SIMULATING AND OPTIMIZING STORM WATER MANAGEMENT STRATEGIES IN AN URBAN WATERSHED

A Thesis

by

CHANDANA DAMODARAM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2010

Major Subject: Civil Engineering

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Approved by:

Co-Chairs of Committee,	Emily M Zechman
	Francisco Olivera
Committee Members,	Clyde L Munster
Head of Department,	John Niedzwecki

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ABSTRACT

Simulating and Optimizing Storm Water Management Strategies in an Urban Watershed.

(December 2010)

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Co-Chairs of Advisory Committee: Dr. Emily M Zechman
Dr. Francisco Olivera

Land development transforms the natural landscape and impacts in stream ecosystems and downstream communities as it alters the natural flow regime. An increase in impervious areas results in higher volumes of storm water runoff, reduced time to peak, and more frequent flooding. Best Management Practices (BMP) and Low Impact development (LID) are a few of the set of measures which are used to mitigate the impact of urbanization. Peak flow, runoff volume are few of the conventional metrics which are used to evaluate the impact and performance of these storm water management strategies on the watershed. BMP are majorly used to control the flood runoff but results in the release of large volumes of runoff even after the flood wave passed the reach and LIDs are used to replicate the natural flow regime by controlling the runoff at the source. Therefore need to incorporate a metric which includes the timing and area being inundated needs to be considered to study the impact of these strategies on the downstream.

My proposed research will focus on simulating the Low Impact Development (LID) techniques like permeable pavements and rainwater harvesting on an urbanized watershed using a curve number approach to quantify the hydrologic performance of these strategies on the watershed. LID, BMPs, and combined strategies are introduced for retrofitting existing conditions and their hydrologic performance is accessed based on the peak flow and a new metric Hydrologic Footprint Residence. A simulation optimization framework would be developed which identifies cost effective LID options that maximize the reduction of peak flow from the existing condition design storms while meeting budget restrictions. Further LID and BMP placement is included in the optimization model to study the impact of the combined scenario on the storm water management plans and their performance based on different storms and corresponding budget. Therefore a tradeoff can be illustrated between the implementation cost and the hydrological impact on the watershed based on the storm water management approach of using only LID and combination of LID and BMP corresponding to varied spectrum of design storm events.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

I extend my deepest gratitude to my committee Dr. Emily M Zechman, for her constant support, encouragement and guidance throughout my course of study. Dr. Francisco Olivera, and Dr. Clyde L Munster, for their assistance and valuable suggestions which were very helpful in carrying out my research work.

I am indebted to my parents for their encouragement and blessing all through my life without whom all the achievements in my life would not have been possible. I also thank my friends for their love and support in all walks of my life.

Lastly, I would like to offer my regards to my colleagues for making it a worthwhile and great experience here in Texas A&M University.

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CHAPTER I

INTRODUCTION

Watershed urbanization increases the peak flows and runoff volume, which alters the natural flow regime of the stream and affects the in-stream ecosystem. Best Management Practices (BMPs), such as detention ponds, are designed to control volume of runoff of flood events thus preventing flooding; however, they do not mitigate other hydrologic impacts of development, such as inadequate base flow and flashy hydrology, which can adversely impact ecosystems (USEPA 2000; Coffman 2000). Low Impact Development (LID) practices are an alternative approach for controlling storm water at the source like rooftops, parking lots and sidewalks. LID technologies include permeable pavements, rainwater harvesting, roof gardens, infiltration swales, bioretention areas, disconnected impervious areas, and cluster development. LID goals at replicating the natural hydrologic landscape and create flow conditions that mimic the pre-development flow regime through the mechanisms of micro-scale storm water storage, increased infiltration, and lengthening flow paths and runoff time (USEPA 2000; Coffman 2000). About the hydrological impacts of LID and their ability to mimic better natural flow regime compared to BMP at a watershed scale is little knows. (Hood et al. 2007; Bledsoe and Watson 2001; Gilroy and McCuen 2009; Xiao et al. 2007; Dietz and Clausen 2008; Williams and Wise 2006).

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This thesis follows the style of *Journal of Water Resource Planning and Management*.

A set of studies have investigated the impact of LID on the hydrologic flow regime and found that LID is able to reduce the peak flow for frequent, less intense storms. For other rainfall events, LID may not be effective in lowering the peak flow, but may increase the time to peak or decrease the period of sustained high flows (Hood et al. 2007; Dietz and Clausen 2008; Holman et al. 2003; Brander et al. 2004; Damodaram et al. 2010). However it was observed that, reduction was higher for small frequent rainfall events, and for less frequent higher intense storms flood management was needed. Therefore, a combined LID-BMP approach thereby helps in flood management and improving hydrologic sustainability of the watershed.

The goal of watershed management is to select LID, BMPs, or a combination of technologies to mitigate the hydrologic effects of development in a watershed, based on the peak flow at the watershed outlet for a design storm. Typically, the peak flow for a set of management scenarios is simulated using a hydrologic model, and the strategy that generates a peak flow that most nearly matches predevelopment conditions would be selected for implementation. Alterations in the timing of flows and duration of flooding can significantly impact the health in the downstream ecosystem communities, which should be incorporated when evaluating and selecting sustainable watershed management plans. Poff et al. (1997) observed that many characteristics of the flow regime are important to maintain ecosystem health, including magnitude, frequency, duration, timing and rate of change of discharge. A few metrics have been proposed to better quantify the hydrologic alterations due to increased impervious cover. The Tennant method (Tennant 1976) evaluates the impact of urbanization by comparing annual flow rates. The Indicators of Hydrologic Alteration (IHA) approach (Poff et al. 1997; Richter et al. 1996, 1997) provides a set of quantitative metrics to represent multiple characteristics of the natural flow regime. A new event-based metric for evaluating the sustainability of watershed management plans was recently developed to incorporate both the magnitude and timing of changes in the hydrograph called Hydrologic Footprint Residence (HFR) which evaluates the modification of flood plain areas and duration of flood residence time (Giacomoni and Zechman 2009). HFR is designed to capture both temporal and spatial hydrological changes downstream caused due to urbanization. This metric is used to evaluate the performance of the storm water management strategies in comparison to peak flow. As the HFR captures both the timing and area being inundated, this metric would give a better understanding on the downstream impacts caused due to the development and strategies used to in watershed management.

While LID may effectively manage stormwater and restore the pre-development flow regime for small design storms, budget constraints may not allow retrofitting all existing parking lots or rooftops in a watershed with these techniques. Some locations in a watershed may be critical for reducing stormwater, and effective watershed management should identify these locations where LID should be implemented to best mitigate the peak flow and improve the hydrologic sustainability of the watershed while minimizing costs. Mathematical optimization techniques may be utilized to select the number and location of LID technologies to maximize the reduction of peak flow for a design storm. While several studies have addressed the optimal location of stormwater control structures in a watershed, only a few studies have optimized infiltration-based BMP or LID placement (Elliott 1998; Srivastava et al. 2002, 2003; Veith et al. 2003; Perez-Pedini. 2004; Perez-Pedini et al. 2005; Zhang 2009). Perez-Pedini et al. (2005) used a genetic algorithm (GA) (Goldberg 1989) to optimize the number and location of infiltration-based BMPs for an urban watershed, by maximizing the peak flow reduction while meeting budget constraints. Perez modeled the watershed as a network of hydrologic response units and simulated an infiltration-based BMP as a reduction in the curve number by five units. Guoshun Zhang (2009) in this dissertation has developed a multi-objective optimization framework integrating the simulation model with ε-NSGA II for placement of LIDs in the watershed by minimizing the total cost and total runoff by constraining it with the predevelopment flow rate. Zhang (2009) considered permeable pavements, bio retention and green roofs which were modeled using Storm Water Management Model (SWMM) with components flow divider, storage units, weir and orifices.

This research focuses in simulating the hydrologic behavior of Low impact development on a watershed. The LID practices, including permeable pavements, rainwater harvesting, and green roofs, were considered to investigate the impact of LID on watershed. These LID strategies are simulated within a hydrologic model to facilitate watershed management for an illustrative case study on the Texas A&M University campus where storm water runoff and erosion problems have been documented. Approaches based on the Curve Number method are developed and integrated into the watershed model to represent each of the LID technologies. BMPs and LID are simulated for varied flood events, including 2-yr, 10-yr, and 100-yr design storms, and for frequent events, which generate a depth of rain that is less than the 1-yr storm. A set of scenarios is evaluated based on a three design storms and two recorded rainfall events, and a combined BMP-LID approach is demonstrated for managing a range of events. Hydrologic performance of these simulated scenarios is evaluated based on peak flow and Hydrologic Footprint Residence (HFR) for different storm events.

Further this simulation model will be coupled with an optimization model to find number and location of the LID on the watershed based on the preselected budget which maximizes the reduction of the peak flow. Further the optimization model will be extended to include implementation of BMP along with the LID thereby maximizing the peak flow reduction for various design storms and for different pre selected budgets. Considering varied spectrum rainfall events helps capturing both the goals of storm water management – flood control and sustainability. Tradeoff between the implementation cost and the hydrological impacts with respect to different storm water management approaches and different design storms can be illustrated with the above explained simulation-optimization framework. Optimal solutions found for each design storm are evaluated based on the other design storm to estimate the performance, this analysis helps in capturing if any tradeoff exists between the optimal solutions found for each design storm. This approach is carried out on Texas A&M University west campus watershed.

CHAPTER II

STUDY AREA:

TEXAS A&M UNIVERSITY CAMPUS WATERSHED*

The modeling approaches and optimization model is demonstrated for an illustrative watershed to investigate the placement of these strategies and evaluate their impact on stormwater management. The main Texas A&M University campus, located in College Station, Texas, covers an area of 21.37 square kilometers (5,280 acres), most of which is not densely developed. The campus has witnessed unprecedented growth with a student population increasing from 7,500 in 1962 to 52,000 in 2004 (Barnes Gromatzky Kosarek Architects and Michael Denis & Associates 2004). The two sections of campus, Main Campus and West Campus (3.03 and 4.39 square kilometers, respectively), are located in two different watersheds. West Campus is less developed when compared to Main campus. West Campus has greatly witnessed the development over the past 50 years increasing the impervious surface and volume of storm water draining into White Creek, subsequently degrading the structure of the creek and the ecosystem. Two tributaries on West Campus contribute to White Creek and have undergone a transformation from small and slow moving creeks to large creeks that

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move large amounts of storm water during typical 2-5 year rainfall events.

