A DISTRIBUTED MODELING APPROACH FOR EVALUATING HYDROLOGICAL EFFECTS OF RAIN GARDENS IN URBAN WATERSHEDS

BY

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THESIS

Submitted in partial fulfillments of the requirements for the degree of Master of Science in Civil Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2009

Urbana, Illinois

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Best management practices (BMPs) and low impact development (LID) are sustainable stormwater management practices used to mitigate the effects of urbanization such as excess runoff and water quality issues. Implementation of BMPs and LID have been limited and sometimes restricted because of the lack of recognized methodologies to estimate their hydrologic effects in urban watersheds under a continuous rainfall period. It is expected that rain gardens will have a significant effect in the reduction of peak discharge and volume for a range of different storms magnitudes including less frequent events.

Rain gardens are small depressions covered by native vegetation, which receive the runoff coming from impervious areas. These practices are part of the sustainable LID and BMPs approach with the goal of reducing runoff coming from urban areas, promoting evapotranspiration and restoring some of the infiltration capability of the predevelopment site. These distributed stormwater management practices modifies the urban watershed’s hydrologic response by varying the size and quantity of these distributed stormwater practices. Hydrologic processes of BMPs can be complex and non-linear. Uncertainty could arise when commonly simplified models are use to simulates the effects of BMPs on the hydrologic response of the watershed.

This research used a methodology developed to understand the hydrologic effects of rain gardens at different quantities distributed in an urban watershed for a continuous rainfall period. The methodology used in this research tries to improve the estimation of hydrologic process of rain gardens by using a physically distributed model, Mike SHE. Mike SHE, distributed by DHI, Inc. is a fully distributed model that is able to estimate a range of hydrological processes.
occurring in a rain garden. This model provides an improvement over simplified models, which cannot estimate relevant hydrologic processes. The Mike SHE model simulates evapotranspiration, subsurface flow and overland flow by coupling a finite difference method in two dimensions and the Richard’s equation for the unsaturated zone calculations.

As part of the methodology used in this research, two rain garden scenarios with different quantities of rain gardens simulated are implemented in an urban watershed. Data from rain garden sites monitored by the U.S. Geological Survey Wisconsin Water Science Center were used to build and calibrate single rain garden models. The calibrated rain gardens were incorporated to an urban watershed with an area of 13 acres and 86 houses. The urban watershed model was calibrated by using observed data monitored in the 1960s without rain gardens. Rain garden scenarios were simulated under a continuous rainfall period.

Results from this research showed that simulated rain gardens are able to reduce the peak discharge and volume among different return periods. The reduction of peak discharge and volume increased when the quantity of rain gardens increased. The hydrologic effects of rain gardens decreased when the magnitude of the storm increased. The reduction of peak discharge and volume ranged from 5% to 80% depending on the magnitude of the storm. It was found that the antecedent moisture conditions of rain gardens affected their capacity for runoff retention.

The results found in this research show that physically distributed models are able to estimate hydrologic effects of rain gardens inside urban watersheds. This modeling approach provides the flexibility to estimate hydrologic effects of different rain gardens layouts under continuous
rainfall periods. This modeling approach could be used by engineers and planners to examine hydrologic effects in urban watershed for design purposes.
ACKNOWLEDGMENTS

First of all, I would like to thank my advisor, Arthur Schmidt and the Environmental Hydrology and Hydraulic Engineering Department at the University of Illinois at Urbana Champaign. I really appreciate the time and knowledge he has provided me during the master’s program. This thesis would not have been possible without his advice and guidance. I also would like to show my gratitude to the people of Hydrosystems Laboratory, led by Professor Marcelo Garcia and graduate student who motivated me during the process of this work. I thank the Metropolitan Water Reclamation District of Greater Chicago (MWRD), for the financial support of this project and the TARP Research Group – Dan Christensen, Pablo Cello, Nathaniel Hanna Halloway, Nam Jeong Choi, Yongwon, Yovanni Catano, Josh Cantone, Michelle Hollander, and Andrea Zimmer.

I would like to acknowledge the help of Bill Selbig of the U.S. Geological Survey (USGS), Wisconsin Water Science Center who provided me the field monitored data for the native rain gardens in Madison, Wisconsin. I also thank David Fazio and Elizabeth A. Murphy of the USGS, Illinois Water Science Center who provide me monitored precipitation and potential evapotranspiration data near to Oakdale Avenue in Chicago, Illinois. Thank you - Juan Camilo Quijano and Darren Drewry for helping me to understand hydrological processes occurring between vegetation, soil and climate.

Finally, I thank my family for always believe in me and for the unconditional support during the master’s program.
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# List of Symbols

- $A_{ET}\%\Delta$: Actual evapotranspiration percent total percent change
- $AROOT$: Root mass distribution
- $B$: Soil water capacity
- $C_{int}$: Empirical interception coefficient
- $C_x, C_y$: Manning Strickler coefficient for the x and y direction of flow, respectively
- $C_1, C_2, C_3$: Empirical Kristensen and Jensen constants
- $E_{at}$: Actual evapotranspiration
- $E_{can}$: Evaporation from the canopy
- $ET_p$: Potential evapotranspiration
- $E_s$: Soil surface evaporation
- $E_v$: Plant transpiration
- $h$: Flow depth
- $h_o\%\Delta$: Pond depth total percent change
- $I_{max}$: Interception storage capacity
- $K_c$: Crop coefficient
- $K_s$: Saturated hydraulic conductivity
- $K_x, K_y$: Strickler coefficients in the x and y directions respectively
- $K(\theta)$: Unsaturated hydraulic conductivity
- $LAI$: Leaf Area Index
- $M$: Manning’s M
- $m, n, \alpha$: Empirical Van Genuchten constants
- $q$: Lateral inflow
- $pF_{fc}$: Capillary pressure at field capacity
- $pF_W$: Capillary pressure at wilting point
- $Q_p$: Peak flow rate
- $Q_o$: Peak flow rate from monitored data
- $Q_m$: Peak flow rate from model simulation
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$R$</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Nash – Sutcliffe coefficient</td>
</tr>
<tr>
<td>RDF</td>
<td>Root distribution function</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>$S_{fx}, S_{fy}$</td>
<td>Friction slopes in the x and y directions respectively</td>
</tr>
<tr>
<td>$S_{ox}, S_{oy}$</td>
<td>Surface slopes in the x and y directions respectively</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Time to peak difference</td>
</tr>
<tr>
<td>$T_{po}$</td>
<td>Time to peak from monitored data</td>
</tr>
<tr>
<td>$T_{pm}$</td>
<td>Time to peak from model simulation</td>
</tr>
<tr>
<td>$u$</td>
<td>Flow velocity in the x direction</td>
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<tr>
<td>$v$</td>
<td>Velocity flow in y direction</td>
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<tr>
<td>$V$</td>
<td>Total runoff volume</td>
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<tr>
<td>$V_o$</td>
<td>Total runoff volume from monitored data</td>
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<tr>
<td>$V_m$</td>
<td>Total runoff volume from model simulation</td>
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<tr>
<td>$z$</td>
<td>Stage</td>
</tr>
<tr>
<td>$z_g$</td>
<td>Ground surface elevation</td>
</tr>
<tr>
<td>$Z_h$</td>
<td>Gravitational component</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Soil moisture content</td>
</tr>
<tr>
<td>$\theta_{%\Delta}$</td>
<td>Soil moisture content total percent change</td>
</tr>
<tr>
<td>$\theta_{fc}$</td>
<td>Volumetric soil moisture content at field capacity</td>
</tr>
<tr>
<td>$\theta_o$</td>
<td>Soil moisture content from monitored data</td>
</tr>
<tr>
<td>$\theta_m$</td>
<td>Soil moisture content from model simulation</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Residual moisture content</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>Saturated moisture content</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>Volumetric soil moisture content at wilting point</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Capillarity pressure head</td>
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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The naturally built environment has been altered by manmade infrastructure over the years. The development of natural areas has promoted the advancement of society. However, people have been disconnected from natural systems and the quality of the environment has been degraded. Adverse changes to the environment have to be considered by engineers and designers. The use of sustainable practices could be a viable approach to limit the manmade alterations to the environment and reconnect the society to the natural environment.

As part of the infrastructure, stormwater systems have been implemented in urban areas to manage and treat stormwater through drainage systems and facilities. Urban drainage could be seen as having great potential to address urban issues such as flood protection and combined flow treatment. In reality, many problems related with stormwater systems remain. Chocat et al. (2007) described some problems related with stormwater management as follows:

1. Problems related with runoff quantity – Increased runoff volumes and peak flows, low groundwater recharge, channel erosion and habitat degradation.

2. Problems related with urban runoff quality – Urban runoff disperses sources of pollutants such as nutrients, contaminated sediments and chemicals contributing to the water quality degradation.

3. Problems related with landscape aesthetics and beneficial uses – Drainage systems contaminate water bodies and natural areas. Beneficial uses such as potable water supply, fishing and other activities are impacted adversely by the conventional stormwater system.

Sustainable strategies for urban stormwater management are needed to improve the conventional stormwater system, promoting environmental and economic benefits.

