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Effectiveness of Low Impact Development Practices in Reducing Urban Stormwater Runoff Under Land Use and Climate Change Scenarios

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EFFECTIVENESS OF LOW IMPACT DEVELOPMENT PRACTICES IN REDUCING URBAN STORMWATER RUNOFF UNDER LAND USE AND CLIMATE CHANGE SCENARIOS

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ABSTRACT

Urbanization and climate change are the two major environmental concerns in today's world. It is important to quantify their effects on future runoff for sustainable water resources management. This study focused on measuring the increase in streamflow caused by land use and climate change using the Personal Computer Storm Water Management Model (PCSWMM). It was also desired to see the extent of stormwater reduction after a watershed-scale implementation of two main low impact development (LID) practices- namely rain garden and rain barrel. The model was successfully calibrated and validated for the baseline scenario with calibration period of 10 years (2006 to 2015) and validation period of 6 years (2000 to 2005). The corresponding values of NSE and R^2 were obtained to be 0.79 and 0.81 for calibration period and 0.81 and 0.83 for validation period respectively. For the increase in urban land use from 32.44% in 1992 to 81% in 2050, runoff was found to increase by 53.49%. Similarly, when the level of urbanization increased from 10% to 70%, runoff increased by a range of 24% to 120%. Evaluation of five high resolution NARCCAP climate change models predicted 36.44% to 70.12% increase in runoff. In the baseline case, the runoff decreased by 10% when using rain barrel only, by 21.3% when using rain garden only and by 34% when using both. Both LID practices were able to reduce runoff by 26.8% when installed in the future climate and urbanization case. It is recommended that LID practices be used synergically with improved drainage facilities for the successful management of stormwater in the imminent urbanization and climate change situation.

DEDICATION

To my dear friends and family

ACKNOWLEDGMENTS

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CHAPTER ONE

INTRODUCTION

1.1. Background

The growth of the United States population has occurred substantially since the last two centuries. Owing to this population increase along with other external factors like technological development and social reforms, urbanization in the US has also expanded exponentially. It is reported that since 1910, there has been nearly 500 percent growth in urban population, while the rural population has grown by 19 percent (U.S. Census Bureau, EPA Urbanization and Population Change). Urbanization occurs due to the conversion of forest and agricultural land to developed land for residential, commercial or industrial purposes. This results into increase in imperviousness cover; which in turn leads to a decrease in infiltration and an increase in stormwater runoff than those generated by natural or pervious surfaces (Harbor, 1994; Seth and Peters, 2011). In the long run, this land use change from pervious to impervious surface ultimately amplifies the risk of urban flooding (Hollis, 1975; Huong and Pathirana, 2013).

Stormwater management facilities like pipes, channels, manholes, etc. are constructed based on the historical streamflow data and with an assumption that future variability in stormwater runoff will not exceed past variability. This is a major assumption which stresses that the statistical parameters of hydrological variables remain constant over time without major fluctuations. But this expectation might not hold true when considering another main factor that affects stormwater runoff, which is climate change. Climate change is brought about due to the increase in certain active gases in the atmosphere. It is

predicted that the hydrologic cycle will become more progressive as the global mean temperature increases (IPCC, 2007). Evaporation rate and the number of extreme precipitation are likely to increase accordingly (Douglas and Fairbank, 2011). This will bring about various spatial and temporal changes in a basin's hydrology; which will in turn pose a challenge to the current drainage system that was designed based on a certain return period.

When coupled together, urbanization and climate change phenomena interact in a complex way to bring about major hydrological modifications that adversely affect water quality and quantity in a global, regional as well as basin scale.

Based on these considerations, a variety of concepts have been developed over time in an attempt to mitigate the increasing amount of urban runoff. Low Impact Development (LID) or Water Sensitive Urban Design (WSUD) is one of those ways that focuses on local treatment, retention, re-use, infiltration and conveyance of excess runoff with an overall goal to preserve the pre-development hydrology of a site (Prince George's County, 1999a). As opposed to the conventional stormwater management techniques, LID uses simple and cost-effective techniques (e.g. rain-garden, green roof and pervious pavement) that are not limited in their ability to protect the watershed and maintain its hydrological regime. The implementation of LID structures has proven to offer a more sustainable solution to stormwater management at both site-scale and watershed-scale (Roy et. al, 2008; Lee, 2012; Guan et. al, 2015).

1.2. Problem Statement

Due to the combination of population growth and urban development, land use changes have occurred significantly. Non-urban areas like forest and agricultural land have changed to semi-developed and developed urban areas resulting into increase in runoff (Kim et. al, 2002). Furthermore, extreme weather events occur owing to the ongoing climate change. This also increases the runoff and suggests that historical observations may not be a reliable guide to predict the future conditions (Waters et. al, 2003). It is important to quantify the exact effects in runoff due to these phenomena for proper long-term sustainable stormwater management strategies (Debo and Reese, 2002).

1.3. Objectives and Hypothesis

The main objective of this study is to assess the sensitivity of stormwater runoff from historical and projected land use scenarios across a range of hypothetical future climate change situations in an urban watershed. This study also aims to assess LID practice as an approach to mitigate the runoff at a watershed scale. The specific objectives are outlined below:

a. to develop a well-calibrated hydrological model of an urban watershed using a rainfall-runoff simulation model, PCSWMM
b. to quantify the change in runoff due to various land use and climate change scenarios
c. to evaluate the effectiveness of two major LID practices (rain garden and rain barrels) in reducing runoff

The underlying hypothesis driving this research is that *the performance of LID infrastructures to mitigate the potential increase in runoff due to urbanization and climate change scenarios is crucial for competent stormwater management.*

1.4. Significance of Thesis

It is prevalent that due to the increase in urbanization and uncertainty due to climate change, there is an ever-increasing demand of a novel stormwater management approach to protect human health and property. This research demonstrates how urbanization and climate change act as two major sources of urban runoff volume increase and evaluates the possibility of using LID techniques for its mitigation. This study will thus help water resource managers to make informed decisions that aim for significant overall reduction in stormwater runoff.

1.5. Thesis Outline

This thesis is divided into five chapters. Chapter one consists of the introduction. It contains the background information, problem statement, objectives and hypothesis, significance of thesis and thesis outline. Chapter two reviews the research work that have been done so far and justifies the development of a detailed hydrological model. Explanation to the theory related to model development and the working principles of PCSWMM are also discussed. Chapter three discusses the description of study area, datasets used, modeling using PCSWMM, calibration and validation of the model and different scenario analysis for varying land use, climate change and LID effects. Chapter four presents and discusses the results obtained from model simulations for each scenario.

Chapter five gives the summary of the whole work and simulation results. Moreover, this chapter also gives future recommendations based on the current study.

CHAPTER TWO

LITERATURE REVIEW

2.1. Urbanization and its impacts

A study by United Nations Department of Economic and Social Affairs' (UN DESA) Population Division reports that the urban population of the world has increased tremendously by 466% (from 746 million to 4.2 billion) over the span of 69 years (1950 to 2018). This report, which is titled World Urbanization Prospects 2018, also states that as of 2018, 55.3% of the world population live in urban areas and by 2050, that number is expected to reach 68.4%. In USA also, the urban population has consistently increased since 1950s, with the urban population percentage being 75.3%, 79.1%, 79.9%, 80.8% and 82.3% for the years 1990, 2000, 2005, 2010 and 2018 respectively. Again, this number is expected to reach 89.2% in 2050.

Urbanization causes changes in land use by activities like removal of trees and vegetation, building of infrastructures, diversion of stream to supply water for people, discharge of wastewater to stream, etc. (USGS Report). This results into increment of stormwater runoff as there is less vegetation to slow water down due to an increase in impervious areas (White and Greer, 2006; Francisco and DeFee, 2007; Du et. al., 2012). Also, the amount of sediment washed into stream increases which impacts its water quality (Hall et. al., 1999; Ren et. al., 2003; Tu, 2011) and causes pollution, thus harming the ecosystem and natural habitat of aquatic animals and plants (Chadwick et. al., 2006; McKinney, 2008; Seto et. al., 2012). The replacement of natural landscape by impervious surface also results into less water being infiltrated, which in turn leads to lowering of the

water table (Murabayashi and Fok, 1979; Foster et. al., 1994; Carlson et. al., 2011). Due to the modifications in natural water-drainage patterns and decrease in infiltration, more stormwater runoff occurs frequently. This increased amount must be collected and carried to streams by a combination of drainage system consisting of inlets, curbs, storm sewers, and ditches. Since more water arrives in the streams more frequently, there is an increased risk of severe flooding (Hammer, 1972; Nirupama and Simonovic, 2007; Suriya and Mudgal, 2012; Jinkang et. al., 2012).

Figure 2.1 compares some important processes involved in rainfall-runoff process and shows how runoff is increased in urban scenario.

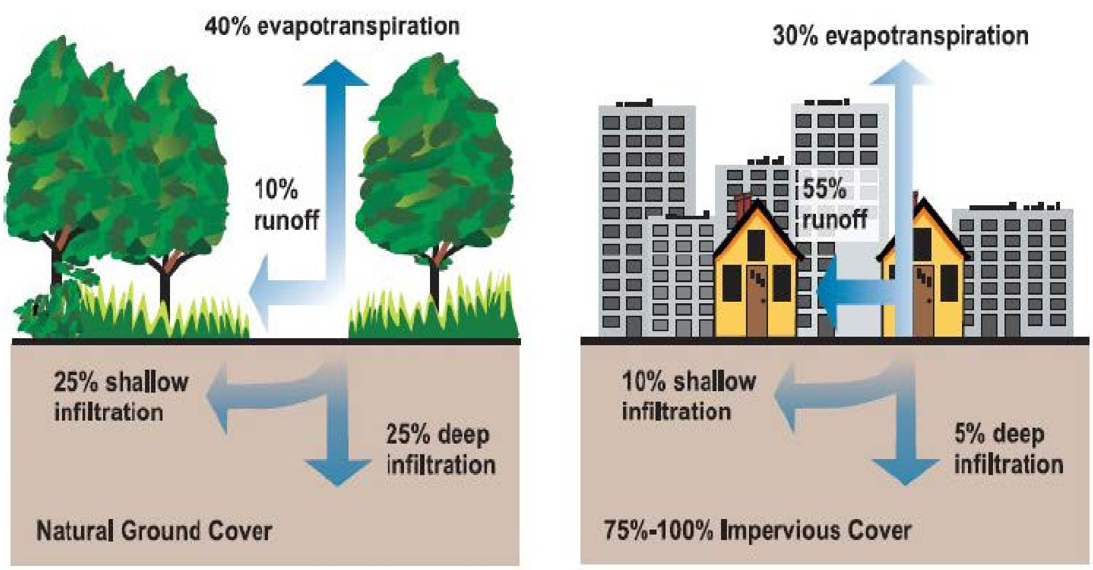

Figure 2.1: Natural versus Urban Runoff Response (Source: USEPA, 2003)

2.2. Conventional Stormwater Management

To provide good drainage, it is crucial to remove stormwater runoff from a site as quickly and as efficiently as possible. For this, design of an efficient stormwater runoff conveyance system is prioritized in any community; so that runoff is conveyed in a systematic and timely manner to a centrally located management device and eventually to a nearby stream (Stahre, 2006). In a classical stormwater management system, decrease in runoff volume and frequency is emphasized for the protection of human health and property, but a low priority is given for ecosystem preservation and water quality issues due to stream degradation (Roy et. al., 2008). There is a limited concern to enhance the reusability of water, decrease travel times and detain or infiltrate runoff (Prince Georges' County report, 2006). In addition to this, previous studies (Wilderer, 2004; Zevenbergen et. al., 2008; Burns et. al., 2012) have been concerned about the long-term effectiveness and sustainability of traditional drainage systems, many of which talk about their interference with environment- focusing on the costs and time needed for its installation and maintenance. These factors, combined with ever-increasing urbanization and climate change phenomena, demand a new, improved and cost-effective drainage system that not only reduces stormwater volume, but also reproduces predevelopment hydrological functions and protects aquatic biodiversity (Zahmatkesh et. al., 2014, Zhou, 2014).

2.3. Low Impact Development Techniques

2.3.1. Introduction

One such innovative technique which ensures that post-development hydrology of a site closely resembles its natural condition is called low impact development (USEPA, 1999a). USEPA defines LID as "systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat". It promotes the natural movement of water within a watershed, minimizes effective imperviousness and treats stormwater as a resource, rather than a waste product. USEPA further states that when applied on a broad scale, LID can maintain or restore a watershed's hydrologic and ecological functions.

Although there are different terminologies for LID across different regions, the objectives are more or less the same. Terms like Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage System (SUDS), Low Impact Urban Design and Development (LIUDD), Green Infrastructure (GI) and Best Management Practices (BMP) are used interchangeably in Australia, Europe, New Zealand and USA respectively. Detailed planning and design techniques also vary for each region- according to their own county, state and federal regulations. However, the main goals of such techniques are to combine key elements to perform all the functions of a traditional drainage system, along with the protection of environment and reduction of construction and maintenance costs of the stormwater infrastructure (Figure 2.2).

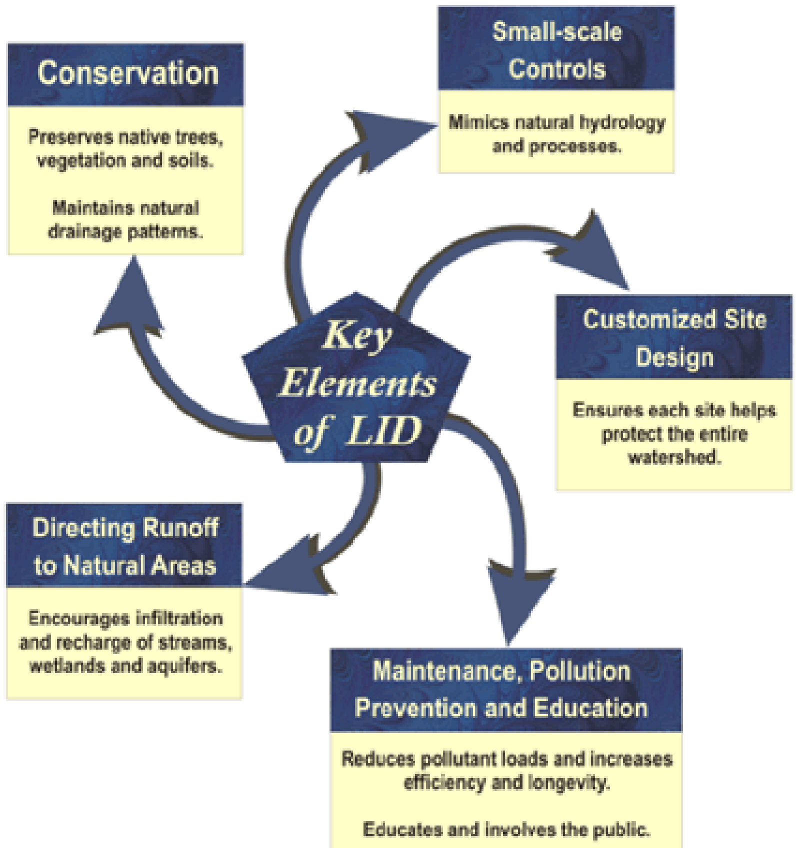

Figure 2.2: Key Elements of LID (Source: Guillette and LID Studio, 2010)

2.3.2. LID practices

There are various LID practices that are implemented world-wide having their own unique functions and stormwater management techniques. According to USEPA 2000, the type of LID practices used depends on site conditions such as soil type, impervious surface, slope and water table depth. Previous studies have shown promising results for both individual and combination of LID controls like porous/pervious pavements (Legret and Colandini, 1999; Ahiablame and Shakya, 2016), bioretention areas/rain gardens (Dietz and Clausen, 2005; Davis, 2008), rain barrels (Abi Aad et. al., 2009; Jones and Hunt, 2010), grass swales (Abida and Sabourin, 2006; Stagge et. al., 2012) and vegetative roofs (Carter

and Todd, 2006; Carter and Jackson, 2007) among many others. They are designed to capture and temporarily retain stormwater (rain barrels), infiltrate stormwater (rain gardens, porous pavement) and promote evapotranspiration (vegetative roofs, rain gardens) (USEPA 2000). For this study, we consider two of these LID practices and explain them in brief.

A. Rain Garden

Rain garden is a depressed area that collects rain water from impervious areas like parking lots, individual home or small commercial facilities; and allows it to soak into the ground (USEPA 2000; SCDHEC BMP Handbook). It also filters out impurities in water, thus improving its quality and decreases runoff by enhancing infiltration. Moreover, it consists of three or more native plant species; which provide a habitat to butterflies and other wildlife, transpire runoff and improve the aesthetics of its surroundings (Figure 2.3). Technically, if a rain garden consists of an underdrain system, it is called a bioretention area. However, in usual practice, those two words are used interchangeably.

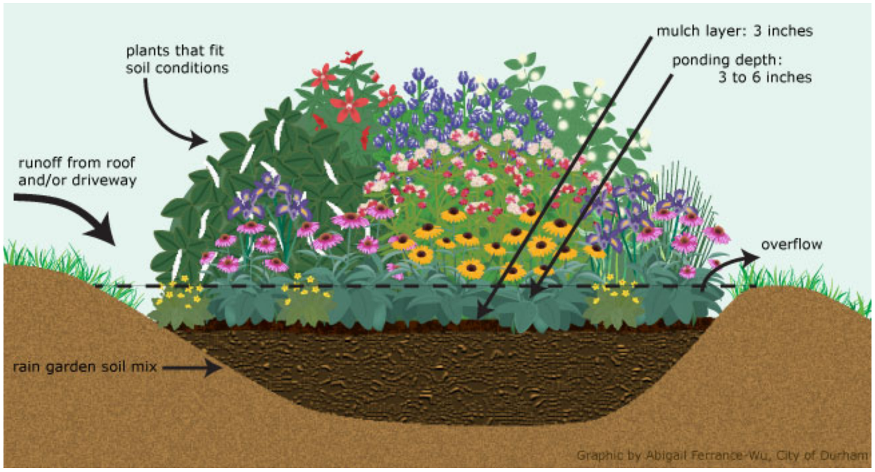

Figure 2.3: Rain garden and its components (Source: Abigail Wu, Durham)

According to SCDHEC, the minimum width of a rain garden should be 10 feet and its surface area is calculated either by using North Carolina Extensive Service (1999) equation (Equation 1) or Prince George's County equation (Equation 2) as shown below.

$$A = \frac{DA * R_v}{D_{avg}} \qquad \textit{Equation 1}$$

$$A = 0.1\ (R_v)\ (DA) \qquad \textit{Equation 2}$$

Where:

A	=	Rain garden surface area (sq. ft.)
DA	=	Contributing drainage area of rain garden (sq. ft.)
R_v	=	Runoff volume (ft); 1-inch or 0.083 ft for SCDHEC
D_{avg}	=	Average ponding water depth above ground (feet)
0.1	=	Empirical conversion factor

SCDHEC further explains that the planting mix needs to be installed at 0% grade and maximum ponding depth should not exceed 12 inches. The soil should contain mostly sand (60-75%), silt (25%) and organic compost (10%). Minimum depth can vary from 1.5 ft to 4 ft according to the types of plants used. Below the soil, 2 to 3 inches deep mulch layer should be applied to reduce erosion, maintain soil moisture, trap fine sediments and promote the decomposition of organic matter. In addition to these components, pre-treatment area consisting of grass buffer strip of vegetated swale can also be installed. Regular inspection and maintenance like replacement of mulch, removal of trash, pruning and weeding, etc. needs to be done periodically for the effective operation of a rain garden.

B. Rain Barrel

USEPA (2000) defines rain barrel as special cisterns used to “capture water from a roof and hold it for later use such as on lawns, gardens or indoor plants”. The principle behind a rain barrel is quite simple: the collection roof runoff reduces the amount of water that flows in a property and delays the peak runoff. Moreover, since the collected water can be reused, it is a sustainable form of stormwater management. Its size depends upon the rooftop surface area and amount of rainfall to be stored. For example, one 42-gallon barrel provides 0.5 inch of runoff storage for a rooftop area of approximately 133 square feet (Prince George’s County, 1999a). Water is transported from the rooftops into the barrel with the help of gutters and down spouts (Figure 2.4). Rain barrels usually consist of overflow and drain outlets. The drain outlet can be connected to a garden hose and the water can be used for irrigation. However, care must be given not to use this water on edible plantings, as it contains impurities and bacteria from roof materials. Periodic maintenance of rain barrels need to be done for higher efficiency. Gutters should be equipped with filtration screens to prevent clogging of debris.

