ABSTRACT

GARCIA-CUERVA, LAURA. Exploring Low Impact Development Strategies for Marginalized Communities in Urbanizing Watersheds. (Under the direction of Dr. Emily Berglund.)

Increasing urbanization augments impervious surface area, which results in increased run off volumes and peak flows. Low Impact Development (LID) approaches present a decentralized alternative for sustainable urban stormwater and provide water conservation opportunities. They also provide a wide array of ecosystem services and foster community building by enhancing neighborhood aesthetics, increasing property value, and providing shared green spaces. While projects involving sustainability concepts and environmental design are favored in privileged communities, marginalized communities have historically been located in areas that suffer from environmental degradation. Underprivileged communities typically do not receive as many social and environmental services as advantaged communities.

This research explores different LID based strategies at the watershed scale to address environmental justice in impoverished communities and to improve hydrological performance by mitigating storm water run off volumes and peak flows. LID deployment strategies target communities that are underprivileged and locations with high outreach potential within an urbanizing watershed. A hydrologic/hydraulic stormwater model is developed in EPA´s Storm Water Management Model (SWMM 5.1) to simulate the impacts of different management strategies. Management scenarios include the implementation of Rain Water Harvesting in private households, the decentralized implementation of bioretention cells in private households, the centralized implementation of bioretention cells in municipally owned vacant land, and combinations of those strategies. The impacts of these strategies are measured by the volumetric reduction of run off and peak flows. This approach is applied in an underprivileged community within the Walnut Creek Watershed in Raleigh, North Carolina.

Keywords: Urban Stormwater, Low Impact Development, Hydrologic/Hydraulic Modeling, Simulation, Marginalized Communities.

Exploring Low Impact Development Strategies for Marginalized Communities in Urbanizing Watersheds

by
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BIOGRAPHY

Laura Garcia-Cuerva has a BS and a MS degree in Forestry Engineering from the Universidad Politecnica de Madrid, Spain. She has worked as a translator, as a naturalist in a Natural Preserve, as a Forestry Technician in a project based basis, as a continuous educator for Forestry and Environmental workers and as a Research Assistant both in Forestry Engineering and in Civil Engineering departments.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Land use change associated with rapid urbanization increases the amount of impervious surface, generating high runoff volumes and flow rates, which overwhelm traditional centralized drainage systems. Stormwater sewer overflow degrades stream health, damages infrastructure systems, and creates safety hazards. Private residential owners, business, industries, and municipalities in charge of public land and infrastructure bear the economic burden of increased flooding and erosion. Low Impact Development (LID) approaches present a decentralized alternative for sustainable urban stormwater by mitigating flooding and providing water conservation opportunities. Best Management Practices (BMPs), Low Impact Development (LID), and Green Infrastructure (GI) are now grouped under the umbrella term Stormwater Control Measures (SCMs), which include both structural and non-structural strategies (National Research Council 2008). SCM manages stormwater through the onsite treatment of runoff. LID mimics the natural hydrological behavior of predeveloped urban environments. Applied on a broad scale, LID can maintain or restore a watershed's hydrologic and ecological functions (USEPA 2009). Compared with grey infrastructure, which is the infrastructure that comprises traditional conveyance drainage networks and water treatment systems, LID strategies provide an array of ecosystem and social services. These services include but are not limited to: energy savings, CO_2 sequestration, heat island effect mitigation, increase of biodiversity, habitat provision, fostering community building, enhance neighborhood aesthetics, augmentation of property values, provision of shared green spaces, public health improvement and crime reduction.

Great advances have been made in the implementation of decentralized stormwater management infrastructure across the country. Established programs range from small scale demonstrations to notable efforts like the ‘Green Alley Program’ in Chicago (Chicago Department of Transportation 2007) or the ‘Green City, Clean Waters Program’ in Philadelphia (Philadelphia Water Department 2011*)*. Despite growing interest in these techniques and the benefits they present to stakeholders and municipalities, concerns about efficiency, implementation and maintenance costs, shared and fragmented responsibilities, institutional limitations, and resistance to change limit the wide adoption of these approaches on a large scale (Doberstein et al. 2010; Roy et al. 2008).

Designing and implementing LID strategies has a strong social dimension. Because they are decentralized and distributed at many locations throughout a community, a large number of individual citizens or neighborhoods may be actively involved in their implementation. Impoverished communities have historically been institutionally neglected, lack appropriate infrastructure, and in general, enjoy fewer environmental services than more privileged communities. In many instances, watershed management projects and sustainability efforts are implemented in affluent neighborhoods, while marginalized communities disproportionately experience the consequences of environmental degradation (Norman et al. 2012; Sanchez et al. 2014). Effective implementation of LID infrastructure in marginalized communities would address environmental justice concerns and contribute to provide opportunities for the social and environmental growth of community well-being.

Adoption of innovative LID practices is hindered by uncertainty and risk perception (Olorunkiya, Fassman and Wilkinson, 2012). Familiarity is a factor in risk perception (Beecher, et al., 2005) and limited or inaccurate knowledge can create barriers to the widespread adoption of LID technology (Bowman & Thompson, 2009). In contrast, familiarity and education can positively influence adoption rates and willingness to adopt LID practices (Stacy, 2015). Selection of high impact locations with elevated foot traffic provides opportunities for continued and sustained outreach. Exposure of the public to these practices increases awareness of stormwater management challenges and improves understanding of the processes and impacts of the employment of LID infrastructure.

One of the most frequently used LID practices for storm water management in urbanizing watersheds is bioretention (Liu et al., 2014; Davis et al. 2009). Bioretention systems mimic the natural hydrologic cycle by incorporating filtration and infiltration, which results in substantial reduction of run off volumes and peak flows (Dietz, 2007; Davis et al. 2009). Bioretention has added benefits like improving aesthetics, enhancing habitat for wildlife, reducing soil erosion and recharging groundwater (USEPA, 2012). Rain Water Harvesting Systems (RWHS) intercepts rooftop run off and can serve as a tool for decentralized water supply and management of storm water (Steffen et al., 2013). Research shows that RWHS can have significant impacts on potable water demand (Mitchell et al., 1996; Jensen, 2008). Typically, however, RWHS have limited effects on runoff mitigation, and large storage sizes are needed for adequate stormwater control (Jones and Hunt, 2010).

A set of studies explores the impacts of LID practices on the hydrology of a catchment (Walsh, Pomeroy and Burian, 2014; York, Goharian and Burian, 2015; Petrucci et al. 2012, Vargas, 2009; Jones and Hunt, 2010; Jensen et al., 2010) but, to our knowledge, limited peer reviewed literature exists on the impacts of LID implementation at a watershed scale (Hood et al., 2007; Bedan and Clausen, 2009; Line et al., 2012). In this research we focus on the watershed-wide implementation of two LID practices, Rain Water Harvesting systems (RWHS) and Bioretention Cells as a means of flood control and runoff mitigation. Past studies on the effects of LID practices on the hydrology of a watershed show a wide arrange of possible outcomes. Improvements have documented on the reduction of stormwater runoff and water quality. Wash et al (2014) found that for a high density urban watershed, a RWHS based management strategy has the potential to reduce the volume of stormwater run off by 10.4% using 50 gallon rain tanks and by 12.4% for 200 gallon rain tanks at full implementation capacity (100% watershed coverage). In contrast, Petrucci et al. (2012) found that with 33.3% watershed coverage and rain tank sizes of 0.6 m^3 (158.5 gallon) and 0.8 m^3 (211 gallon), hydrological impacts were negligible. Research indicates that systems with elevated storage capacity (200 to 1,000 gallon) are most effective for stormwater management (York, Goharian and Burian, 2015)

The impacts of bioretention cell implementation at the watershed scale have not been explored extensively (York et al. 2015). A limited number of studies have explored the issue with varying results. Barich (2014) found run off volume reductions of 20-30%; a study in the North Creek Watershed in Illinois (TT, 2012) found volume reductions after cell implementation of 50%; and York et al. (2015) observed minimal (<1%) reduction for an average year after moderate implementation of cells in the watershed. These studies vary in watershed size, percentage of impervious surface, and level of implementation, and as a result, generalization of results is not possible. Research employing SWMM to model impacts of bioretention cell implementation tends to route all (100%) impervious flows towards the cell (Masi, 2012; Barich, 2014). This may be an unrealistic assumption, particularly in watershed scale models where site selection is limited and not analyzed in a case-by-case basis. Studies assessing the watershed scale impacts of bioretention cell implementation explore the implementation of bioretention cells in municipally owned land (York et al. 2015; Masi, 2012) or consider the conversion of a percent of impervious surface in the watershed to LID without considering the ownership of the locations retrofitted (Barich, 2014). To our knowledge, a comparison of the impacts of a centralized and decentralized management strategy has not been explored. In addition, none of the studies assessing the benefits of LID-based management strategies address environmental justice by focusing on the selection of underprivileged areas in where to implement these technologies.

In this research, we aim to evaluate the impacts of a suite of LID based management scenarios on the hydrologic performance of an urbanizing watershed by simulating strategies that are conservative and feasible. This research also addresses socioeconomic aspects of placing LID. We perform spatial analysis of the distribution of the socioeconomic conditions of a watershed to identify distressed communities that could socially and environmentally benefit from the deployment of LID technologies. Further analysis is performed to identify areas with elevated outreach potential. Sites within distressed communities and with high outreach potential are selected as preferred locations for LID placement. A subcatchment of the watershed with high density of preferred ideal locations is selected and management strategies for runoff mitigation are explored. A hydrological and hydraulic model of the watershed is constructed to capture the hydrological performance of the catchment and to simulate management scenarios of LID implementation. The impacts of catchment implementation of RWHS and bioretention cell at different density levels and with different infrastructure characteristics are evaluated. Impacts of bioretention cell deployment are assessed for centralized (municipally owned vacant land) and decentralized (e.g., private households) scenarios. This integrated approach to stormwater management is applied to the Walnut Creek watershed located in south Raleigh in Wake County, North Carolina. Results from this research will contribute to assist planners and managers to better select effective management strategies for runoff mitigation.

CHAPTER 2

METHODS

2.1 Spatial Analysis

Analysis using a geographic information system (GIS) is employed to identify preferred locations for the placement of LID infrastructure within a watershed. These potentially ideal locations for the placement of LID infrastructure are selected according to two criteria: socioeconomic status and outreach potential.

Target locations for LID implementation are socioeconomically underprivileged or marginalized communities. These communities do not usually benefit from sustainable and environmentally conscious practices and could greatly benefit from the implementation of LID practices to enhance community social and environmental wellbeing. The second selection criteria, outreach potential, offers the opportunity to expose and familiarize the public with LID infrastructure. These locations are referred to as High Impact areas.

Underprivileged and High Impact Areas

Socioeconomically underprivileged, distressed or disadvantaged areas are defined in terms of three criteria: average unemployment rate, annual per capita income and average poverty rate. These criteria abide by the definition of underprivileged areas provided by the University of North Carolina at Chapel Hill Center for Urban and Regional Studies, stating that distressed areas are those that meet the following criteria (High and Owen 2014):

- average unemployment rate 50% greater than the states' average unemployment rate,

- annual per capita income one third lower than the states’ average annual per capita income, and
- average poverty rate 50% greater than the states’ average poverty rate.

High Impact areas are defined here as areas in which elevated foot traffic facilitates exposure to LID infrastructure so that the public becomes more familiar with these practices. Familiarity can provide a better understanding on the functionality and benefits of these practices, which in turn is expected to facilitate adoption of these practices at a large scale. Places of interest such as schools, churches, libraries, supermarkets and post offices are identified, and the surrounding 500 ft. radius area is considered as a High Impact area. Shapefiles containing planimetric data allows the identification of target facilities.

Overlapping High Impact areas that are in underprivileged areas are classified as Preferred LID locations. These potentially ideal locations for the placement of LID infrastructure have a higher value when deploying LID based management strategies due to their combined environmental and social benefits as well as due to their outreach potential.

Specific LID Site Selection

Suitable locations for the implementation of specific LID practices − Rain Water Harvesting Systems (RWHS) or rain barrels and Bioretention Cells or rain gardens in this study – are selected from the Preferred LID locations, according to the specific requirements of these different practices. Bioretention cells can be placed in either public or private open space or vacant land as well as in single-family residential housing. RWHS can be placed in private residential property and commercial and institutional facilities. GIS data on property is employed to identify suitable locations for the selected LID infrastructure.

The analysis may be limited by the lack of detailed and dated information on buildings and property. Projects involving site specific selection should be conducted to carefully review census and planimetric data to identify appropriate sites for LID implementation.

2.2 Modeling

Catchment Selection

Hydrological modeling is a complex process that demands a considerable amount of parameter input and computational resources, especially for large watersheds. Catchment delineation is performed using ArcHydro (Maidment, 2002) on a raw Digital Elevation Model. A catchment with high density of preferred LID placement sites is selected for modeling and simulation of LID management scenarios. Additional data such as topographic information, soil classification, imperviousness, and land use is obtained from federal, state or municipal databases. Roughness and depression storage coefficients are assigned based on land use and present vegetation.

Hydrologic and Hydraulic Model

The Environmental Protection Agency Storm Water Management Model (SWMM 5.1) (USEPA 2015) is used in this research to model the hydrological and hydraulic behavior of the catchment. SWMM is a dynamic rainfall runoff model that estimates Combined Sewer

Overflows, runoff volumes, and velocity generated by rainfall events.

SWMM was selected when compared with other hydrological and hydraulic modeling tools because it is open ware, non-proprietary and designed primarily, though not exclusively, to model urban areas. It can model single events or long-term continuous simulations. The possibility to model water quality and analyze quality problems associated with urban runoff also offers potential to extend the scope of this research to explore water quality impacts in future research activities. In addition, the latest version SWMM 5.1 allows explicit simulation of LID infrastructure.

The catchment of study is discretized into smaller subcatchments according to land use, overland flow path and draining direction. Subcatchments are defined in terms of area, flow path length, width, slope and imperviousness.

Overflow path length is estimated as 500 ft for non developed areas and as the distance from back of a typical lot to the middle of the street for residential lots. The total number of residential lots in the subcatchment is identified from GIS planimetric data. Visual analysis of aerial imagery of a random sample of private lots from the total number of lots is performed to calculate the average distance from the back of the lot to the middle of the street. The width parameter is calculated as the subcatchment area divided by the flow path length. Impervious surfaces are assigned a slope of 2 % and the slope of un-developed areas is calculated from topographical data. The slope for each discretized subcatchment is estimated as the area-weighted average of both developed and un-developed areas.

Subcatchments are divided into pervious subareas – areas where run off can infiltrate into the upper soil zone – and impervious subareas – areas where run off cannot infiltrate into the upper soil zone (USEPA, 2010). Imperviousness is estimated from land use data collected from the National Land Cover Use Database (Xian et al., 2011). Total Impervious Areas (TIA) is not the most appropriate predictor of stormwaters impact to surface waters (Wash et al, 2004). Directly Connected Impervious Area (DCIA) is considered the primary contributor of storm water run off during small rain events (<25.4 mm or 1 inch) (Walsh, 2000; Walsh et al., 2004; Flint and Davis, 2007). DCIA is the impervious area including streets and roadways that are directly connected to conventional storm sewer networks with curb and gutter drainage systems. (Perrin and Hunt, 2013). The imperviousness parameter in SWMM is therefore considered to be the watershed's DCIA. Numerous approaches exist to estimate the DCIA including those based on a combination of analysis of aerial imagery and GIS data plus field observations (Lee and Heaney, 2003; Bochis and Pitt, 2005; Roy and Shuster, 2009), approaches based on regression analysis of rain and runoff data (Ebrahimian et al. 2016; Boyd et al. 1993; Boyd et al. 1994), approaches based on land use classification and run off coefficients (Pitt, 2011; UDFCD 2001) and lastly, approaches based on the study of empirical relationships between TIA and DCIA (Wenger et al, 2008; Roy and Shuster, 2009). Approaches based on rain-runoff relationships rely on long-term data, which is not readily available for a great number of catchments. Approaches based on analysis of GIS and aerial imagery analysis in combination with field observations are time consuming, labor intensive and costly for larger catchments (Ebrahimian et al. 2016). Therefore, we select an empirical based approach to estimate the DCIA of our watershed. The method selected is the Wenger et al. method (Wenger et al., 2008) in which DCIA and TIA follow the following relationship and are given as percentages of the watershed area:

$$\mathrm{DCIA} = (1.046\ \mathrm{TIA}) - 6.23 \tag{1}$$

However, discrepancies exist with other existing approaches such as that of Roy and

Shuster (2009), Wibben (1976), Miller (1979) and Dinicola (1989). Therefore, the imperviousness parameter in terms of DCIA is a key parameter for model calibration and it may be adjusted for model fitting.