A study was commissioned to assess the extent of erosion within the watershed and to propose the most effective engineering solutions (JF Thompson Inc. 2005). The study documented the erosion and massive slope failure that has occurred throughout the extent of Tributary D (Fig. 1), and predicted that, if left unmitigated, erosion would likely undermine adjoining structures including buildings, roads, bridges, and ponds. As a result of this study, immediate protection of critical locations was recommended, and riprap and gabions with vegetation were implemented to decrease velocities in the streams. To prevent further damage and improve the aesthetics of the campus as a whole, a master plan was commissioned and was released in July 2004 (Barnes Gromatzky Kosarek Architects and Michael Denis & Associates 2004). It is suggested that a more comprehensive stream restoration plan is required to address erosion and hydrologic problems in the long term and plan for the further development of West Campus as proposed in the master plan (JF Thompson Inc. 2005).

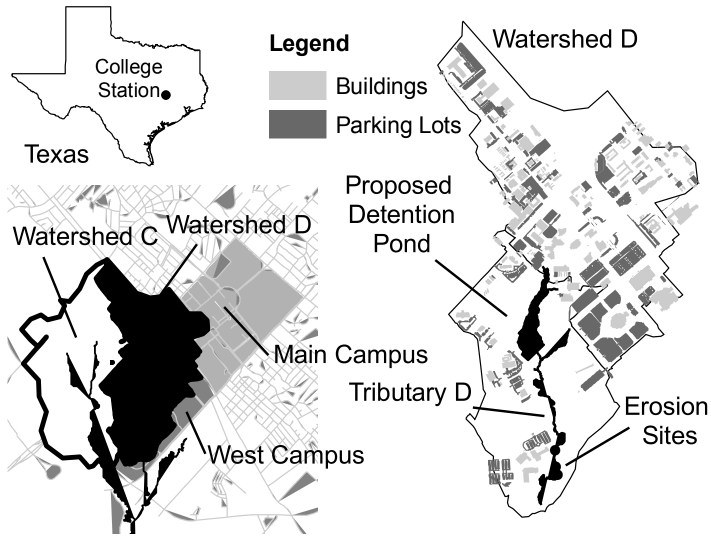

Fig. 1. Location and characteristics of Watershed D and documented sites of erosion.

Hydrologic and Hydraulic Model

Hydrologic and hydraulic models of Watershed D in West Campus have been developed and implemented using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) (US Army Corps of Engineers 2008) for hydrologic simulation and the Storm Water Management Model (SWMM) (USEPA 2008) for hydraulic simulation (AECOM 2008). Watershed D is 3.18 km^2 in area and was divided into 440 subwatersheds, delineated corresponding to storm sewer manholes, culverts, channel junctions, buildings, and streets. Curve numbers for the watershed, as specified in the Bryan-College Station Unified Design Guidelines (2007), vary only between 75 for natural woodlands and grasslands and 77 for landscaped area, due to the clay-based nature of the underlying soil. Streets, building roofs, and parking lots contribute to the impervious area in each sub-catchment. In total, 41% of Watershed D is covered by impervious areas, where streets cover 9%, parking lots cover 14%, and rooftops cover 8% of the area. A combination of links and nodes represent the storm water infrastructure, composed of box and circular storm sewers and open channels. SWMM routes flow hydrograph information from HEC-HMS through sewers, conduits, and open channels.

Rainfall and stream depth data in Watershed D were collected for two small rainfall events occurring in September 2009. The rainfall depth of Event 1 was 108 mm and the depth of Event 2 was 45 mm. For the two rain events, the HEC-HMS/SWMM framework captured the timing and magnitude of discharge at the watershed outlet, as shown in Fig. 2. The two recorded events represent a large portion of the rain events that occur at Watershed D. During the period of 2003–2008, 154 rain events were recorded at the College Station Climate Data Station (www.srh.noaa.gov), which is administered by the National Weather Service and located within 2 miles of Watershed D. Based on this data, 97% of the rainfall events were smaller than a 24-hr 1-yr, which is 76 mm. Of the 154 recorded events, 49% resulted in total depth of rainfall between 13 mm and 25 mm, and another 48% of rain events generated a rainfall depth between 25 and 76 mm. As issues of erosion and habitat health rely not only on flood events, but also on frequent less intense rain events. The following analysis evaluates storm water management plans for three typical design storms and the two recorded small events (Fig. 2).

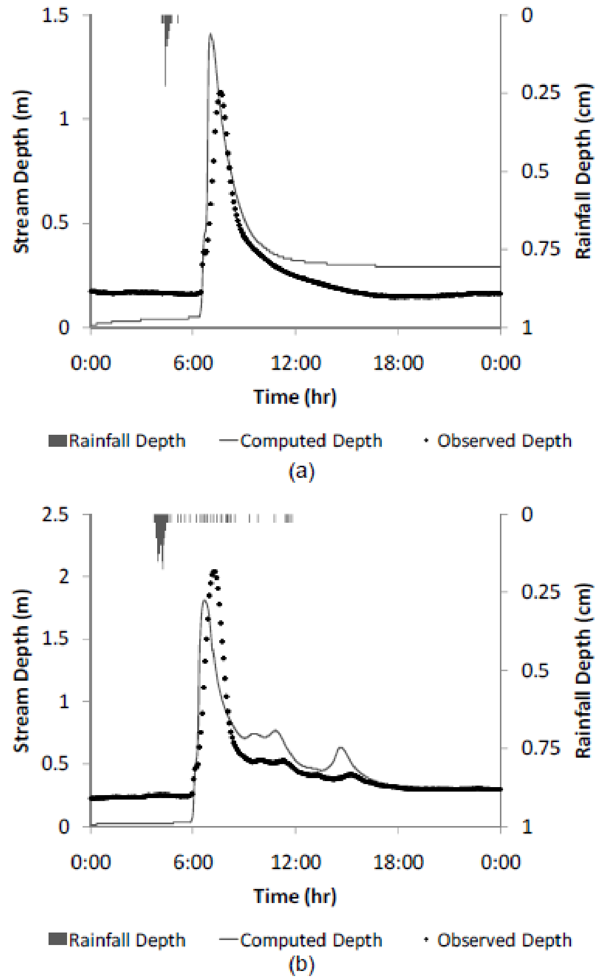

Fig. 2. Computed and observed hydrograph and rainfall hyetograph for (a) Event 1 and (b) Event 2. Rainfall depth is at 5-minute intervals, shown on the secondary axis.

CHAPTER III

SIMULATION OF COMBINED BEST MANAGEMENT PRACTICES AND LOW IMPACT DEVELOPMENT*

Low Impact Development Technologies for Highly Urbanized Areas

In highly urbanized areas, allocating land for infiltration swales, bioretention areas, retention ponds, or cluster development may not be a feasible option. To achieve the objectives of LID, a more viable strategy would be to retrofit existing infrastructure, including parking lots, roads, sidewalks, and buildings. For example, permeable pavements can be used in place of conventional asphalt or concrete for covering roads, parking lots, and sidewalks, thus increasing on-site storage by retaining water within a highly permeable matrix as it slowly infiltrates into the underlying soil (Schluter and Jefferies 2002; Brattebo and Booth 2003; Dreelin et al. 2006; Scholz and Grabowiecki 2007; Schluter and Bean et al. 2007; Collins et al. 2008). Permeable pavements include porous concrete, which consists of an aggregate base located above a well-draining soil; plastic grid systems, which are filled with sand or gravel or planted with grass; and pavers, or concrete block lattices, which are typically covered by 60-90% of impervious material, while spaces between blocks are filled with gravel or planted with grass.

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Permeable pavement systems are often underlain by underdrain systems.

Rainwater harvesting systems (RHSs) are used to collect and store stormwater from rooftops for post-storm irrigation. RHSs consist of a catchment area, which is typically a building rooftop, a storage tank, and conveyance system for discharging overflow to a stormwater sewer or rain garden (Gould and Nissen-Petersen 1999). Green roofs are alternative LID technologies that lengthen flow paths and runoff times by establishing plant materials on rooftops to restore the vegetated footprint lost to the building construction (Getter et al. 2007). A set of experimental studies demonstrated that green roofs delay runoff and can significantly reduce runoff volumes for frequent events (Liu 2003; Moran et al. 2004; Mentens et al. 2006; VanWoert et al. 2005; Teemuska and Mander 2007).

Simulation of green roofs, rainwater harvesting, and permeable pavements within a hydrologic watershed model is needed to facilitate urban planning at a catchment scale. Many hydrologic models simulate watershed runoff using the SCS Curve Number method (USDA 1986), which is an empirical approach for calculating the volume of stormwater based on a single parameter, the curve number, that represents the impact of landuse, soil type, vegetative cover, and moisture conditions on runoff generation. Identifying appropriate *CN* values for permeable pavements, RHS, and green roofs will allow these LID practices to be easily integrated within most hydrologic models.

A curve number for describing the expected hydrologic performance of green roofs has been identified by Getter et al. (2007). *CN*s ranging between 84 and 90 were identified for four green roofs sloped at varying angles. A set of 2.44 m × 2.44 m (8 ft. ×

8 ft.) roofs were covered with a 0.75 cm (0.26 in.) thick moisture retention fabric and 6.0 cm (2.4 in.) of a growing substrate. Analysis was based on a set of rainfall events ranging in depth from 1-40 mm. An earlier study (Carter and Rasmussen 2006) identified a similar *CN* value of 86 for a green roof constructed with a slope of less than 2% and 7.62 cm (3.0 in.) of substrate. In the absence of measured data to compute the *CN* for an implemented green roof, these modeling results can be generalized to assist engineers and stormwater managers in watershed planning.

For permeable pavements and RHS, however, representative curve numbers that could be used in a predictive manner have not been well developed. A few studies developed distributed models to simulate RHS using linear routing and simple reservoir calculations (Vaes and Berlamont 2001; Kim and Yoo 2009; Gilroy and McCuen 2009). Sample and Heaney (2006) used a lumped approach to simulate a RHS and calibrated an SCS Curve Number model of a watershed with rainwater harvesting based on observed data by adjusting *CN* values and the time of concentration. These values are highly dependent on the configuration of the RHS and the original land use and soil conditions, and cannot be generalized. Similarly, *CN* values and runoff coefficients were fitted to data sets for various designs of permeable pavements (Bean et al. 2007; Rushton 2001; Schluter and Jefferies 2002; Dreelin et al. 2006). As the hydrologic response of permeable pavements varies widely depending on the specific technology, the underlying soil type and surface slope, these modeling parameters are not generally applicable for the implementation of permeable pavements under new conditions and locations. New Curve Number-based modeling approaches are described in the following sections to facilitate simulation of RHS and permeable pavements within a watershed model.

