LID practices was validated by showing acceptable agreement in percentage of reductions in total runoff between field experiments and model data.

CHAPTER V

EFFECT OF URBANIZATION ON AQUATIC-SYSTEM DEGRADATION

Synopsis

Urban stormwater runoff is a leading factor for impairing surface water quality and quantity, public health, biological resources and aquatic life. Sub-hourly time step SWAT (Soil Water Assessment Tool) model was calibrated and validated to evaluate the potential impact of Low Impact Development (LID) practices on aquatic life in the Blunn Creek Watershed. This watershed encompasses 3.73 square kilometers and has 54 % impervious cover and based on census projection it will reach 65% by 2040. The evaluation of LID practices performance was based on incorporating and representing these practices into SWAT model, studying output flows, and assessing watershed hydrological responses and their impact on aquatic life communities in the Blunn Creek. Reducing peak flows and increasing both baseflows and Aquatic Life Potential values were the factors used to assess flows coming out of LID practices. Stream flows using 15-min time step were successfully calibrated and validated for a 2-year period. During the calibration period; Nash-Sutcliffe (NS) value and R^2 were 0.78 for sub-hourly and during validation; R^2 was 0.70 and a NS was 0.67.

Results showed that a combination of permeable pavement and raingarden resulted with the highest percentage of increase in AQP values and baseflows and greatest reduction in peak flows. Detention pond had the lowest percentage of increase in AQP and baseflows as well as the lowest percentage of reduction in peak flows.

Introduction

On an annual basis there is an addition of 78 million people to the current world population of 6 billion (United Nations, 2000), therefore impacts of urbanization on water resources and environment is expected to increase. The role of urban development in soil and water conservation is crucial for developing comprehensive water resources practices. Detailed information and field data on a watershed scale and their linkages to downstream effects are required in order to develop alternative practices and technology that aim to mitigate the negative impact of urbanization on water resources. Low impact Development (LID) practices were developed to negate the negative impacts of urbanization on water resources by reducing runoff volume and peak flows as well as improving outflow water quality (Villarreal et al. 2004). LID practices include the installation of any of the following structural measures, to retrofit existing infrastructure and reduce runoff volumes and peak flows; bioretention, green roofs, rainwater harvesting, and permeable pavements (Damodaram, 2010). LID practices can be costly and form a burden on municipalities and states (Sample et al. 2002). Therefore, understanding the impact of installing LIDs on a watershed scale is an important step toward a healthier environment.

Aquatic life and aquatic biological indexes such as biotic integrity indexes are commonly used approaches for studying the impact of urbanization on a watershed scale (Karr, 1981; Karen’s and Karr, 1994; Horner et al., 1999). For instance, biological assessment accounts for an integrated investigation of functional and structural components of aquatic communities (McCarron et al., 1997).

Stream ecosystems are the most fragile, degraded, and threatened ecosystems because of the strong interactions between aquatic and terrestrial environments and human disturbances that can affect either system (Nature Conservancy, 1996). Changes in demographic characteristics and land use due to urbanization have brought about profound changes in the physical, chemical, and biological integrity of streams (Hollis, 1975). Both physical and chemical factors associated with urbanization, such as high peak flows and low water quality further stress aquatic life and contribute to overall biological condition of urban streams (Maxted et al., 1995). Variation in flow over a day and a season will affect aquatic life (May, 1997). Low base flows during summer and dry periods can cause fish mortalities due to reduced velocity, cross-sectional area, and water depth (Williamson et al., 1993). Also, high flows can wash salmonid eggs from reeds (Vronskii and Leman, 1991). While high flows can be essential to help in the migration of all fish when water velocity exceeds theirs swimming speed, juveniles are more vulnerable to high flows (Chilibeck et al., 1993). Moreover, high water velocity due to urbanization can be extremely harmful to the stream environment if there is a lack of boulders and large woody debris, which provide eddies where fish can rest and have shelter. Rood and Hamilton (1994) found out that Salmon habitat had a significant degradation level over the past one hundred years due to altering flow regimes and removal of riparian vegetation. Klein (1979) concluded that when watershed imperviousness exceeded 10 % a rapid decline in biotic diversity might result. Sovern and Washington (1997) concluded that urbanization causes an increase in sediment load due to stream enlargement through bed and bank erosion. These additional volumes of sediment loads contribute to clogging and degrading Salmonid spawning gravel quality by reducing the gravel porosity, hence hindering the resupply of dissolved oxygen to fish eggs. Reed (1978) conducted a study in the state of Pennsylvania where he looked at the effectiveness of sediment-control techniques during highway construction in respect to aquatic life. Results showed that suspended sediments coming from construction activities can harmfully affect aquatic life by habitat elimination under heavy loading or by interference with feeding under lighter stress. Whipple et al. (1981) concluded in their study that the decrease in low flow discharges eliminates the available stream habitat, increases the probability that the stream may go dry, may increase temperature fluctuations and increases the concentration of pollutants due to lack of dilution which in its turn negatively reflects on aquatic life health. DeGaspari et al. (2009) utilized hydrologic modeling to emulate hydrologic metrics for different development scenarios. The aim of the study was to determine which combination of LID practices best met management plans with respect to aquatic life. Though this was found to be a suitable method, hydrologic metrics which can be reliably predicted by the model should be selected over other metrics that cannot be predicted well.