Low Impact Development (LID) and Best Management Practices (BMPs) are sustainable approaches to mitigate the runoff effects of urban areas. At the same time these practices are seeking to protect the environment by increasing pervious and green areas. Green roofs, bioswales, porous pavements and rain gardens are examples of LIDs (Graham et al., 2004). Rain gardens, which are the focus of this research, are small depressions in the landscape planted with native vegetation (Christensen, 2008). Commonly they are established in recreational or residential areas to promote storage and infiltration of the runoff. Rain gardens are considered a decentralized storm management practice because their locations are distributed.

Rain gardens and BMPs in general are sustainable practices developed to reduce stormwater runoff and protect the environment. At present there are not enough model tools and methodologies to review their hydrologic effects properly (Dietz, 2007; Graham et al., 2004). Moreover, their performance for continuous rainfall events is still unknown. These limitations have been the motivation of this research. The purpose of this research is focused on modeling real rain garden sites to assess their hydrologic effects and to simulate rain garden scenarios in an urban watershed model to see how this sustainable practice performs under sequences of rainfall events. Results of the catchment simulation with each rain garden scenario are compared with results of the same catchment without rain gardens. Percent reductions of volume and peak flows are evaluated in order to quantify the hydrologic effect of rain gardens.
1.2 BEST MANAGEMENT PRACTICES AND LOW IMPACT DEVELOPMENT

LID and BMPs are being viewed by municipalities and developers as a sustainable alternative to conventional stormwater management. These practices seek to reduce the harmful effects of stormwater runoff from developed areas, restore and protect the environment and minimize the cost of stormwater infrastructure. The city of Seattle is implementing LID in a project called “High Point Redevelopment Project”. The redevelopment consists of 1,600 residential housing units and integrates a City Natural Drainage System (NDS) – an approach that achieves a balance between neighborhood green space and water-quality improvements (City of Seattle, 2009). In addition, the City of Portland is one of the greenest American cities (POPSCI 2008). The city has several sustainable projects such as rain garden at Glencoe Elementary School and other BMPs projects included in the City Stormwater Management Plan (City of Portland, 2009). Kansas City is another place where rain gardens have been implemented throughout the city to contribute to the stormwater management (KCMO 2008).

The main goal of LID and BMPs is to minimize the volume and rate from runoff on developed surfaces served by conventional stormwater systems (Graham et al., 2004). Some of the benefits from these practices are:

- Protect and restore ecosystems
- Increase pervious areas
- Reduce stormwater infrastructure costs
- Avoid stream pollution, flooding, channel degradation and combined sewer flow (stormwater and sanitary)
- Promote stormwater reuse (plants are fed by rainwater rather than irrigation)
- Promote natural drainage
- Disconnect impervious areas from conventional stormwater systems
Even though BMPs and LID practices are sustainable strategies for reducing the impacts of stormwater impacts reduction, their implementation has been questioned because of the lack of techniques to quantify their potential benefits (Strecker and Urbonas, 2001). At the same time there are few design regulations, which makes implementation of BMPs difficult for engineers and developers (Holman-Dodds et al., 2003). Drainage design tools are needed to make design and application of LID more efficient (Elliot and Trowsdale, 2007).

Articles from the literature emphasize the dearth of design tools and modeling software able to simulate LID and their dynamic natural processes (Elliot and Trowsdale, 2007; William and Wise, 2006). This limitation hinders the implementation of LID’s since their effectiveness is not clear enough (Elliot and Trowsdale, 2007; Dietz, 2007). Little research has been performed to deal with this issue. Many studies have focused on scale models of single practices to study the LIDs hydrologic processes, while little research has been done to analyze the hydrologic impact of a group of LIDs located inside an urban watershed (Dietz, 2007).

### 1.3 Rain Gardens

Rain gardens are small depressions covered by native vegetation, which receive the runoff coming from impervious areas such as streets, roofs and sidewalks. This practice is part of the LID and BMPs sustainable approach with the goal of reducing runoff coming from urban areas and restoring some of the infiltration capability of the predevelopment site (Christensen, 2008). Figure 1.1 illustrates a rain garden with native vegetation located in Maplewood Minnesota and figure 1.2 shows a simple rain garden design with different types of native plants.
Figure 1.1 Typical rain garden in Maplewood Minn.

Figure 1.2 Rain garden basic design (Brooklyn Botanic Garden, 2004).
Rain gardens have hydrologic benefits including:

- Runoff reduction promoting infiltration, evapotranspiration and stormwater storage
- Groundwater recharge
- Provide disconnection of impervious areas
- Promotes water conservation - plants are watered by stormwater rather than irrigation
- Increase flow lengths and contribute to peak flow reductions
- Promote surface and sub surface storage, delaying the time to peak

In addition, rain gardens are considered attractive landscaping features that are easy to build. At the same time, construction and maintenance costs are relative low for bio-retention BMPs including rain gardens (Wossink and Hunt, 2003). There are books, internet websites, and design manuals that provide instructions to homeowners to build a rain garden properly (Wisconsin DRN 2009; KCMO 2008). The implementation of rain gardens connects urban areas to a natural environment promoting an aesthetic appearance and contributing toward remediating the harmful effects of urbanization.

Rain gardens can help to mitigate the effect of urbanization in the environment. They represent an environmental friendly alternative to stormwater runoff management. The efficiency of BMPs and LID depends on how they are designed, taking into account their size, quantity, and location throughout the watershed (Brander et al., 2004). Rain gardens hydrologic impacts of depend on factors such as: type of vegetation, underlying soil properties, size and location inside a catchment, weather conditions (spring, winter), depression depth, initial soil water content, and contributing runoff areas. More studies are needed in other to understand the dynamic interactions among these factors and the effect they have in rain gardens performance. Investigations including monitoring and modeling studies have the objective to expand the knowledge about rain garden’s hydrologic effects. Monitoring studies are necessary to collect different types of data. However monitoring studies cannot examine the interaction among
factors affecting the rain garden hydrologic behavior. Modeling studies instead are able to estimate the interaction between different factors affecting the rain gardens behavior under different conditions.

1.4 RESEARCH OBJECTIVES AND SCOPE

The objective of this research is to describe relations among the percentage of a watershed served by rain gardens, the number of those rain gardens, the effect of antecedent conditions and the peak discharge of runoff from the watershed for continuous rainfall simulations. This analysis will be performed following a predictive methodology proposed by Christensen 2008. The methodology is implemented by using a physically distributed hydrologic model (Mike SHE) at fine resolution. Mike SHE (MIKE by DHI, 2008) is able to simulate the main hydrologic processes of several rain gardens at fine resolution since the model covers the major processes in the hydrologic cycle and their interactions.

Data from monitored rain gardens by the U.S. Geological Survey (USGS) were provided and used to calibrated and validate single rain garden models. Calibrated soil and evapotranspiration parameters were then incorporated into a calibrated model for the watershed being studied. This example application allows different scenarios to be tested, providing an understanding of how rain gardens interact inside a watershed. The Oakdale Avenue urban site was chosen for this analysis. This urban catchment is located in Chicago IL. The physically distributed model Mike SHE (Abbot et al., 1986a) was used to build the single rain garden models and Oakdale avenue models. The Oakdale Avenue monitored data from 1960s was used to validate the calibrated urban watershed distributed model. The model was validated by generating initial conditions using observed precipitation data. Two different rain gardens scenarios were implemented inside the Oakdale watershed model to analyze their hydrologic effects for continuous rainfall simulations. Outflow results at the outlet of the Oakdale watershed with rain gardens with were compared with outflows at the outlet without rain gardens. Each
rain garden scenario was simulated for continuous rainfall events and evaluated separately. The analysis of results provide an idea about how rain gardens impact the hydrological cycle of the urban watershed varying the rain garden size and distribution through the catchment.

Physically distributed models such as Mike SHE are able to describe hydrologic processes at very small scales required to define rain gardens on-site. These models allow the user to define the resolution and physical parameters according to the model purpose. It is expected that by using this physically distributed model the main hydrologic process of rain gardens will be modeled properly and their implementation will reduce the total runoff volume and peak flows. Also it is projected that the volume and peak flow reduction will depend on the number and size of rain gardens through the watershed. It is anticipated that the time to peak will be reduced after rain gardens implementation through the watershed due to the flow path modification.

As mentioned before the simulations were performed for continuous rainfall events. It is expected that the impact of rain gardens will be affected, compared to event simulations, due to the capacity of runoff retention and the percolation and evapotranspiration processes during dry time periods.

1.5 THESIS OUTLINE

The next chapter (Chapter 2) provides a literature review about previous research that has been performed to study the effects of LID and BMPs practices on hydrology. The review is mainly focused on rain gardens and their contribution to runoff retention and environment preservation. A detailed description of rain gardens is provided in this chapter including an overview, actual monitoring sites and previous modeling studies. In addition, Mike SHE (DHI) (the physical distribute model used in this research) is described briefly.
Chapter 3 describes the monitored rain gardens and urban watershed sites used to build the models. Chapter 4 shows the modeling methods used to conduct this research, including model description and calibration procedures. Chapter 5 discusses the results of simulation of the monitored rain gardens. Chapter 6 discusses the results of the example application – Oakdale Avenue model. Chapter 7 gives the conclusions and the future work.
CHAPTER 2: LITERATURE REVIEW

2.1 BEST MANAGEMENT PRACTICES AND LOW IMPACT DEVELOPMENT

Best Management Practices and Low Impact Development are sustainable stormwater management practices that seek to reduce the adverse effect of urbanization, connect developed areas to the environment and preserve ecosystems. These practices promote a distributed and integrated implementation of green and pervious areas through the watershed. Currently, conventional stormwater management systems predominate in developed areas. Moreover engineers and planners are viewing these practices as a viable alternative to traditional stormwater management practices (Graham et al., 2004).