Curve Number-based Modeling for Permeable Pavement and Rainwater Harvesting Systems

New modeling approaches were developed to estimate the hydrologic performance of LID using the CN approach, which employs the following equations to simulate runoff (R) based on precipitation (P):

$$S = \frac{25400}{CN} - 254 \qquad \text{(mm)} \qquad (1)$$

$$Ia = 0.2S \qquad \text{(mm)} \qquad (2)$$

$$R = \frac{(P - Ia)^2}{P + S - Ia} \qquad \text{(mm)} \qquad (3)$$

where CN is the curve number, which represents the rainfall-runoff characteristics of a watershed; Ia is the initial abstraction; and S is the maximum potential retention.

Permeable Pavement: For watersheds where there is no data for representing the hydrologic characteristics of a specific permeable pavement design, HydroCAD Software Solutions (2006) suggests a method for identifying an appropriate CN pavement, named here as the *S*-Storage Curve Number Method. The maximum potential retention is set equal to the effective storage (s_e), which is the depth of rain stored by the permeable pavement, as determined by the depth (d) and porosity (n) of the pavement:

$$S = s_e = d \times n \qquad \text{(mm)} \qquad (4)$$

CN and *Ia* are calculated using Eqs. 1 and 2, respectively, and Eq. 3 is used to calculate runoff for any precipitation event. The *S*-Storage Curve Number Method can be used by executing the following steps: (1) *S* is fixed at the depth of available storage provided by a lot of permeable pavement, (2) *CN* and *Ia* are calculated using Eqs. 1 and 2, respectively, and (3) for a rainfall event, the runoff is calculated using Eq. 3.

Three rainfall-runoff data sets are used to test the S-Storage Curve Number Method. The predicted runoff is calculated by following the S-Storage Curve Number Method by fixing *S* equal to s_e, as described above, and compared to the recorded runoff by evaluating the coefficient of determination, R^2. A second approach is to use regression to find the value of *S* that would best fit the dataset to directly maximize R^2. The R^2 found through regression represents the best (maximum) value that could be found using Curve Number equations and provides a baseline for evaluating the S-Storage Curve Number Method. Three data sets are available in the literature to conduct these tests. A porous concrete parking lot with 40 mm of effective storage placed was placed in Wilmington, NC, and monitored for a set of 19 storms (Bean et al. 2007). A second site of concrete grid pavers filled with coarse grade sand and a base of gravel providing 70 mm of effective storage was monitored in Kinston, NC, for a set of 47 rainfall events (Beat et al. 2007). Finally, a porous concrete parking lot with 9 mm of effective storage and installed with an underdrain was monitored in Edinburgh, Scotland, for 15 rainfall events (Schluter and Jefferies 2002). For each of the three sites, rain events were recorded up to a depth of approximately 100 mm (Fig. 3).

The results of this analysis are shown in Table 1. The value for R^2 found using the *S*-Storage Curve Number Method is nearly equivalent to the R^2 found through regression for all three data sets, and the predicted runoff shows a reasonable fit to the observed runoff (Fig. 3). The values for *S* as determined using the S-Storage Curve Number Method are very similar to corresponding values of *S* that were identified using regression, indicating that using the effective storage as a value of *S* realistically represents the rainfall-runoff process. The fit for the Edinburgh site shows the most difference between the value of *S* identified through regression and the actual amount of effective storage. The Edinburgh site differs from the NC sites in two characteristics: the amount of effective storage is significantly less, and the porous concrete is fit with an underdrain.

Sites with underdrains may have a significantly different hydrologic behavior and may require a more mechanistic modeling technique than the Curve Number approach. For the data sets available, this modeling approach is effective, as the rainfall events modeled here are all relatively small events. This methodology should be tested further for larger events as more permeable pavement data sets become available.

Table 1. Modeling results for three permeable pavement sites

Site	Permeable Pavement Design	*S*-Storage Curve Number Method			Regression Analysis		
		S	CN	R^2	S	CN	R^2
Wilmington, NC	Porous pavement	40 mm	85.4	0.89	42 mm	84.8	0.89
Kinston, NC	Concrete grid paver	70 mm	77.5	0.66	67.9 mm	78.0	0.66
Edinburgh, Scotland	Porous pavement & underdrain	9 mm	95.4	0.93	18.7 mm	92.0	0.95

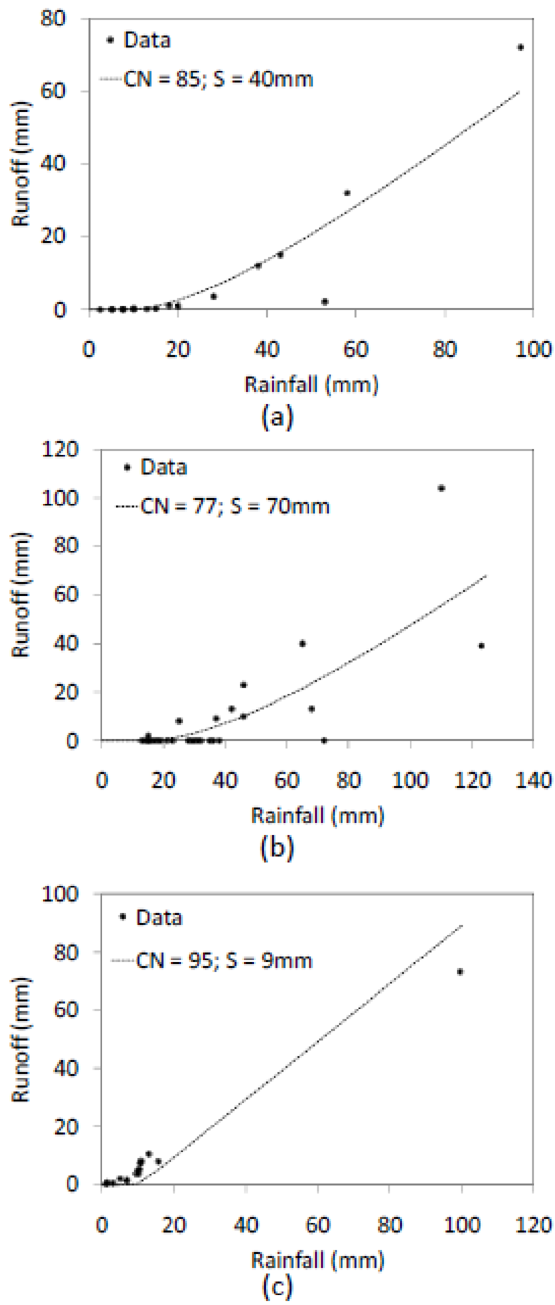

Fig. 3. Modeling rainfall-runoff data using the *S*-Storage Curve Number approach. (a) Porous concrete at Wilmington, NC (b) Concrete grid pavers at Kinston, NC. (c) Porous concrete at Edinburgh, Scotland.

Rainwater Harvesting System: A CN-based modeling approach can also be adopted to predict the watershed-level impact of placing RHS. A RHS captures the initial abstraction from a rooftop, and once the RHS has reached its capacity, runoff will be generated from the roof as an impervious surface. To represent this behavior, the *Ia*-Storage Curve Number approach is proposed here. The initial abstraction, *Ia*, is set equal to the effective depth (s_e) of the RHS by using Eq. 5 in place of Eq. 2.

$$Ia = s_e = \frac{V}{A} \qquad \text{(mm)} \qquad (5)$$

where *V* is the volume of storage provided by the RHS, and *A* is the area of the rooftop. Using a *CN* value of 98, the maximum potential, *S,* is calculated using Eq. 1 as 2.1 mm. Eq. 3 is used to calculate the runoff for a precipitation event. Consider, for example, a rooftop of 3,940 m^2 and a water tank storing 100 m^3. The tank will store 25.4 mm of rainfall before runoff is generated. Using the *Ia*-Storage Curve Number Approach, *Ia* is set at 25.4 mm and *S* remains fixed at 2.1 mm. The rainfall-runoff behavior of this modeled system is shown in Fig. 4.

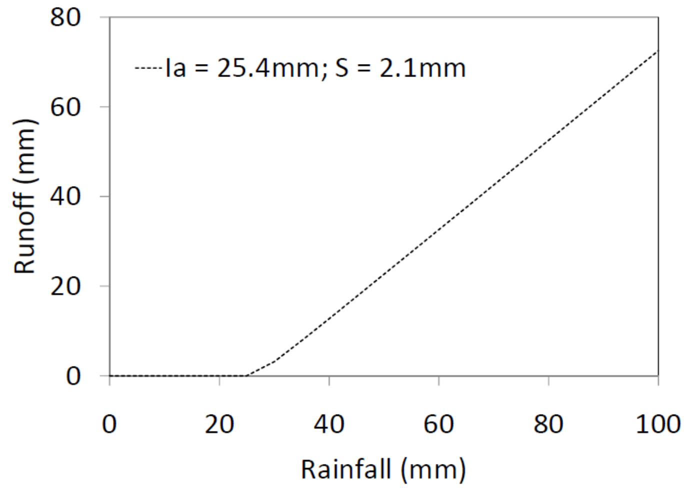

Fig. 4. Behavior of hypothetical RHS using the *Ia*-Storage Curve Number approach.

Application to Texas A&M University Campus Watershed D: Modeled Scenarios

A set of scenarios are modeled to test the use of BMP and LID practices for managing stormwater in Watershed D. LID and BMP configurations are compared to a pre-development condition and existing conditions. BMP scenarios investigate implementation of a detention pond, and LID scenarios explore options for retrofitting rooftops and parking lots. Streets and roads were not considered for replacement, due to additional durability, strength, and safety implications that should be considered. Modeling characteristics for the scenarios are summarized in Table 2.

Pre-development Conditions: A model of pre-development conditions is used to represent conditions that existed before development of the watershed. Pre-development conditions were based on an aerial photograph from 1940 (Texas A&M University

Libraries Map & GIS Collection and Services). At that time, a majority of the university infrastructure was concentrated on Main Campus, and Watershed D was generally undeveloped and covered with natural grassland. A curve number of 75 was adopted for these areas (Bryan-College Station 2007). The delineation of the existing sub-watersheds was restructured to reflect the natural topography of the watersheds for pre-development conditions. After this restructuring, the total number of sub-watersheds modeled in the predevelopment scenario is 52. The channel configuration and cross section of the open channel in Tributary D were adopted from the existing conditions.