The Watershed Protection Department at City of Austin has developed a process to identify watersheds with declining environmental health based on the Environmental Integrity Index (EII) scores (COA 2007). Glick et al., (2011) have developed a statistical relationship between aquatic life data and three flow metrics- that are part of the EII developed by COA-, fraction of time the creek is dry, single pass baseflow ratio and the natural log of the 90th percentile flow. The resulting model had an adjusted $R^2 = 0.702$

and had been tested for estimating aquatic life potential for several watersheds in the Austin area (Glick and Gosselink, 2009). It is worth noting that the developed model was tested for several scenarios by varying development densities and impervious cover. The contribution of LID practices was not studied as potential practices in enchasing potential aquatic life communities in urban streams.

While, all previous literature studied the influence of urbanization, landuse, variability of flow, and suspended solids due to bed and bank erosion on aquatic life, there is a great need for modeling the effect of LID practices at a watershed scale on aquatic life. Most of the available research considered metrics that were poorly suited to characterize the magnitude of hydrological changes and their impact on biological stream health. Modeling the impact of change in hydrology due to urbanization on aquatic life is becoming very important. This study is trying to bridge this gap by using a comprehensive approach with different variables and scenarios to this issue through modelling and assessment a design of LID practices to mitigate urban impacts on water resources.

The main goal of this paper is to study the relationship between urban development and aquatic life degradation at a watershed scale in order to identify the nature of impacts at numerous stages of land development and to develop a combination of LID practices to mitigate these impacts. Specific objectives are (1) to assess the nature and potential impact of urban development on aquatic life, (2) to quantify the relationship between LID practices and total water runoff at a watershed scale, and (3) to evaluate different levels of LID practices to mitigate the negative effects of urbanization.

Methodology

For the purpose of this study, the GIS version of the SWAT model was used (ArcSWAT 2012.10.0.12). This study accounted for two parts: model calibration/validation, and LID development with respect to aquatic life in urban streams (Figure 5-1). First, sub-hourly flow was calibrated and validated at 08157700 USGS station for the period 1998 - 1999 and 2001-2002. Second, several levels of LID practices were developed and applied including detention only, bioretention only, permeable pavement, and a combination of bioretention and permeable pavement. These LID practices were selected based on their ease of adoption by developers, their potential effectiveness, and the viability of associated processes in the SWAT model. The detention pond was placed in the middle of the watershed on the stream network. A bioretention was placed arbitrary as one in each subbasin. The permeable pavement was placed to represent 27% of the watershed. This ratio was derived from an average parking lot in the Dallas downtown area which has the same total watershed area of the Blunn Creek Watershed. The various scenarios were run using the same calibration parameters and weather as the base model. SWAT provides built in detention pond but not bioretention or pavement area. For this study, the partial scale design of the Sedimentation Filtration (Sedfil) provided by SWAT was used to simulate bioretention and permeable pavement. Two parameters were considered in adjusting the Sedfil design; water ponding and depth of filtration media. Initial run proceeded with an automatic sizing function in order to size the pipes required to release runoff inside and outside the system in order to minimize the role of the sedimentation basin and concentrate only on a filtration basin that best simulates the bioretention and permeable pavement, the following steps were followed: the surface area of the sedimentation area was selected to represent a forebay area that might be installed before a bioretention area and in case of the permeable pavement that was totally ignored by selecting a minimum number that the system would allow in order to minimize this effect, the outlet orifice pipe was selected to be bigger than the one for the filtration in order to divert most of the runoff to the filtration basin where it will be treated there, the depth of the filtration media for the bioretention was selected to be 1200 mm and maximum ponding depth of the water to be 420 mm, the depth of the filtration media for the permeable pavement was 356 mm and maximum ponding depth of the water was 10 mm.