Additionally, BMPs and LID have other hydrologic benefits including (Dietz, 2007; Graham et al., 2004):

- Protection of the environment
- Restoration of ecosystems
- Reduction of channel erosion and water quality problems
- Increase of pervious areas reducing runoff volumes
- Reuse rainwater for irrigation
- Reduce the cost of construction and maintenance of stormwater infrastructure

Stormwater BMPs are classified into structural BMPs and non-structural BMPs. Structural BMPs are designed to retain and infiltrate stormwater runoff. These include green roofs, detention basins, bioswales, and rain gardens among others. Structural BMPs allow groundwater recharge and reduce runoff volumes. Figure 2.1 shows an example of structural BMP.
Non-structural BMPs are focused on protecting natural systems and incorporating landscape features to manage stormwater at its source. Non-structural BMPs include community planning controls, environmental education and participation programs, pollution prevention procedures and regulations. The combination of structural and non-structural BMPs can reduce costs of improving water quantity and quality issues (Taylor and Wong, 2002). Figure 2.2 illustrates a site planning and design procedure including structural and non-structural BMPs.
2.1.1 Watershed Modeling Incorporating BMPs and LID

Several modeling studies of BMPs and LIDs have been discussed in the literature. Most of the modeling research has been done by using lumped hydrologic models. Lumped models are easier to use than distributed models because they are simplified models with fewer inputs parameters (Reegards, 1997). Nevertheless, lumped models have to be calibrated in order to avoid uncertainty in the results (Abbott et al., 1986b). Model accuracy is an important factor to take in account in order to understand BMP’s hydrologic effects inside a watershed. A good understanding of these stormwater management practices can help engineers and planners to develop design standards and regulations.

Tang et al. (2005) developed a SCS curve model called Low Term Hydrologic Assessment (L-THIA) that proposed to minimize the impacts on water resources by optimization of landuse distribution. The model is designed to simulate several watersheds for long rainfall periods, rather than design storm
events. The SCS curve number method is commonly used for design storm analysis (Dietz, 2007). This method uses parameters without physical meaning to approximate the amount of runoff from a rainfall event over a particular soil type and land use. Physical parameters describing the hydrologic processes inside the watershed could be important to estimate the runoff of rainfall and other important processes occurring inside a watershed. Understanding of hydrologic processes is required and could be possible using appropriate modeling tools (Elliot and Trowsdale, 2006).

In an article by Perez-Pedini et al. (2005), a fully distributed model was presented, which was focused on identifying optimal distribution of BMPs implemented into watersheds. This distributed model had a grid size of 120 meters and used the SCS curve number to characterize different objects inside the watershed. In the case of BMPs, a CN number of 5 was used to characterize the stormwater management practices in the watershed (Perez-Pedini et al., 2005). The model optimization was done using a genetic algorithm. The research goal dealt with a watershed system problem and not just BMP design. After a detailed statistical analysis comparing results from a lumped model and the proposed distributed model in the same area, the authors concluded that lumped models are not able to properly estimate temporal and spatial variation of runoff inside a watershed (Perez-Pedini et al., 2005). This research is one more example that shows the need for modeling tools that are able to simulate BMP implementation in watersheds.

Another research that used a simplified modeling approach was done by Kronaveter et al. (2001). The authors developed and presented a model called Hydrologic Micromodel (HMM). The model was used to simulate hypothetical neighborhoods at different spatial scales ranging from lumped watersheds to individual lots. The purpose of this research was to estimate the annual reduction of stormwater runoff due to the increment of pervious areas inside the watershed. Stormwater runoff coming from building’s
roofs was directed to pervious surfaces. The authors concluded that pervious surfaces receiving stormwater runoff from building roofs can increase the infiltration capacity of the lot by approximately 15% (Kronaveter et al., 2001). However, this model accuracy is unknown because it was not calibrated to observed data.

2.1.2 BMPs and LID Challenges

At present BMPs and LID are being implemented throughout the United States and Europe. Engineers and planners view these practices as viable approaches to conventional stormwater systems that can contribute to minimize stormwater runoff issues and protect the environment (Graham et al., 2004). Despite the reported contribution of BMPs and LIDs to water quantity and quality issues, there is a lack of watershed monitoring sites, which limits the understanding of the processes controlling these sustainable approaches (Xiao et al., 2007).

According to some literature articles, at present there are not enough modeling tools that are able to properly estimate hydrologic impacts of BMPs (Graham et al., 2004; William and Wise, 2006; Dietz, 2007). Accurate modeling tools for BMPs are needed to simulate their hydrologic processes and prove their effectiveness (Elliot and Trowsdale, 2006). Questions about watershed scale effects of BMPs and spatial detail required for simulating theses practices are coming out (Elliot and Trowsdale 2007; Xiao 2007). Other researchers are concerned about a developing an accurate model able to simulate LID practices properly (Graham 2004; Dietz 2007).

Elliot and Trowsdale (2007) have done research about several hydrologic models in order to identify models able to simulate BMPs. Around 40 hydrologic models were analyzed evaluating attributes such as temporal and spatial scale, representation of the watershed drainage, representation of hydrologic
processes and possible integration with other software (Elliot and Trowsdale, 2007). The authors concluded that the 10 hydrologic models commonly used from the 40 models analyzed cannot properly simulate BMP and LID practices because of their limited abilities to estimate complex hydrologic processes and predict flow rates from small watersheds (Elliot and Trowsdale, 2007).

Some researchers emphasize the use of physically based hydrologic model rather than lumped models to simulate BMPs and LIDs. For example, Graham et al. (2004) introduce of a water balance modeling concept where physical parameters of an object located in the watershed are included in the simulation in order to estimate its physical behavior. In addition this water balance modeling approach focused on describing hydrologic and hydraulic components in detail and performing continuous rainfall simulation instead of design storm analysis (Graham et al., 2004).

According to numerous researchers, lumped models cannot simulate BMP and LID properly because of the limited ability to represent land alterations inside a watershed (Graham et al., 2004; Xiao et al., 2007; Elliot and Trowsdale, 2007). Cantone and Schmidt (2009) demonstrated that lumping the non-linear processes occurring in a subcatchment into larger aggregated (lumped) subcatchments introduces errors into the simulations. Physically distributed models, as opposed to lumped models assign parameters to watershed components providing their physical characteristics. In other words, physical distributed models are an alternative to resolve the limitations arising from lumped models (Williams and Wise, 2006).

2.2 RAIN GARDENS

Rain gardens are small depressions on the land surface where native species are planted, promoting the infiltration of stormwater runoff. This sustainable approach is one of many BMP and LID practices. Rain
garden design involves specifying important features such as the size, soil properties, storage depth, and plants. Dussaillant et al. (2003) points out that the rain garden size is often estimated by a ratio of contributing impervious area to the rain garden area. Soils layers of rain gardens can be the native soil if they drain fast. Engineered soils are used when the native rain garden soils do not drain properly. The design of rain garden soil plays an important role in their performance (Hsieh, 2005). Davis (2008) recommends that the first soil layer of rain gardens should utilize a mix of sandy and organic soils to infiltrate the stormwater runoff quickly and keep the vegetation healthy at the same time. The storage or ponding depth should be around 0.1 to 0.15m (Davis, 2008). Native plant species with deep roots are commonly planted in the depression (Christensen, 2008). Figure 2.4 illustrates the root system of native plants, comparing to turf grass, showing that root depths for native prairie plants
may be up to 40 times deeper than turf grass, promoting infiltration through the soil layers. The first root system (left to right) shown in figure 2.4 corresponds to turf grass. The following plant root systems correspond to several native prairie plants.

Figure 2.4 Native plants root system (IEPA 2005).

Rain gardens are being seen as sustainable alternatives to mitigate harmful effects of stormwater runoff. As with other BMPs, cities around the U.S. are implementing these practices as part of the stormwater management plan (City of Portland, 2009; KCMO 2008). The literature provides references of rain garden hydrologic effects for watershed scales applications but still more research is needed. Most of the rain garden investigations deal with single rain garden modeling approach and water quality issues. As with other BMPs, there is a lack of modeling tools that can accurately simulate their hydrologic processes of rain gardens (Williams and Wise, 2006).
2.2.1 Field Monitoring Studies

Monitored studies of single rain gardens have been done in many places around the U.S. Some of them are well cited in the literature. Table 2.1 gives the list of the most widely cited rain garden monitored sites in the country.