Permeable Pavements: In Watershed D, 14 % of the total area is attributed to the 50 parking lots (Fig. 1). Each parking lot is modeled as a separate subbasin, contributing to the same link in the hydraulic model, and represented using the *S*-Storage Curve Number Approach. Four designs were tested, with effective storage of 25, 51, 76, and 102 mm (1.0, 2.0, 3.0, and 4.0 in.). In addition, a second design retrofitted 50% of parking lots using 102 mm-permeable pavement.

Rainwater Harvesting: The building footprints of 240 buildings make up 7% of the area of Watershed D (Fig. 1) (Saour 2009). Each building in Watershed D is simulated as a separate subbasin. To simulate utilization of RHSs, the *Ia*-Storage Curve Number Method is used, and four designs were tested to store rainfall depths of 25, 51, 76, and 102 mm (1.0, 2.0, 3.0, and 4.0 in.).

Green Roofs: Each building is replaced with a green roof, which is represented in the simulation model using a curve number of 86.

Detention Pond: A detention pond was simulated at a central node in Tributary D of White Creek (Fig. 1). The reservoir has a maximum depth of 5.4 m, volume capacity of 73,372 m^3 and inundated surface area of 46,888 m^2. The outlet structure is a 1 x 1 m concrete box.

Table 2. Modeling details for LID technologies, including permeable pavement (PP), rainwater harvesting system (RHS), and green roofs (GR). The value of the effective storage is given for PP and RHS

LID	Pervious Area		Impervious Area		LID Area		
	% Area Covered	CN	% Area Covered	CN	% Area Covered	CN	Ia (mm)
25 mm PP	59%	77	27%	98	14%	90	5.1
51 mm PP	59%	77	27%	98	14%	82	10
76 mm PP	59%	77	27%	98	14%	76	15
102 mm PP	59%	77	27%	98	14%	71	20
102 mm PP (50% area)	59%	77	34%	98	7%	71	20
25 mm RHS	59%	77	34%	98	7%	98	25
51 mm RHS	59%	77	34%	98	7%	98	51
76 mm RHS	59%	77	34%	98	7%	98	76
102 mm RHS	59%	77	34%	98	7%	98	102
GR	59%	77	34%	98	7%	86	7.6
102 mm RHS & 102 mm PP	59%	77	20%	98	7% (RHS) 14% (PP)	98 71	102 20
GR & 102 mm PP	59%	77	20%	98	7% (GR) 14% (PP)	86 71	7.6 20

Results

LID and BMP scenarios were simulated and compared to Pre-development and Existing Scenarios. The LID Scenario replaces all parking lots with 4 in. permeable pavements, and all rooftops are converted to RHS, where each RHS stores 4 in. of rain. The BMP Scenario simulates the detention pond described above, and the Combination Scenario combines the LID and BMP Scenarios (Table 3). These scenarios were evaluated for a two small events of record, Event 1 (18 mm) and Event 2 (45 mm), and three design storms (AECOM 2008), a 2-yr 24-hr rainfall event (114 mm or 4.42 in.), a 10-yr 24-hr rainfall event (185 mm or 7.44 inches), and a 100-yr 24-hr rainfall event (279 mm or 11.35 inches). Rainfall distributions for the design storms are based on the SCS center-weighted distribution method.

Table 3. Five watershed scenarios are described based on land use coverage characteristics and implementation of a detention pond

Watershed Scenario	Pervious Area		Impervious Area		LID Area			BMP
	% Area Covered	CN	% Area Covered	CN	% Area Covered	CN	Ia (mm)	Installed
Pre-Development	87%	75	13%	98	-	-	-	No
Existing	59%	77	41%	98	-	-	-	No
BMP (Pond)	59%	77	41%	98	-	-	-	Yes
LID	59%	77	20%	98	7% (RHS)	98	102	No
					14% (PP)	71	20	
Combination	59%	77	20%	98	7% (RHS)	98	102	Yes

Hydrographs for the five storms are displayed in Fig. 5. For each event, the Existing Scenario generates a peak flow that is significantly higher than the peak flow generated by the Pre-development Scenario, and the hydrographs for the Existing Scenario rises and falls more quickly than those of the Pre-development Scenario. For the 2-yr storm, the BMP Scenario lowers the peak flow to nearly the same level in the Pre-development Scenario, but sustains a longer flow as the stored stormwater is released. While the use of RHS and permeable pavement in the LID Scenario do not reduce the peak flow to the same extent, high flows are not sustained for a long duration, indicating that while the magnitude of discharge is greater than Pre-development Scenario, the rise and fall of the hydrograph is similar. This same trend is seen in comparing stormwater control strategies for Event 2. Finally, the Combination Scenario generates a hydrograph that matches most closely the Pre-development Scenario hydrograph in both timing and flow values compared to the LID and BMP Scenarios.

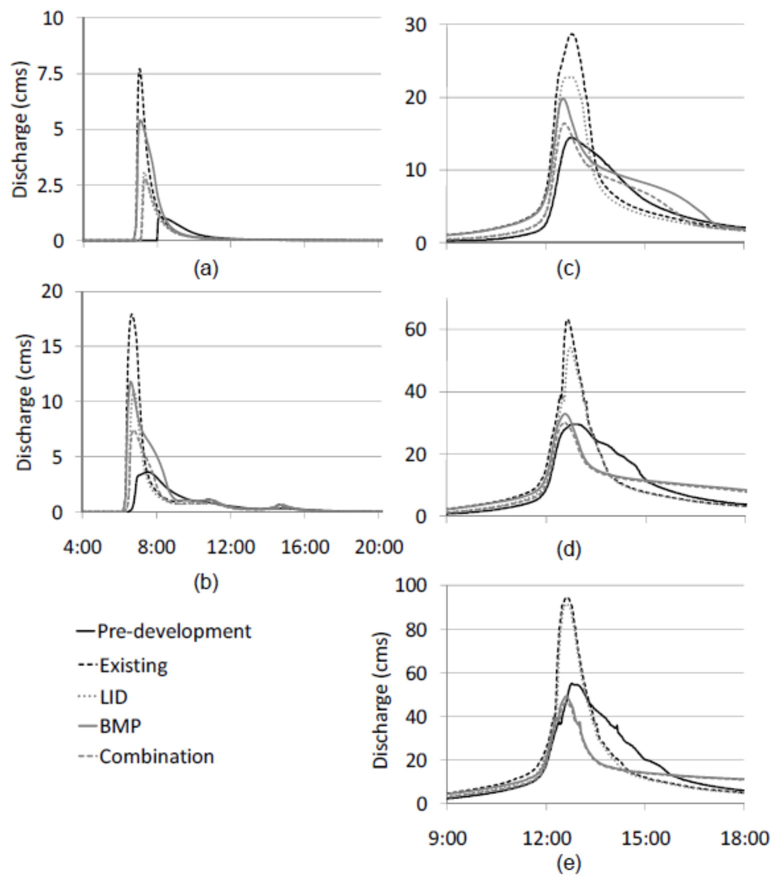

Fig. 5. Hydrographs for five storms are simulated: (a) Event 1, (b) Event 2, (c) 2-yr event (d) 10-yr event, and (e) 100-yr event. Five watershed Scenarios are simulated.

The percent reductions of the peak flow for existing conditions for each scenario and event are shown in Fig. 6. For the smallest storm, Event 1, the LID Scenario reduces the peak flow more effectively than the BMP, and for Event 2, the two scenarios have similar impact. For the three design storms, the BMP Scenario reduces the peak flow more than the LID Scenario, and the impact of the LID decreases with increasing rainfall depths of the storms. The Combination Scenario reduces peak flow to a marginally higher value than the better of LID and BMP for all events except Event 2. For Event 2, the Combination Scenario reduces the peak flow significantly more than either LID or BMP Scenarios. These results demonstrate that the use of LID is highly effective for smaller storms and may be more effective than storage-based BMPs, and as the intensity of the rainfall event increases, the infiltration-based improvements become less effective in impacting the peak flow.

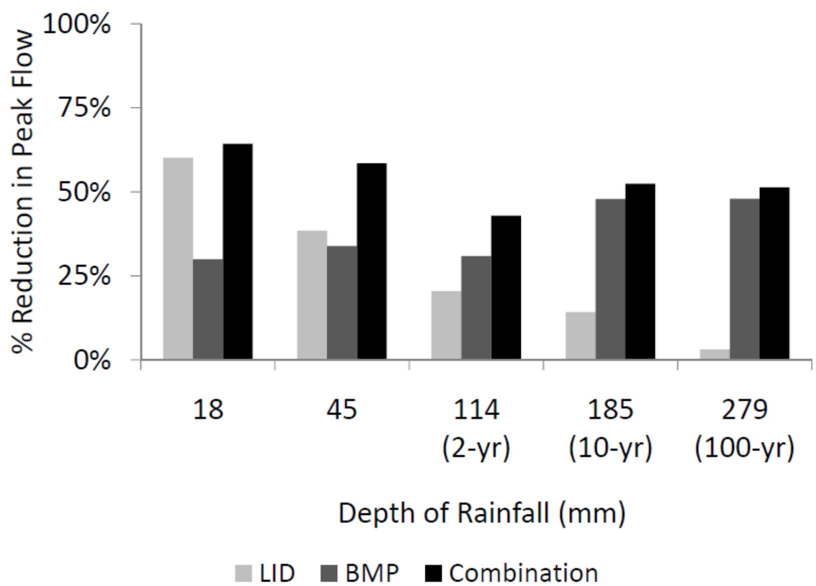

Fig. 6. Reduction in peak flow of Existing conditions for LID, BMP, and combined LID and BMP scenarios for all five storms. The modeled peak flows for existing conditions are 7.7, 17.9, 28.7, 63.2, and 94.5 cms for the five events.

Additional analysis was conducted to test the sensitivity of different LID strategies (described in Table 2). The LID strategies tested include: all parking lots are retrofitted with permeable pavement; 50% of parking lots (or 7% of watershed area) are retrofitted with permeable pavement; green roofs; RHS; a combined strategy of RHS with permeable pavement; and a combined strategy of green roofs with permeable pavement. Fig. 7 graphs the performance of each LID strategy for Event 1, Event 2, the 2-yr event, and the 10-yr event. Different values for the effective storage of RHS and permeable pavement are simulated. Results for the 100-yr event are not included, as no LID technology is able to reduce the peak flow more than 3%.

This analysis can provide decision support for choosing LID for implementation. For Event 1, all four RHS designs perform equally well as each one is able to store the entire depth of rainfall, while higher values for effective storage increase the performance of permeable pavement. In general, permeable pavement has a larger impact than RHS, but this may be attributed to the area of each; RHS replaces 7% of the watershed area with LID and permeable pavement, 14%. The second permeable pavement scenario, which replaces 50% (rather than 100%) of parking lots, is evaluated to provide an equivalent comparison between parking lot-based and rooftop-based LID technologies. RHS and permeable pavement perform similarly when the same amount of impervious surface is converted to LID.