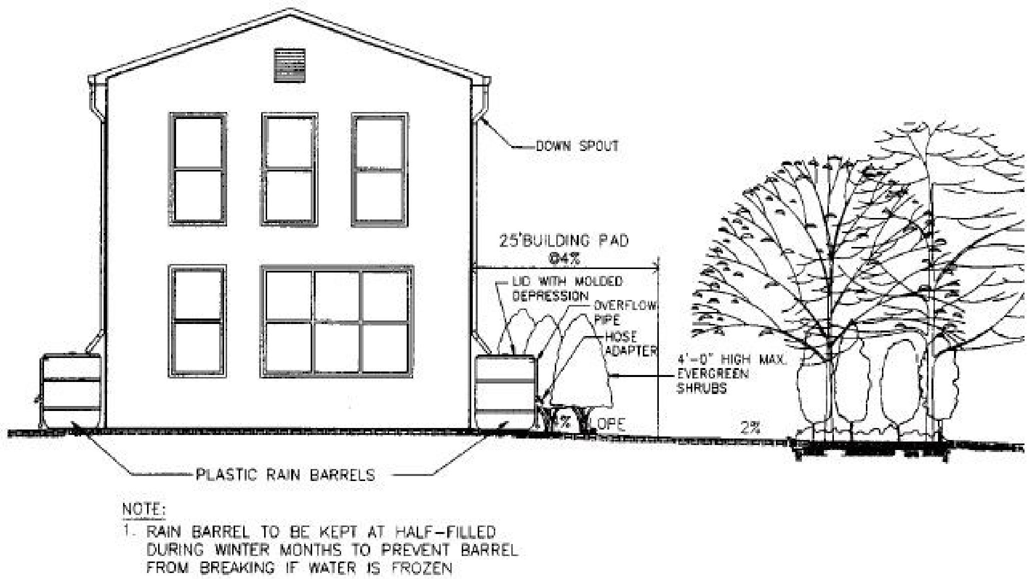

Figure 2.4: Typical rain barrel usage (Source: Prince George's County, 1999a)

2.3.3. Effectiveness and limitations of LID controls

Many studies have been conducted to check the performance of LID over time, how they behave immediately after installation and when maintenance is required. Its performance is checked based on the criteria like the amount of runoff detained, types and extent of pollutants removed and its long-term sustainability. Previous studies have been conducted to review LID effectiveness in both water quantity and quality measures.

Davis (2008), Line and Hunt (2009), Chapman and Horner (2010) and DeBusk and Wynn (2011) reported up to 58%, 49%, 74% and 97% reduction in runoff respectively after the use of bioretention areas. Moreover, several researches by DeBusk and Wynn (2011), Davis (2008), Rusciano and Obropta (2007), Hunt et al. (2006), Hsieh and Davis (2005) and Roseen et al. (2006) highlight the success of bioretention system to improve water quality by removing pollutants like total suspended solids (up to 99%), nitrates (up to 83%),

fecal coliform (up to 92%), copper (up to 99%), lead (up to 98%), zinc (up to 99%), phosphorus (up to 98%) etc. In the case of rain barrels, studies by Trieu et al (2001), Jones and Hunt (2010), Stephen et. al. (2013) and Jennings et. al. (2012) report 11.5%, 58%, 17% and 7% reduction in stormwater runoff volume respectively.

However, there are studies which doubt the performance and feasibility of LID controls, especially if regular maintenance is not conducted. For example, their efficiency can decrease over time due to clogging issues (Hsieh and Davis, 2005; Hsieh et. al., 2007; Bergman et. al., 2011). Asleson et. al. (2009) also found out that they could not reach their expectations for reduction in drain time of rain garden due to restrictions caused by existing soil. Some researchers are also concerned about the ability of the infiltration-based LID systems to perform in the winter and about the possible contamination of groundwater due to absorption of impurities (Dietz, 2007). It was also found that in some cases, the reduction of runoff volume after the implementation of LID is lesser than expected in extreme events and this reduction is highly sensitive to local conditions (Nascimento et. al., 1999; Holman-Dodds et. al., 2003).

Details of the effectiveness and limitation of various LID practices are explained in review papers by several researchers like Dietz (2007), Roy-Poirier et al. (2010), Ahiablame et. al. (2012) and Zhou et. al. (2014).

2.3.4. LID implementation levels

To assess the effectiveness of LID practices, many studies have been performed across various regions at both site-scale (Dietz and Clausen, 2005; Muthanna et. al., 2008; Line et. al., 2011) and watershed-scale (Zahmatkesh et. al., 2014; Akhter et.al., 2016;

Ahiablame and Shakya, 2016) levels. Both modeling approaches are equally important to evaluate LID benefits for proper planning and decision-making process.

Site-scale evaluation is a traditional method which involves micromanagement of hydrology and control of stormwater at the source. In this case, identification and preservation of sensitive areas like streams, floodplains, soil, steep slopes, etc. occur at a microsubshed level. Since it is conducted at a smaller spatial scale, it uses data having a higher resolution and thus is more accurate than the watershed-scale analysis. However, it is costlier and more time consuming due to the fine nature of data that needs to be evaluated.

On the other hand, watershed-level modeling can be useful in identifying target areas for LID implementation, avoiding costly individual hydrologic analysis of LID features during each design. Using this technique, broad scale evaluation of LID site selection and its effects can be studied, and priority sites can be selected using data of little or no costs (Martin-Mikle et. al., 2015). Watershed-scale evaluation tests the feasibility of a site for LID implementation using a “top-down” approach rather than the traditional “bottom-up” approach (Fleischmann, 2014). This is important especially because most community and watershed-level land use management planning decisions are usually performed at a larger scale. Also, since there are many uncertainties regarding the effectiveness and feasibility of LID practices -especially in the ever-increasing urbanization and climate change settings- it can be cost effective to first check the usefulness of LID controls at a much bigger scale and then if that gives promising results,

move on to the small-scale evaluation. Thus, the top-down watershed-level approach is a very important method to study LID performance.

2.4. Climate change

According to the 2007 report by Intergovernmental Panel on Climate Change (IPCC, 2007), climate change can be defined as "*a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.*" The report also says that climate change refers to any change in climate over time, whether due to natural variability or because of human activity. NASA's Global Climate Change report states that climate change is mainly caused by human expansion of the greenhouse effect, which occurs when gases like nitrous oxide, methane, water vapor and carbon dioxide in the atmosphere traps heat radiating from Earth, thus raising its temperature. In a broad sense, climate change affects many sectors important to society- such as human health, agriculture and food security, water supply, transportation, energy, ecosystems, etc. (McMichael et. al., 2006; Nelson et. al., 2014; Schmidhuber and Tubiello, 2007; Jentsch and Beierkuhnlein, 2008). It also changes the global hydrological cycle by increasing precipitation, evaporation and runoff and also the number of extreme events (Mishra and Singh, 2010[1,2]).

The scientific community has been trying to develop several models to reliably estimate the changes in regional climate due to anthropogenic emissions (Mearns et. al., 2013). Meehl et. al. (2007) describe that out of many, there are two major uncertainties in determining future climate: the trajectories of future emissions of greenhouse gases and

aerosols, and the response of the global climate system to it. Atmosphere- ocean general circulation models (AOGCMs, or GCMs hereafter) have, to some extent, tried to remove these uncertainties, but at a relatively coarse spatial resolution (100-300 km). Another technique is the use of dynamical regional climate models (RCMs) to downscale multiple coupled GCMs to obtain climate projections at the scale of tens of kilometers, rather than the hundreds of kilometers that the GCMs provide (Sobolowski and Pavelsky, 2012). One such program is the North American Regional Climate Change Assessment Program (NARCCAP), which uses RCMs driven by GCMs forced with the A2 and A1B SRES scenarios for the 21st century (2041-2070), over a domain covering the conterminous US and most of Canada (http://www.narccap.ucar.edu/). The same sets of models were also used to produce simulations for the current (historical baseline) period of 1971 to 2000. All the RCMs are run at a spatial resolution of 50 km. The current regional models participating in NARCCAP are given below:

- CRCM (Canadian Regional Climate Model / le Modèle Règional Canadien du Climat)
- ECP2 (Experimental Climate Prediction Center Regional Spectral Model)
- HRM3 (Hadley Regional Model 3 / Providing REgional Climates for Impact Studies)
- MM5I (MM5 – PSU/NCAR mesoscale model)
- RCM3 (Regional Climate Model version 3)
- WRFG (Weather Research and Forecasting Model)

Similarly, the names of the 4 driving AOGCM models are given below:

- CCSM (Community Climate System Model)
- CGCM3 (Third Generation Coupled Global Climate Model)
- GFDL (Geophysical Fluid Dynamics Laboratory GCM)
- HadCM3 (Hadley Centre Coupled Model, version 3)

The different RCM-GCM combinations simulated in NARCCAP are shown in Table 2.1 below.

Table 2.1: RCM-GCM combinations

RCM	**Driving model**			
	CCSM	**CGCM3**	**GFDL**	**HadCM3**
CRCM	x	x		
ECP2			x	x
HRM3			x	x
MM5I	x			x
RCM3		x	x	
WRFG	x	x		

Even though the process of downscaling data produces a fine resolution dataset similar to the observed data, it has a slightly different distribution, mean or standard deviation. This is due to the biases found in the GCM and RCM. The first step of climate change study is removing these biases. This allows datasets from multiple GCM-RCM combinations to be compared to each other. For this, several bias correction methods have been developed, each of which have its own level of success (Teutschbein and Seibert, 2012). One of such methods is distribution mapping which uses a transfer function that systematically adjusts individual data points such that the cumulative distribution function (CDF) of the model data matches the CDF of the observations. When this mapping is done

using empirical CDFs, it is called quantile mapping. Maraun (2013) suggests that if the observations are of similar resolution as the regional climate model, quantile mapping is a practical approach.

Many researchers have incorporated NARCCAP model into their study. Thakali et. al. (2017) evaluated different combinations of GCMs and PCMs in the NARCCAP climate experiment for two watersheds in Las Vegas valley using HEC-HMS. They concluded that existing design standard for stormwater may not be valid anymore and existing flood control facilities may not be able to convey the projected flow due to the changing climate. Takle et. al. (2010) used Soil and Water Assessment Tool (SWAT) in the Upper Mississippi River Basin (UMRB) and observed that climate models from NARCCAP were able to capture extremes flows represented by the flood of 1993 and the dry conditions of 2000. The models were also able to correctly simulate the seasonal cycle of precipitation, temperature, and streamflow. In a study by Najafi and Moradkhani (2015), eight RCM-GCM combinations were used, and it was found that extreme runoffs were predicted to increase during fall and decrease during summer over the Pacific Northwest area.

2.5. SWMM and PCSWMM

USEPA Storm Water Management Model (SWMM) is a computer program that computes dynamic rainfall-runoff for single event and long-term (continuous or period-of-record) runoff quantity and quality. The runoff component of SWMM consists of subcatchment areas that receive precipitation and generate runoff and pollutant loads in each subcatchment. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage and treatment devices, pumps, and regulators ad tracks the flow

rate, flow depth, and quality of water in each component (James et. al., 2005). Since its development in 1971, it has undergone several major updates and been extensively used for planning, analysis and design of drainage system for successful management of stormwater runoff in both urban as well as non-urban areas. The current version SWMM is Version 5 which consists of an innovative color-coded environment for editing data, inputting time series graphs and table, viewing results and modeling various types of LID practices.

Personal Computer Storm Water Management Model (PCSWMM) is a proprietary stormwater modelling software that integrates the SWMM5 computational engine with a geographic information system. PCSWMM has a better Graphical User Interface (GUI) which allows easy transfer of files and is thus easier to use and more user-friendly. It is also equipped with training videos and tutorials along with interactive online help and expert consultation (https://www.chiwater.com/Training/).

In PCSWMM, there are four main compartments (listed below) which are used to model a drainage system.

- Atmosphere compartment: It is modeled by Rain Gage through which rainfall inputs are given.
- Land Surface compartment: It consists of Subcatchment objects, which are smaller discretized units of the study area that receives rainfall and pollutant from both the Atmosphere compartment and fellow upstream subcatchments. Outflow comprises of infiltration, evaporation, and surface runoff. Each subcatchment surface is treated as a nonlinear reservoir with a maximum capacity equal to the maximum

depression storage (d_p) provided by ponding, surface wetting and interception. Runoff (Q) occurs when depth of water (d) exceeds d_p (Figure 2.5) and is represented by the continuity equation (Equation 3). The outflow is then given by Manning's equation (Equation 4). Runoff from a subcatchment is directed to a single discharge point called outlet. Each subcatchment also consists of Pervious and Impervious areas (Figure 2.6).

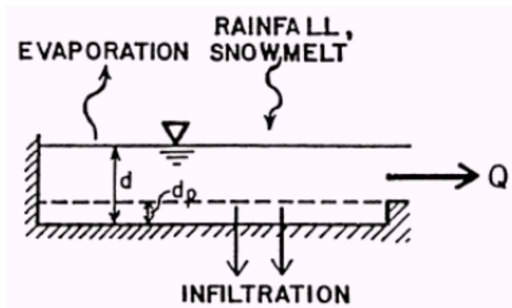

Figure 2.5: Conceptual view of surface runoff (Source: Rossman, 2004)

$$\frac{dV}{dt} = A\frac{d(d)}{dt} = Ai^{*} - Q \qquad \textit{Equation 3}$$

$$Q = \frac{Wk}{n}(d - d_p)^{5/3}S^{1/2} \qquad \textit{Equation 4}$$

Where:

V	=	Volume of water on the subcatchment
t	=	Time
A	=	Surface area of subcatchment
i*	=	Rainfall excess (Rainfall minus evaporation/infiltration rate)
W	=	Subcatchment width
k	=	Conversion factor

n	=	Manning's roughness coefficient
S	=	Subcatchment slope

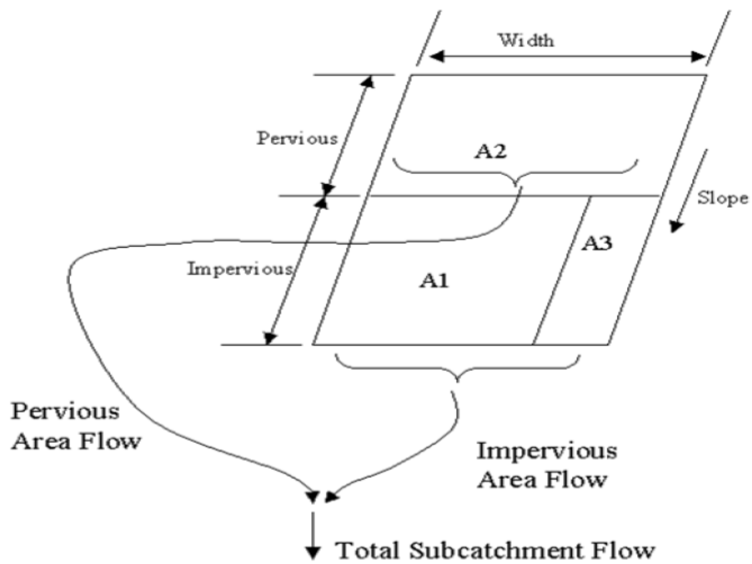

Figure 2.6: Subcatchment Schematization (Source: James et. al., 2005)

- Groundwater compartment: It is modeled by Aquifer objects and are optional in a model. When added, it receives infiltration from the Land Surface compartment and transfers part of it to the Transport compartment
- Transport compartment: It consists of Node and Link objects like Junction, Conduit, Divider, Storage Unit, Outfall, etc. and represents a network of conveyance elements (channels, pipes, pumps, and regulators) and storage/treatment units that transport water to outfalls or to treatment facilities (Figure 2.7).

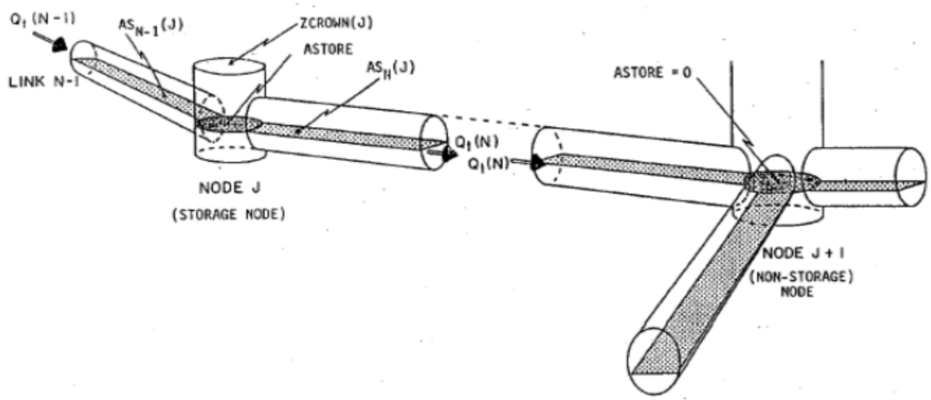

Figure 2.7: Transport Component in SWMM (Source: Roesner et. al., 1992)

Figure 2.8 shows examples of the physical objects used in SWMM modeling.

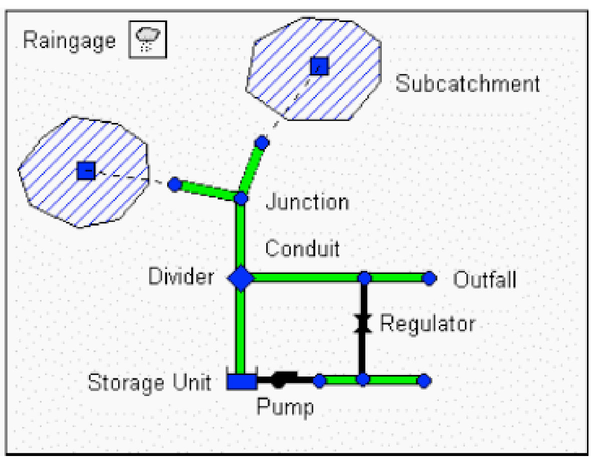

Figure 2.8: Some physical objects used in SWMM (Source: James et. al., 2005)

In SWMM, a combination of vertical layers is used to represent LID controls. The properties of each layer are defined on a per-unit-area basis allowing them to be implemented in multiple subcatchments of different sizes. Evaporation, infiltration, runoff and storage of water through each layer is tracked by performing a moisture balance. Figure

2.9 shows a conceptual representation of a bioretention cell and Table 2.2 shows the layers used in different LID controls (x means required, o means optional).

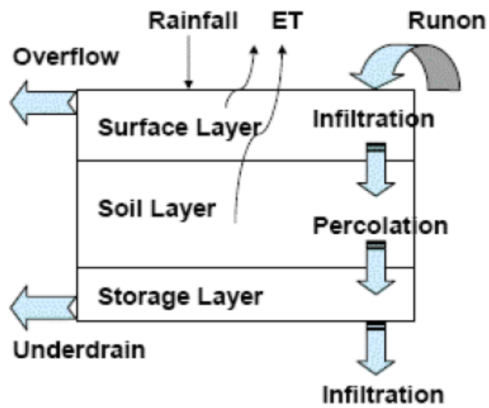

Figure 2.9: Representation of a bioretention cell (Source: James et. al., 2005)

Table 2.2: Layers used to model LID practices

LID Type	Surface	Pavement	Soil	Storage	Underdrain
Bio-retention Cell	x		x	x	o
Porous Pavement	x	x		x	o
Infiltration Trench	x			x	o
Rain Barrel				x	x
Vegetative Swale	x				

CHAPTER THREE

METHODOLOGY

3.1. Outline

The flowchart in Figure 3.1 outlines the general methodology adopted for analysis in this study.