The remaining properties of the catchment such as depression storage, Manning’s roughness coefficients (for overland flow, for closed conduits and for open channels) and infiltration parameters (NRCS Hydrologic Soil Group Definition, hydraulic conductivity, porosity, suction head, field capacity and wilting point, maximum infiltration rate, minimum infiltration rate and infiltration decay coefficient) are additional SWMM parameters. When possible, they should be extracted from site-specific data from the study area but, if unavailable, they can be extracted from literature, namely the SWMM User’s manual (Rossman, 2010) or the Urban Drainage and Flood Control District Guidance Manual (UDFCD, 2016).

The physically based Green Ampt infiltration model is chosen against the Horton model, which has a long history of use in dynamic simulations and over the Curve Number model, more suited for simplified models.

The catchment´s storm water drainage network is modeled in SWMM. The drainage data was obtained directly from the City of Raleigh Stormwater Management Division in Shapefile format. Given the extension of the network and the amount of available data, the complete network is assimilated to a simplified representation of all the elements that comprise the network. The number of stormwater inlets is reduced to represent the inlets of the main lines of the network and subdivision branches of the drainage lines are omitted favoring the main stem of the network.

Invert elevation is estimated from the spatial location in topographical maps and a 3 ft depth is added to the estimated elevation consistent with the recommended minimum cover depth for stormwater pipes (Brown et al. 2009). Channel geometry, length and roughness coefficients are characterized from the GIS shapefiles for closed conduits. Data is lacking for most natural open channels and so assumptions are made for these elements.

2.3. LID Simulation

Using SWMM-5.1, LIDs can be placed in an existing subcatchment or an entire new subcatchment can be created and devoted exclusively to the LID structure. When LIDs are modeled as individual subcatchments, the subcatchment's properties such as area, slope, curve number or imperviousness are encoded as those of the LID (USEPA 2015). LID implementation reduces the percentage of impervious surface, and a fraction of the run off can be rerouted to pervious areas, further reducing the runoff volume received by the LID. For example, bioretention cells receive stormwater runoff while RWH systems only treat direct precipitation.

LIDs are characterized in SWMM by a series of vertical layers defined by a per-unit-area composition. These process layers include Surface, Pavement, Soil, Storage, and Drain System layers. Alternative LID practices have different layer combinations. Bioretention cells require Surface and Soil layers and can optionally include Storage and Drain layers depending on the magnitude of the control measure. RWHS are characterized only by Storage and Drain layers (USEPA 2015). These layers define a number of characteristics such as vegetation cover, Manning's surface roughness, slope, imperviousness, soil thickness, porosity, field capacity, conductivity, drain coefficient or drain delay (USEPA 2015).

LID performance is assessed through the variation in the subcatchment's runoff, infiltration, and evaporation rates after the implementation of distributed control structures. Overall water balances for each LID are also available containing information on inflow, infiltration, evaporation, surface runoff, drain flow and initial and final stored volumes (USEPA 2015).

Rain Water Harvesting Systems

In this study, two household appropriate RWHS capacities are considered, 50 gallons and 200 gallons tanks. Specifications for each tank type are based on standard rain barrel designs in common retailers and include 23" diameter and 34" height for the 50 gallon tank (Hayneedle, 2016) and 36" diameter and 56" height for the 200 gallon tank (Acquabarrel, 2016). Overflow is 3" diameter and outlet height from the bottom is 0.75" for both designs. Corresponding footprint areas are 2.89 and 7.07 sq ft respectively. The smaller design ensures viability in every residence despite lot size restrictions, additionally preventing vector and water quality issues with drain time duration consistent with mosquito prevention. Larger RWHS capacity allows for increased catchment in greater storm events and longer residence time, however, drain time becomes more critical as risk of vector issues increase after 48 hours (Walsh, Pomeroy, Burian 2014)

Rate of flow through the underdrain is a function of the height of stored water over the underdrain outlet, the drain coefficient and the drain exponent. Flow rate per unit area of LID unit in in/hr is expressed in Eq (2) where C is the drain coefficient, h is the height of stored water in inches, H_d is the drain height over the bottom in inches and n is the drain exponent.

$$q = C(h - H_d)^n \tag{2}$$

The drain coefficient (or Flow coefficient in SWMM's LID editor) is a function of the drain time T of a depth of stored water D as shown in Eq (3).

$$C = \frac{2D^{1/2}}{T} \tag{3}$$

The drain is considered an orifice and drain exponent n adopts a typical value of 0.5. Drain time is assumed 24 hours for the 50 gallon tank and 48 for the 200 gallon tank. Rough estimates of C provide values of 0.49 in/hr and 0.78 in/hr respectively.

To account for the routing of precipitation from impervious surfaces (e.g. rooftops) to pervious surfaces (e.g. lawns), downpour disconnection is considered and all outflow from RWHS is returned to said pervious areas. Drain delay – the number of dry hours that it takes for the rain barrel to be emptied through its drain – is set at 24 hours. Units are considered initially empty, which requires 24 hours dry periods before precipitation events occur.

Rain barrels are usually located on one side of residential lots and only one side of rooftops drain to the rain water harvester. Therefore, the appropriate percentage of impervious surface treated (e.g rooftops) is simulated as 50% of the building footprint area.

Modeling of RWHS units is conducted using the SWMM LID editor as opposed to the traditional method based on cumulative storage volume conversion into impervious area depression storage. Usage of SWMM's LID editor has proven to produce less overestimation and underestimation of runoff volumes than the cumulative storage/depression storage method as evidenced by Walsh, Pomeroy and Burian, (2013). Usage of the SWMM LID editor also allows for easy replication of RWHS units and design types throughout the watershed. Implementation of RWHS is simulated at different density levels or percent of households in the catchment in which RWHS are implemented. Density levels considered in this research, also referred to as watershed coverage, are 10, 25, 40 and 100%.

Although commercial and institutional buildings could accommodate larger harvesting systems or cisterns, this approach is considered too site-specific and therefore not included within the scope of this study. Therefore RWHS implementation is only considered in residential properties.

Bioretention Cells

Bioretention basins are subdivision scale drainage control structures that capture surface runoff and provide a combination of detention, infiltration, and evaporation. Bioretention cells are constructed as engineered depressions containing vegetation grown on specially mixed soils over a drainage gravel bed. RWHS rely on small scale storage by collecting direct precipitation and roof run off that can be subsequently released or reused (James et al. 2010; USEPA 2015).

Soil characteristics play a key role in the modeling of bioretention cells and the bigger the extent of the area of study the bigger the complexity to adopt a standardized set of design specifications. Therefore, assumptions on the generalized soil type throughout the watershed must be made. Once soil characteristics are identified, saturated hydraulic conductivity, average capillary suction and soil moisture deficit are estimated according to the SWMM User Manual Version 5.0 (Rossman, 2010). Media depth is considered one of the key drivers of hydrologic performance in bioretention systems. Construction cost and local groundwater level need to be taken into consideration but, in general, a media layer between 0.7 and 1 m (2.3 and 3.3 ft) is recommended (Liu et al., 2014). A media depth of 3 ft is assigned. Percentage of impervious area treated or percentage of flows routed from impervious surfaces into the cell is

b)

a key input parameter in the SWMM LID editor. It accounts for the percent of impervious portion of the subcatchment's non-LID area whose runoff is treated by the LID practice (USEPA, 2010).

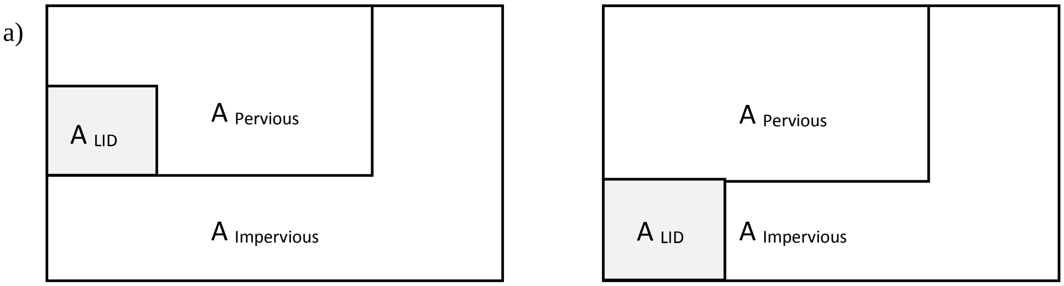


Figure 1. Conceptual subcatchment partitioning in SWMM with LID implemented in a) impervious area and b) pervious area.

Run off volumes are greater with limited impervious area treated. The reduction in run off volumes increases with increased treatment of impervious area, as flows are routed to pervious areas where infiltration can occur and impervious areas are converted to LID structures. Impervious area treated is therefore dependent on the catchment area, the pervious area, the non- pervious area occupied by a LID structure and the percent of run off flows originated on impervious surfaces that are routed to the LID structure, as shown in Fig. 1. Eq. 4 is used to calculate the amount of impervious area that is treated where A impervious treated is the impervious area in the catchment that is treated, A catchment the total area of the catchment, A pervious the pervious area in the catchment, A Non-impervious LID the impervious area in the catchment devoted to LID and Routing the percent of impervious flows routed to the LID structure.

$$A_{impervious\ treated} = \left(A_{catchment} - A_{pervious} - A_{Non-pervious\ LID}\right) * \frac{Routing}{100} \qquad (4)$$

In this research, different levels of impervious routing are explored. Routing levels are

10, 25 and 40% for the decentralized scenario and 25, 40 and 70% for the centralized approach. Variation in routing level is achieved through LID site placement, which affects the ability of flow to be directed towards the cell and be captured by it. In the decentralized scenario, cell implementation is limited by the layout of yard and household. In the centralized scenario, fewer limitations are expected because the land that is converted is owned and managed by a utility or governing agency. Different type of cell units are replicated across the watershed with the SWMM LID editor. In the decentralized scenario, three different cell unit sizes based on the mean yard area are simulated, and one size is selected in a simulation run. This allows us to explore the hydrologic impact of the cell size. Only one cell unit size is considered in the centralized scenario because deployment is not restricted by yard area. The extension of deployment in the centralized scenario is driven by the density level of implementation.

Finally, density level in the decentralized scenario accounts for the percent of households in the catchment in which bioretention cells are implemented. In the centralized scenario, density level represents the percent of available vacant land area that will be covered by bioretention cell units of equal size.

Using SWMM, the hydrologic performance can be evaluated as it is impacted by the amount of pervious surface converted into LID engineered pervious surface and by the amount of impervious surface treated. Impervious surface treated is impacted by routing level and by the amount of impervious area converted into pervious LID.

2.4. Storm Events

To estimate hydrological performance under different precipitation scenarios, simulations are performed for the Type II 24 hrs - 2 yr, 10 yr, 25, 50 yr and 100 design storms for the area of study (NOAA, 2016). In addition simulations are run for small frequent events registered in the area of study. Historical precipitation data is analyzed to select representative frequent storm events. Events are selected from both the lower and upper 50% percentile of recorded small events.

LID infrastructure is expected to have a significant impact on the magnitude and timing of run off discharges from design storms of smaller return period. Impacts on discharges from precipitation events of higher return period are expected to decrease with event size.

CHAPTER 3

CASE STUDY: THE WALNUT CREEK WATERSHED

The selected area of study is the Walnut Creek watershed, which is part of the Neuse River Basin in central North Carolina. Located within in Wake County (Fig.2), the Walnut Creek watershed extends from the town of Cary in the west throughout the south of the City of Raleigh until it reaches the Neuse River on its east end (Fig.3). The Walnut Creek watershed (Hydrologic Unit Code 030202011101) (USGS, 2012) has a total surface area of almost 30,000 acres and over 290 miles of stream.

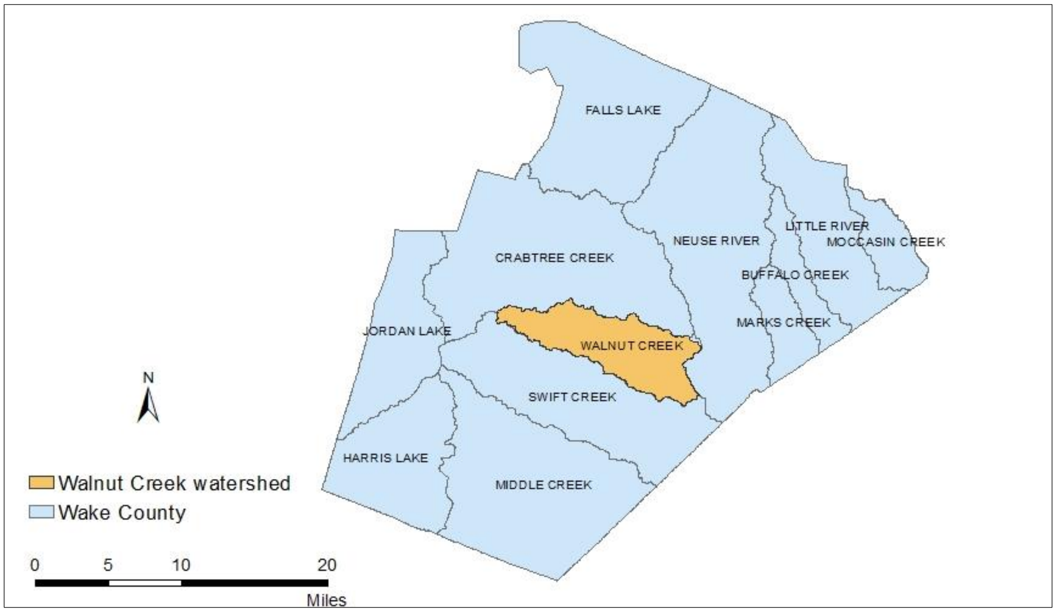


Figure 2. Watersheds within Wake County, North Carolina.

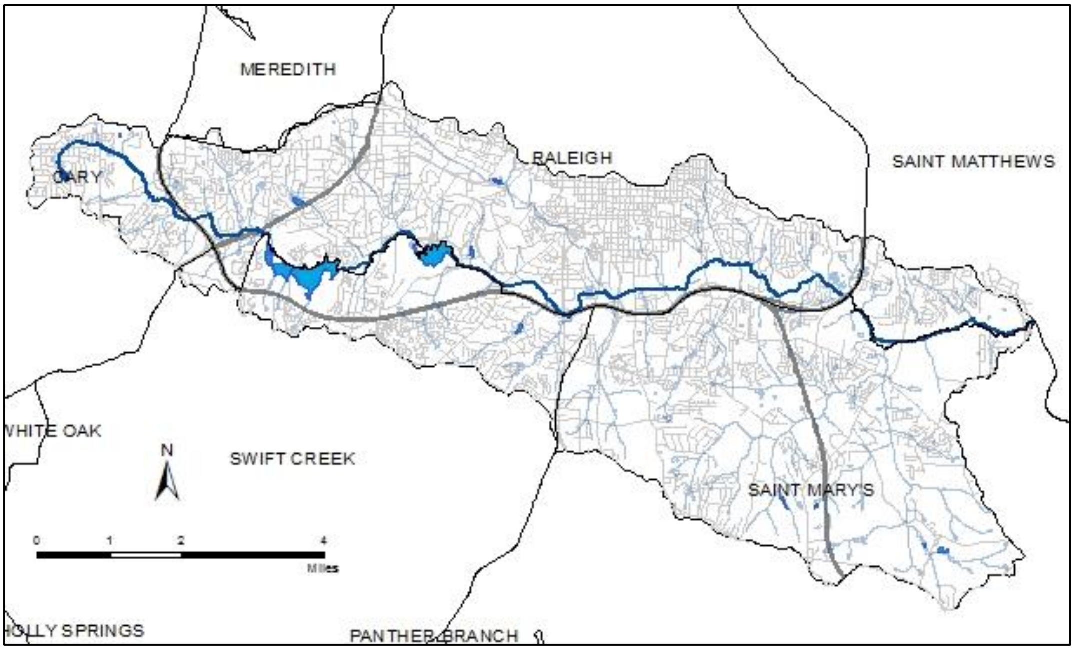


Figure 3. Walnut Creek watershed, North Carolina.

The watershed is the most urbanized area within the Neuse River Basin, and with a projected population increase of 40% in Wake County for the year 2035, rapid urbanization and increase of impervious surface is expected (North Carolina Office of State Budget and Management, 2015). A total of 66.8% of the watershed is developed and the current distribution of land uses in the watershed (National Agricultural Statistics Service, 2014) is given in Table 1.

Table 1. Distribution of land use types in the Walnut Creek watershed.