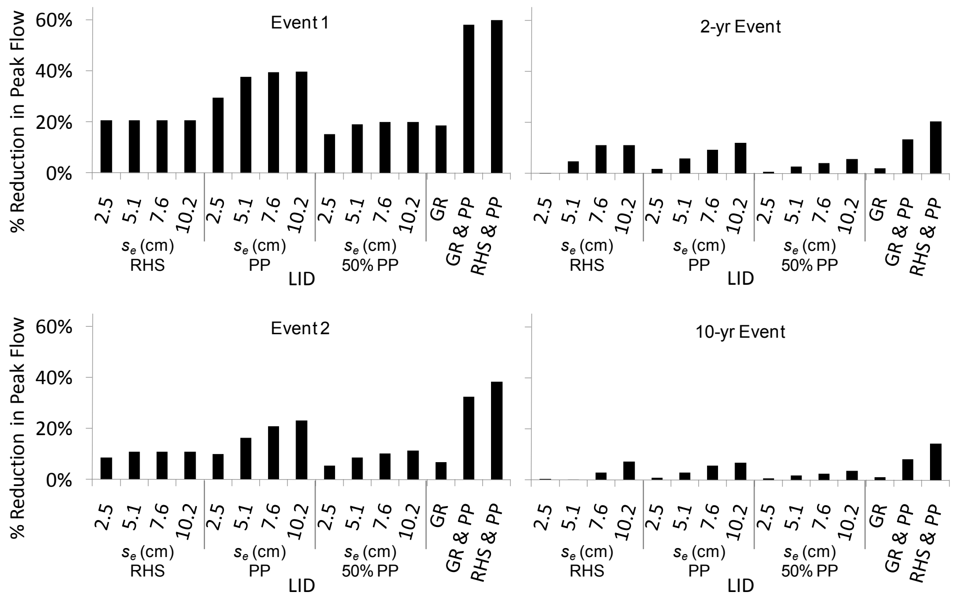

Fig. 7. Reduction in peak flow from existing scenario for LID technologies and varying settings for effective storage (s_e). “50% PP” indicates 50% of parking lots are replaced with permeable pavement.

For each LID technology, the reduction in peak flow is higher for smaller storms. The most effective strategies are those that combine use of rooftop and parking lot LIDs to replace a total of 21% of watershed area with LID. Permeable pavement, green roof with permeable pavement, and RHS with permeable pavement scenarios perform better than the BMP alone for Event 1. For Event 2, only the RHS with permeable pavement scenario performs better than the BMP alone.

Discussion

To effectively manage watersheds to meet goals of sustainability, smaller, more frequent storms should not be ignored in stormwater management, as they may have a significant impact on erosion and ecosystem health. The analysis conducted here indicates that infiltration-based LID technologies are more effective than BMPs for small storms, and storage-based BMP infrastructure is more effective for managing runoff from more intense storms. To achieve both flood control and sustainability objectives of stormwater management, LID and BMPs may be used in combination.

A new CN-based modeling approach was used to simulate hydrologic sustainability of LID. In effect, these modeling techniques simply lower the CN of existing impervious surfaces, which is a reasonable approach for simulating LID technologies that increase infiltration and lengthen flow paths (Perez-Pedini et al. 2005). Further research will test these modeled assumptions for datasets that describe RHS, green roof, and permeable pavement performance for stormwater control. The analysis of differing LID technologies and characteristics indicates that various LID technologies and implementations differ in the magnitude of reduction of stormwater runoff, though all techniques are able to reduce stormwater runoff volumes for smaller storms. These results are sensitive to the rainstorms that were modeled, including typical design storms, and recorded events. In addition, LID was limited to rooftops and parking lots, which cover a total of 21% of the watershed area, and other impervious areas covering 20% of the watershed area were not considered for LID.

One goal of sustainable natural resources management is that prior conditions should be restored, and therefore, a representation of pre-development conditions is required to evaluate the sustainability of any watershed management plans. Here an available aerial photograph was used as a basis for changing land use parameters and removing impacts of stormwater infrastructure in the simulation model. Though the model represents conditions that governed watershed health at a time prior to the existing conditions, it does not necessarily represent the unique state of the system that best represents natural conditions. For watersheds where data is not available to describe pre-development land use, discharge values, and ecosystem functions, further research in sustainable watershed management should address questions regarding the landuse conditions and resulting hydrologic flow regime that would be considered optimal and used as a target for maintaining instream ecosystem health.

CHAPTER IV

USING HYDROLOGIC FOOTPRINT RESIDENCE TO EVALUATE LOW IMPACT DEVELOPMENT AND BEST MANAGEMENT PRACTICE PERFORMANCE*

The simulation study demonstrated that though LID may not lower peak flow to the same extent as BMPs for design storms (e.g., a 2-yr event), LID may preserve the timing of flows to match better pre-development flow regimes for these storms. While timing of flows is an important characteristic of the natural flow regime, evaluating stormwater management strategies based only on reduction in peak flow does not capture the capabilities of LID or BMPs to maintain the duration of high flows or match the shape of the pre-development hydrograph. New metrics and simulation approaches are currently being investigated and developed to address these issues of evaluating hydrologic sustainability (Giacomoni and Zechman 2009). Hydrologic Footprint Residence is an event-based metric which evaluate the sustainability of watershed management plans by incorporating both the magnitude and timing of changes in the hydrograph (Giacomoni and Zechman 2009). This chapter illustrates the hydrologic performance of the simulated scenarios based on peak flow and HFR,considering both temporal and spatial alterations caused by the development on downstream.

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Hydrologic Footprint Residence

The HFR associated with a rainfall-runoff event is the area of land that is inundated and the duration during which it is inundated as a storm wave passes through a specific reach of the receiving water body, expressed in units of acre-hours. The value of the HFR associated with a storm is calculated by evaluating the definite integral of the inundated land curve in a reach. Consider, for example, a rainfall event in a watershed that generates direct runoff and a flood wave as it reaches the receiving water body. The flood wave passing through the reach is represented as a water surface elevation time series and a time series of instantaneous discharge values, or a hydrograph. If proper geomorphologic information of the reach is available, the extent of inundated land for a given flow discharge and surface elevation can be calculated based on field measurements or hydrologic and hydraulic models, and represented as an inundated area time series, or the inundated land curve. By definition, the area under the inundated land curve is termed the Hydrological Footprint Residence.

Results

The set of scenarios including LID, BMP and combination of LID and BMP which were illustrated in the earlier chapter are taken into consideration which were analyzed for three 24-hour rainstorm events, corresponding to 2, 10 and 100-year return periods (112.77, 188.97, and 288.89 mm respectively). For each scenario, the peak flow and HFR were calculated using the HEC-HMS/SWMM modeling framework. The HFR was calculated for 13 reaches at the downstream section of Tributary D (Fig. 8). The detention pond would be located just upstream of these reaches.

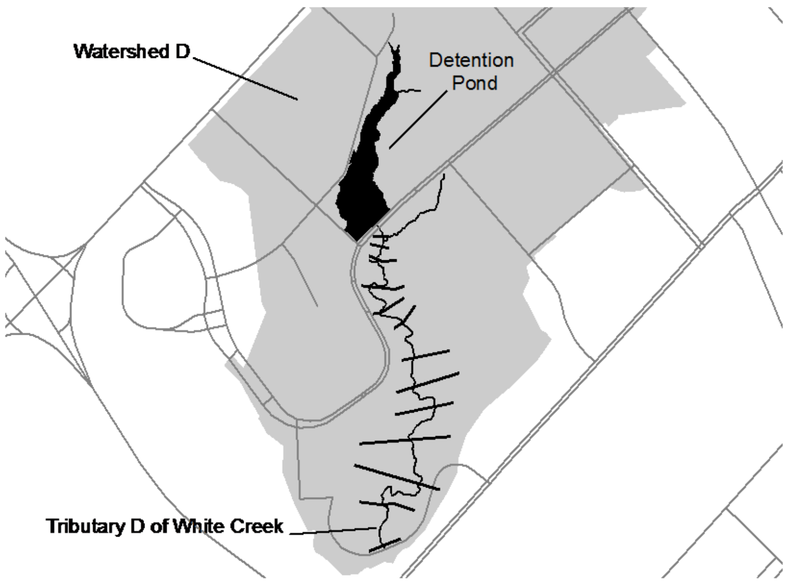

Fig. 8. Thirteen reaches of Tributary D are downstream to the detention pond and used to calculate HFR.

The performance of each scenario is evaluated based on the peak flow and HFR. BMP and the combination of LID and BMP generate a peak flow that is lower than that of the LID scenarios for all three design storms (Fig. 9). When comparing BMP to LID scenarios based on the HFR, the LID scenarios perform better than BMP for the 2-yr storm (Fig. 10). This is due to alterations in the timing of the hydrograph; the shape of the hydrograph for the LID scenarios follows more closely the shape of the predevelopment hydrograph, though the peak flow is lowered more by the BMP scenario.

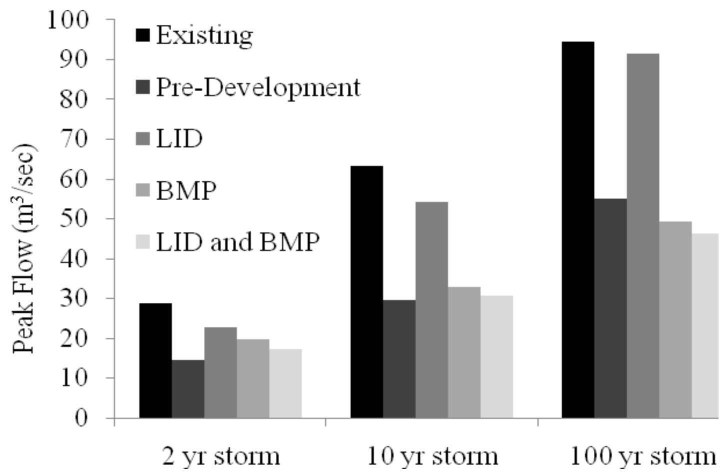

Fig. 9. Estimated peak flow at the outlet of the watershed for modeled scenarios.