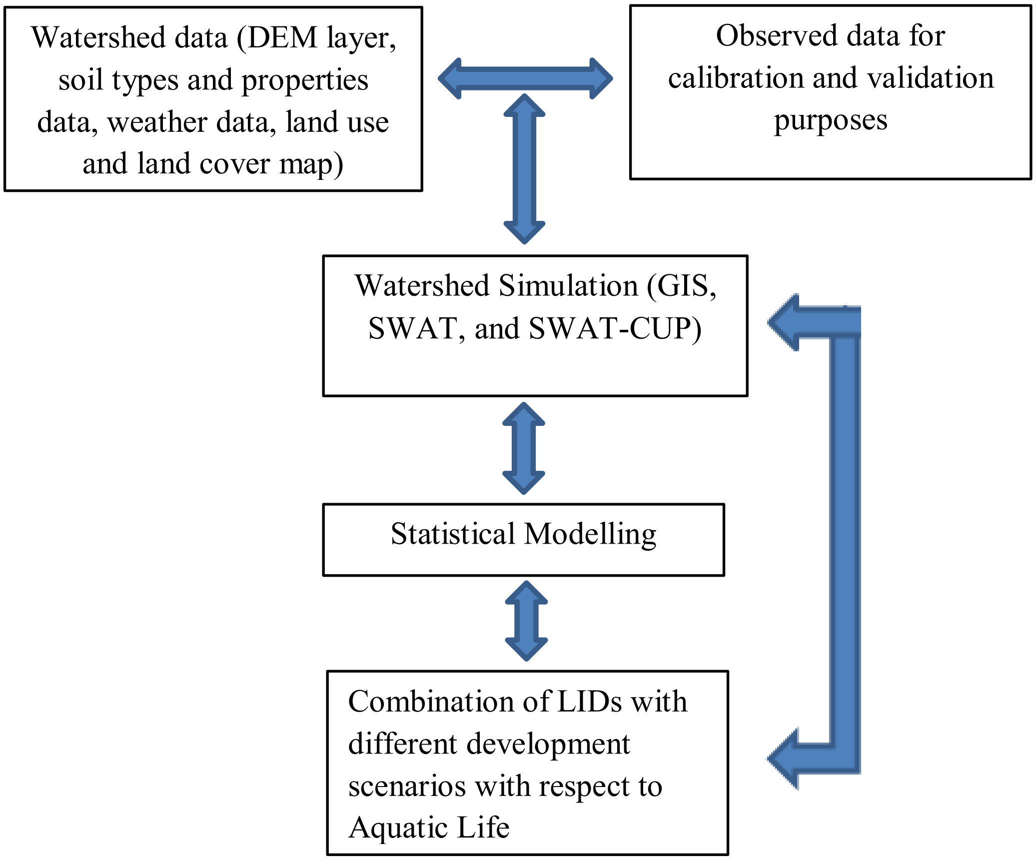


Figure 5-1. Logical model of the study

Input Data

The Soil and Water Assessment Tool (SWAT) was used to simulate stream flows in the studied watershed. SWAT is a continues time step model designed to predict the impacts of management practices on water quantity and quality in large complex watersheds and yields of agricultural chemicals over long periods of time (Neitsch et al., 2002). The model runs in a semi-distributive manner so it accounts for spatial differences in topography and land use, weather conditions, soil, crops, and channel morphology. SWAT works on dividing a basin into several subbasins and within the subbasin, further subdivisions can be done to account for variances in land use, weather and soil. The main components of the model are: transmission losses, groundwater flow, reach routing, weather, surface runoff, percolation, return flow, reservoir storage and evapotranspiration.