Land Use Type	Area (acres)	Percentage (%)
Agricultural	543.53	1.83
Open Water	286.89	0.97
Shrubland	175.25	0.59
Deciduous Forest	4304.45	14.53
Evergreen Forest	2164.57	7.31
Mixed Forest	391.86	1.32
Grass Pasture	1134.43	3.83
Woody Wetlands	661.85	2.23
Herbaceous Wetlands	8.01	2.70
Developed Open Space	10077.14	34.01
Developed/Low Intensity	5349.48	18.05
Developed/Med Intensity	3483.59	11.76
Developed High Intensity	872.23	2.94
Barren	174.58	0.59

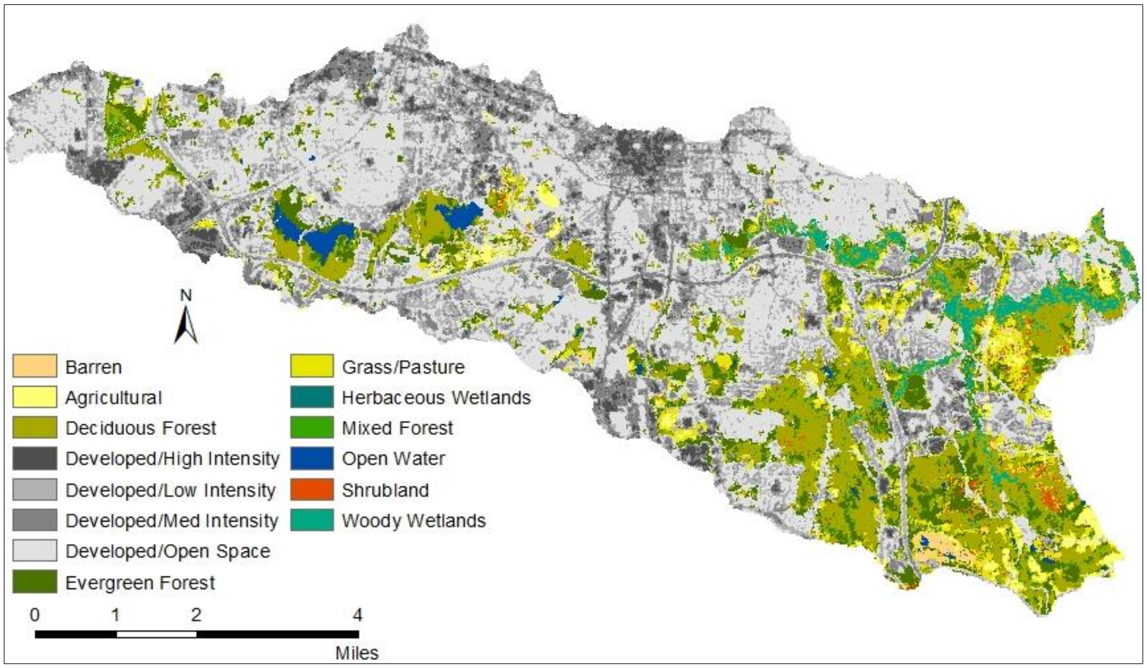


Figure 4. Distribution of land use types in the Walnut Creek watershed.

Areas of the Walnut Creek watershed are located in underprivileged communities with a predominantly African American racial makeup and have been significantly affected by repeated flooding. Specifically, the Rochester Heights neighborhood, the first African American housing development in Raleigh is built partly within the Walnut Creek floodplain and has been historically neglected and environmentally impaired. Raw sewage was discharged into Walnut Creek, next to the subdivision, up until the 1960s, and until recently, the community and the wetland area was commonly used as a dumping facility (The Natural Learning Initiative 2002). Due to frequent flooding events, residents were charged by the City of Raleigh for stormwater management services despite the faulty conditions of the drainage system. In contrast, residents of more privileged areas suffering the same flooding events were not charged for the same services (NCSU 2000).

In the mid 1990s, a grassroots group of stakeholders, community leaders and advocates decided to take action and formed what eventually would become Partners for Environmental Justice (PEJ), whose goal was to promote the growth and quality of life of Southeast Raleigh. This group focused on the conservation and restoration of 49 acres of Walnut Creek wetlands in Southeast Raleigh and created the Walnut Creek Urban Wetlands Educational Park, which resolved some flooding issues in the area and improved the environmental health of the wetlands. In addition, the Park provided a healthy wildlife habitat, beautified a neglected area of the City of Raleigh, and created a recreational resource for the residents of the surrounding areas while serving as an environmental outreach and educational opportunity. The park helps to conserve the City's ecological system and contributes to the revitalization of economically depressed areas (The Natural Learning Initiative 2002). PEJ continues to strive to improve the conditions of the community, its residents, and the ecosystem; however, flooding issues and environmental disparity persist, as shown in recent photographs of Walnut Creek (Fig.5).

Figure 5. Evidence of environmental degradation at the Walnut Creek Wetlands.
Photos by Laura Garcia-Cuerva

The health of Walnut Creek may improve from the multiple benefits that LID approaches bring to urban communities. In the face of climate change, population increase, and rapid urbanization, urban communities such as those within the Walnut Creek watershed may consider LID approaches as a critical component of revitalization projects (Detwiler 2012).

3.1. Selection of preferred locations for LID placement

Analysis using GIS is employed to identify preferred locations for the placement of LID infrastructure. Preferred locations are selected according to a number of conditions and preferences. We define preferred locations as those that are located in socioeconomically Underprivileged communities within the watershed and that intersect with High Impact locations. Census data was obtained at the block Group Level from the National Historical Geographic Information System (Minnesota Population Center, 2011) for the 2010-2014 five year period. According to the United States Census Bureau and the 2010-2014 American Community Survey 5-Year Estimates, the unemployed rate is 6.6 %, the per capita income is $25,608 and the poverty rate is 17.6% (US Census Bureau, 2015). Therefore, for a community to be considered underprivileged it must have an unemployment rate of 9.9 or greater (Fig.6), a per capita income lower than $17,072 (Fig. 7) and a poverty rate greater than or equal to 26.4% (Fig 8).

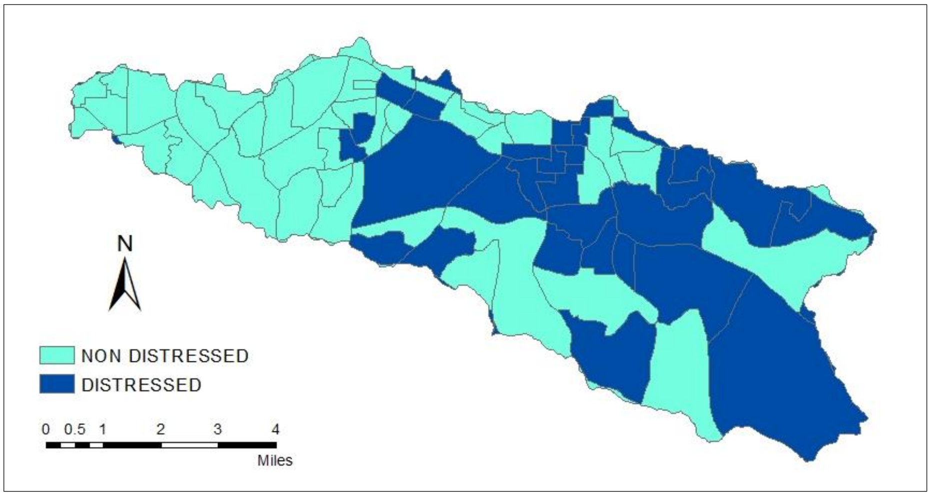


Figure 6. Distribution of Distressed and Non Distressed communities in relation to unemployment rate in the Walnut Creek watershed.

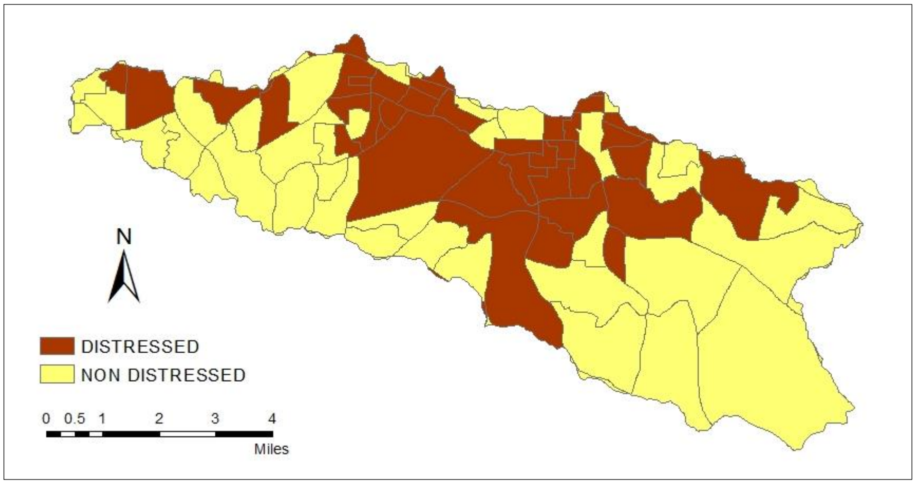


Figure 7. Distribution of Distressed and Non Distressed communities in relation to per capita income in the Walnut Creek watershed.

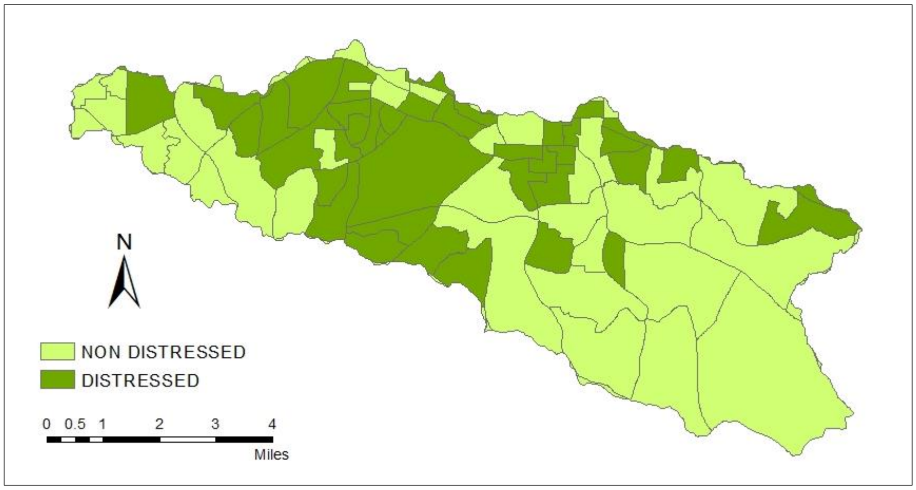


Figure 8. Distribution of Distressed and Non Distressed communities in relation to poverty rate in the Walnut Creek watershed.

High Impact areas are defined here as areas in which elevated foot traffic facilitates exposure to LID infrastructure so that the public becomes more familiar with these practices. Places of interest such as schools, churches, libraries, supermarkets and post offices are identified, and the surrounding 500 ft. radius area is considered as a High Impact area. Data were collected from the Wake County GIS Service (Wake County GIS Service, 2016). Overlapping High Impact areas that are in underprivileged areas are classified as Preferred LID locations (Fig. 9).

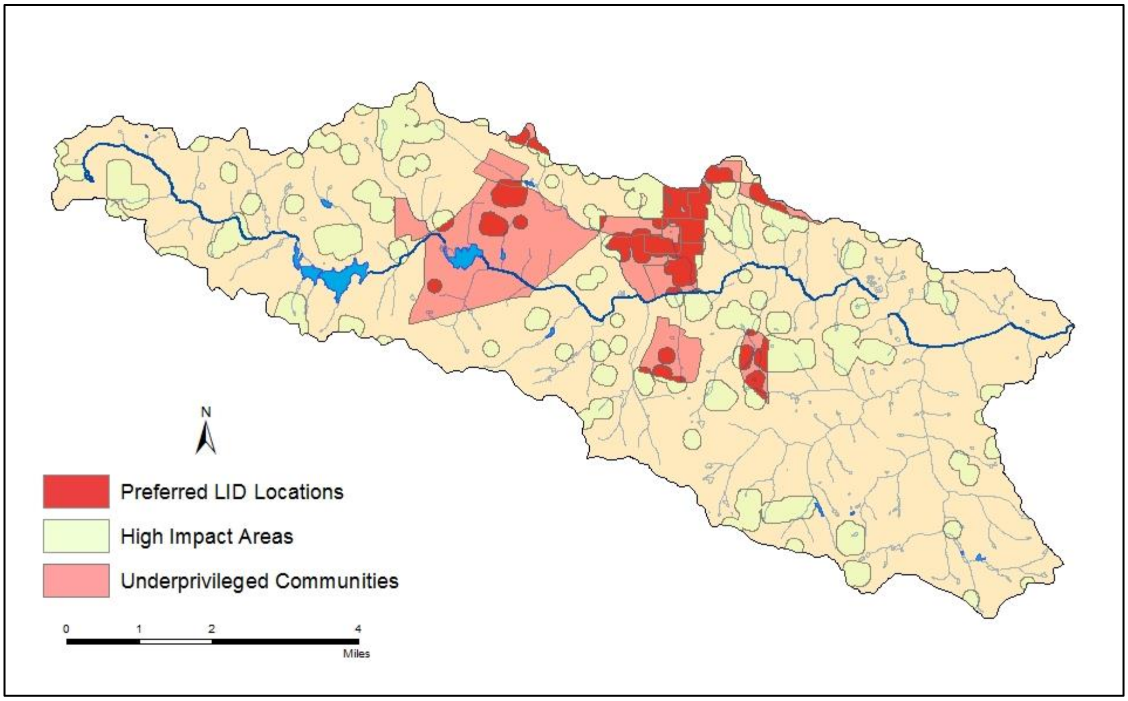


Figure 9. Spatial distribution of preferred LID placement locations in the Walnut Creek watershed.

Suitable locations for the implementation of different LID practices – bioretention cells and RWHS – are selected from Preferred LID locations (Fig.10), according to the specific requirements of these different practices. Bioretention cells can be placed in either public or private open space or vacant land. RWHS can be placed in private residential property and commercial and institutional facilities.

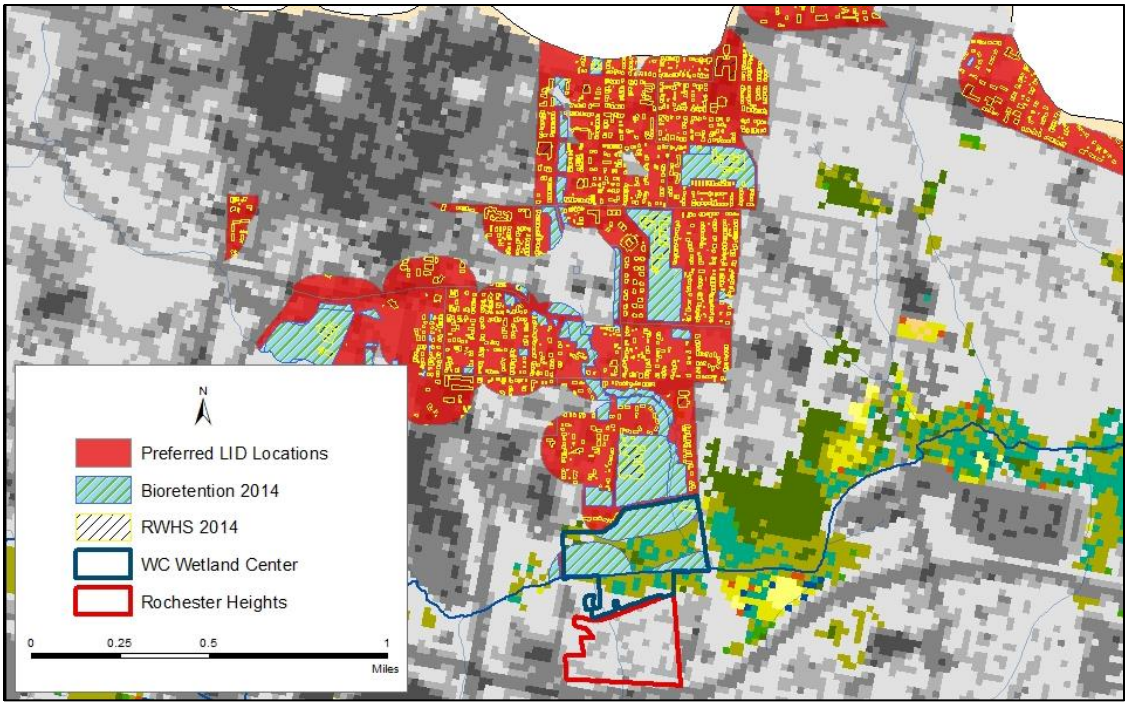


Figure 10. Close up of the spatial distribution of preferred LID placement locations for specific types of LID infrastructure in the Walnut Creek watershed.

Analysis shows that a large percentage of the potential sites for LID implementation are located in the southeast Raleigh area (Fig. 9), and particularly in the vicinity of the Rochester Heights neighborhood, the area that sparked initial local interest in flood mitigation and environmental protection and that led to the creation of the Walnut Creek Wetland Center (Fig. 10).