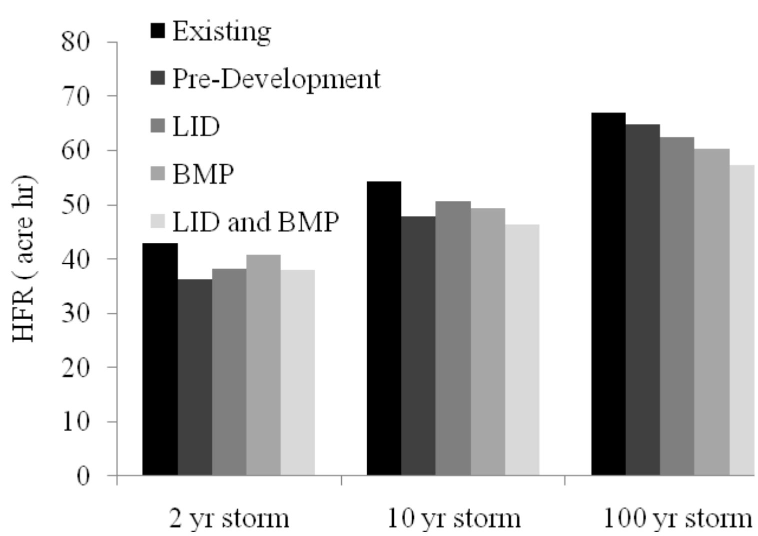

Fig. 10. Estimated HFR for different modeled scenarios.

Discussion

Sustainability and flood control are the two goals which an effective stormwater management plan should be able to accomplish. Conventional watershed management considers set of design storms and access the impacts of the development based on the peak flow. As demonstrated here, accessing the impacts of development should include even the temporal and spatial alterations to properly evaluate sustainability. For small frequent storms though BMP matches the peak flow to the pre-development it has a higer HFR because of the sustained flow. Combined LID and BMP matches the peak flow to the pre-development and has a lower HFR value than the other scenarios. This analysis can be used to assist decision-makers in developing sustainable stormwater management strategies. Finally, cost studies should be included to reflect the feasibility of implementing designs that prescribe LID or BMPs.

CHAPTER V

OPTIMIZING THE PLACEMENT OF LOW IMPACT DEVELOPMENT IN AN URBAN WATERSHED*

Solution Approach

Simulation studies carried out in Chapter III demonstrated how effectively storm water management practices mitigate the urbanization impacts on the watershed. It was observed from the simulation results that LID performance decreases with the increase in the storm intensity. Maximum peak flow reduction was noticed for the scenario where all existing parking lots and rooftops were retrofitted into LID choices and with the implementation of BMP. As it is not practical to replace all the available impervious land cover into LID choices, therefore most cost effective LID option that best reduces the hydrological impacts needs to be implemented. A feasibility study needs to be studied which reflects the relation between the implementation cost and the hydrological impacts. The performance of the LID changes based on the storm event considered, therefore we need to explore the tradeoff between the performance of LID with increasing budget and different spectrum rainfall events. Mathematical optimization techniques may be utilized to select the number and location of LID technologies to maximize the reduction of peak flow for a design storm in an urban watershed with a pre selected budget which is based on the area of the watershed being retrofitted into LID practices.

This study frames a solution approach which couples simulation and optimization to identify the tradeoff between hydrologic impacts and implementation costs of LID strategies based on different design storms. Amount of area being retrofitted into LID choices is used to estimate the cost, therefore in this study different percentages of area is considered to be retrofitted to study and estimate the tradeoff between the cost and the hydrological impacts. A GA-based approach is applied to identify the placement of LID options in the watershed based on the different budget constraint. By applying optimization for various limits on the budget a tradeoff between the project budget and the maximum reduction of the peak flow can be observed. This optimization model will be analyzed considering varied spectrum of storm events ranging from 2yr (small storms) to 100 yrs (intense storms). Results identified through this optimization will explore the best flow reduction for different levels of cost and report a trade-off among cost and peak flow reduction for different design storms. Placement of LID is optimized based on each budget for each storm event. It is expected that the development of a simulation-optimization framework will allow city planners and land developers to identify the best placement and use of LID in a watershed, leading to more sustainable protection of water resources.

This simulation optimization approach is applied to the study area - Watershed D (Fig.1) which has 65 parking lots (0.44 square kilometer) and 62 rooftops (0.30 square kilometer). Rooftops whose area is more than 2000 square feet are considered for implementing rainwater harvesting systems (Saour 2009). Implementation cost for permeable pavement was considered to be 2.25 $/square feet which was the average of different type of permeable pavement (http://www.toolbase.org/Technology - Inventory/Sitework/permeable-pavement). Rainwater harvesting system implementation cost was considered to be 2.25 $/ gallons (http://www.twdb.state.tx.us/ publications /reports/ RainwaterHarvestingManual _3rdedition.pdf). Rainwater harvesting systems are designed to store 101.6 mm of rainfall, height of the tank is considered to be the depth of rainfall designed to be stored. For each percentage of area being retrofitted corresponding total implementation cost is estimated which is considered as the total budget available which is shows in Table 4. Each option is analyzed for five different trials to evaluate and observe different solutions (placement of the LIDs) in the watershed with a similar cost and a similar reduction peak flow.

Table 4. No. of parking lots and rooftops being retrofit based on the percentage of area

Options	10% Area each	25% Area each	50% Area each
P_i	7	16	33
R_i	6	16	31
Budget	2.75	6.75	13.25

Model Formulation

$$Maximize \quad Q_o = PF_{EX} - PF_{LID} \tag{1}$$

$$subject \quad to \quad C_{PP} \times C_P \times \left[\sum_{i=1}^{P} A_i \right] \times C_{RHS} \times C_R \times \left[\sum_{i=1}^{R} A_i \right] \leq C_{Budget} \tag{2}$$

where Q_o = difference metric (cms); PF_{EX} = peak flow for existing conditions for a design storm event (cms); PF_{LID} = peak flow for a solution specifying LID strategies for a design storm event, which is calculated using a hydrologic/hydraulic modeling system (cms); A_i = Area of parking lot i (km^2); C_P = conversion factor i.e. 10763910.4; C_R = conversion factor i.e. 26839773.12; Pi = decision variable indicating the parking lot number i that should be retrofit with permeable pavement; R_i = decision variable indicating the rooftop number i that should be retrofit with rainwater harvesting system; C_{PP} = cost of permeable parking lot implementation ($\$/ft^2$); C_{RHS} = cost of rainwater harvesting implementation ($/gallons).

Results

Considering LID technologies such as permeable pavement and rain water harvesting, optimization model was carried out based on different budget constraints and for three different design storms 2yr, 10yr and 100 yr. For the 2 yr design storm the model was evaluated based on 5 trails and the average performance for each budget options was estimated. Similar optimization was carried out for the other two design storms – 10 yr and 100 yr which was evaluated for only one trial. From these results we can observe a tradeoff between the total percentage of reduction of peak flow based on the implementation cost and this can be observed for the three design storms. Fig 11 illustrates the tradeoff between the cost and the hydrological impacts for the three storms. Fig – 12 illustrates the performance of LID with respect to each design storm and different area being converted to LID practices. It can be observed that for smaller storms the performance of LID increased with the increase in the area being retrofitted and decreased for intense storms. From the figure we observe that the improvement of reduction of peak flow reduces even with the increase in the area being retrofitted.

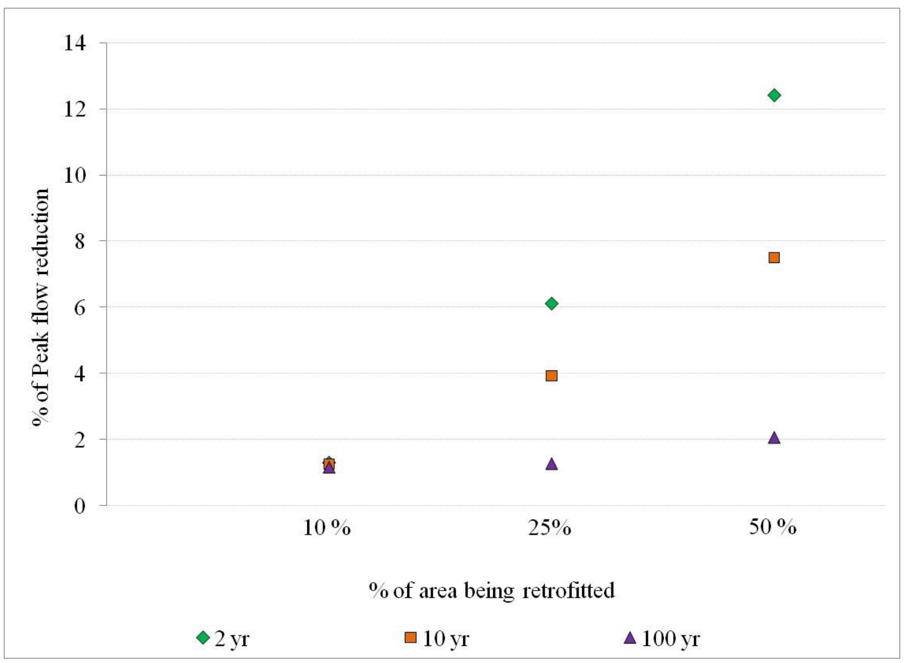

Fig. 11. Tradeoff between area being retrofitted to LID and percentage of peak flow reduction based on different design storms.

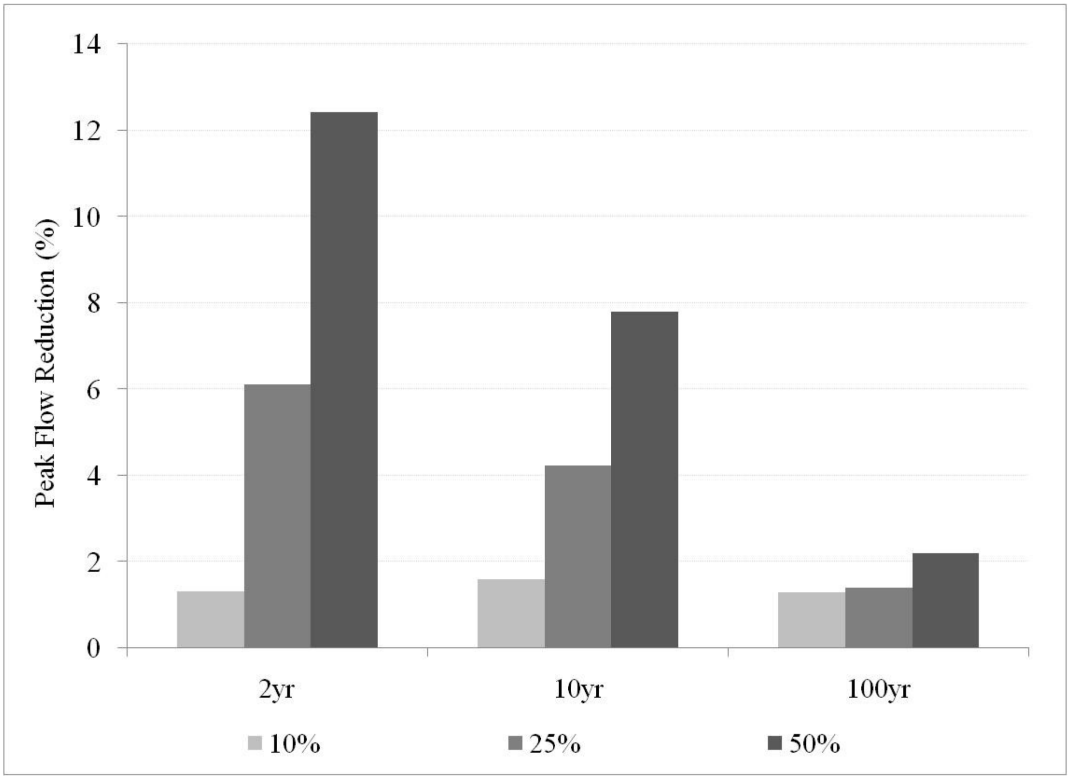

Fig. 12. Illustrates the performance of LID with respect to peak flow reduction based on different percentages of area being retrofitted and different storm events.