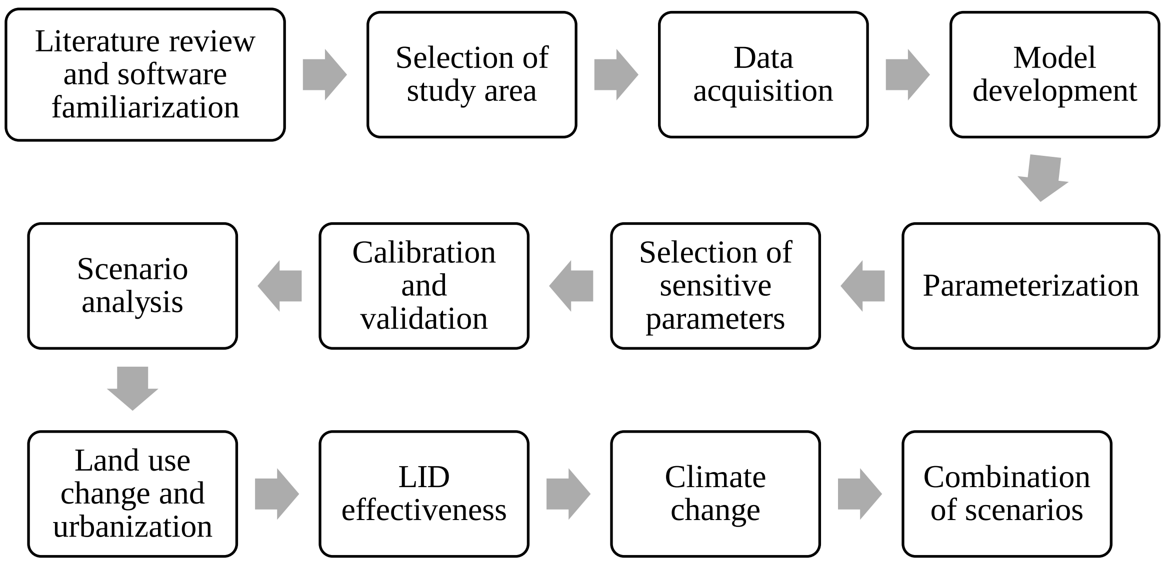

Figure 3.1: Summary of Methodology

3.2. Study area

This research focuses on a 138 sq.km watershed (Figure 3.2) in South Carolina that ranges from Lake Murray in the west to West Columbia in the east (Figure 3.3). It is a part of Saluda River Basin. 70% of this area lies in Lexington County while the rest 30% lies

in Richland county. It comprises of two sub watersheds: Upper Congaree River (80%) and Outlet Saluda River (20%). The main stream in UCR basin is Saluda River. This river runs from Lake Murray to OSR basin and then merges with Broad River to form Congaree River. The approximate lengths of Saluda river and Congaree river within the watershed are 16 km and 6 km respectively. The outlet of this area lies in OSR basin.

This site is characterized by a variety of land cover types, including forests and cultivated land. Most of the area is developed with large-lot family housing units. The eastern part of the study area consists of highly developed Downtown Columbia region with a mixture of park, residential and commercial areas. The average annual rainfall received by the watershed is 45 in and the average daily temperature ranges from 33°F to 93°F. Details of land use distribution is given in Table 3.1.

Table 3.1: Land use distribution within the study area (NLCD 2011)

Land use type	**Percentage of watershed area**
High Intensity Developed	36.76
Low Intensity Developed	31.66
Grass/Pasture	4.57
Forest/Woods	20.87
Agricultural	0.11
Water/Wetland	4.75
Bare land	1.26

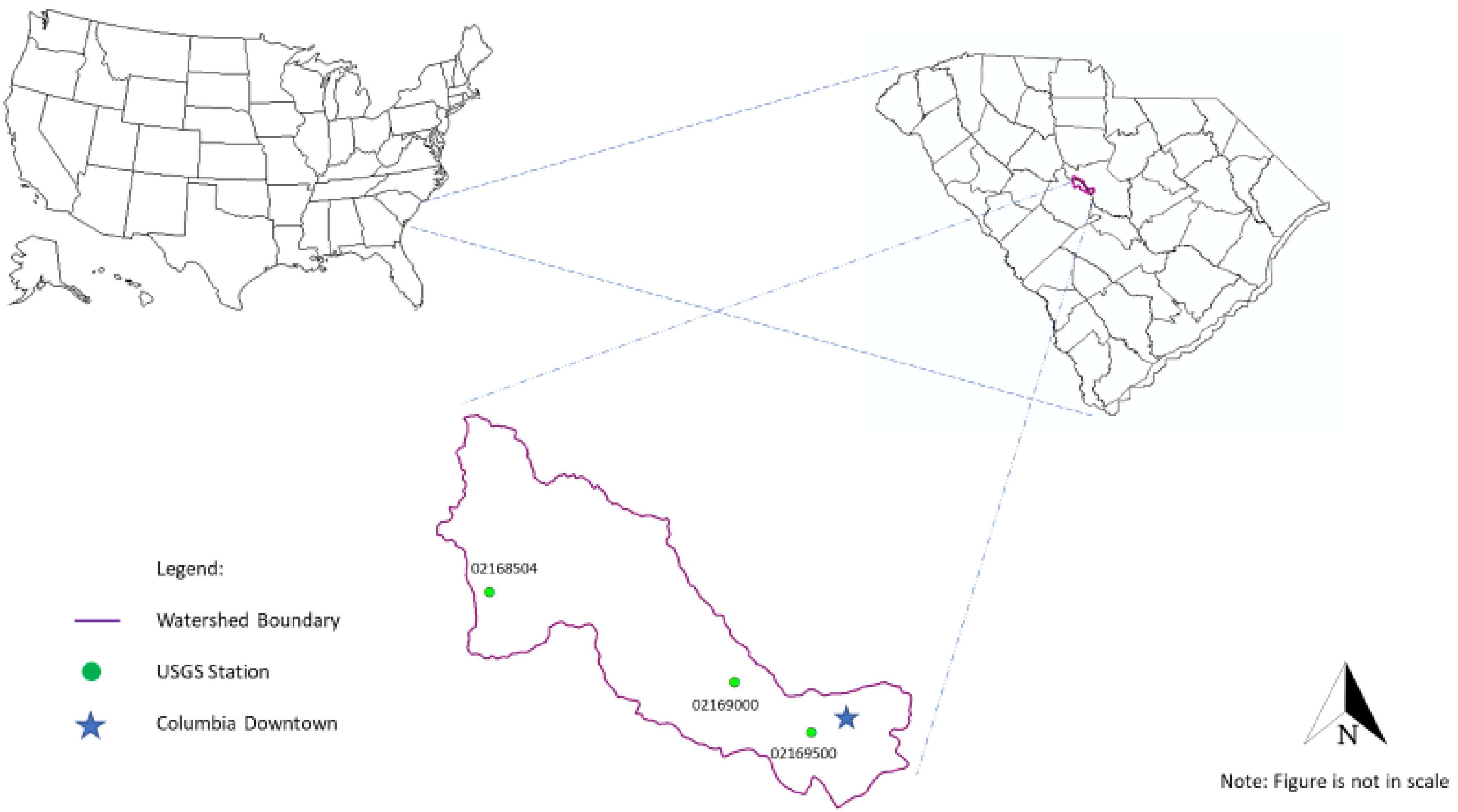

Figure 3.2: Location of study area

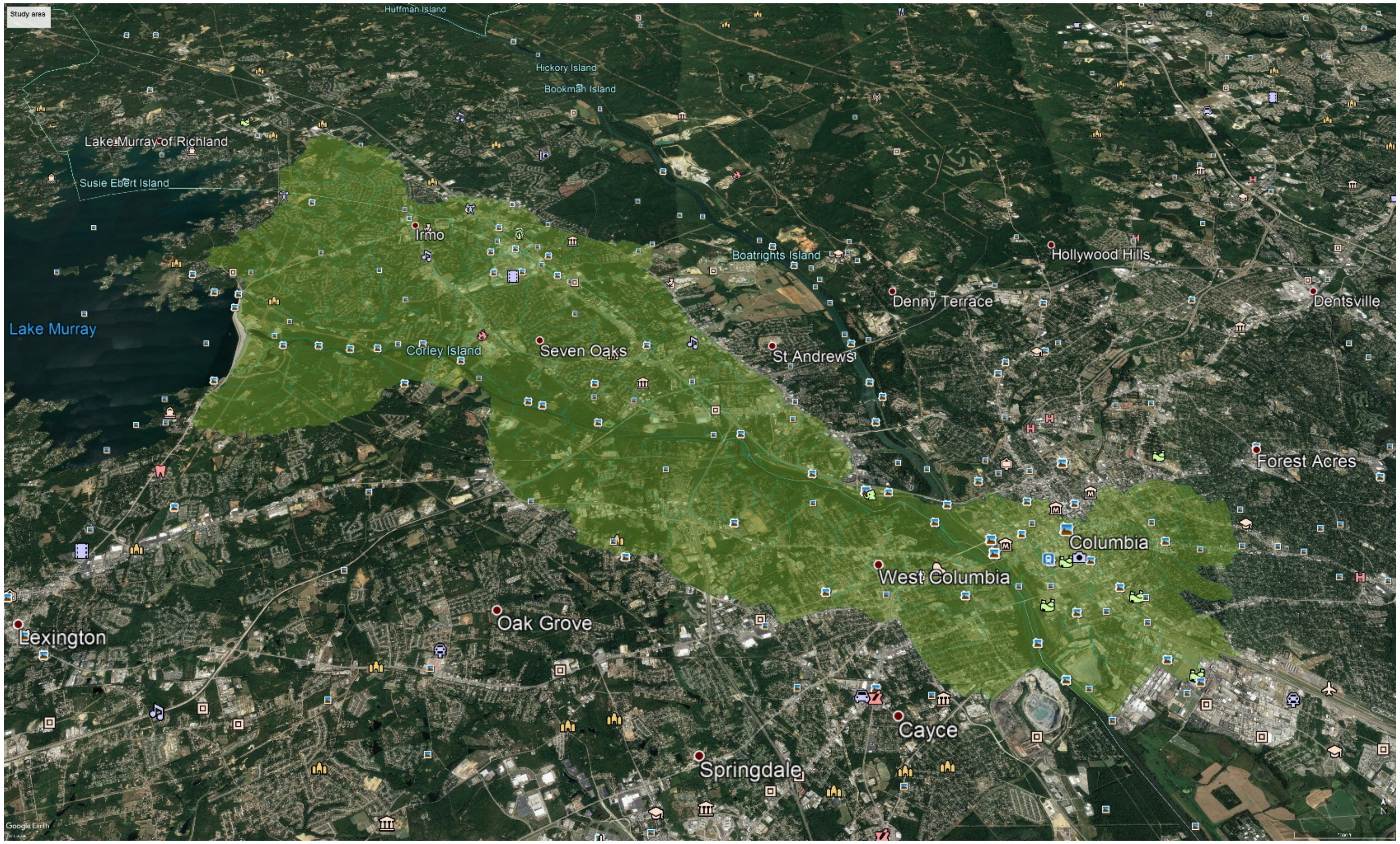

Figure 3.3: Google map view of the study area

3.3. Datasets

The study area was extracted from the most current 12-digit hydrologic unit codes (HUC) and obtained from United States Department of Agriculture - National Resources Conservation Service (USDA-NRCS) website. The digital elevation model (DEM) was obtained at a resolution of 10 ft as a LiDAR product from South Carolina Department of Natural Resources (SCDNR). This DEM was used to delineate the subcatchments and extract land use features (slope, area). The observed elevation ranges from -350 m to 450 m.

Daily average streamflow data were taken from three USGS stations (02168504, 02169000 and 02169500) for the period of 2010-2015. Stations 02168504 and 02169500 were treated as inflow and outflow boundary conditions respectively in model development. Data from station 02169500 was used for model calibration and validation. The flow data recorded by the USGS stations is the amalgamation of two types of flow: baseflow and direct runoff. The base flow component from the streamflow hydrograph was separated using Web based Hydrograph Analysis Tool (WHAT) developed by Purdue University (https://engineering.purdue.edu/mapserve/WHAT/). This separation is necessary because only the runoff parameter is simulated in PCSWMM.

Precipitation data for the same time period was obtained from National Oceanic and Atmospheric Administration (NOAA). The raingage station (ID: USW00053867) lies about 12 km south east of the basin centroid. This data was verified using data from PRISM Climate Group.

Average monthly evaporation data (Figure 3.5) was collected from the monthly evaporation maps (Figure 3.4) obtained from National Weather Services - Climate Prediction Center (http://www.cpc.ncep.noaa.gov/soilmst/e.shtml).

Figure 3.6 shows the average monthly values for evaporation and temperature in the study area.

The observed flow and rainfall values were plotted at an annual scale in Figure 3.7 to see if any trends exist. It is seen that despite some fluctuations, the general trends are positive for both annual runoff and rainfall. This increase in runoff can be contributed by change in land use and climate change within the modelling period.

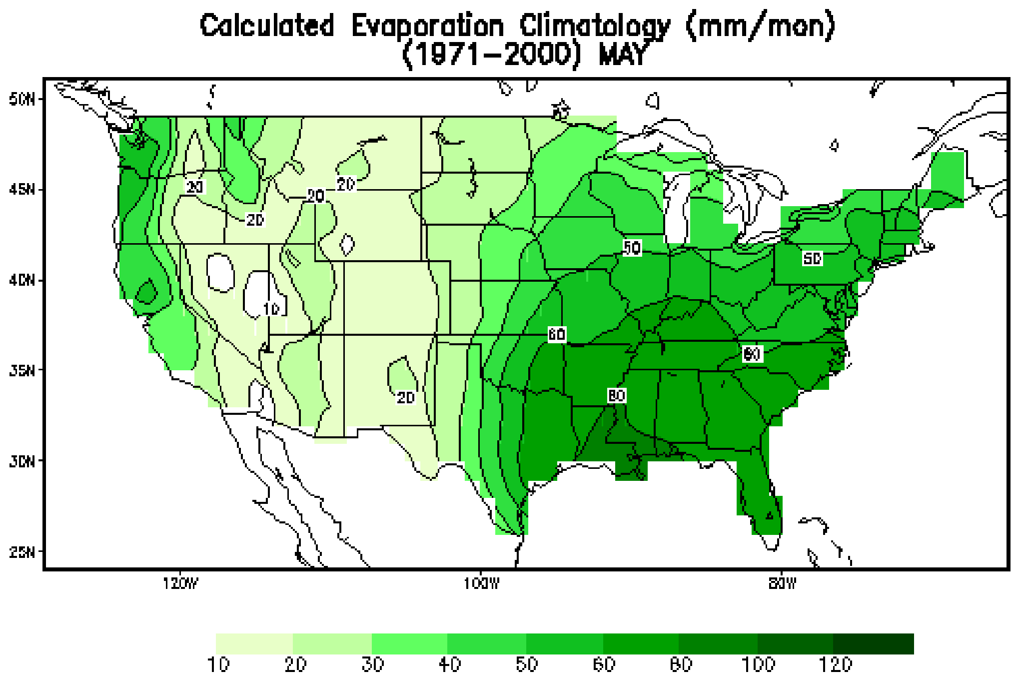

Figure 3.4: Average Evaporation for May from 1971 to 2000

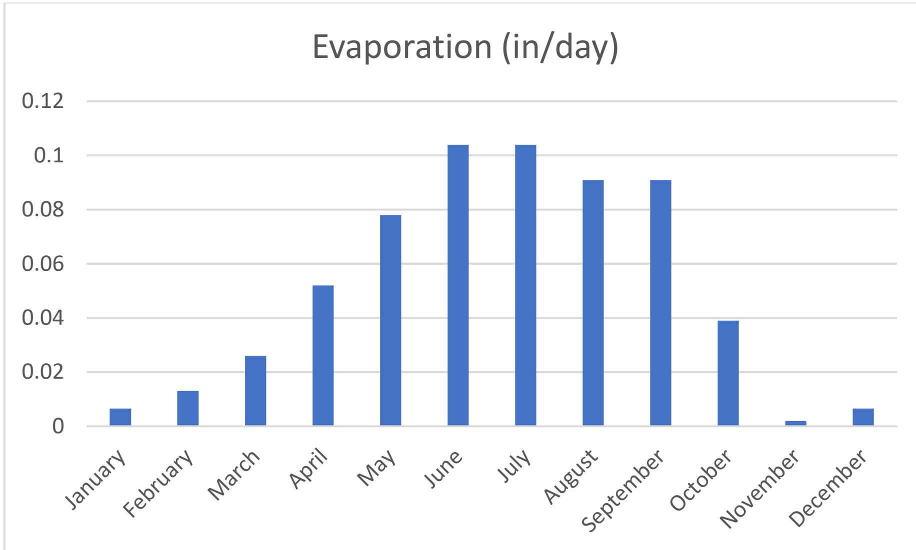

Figure 3.5: Average monthly evaporation for the study area

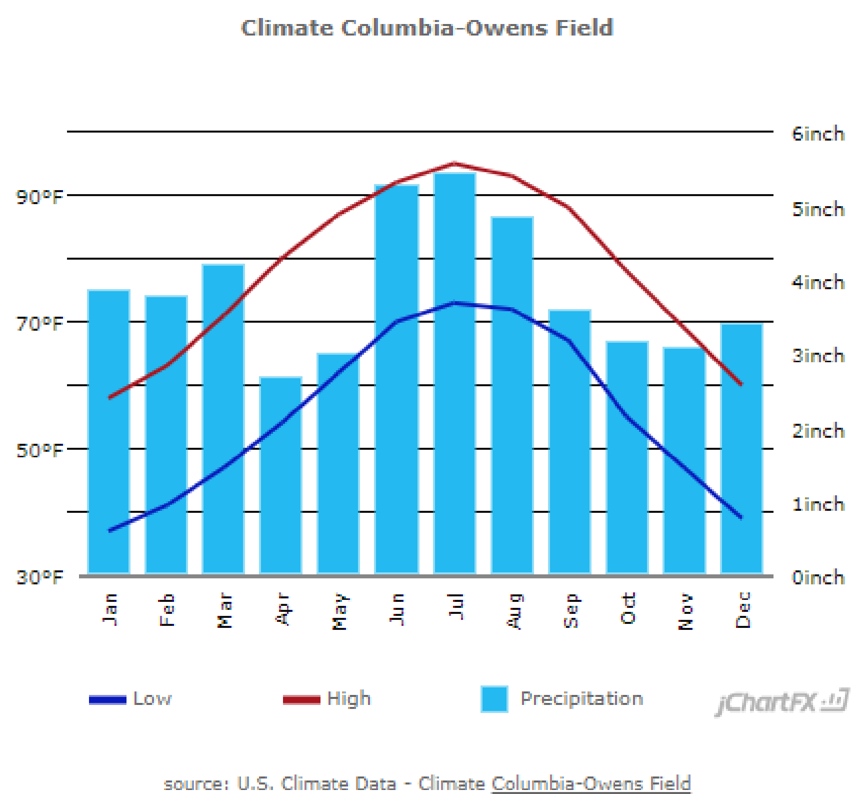

Figure 3.6: Average monthly precipitation and temperature for the study area

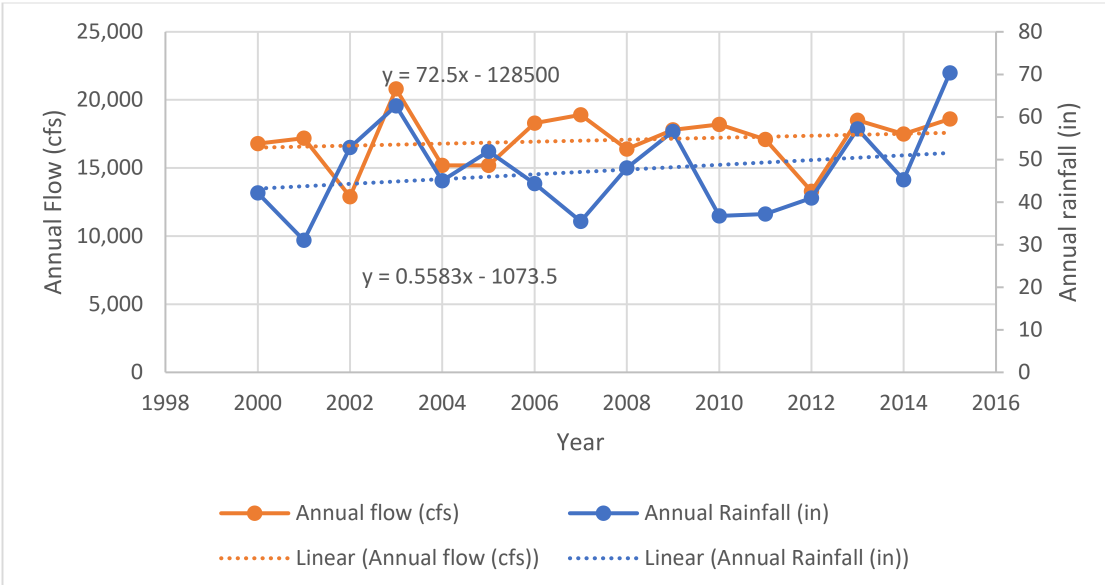

Figure 3.7: Rainfall and flow trends within the baseline modelling period for the study area

For baseline scenario, land use maps were taken from National Land Cover Dataset (NLCD) for year 2011. The land use was reclassified (Figure 3.9) as High Intensity (developed high intensity and developed medium intensity land uses), Low Intensity (developed open space and developed low intensity land uses), Grass/Pasture (grassland/herbaceous and pasture/hay land uses), Forest/Woods (deciduous forest and evergreen forest), Agricultural (cultivated crops), Water/Wetland (open water, woody wetlands and emergent herbaceous wetlands), and Barren Land (bare rock, bare sand, and bare clay). This was used to calculate percentage imperviousness of each sub-catchment using NOAA's Impervious Surface Analysis Tool (ISAT; https://coast.noaa.gov/digitalcoast/tools/isat.html) on an ESRI ArcGIS 10.3 platform. Population data was taken from United States Census Bureau in the form of TIGER/Line (Topologically Integrated Geographic Encoding and Referencing) shapefiles.