3.2 Catchment Selection

Catchment delineation is performed using ArcHydro on a raw Digital Elevation Model obtained from the North Carolina Floodplain Mapping Program (NCFMP) and 2,031 catchments are identified in the Walnut Creek watershed. The area selected for hydrologic modeling and simulation is the area draining to the inlet of the Walnut Creek Wetlands. The area is selected because of its high density of preferred LID locations and due to its location in the vicinity of the area affected by flooding that originally triggered the creation of Partners for Environmental Justice. In this document, the selected catchment of study will be referred to as the Walnut Creek Wetland Watershed (WCWW) (Fig.11).

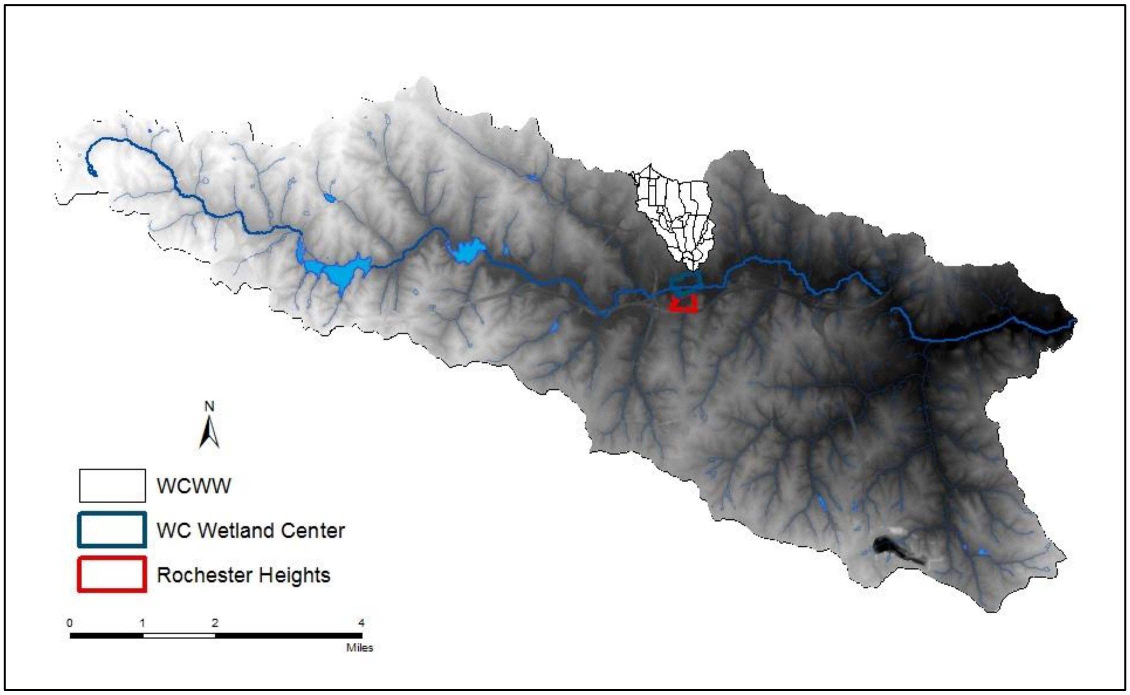


Figure 11. Selected catchment of study.

The catchment´s size is 628 acres and has a percentage of imperviousness of 36.53% based on the land use map of imperviousness from the National Land Cover Database (Xian et al. 2011). The catchment has a moderate population density of 1,699.2 people/Km^2.

There are 67.83 acres of vacant land available for placement of bioretention cells and 1,222 households with potential for RWHS or small size bioretention cells. For modeling purposes the catchment is further discretized in 28 subcatchments according to land use and flow path direction.

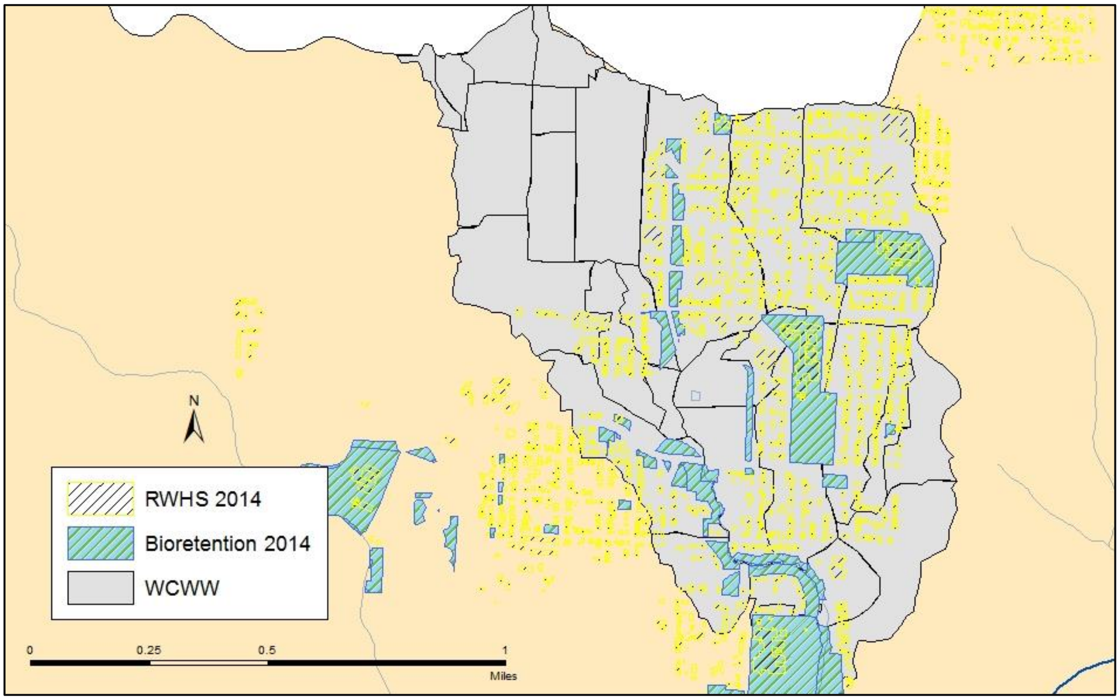


Figure 12. Close up of the spatial distribution of preferred LID placement locations at the selected catchment of study.

3.3 Precipitation Data

The average annual precipitation in Raleigh is 46.58 inch (US Climate Data, 2016). Both design storms and small frequent events are employed to evaluate the model and perform LID management simulations. Total depth is 3.46 inches for the 2yr-24 hr design storm; 4.37 inches for the 5yr-24 hr; 5.08 inches for the 10 yr-24 hr; 6.03 inches for the 25 yr - 24 hr; 6.79 for 50 yr-24 hr; and 7.57 for 100 yr- 24 hr storms.

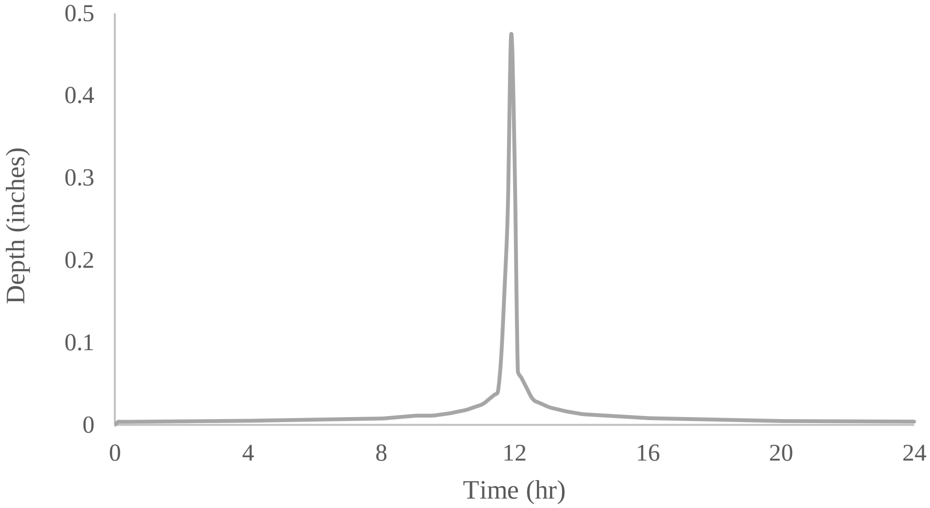


Figure 13. 2 yr- 24 hr design storm.

In addition, small frequent events are simulated to evaluate more realistic behavior of the watershed. Data is collected from the USGS monitoring station 0208735012 at Rocky Branch below Pullen Drive in Raleigh (USGS, 2016). This station is located 1.5 miles from the Walnut Creek Wetland Center. 708 recorded events spanning from January 1st 2010 to December 31st 2015 were considered. The event with maximum depth is 4.2 inch, which is smaller but close to the depth of a 5 yr – 24 hr event. 99 % of events are smaller than the 24 hr- 1 yr design storm (2.87 inches) and only two events are greater. Median precipitation is 0.15 inches with 9 events, and there are 356 events greater than and 352 events smaller than 0.15 in. Four events are selected with 0.05, 0.11, 1.35 and 2.98 inches of precipitation (Figure 13). They are selected as representative of different frequent storm magnitude, and each of these events does not follow previous events in the preceding days. This means that conditions in the watershed are no saturation with a maximum field capacity and ensures the performance of RWHS. Data is available in 5-minute intervals.

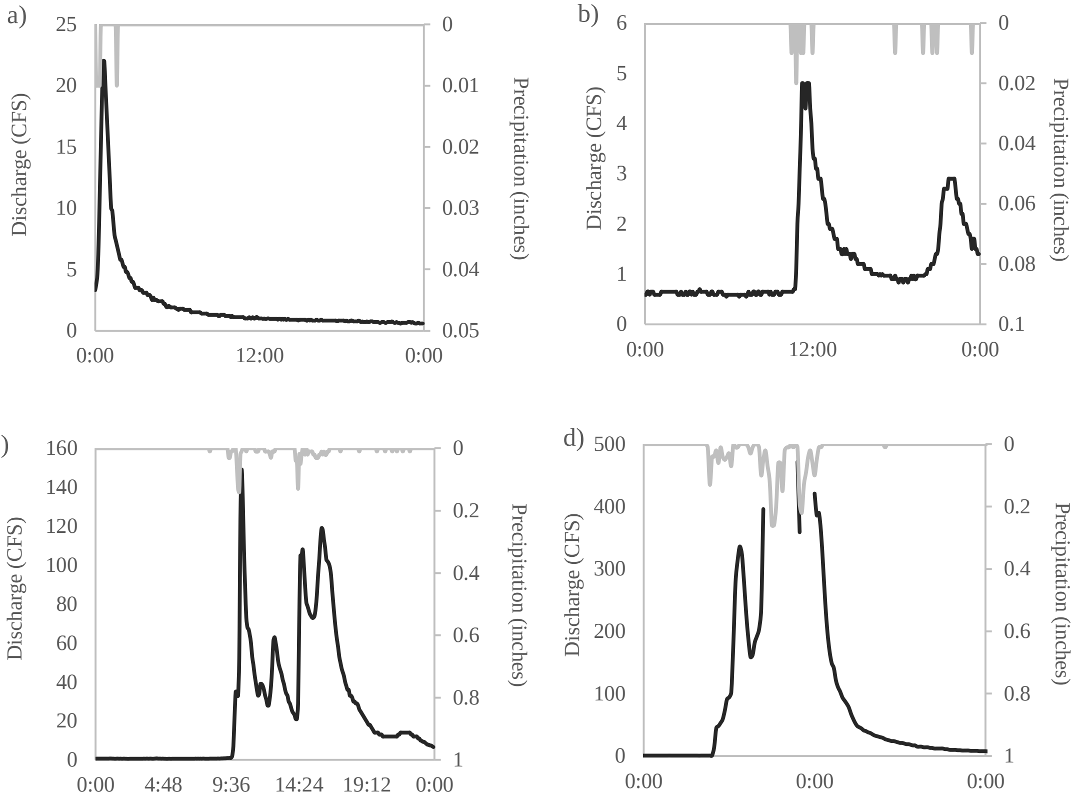


Figure 14. Precipitation depth and discharge for different small frequent precipitation events: a) 0.05, b) 0.11, c) 1.35 and d) 2.98 inches.

3.4 SWMM Model

The watershed is discretized in 28 subcatchments according to land use and direction of flow path. Flow direction is evaluated through the use of ArcHydro and Digital Elevation Models. Because some of the subcatchments have variability in land use, the width parameter in SWMM, as explained in section 2.2, is estimated by employing an area weighted average between longest overland flows in natural and urban areas. Longest overland flow was estimated through visual analysis of ortophotos and GIS shapefiles. Overflow path length is estimated as 500 ft for undeveloped areas and as the distance from back of a typical lot to the middle of the street for residential lots.

Slope was considered 2% in impervious land as recommended in the SWMM User's Manual (USEPA, 2010). For pervious areas, overland slope was calculated from topographical elevation data and by manually measuring overland flow length. The catchment slope was subsequently calculated again as an area weighted average. Subcatchment slope values ranged from 0.03% to 6.9%.

Imperviousness was estimated through visual analysis of ortophotos and GIS shapefiles. Imperviousness shapefiles from the National Land Cover Database (Xian et al. 2015) estimates the watershed´s imperviousness at 36.53%. Imperviousness varies greatly depending on whether it is estimated through visual analysis of ortophotos and GIS or through imperviousness data from the National Land Cover Data Base (Xian et al, 2015). The later greatly underestimates imperviousness and so is recommended to conduct visual analysis wherever the modeling efforts allow for the use of the greater amount of necessary time and resources. Imperviousness coefficient is key for model calibration. Total Impervious in the watershed is estimated as 64.90% through visual analysis and model calibration. There is great variability in the WCWW imperviousness ranging from total imperviousness in three subcatchments (100%) to 22.36 % of impervious surface in another subcatchment. Directly Connected Impervious Area is calculated trough the Wenger et al method (Wenger et al., 2008).

Manning's Roughness coefficient for overland flow is obtained from the SWMM User's Manual Version 5.1 (USEPA, 2015) and is estimated as 0.11 for impervious areas, corresponding to that of smooth asphalt. Pervious areas are considered either dense grass or woods with light underbrush with values of 0.24 and 0.4 respectively. Some of the catchments are weighted by the portion of area corresponding to each land use type. Roughness coefficients are also key parameters for model calibration.

Depression Storage is also extracted from the SWMM's User Manual 5.1 (USEPA, 2015). It is estimated as 0.075 for impervious surfaces and it has values of 0.2 for pasture and 0.3 for forest litter. The percentage of impervious surface without depression storage is estimated as 25% as recommended by the SWMM User's Manual.

The selected Infiltration Model is the Green Ampt, because it is a more physically based and simplified model. The necessary parameters that define the model are: suction head or average value of soil capillary suction along the wetting front (inches or mm), soil's saturated hydraulic conductivity and the initial deficit, calculated as the difference between the soil's porosity and its field capacity. These values are obtained from the recommended values in the SWMM's User Manual for different soil types. The soils present in the catchments are Appling sandy loam (ApB2, ApC2), Cecil sandy loam (CeB2, CeC2, CeD, CeF), Cecil clay loam (CIC3), Helena sandy loam (HeD), Made land (Ma), Wehadkee (Wo) and Bib soils and lastly Worsham sandy loam (Wy) (Fig. 15). The catchment presents soil homogeneity throughout most of its surface with mostly sandy loam soils. Towards the bottom part of the catchment in the proximity of the wetlands there is a concentration of clay loam soils that affect hydrologic behavior.

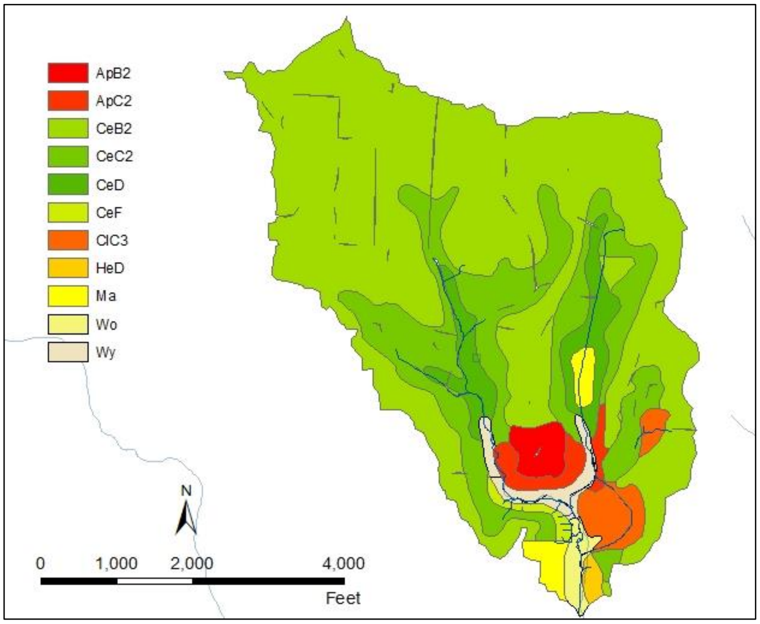


Figure 15. Soil types in the watershed.