The main input files for SWAT consist of GIS data supplied by the City of Austin (weather data, Digital Elevation Model layer (DEM), and landuse). Nevertheless, stream flow data were downloaded from the U.S. Geological Survey (USGS) websites, and soils data from the National Resources Conservation Service.

The model was calibrated and validated using observed flows that were available at station 08157700 and retrieved from USGS website for the period between 1998 and 1999 for calibration purposes and for the period between 2001 and 2002 to ensure the validity of the selected uncertainty parameters through the calibration process.

Potential Aquatic Life Evaluation

Stream discharge flows would affect aquatic life development. If a stream experiences a low amount of flows or is in a state of drought that will negatively impact the effect of pollutants on aquatic life. Dilution is a main mechanism to reduce the concentration of pollutants and their impact on aquatic life. Therefore, this study will focus on two main factors that have a potential to impact aquatic life; flow variability and drought.

COA collects water quality and aquatic health data as a part of Environmental Integrity Index (EII) (COAb 2013). Flow output from SWAT model along with a statistical model developed by Glick et al, (2011) that analyzed the relationship between hydrological measures and aquatic life were used in assessing the impact of LID practices on potential aquatic life communities in the Blunn Creek Watershed. Glick et al., (2011) have developed a statistical relationship between flow metrics that are part of the EII developed by the COA to quantify future aquatic life potential score. The developed model was expressed as follows:

$$AQP = 87.7539 - 1.5961 \text{ x } (Qpeak/area) + 4.3842 \text{ x } \mathrm{Ln}\,(Q90) - 21.2655 \text{ x } (Avg\_Rise)$$

Where, AQP : Aquatic life potential

Qpeak/area : peak flow rates ($m^3/s/km^2$)

Q90 : 90th percentile flow rate in m^3/s, 90% of the flow is below this this value

Avg_Rise: Median of all positive differences between consecutive rising values (rise rate, m^3/s / sec)

The potential impact of LID practices on aquatic life was analyzed at the end of each subbasin in the Blunn Creek Watershed. Flow outputs were monitored at the end of each subbasin and the following statistical analyses were conducted to evaluate their impact on potential aquatic life. Peak flows were monitored for flow data for the period between 1987- 2012. The 90th percentile of flow rate was estimated for different storm events.

One of the limitations of the SWAT model is that it uses a conceptual linear approach to simulate baseflow. SWAT divides groundwater into two aquifers, first, shallow aquifer which contributes to baseflow to streams within the watershed, and second, deep aquifer which contributes stream flow to streams outside the watershed and these are considered losses from the system (Arnold et al., 1993). This contributes in weak simulation of baseflow as several studies showed (Kalin and Hantush, 2006; Srivastva et al. 2006, Peterson and Hamlett, 1998, Chu and Shirmohammadi, 2004, Wu and Johnston, 2007). Maintaining base flow is essential to the habitat and biological integrity of streams (Bunn, and Arthington, 2002). Having said that, the following steps were followed to make up for this limitation and represent baseflow in SWAT model. Observed data for the period 1997 to 2009 were downloaded from COA and put in use. Baseflow data were separated from storms using excel spreadsheets by comparing rainfall events (peaks) and baseflow. These baseflow data replace the baseflow data of the current scenario (control) that does not account for any type of LID practices. For the scenarios that account for raingarden/ bioretention (RG) and permeable pavements (PP), the observed baseflows were used after accounting for 40% increase (Friedlich, 2004). The scenario that accounts for detention pond (DP), the baseflow was treated the same way the control treatment was treated by replacing baseflows from observed data without any addition.