3.4. Development of PCSWMM Model

For the model development, PCSWMM version 7.1.2480 (64-bit) was used which ran SWMM version 5.0.013 – 5.1.012 (CHI, 2014a; CHI, 2014b).

Using DEM from SCDNR, PCSWMM's Watershed Delineation Tool (WDT) was run to delineate sub-catchments (Figure 3.8). The WDT tool works similarly as other watershed delineation tools, except it uses the concept of target sub-catchment size rather than minimum area for channelization. To ensure continuous flow over the watershed, the first step is removing any local low spots in the form of pits/depressions. Then, flow direction is defined which indicates the direction in which water flows from various points in the watershed. Based on the flow direction, slope and contributing area layers are generated for each sub-catchment. Lastly, streams and flow path layers are created which show the stream networks and their direction. The Transect Creator and Transect Editor tools were used and Conduits layer was created by dividing the flow path into smaller segments- each having a different cross-section. To represent the land uses, topography and drainage pattern of the watershed, it was divided into 106 subcatchments, 7473 nodes and 7950 links (Figure 3.8).

Table 3.2: Statistics of parameters used as PCSWMM inputs

Parameters	Average	Minimum	Maximum	Standard Deviation
Area (ac)	306.59	108.83	797.79	139.47
Width (ft)	3244.41	1381.70	7358.60	1173.86
Flow length (ft)	4298.85	1356.27	10463.49	1646.65
Slope (%)	8.51	4.34	28.74	3.06
Imperviousness (%)	48.72	3.89	92.79	22.39
Conduit length (ft)	1701.22	5.34	4817.21	1292.21
Node invert elevation (ft)	188.16	54.96	320.07	48.11

The stormwater management infrastructures like pipes, gutters, swales, catch-basins, etc. were not considered in this model because it was assumed that the stormwater from these structures will eventually drain to the natural flow paths mentioned above. The model simulated surface runoff at each sub-catchment, node and links at an hourly time step. The average daily runoff was calculated by averaging this hourly runoff values to compare with the data from WHAT analysis.

Figure 3.8: Catchment discretization of study area

3.5. Calibration and Validation

The Sensitivity-based Radio Tuning Calibration (SRTC) tool is an in-built calibration tool in PCSWMM which uses user-defined uncertainty estimation (as a percentage of the current, best-estimated value) for all attributes to be calibrated (CHI, 2013). The initial values of most of the uncertain parameters were taken from literature (CHI's Rules of responsible modeling, 4th edition, by William James). In this model, the following parameters were checked during sensitivity analysis using their chosen uncertainty values given in Table 3.3.

Table 3.3: Range and ranking of parameters used for model development

Parameters	Initial values	Source	Range	Rank
Width	Variable	Geometry	0.5*Width – 2*Width	2
Slope	Variable	DEM	0.5*Slope – 2*Slope	3
Percent imperviousness	Variable	ISAT	0.526*Imp – 1.9*Imp	1
N Imperv	0.01	CHI	0.00513 - 0.0195	6
N Perv	0.1-0.4	CHI	0.0513 - 0.78	8
DSIMPERV(in)	0.05	CHI	0.0256 - 0.0975	7
DSPERV (in)	0.05-0.2	CHI	0.0256 - 0.39	9
ZEROIMPERV (%)	25	CHI	12.821 - 48.75	5
Curve Number	Variable	ISAT	0.556*CN – 1.8*CN	4
Conduit length	Variable	Geometry	Depends on Geometry	10

In Table 3.3, N Imperv and N Perv are Manning's n values for overland flow over the impervious and pervious portion of a sub-catchment. Similarly, DSIMPERV and DSPERV are depths of depression storage on the impervious and pervious portions of sub-catchment. ZEROIMPERV gives the percent of impervious area with no depression storage and accounts for immediate runoff that occurs at the beginning of rainfall before depression storage is satisfied. A trial sensitivity analysis was conducted to see which of the above parameters are the most sensitive ones in this model.

The model was calibrated using SRTC tool for two different scenarios. In the first scenario B1, calibration period was the first 10 years (2000-2009) and validation period was the last six years (2010-2015). However, there is an extreme event (October 2015 flood) occurring in the validation period of Scenario B1. Thus, a second calibration scenario B2 was introduced in which the model was calibrated such that the extreme event lied within the ten years of calibration period (2006-2015). In B2, the validation period was 2000-2005 (six years). The adoption of two different calibration scenarios provided an opportunity to see whether or not including an extreme event in the calibration of a model improved its accuracy.

The average daily runoff obtained from the model was compared to runoff values from WHAT analysis of daily flow from USGS station 02169000.

3.6. Land use change and urbanization

To assess the impacts of land use change in the study area, different land use scenarios were compared with the baseline scenario of NLCD 2011 land use. Maps were

extracted using NLCD 1992, 2001 and 2006 database and the land use pattern of the study area was determined for all scenarios (Figure 3.9).

Table 3.4 shows the distribution of land use type for NLCD 1992, 2001, 2006 and 2011 based on percentage of watershed area. From 1992 to 2011, there was a 13% increase in high intensity developed area and 78% increase in low intensity developed area making the total increase in urban area (high and low intensity developed) to be 36%. Similarly, the forest and agricultural area decreased by 45% and 97% respectively.

Table 3.4: Land use distribution in the study area using land use from NLCD

	Percentage of watershed area			
Landuse type	**Year 1992**	**Year 2001**	**Year 2006**	**Year 2011**
High Intensity Developed	32.44	19.82	34.53	36.76
Low Intensity Developed	17.76	45.64	33.90	31.66
Grass/Pasture	2.37	4.86	4.57	4.57
Forest/Woods	37.66	23.70	20.87	20.87
Agricultural	4.31	0.10	0.11	0.11
Water/Wetland	3.59	4.85	4.75	4.75
Bare land	1.86	1.03	1.26	1.26

<u>Prediction of future urbanization</u>

It was also desired to see the effects of urbanization in the future and for this, two different approaches were carried out:

- Increasing the percentage imperviousness:

  In this approach, it was assumed that increase in urbanization directly results into increase in impervious percentage. Hence, the values of percent imperviousness for each subcatchment (calculated in baseline model using NLCD 2011 and ISAT tool) was increased manually by 10%, 30%, 50% and 70%. By doing this, four urbanization

scenarios were hypothetically generated and the corresponding new values of percentage imperviousness were assigned in the model.

- Predicting the 2050 land use:

In this method, the existing land use records were used to predict future land use behavior for the study area. A predicted map showing probable urbanization (high intensity developed and low intensity developed) in the year 2050 was generated and treated as future land use scenario. For this map development, past land use data of NLCD 1992, 2001, 2006 and 2011 were used to plot urban, forest and agricultural land use type against different year. Then, using best fit curve, the total urban area percentage for 2050 was computed by interpolation and verification. It was found that the total urban area in 2050 would be 111 km^2, that is 81% of the total watershed area (as opposed to 68% in 2011). After this, site suitability analysis was done using ArcGIS and the critical parameters were defined to be land use, slope and road proximity (Kumar and Shaikh, 2013).

The first step of site suitability analysis was data acquisition. Besides land use data, slope and roadway data was required which was extracted from DEM layer and SCDNR respectively. Ranking table was created by reclassifying the values with respect to self-assigned ranking points with 5 being the best (Table 3.5).

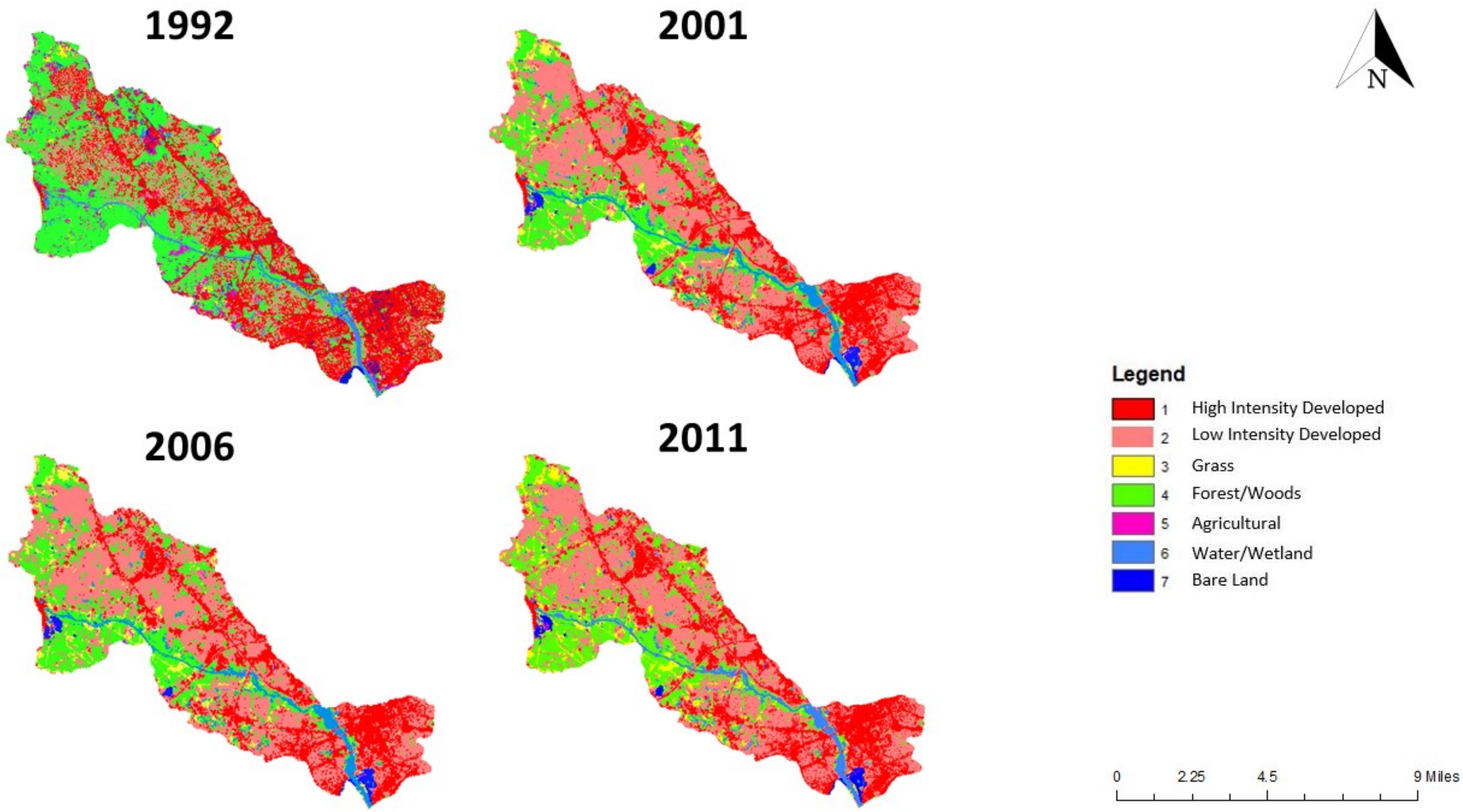

Figure 3.9: Land use from NLCD

Table 3.5: Reclass Table for Site Suitability Analysis

Input	**Type/Value**	**Reclass assigns**	**Weight**	**Product range**	**Total range**
Land Use	Forest/Woods	5	10	0 to 50	0 to 50
	Grass/Pasture, Agricultural, Bare land	3			
	Water/Wetland, Urban	0			
Roads proximity (miles)	0 to 1	5	8	8 to 40	
	1 to 2	3			
	>2	1			
Slope (%)	0 to 10	5	5	5 to 25	
	10 to 20	3			
	>20	1			

After the ranking and reclassification of the three inputs, examination of each input was done and its relative importance to others was evaluated and weight was assigned accordingly (Table 3.5). For example, it was considered that while slope of a land is an important parameter to determine its suitability (or chance) to get urbanized, it may not be as important as the current land use type of the land. So, a lower weight of 5 was given to slope as compared to land use, which was given a weight of 10. Then, Raster Calculator tool was used to calculate the weighted value of each cell for all the parameters. In Table 3.5, the reclass assigns are the actual values in the cells, product range are the cell values that result from the multiplication of the weight, and total range shows all the possible values in the final calculation after the inputs are added together. In the next step, final

reclassification was done using the weighted average values and final rank table (Table 3.6) was constructed which showed the suitability of site where urbanization can occur.

Table 3.6: Final rank table for Site Suitability Analysis

Suitability	Range
Excellent	35 to 50
Good	10 to 35
Satisfactory	0 to 10

Finally, Grid & Raster Editor tool, developed by a Dutch company ARIS (https://www.aris.nl/index.php?option=com_content&view=article&id=210:aris-grid-editor-for-arcmap&catid=64:arcgis-tools&Itemid=169&lang=en) was used to manually change the pixel values in ArcGIS from forest or agricultural land to urban land. This resulted into the final projected map of 2050 land use as shown in Figure 3.10. This map was then used along with ISAT tool to predict the percentage imperviousness of each subcatchment of the watershed in 2050.

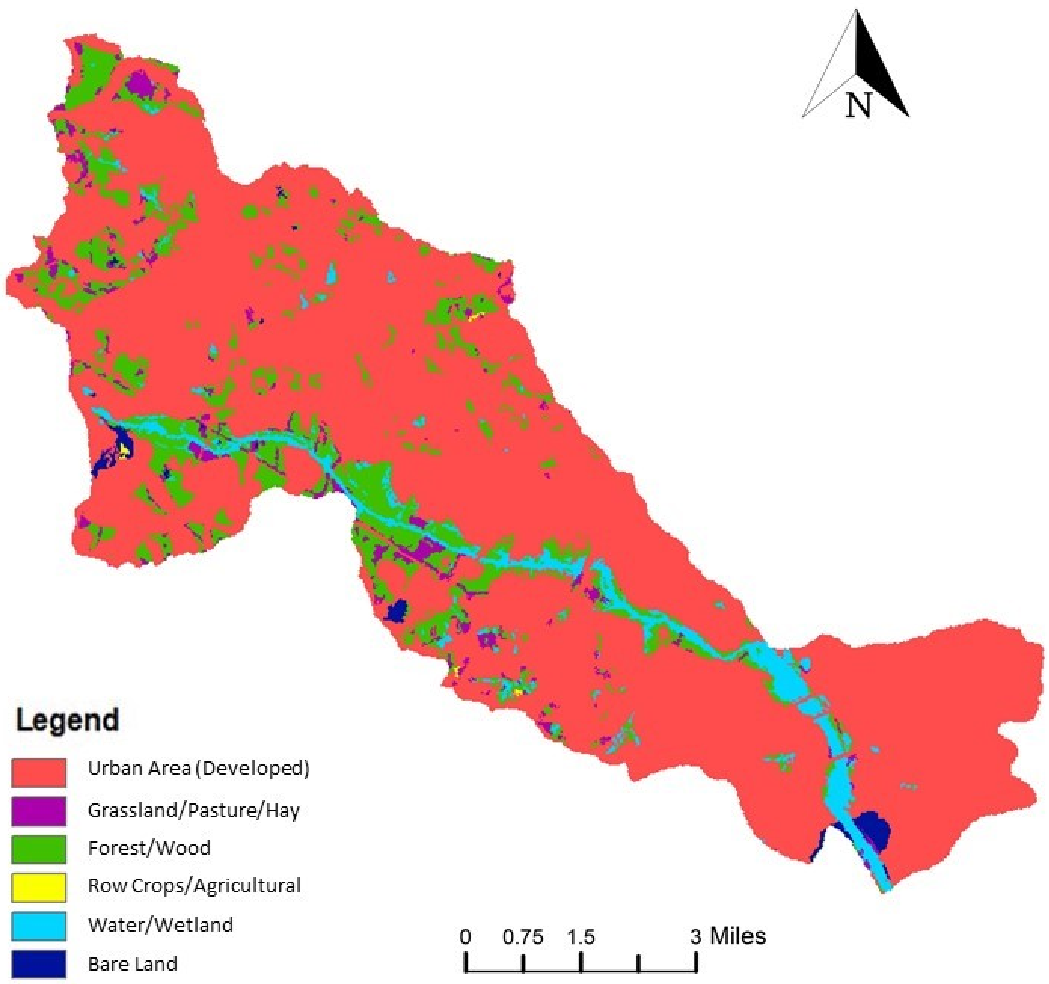

Figure 3.10: Projected land use map for 2050

3.7. Climate change

To simulate the climate change scenario, data was taken from the North American Regional Climate Change Assessment Program (NARCCAP) website (http://www.narccap.ucar.edu/data/). NARCCAP produces simulations considering A2 emission scenario in 50 km resolution regional climate model (RCMs) driven by atmosphere-ocean general circulation models (AOGCMs) over a domain covering the

conterminous United States and most of Canada. Simulations consider the current or baseline period as 1971 to 1999 and the future period as 2041 to 2069.

For analysis, 3-hour time step precipitation data was extracted and converted into daily time step. Then, quantile mapping was used as the method of bias-correction for each month. For this, observed precipitation data were taken from NOAA. It was necessary to compare the predicted future runoff with the runoff calculated from baseline data. Hence, the PCSWMM model was run two times for each climate change model- one using baseline (also known as current or historical) data (1968 to 1999) and another using future precipitation data (2038 to 2069) at a daily time step. For the baseline case, land use of NLCD1992 was used whereas for future case, projected land use of 2050 was used.

Kim, Band and Ficklin (2017) also used NARCCAP model to predict hydrological changes in the North Carolina piedmont and found out that out of 12 GCM-RCM combination models, 5 were the most relevant to their study area. Considering the geographical proximity of our study area with theirs, the same 5 models were used in this study as well. These models are listed below:

- CCSM-CRCM (NCAR Community Climate System Model − Canadian Regional Climate Model)
- CGCM3-CRCM (Canadian Global Climate Model v.3–Canadian Regional Climate Model)
- CGCM3-RCM3 (Canadian Global Climate Model v.3–Regional Climate Model v.3)

- GFDL-RCM3 (Geophysical Fluid Dynamics Laboratory GCM − Regional Climate Model v.3)
- GFDL-ECP2 (Geophysical Fluid Dynamics Laboratory GCM − Experimental Climate Prediction Center)

The monthly precipitation so obtained from these models are plotted in Figure 3.11 along with the observed rainfall data from NOAA at a monthly scale.

Similarly, predicted and observed temperature was also compared in a monthly scale as shown in Figure 3.12.

3.8. Low impact development

Two LID elements (rain garden and rain barrel) were used in the model. Since this was just a hypothetical scenario, parameterization of LID structures was mostly done by assuming the values and making an educated guess using the help of existing literature.

3.8.1. Rain Garden

The values of parameters that were used for modeling rain garden are shown in Table 3.7.

It was assumed that there are no clogging issues and no underdrain. The modeled rain garden was assumed to have a size of 200 ft^2 each. The number of rain gardens in each sub-catchment was determined according to the percent imperviousness and percentage of sub-catchment area occupied by rain garden as given in Table 3.8.

Table 3.7: Values of parameters used in Rain Garden modeling

Type	Attributes (units)	Value
Surface	Berm height (in)	6
	Vegetation volume (fraction)	0.1
	Surface roughness (Manning's n)	0
	Surface slope (percent)	0
Soil	Thickness (in)	18
	Porosity (volume fraction)	0.5
	Field capacity (volume fraction)	0.23
	Wilting point (volume fraction)	0.12
	Conductivity (in/hr)	0.13
	Conductivity slope	10
	Suction head (in)	3.5
Storage	Thickness (in)	8
	Void ratio (voids/solids)	0.75
	Seepage rate (in/hr)	0.4
	Clogging factor	0
Underdrain	Drain coefficient (in/hr)	0
	Drain exponent	0
	Drain offset height (in)	0

Table 3.8: Percentage of Rain Garden occupancy in subcatchment

Imperviousness (%)	**Percentage of sub-catchment area occupied by rain garden**
Less than 15%	0%
15-30%	1%
More than 30%	5%

3.8.2. Rain Barrel

Each modeled rain barrel was assumed to have a capacity of 94 gallons and was 48-inch tall and 24 inches in diameter. The values of parameters that were used for modeling rain barrel are shown in Table 3.9.