**Table 2.1 Monitored rain garden sites (Christensen 2008)**

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Entity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Villanova RG</td>
<td>Villanova, PA</td>
<td>Villanova Univ.</td>
<td>Heasom et al. (2006)</td>
</tr>
<tr>
<td>Burnsville RGs</td>
<td>Burnsville, MN</td>
<td>City of Burnsville</td>
<td>Barr Engineering 2006</td>
</tr>
<tr>
<td>Maryland RGs</td>
<td>College Park, MD</td>
<td>Univ. of Maryland</td>
<td>Davis (2007)</td>
</tr>
<tr>
<td>North Carolina RGs</td>
<td>Greensboro &amp; Chapel Hill, NC</td>
<td>NC State</td>
<td>Hunt et al. (2006)</td>
</tr>
<tr>
<td>Glencoe RG</td>
<td>Portland, OR</td>
<td>City of Portland</td>
<td>Portland (2008)</td>
</tr>
<tr>
<td>Old Sauk &amp; Owen RGs</td>
<td>Madison, WI</td>
<td>USGS</td>
<td>USGS (2008)</td>
</tr>
<tr>
<td>Haddam RG</td>
<td>Mansfield, CT</td>
<td>Univ. of Connecticut</td>
<td>UCONN (2008)</td>
</tr>
</tbody>
</table>

The University of Villanova in Pennsylvania has a BMP monitoring site sponsored by the Villanova Urban Stormwater Partnership (VUSP). The monitored site includes a rain garden, porous pavement and an infiltration trench located on campus. Monitored data including rainfall, pond depth and soil moisture have been collected since 2001. Soil moisture data has been measure at 5 minute intervals at depths of 6m, 1.2 meters and 2.4 meters (Heasom et al., 2006). VUSP provides monitored data and other relevant information from this project on its website.
Another rain garden monitoring site is located in Burnsville, MN. This study deals with a hydrologic analysis of 17 rain gardens implemented into a small watershed with an approximate area of 5.5 acres (Barr Engineering 2006). The rain gardens are spread throughout the watershed. Most of them are collect stormwater runoff coming from the roof gutters and streets. Some others are located in backyards, collecting runoff from surrounding areas. The predominant soil type in the area is sandy (Barr Engineering 2006). Storm and runoff data have been collected at the outlet of the catchment for two periods. The site was monitored with rain gardens and without rain gardens. The study shows that during the treatment period there was a marked reduction in the runoff volume (approximately 90%) and peak flow from the 48 monitored storms (Barr Engineering 2006). The results of this study show that implementation of rain garden is an effective approach for stormwater management, they do not provide process data needed to transfer these results to other locations or conditions.

The Glencoe rain garden is another monitored site located on an elementary school property in Portland, OR. The site has been monitored since 2003, collecting inflow, outflow and rainfall data (City of Portland, 2004). Data have been collected from actual and artificial storms (from a fire-hydrant). The rain garden has reduced the volume of runoff by approximately 80% for a 25 year design storm and for an artificial combined sewer design storm At the same time the peak flows of both storms have been reduced by 79% and 67% (City of Portland, 2004). Again, this study shows that the rain gardens are able to reduce runoff volumes and peak flows, but does not provide the process data required to transfer these results to other locations.

2.2.2 Watershed Modeling incorporating Rain Gardens

As mentioned before, there are rain garden sites that have been monitored and cited in the literature. The results show that rain gardens help to minimize the stormwater runoff volume and peak flows.
However, few design standards and modeling tools exist for rain gardens. Modeling approaches found in the literature are simplified, which limits the understanding of these practices that can be determined by these models (Dietz, 2007). At present there are a small group of models that are used to simulate rain gardens contributing their design. Table 2.2 gives the models found in the literature divided in two groups: single rain garden models and watershed scale models that incorporate multiple BMPs. The single rain garden models are focused on rain garden design while watershed scale models are focused on studying the hydrologic effects of rain gardens combined with other BMPs.

Table 2.2 Models for simulating rain gardens (Christensen 2008)

<table>
<thead>
<tr>
<th>Models</th>
<th>Methods used</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Rain Garden Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recharge (Dussaillant, 2004)</td>
<td>Richard Equation</td>
<td>Design purposes</td>
</tr>
<tr>
<td>Recarga (Dussaillant, 2003)</td>
<td>Green &amp; Ampt, SCS TR-55</td>
<td>Design purposes</td>
</tr>
<tr>
<td>TSA Tools (T.E. Scott Assoc., 2008)</td>
<td>Darcy law; Bioretention manual; Impervious areas; Rational method</td>
<td>Design purposes</td>
</tr>
<tr>
<td><strong>Watershed Scale Models: Multiple BMPs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WINSLAMM (Pitt 2004)</td>
<td>Watershed based</td>
<td>Design, continuous simulation</td>
</tr>
<tr>
<td>P8 (Walker, 2008; Dietz, 2007)</td>
<td>SCS CN</td>
<td>Design, Lumped</td>
</tr>
<tr>
<td>WWHM (Dietz 2007)</td>
<td>HSPF plataform</td>
<td>Design and continuous simulation Web based</td>
</tr>
<tr>
<td>Water Balance Model-QUALHYMO (Water Balance 2008) LIFE™ (CH2MHill)</td>
<td>Object oriented (water balance based)</td>
<td>CH2 Mhill Proprietary</td>
</tr>
<tr>
<td>Aqua Cycle (Mitchell et al., 2005)</td>
<td>Water balance base</td>
<td>Daily time steps</td>
</tr>
<tr>
<td>UVQ (Mitchell et al., 2005)</td>
<td>Water balance based</td>
<td>Aqua Cycle predecessor</td>
</tr>
</tbody>
</table>

Modeling methods and tools to simulate rain gardens and other BMPs are scarce in the literature. Most of the modeling tools available are simplified and are not able to estimate hydrologic processes in a rain
garden (Elliot and Trowsdale, 2007). Modeling tools involving physical characteristics of the site at the accurate scale are needed to represent and understand hydrologic processes of rain gardens and BMPs in general (Heasom et al., 2006). Many researchers are questioning what modeling approach (lumped or physically distributed) is the best one to simulate BMPs at different scales (from single rain garden scale to watershed scale).

Chow at al. (1988) defined lumped models as simplified methods where the input parameters are averaged in space and are considered a single point without physical meaning. Simplified models are commonly used to represent hydrologic processes. Abbot et al. (1986) mentions that lumped parameters make understanding the hydrologic processes occurring in the site very difficult. Semi-distributed models are considered lumped models as well. The only different between them is that semi-distributed models are placed in series conveying the stormwater runoff downstream.

On the other hand, physically distributed models define input parameters that are distributed throughout the watershed (Chow et al., 1988). Physically distributed models are able to define the grid size, topography and other important physical input variables on the site. Monitored data such as soil properties, vegetation properties, detention, etc. are assigned spatially by using the same grid format (Abbot et al., 1986b). A physical distribution of parameters facilitates understanding the physical meaning and results from the model (Abbot et al. 1986a).

Lumped models bring up uncertainty problems in the results because of the scale differences between the watershed itself and the BMPs inside the watershed (Elliot and Trowsdale, 2006). Lumped parameters are difficult to alter properly in order to represent small stormwater management practices as BMPs. (Dietz, 2007).
Conversely, fully distributed models provide the option to add input parameters, choosing an accurate grid resolution for a specific case. High resolution models require long computation time while coarse resolution models take a short simulation computation. The user has to identify a proper resolution in order to save simulation time while minimizing the error at the same time (Abbott et al., 1986a).

2.3 MIKE SHE (DHI)

The MIKE SHE (DHI, 1998) model originally named European Hydrology System - Système Hydrologique Européen (SHE) was developed and became operational in 1982 (Yan and Joyce, 1998). The model development was possible because of the contribution of three European organizations: Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH. This section provides a general discussion of the main processes that can be modeled in MIKE SHE such as evapotranspiration, unsaturated flow, overland flow and channel flow. MIKE SHE is able to model saturated flow as well. This section does not provide further description of saturated flow simulations because this process will not be included in the models.
2.3.1 Evapotranspiration

Evapotranspiration and net rainfall are estimated by Mike SHE from the following processes (Mike SHE, 2008):

- Interception of the rainfall by the canopy
- Drainage from the canopy to the soil surface
- Evaporation from the canopy surface
- Evaporation from the soil surface
- Uptake of water by plant roots and its transpiration

The interception of the rainfall by the canopy is estimated as follows:

$$ I_{\text{max}} = C_{\text{in}} \cdot LAI $$  \hspace{1cm} (2.1)

where $ I_{\text{max}} $ is the interception storage capacity [L], $ C_{\text{in}} $ is an empirical interception coefficient [L], and $ LAI $ is the leaf area index [L$^2$].

Evaporation from the canopy surface is given by:
\[ E_{can} = \min(I_{\max}, ET_p dT) \]  

(2.2)

where \( E_{can} \) is the minimum value between \( I_{\max} \) and \( ET_p \) and \( dT \) is the simulation interval. \( ET_p \) is the potential evapotranspiration. \( ET_p \) is estimated as follows:

\[ ET_p = ET_0 K_c \]  

(2.3)

where \( ET_0 \) is the reference evapotranspiration and \( K_c \) is the crop coefficient. Actual evapotranspiration is given by

\[ E_{at} = (C_2 + C_1 LAI) \left[ 1 - \left( \frac{\theta_{FC} - \theta}{\theta_{FC} - \theta_W} \right) (RDF) \right] ET_p dT \]  

(2.4)

where \( C_1 \) and \( C_2 \) are empirical parameters [-], \( C_3 \) is also an empirical parameter, \([\text{LT}^{-1}]\), \( \theta_{FC} \) is the volumetric moisture content at field capacity\([\text{L}^3\text{L}^{-3}]\), \( \theta_W \) is the volumetric moisture content at wilting point \([\text{L}^3\text{L}^{-3}]\), and the RDF is the root distribution function [-].