Representation of the hydraulic features of the watershed is completed through modeling the stormwater drainage network. Data was obtained in the form of GIS Shapefiles provided from the City of Raleigh Stormwater Management Division (B. Hinkle, personal communication, August 2015). The files contain information on pipes, junctions, bridges, swales and open channels. Given the extent of the network, this is simplified to represent only the most representative features. The storm drainage network is comprised of 916 closed conduits, many of which are part of a main stem of the drainage network and represent identical characteristics. Subdivision branches of the network are not considered and only main stems of the piping system and open or natural channels are modeled. The network is reduced to 73 drainage elements for simplification. Characterization of channel geometry and length was obtained from storm sewer GIS shapefiles. Invert elevation was estimated from topographical information and a cover depth of 3 ft. under the terrain's surface was assigned to every closed conduit. Conduit roughness (Manning’s n coefficient) was set as 0.013 for circular, concrete pipes, as 0.02, for trapezoidal concrete-lined channels (ASCE, 1992) and as 0.05 for natural channels (USEPA, 2015). Data was not available for natural channel characterization, and assumptions were made based on personal observations of the channels. They were characterized as trapezoidal with a maximum depth of 3 ft. and a bottom width of 12 ft.

3.5 LID Simulation

LID based managements scenarios are simulated on SWMM 5.1 to evaluate the reduction of stormwater volumes and peak flows under different strategies.

Implementation of Rain Water Harvesting Systems is simulated by placing one 50 gallon or one 200 gallon rain barrel in residential households at different density levels. In the cachment upstream of the Walnut Creek Wetland Center and within the selected preferred location for LID placement there are a total of 1,222 residences. The median building footprint is 1,408,86 sq. ft. The impervious surface area treated by each RWHS is estimated as half of that (704.43) because roofs typically drain to two sides and only one side has the receiving rain barrel.

The average residential property size is 7,057.22 sq ft. Substracting the mean area of the building´s footprint, the resulting mean yard area is 5648.36 sq ft. If we consider bioretention cells occupying 25% of the total yard size, the mean cell size would be 1,412.09 sq ft (0.03 acres). In addition, bioretention cells doubling that size (0.06 acres or 50% of the mean yard area) and cells that are a third of that size (0.01 acres or 8.33% of the mean yard area) are also simulated.

CHAPTER 4

RESULTS

4.1. Model Calibration

Continuous streamflow data for the location of interest was unavailable. The hydrologic model was evaluated using small frequent events measured at the Rocky Branch below Pullen Park USGS monitoring station, located 1.5 miles away from the catchment´s outlet. The catchment draining to this monitoring station is not the selected catchment of study; however, the size, percent of impervious surface, soil types and slope are very similar to those of the catchment of study and thus is considered suitable for calibration purposes. A number of iterations are performed to achieve best model fitting by adjusting imperviousness, depression storage, roughness coefficients and overland flow path width. Five small frequent events – 0.05, 0.11, 1.35, 1.53 and 2.98 inches - are used for model calibration. The average difference between observed and modeled values is 19% for total flow volumes and 14% for peak flows. After calibration, a different set of eight storm events selected from the same time period of 1010-1015, varying in size and duration, is employed for model validation. Difference in values for observed and simulated events is averaged at 10% for total run off volumes and 35% for peak flows. Figure 15 compares the differences between observed and monitored total flow versus peak flows.

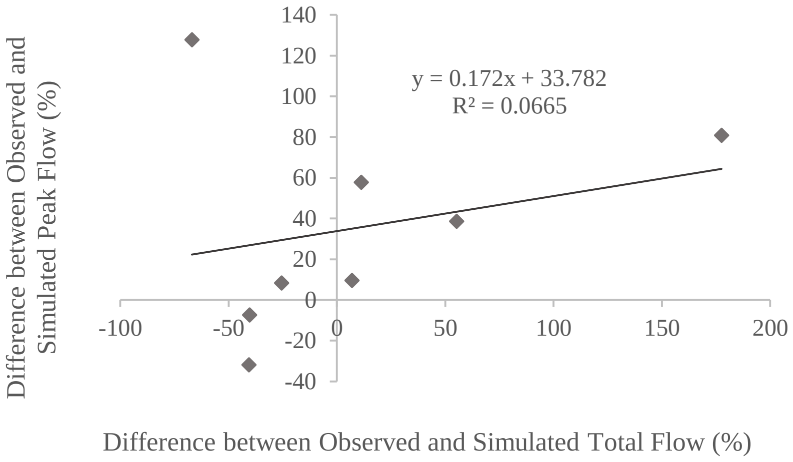


Figure 16. Comparison of differences between observed and simulated total flow and peak flow volumes.

Diversion from model and observed values can be attributed to the physical and structural differences of the catchment of study and the catchment draining to the USGS monitoring station. Model and observed flow rates follow similar trends, though peak flows seem to be underestimated (Fig.17). Better model fitting was obtained, particularly in terms of better capturing peak flows, but only after pushing imperviousness levels to unrealistic values of almost 100%. The model has limitations due to the lack of continuous monitoring data for the watershed, but it is considered acceptable for the purposes of this research.

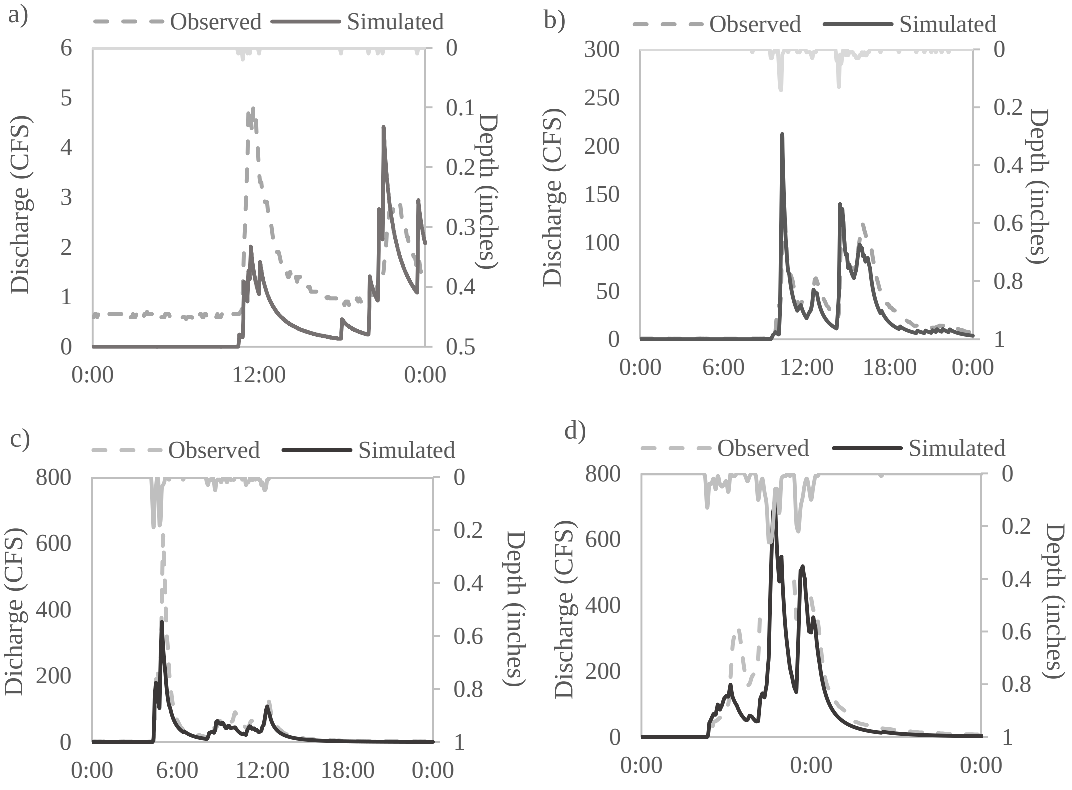


Figure 17. Observed and simulated flows for different storm events:
a) 0.11 inch, b) 1.35 inch, c) 1.53 and d) 2.98 inch.

4.2. LID Management Scenarios

Through SWMM 5.1, different LID management scenarios can be simulated, and the efficiency and impact of these strategies can be assessed. In this research, we evaluate the impact of implementing Rain Water Harvesting Systems (RWHS) or rain barrels and Bioretention Cells or rain garden based strategies. Two different sizes of RWHS are simulated: 50 gallon (189.3 liters) and 200 gallon (757.1 liters). Deployment of RWHS is simulated at different density levels in private households: 10, 25, 40 and 100% density. There are eight RWHS simulation scenarios in total.

Bioretention Cells are simulated as a centralized system in which they are implemented in municipally owned vacant land, and as a decentralized system in which they are implemented at the lot level in private residences. In addition, a small number of combined scenarios are considered, either as a combination of decentralized and centralized bioretention cell deployment or as a combination of decentralized bioretention cells and RWHS.

Decentralized implementation of bioretention cells is simulated at watershed density levels of 10, 25, 40 and 100%. Three different bioretention cell sizes - 0.01, 0.03 and 0.06 acres - are simulated at each density level. Existing research assumes total capture of run off volumes from impervious surfaces by the bioretention cells (Masi, 2012; Barich, 2014). In reality, multiple limitations to this assumption may exist due to the layout of both private property and municipal impervious surfaces. In this research we assume that such limitations are persistent and that only a fraction of runoff volumes is captured by the cells. Two percentages of impervious surface routing levels – 25 and 40% - are simulated for each density and sizing scenarios. In total, there are twenty-four decentralized bioretention management scenarios.

Centralized implementation is simulated at density levels of 10, 25 and 40% under the assumption that greater implementation will be difficult at the municipal level. Bioretention cell size is set at 0.01 acre for the SWMM modeling software input, but the deployment density is set by the total bioretention acreage in each subcatchment. Routing levels are 25, 40 and 70% as a greater degree of placement flexibility is assumed. There are a total of nine centralized bioretention management scenarios.

The combined scenarios simulate the implementation of decentralized 0.01 acre bioretention cells at a 25% density level and a 25% routing with: a) 50 gallon RWHS at a 25% density level and b) 200 gallon RWHS at a 25% density level. In addition, centralized bioretention deployment is simulated at a 25% density level with a 25% routing with decentralized bioretention cell deployment at 25% density level with 25% routing with a cell size of: c) 0.01 acre and d) 0.03 acre. In total there are four combined management scenarios.

A summary of the forty-five different management scenarios is presented in Table 2.

Table 2. Summary of LID management scenarios.

LID Type		**Size**	**Density (%)**	**Routing (%)**
RWHS	Decentralized	50 gallon	10	
			25	
			40	
			100	
RWHS	Decentralized	200 gallon	10	
			25	
			40	
			100	
Bioretention	Decentralized	0.01 acres	10	25
			25	25
			40	25
			100	25
Bioretention	Decentralized	0.01 acres	10	40
			25	40
			40	40
			100	40
Bioretention	Decentralized	0.03 acres	10	25
			25	25
			40	25
			100	25
Bioretention	Decentralized	0.03 acres	10	40
			25	40
			40	40
			100	40
Bioretention	Decentralized	0.06 acres	10	25
			25	25
			40	25
			100	25
Bioretention	Decentralized	0.06 acres	10	40
			25	40
			40	40
			100	40
Bioretention	Centralized	0.01 acres	10	25
			25	25
			40	25
	Centralized	0.01 acres	10	40
			25	40
			40	40
	Centralized	0.01 acres	10	70
			25	70
			40	70
RWHS +		50 gallon	25	
Bioretention	Decentralized	0.01 acres	25	25
RWHS +		200 gallon	25	
Bioretention	Decentralized	0.01 acres	25	25

Table 2. Continued.

Bioretention +	Centralized	0.01 acres	25	25
Bioretention	Decentralized	0.01acres	25	25
Bioretention +	Centralized	0.01 acres	25	25
Bioretention	Decentralized	0.03 acres	25	25

These simulation scenarios allow the evaluation of individual and combined effects on stormwater discharge to the catchment outlet. Impacts of centralized and decentralized strategies are also evaluated. Given the relevance of maintenance in sustaining the performance of bioretention cells, it is important to assess the impact at the catchment level of a strategy that relies heavily on the involvement of the community and its residents.

Ten different storms were simulated for the different management scenarios producing a total of 450 simulations. A summary of results for the 24 hr – 2 yr design storm and the monitored 1.35 inches event is shown in Table 3. Further results and analysis are discussed as follows.

Table 3. Summary of simulation results for the 24 hr -2 yr design storm and the 1.35 inches monitored event.

LID Type	Approach	Size	Density (%)	Routing (%)	2 yr		1.35 inch	
					Total Volume Reduction (%)	Peak Flow Reduction (%)	Total Volume Reduction (%)	Peak Flow Reduction (%)
RWHS	Decentralized	50 gallon	10		0	0	0	0
			25		0	0	0	0.6
			40		0	0	0	1.5
			100		0.2	0	0.3	3.3
RWHS	Decentralized	200 gallon	10		0	0	0	0
			25		0.2	0	0.3	0.7
			40		0.3	0	0.6	1.4
			100		0.9	0	1.9	4.1
Bioretention	Decentralized	0.01 acres	10	25	2.4	0.5	4.2	9.2
			25	25	5.4	0.4	10.1	14.9
			40	25	7.8	2.5	13.2	17.7
			100	25	13.8	8	17.1	19.6
Bioretention	Decentralized	0.01 acres	10	40	2.5	0.5	11.7	15.9
			25	40	5.7	0.3	16.5	19.3
			40	40	8.5	0.2	18.3	20.3
			100	40	16.9	9.6	22.1	21.7
Bioretention	Decentralized	0.03 acres	10	25	6.6	0.5	14.9	18.9
			25	25	12.8	7	18.7	20.7
			40	25	15.2	10	20.4	21.3
			100	25	20.1	16	25.3	22.7
Bioretention	Decentralized	0.03 acres	10	40	21.6	25.5	29.0	28.9
			25	40	24	27.2	30.1	31.2
			40	40	25.5	27.8	30.3	31.2
			100	40	29.4	29.6	30.9	31.4
Bioretention	Decentralized	0.06 acres	10	25	10	5.6	29.26	28.9
			25	25	15.9	10.7	30.7	31.4
			40	25	18.2	13.5	31.2	31.6
			100	25	24	20.3	31.6	32.2
Bioretention	Decentralized	0.06 acres	10	40	11	1.4	19.5	24.7
			25	40	20.9	11.1	26.7	29.4
			40	40	24.7	16.5	29.4	31.1
			100	40	31.5	25.3	34.9	33
Bioretention	Centralized	0.01 acres	10	25	8.9	4.5	13.4	16.7
			25	25	13.7	11.5	16.2	18.6
			40	25	16.4	14.6	17.5	19.3
Bioretention	Centralized	0.01 acres	10	40	10.2	1.4	17.7	23.5
			25	40	18.1	12.5	23.9	26.1
			40	40	22.2	17.8	25.7	28.1
Bioretention	Centralized	0.01 acres	10	70	11.3	1.1	21.1	35.9
			25	70	22.5	9.6	35.6	41.5
			40	70	29.5	17.8	40.5	42.9
RWHS Bioretention	Decentralized	50 gallon 0.01 acres	25 25	25	5.5	0.4	10.2	15.8
RWHS Bioretention	Decentralized	200 gallon 0.01 acres	25 25	25	5.5	0.4	10.4	15.7
Bioretention Bioretention	Centralized Decentralized	0.01 acres 0.01 acres	25 25	25 25	15.8	13.3	17.6	20.8
Bioretention Bioretention	Centralized Decentralized	0.02 acres 0.03 acres	25 25	25 25	21.3	10.7	29.8	33.2

Impacts of RWHS

For watershed RWHS density values – 10, 25, 40 and 100% – and for different storm sizes, total volume reduction varies from 0.0% to 4.5% and peak flow reduction from 0.0% to 4.1%. Reduction is greater with increasing watershed coverage for smaller storm events. Storage capacity, or the size of the system, and watershed coverage have a positive correlation with volumetric run off reductions, while storm size is inversely correlated to the reduction of flow volumes (Fig. 18).