Table 3.9: Values of parameters used in Rain Barrel modeling

Type	**Attributes (units)**	**Value**
Surface	Barrel height (in)	50
Underdrain	Drain coefficient (in/hr)	1
	Drain exponent	0.5
	Drain offset height (in)	0.4
	Drain delay (hours)	6

To find the number of rain barrels for each sub-catchment, population data from United States Census Bureau was taken. A homogeneous distribution of population was

assumed such that there is a constant population density over all the sub-catchments. For a household of four members, one rain barrel was modelled.

3.9. Scenario analysis

The baseline scenario (B1) was taken to be the one in which the model was validated. It consists of NLCD 2011 land use and no LID structures.

To study the impacts of urbanization on runoff, four scenarios were created by increasing the impervious percent in each scenario (U1-U4). Using land uses of 1992, 2001, 2006 and 2050, Scenarios LU1 to LU4 were created.

The effectiveness of LID practices for reducing runoff were evaluated using three scenarios (Scenarios L1-L3).

Furthermore, Scenarios C1 to C6 were used to study the climate change impacts without the incorporation of LID structures in the model. The CL scenario was used to predict runoff using average precipitation from all GCM-RCM models as well as LID consideration.

See Table 3.10 and Table 3.11 for complete list of scenarios used in the model along with its description.

Table 3.10: Scenarios used for study

Scenario	**Description**	**Land use type**	**Precipitation data**	**Period of simulation**
Scenario B1	Extreme event not used for calibration	NLCD2011	Observed from NOAA	2000 to 2015
Scenario B2 (Base-line)	Extreme event used for calibration			
Scenario U1	10% urbanization			
Scenario U2	30% urbanization			
Scenario U3	50% urbanization			
Scenario U4	70% urbanization			
Scenario LU1	1992 land use	NLCD1992		
Scenario LU2	2001 land use	NLCD2001		
Scenario LU3	2006 land use	NLCD2006		
Scenario LU4	2050 land use	Predicted 2050		
Scenario L1	Rain garden only	NLCD2011		
Scenario L2	Rain barrel only			
Scenario L3	Both LID			

Table 3.11: Scenarios used for study (continued)

Scenario C1	CCSM-CRCM	NLCD1992 for baseline; Predicted 2050 for future	From model	1968 to 1999 for baseline; 2048 to 2069 for future
Scenario C2	CGCM3-CRCM			
Scenario C3	CGCM3-RCM3			
Scenario C4	GFDL-RCM3			
Scenario C5	GFDL-ECP2			
Scenario C6	Average rainfall from C1 to C5			
Scenario CL	Climate change and both LID	Predicted 2050	Average rainfall from C1 to C5	2048 to 2069

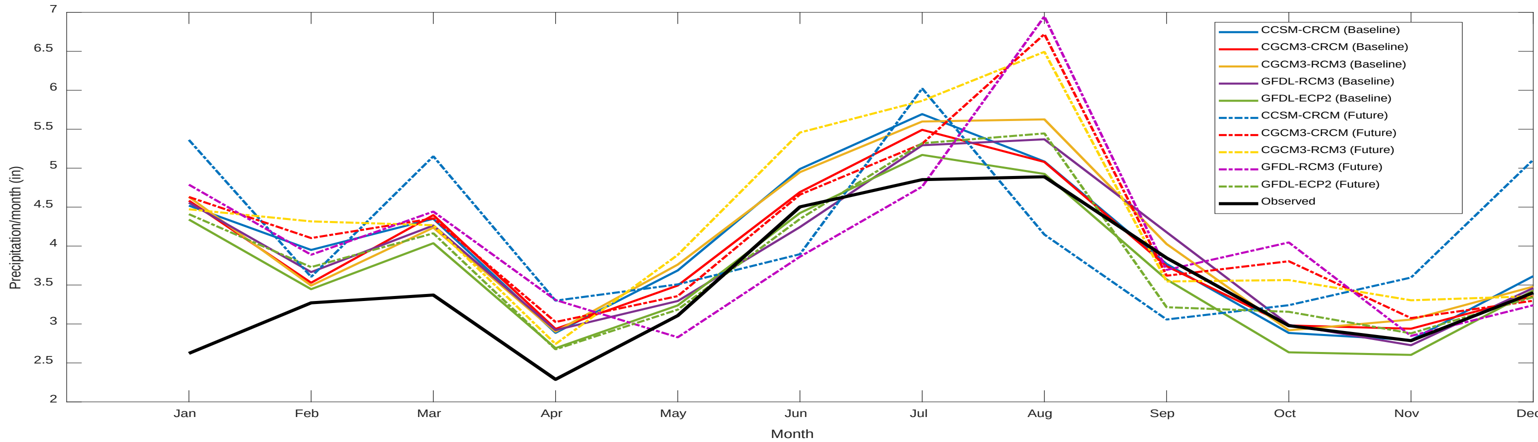

Figure 3.11: Comparison of observed average precipitation (2000-2015) with baseline (1968-1999) and future (2038-2069) prediction

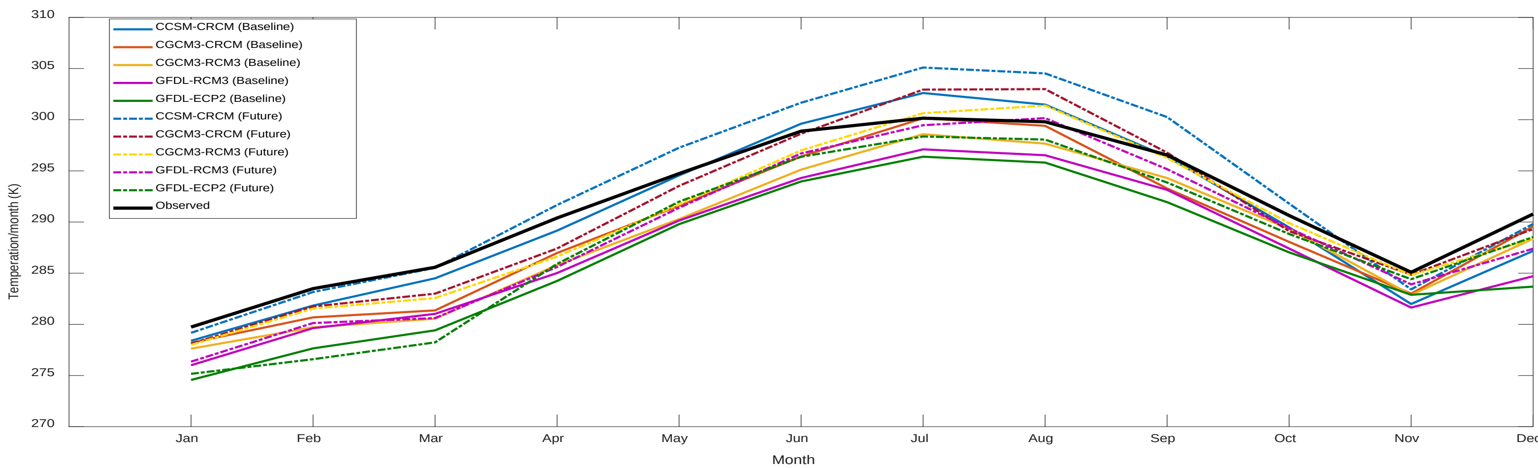

Figure 3.12: Comparison of observed average temperature (2000-2015) with baseline (1968-1999) and future (2038-2069) prediction

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Calibration and Validation

For the calibration and validation of the model, land use map of 2011 from NLCD and observed precipitation data from NOAA was used. The model was run for 16 years (2000 to 2015) in total.

A trial sensitivity analysis conducted using the SRTC tool identified that sub-catchment width, slope, percent impervious and curve number were the most sensitive parameters in this model. This is consistent with the results obtained in previous literature (Ahiablame and Shakya, 2016; Akhter et. al., 2016; Abdul-Aziz and Al-Amin, 2016). All insensitive parameters were left unchanged, whereas these sensitive parameters were adjusted using the tuning bar until the best fit was obtained and the model was validated. To judge the accuracy of the model, both Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) values of simulated and observed daily runoff were compared for both calibration scenarios.

Table 4.1: Calibration Statistics for Scenario B1

Period	NSE	R^2
Calibration (2000-2009)	0.72	0.71
Validation (2010-2015)	0.74	0.72

Table 4.2: Calibration Statistics for Scenario B2

Period	**NSE**	**R^2**
Calibration (2006-2015)	0.79	0.81
Validation (2000-2005)	0.81	0.83

From Table 4.1 and Table 4.2, it can be seen that there was increase in both NSE and R^2 values in scenario B2. It can be further concluded that the model performed better when it was calibrated with respect to the extreme event. Thus, given the good values of NSE and R^2, model performance was found to indicate a realistic response to the variables. Also, it was observed that model could capture the October 2015 flood with reasonable accuracy. From this point onwards, calibration scenario B2 was used as the baseline scenario for all results analysis.

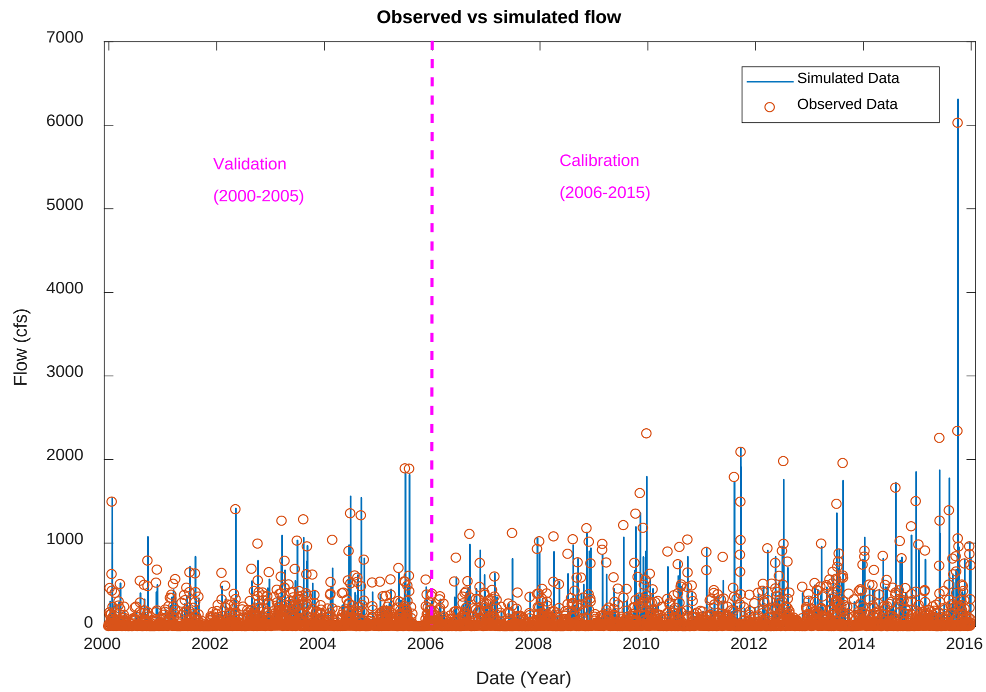

Figure 4.1: Comparison of the simulated and observed flow series during calibration and validation for B2 scenario

4.2. Impacts of land use change and urbanization

To assess the impacts of land use change in runoff in the study area, NLCD data for 1992, 2001 and 2006 was used along with the projected land use data for 2050 (Scenario LU1 to LU4). After finding the corresponding percent imperviousness for different subcatchments for each scenario, the model was run by adjusting this imperviousness values. For the analysis, observed precipitation data from NOAA was used and the model was run for 16 years (2000 to 2015).

From the analysis, it was found that changing the land use changed the runoff significantly. If all other model parameters are kept same, then for all the years, runoff value decreased from baseline for Scenario LU1, LU2 and LU3; and increased for Scenario LU4. This is expected because as the urban area is increasing from 1992 to 2011, pervious surface change to impervious surface and thus more runoff will take place. For Scenario LU1 and LU4, the change in annual runoff is shown in Figure 4.2.

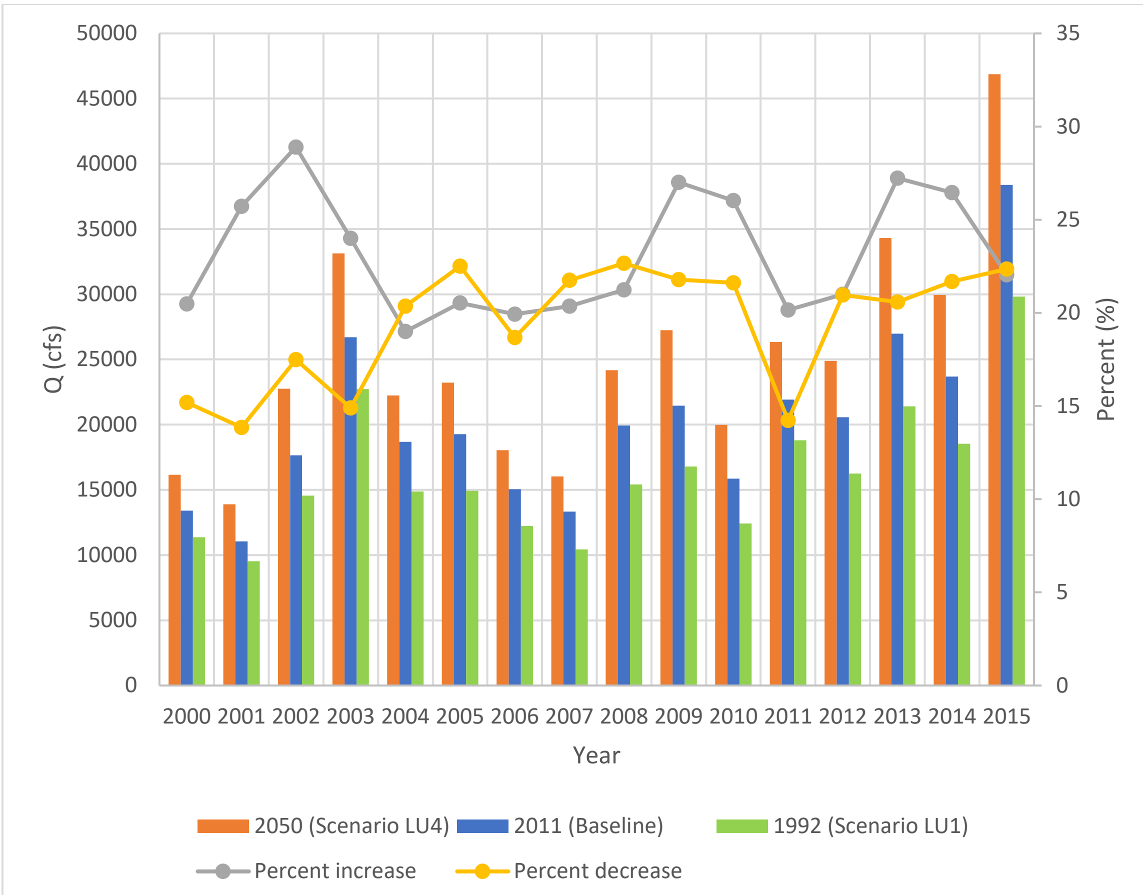

Figure 4.2: Comparison of mean flow for Baseline (2011) scenario, Scenario LU1 (1992) and Scenario LU4 (2050)

Figure 4.3 shows the overall annual runoff for Baseline and Scenarios LU1 to LU4.

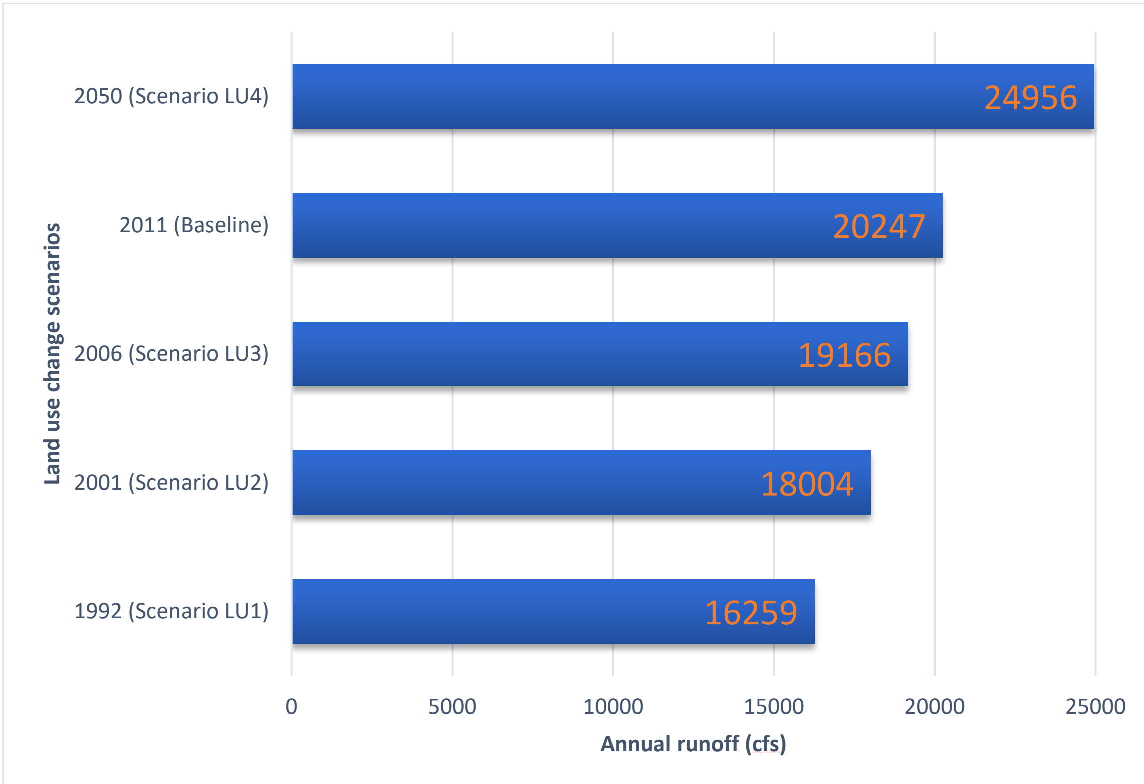

Figure 4.3: Annual runoff for different land use change scenarios

Using Scenarios U1 to U4, the impacts of directly increasing subcatchment percentage imperviousness were quantified. For this analysis, model was run from 2000 to 2015 and observed precipitation data was used for rain gage data. Figure 4.4, Figure 4.5 and Figure 4.6 show the results.