A comparative analysis is carried between the performance of the optimized solution of a particular design storm and evaluating that solution based on other design storms. Fig – 13 shows the tradeoff between the performances of the optimized solution of a particular design storm with respect to other design storms for the 50% scenario.

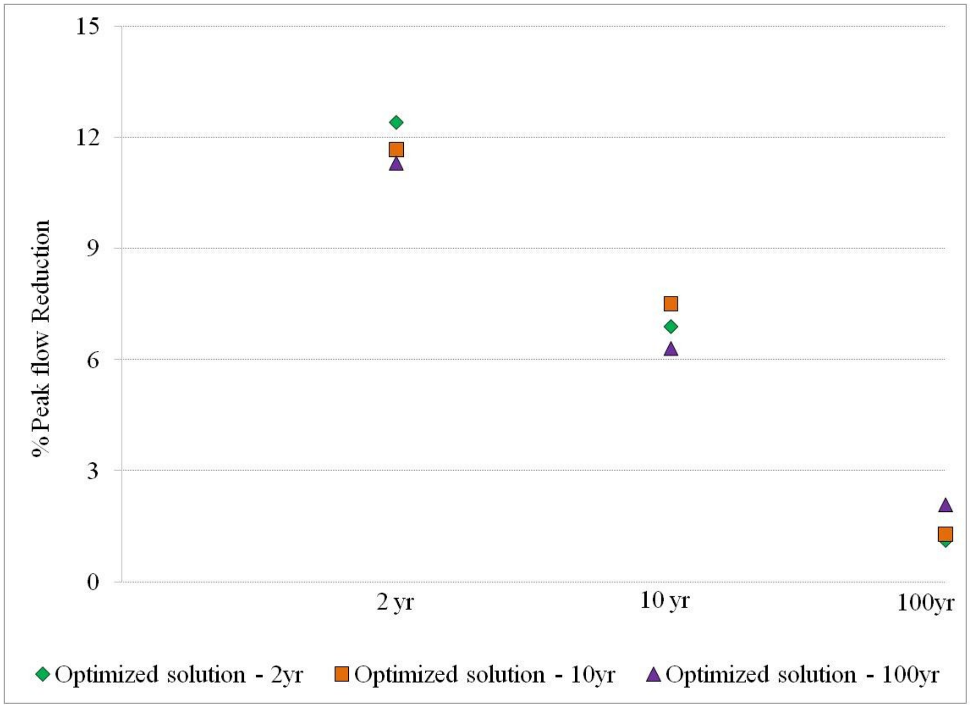

Fig. 13. Comparison between peak flow reduction of optimized solution of each storm and peak flow reduction evaluated based on optimal LID option for other design storms.

Discussion

With the consideration of different percentage of areas being retrofitted it can be observed that the performance of the storm water management strategy increases for all the different storms analyzed. The results shows that the performance of the LID on the hydrological impact based on the area considered to be retrofitted is increased effectively in smaller storms than in larger storms. Therefore, the performance of the LID depends on the percentage of area being retrofitted and the type of design storm it is analyzed for. From the comparative analysis, it is noticed that there is a tradeoff between the optimized solution for a design storm and the solution evaluated based on the characteristics of other storm optimized solution. Multi objective method should be implemented in the simulation-optimization framework to study the tradeoff between the performances of the LID solution for different storm events.

CHAPTER VI

OPTIMIZING PLACEMENT OF COMBINED LOW IMPACT DEVELOPMENT AND BEST MANAGEMENT PRACTICES IN URBAN WATERSHED

Solution Approach

Simulation optimization approach which was developed in the Chapter V is extended to include the decision of implementing a proposed detention pond. The simulation study carried out earlier lead to the discussion that combination of both centralized (BMP) and de-centralized (LID) type of mitigating strategies help in reducing the impact of urbanization caused by varied range of rainfall events both in flood control and improving the sustainability of the watershed. Therefore, to meet both sustainability and flood control combined approach of LID and BMP is implemented in the optimization model which is most cost effective in reducing the hydrological impact on the watershed. The framework will capture the implementation of designed detention pond in the watershed and share the budget to implement the LID choices to optimize the maximum reduction of peak flow within the budget constraint. As implemented in the LID optimization model, different areas being retrofitted are considered and different design storms are analyzed for the combined approach optimization.

Similar scenarios of different setting of area being retrofitted estimates the budget which is incorporated in the optimization model to find an optimal placement of these strategies in the watershed. In this study, a proposed detention pond is included as a decision of implementation. Design storms as considered earlier will be analyzed for different budget constraints to illustrate a tradeoff between the peak flow reduction and the cost. Implementation cost of detention pond is considered to be about 0.7 $/cubic feet (http://www.kalamazooriver.net/pa319new/docs/handouts/pond_costs_loads.pdf). Optimal design of LID and BMP would be obtained for each storm based on the different cost constraint which is implemented in the model as the different percentages of the area being retrofitted.

Model Formulation

$$\text{Maximize} \quad Q_o = PF_{EX} - PF_{LID} \tag{1}$$

$$\text{subject to} \quad \left[d \times C_{Det} \times D_{Det} \times A_{Det}\right] + \left[C_{PP} \times C_P \times \left[\sum_{i=1}^{P} A_i\right] + C_{RHS} \times C_R \times \left[\sum_{i=1}^{R} A_i\right]\right] \leq C_{Budget} \tag{2}$$

where Q_o = difference metric (cms); PF_{EX} = peak flow for existing conditions for a design storm event (cms); PF_{LID} = peak flow for a solution specifying LID strategies for a design storm event, which is calculated using a hydrologic/hydraulic modeling system (cms); P = decision variable indicating the parking lot number i that should be retrofit with permeable pavement; R = decision variable indicating the rooftop number i that should be retrofit with rainwater harvesting system; d = decision variable indicating whether detention pond will be implemented; D_{Det} = depth of the detention pond A_i = Area of parking lot i or rooftop i(km^2); A_{Det} = Area of the detention pond (km^2); C_{Det}= cost of detention pond implementation ($/cubic foot); C_{PP} = cost of permeable parking lot implementation ($/ft^2); C_{RHS} = cost of rainwater harvesting implementation ($/gallons).

C_P = conversion factor i.e. 10763910.4; C_R = conversion factor i.e. 26839773.12

Results

Considering permeable pavements, rain water harvesting as LID technologies and a detention pond the simulation and optimization framework was analyzed for different design storms – 2yr, 10yr and 100 yr. Each option of cost i.e. area being retrofitted was evaluated for each storm event once. Fig – 14 shows the results of optimal LID and BMP design. The tradeoff between the peak flow reduction and the implementation cost of this combined approach of LID and BMP with respect to different storms is illustrated in the Fig -14. It is observed that as the percentage of area being retrofitted to LID is increased peak flow reduction is increased for all the storms. The total budget is being shared for both the implementation of LID and BMP and as the detention pond for all the three storms is the same, the marginal improvement of the peak flow reduction is majorly contributed by only the LID.

Further the peak flow reduction is compared to the performance of implementing only BMP on the watershed peak flow. Fig – 15 shows the performance of different setting of area compared to implementing only BMP for all the design storms. From the figure it can be implied that the peak flow reduction is increased with the increase in the percentage of area being retrofitted. Therefore, both flood control and sustainability is achieved with the combined approach.

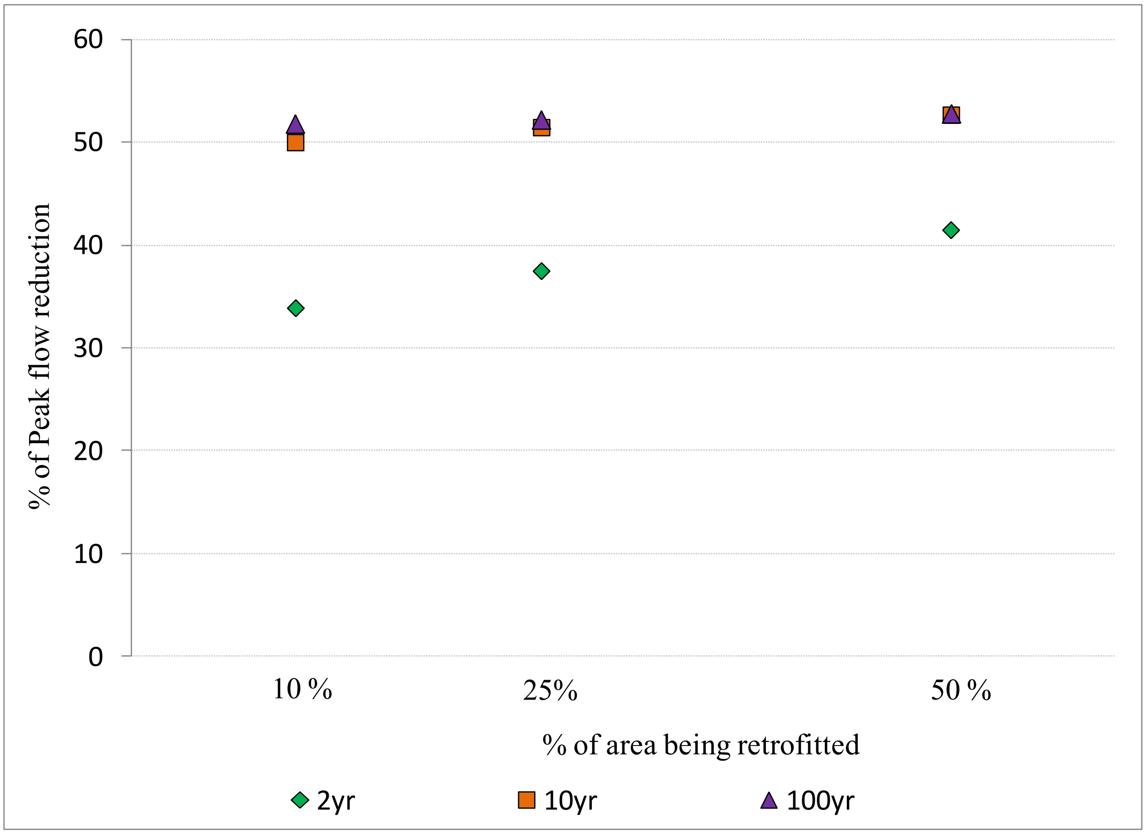

Fig. 14. Tradeoff between area being retrofitted to LID and BMP and percentage of peak flow reduction based on different design storms.