The evaporation from the soil surface \( (E_s) \) is approximated by:

\[ E_s = \left[ ET_p f_3(\theta) + \left\{ ET_p - \frac{E_s}{dT} - ET_p f_3(\theta) \right\} f_4(\theta) \times \left\{ 1 - (C_2 + C_1 LAI) \right\} \right] dT \]  

(2.5)

The functions \( f_3 \) and \( f_4 \) are defined as follows:

\[ f_3(\theta) = \begin{cases} 
C_2, & \text{if } \theta \geq \theta_W \\
\frac{\theta}{\theta_W}, & \text{if } \theta_M \leq \theta \leq \theta_W \\
0, & \text{if } \theta \leq \theta_M 
\end{cases} \]  

(2.6)
\[
f_4(\theta) = \begin{cases} 
\frac{\theta - 0.5(\theta_w + \theta_{FC})}{\theta_{FC} - 0.5(\theta_w + \theta_{FC})} & \text{if } \theta \geq 0.5(\theta_w + \theta_{FC}) \\
0, & \text{if } \theta < 0.5(\theta_w + \theta_{FC})
\end{cases}
\] (2.7)

\(E_r\) is the uptake of water by plant roots and its transpiration. The empirical constant \(C_1\) depends on plants and \(C_3\) depends on soil type and root density (Kristensen and Jensen, 1975). \(C_2\) is an evaporation parameter that describes processes take place when soil moisture content is larger than the wilting point (Kristensen and Jensen, 1975). Then an estimated of the actual transpiration is possible by taking into account the evaporation of the canopy storage, plant transpiration and soil evaporation processes.

The default values Mike SHE provides for the evapotranspiration parameters were set to \(C_{\text{int}} = 0.5\), \(C_1 = 0.3\), \(C_2 = 0.3\), \(C_3 = 20\), and \(AROOT = 0.25\) (Mike SHE, 2008).

2.3.2 Unsaturated Flow

Mike SHE uses the Richards equation as reference to estimate the movement of the water in the unsaturated zone under the surface. Mike SHE provides two more options to estimate the unsaturated flow: Gravity flow and 2-layer water balance method. The gravity flow method estimates the water movement in the unsaturated zone assuming a vertical gradient and ignoring capillary forces while the 2-Layer method is recommended when the water table is close to the surface (Mike SHE, 2008).

Richards’s equation has been chosen in this research to estimate the unsaturated zone flow.
The Richard’s equation is given by:

$$B \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z_h} \left( K(\theta) \frac{\partial \psi}{\partial z_h} \right) + \frac{\partial K(\theta)}{\partial z_h} - R$$

(2.8)

where, \( B = \frac{\partial \psi}{\partial t} \), water capacity of the soil, \( \psi \) is the capillary pressure, \( \theta \) is the saturated water content, \( z_p \) is the gravitational component, \( R \) is the root extraction loss and \( K(\theta) \) is the unsaturated hydraulic conductivity.

Mike SHE provides an unsaturated flow reference in the user manual where the Richard’s equation and other relevant information about the unsaturated flow are provided (Mike SHE, 2008). A variety of soil profiles can be spatially assigned through the model to identify the different soil types. The thickness and texture of each soil layer can be specified by the user. The vertical discretization of the soil is defined by the user as well. Vertical discretization of layer close to the surface should be finer than the discretization of deep soil layers in order to estimate the infiltration accurately.

The unsaturated soil properties are set up by the user. Different soil textures can be added to the soil database and each soil is assigned soil retention curves and hydraulic conductivity curves. The retention curve shows the relation between the soil moisture \( (\theta) \) and the soil water potential \( (\psi) \). On the other hand the hydraulic curve shows the relation between the hydraulic conductivity \( K(\theta) \) and the soil moisture \( (\theta) \). Mike SHE provides some options to estimate the retention and hydraulic conductivity curves. The retention curve can be estimated by the Van Genuchten function (Van Genuchten, 1980) or by the Campbell function (Campbell, 1974). The hydraulic conductivity curve can be estimated by the Van Genuchten (Van Genuchten, 1980), Averjanov function (Averjanov, 1950), or by Campell/Burdine function (Champell, 1974).
The Van Genuchten function has been chosen in this research to estimate the retention curve and the hydraulic conductivity of each soil texture. The retention curve equation is given by,

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha \cdot \psi)^n\right)^m}$$

(2.9)

where $\theta_r$ is the residual water content, $\theta_s$ is the saturated water content, $\alpha$ is an empirical constant, and $m$ and $n$ are empirical constants that are related by $m = 1 - 1/n$.

The hydraulic conductivity curve is given by,

$$K(\psi) = K_s \left(\frac{\left(1 + |\alpha\psi|^n\right)^{m-|\alpha\psi|^{n-1}}}{\left(1 + |\alpha\psi|^n\right)^{m+2}}\right)^2$$

(2.10)

where $K_s$ is the saturated hydraulic conductivity, $\alpha$ is an empirical constant, $\psi$ is the capillary pressure head, and $m$ depends on $n$ by $m = 1 - 1/n$ and $l$ is the shape factor.

2.3.3 Overland Flow

Overland flow is water flowing on the ground surface when the net rainfall rate exceeds the infiltration capacity of the soil. The water movement depends on the catchment’s topography, flow resistance and losses due to evapotranspiration and infiltration occurring on the surface.

Mike SHE (Mike SHE, 2008) uses the diffusion wave approximation of the Saint Venant equations to calculate overland flow in $(x,y)$ coordinates. The conservation of mass and momentum equations are shown bellow.
Conservation of mass:

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (u h) + \frac{\partial}{\partial y} (v h) = i \tag{2.11}
\]

Momentum in x and y directions:

\[
S_{fx} = S_{ox} - \frac{\partial h}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial v}{\partial x} - \frac{qu}{gh} \tag{2.12}
\]

\[
S_{fy} = S_{oy} - \frac{\partial h}{\partial y} - v \frac{\partial v}{\partial y} - u \frac{\partial u}{\partial y} - \frac{qv}{gh} \tag{2.13}
\]

where \( h(x, y) \) is the flow depth, \( u(x, y) \) and \( v(x, y) \) are the flow velocities in the \( x \) and \( y \) directions, \( i(x, y) \) is the infiltration, \( S_{fx} \) and \( S_{fy} \) are the friction slopes in the \( x \) and \( y \) direction, \( S_{ox} \) and \( S_{oy} \) are the ground surface slopes in the \( x \) and \( y \) direction, \( g \) is the acceleration of gravity, and \( q \) is the lateral inflow.

The momentum equation is simplified by dropping the last three terms. Momentum losses caused by local and convective acceleration and lateral inflows perpendicular to the flow are ignored, defining the diffusive wave approximation implemented in Mike SHE.

\[
S_{fx} = S_{ox} - \frac{\partial h}{\partial x} - \frac{\partial z_g}{\partial x} - \frac{\partial h}{\partial x} \tag{2.14}
\]

\[
S_{fy} = S_{oy} - \frac{\partial h}{\partial y} - \frac{\partial z_g}{\partial y} - \frac{\partial h}{\partial y} \tag{2.15}
\]

where \( z_g \) is the surface elevation.

Using the relationship \( z = z_g + h \) equations 2.14 and 2.15 reduce to
\[
S_{fx} = -\frac{\partial}{\partial x}(z_g + h) = -\frac{\partial z}{\partial x} \\
S_{fy} = -\frac{\partial}{\partial y}(z_g + h) = -\frac{\partial z}{\partial y}
\]  
(2.16)

(2.17)

In Mike SHE, the Strickler/Manning equation for each friction slope is used applying the Strickler coefficients \(K_x\) and \(K_y\), then

\[
S_{fx} = \frac{u^2}{K^2_x h^{4/3}} \tag{2.18}
\]

\[
S_{fy} = \frac{u^2}{K^2_y h^{4/3}} \tag{2.19}
\]

If Equations 2.16 and 2.17 are substituted into Equation 2.18 and 2.19, then

\[
\frac{u^2}{K^2_x h^{4/3}} = -\frac{\partial z}{\partial x} \tag{2.20}
\]

\[
\frac{u^2}{K^2_y h^{4/3}} = -\frac{\partial z}{\partial x} \tag{2.21}
\]

By multiplying both sides of the equations by \(h\), the relation between the velocities and depths is given by

\[
u h = K_x \left(-\frac{\partial z}{\partial x}\right)^{1/2} h^{5/3} \tag{2.22}
\]

\[
v h = K_x \left(-\frac{\partial z}{\partial x}\right)^{1/2} h^{5/3} \tag{2.23}
\]

where \(u h\) and \(v h\) represent discharge per unit length along the cell boundary for \(x\) and \(y\) directions.