Results

Use of SWAT flow output and statistical model of aquatic life provided a tool that was used to evaluate the effectiveness of the studied LID practices to offset aquatic life degradation caused by changes in hydrology. The potential impacts of LID practices were evaluated based on Aquatic Life Potential (AQP) value, Q90 which represent baseflow, and lastly peak flows.

The greatest percentage of increase in AQP value for all subbasins was when a combination of RG and PP was utilized (Figure 5-2)

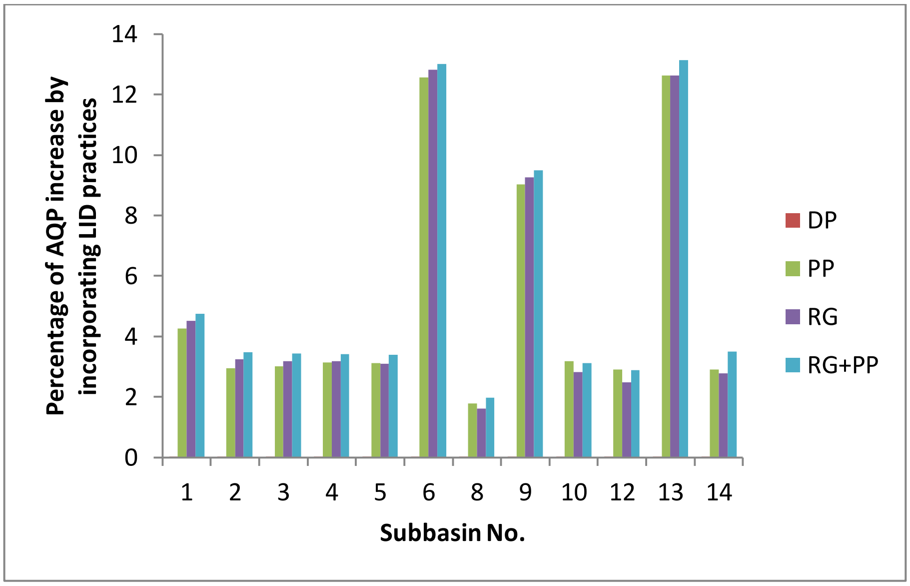


Figure 5-2. Percentage of AQP value increase when utilizing LID practices.

The detention pond had the least percentage of increase and this can be explained by the nature of DP as a conventional stormwater management control. This design was made to release small storm events such as the 2-year recurrence storm and to capture the 100-year storm. The largest peak flow for the simulation period did not reach the 2-year storm and accordingly, huge reduction in baseflow occurred and that was translated in reducing AQP value

The second level of evaluation was based on increasing baseflow that is represented by the Q90 value (Figure 5-3).

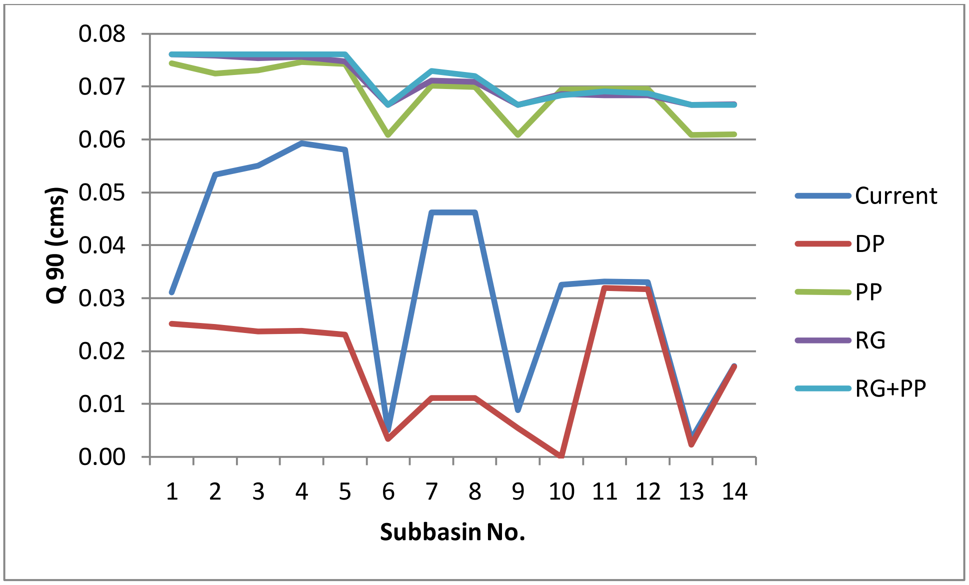


Figure 5-3. The effect of LID practices on increasing baseflow.