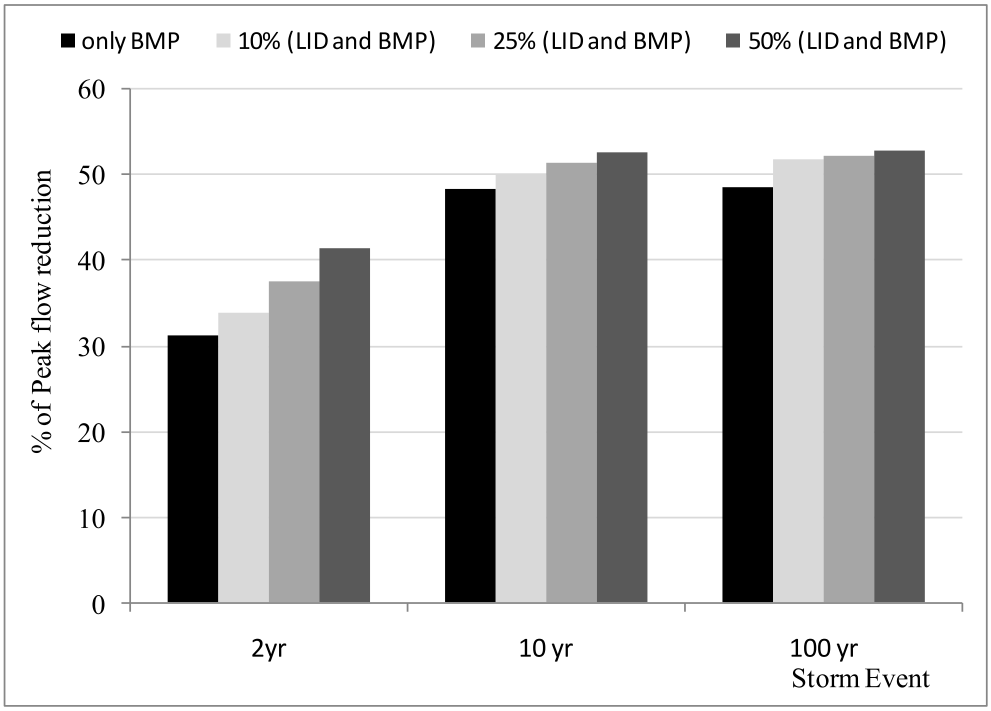

Fig. 15. LID and BMP approach performance compared with the option if implementing only BMP in the watershed based on different design storms.

A comparative analysis is carried between the performances of the optimized solution of a particular design storm and evaluating that optimized solution based on other design storms. Fig – 16 shows the tradeoff between the performances of the optimized solution of a particular design storm with respect to other design storms for 50% of the area being retrofitted. It is observed that the performance of the optimized solution when compared to other storms is almost similar. As the detention pond dimensions for all the design storms is the same, the driving parameter in the reduction of peak flow is majorly the detention pond.

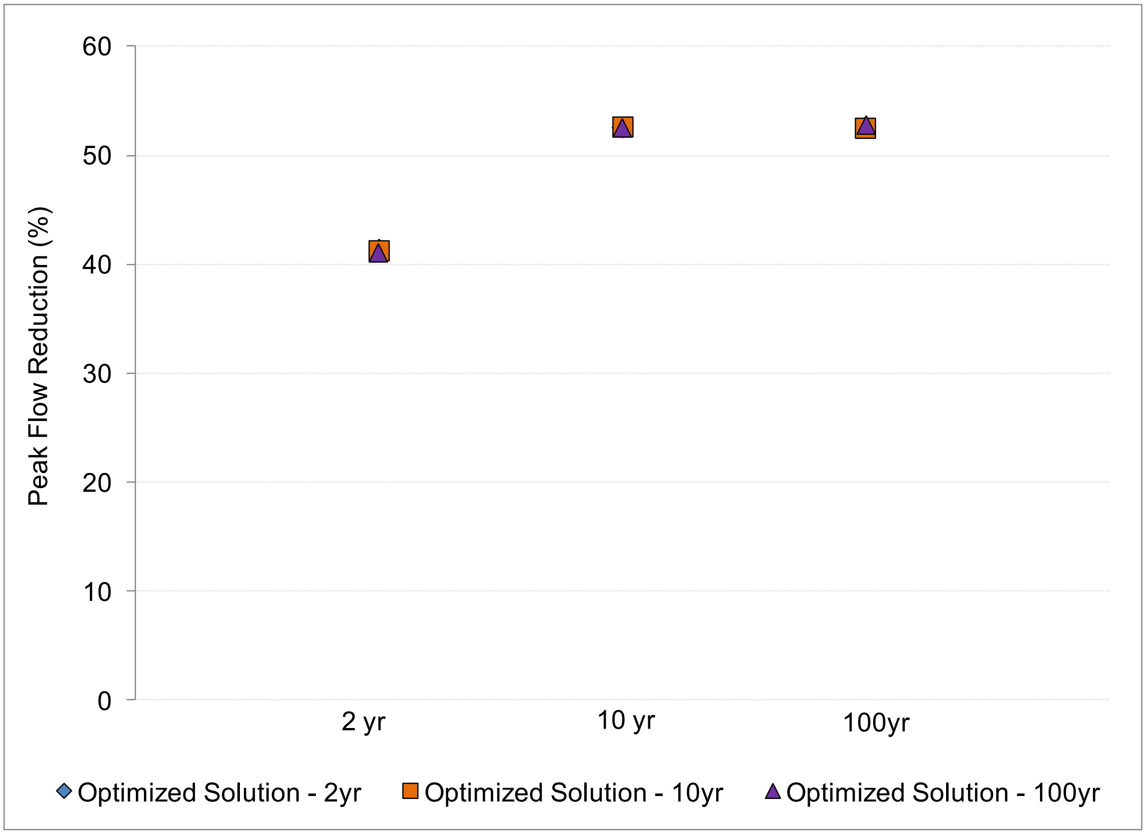

Fig. 16. Comparison between peak flow reduction of optimized solution of each storm and peak flow reduction evaluated based on optimal LID-BMP option for other design storms**.**

Discussion

The optimized solution for all the design storm and different area retrofitted lead us to conclude that the performance of the LID and BMP approach on the hydrological impact is better than implementing only LID or BMP. Performance of implementing only BMP and LID-BMP approach is compared and can be observed that the peak flow reduction increases with the increase in the area being retrofitted and the performance of LID-BMP approach is better than only BMP. As the detention pond design is the same for all the storms, not much of a difference is observed between the optimal solutions. Marginal tradeoff is noticed between the best optimal solutions for a particular design storm and when the solution is evaluated based on other design storms.

CHAPTER VII

CONCLUSION

A modeling approach was build to simulate LID in a watershed level which is further coupled with the simulation-optimization framework to evaluate the implementation of storm water management strategies and its impact on hydrology of watershed when compared to the existing scenario without any mitigating strategies. A varied spectrum of rainfall events need to be considered as the watershed management goals at meeting sustainability and flood control, therefore these storm water management strategies needs to be evaluated based on these storms. The simulation analysis conducted here indicates that infiltration-based LID technologies are more effective than BMPs for small storms, and storage-based BMP infrastructure is more effective for managing runoff from more intense storms. Different scenarios considered in the study indicated that combined approach of using LID and BMP is more effective in reducing the peak flow than using them individually. As BMP releases large volumes of runoff after a flood wave passed a reach, it impacts the downstream ecosystem. Therefore for evaluating the impacts of the mitigating strategies, a new metric HFR was used, which captures both temporal and spatial alterations. In evaluating and comparing various scenarios and different design storms, it was demonstrated that using the combined approach of LID and BMP helps in more effectively meeting both goals of watershed management, flood control and sustainability, when compared to these strategies individually.

Though the storm management strategies reduce the impacts of the development on the health of the watershed, implementation of these strategies in the watershed is dependent on the most cost effective approach that maximizes the reduction of the the hydrological impacts within the pre selected budget. Therefore, through optimizing the location and type of the LID technologies, the feasibility of the implementation of these in the watershed can be included. As observed from the results of optimization for smaller storm, as the budget increases, larger portions of the watershed are retrofitted with these strategies which reduce the peak flow. The improvement of storm water management is dependent on the implications, that is, the location and size, of the implementation cost of these strategies. As the storm event gets intense the impact of LID on the watershed reduces. Through this study, a tradeoff was identified between the implementation cost and the peak flow reduction for different areas being retrofitted and for different design storms.

The simulation-optimization framework is capable of optimizing appropriate storm water management approaches that are most cost effective to meet both the sustainability and flood control goals of watershed management. From the comparative study carried out to see the performance of an optimized solution of particular design storm based on the other storms, there is a marginal tradeoff on the performance of LID-BMP approach, which may be due to the same BMP configuration for all the storms.

Further optimizing the BMP design for different storms will explore the tradeoff of the performance of a particular optimized solution when evaluated based on other storms. This analysis can be completed by extending the framework to include multi objective optimization methods to explore the tradeoff of hydrological impacts for each design storm event considered. In addition, as different trials evaluated for the optimization of LID placement in the watershed resulted in different solutions with a similar peak and implementation cost. Future research can investigate alternative solutions. With these alternatives different set of solutions can be obtained which are different with respect to the decision variables but which results in a similar performance. This would be helpful for the storm water management decision makers to explore different solutions which results of same implementation cost and similar hydrologic impact reduction. Finally, the optimization framework can be extended to include different types of LIDs and BMP.

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