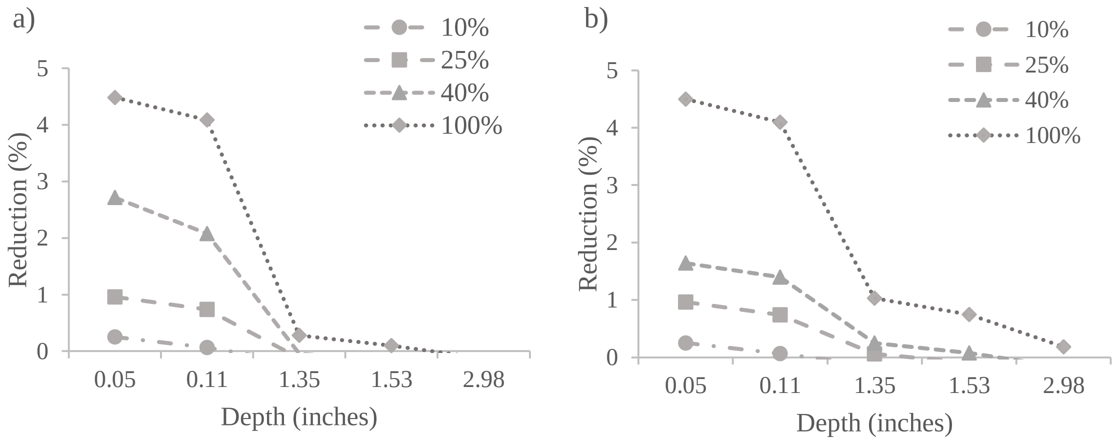


Figure 18. Relationship between storm size and run off volume reduction for different RWHS density and storage capacity: a) 50 gallons and b) 200 gallons.

Substantial reduction is only achieved for small storm events. The differences in flow reduction of implementing a 50-gallon compared to a 200-gallon RWHS are negligible and only noticeable when systems are implemented at a 100% density in the watershed (Fig. 19).

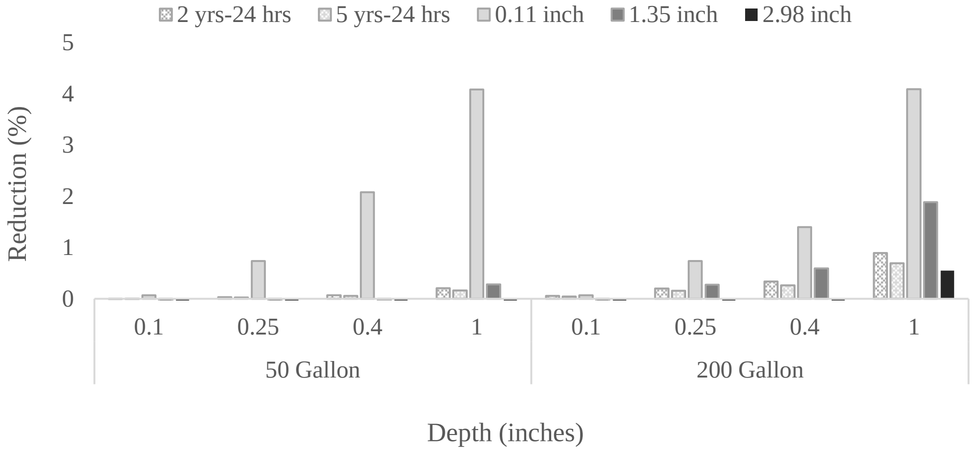


Figure 19. Run off volume reduction according to RWHS storage capacity and storm size.

Impacts of Bioretention cells

Volumetric reduction of total run off and peak flows is directly correlated to cell size, watershed coverage and routing percentage (Fig. 20). Reduction is inversely correlated to storm size with greater reduction occurring for small storm events. However, as opposed to RWHS results, reduction still occurs even for large extreme events, such as the 100-yr return period storm event. Peak flow reduction does not follow a consistent relationship with the parameters that increase volumetric reduction (Fig.20).

Decentralized scenarios

For the Type II design storms corresponding to the area of study, spanning from the 24 h-2 yr to the 24 hr- 100 yr storm, reduction values range from 1.5% to 31.5% for total run off volumes and from 0.0% to 25.3% for peak flows (Fig. 19). For the monitored frequent events, volume reduction ranges from 1.5 to 35.6% and peak flow reduction from 0.6 to 33.3% (Fig. 20).

For the different design storms with a greater range of rain depth, we observe a greater influence of cell size, percent routed and watershed coverage on the reduction outcome. In contrast, for the monitored frequent events, with less variability and smaller rain depths, the variability of volume and peak flow reduction is reduced and substantial differences appear only for larger events (Fig. 21).

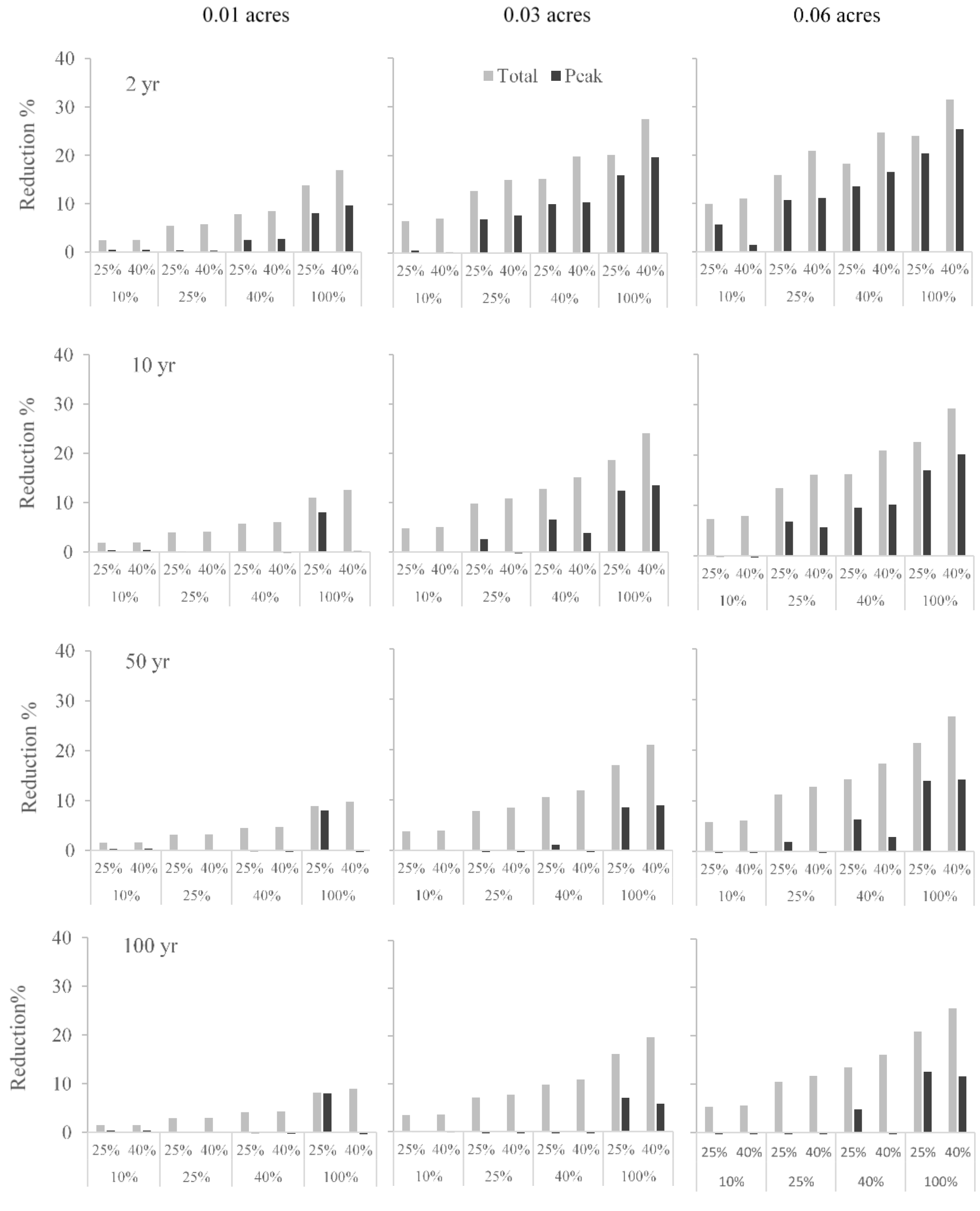


Figure 20. Reduction in total and peak flows according to watershed coverage (10, 25, 40 and 100%), percent of impervious surface treated (25 and 40%) and cell size (0.01, 0.03 and 0.06 acres) for the 24 hr- 2 yr, 10 yr, 50 yr and 100 yr design storms.

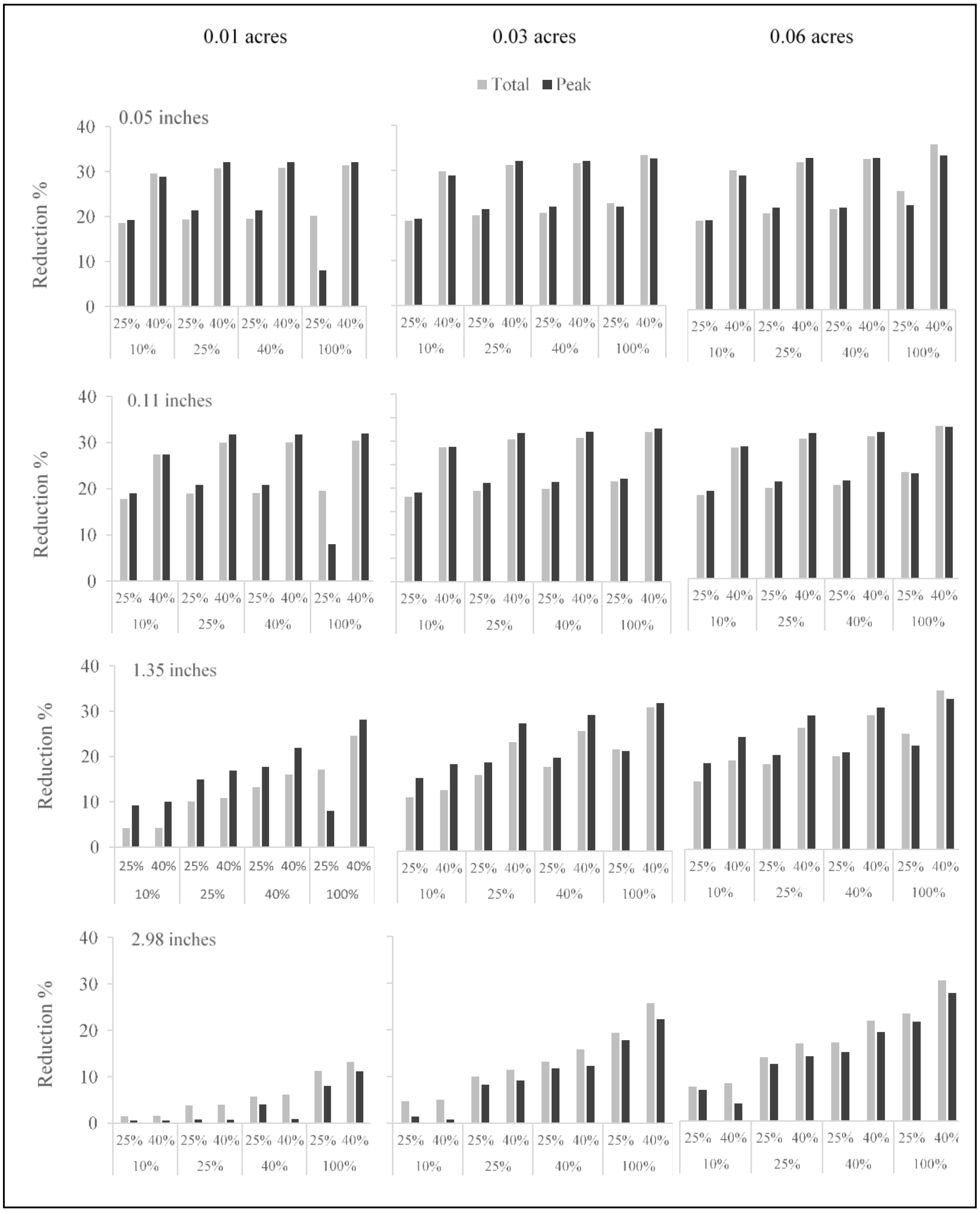
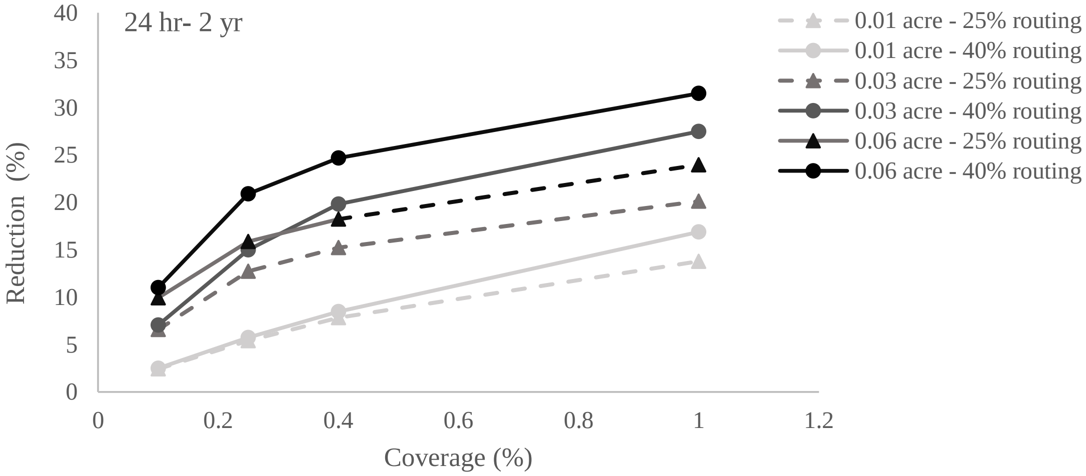


Figure 21. Reduction in total and peak flows according to watershed coverage (10, 25, 40 and 100%), percent of impervious surface treated (25 and 40%) and cell size (0.01, 0.03 and 0.06 acres) for the monitored 0.05, 0.11, 1.35 and 2.98 inch storm events.

Watershed coverage and percent routing follow are strongly correlated to volume reduction for all three different cell sizes. For a given watershed coverage, the reduction increases with routing percent for the smallest cell size. For the 0.03 and 0.06 acres cell sizes, the reduction for the different routing percent settings remains constant for different levels of watershed coverage (Fig. 22). The average coefficient of determination R^2 is 0.9 for the 2 yr design storm and 0.85 for the 1.35 inches storm event.



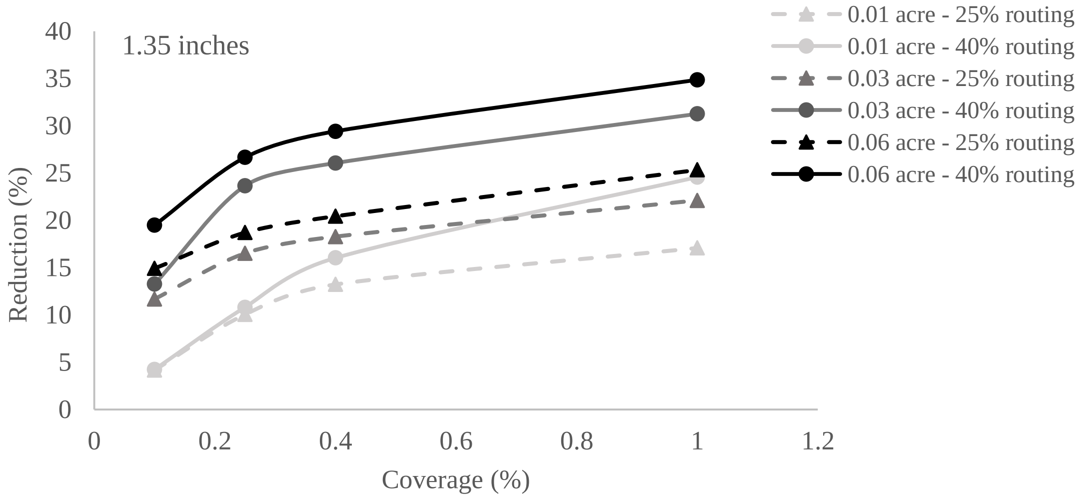


Figure 22. Relationship between run off volume reduction and watershed coverage for different routing percent and cell size, shown for two different storm events.

Results show that for the same cell size, watershed coverage is a larger driver of volume reduction than routing percent. We show this in Fig. 23 through the following analysis. For each cell size, the difference in reduction between routing levels is calculated for each watershed coverage level and then averaged. For example, for the 0.01 acre cell size, we calculate the difference in reduction between the 25 and 40% routing level for the 10, 25, 40 and 100% watershed coverage. These four values are then averaged. The same procedure is employed for the 0.03 and 0.06 acre cell sizes. This represents the influence of routing in run off volume reduction.