A finite difference formulation of the above equations is used by Mike SHE to estimate flow between adjacent cells. Successive Over-Relaxation (SOR) numerical solution is another method applied in Mike
SHE (2008) to solve the set of finite difference equations for overland flow calculations. The reference of this method is found in the Mike SHE (2008) technical reference for water movement. This section describes just the finite difference formulation because it is the method used in this research for overland flow calculations.

2.3.4 Channel Flow

Channel flow can be calculated by the coupling of Mike SHE and Mike 11 (Mike 11, 2008). Mike 11 is a river hydraulic program that estimates the water level and flows of a channel in one direction using the fully dynamic Saint Venant equations. Hydraulic structures such as gates, gutters, weirs and culverts can be simulated by Mike 11. The three basic water movement processes estimated by the coupling of Mike SHE with Mike 11 are listed below (Mike SHE, 2008):

- Branches defined in Mike 11 exchange water with the ground water defined in the Mike SHE flow model
- Flood codes can be specified from Mike 11 to Mike SHE to identify flood zones where if the water level elevation is higher than the topography the cells are considered flooded.
- Mike 11 provides an option of overbank spilling, which is estimated using a weir formulation to allow water to flow onto the topography or into the channel.

The coupling of Mike SHE with Mike 11 allows overland flow between the topography file and the Mike 11 branches. The branches that can interact with Mike SHE have to be specified as “linked” branches. Linked branches are locations where overland flow is allowed to enter Mike 11’s channel network, whereas regular branches do not allow this interaction (Mike SHE, 2008).
The Mike SHE (2008) user manual provides more information about flooding routines and the calculations describing the iterations between Mike 11 and Mike SHE.
CHAPTER 3: DESCRIPTION OF SITES

This chapter describes the monitored sites used in this research to build, calibrate and validate the Mike SHE models. Data provided by the U.S. Geological Survey (USGS) for rain gardens in Madison, WI were used to create the single rain garden models. The single rain garden models were calibrated and validated to monitored data in order to define calibrated parameters that are able to describe a rain garden into a watershed scale model.

The Oakdale Avenue watershed is located in the northwest of Chicago. Physical and monitored data for this site have been used to build a physical distributed model of the site. The Oakdale Avenue model was validated and used to implement rain gardens and predict their hydrologic effects.

3.1 DESCRIPTION OF USGS MADISON RAIN GARDENS

The USGS in Madison, Wisconsin is performing a study of four rain gardens to evaluate infiltration rates at two different sites. Each site has a different soil type (sandy and clayey soil). The rain gardens at each site were planted with different vegetation (turf grass and native plants). This research used physical and monitored data of rain gardens from each site that were planted with native vegetation. The vegetation of each of the two sites is basically the same, while the soil properties are different. The following sections explain what physical and monitored data were used in this research.

3.3.1 Physical Data

Physical data for the USGS rain gardens in Madison were provided by William R. Selbig of the USGS. The Madison rain gardens are located in two different sites, Old Sauk and Owen, which have different soil properties. Physical data for each site include topography, roof areas, rain garden areas, native
vegetation and soil borings. Table 3.1 shows the native vegetation of Old Sauk and Owen rain garden sites.

**Table 3.1 Madison native rain gardens vegetation**

<table>
<thead>
<tr>
<th>Plant</th>
<th>name</th>
<th>Type</th>
<th>Height ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obedient Plant</td>
<td>Physostegia Virginiana</td>
<td>Perennial</td>
<td>3-4</td>
</tr>
<tr>
<td>Sweet Black-Eyed Susan</td>
<td>Ridbeckia Subtomentosa</td>
<td>Perennial</td>
<td>3-6</td>
</tr>
<tr>
<td>Yellow Flag Iris</td>
<td>Iris pseudocorus</td>
<td>Perennial</td>
<td>3-4</td>
</tr>
<tr>
<td>White Turtle Head</td>
<td>Chelone glabra</td>
<td>Perennial</td>
<td>1-4</td>
</tr>
<tr>
<td>Cardinal Flower</td>
<td>Lobelia cardinalis</td>
<td>Perennial</td>
<td>1-6</td>
</tr>
<tr>
<td>Dark-Green Bulrush</td>
<td>Scirpus atrovirens</td>
<td>Perennial</td>
<td>3-6</td>
</tr>
<tr>
<td>Great Bulrush</td>
<td>Schoenoplectus tabernaemontani</td>
<td>Perennial</td>
<td>3-9</td>
</tr>
<tr>
<td>Mountain Mint</td>
<td>Pycnanthemum virginianum</td>
<td>Perennial</td>
<td>2-3</td>
</tr>
<tr>
<td>Starry Campion</td>
<td>Silene stellata</td>
<td>Perennial</td>
<td>2-3</td>
</tr>
<tr>
<td>Wild Columbine</td>
<td>Aquilegia canadensis</td>
<td>Perennial</td>
<td>1-2</td>
</tr>
<tr>
<td>Cream False indigo</td>
<td>Baptisia bracteata</td>
<td>Perennial</td>
<td>1-2</td>
</tr>
<tr>
<td>Asters Smooth</td>
<td>Symphyotrichum laeve</td>
<td>Perennial</td>
<td>2-4</td>
</tr>
<tr>
<td>Wild Bergamont</td>
<td>Monarda fistulosa</td>
<td>Perennial</td>
<td>0.4</td>
</tr>
<tr>
<td>Swamp Milkweed</td>
<td>Asclepias incarnata</td>
<td>Perennial</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Old Sauk rain gardens are located in Madison, Wisconsin. They were planted behind the Madison Municipal Well #28 (43° 04' 32" N and 89° 31' 24" W). There are two rain gardens, one with native plants and other with turf grass. The soil is mostly clay as determined from bore holes previously drilled. Table A1 in the Appendix provides more details about the soil profile of the area. Topography data of the site was provided by USGS. Approximately 140 square meters (1500 square feet) of the roof area drains to each rain garden. The roof slope is around 0.002. Figure 3.1 illustrates the top view of Old Sauk rain gardens. Each rain garden has an area of approximately 28 square meters (300 square feet) which is equivalent to 20% of the roof area, and a depression of 0.15 meters (0.5 ft) deep.
Owen rain gardens are located in Madison, Wisconsin. They were planted behind a Municipal maintenance building (43° 04’ 23” N and 89° 29’ 14” W). The site has two rain gardens as well (one with native plants and other with turf grass) planted in a sandy soil. More details about the soil profile of the area are provided in the table A2 in the Appendix. The topography of this site was provided by USGS. The Owen rain gardens receive runoff from a maintenance building with a steep pitched composite shingle roof. Approximately 46 square meters (500 square feet) of the roof area drains to each garden. Each rain garden has an area of approximately 9 square meters (100 square feet) with a depression of 0.15 meter (0.5 feet) deep. Figure 3.2 shows a top view of Owen rain gardens site including the maintenance building.
3.3.2 Monitored Data

Data for the USGS rain gardens in Madison, Wisconsin has been provided by William R. Selbig of the USGS. USGS rain garden sites in Madison WI have been monitored since 2003. Table 3.1 gives the data type measured from the rain gardens.

Precipitation data were measure by using tipping bucket rain gauges. The pond depth was measured using a stilling well and submersible pressure transducer. Potential evapotranspiration was calculated using the Penman-Monteith approach. Variables required by this method such as air temperature, solar radiation and relative humidity were measured from the site.
Table 3.2 Data type of Madison rain gardens

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Moisture</td>
<td>%</td>
</tr>
<tr>
<td>Precipitation</td>
<td>inches</td>
</tr>
<tr>
<td>Potential Evapotranspiration</td>
<td>mm</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>kW</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>%</td>
</tr>
<tr>
<td>Pond Depth</td>
<td>feet</td>
</tr>
</tbody>
</table>

The soil moisture was measured by using 7 soil moisture sensors in a single vertical profile. The early part of the study collected soil moisture at 15-minute increments but it was increased to 5-minute increments to provide better temporal resolution. Soil moisture data at 0.18 meters depth (the closest depth to the surface) has been used to calibrate and validate the single rain garden models.

Monitored data are useful to see the variability of different types of data over the years. On the other hand hydrologic models are needed to estimated fundamental hydrologic processes in a rain garden in order to better understand better its behavior under different conditions. Measured data from real sites are necessary to calibrate and validate hydrologic models, as it is shown.

3.2 OAKDALE AVENUE SITE DESCRIPTION

The Oakdale Avenue catchment is an urban site located at the northwest of Chicago with coordinates at 41° 56’ 05” N and 87° 45’ 13” W. The site has an area of approximately 12.9 acres, which is used for residential purposes. Figure 3.3 and figure 3.4 show the location and top view of the catchment. Physical data provided by Turker (1968) and Chow and Yen (1976) have been used for the Oakdale Avenue Model development. Precipitation and combined sewer outflows data were monitored for five years.
(1959 – 1964) by the ASCE Urban Water Resources Research Program (Tucker 1968). Christensen (2008) used the data below to create and calibrate the Mike SHE model that will be explained in details in Chapter 4. The Oakdale Avenue model is used in this research to perform continuous rainfall simulations and to implement different rain garden scenarios rain in the same catchment.

Figure 3.3 Oakdale Avenue location with respect to Chicago (Christensen 2008).