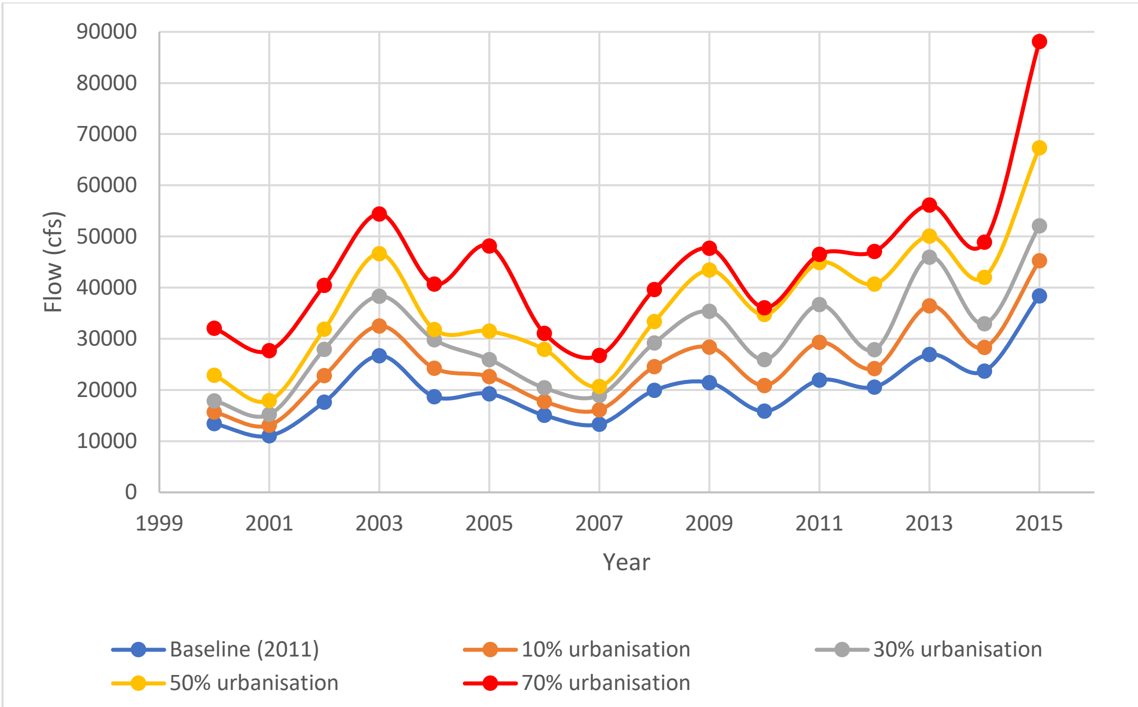

Figure 4.4: Annual flow at different urbanization scenarios

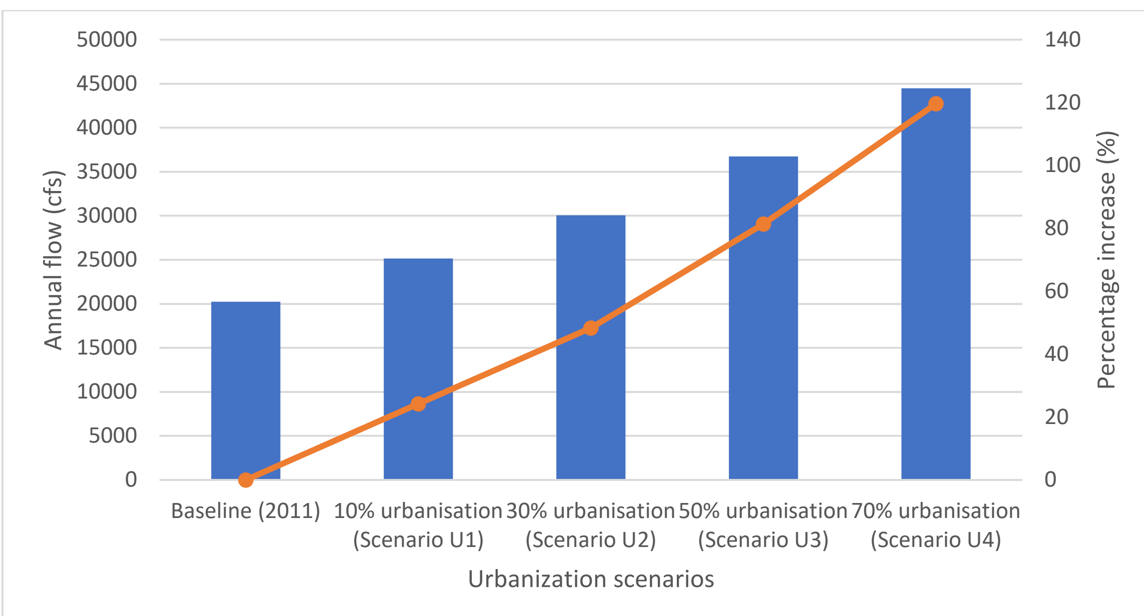

Figure 4.5: Effects of urbanization on mean flow (Q_{mean})

Figure 4.4 indicates that annual flow increases every year for each scenario as the urbanization is increased from 10% to 70%. The overall percentage increase in mean flow occurred from 24% to 120% in Scenario U1 to U4 as shown in Figure 4.5. This increase in flow is most likely due to the decrease in infiltration caused by urbanization.

According to Figure 4.6, it is clear that urbanization effects in high flow is more prevalent than low flows. When urbanization is increased to 70%, extreme flows that are exceeded 1% of the time increase from 1022 cfs 1875 cfs (by 83.46%).

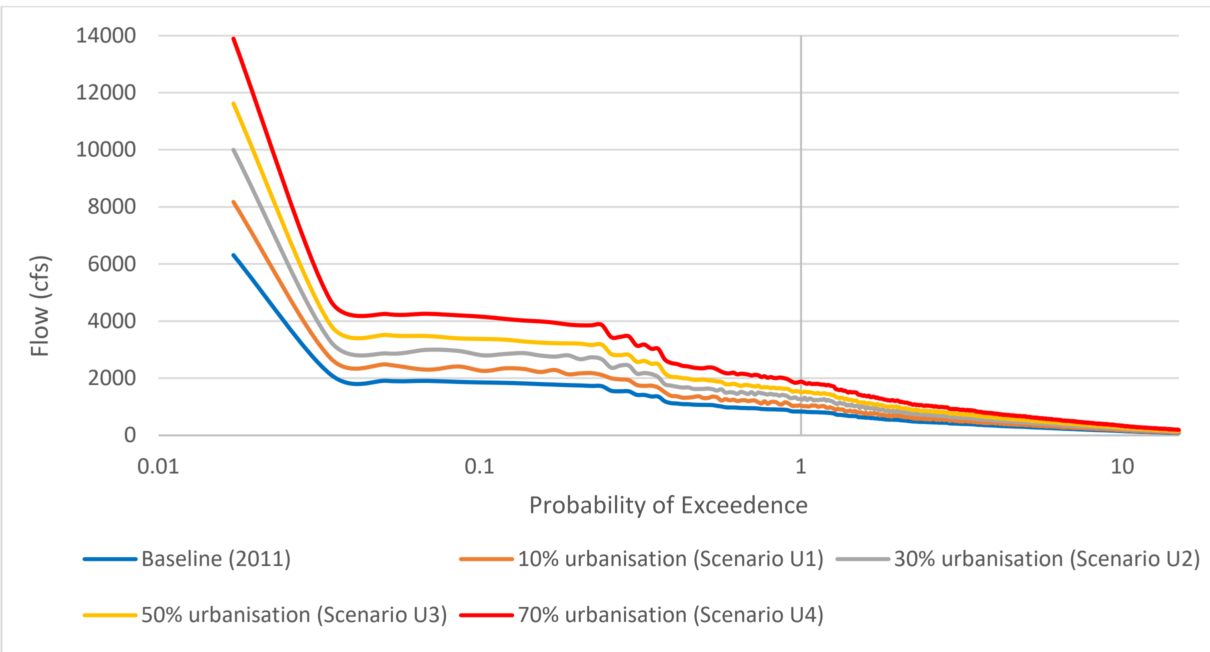

Figure 4.6: Effects of urbanization on Flow Duration Curve (FDC)

A similar study conducted by Akhter et. al. (2016) for an Australian catchment predicted 50% and 320% increase in mean annual runoff by increasing urbanization percentage by 10% and 70% respectively. Ahiablame and Shakya (2016) predicted 63%

increase in runoff from 1992 to 2050 in the City of Normal-Sugar Creek Watershed in Central Illinois. Similarly, Yan and Edwards (2012) studied three different watersheds and discovered that from 1993 to 2019, there was an average of 178% increase in flood peak discharge. From their SWAT model of area 13.42 km^2, Lee and Chung (2007) found out that when the percentage urban area increased by 14.1%, total runoff increased by 3.53%. Huong and Pathirana (2013) reported an overall runoff increase by 21% was resulted due to 55% increase in urban area in their study area of 1390 km^2. A study conducted by Bhaduri et. al. (2001) revealed that for a 10% increase in imperviousness, annual average runoff increased by 10%.

4.3. Effectiveness of LID practices

To quantify the contribution of LID practices in reducing the runoff in the watershed, scenarios L1 (Rain Garden only), L2 (Rain Barrel only) and L3 (Both RG and RB) were used. The modeling period was set to 16 years and land use from NLCD2011 was modeled using observed precipitation data from NOAA. The use of three scenarios enabled us to see the effects of individual LID practices as well as their combined effects.

Obviously, Scenario L3 was found to reduce the most amount of runoff in the catchment. While runoff from Scenario L2 was also observed to be lesser than Baseline Scenario, it was still more than runoff from Scenario L1. This can be clearly seen in Figure 4.7 and Figure 4.8. On average, the mean annual runoff decreased by 10% (2005 cfs) when using rain barrel only, by 21.3% (4314 cfs) when using rain garden only and by 34% (6563 cfs) when using both as LID practices.

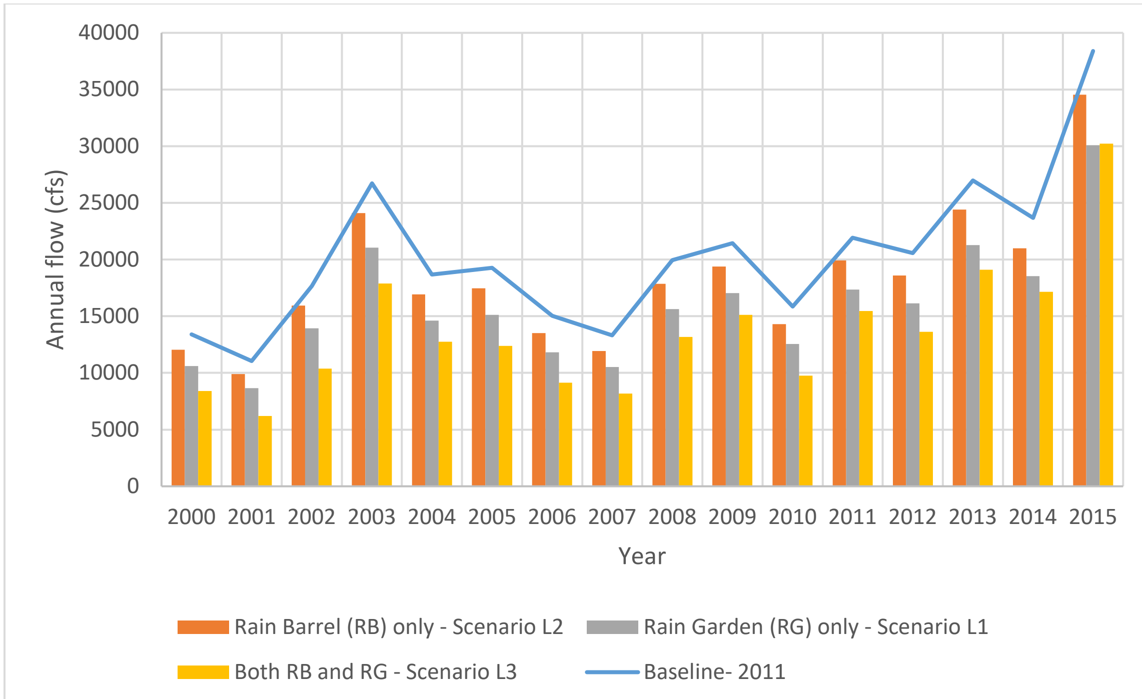

Figure 4.7: Annual flow for different LID scenarios

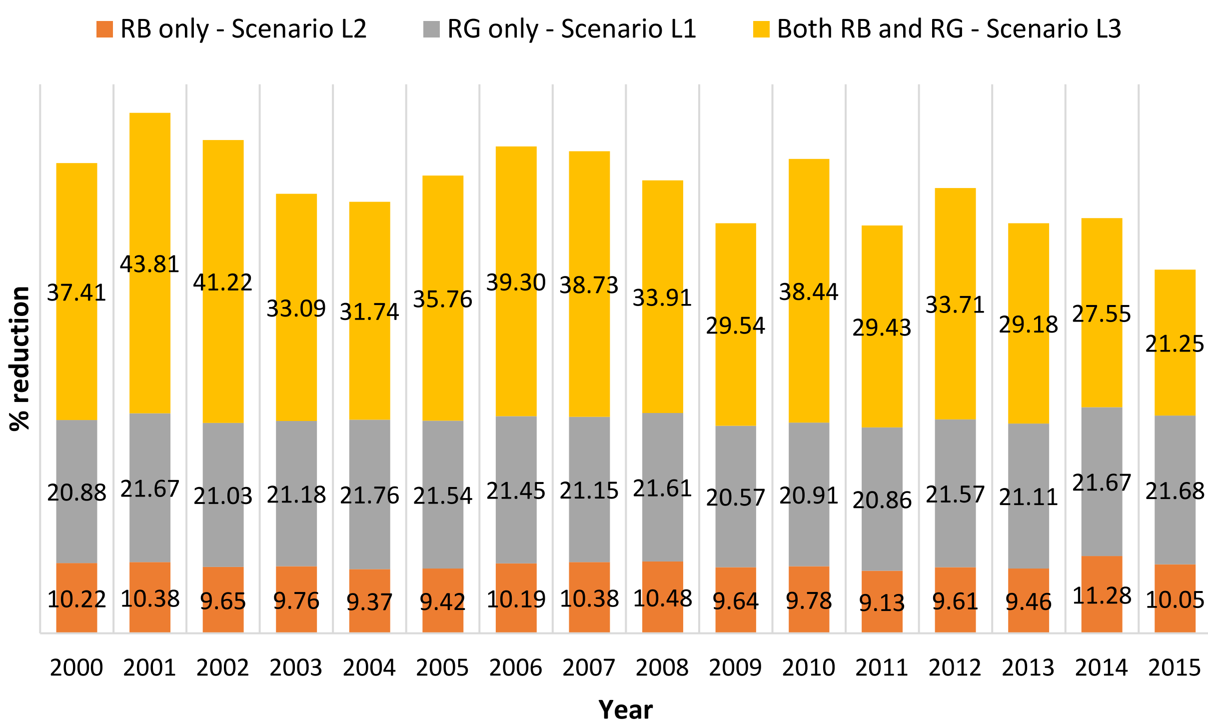

Figure 4.8 Percentage reduction for LID scenarios

Akhter et. al. (2016) reported that with the use of rain garden, the total runoff volume decreased by 42%. Similarly, Ahiablame and Shakya (2016) reported that using rain garden to capture runoff from roof area and parking decreased average annual runoff by 12.75% and 28.3% respectively. Using rain barrel, it decreased by 19.37%. A study by Abi Aad et al. (2010) presented that rain garden contributed in 38% total runoff reduction. The same study found rain garden to have the best response in peak and volume reduction as compared to rain barrel. Likewise, results from a study by Jennings et al. (2013) indicate that rain barrel installed to capture 25% of roof runoff would reduce the runoff by 1.4 to 3.1%. These runoff reductions obtained from the literature are similar to runoff reduction obtained in this study, but depends largely on several factors like percentage of impervious area treated, nature of study area, specific sizes and number of LID units, etc. (Ahiablame and Shakya, 2016). Results from a study by Damodaram et. al. (2010) conclude that use of these LID practices gives significant stormwater control for small events but less control for flood events.

4.4. Evaluation of climate change effects

Preliminary analysis of the precipitation and temperature data from each of the climate change model showed that there has indeed been an increase in future rainfall and temperature. To quantify these effects in terms of runoff, each climate change scenario (C1 to C6) was run twice: once using baseline data and next using future data. For baseline, land use from 1992 was used and period of simulation was chosen from 1968 to 1999. For the latter, predicted land use of 2050 was used for 2048 to 2069 simulation period. Analysis of quantile mapped rainfall data for each model showed that the total future precipitation

volume was found to have increased by 3.68%, 5.81%, 5.32%, 3.6% and 3.05% respectively for scenarios C1 to C5. It was desired to see the amount of runoff increased for each climate model. But it is difficult to identify which is the most appropriate model as they all try to simulate future precipitation data. Some models might under-predict the actual data, while some might over-predict. So, to get an overall idea about the average climate change effects, Scenario C6 was created by taking mean of the daily precipitation data from all five models. For this, the net increase in precipitation volume was found to be 4.29%.

After model simulation, it was found that for each simulation, there has been significant increase in runoff in the future scenario than the baseline scenario. Although the model was run at a daily time step using daily precipitation, the end results so obtained were compared at an annual monthly scale because the impacts of climate change would be seen more clearly at this time step. Figure 4.9, Figure 4.10, Figure 4.11, Figure 4.12, Figure 4.13 and Figure 4.14 compare monthly runoff for scenarios C1, C2, C3, C4, C5 and C6 respectively.