In the same way, we calculate the difference in reduction between different watershed coverage levels for each routing level and the results are then averaged for each cell size. For example, for the 0.01 acre cell size we calculate the difference in reduction between the 25 and 10% watershed coverage, the reduction between the 40 and 10% and the reduction between the 100 and 10% for the 25% routing level. We do the same for the 40% routing level. The same procedure is employed for the 0.03 and 0.06 acre cell size. Six averages are calculated and reported to evaluate the influence of watershed coverage in run off volume reduction.

For the same cell size, reduction is driven by the level of routing of impervious flows for small rain events (continuous lines in Fig. 23), and the influence of that factor decreases for increasing storm event sizes. In contrast, for small rain depths, the influence of watershed coverage (dashed lines in Fig. 23) lessens but increases rapidly with depth of precipitation. Logically, the influence of watershed coverage also increases with cell size as a larger cell size translates into greater watershed coverage.

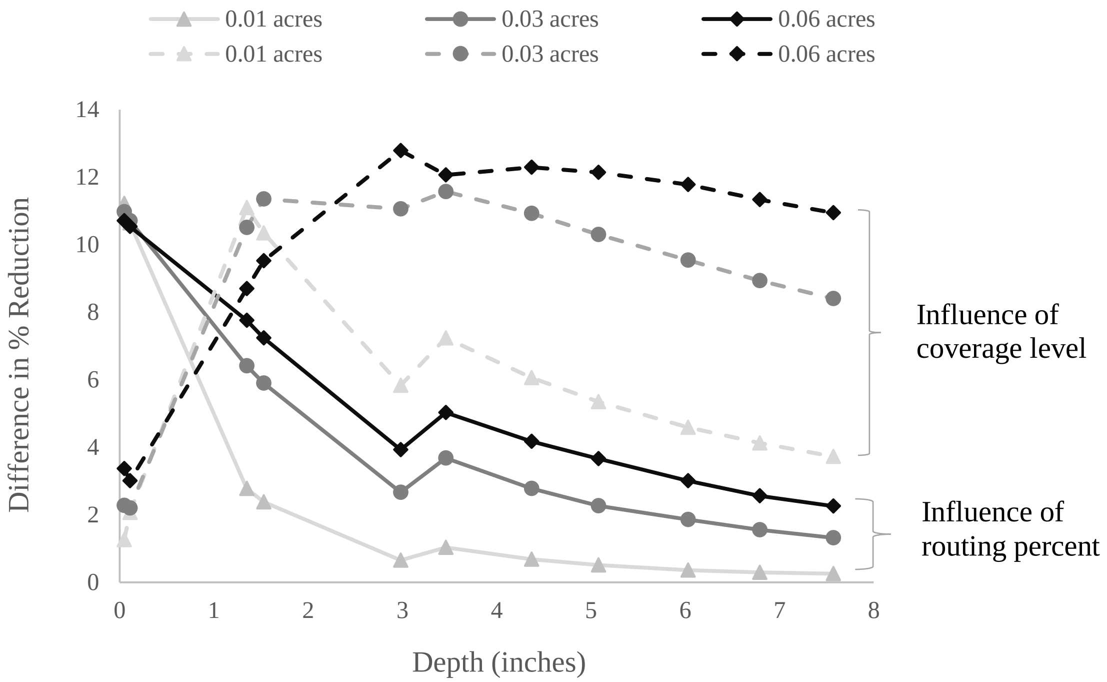


Figure 23. Average difference in percent of volume reduction for each cell size in relation to watershed coverage and percent of impervious surface routed to the bioretention cells. Dashed lines represent results for differences among watershed coverage settings, while routing is kept constant. Continuous lines represent results for differences among routing percentage scenarios, while coverage is kept constant.

Similarly, results show that for the same routing percent, watershed coverage has the largest influence in run off volume reduction. The average difference in volume reduction is greater due to changes in watershed coverage (dashed lines in Fig. 24) rather than cell size (continuous line in Fig. 24). In both cases, differences increase rapidly with a small storm event depth (< 2 inches). For the smaller routing percent (25%) the differences in reduction due to cell size and watershed coverage are virtually the same, with a slight decrease due to watershed coverage for large storms, such as the 100-yr event.

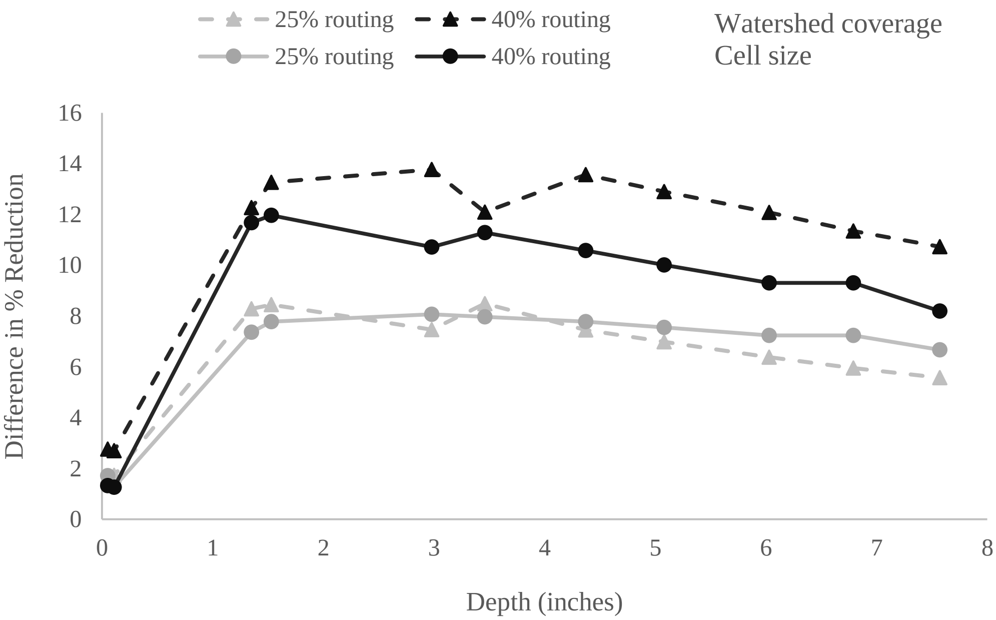


Figure 24. Average difference in volume reduction percent for each routing scenario in relation to watershed coverage (dashed line) and cell size (continuous line).

For the same coverage level, results show that the cell size has a greater influence in volume reduction than routing percent. As before, the average difference in reduction in relation to routing percent decreases rapidly with storm size (continuous lines in Fig. 25) while the influence of cell size inversely increases with precipitation depth (dashed lines in Fig. 25). Because the cell size is intrinsically related to watershed coverage, results are consistent with the importance of watershed coverage in the implementation of LID in mitigating run off for large storm events.

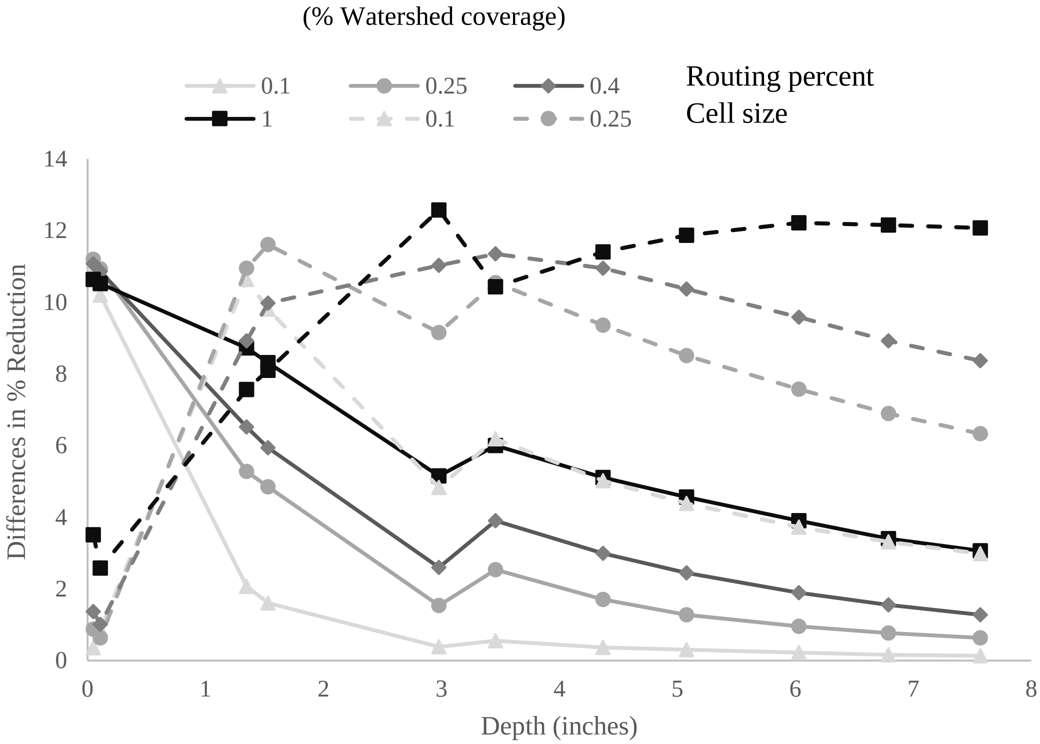


Figure 25. Difference in percent of volume reduction for each coverage level in relation to routing level and cell size.

Centralized Scenarios

In the centralized scenarios, watershed coverage is based in the area of available municipally owned vacant land, unlike the decentralized scenario, which is based on the number of private households in the catchment. This results in less watershed coverage for the maximum density level when compared to the maximum density level for the decentralized scenario (27.12 acres vs 73.32 acres). In contrast, the greatest level of routing that is simulated is 70%, while, in the decentralized scenario, the maximum level of routing that is simulated is 40%. As a consequence, greater reduction is achieved with the centralized approach. For design storms, reduction values for total volume range from 5 to 29.5% and from 0 to 17.8%

for peak flows. For the monitored events reduction values range from 6.82 to 43.8% for total flow reduction and from 3.2 to 48.1% for peak flows (Fig. 26).

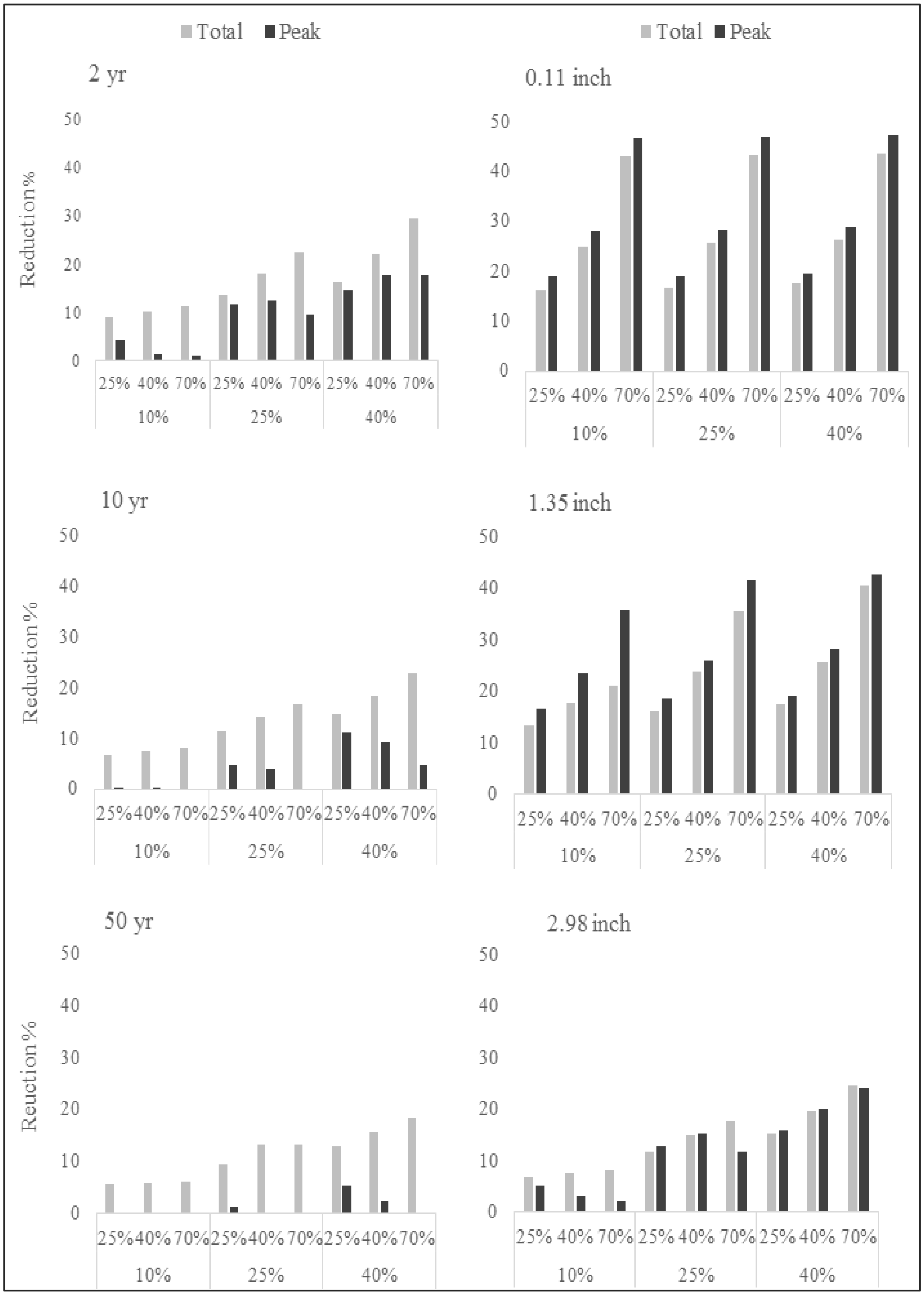


Figure 26. Reduction in total and peak flows according to watershed coverage (10, 25, 40 and 100%) and percent of impervious surface treated (25, 40 and 70%) for different design storms and monitored events.

As with the decentralized scenarios, volume reduction positively correlates to watershed coverage for every routing percent scenario (Fig. 27). The average coefficient of determination R^2 is 0.98 for the 2 yr design storm and 0.93 for the 1.35 inch storm event.

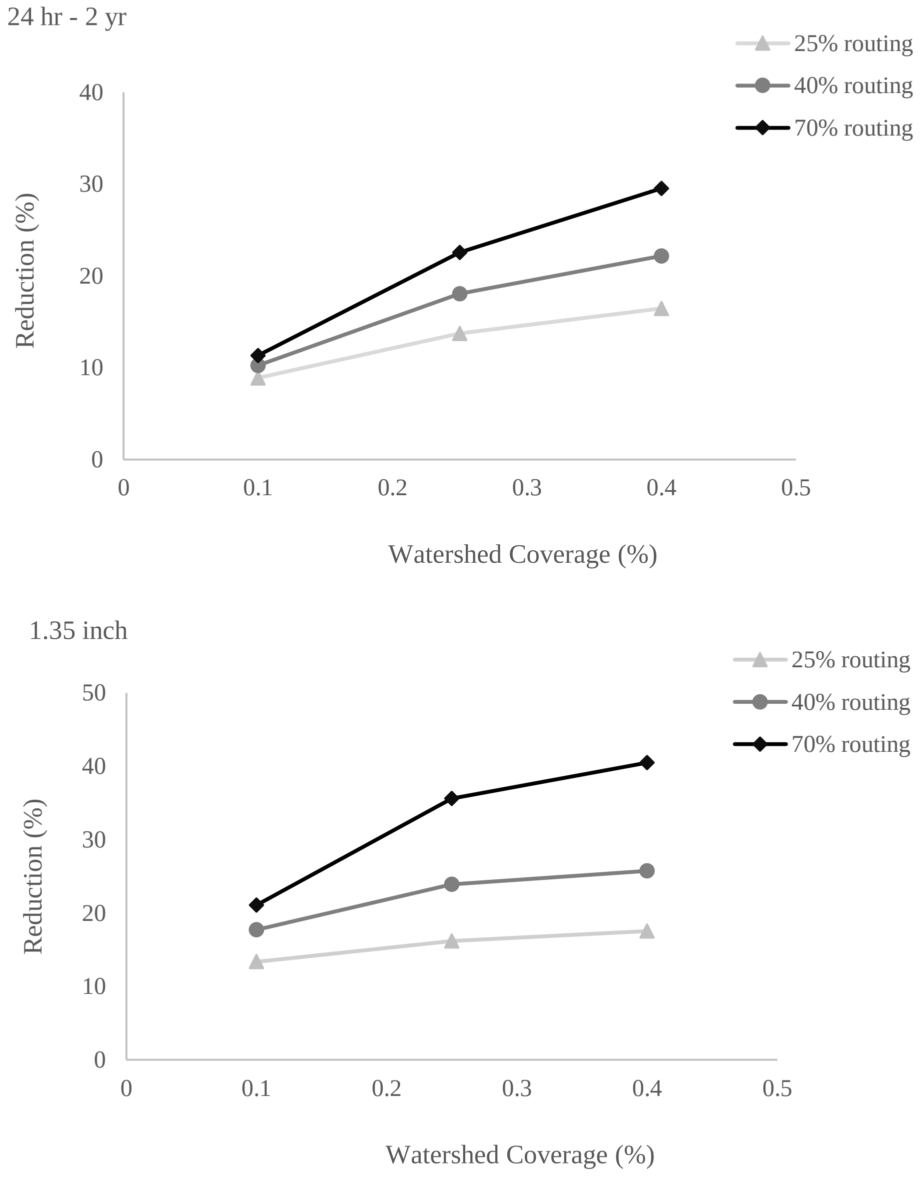


Figure 27. Relationship bettween volume reduction and watershed coverage for the different routing percent.