The same trend continued to hold and a combination of RG and PP resulted with the greatest values of Q90. DP had again the least values of Q90 because it contributed to capture most of the storm and not to release it as baseflow. The scenarios that account for PP only and RG only had almost the same impact on Q90 and both contributed significantly to increase in Q90 value.

Reduction in peak flows was also monitored as an indicator to enhancement in the environment of aquatic habitat. The combination of PP and RG resulted with the greatest reduction peak flows by 80%. The scenario that accounts for RG only came in the second order with reduction percentage equal to 78%, PP had a reduction percentage equal to 50% and lastly DP had a reduction percentage of 23%.

Reduction in the volume of water runoff was also analyzed and a combination of PP and RG had the greatest reduction in total volumes by 82%, followed by RG which had a reduction by 80%, PP had a reduction of 57% and DP had a reduction of 47%.

Conclusions

Conventional stormwater management controls such as detention pond have been used extensively to control peak flows. Little attention had been given to alternative practices that would contribute to reduce total runoff volumes, pollutant loadings, delay time to peak, and maintain baseflow which is considered essential to the biological and habitat integrity of streams. A sub-hourly 15-min time step SWAT model to increase the accuracy of simulations used to estimate flows in the Blunn Creek Watershed. In this study, bioretention area, permeable pavement, detention pond, combination of bioretention and permeable pavement were modeled in SWAT and analyzed with respect to providing acceptable flows and baseflows to maintain healthy environment for aquatic habitat in urban streams. The evaluation of LID practices was based on reducing peak flows, increasing baseflows and increasing the value of Aquatic Life Potential. Results showed that a combination of permeable pavement and raingarden resulted with the greatest percentage of increase in AQP values and baseflows and greatest reduction in peak flows. Detention pond had the least percentage of increase in AQP and baseflows as well as the least percentage of reduction in peak flows.

CHAPTER VI

OVERALL CONCLUSIONS

Urban growth contributes to increased stormwater runoff due to the increase in impervious surfaces. The increased stormwater runoff has negative hydrological impacts on streams. Stormwater runoff contributes to impairment of stream water quality and results in problems such as loss of habitat, sedimentation, increased temperature, and loss of fish population. Traditionally stormwater control measures such as detention pond were designed and constructed to reduce and control peak flows. Controlling nonpoint source pollutants was not addressed by using these measures. Therefore, Low Impact Development (LID) practices were developed to negate the impacts of urbanization on water resources by reducing the runoff volume and peak flows as well as improving outflow water quality. This study evaluates the effectiveness of LID practices in reducing stream bank erosion, flooding, and enhancing aquatic life environment.

The first chapter introduces the topics addressed in this study. In the second chapter a sub-hourly time step of the Soil and Water Assessment Tool (SWAT) model was calibrated and validated to predict stream flows for the Blunn Creek Watershed for the time period 1987-2012. Traditionally, the SWAT model operates at a daily time step and it estimates the influence of landuse and management practices on water, agricultural chemical yields in a watershed. The daily time step format provided by SWAT may not be sufficient to capture the impact of flashy storms where peak flows last for minutes only and are not reflected in daily average flows. It might also miss important processes such as the first flush of urban runoff. Therefore, a customized version of 15-minute time step SWAT model was developed. The model was calibrated and evaluated for a 2-year period. Sub-hourly simulation model was optimized successfully using SWAT 2012 and also calibrated using SWAT-CUP, SUFI2 procedures.