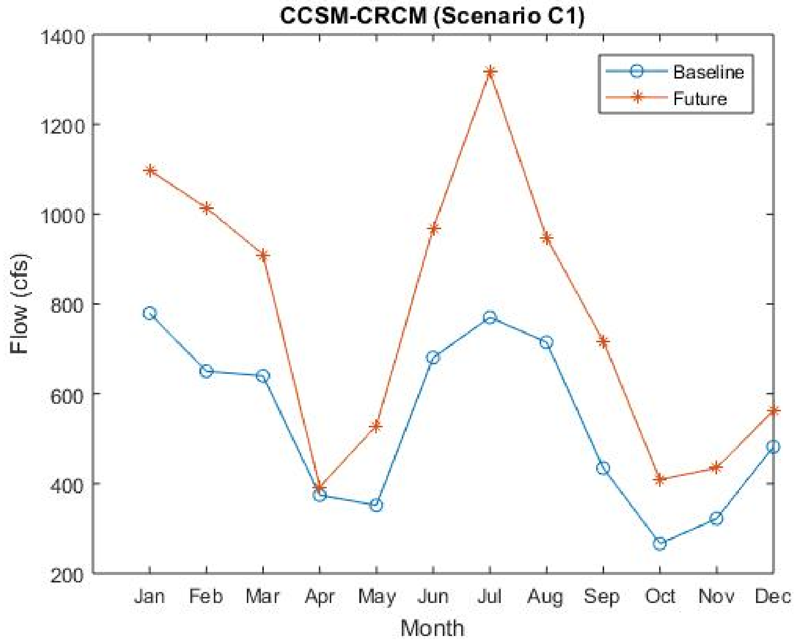

Figure 4.9: Climate change impacts on runoff for CCSM-CRCM model

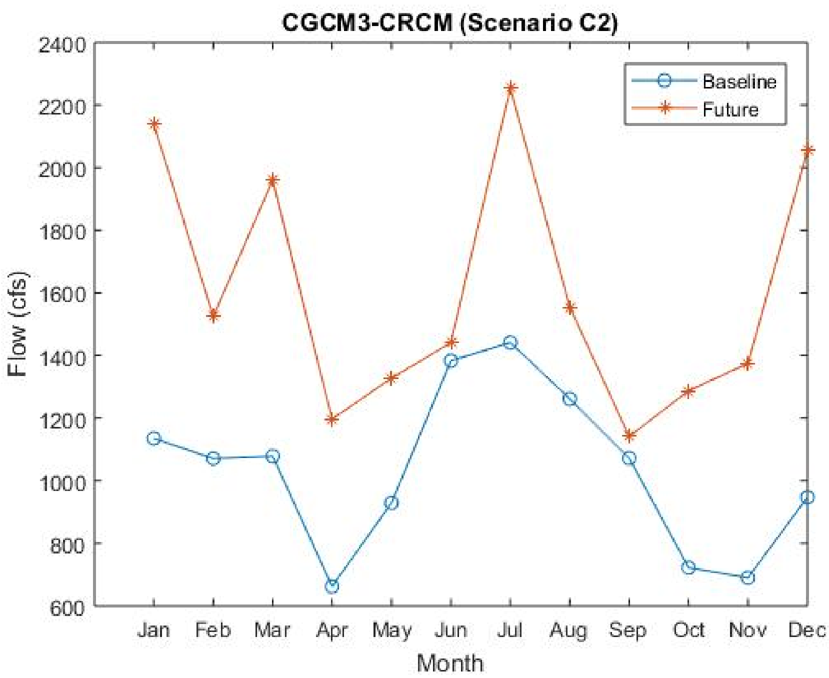

Figure 4.10: Climate change impacts on runoff for CGCM3-CRCM model

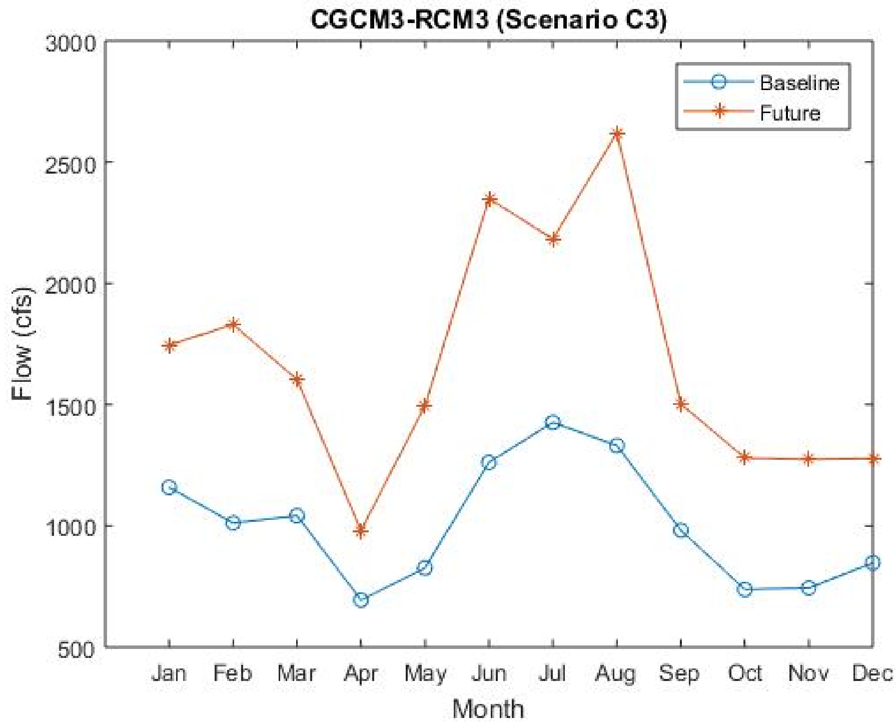

Figure 4.11: Climate change impacts on runoff for CGCM3-RCM3 model

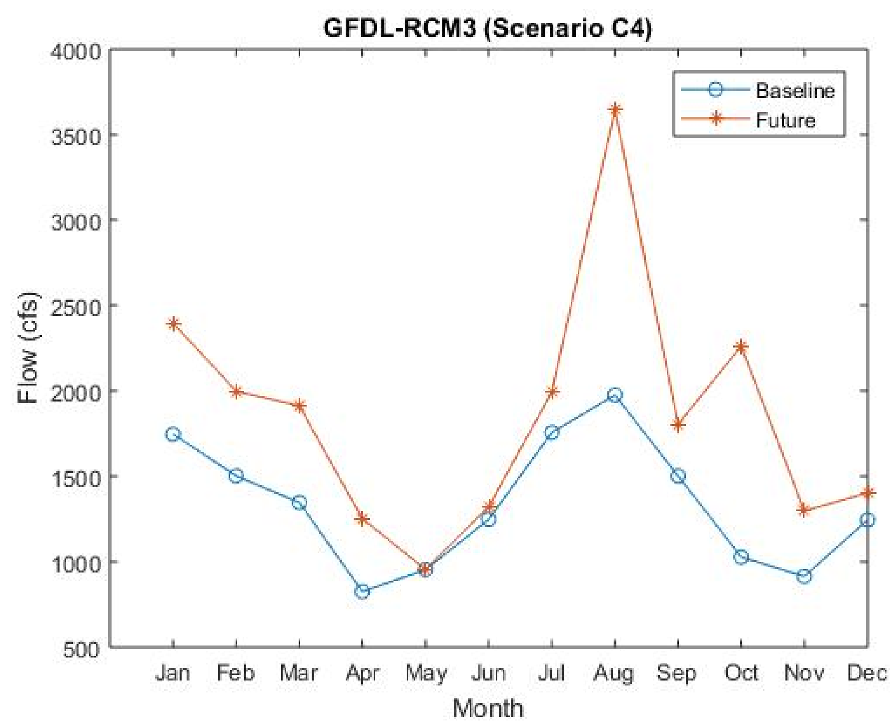

Figure 4.12: Climate change impacts on runoff for GFDL-RCM3 model

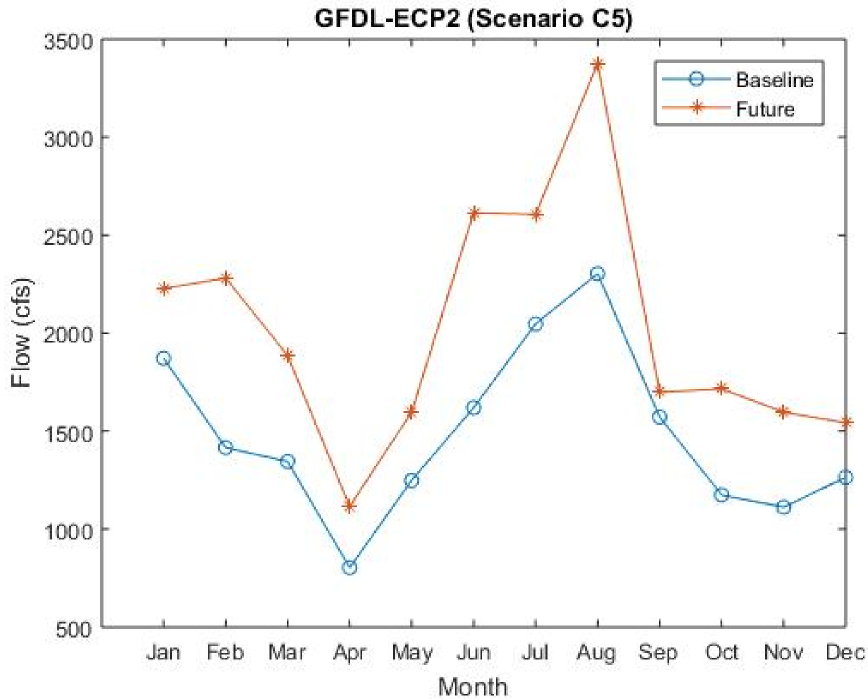

Figure 4.13: Climate change impacts on runoff for GFDL-ECP2 model

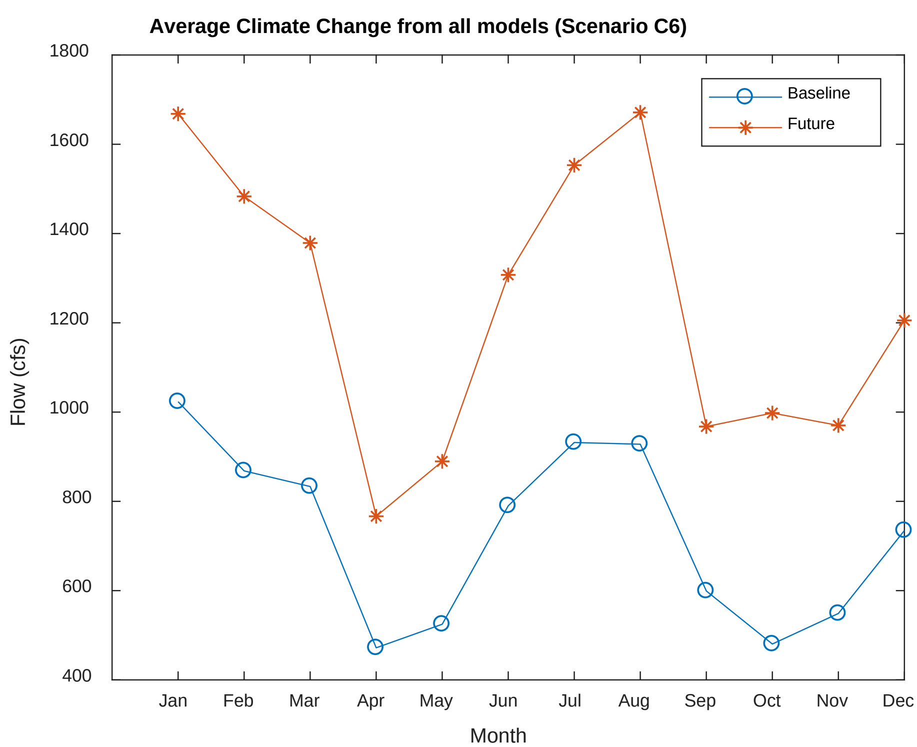

Figure 4.14: Climate change impacts on runoff for average of all models

Overall, it was seen that the average annual runoff increased by 43.8%, 55.37%, 66.93%, 38.61% and 36.44% for scenarios C1 to C5 respectively (Figure 4.15). For the average climate change scenario C6, it was found that the runoff increased by 70.12%. Figure 4.16 illustrates that even a low percentage increase in rainfall volume (in the range of 3.05% to 5.81%) can result into a very high increase in runoff (36.44% to 70.12%).

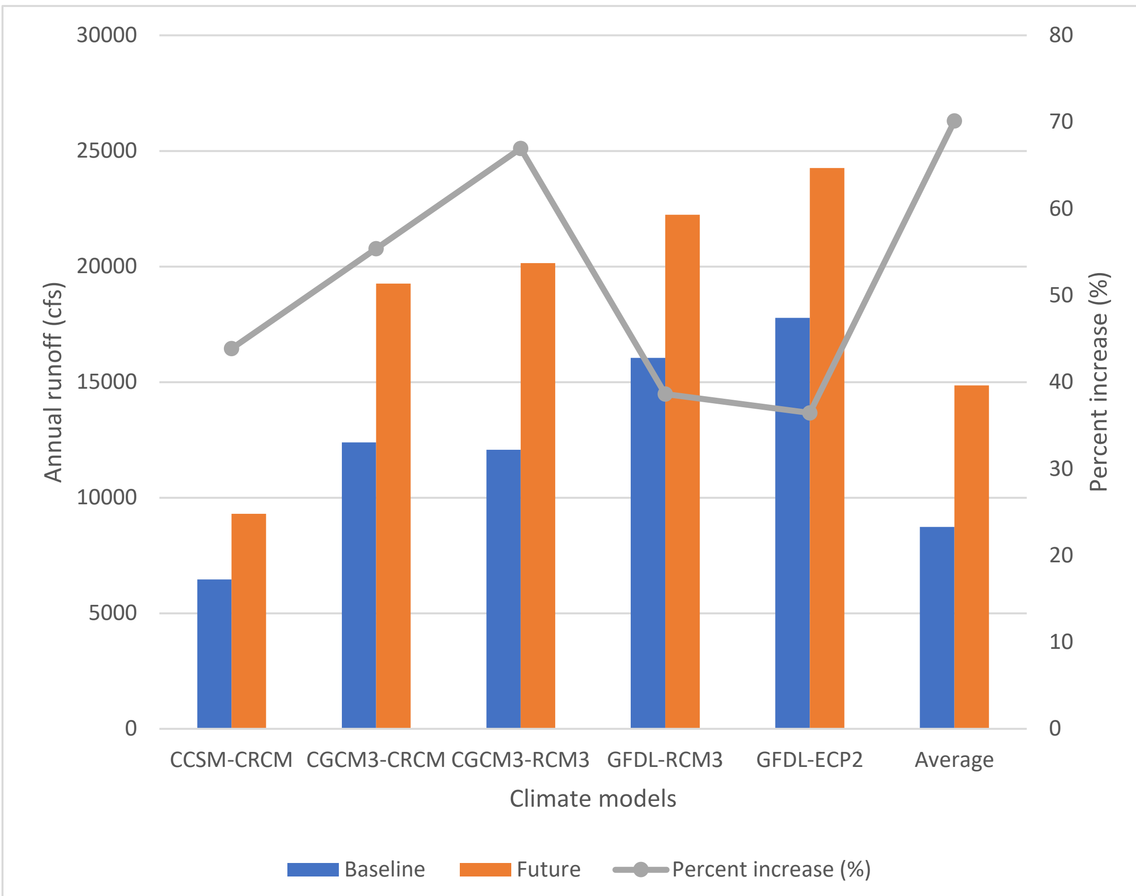

Figure 4.15: Comparison of annual baseline and future runoff

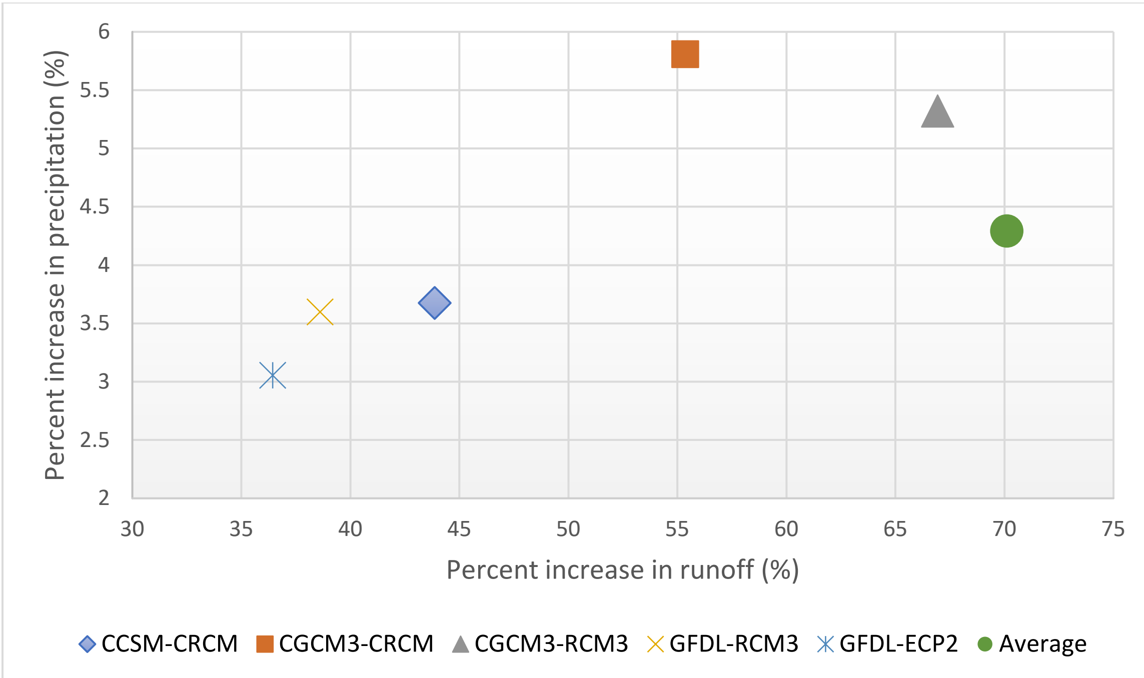

Figure 4.16: Comparison of rainfall and runoff increase for each climate model

The results of climate change impacts on runoff depends on many factors like consideration of urbanization, scale of projected data and study area, sensitivity of the software used for simulation, etc. and thus are subjected to many uncertainties, as evident in the existing literature. Thakali, Kalra and Ahmad (2017) predicted an average of 144.5% increase in outflow from a 570 km^2 watershed in Las Vegas valley using NARCCAP climate change prediction. Chiew et. al. (2009) forecasted 17% decrease to 7% increase in mean annual runoff averaged across their 1.3 million km^2 study area (southeast Australia) using 15 global climate models (GCMs). This reflects the uncertainties sourced from the use of GCMs in large-scale hydrological model. In a study by Waters et.al. (2003), climate change increased the total runoff volume by 19% for a small urban catchment in Ontario

using GCM simulations. Franczyk and Chang (2008) also used GCM simulation to model the Rock Creek basin in Portland and found out that for a 2% increase in average annual precipitation, average annual runoff increased by 2.7%, when only the precipitation factor was changed in the model. Di and Mishra (2017) studied the sensitivity of runoff to precipitation, evapotranspiration and 2 m air temperature to see how the hydroclimatic variables other than precipitation contribute to runoff during climate change. In their study area which comprised of eight subregions along the main river basins of Asia, they found out that runoff was the most sensitive to precipitation and change in 1% precipitation resulted in 1%-3.5% change in runoff. In another research conducted by Yaning et. al. (2009), the annual runoff in the Tarim River basin in China increased by 10.9% when using trend analysis to predict future climate data. Overall research has shown that the effects of climate change on watersheds can vary, yet when coupled with urbanization, the two factors can operate synergistically, increasing the magnitude of stormwater runoff (Pyke et al., 2011).

4.5. Combined climate change and LID effects

Scenario CL was used to evaluate the effectiveness of LID practices in climate change situation. Future precipitation data from Scenario C6 was used for analysis along with the predicted future land use data. Both rain garden and rain barrel were modeled for a simulation period of 32 years (2048 to 2069). The simulated daily runoff values were averaged at a monthly scale (Figure 4.17) and it was found that there was an overall decrease in monthly runoff than that of the average future scenario. However, even after using both LID practices, it was not sufficient to decrease the runoff to the average baseline

value. Annual total runoff decreased from 14859.23 cfs to 10879.5 cfs (26.8%) after using LID, but it was still 24.5% greater than 8734.547 cfs, which is the annual total runoff in baseline scenario. However, in April, May and June, the monthly runoff was found to be lesser or very close to the baseline scenario (Figure 4.17).

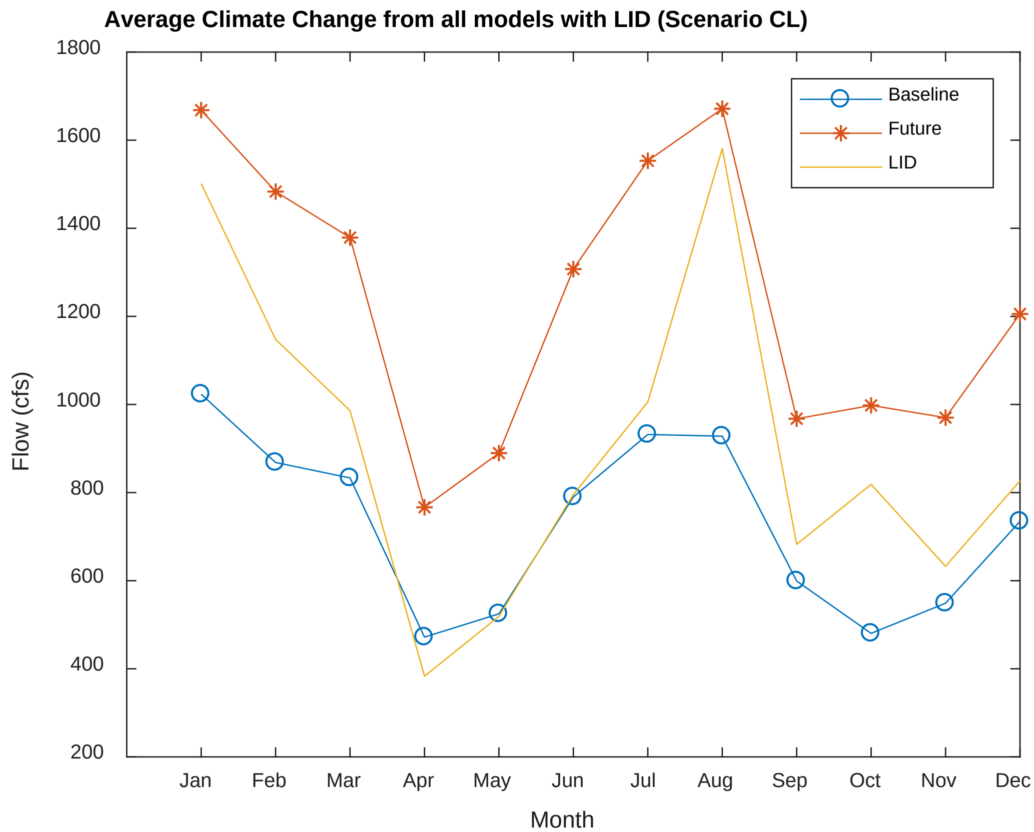

Figure 4.17: Effectiveness of LID for mean climate change scenario

Zahmatkesh et. al. (2014) conducted similar research to quantify LID effectiveness in climate change scenario using IPCC CMIP5 projections. In their study area of 124 km^2 in New York, they observed that average runoff volume decreased from 7817 m^3 to 6261 m^3 (20%) which was close, but still greater than their baseline runoff volume of 5977 m^3. They also observed maximum decrease in runoff volume in the month of June, when their

projected precipitation was minimum. Similar study conducted by Pyke et. al. (2011) in a Boston watershed resulted in a runoff volume decrease from 2785.2 m^3 to 2007.2 m^3 (27.2%). In this case, LID tools were able to reduce runoff to a value less than the historical volume of 2634 m^3. Despite several researches supporting the use of LID techniques to reduce runoff caused by climate change, there has also been some questions regarding its feasibility and performance. Zhou (2014) addressed that LID techniques does impact water flows, but reduction of water volume is very limited in extreme events and sensitive to local conditions, such as size and duration of rainfall event, soil material and texture. Holman-Dodds et. al. (2003) also concluded that LID techniques are most useful for small, relatively frequent rainfall events, and not very useful when it comes to large, extreme events.

CHAPTER FIVE

SUMMARY

This thesis studied the use of two LID practices for stormwater control using a hydrological model developed in PCSWMM under various land use and climate change scenarios.

The results of objective 1 (to develop a well-calibrated hydrological model of an urban watershed using a rainfall-runoff simulation model, PCSWMM) are given below:

- Model was developed and ran for 16 years (2000-2015).
- Sensitivity analysis concluded that subcatchment width, slope, percent impervious and curve number were the most sensitive parameters in this model.
- It was found that using extreme event for calibration gave much better results than when the extreme event was used for validation.
- Good values of NSE and R^2 (>0.79 for both calibration and validation) were observed, indicating it that a well-calibrated model was developed.