Percent of impervious surface routed to the cell (color scheme in Fig. 28) is a key driver of volumetric reduction for small size storm events, and its influence diminishes as storm size increases. The influence of watershed coverage (pattern scheme in Fig. 28) is minimal for small rain depth and increases with event size as event size. Beyond the 2-yr storm event, this influence does not change substantially.

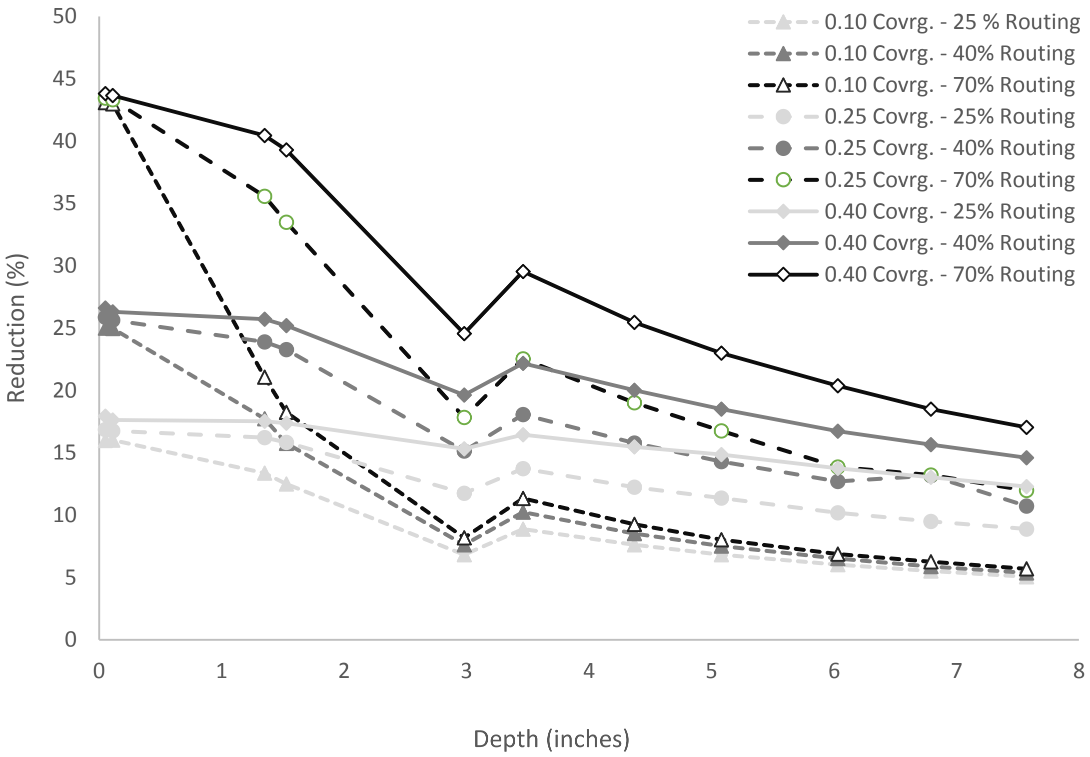


Figure 28. Total run off volume reduction in relation to watershed coverage and routing for centralized deployment of bioretention cells.

For the same routing level, the average difference in volume reduction according to watershed coverage increases rapidly with storm size and stabilizes beyond the 24 hr – 2 yr design storm (Fig. 29).

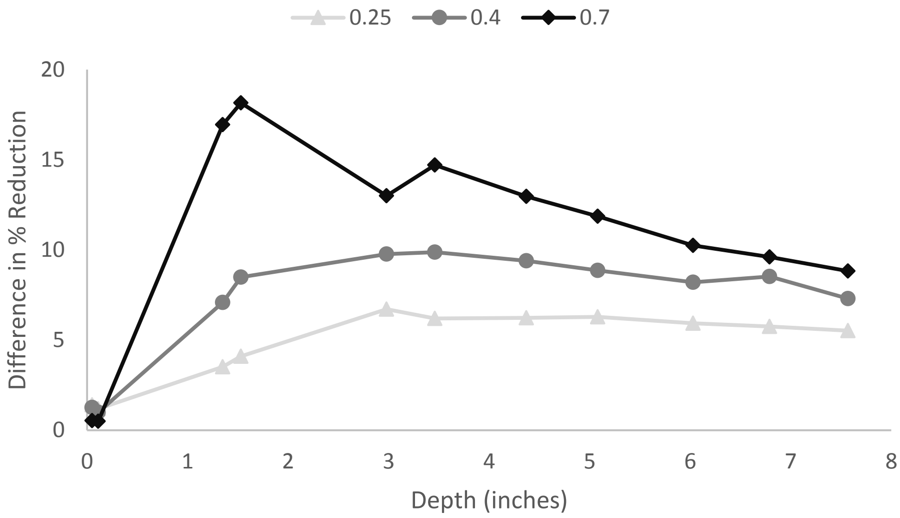


Figure 29. Difference of impact on total flow volume of watershed coverage for different routing levels (25, 40 and 70%).

For a given watershed coverage level, the average difference in volumetric reduction according to routing level is greater for small storm events and decreases with storm size. The influence of the routing level is greater when greater watershed coverage exists (Fig. 30).

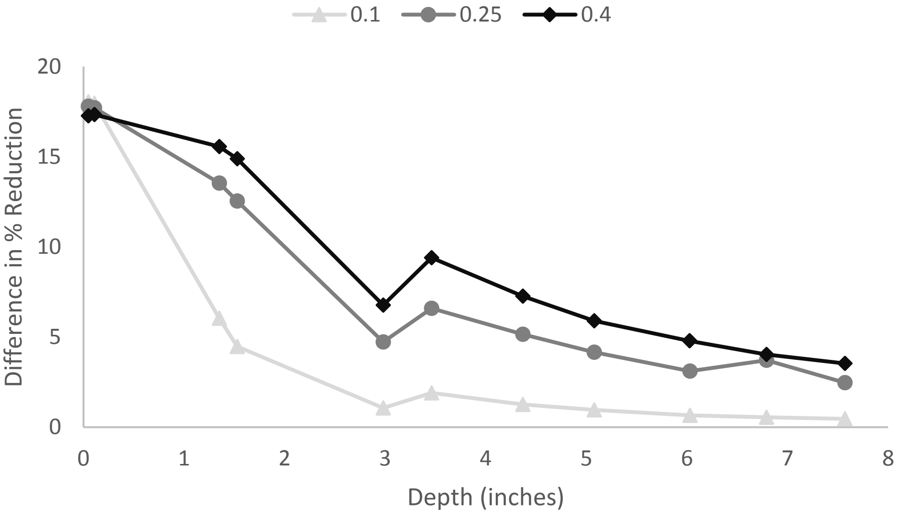


Figure 30. Difference of impact on total flow volume of routing levels for different watershed cover levels (10, 25 and 40%).

Combined Scenarios

Four different conservative combined scenarios are explored. The two first scenarios explore the results of implementing decentralized 0.01 acres bioretention cells with a 25% watershed density and with a 25 % routing with a 25% density of 50 gallon RWHS (A) and 200 gallon RWHS (B). The other two combined scenarios explore the implementation of bioretention cells at a 25% watershed density level and with 25% routing with decentralized cell size of 0.01 acres (C) and 0.03 acres (D). Since the effect of RWHS implementation is limited because of the moderate household density of the watershed, its impact in volumetric reduction on a combined scenario is marginal. Results for scenarios C and D show that impacts are not the direct sum of the effects of each management strategy (Fig. 31)

Volumetric reduction of run off in the combined scenarios is also correlated to storm size, with reduction declining as storm size increases (Fig. 32).

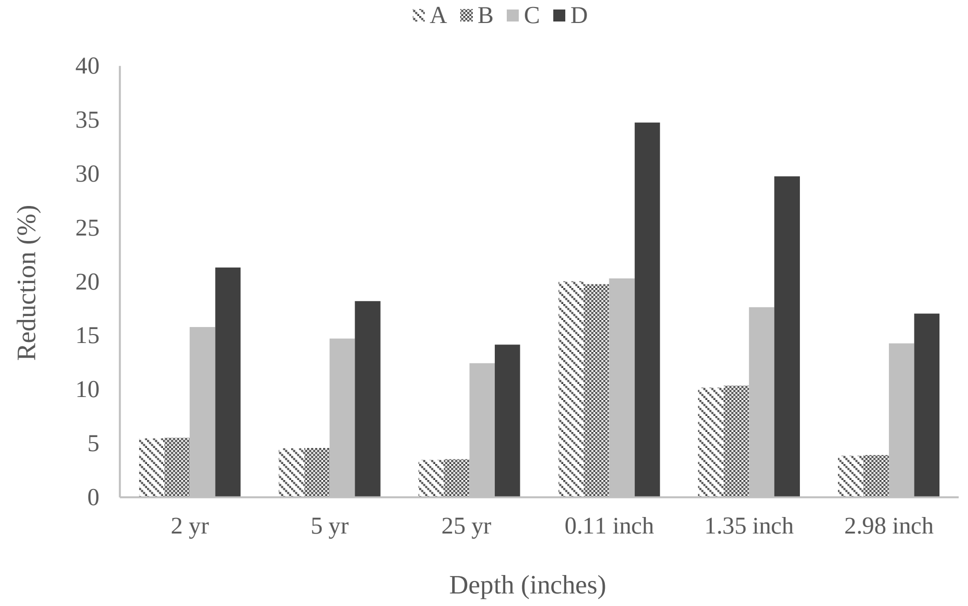


Figure 31. Volumetric reduction for each combined scenario.

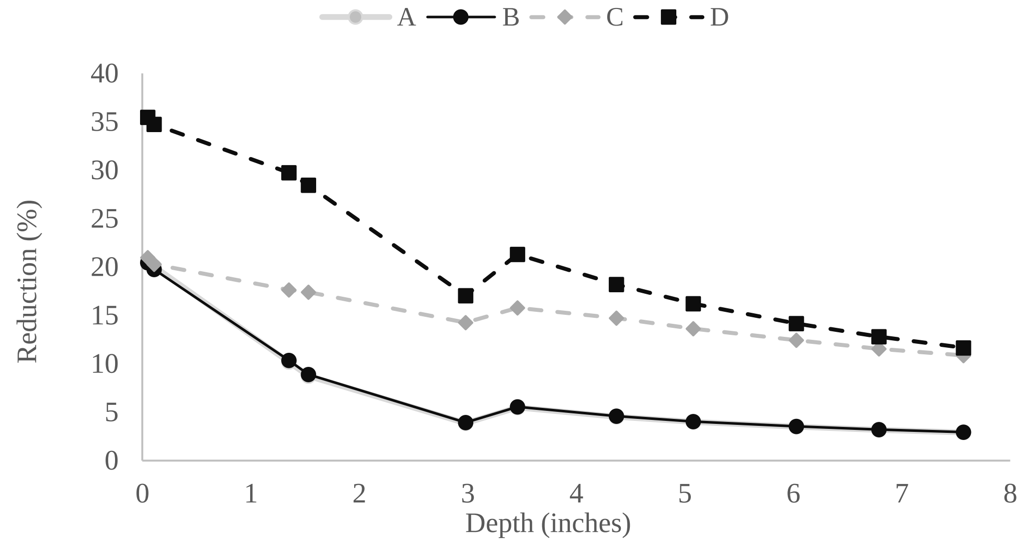


Figure 32. Relationship between volumetric reduction for the four combined scenarios and rain depth.

CHAPTER 5

CONCLUSION

This research explores the hydrological impacts of a set of different LID based management strategies at the watershed scale. The placement of LID site was designed to target locations in underprivileged communities with high outreach potential. Simulation of management scenarios included the implementation of RWHS, bioretention cells, and combinations of the two LID technologies, Run off mitigation was assessed for different storm sizes. This approach was applied to the Walnut Creek Wetland Watershed in central North Carolina. This research contributes to the array of studies evaluating the impacts of LID deployment at the watershed scale. In contrast with previous research, this study evaluates the different outcomes of centralized management strategies that rely on municipally owned land versus decentralized strategies that rely on privately owned residential properties. In addition, this research addresses the physical limitations of LID placement in selected sites and considers different levels of pervious flow routing to the LID structure. This approach facilitates comparison of the influence of pervious flow routing and watershed LID density level when deploying LID structures at the watershed scale.

Implementation of RWHS has limited effect on run off volume reduction in areas with moderate population and urbanization density. Full catchment deployment is necessary for achieving relevant run off mitigation effect. A RWHS based management strategy targeted at private households is more effective in high density environments. Although large storage systems would also be more effective for stormwater management in wet areas, financial and structural limitations may hinder widespread adoption. However, regardless of the density level of a municipality, the impacts on water conservation of a management approach that considers the implementation of RWHS should not be overlooked. In addition to stormwater runoff reduction, RWHS can serve as a familiarization and educational tool that can pave the way to the adoption of integrated water resources management approaches by exposing the public to the challenges of urban water management in a changing climate. The marginal cost of small size RWHS and the minimal maintenance these systems require facilitates the viability of adopting RWHS implementation by the general population.

Storm water management strategies that incorporate bioretention cells can be greatly effective in run off mitigation achieving considerable reduction even in extreme events. For small storm events (< 1.5 inches), the percent of impervious surface draining to the bioretention cells have an overall greater influence than cell size and watershed coverage. As storm size increases, watershed coverage and cell size have a greater impact on volume and peak flow reduction. The fact that both watershed coverage and cell size have a similar impact is consistent with the fact that both are inextricably related. Greater cell size equals greater watershed coverage and thus the impact of this characteristic resembles the impact of watershed coverage. In order to effectively achieve run off mitigation, both routing and coverage should be carefully considered.

The decentralized and centralized scenarios result in different watershed coverage levels, with more area covered in the decentralized scenario. In contrast, the centralized scenario simulates greater routing of pervious flows. Both scenarios can achieve significant reduction of run off volumes and peak flows even for extreme precipitation events. The greatest reduction is in the decentralized scenario, which is achieved when the bioretention cell size is largest. This may be challenging to implement, as individual owners may not be willing to allocate significant portions of their yards for storm water management. In addition, a decentralized scenario relies on the constant maintenance of the implemented structures by owners. Lack of engagement and consistency by initial and future owners and neglect may occur which would translate in the failure of a decentralized management scenario. Strong community involvement and commitment would be necessary to ensure the success and efficiency of a decentralized scenario.

Appropriate location placement of bioretention cell is also an important factor of cell efficiency. Maximum routing of the run off produced by impervious surfaces is desired. Private household owners may not have many choices and instead a set of limitations when it comes to location selection. In a centralized management scenario, municipalities may have a wider number of options in terms of site selection. In addition, retrofits may be possible that could result in increasing the routing of run off from impervious surfaces to the cell. In contrast, the maintenance cost of the deployed structures would be assumed by the municipality and could counter the benefits of this management strategy.

A combined centralized-decentralized scenario could offer an alternative management approach that would relieve municipalities of the associated costs of implementation and maintenance while engaging members of the community in storm water management and sustainability.

The different array of stormwater management options offer not only run off mitigation benefits but also water conservation and water quality management opportunities. In addition, the placement of these practices in areas with high outreach potential contribute to educate and familiarize the public with urban sustainability and water resources management issues which facilitates the adoption of additional practices and conservation measures. Finally, underprivileged communities could greatly benefit from the implementation of these practices. LID based management strategies can offer opportunities for environmental education and awareness of communities that have been traditionally disconnected from these issues. Water conservation and diminishing flooding provides economic relief. However, this study does not evaluate through tangible metrics the potential social benefits of watershed scale implementation of LID infrastructure in the targeted underprivileged community. Experimental research following the site selection approach of this study could evaluate the resulting social benefits. In addition, evaluation of the trade off between cost of different LID deployment levels and the environmental and social benefits should be explored and should be the subject of future research. The results of this research are specific to the case study, however, they can provide insight about selecting LID strategies for stormwater management decision-making.

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