Figure 3.4 Areal view of Oakdale Avenue (Christensen 2008).
3.2.1 Physical Data

Oakdale Avenue site has a data base of physical and monitored data that are needed to build a physical distributed model. Physically distributed models generally require more data than lumped models. Data available for this site allow a physically distributed model development using Mike SHE.

Oakdale Avenue stormwater system includes sewers, inlets and manholes. Each hydraulic structure has an ID number to identify each structure in the Mike 11 model. Figure 3.5 shows the Oakdale Avenue subcatchments and the IDs for each drainage structure.

![Figure 3.5 Oakdale Avenue subcatchments and sewer IDs (Chow and Yen 1976).](image)

Surface drainage and sewer pipe data for Oakdale Avenue include the gutter’s ID, length and slope, subcatchment areas, type of inlet and contribution to sewer junction. Additionally there are data available for sewer pipes including the nodes (points where two or more pipes are connected), length, slope and diameter of each pipe. The name, open area and perimeter of the inlets inside the catchment...
are also available. Alley drainage data include location, subcatchment area, length, width, slope and inlet ID. The data described above are in the Appendix from Table A3 to Table A6.

Oakdale Avenue land cover areas are divided into impervious and pervious areas. Table 3.3 shows the impervious and pervious areas in Oakdale Avenue. The main combined sewer (sanitary and storm water flows) trunk of the catchment runs from west to east with a range of diameters from 0.3 to 0.76 meters (1.0 to 2.5 feet). Aerial photos and LIDAR data were provided by Cook County. These data are useful to delineate the catchment physical features such as roads, alleys, houses, yards, and sidewalk. LIDAR data also are useful to create the topography file of the site. This data base includes 6,300 elevation points inside the catchment. Elevation points for houses and streets are not included. In spite of lack of data for houses and streets, the LIDAR data base helps to produce an accurate topography file of this catchment. Figure 3.6 illustrates LIDAR data points inside the watershed.

### Table 3.3 Impervious and pervious areas (Tucker 1968)

<table>
<thead>
<tr>
<th>Impervious Area Draining Directly to Combined Sewer</th>
<th>acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houses</td>
<td>2.52</td>
</tr>
<tr>
<td>Streets</td>
<td>1.58</td>
</tr>
<tr>
<td>Alleys</td>
<td>0.58</td>
</tr>
<tr>
<td>Garages</td>
<td>0.27</td>
</tr>
<tr>
<td>Sidewalks to Street</td>
<td>0.11</td>
</tr>
<tr>
<td>Sidewalks ro alleys</td>
<td>0.09</td>
</tr>
<tr>
<td>Subtotal =</td>
<td>5.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impervious Area Draining Indirectly to Combined Sewer</th>
<th>acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Walks</td>
<td>0.57</td>
</tr>
<tr>
<td>Private Walks</td>
<td>0.15</td>
</tr>
<tr>
<td>Subtotal =</td>
<td>0.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pervious Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtotal =</td>
</tr>
<tr>
<td>Total Drainage =</td>
</tr>
</tbody>
</table>
Oakdale Avenue watershed was monitored in 1960’s. The residential lots in the catchment have roof downspouts used to drain the stormwater from the roof and convey the flow into a sewer. This feature is important for calibration purposes because the roof runoff contributes to the runoff of the whole catchment. Physical data in general have to be defined as close as possible to the real site in order to estimate accurate flow at the catchment outlet.

3.2.2 Monitored Data

The Oakdale Avenue has a monitored data record of five years. Precipitation and sewer flow near the catchment outlet were measured from 1959 to 1964. A monitoring vault was installed in 1958, at the same time the sewer was installed. The catchment has a trunk-main with a diameter of 0.76 meters (2.5 ft) which is connected to a combined sewer running along the eastern boundary of the catchment. Data collected during large precipitation events were erratic because the combined sewer (3.2 m x 3.2 m) surcharged in those intense cases. Flow measurements were taken using a Simple 760 millimeters parabolic Type “S” flume (Turker 1968). Schematics drawing of the monitoring system and the vault details are available in the Appendix.
The precipitation data were measured using a tipping bucket rain gage located on the roof of Falconer Elementary School which is located one block north of Oakdale Avenue. Precipitation data were recorded just when there was a storm event. The instrument collected data beginning where the first 1/100 inches of rain resulted in the first rain bucket tip. After 110 minutes without any rain the tipping bucket stopped recording data (Tucker, 1968). Many storm events were measured but runoff and precipitation data for only 21 storms for which the data were considered consistent were provided by Tucker (1968). Table 3.4 gives 14 of the 21 storms with the number of peaks.

<table>
<thead>
<tr>
<th>Date of Storm</th>
<th>Number of Peak</th>
<th>Peak Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-May-59</td>
<td>1</td>
<td>Good Peak Flow</td>
</tr>
<tr>
<td>29-Jul-59</td>
<td>1</td>
<td>Good Peak Flow</td>
</tr>
<tr>
<td>6-Oct-59</td>
<td>2</td>
<td>Small Peaks, Long Rainfall period</td>
</tr>
<tr>
<td>26-Jul-60</td>
<td>3</td>
<td>Medium Peak Flow</td>
</tr>
<tr>
<td>18-Sep-60</td>
<td>1</td>
<td>Medium Peak Flow</td>
</tr>
<tr>
<td>14-Oct-60</td>
<td>1</td>
<td>Small Peak Flow</td>
</tr>
<tr>
<td>2-Jul-62</td>
<td>4</td>
<td>Fourth Peak Flooded</td>
</tr>
<tr>
<td>17-Apr-63</td>
<td>2</td>
<td>Medium Peak Flow</td>
</tr>
<tr>
<td>19-Apr-63</td>
<td>1</td>
<td>Good Peak Flow</td>
</tr>
<tr>
<td>29-Apr-63</td>
<td>2</td>
<td>Medium Peak Flow</td>
</tr>
<tr>
<td>13-Jul-63</td>
<td>5</td>
<td>Small Peak Flow</td>
</tr>
<tr>
<td>2-Aug-63</td>
<td>2</td>
<td>Medium Peak Flow</td>
</tr>
<tr>
<td>24-Aug-63</td>
<td>2</td>
<td>Small Peak Flow</td>
</tr>
<tr>
<td>22-Sep-64</td>
<td>2</td>
<td>Small Peak Flow</td>
</tr>
</tbody>
</table>
CHAPTER 4: MODELING METHODS

4.1 BACKGROUND/DESCRIPTION

This chapter describes the methodology used to model surface and subsurface processes in one and two dimensions occurring in rain gardens and the hydrologic impacts of rain gardens in urban watersheds. The two main components that are emphasized by the methodology are: physical distributed rain garden models are calibrated and validated to observed data, and afterwards calibrated parameters describing the rain gardens will be merged into a calibrated urban watershed model to examine hypothetical rain gardens scenarios.

This research provides a methodology that links previous monitoring studies of rain gardens with a physically distributed model which couples surface and subsurface processes in order to understand the main hydrologic processes of rain gardens and how they interact with a larger model. Physical distributed models are able to describe the hydrologic behavior of a wide range of conditions that have not been monitored. These models incorporate many parameters with physical meaning making possible the prediction of non-existing conditions. This type of modeling is also known as predictive modeling approach because hypothetical scenarios or alterations to the real system (BMPs, watershed etc.) can be simulated to see how the system responses. In other words a physical distributed model provides greater flexibility to generate changes to the system and examine their hydrologic impacts. That is possible with empirical models.

The methodology is tested using the physical distributed model Mike SHE. Mike SHE is able to simulate hydrologic processes like evapotranspiration, overland flow, unsaturated flow, channel flow and saturated flow at different spatial and temporal resolutions (Mike SHE, 2008). Mike SHE uses the
Kristensen and Jensen (1975) method for evapotranspiration calculations. Richards’s equation and diffusive wave approximation are used to calculate the unsaturated flow and the overland flow respectively. Overland flow paths are defined in two dimensions while the soil properties are defined in three dimensions.

4.2 SINGLE RAIN GARDEN MODELING

Data from monitored sites are necessary to verify a physical distributed model performance. Observed data from rain gardens have been used in this research to calibrate and validate rain garden models built by using Mike SHE. Mike SHE is a physical distributed model able to simulate the hydrologic processes occurring in a rain garden. After rain garden models calibration and validation, calibrated parameters could be implemented into a calibrated model for larger model. Afterward the effects of implementing rain gardens in a larger site can be predicted.

The following sections describe how the single rain garden model was built. The procedures for building the input files for a single rain garden model have been modified from those proposed by Christensen (2008). Sensitivity analysis, calibration and validation procedures described in the following sections have been applied in this research.

4.2.1 Mike SHE Model Description

As motioned before, Mike SHE is a physical distributed model that requires input data and parameters with physical meaning. This software couples multiple input parameter files describing different hydrologic such as evapotranspiration, groundwater recharge, soil water content, and pond depth. The following sections explain the main inputs files required to build a Mike SHE model of a single rain
garden. The model domain, topography, vegetation, soil and initial conditions of soil water content are basically the main input files considered in this research. The details of each file are described below.

4.2.1.1 Model Domain and Topography

The model domain defines the watershed boundaries. The topography file describes the topography of the area. This file is a main input for overland flow calculation (Christensen, 2008). The topography file can be generated manually or created automatically using digital topographic maps.