Similarly, the results of objective 2 (to quantify the change in runoff due to various land use and climate change scenarios) are listed below:

- Both urbanization and climate change significantly affect the study area.
- Increase of percent imperviousness by 10% to 70% increased the annual flow from 24% to 120%.
- Land use map of 2050 was predicted using site suitability analysis and previous land use records.

- For the increase in urban land use from 32.44% in 1992 to 81% in 2050, runoff increased by 53.49%.
- Runoff was expected to increase by 23.3% from 2011 to 2050. Had the land use in 2011 been same as that in 1992, the runoff would have decreased by 19.69%.
- Five high resolution NARCCAP climate change models were used to predict future changes in precipitation and runoff.
- In all cases, average annual runoff increased by a range of 36.44% to 70.12%.

Likewise, the following summary of the results were obtained for objective 3 (to evaluate the effectiveness rain garden and rain barrels in reducing runoff):

- Watershed-scale implementation of LID practices was incorporated in the model, as opposed to the more famous site-scale implementation.
- Rain gardens proved to be more effective than rain barrels to reduce runoff.
- Combination of both LID gave the best results.
- The mean annual runoff decreased by 10% when using rain barrel only, by 21.3% when using rain garden only and by 34% when using both as LID practices.

Most importantly, when combined urbanization, climate change and LID effects were studied, it was found that although the LID practices were able to reduce runoff by 26.8% when installed in the future climate and urbanization scenario, it was not able to reduce the flow to the baseline condition. This means that LID practices cannot be solely relied upon to dramatically reduce stormwater especially in the conditions of extreme events brought by climate change. In addition to the installation of LID components, improvement of existing storm drainage structures also need to be prioritized. When

integrated with improved forms of traditional drainage, LID controls can prove to successfully manage stormwater runoff even in the future urbanization and climate change scenario.

Information from this study can support urban planners and policy makers in the City of Columbia during the land use planning of this watershed or other similar watersheds. It can act as a tool and a guide to select the most productive type and location of LID practices for maximum runoff reduction. This study can further be extended to evaluate other LID controls like porous pavements, vegetative swales, etc. Future work can also include the cost-benefit analysis of installing different types of LID practices and the comparison of their effectiveness based in their life expectancy. Water quality aspect can further be incorporated in the model, and the effectiveness of LID in improving water quality can be studied.

REFERENCES

Abi Aad, Maya P., Makram T. Suidan, and William D. Shuster. "Modeling techniques of best management practices: Rain barrels and rain gardens using EPA SWMM-5." *Journal of Hydrologic Engineering* 15.6 (2009): 434-443.

Abida, H., and J. F. Sabourin. "Grass swale-perforated pipe systems for stormwater management." *Journal of irrigation and drainage engineering* 132.1 (2006): 55-63.

Ahiablame, Laurent M., Bernard A. Engel, and Indrajeet Chaubey. "Effectiveness of low impact development practices: literature review and suggestions for future research." *Water, Air, & Soil Pollution* 223.7 (2012): 4253-4273.

Ahiablame, Laurent, and Ranish Shakya. "Modeling flood reduction effects of low impact development at a watershed scale." *Journal of environmental management* 171 (2016): 81-91.

Akhter, Muhammad Saleem, and Guna Alankarage Hewa. "The Use of PCSWMM for Assessing the Impacts of Land Use Changes on Hydrological Responses and Performance of WSUD in Managing the Impacts at Myponga Catchment, South Australia." *Water* 8.11 (2016): 511.

Bergman, Maria, et al. "Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation." *Water Science and Technology* 63.10 (2011): 2279-2286.

Bhaduri, Budhendra, et al. "Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model." *Environmental management* 26.6 (2000): 643-658.

Bhaduri, Budhendra, et al. "Long-term hydrologic impact of urbanization: a tale of two models." *Journal of Water Resources Planning and Management* 127.1 (2001): 13-19.

Burns, Matthew J., et al. "Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform." *Landscape and urban planning*105.3 (2012): 230-240.

Carlson, Mark A., et al. "Impacts of urbanization on groundwater quality and recharge in a semi-arid alluvial basin." *Journal of Hydrology* 409.1-2 (2011): 196-211.

Carter, Timothy L., and Todd C. Rasmussen. "Hydrologic behavior of vegetated roofs." *JAWRA Journal of the American Water Resources Association* 42.5 (2006): 1261-1274.

Carter, Timothy, and C. Rhett Jackson. "Vegetated roofs for stormwater management at multiple spatial scales." *Landscape and urban planning* 80.1-2 (2007): 84-94.

Chadwick, Michael A., et al. "Urbanization affects stream ecosystem function by altering hydrology, chemistry, and biotic richness." *Ecological Applications* 16.5 (2006): 1796-1807.

Chapman, Cameron, and Richard R. Horner. "Performance assessment of a street-drainage bioretention system." *Water Environment Research* 82.2 (2010): 109-119.

CHI (Computational Hydraulics Int.). (2013). "Calibrating a SWMM5 model using the SRTC tool." Computational Hydraulics Int. Available at: http://support.chiwater.com/support/articles/29894-calibrating-a-swmm5-modelusing-the-srtc

CHI (Computational Hydraulics Int.). (2014a). "The Modeling Programs – About PCSWMM." Available at: http://www.chiwater.com/Training/Workshops/NorthAmericaworkshops.asp

CHI (Computational Hydraulics Int.). (2014b). "PCSWMM- Advanced Modeling of Stormwater, Wastewater and Watershed Systems Since 1984." Available at: http://www.chiwater.com/Software/PCSWMM/

CHI Support (Computational Hydraulics Int.). (2014). "Flow Routing." Available at: http://support.chiwater.com/support/articles/38406-flow-routing

Chiew, F. H. S., et al. "Estimating climate change impact on runoff across southeast Australia: Method, results, and implications of the modeling method." *Water Resources Research* 45.10 (2009).

County, Prince George'S. "Low-impact development design strategies: An integrated design approach." *Department of Environmental Resources, Programs and Planning Division, Prince George's County, Maryland* (1999).

County, Prince George'S. "Maryland, Department of Environmental Resources Programs and Planning Division (1999)." *Low-impact development design strategies—an integrated design approach* (2006).

Damodaram, Chandana, et al. "Simulation of combined best management practices and low impact development for sustainable stormwater management." *JAWRA Journal of the American Water Resources Association* 46.5 (2010): 907-918.

Davis, Allen P. "Field performance of bioretention: Hydrology impacts." *Journal of Hydrologic Engineering* 13.2 (2008): 90-95.

Debo, Thomas N., and Andrew Reese. *Municipal stormwater management*. CRC Press, 2002.

DeBusk, K. M., and T. M. Wynn. "Storm-water bioretention for runoff quality and quantity mitigation." *Journal of Environmental Engineering* 137.9 (2011): 800-808.

Desa, U. N. "World urbanization prospects, the 2018 revision." *Population Division, Department of Economic and Social Affairs, United Nations Secretariat* (2018).

Dietz, Michael E., and John C. Clausen. "A field evaluation of rain garden flow and pollutant treatment." *Water, Air, and Soil Pollution* 167.1-4 (2005): 123-138.

Dietz, Michael E. "Low impact development practices: A review of current research and recommendations for future directions." *Water, air, and soil pollution* 186.1-4 (2007): 351-363.

Douglas, Ellen M., and Chelsea A. Fairbank. "Is precipitation in northern New England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm." *Journal of Hydrologic Engineering* 16.3 (2010): 203-217.

Du, Jinkang, et al. "Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China." *Journal of Hydrology* 464 (2012): 127-139.

EPA. Report on the Environment: Urbanization and Population Change. https://cfpub.epa.gov/roe/indicator_pdf.cfm?i=52 (PDF)

Fleischmann, Corinna M., "Evaluating Management Strategies for Urban Stormwater Runoff" (2014). *Doctoral Dissertations. 620.* https://opencommons.uconn.edu/dissertations/620

Foster, S. S. D., B. L. Morris, and A. R. Lawrence. "Effects of urbanization on groundwater recharge." *Groundwater problems in urban areas: Proceedings of the International Conference organized by the Institution of Civil Engineers and held in London, 2–3 June 1993*. Thomas Telford Publishing, 1994.

Franczyk, Jon, and Heejun Chang. "The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA." *Hydrological Processes* 23.6 (2009): 805-815.

Guan, Mingfu, Nora Sillanpää, and Harri Koivusalo. "Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in southern Finland." *Water Science and Technology* 71.10 (2015): 1485-1491.

Guillette, Anne, and Low Impact Design Studio. "Achieving Sustainable Site Design through Low Impact Development Practices." *National Institute of Building Sciences: Washington, DC, USA* (2010).

Hall, Roland I., et al. "Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains." *Limnology and Oceanography* 44.3part2 (1999): 739-756.

Hammer, Thomas R. "Stream channel enlargement due to urbanization." *Water Resources Research* 8.6 (1972): 1530-1540.

Harbor, Jonathan M. "A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology." *Journal of the American Planning Association* 60.1 (1994): 95-108.

Hollis, G. E. "The effect of urbanization on floods of different recurrence interval." *Water Resources Research* 11.3 (1975): 431-435.

Holman-Dodds, Jennifer K., A. Allen Bradley, and Kenneth W. Potter. "Evaluation of hydrologic benefits of infiltration based urban storm water management." *JAWRA Journal of the American Water Resources Association* 39.1 (2003): 205-215.

Hsieh, Chi-hsu, and Allen P. Davis. "Evaluation and optimization of bioretention media for treatment of urban storm water runoff." *Journal of Environmental Engineering* 131.11 (2005): 1521-1531.

Hunt, W. F., et al. "Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina." *Journal of Irrigation and Drainage Engineering* 132.6 (2006): 600-608.

Huong, H. T. L., and A. Pathirana. "Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam." *Hydrology and Earth System Sciences* 17.1 (2013): 379-394.

Intergovernmental Panel on Climate Change (IPCC). (2007). “Summary for policymakers. Climate change 2007: The physical science basis.” Contribution of Working Group I to the 4th Assessment Rep. of the IPCC, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds., Cambridge University Press, Cambridge, U.K.

Intergovernmental Panel on Climate Change, Fourth Assessment Report: Climate Change 2007, (AR4), available at http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

James, W., et al. "Storm Water Management Model (PCSWMM)-Version 5: User’s guide to SWMM." *Computational Hydraulics International (CHI), Guelph, Ontario, Canada* (2005).

Jennings, Aaron A., et al. "Rain barrel–urban garden stormwater management performance." *Journal of Environmental Engineering* 139.5 (2012): 757-765.

Jentsch, Anke, and Carl Beierkuhnlein. "Research frontiers in climate change: effects of extreme meteorological events on ecosystems." *Comptes Rendus Geoscience* 340.9-10 (2008): 621-628.

Jones, Matthew P., and William F. Hunt. "Performance of rainwater harvesting systems in the southeastern United States." *Resources, Conservation and Recycling* 54.10 (2010): 623-629.

Kim, Youngsug, et al. "Runoff impacts of land-use change in Indian River Lagoon watershed." *Journal of Hydrologic Engineering* 7.3 (2002): 245-251.

Kim, Yuri, Lawrence E. Band, and Darren L. Ficklin. "Projected hydrological changes in the North Carolina piedmont using bias-corrected North American Regional Climate Change Assessment Program (NARCCAP) data." *Journal of Hydrology: Regional Studies* 12 (2017): 273-288.

Kumar, Manish, and Vasim Riyasat Shaikh. "Site suitability analysis for urban development using GIS based multicriteria evaluation technique." *Journal of the Indian Society of Remote Sensing* 41.2 (2013): 417-424.

Lee, Joong Gwang, et al. "A watershed-scale design optimization model for stormwater best management practices." *Environmental Modelling & Software* 37 (2012): 6-18.

Lee, Kil Seong, and Eun-Sung Chung. "Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed." *Hydrological Processes* 21.22 (2007): 3046-3056.

Legret, Michel, and Valérie Colandini. "Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals." *Water Science and Technology* 39.2 (1999): 111-117.

Line, D. E., et al. "Effectiveness of LID for commercial development in North Carolina." *Journal of Environmental Engineering* 138.6 (2011): 680-688.

Liu, Di, Ashok K. Mishra, and Ke Zhang. "Runoff sensitivity over Asia: Role of climate variables and initial soil conditions." *Journal of Geophysical Research: Atmospheres*122.4 (2017): 2218-2238.

Maraun, Douglas. "Bias correction, quantile mapping, and downscaling: Revisiting the inflation issue." *Journal of Climate*26.6 (2013): 2137-2143.

Martin-Mikle, Chelsea J., et al. "Identifying priority sites for low impact development (LID) in a mixed-use watershed." *Landscape and urban planning* 140 (2015): 29-41.

McKinney, Michael L. "Effects of urbanization on species richness: a review of plants and animals." *Urban ecosystems*11.2 (2008): 161-176.

McMichael, Anthony J., Rosalie E. Woodruff, and Simon Hales. "Climate change and human health: present and future risks." *The Lancet* 367.9513 (2006): 859-869.

Mearns, L. O., et al. "Climate change projections of the North American regional climate change assessment program (NARCCAP)." *Climatic Change* 120.4 (2013): 965-975.

Mishra, Ashok K., and Vijay P. Singh. "A review of drought concepts." *Journal of hydrology* 391.1-2 (2010): 202-216.[1]

Mishra, Ashok K., and Vijay P. Singh. "Changes in extreme precipitation in Texas." *Journal of Geophysical Research: Atmospheres* 115.D14 (2010).[2]

Murabayashi, Edwin T., and Yu-Si Fok. "Urbanization-induced impacts on infiltration capacity and on rainfall-runoff relation in a Hawaiian urban area." *Available from the National Technical Information Service, Springfield VA 22161 as PB 80-206196, Price codes: A 04 in paper copy, A 01 in microfiche. Technical Report* 127 (1979).

Muthanna, Tone M., Maria Viklander, and S. T. Thorolfsson. "Seasonal climatic effects on the hydrology of a rain garden." *Hydrological Processes* 22.11 (2008): 1640-1649.

Najafi, Mohammad Reza, and Hamid Moradkhani. "Multi-model ensemble analysis of runoff extremes for climate change impact assessments." *Journal of Hydrology* 525 (2015): 352-361.

NASA's Global Climate Change report available at: https://climate.nasa.gov/causes/

Nascimento, N. O., et al. "Using detention basins: operational experience and lessons." *Urban water* 1.2 (1999): 113-124.

Nelson, Gerald C., et al. "Climate change effects on agriculture: Economic responses to biophysical shocks." *Proceedings of the National Academy of Sciences* 111.9 (2014): 3274-3279.

Nirupama, N., and Slobodan P. Simonovic. "Increase of flood risk due to urbanisation: a Canadian example." *Natural Hazards* 40.1 (2007): 25.

Olivera, Francisco, and Buren B. DeFee. "Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas." *JAWRA Journal of the American Water Resources Association* 43.1 (2007): 170-182.

Pyke, Christopher, et al. "Assessment of low impact development for managing stormwater with changing precipitation due to climate change." *Landscape and Urban Planning* 103.2 (2011): 166-173.

Ren, Wenwei, et al. "Urbanization, land use, and water quality in Shanghai: 1947–1996." *Environment international* 29.5 (2003): 649-659.

Rose, Seth, and Norman E. Peters. "Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach." *Hydrological Processes* 15.8 (2001): 1441-1457.

Roseen, Robert, et al. "Storm water low-impact development, conventional structural, and manufactured treatment strategies for parking lot runoff: Performance evaluations under varied mass loading conditions." *Transportation Research Record: Journal of the Transportation Research Board* 1984 (2006): 135-147.

Rossman, L. "Storm Water Management Model (SWMM version 5.0) user's manual." *United States Environment Protection Agency* (2004).

Roy, Allison H., et al. "Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States." *Environmental management* 42.2 (2008): 344-359.

Roy-Poirier, Audrey, Pascale Champagne, and Yves Filion. "Review of bioretention system research and design: past, present, and future." *Journal of Environmental Engineering*136.9 (2010): 878-889.

Sawyer, R. M. "Effect of urbanization on storm discharge and ground-water recharge in Nassau County, New York." *US Geological Survey Professional Paper* 475 (1963): 185-187.

Schmidhuber, Josef, and Francesco N. Tubiello. "Global food security under climate change." *Proceedings of the National Academy of Sciences* 104.50 (2007): 19703-19708.

Seto, Karen C., Burak Güneralp, and Lucy R. Hutyra. "Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools." *Proceedings of the National Academy of Sciences* 109.40 (2012): 16083-16088.

Sobolowski, S., and T. Pavelsky. "Evaluation of present and future North American Regional Climate Change Assessment Program (NARCCAP) regional climate simulations over the southeast United States." *Journal of Geophysical Research: Atmospheres* 117.D1 (2012).

Stagge, James H., et al. "Performance of grass swales for improving water quality from highway runoff." *Water research* 46.20 (2012): 6731-6742.

Stahre, Peter. *Sustainability in urban storm drainage: planning and examples*. Svenskt vatten, 2006.

Steffen, Jennifer, et al. "Water supply and stormwater management benefits of residential rainwater harvesting in US cities." *JAWRA Journal of the American Water Resources Association* 49.4 (2013): 810-824.

Suriya, S., and B. V. Mudgal. "Impact of urbanization on flooding: The Thirusoolam sub watershed–A case study." *Journal of Hydrology* 412 (2012): 210-219.

Teutschbein, Claudia, and Jan Seibert. "Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods." *Journal of Hydrology* 456 (2012): 12-29.

Thakali, Ranjeet, Ajay Kalra, and Sajjad Ahmad. "Urban Stormwater runoff under changing climatic conditions." *World Water Congress*. 2017.

Trieu, Phong, et al. "Combined sewer overflow rooftop type analysis and rain barrel demonstration project." (2001).

Tu, Jun. "Spatially varying relationships between land use and water quality across an urbanization gradient explored by geographically weighted regression." *Applied Geography* 31.1 (2011): 376-392.

U.S. Census Bureau. 2002b. Demographic trends in the 20th century: Census 2000 special reports. Washington, DC. https://www.census.gov/prod/2002pubs/censr-4.pdf (PDF) (222 pp, 3.3MB).

UN-DESA-PD (United Nations Department of Economic and Social Affairs, Population Division) (2018) *World urbanization prospects, the 2018 revision*. United Nations, New York, NY.

United States Environmental Protection Agency (U.S. EPA). 2013. Managing Wet Weather with Green Infrastructure. Available at: http://cfpub.epa.gov/npdes/home.cfm?program_id=298.

USEPA (US Environmental Protection Agency). (2000a). Low impact development (LID). A literature review. Washington, D.C: Office of Water. EPA-841-B-00-005.

USGS Report: How urbanization affects the hydrologic system. https://water.usgs.gov/edu/urbaneffects.html

Waters, Darren, et al. "Adaptation of a storm drainage system to accommodate increased rainfall resulting from climate change." *Journal of Environmental Planning and Management*46.5 (2003): 755-770.

White, Michael D., and Keith A. Greer. "The effects of watershed urbanization on the stream hydrology and riparian vegetation of Los Penasquitos Creek, California." *Landscape and urban Planning* 74.2 (2006): 125-138.

Wilderer, Peter A. "Applying sustainable water management concepts in rural and urban areas: some thoughts about reasons, means and needs." *Water Science and Technology*49.7 (2004): 7-16.

Yan, Hongxiang, and Findlay G. Edwards. "Effects of land use change on hydrologic response at a watershed scale, Arkansas." *Journal of Hydrologic Engineering* 18.12 (2012): 1779-1785.

Yang, Long, et al. "Urbanization and climate change: An examination of nonstationarities in urban flooding." *Journal of Hydrometeorology* 14.6 (2013): 1791-1809.

Yaning, Chen, et al. "Fifty-year climate change and its effect on annual runoff in the Tarim River Basin, China." *Quaternary International* 208.1-2 (2009): 53-61.

Zahmatkesh, Zahra, et al. "Low-impact development practices to mitigate climate change effects on urban stormwater runoff: Case study of New York City." *Journal of Irrigation and Drainage Engineering* 141.1 (2014): 04014043.

Zevenbergen, C., et al. "Challenges in urban flood management: travelling across spatial and temporal scales." *Journal of Flood Risk Management* 1.2 (2008): 81-88.

Zhou, Qianqian. "A review of sustainable urban drainage systems considering the climate change and urbanization impacts." *Water* 6.4 (2014): 976-992.