SWAT-CUP presented an effective graphical interface in order to visualize calibration components such as observed data, simulated data, 95 PPU and the best fit model. The sensitivity analysis adopted for stream flow calibration was very successful and contributed to optimizing the total number of uncertainty parameters and accordingly more efficient calibration procedures. The presented study shows that the sub-hourly SWAT model provides reasonable estimates of stream flow for multiple storm events. Calibrated stream flows for a 2 year period using the 15- minute time step had an R2 of 0.78 and a Nash-Sutcliff coefficient (NS) of 0.78. The 2-year validation period had an R2 of 0.70 and a NS of 0.67.

In the third chapter, the calibrated SWAT model was used to estimate potential stream bank erosion in the Blunn Creek Watershed. Low Impact Development (LID) practices were incorporated in the SWAT model as alternative stormwater control measures. The practices evaluated include: bioretention area or rain garden, permeable pavement, detention pond, and a combination of permeable pavement and bioretention area. The current version of SWAT model (SWAT2012) does not include permeable pavement or bioretention area and one of the objectives of the third chapter was to develop a methodology to represent these practices in SWAT model. The evaluation of stream bank erosion was based on shear stress and the exceedance of shear stress.

Results showed that the greatest reduction in runoff volumes, peak flows, and excess shear stress under both real and design storms was obtained when combining bioretention and permeable pavement. bioretention alone resulted with the second greatest reduction percentage and detention pond alone had the least reduction percentage. The soil particle with median diameter equal to 64 mm size had the least excess shear stress among all design storms, while 0.5 mm soil particle size had the largest magnitude of excess shear stress.

The fourth chapter discussed the potential impact of LID practices in reducing flooding. Field experiments at the Texas AgriLife Research and Extension Center located in Dallas, TX was constructed and monitored for one year to evaluate and validate the performance of the modeled LID practices. The evaluation of flooding in SWAT model was based on the percentage of flows that exceeded bank-full flows. Results showed that combining bioretention and permeable pavement had the greatest reduction in peak discharges for all recurrence intervals (2-year, 10-year, 25-year, and 100-year). Permeable pavement had the least percentage of reductions for all recurrence intervals. All LID practices had 100% reduction in percentage of exceeding bankfull flows for the 2-year recurrence intervals. The same trend continued to hold and combining bioretention and permeable pavement resulted with the greatest reductions in the percentage of exceedance of bankfull flows. Performance of modeled LID practices was validated by showing acceptable agreement in the percentage of reductions in total runoff between field experiments and model data.

In the fifth chapter the evaluation of LID practices performance was based on assessing watershed hydrological responses to aquatic life communities in Blunn Creek. SWAT output of stream flows along with a statistical model that was developed by the City of Austin, which analyzes the relationship between hydrological measures and aquatic life were used in assessing the impact of LID practices on potential aquatic life communities. The evaluation of LID practices' performance was based on incorporating and representing these practices into SWAT model, studying output flows, and assessing watershed hydrological responses and their impact on aquatic life communities in the Blunn Creek. Reduction in peak flows and increasing both baseflows and Aquatic Life Potential (AQP) values were the factors used to assess flows coming out of LID practices. Results showed that a combination of permeable pavement and raingarden resulted with the highest percentage of increase in AQP values and baseflows and greatest reduction in peak flows. Detention pond had the least percentage of increase in AQP and baseflows as well as the least percentage of reduction in peak flows. All in all, the studied LID practices have enhanced the stream environment by maintaining baseflows and reducing peak flows. These practices were effective in controlling stormwater runoff, reducing flooding, and enhancing the environment of aquatic life.

CHAPTER VII

RECOMMENDATIONS FOR FUTURE STUDIES

1. The impact of LID practices on groundwater quality
2. The impact of increasing groundwater level due to high infiltration caused by some types of LID practices and potential flooding
3. Understanding the effect of LID practices on baseflow through field experiment
4. Enhancing the ability of SWAT model to simulate low flows and baseflow
5. Building new routines and algorithms that represent LID practice in SWAT model
6. Maximizing pollutant load reduction
7. Evaluating impacts on floodplains and channel stability

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