The topography file of a rain garden incorporates the rain garden and the area contributing flow to the rain garden. For the Old Sauk and Owen rain gardens, the contributing area is the roof of the adjacent building. While the topography file describes the rain garden depression in the model, the depth-storage volume relation is assigned by the user using the topography data of the site. Mike SHE uses the topography file for overland flow calculations. The overland flow and unsaturated flow components work together with the Richard’s equation in order to estimate how the water pond in the rain garden infiltrates. For more details about the topography file refer to Christiansen (2008).

4.2.1.2 Vegetation Definition

Vegetation is defined by the vegetation dialogue and the vegetation properties file. The vegetation dialogue defines the vegetation distribution across the model area (Mike SHE, 2008). The spatial distribution of vegetation can be uniform or station based. The spatial distribution of vegetation in this research is station based. When the distribution is station based, data type can be grid code or polygons. The vegetation grid code file is the input file that assigns vegetation spatially on the surface. Grid codes are integer IDs for each grid cell in the model domain that represent vegetation distribution, soil profiles or any spatially distributed input parameter assigned by the user.
For vegetation, each integer (grid code) represents a different user defined vegetation type. Different vegetation types and their properties are manually assigned in the vegetation properties file. The vegetation properties file specifies the vegetation type development schedule assigned by the user. The file contains a time series of the root depth and leaf area index \((LAI)\) for the growing season (Mike SHE, 2008). The name and growing season of each crop is assigned by the user as well. For each vegetation type, the user has to assign values to the following parameters: 1) \(LAI\), 2) root depth, 3) crop coefficient \((K_c)\) and 4) the evapotranspiration parameters for each growing season. These parameters are the main parameters of the vegetation file properties. Table 4.1 shows the vegetation parameters with their meaning and typical values and Table 4.2 gives the evapotranspiration input parameters required by Kristensen and Jensen method (Kristensen and Jensen, 1975). Figures 4.1 and 4.2 illustrate how Mike SHE assigns vegetation properties spatially over a catchment and the definitions of different vegetation types for each integer.

**Table 4.1 Vegetation parameters**

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Meaning/Function</th>
<th>Units</th>
<th>Range of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf Area Index</td>
<td>(LAI)</td>
<td>The leaf area index, which is the (Area of leaves)/(Area of the ground).</td>
<td>[-]</td>
<td>0   7</td>
</tr>
<tr>
<td>Root depth</td>
<td>(Root)</td>
<td>The rooting depth of the crop. It will normally vary over the season.</td>
<td>mm</td>
<td>-   -</td>
</tr>
<tr>
<td>Crop Coefficient</td>
<td>(K_c)</td>
<td>Crop coefficient is used to adjust the reference ET relative to the actual ET of the specific crop.</td>
<td>[-]</td>
<td>0   1</td>
</tr>
</tbody>
</table>
Table 4.2 Evapotranspiration parameters (Kristensen and Jensen 1975)

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Meaning/Function</th>
<th>Units</th>
<th>Range of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy interception</td>
<td>$C_{int}$</td>
<td>Cint defines the interception storage capacity of the vegetation.</td>
<td>mm</td>
<td>0.05 - -</td>
</tr>
<tr>
<td>Empirical coefficient - $C_1$</td>
<td>$C_1$</td>
<td>$C_1$ is canopy dependent.</td>
<td>[-]</td>
<td>0.3 0 1</td>
</tr>
<tr>
<td>Empirical coefficient - $C_2$</td>
<td>$C_2$</td>
<td>$C_2$ is permanent wilting point dependent.</td>
<td>[-]</td>
<td>0.2 0 0.5</td>
</tr>
<tr>
<td>Empirical coefficient - $C_3$</td>
<td>$C_3$</td>
<td>$C_3$ depends on vegetation and soil type.</td>
<td>mm/day</td>
<td>20 10 -</td>
</tr>
<tr>
<td>Root mass distribution</td>
<td>$AROOT$</td>
<td>$AROOT$ controls how the water extraction is distributed with depth.</td>
<td>1/mm</td>
<td>0.25 - -</td>
</tr>
</tbody>
</table>

![Vegetation grid code example](image)

**Figure 4.1 Vegetation grid code example.**
### Figure 4.2 Vegetation properties example.

<table>
<thead>
<tr>
<th>Stage name</th>
<th>End day</th>
<th>LAI</th>
<th>Root (mm)</th>
<th>Kc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native Vegetation = Grid code 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>0</td>
<td>1.2</td>
<td>950</td>
<td>0.65</td>
</tr>
<tr>
<td>April</td>
<td>91</td>
<td>1.8</td>
<td>980</td>
<td>0.72</td>
</tr>
<tr>
<td>June</td>
<td>152</td>
<td>2</td>
<td>990</td>
<td>0.86</td>
</tr>
<tr>
<td>September</td>
<td>244</td>
<td>1.5</td>
<td>990</td>
<td>0.76</td>
</tr>
<tr>
<td>November</td>
<td>305</td>
<td>1.1</td>
<td>985</td>
<td>0.62</td>
</tr>
<tr>
<td>Turf Grass = Grid code 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>0</td>
<td>0.8</td>
<td>250</td>
<td>0.6</td>
</tr>
<tr>
<td>April</td>
<td>91</td>
<td>1.5</td>
<td>280</td>
<td>0.68</td>
</tr>
<tr>
<td>June</td>
<td>152</td>
<td>1.6</td>
<td>290</td>
<td>0.78</td>
</tr>
<tr>
<td>September</td>
<td>244</td>
<td>1.2</td>
<td>290</td>
<td>0.72</td>
</tr>
<tr>
<td>November</td>
<td>305</td>
<td>1</td>
<td>285</td>
<td>0.63</td>
</tr>
</tbody>
</table>

### 4.2.1.3 Soil Definition

The soil profile definition is the input that describes the soils predominating on the site. In Mike SHE the soil profile definition input is required to perform unsaturated subsurface calculations. The soil profiles are described using three separate files to define soils on the surface, underneath the surface and then describe the soil texture using parameters required to use the Richards equation. The soil grid code assigns diverse soil types spatially on the site. The soil grid code works as the vegetation grid code but in this case different soils types are assigned instead of vegetation types.

Soil profiles are defined by layers with start and end depth assigned manually by the user. A variety of soil textures can be assigned per layer. Mike SHE links the soil grid code file with the soil profile file to assign soil description in 3D. A variety of soil profiles could be assigned spatially based on the soil data available from the site.

The soil texture file is the input file where different soils textures are define by parameters for the unsaturated flow calculations. Retention curves and hydraulic conductivity curves are estimated for
each soil texture to perform the unsaturated flow calculation using the Richard's equation. As mentioned in Chapter 2, the Van Genuchten method has been used in this research to estimate both curves. Tables 4.3 and 4.4 give the input parameters required by this method and the inputs parameters to define the field capacity and wilting point of the soil. Mike SHE default values for Van Genuchten have to be adjusted depending on the soil texture. Tables 4.5 and 4.6 show Van Genuchten average values for different soil textures. Average values in table 4.5 were estimated by Rawls et al. (1982) and the average values in table 4.6 were estimated by Carsel and Parrish (1988). Typical values for organic soils (A horizon) estimated by Ippisch et al. 2006 were used in this research as well.

### Table 4.3 Van Genuchten input parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning/Function</th>
<th>Units</th>
<th>Mike SHE Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_s$</td>
<td>It is the maximum water content of the soil, which is equal to the porosity.</td>
<td>[-]</td>
<td>0.38</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>It is the minimum water content at very high suction pressures.</td>
<td>[-]</td>
<td>0.001</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>It is related to the inverse of the air entry suction.</td>
<td>1/cm</td>
<td>0.067</td>
</tr>
<tr>
<td>$n$</td>
<td>It is a measure of the pore-size distribution.</td>
<td>[-]</td>
<td>1.446</td>
</tr>
<tr>
<td>$K_s$</td>
<td>It describes the ease with which water can move through pore space.</td>
<td>cm/d</td>
<td>17.28</td>
</tr>
</tbody>
</table>
Table 4.4 Field capacity and wilting point parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning/Function</th>
<th>Units</th>
<th>Mike SHE Default Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pF_{fc}$</td>
<td>It is the capillary pressure at field capacity.</td>
<td>[-]</td>
<td>2</td>
</tr>
<tr>
<td>$pF_{w}$</td>
<td>It is the capillary pressure at wilting point.</td>
<td>[-]</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 4.5 Van Genuchten average values for soil water retention and hydraulic conductivity according to Raws et al. (1982)

<table>
<thead>
<tr>
<th>Texture</th>
<th>$\theta_c$</th>
<th>$\theta_s$</th>
<th>$\alpha$</th>
<th>n</th>
<th>$K_s$</th>
<th>cm/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.020</td>
<td>0.417</td>
<td>0.138</td>
<td>1.592</td>
<td>504.00</td>
<td></td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.035</td>
<td>0.401</td>
<td>0.115</td>
<td>1.474</td>
<td>146.60</td>
<td></td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.041</td>
<td>0.412</td>
<td>0.068</td>
<td>1.322</td>
<td>62.16</td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>0.027</td>
<td>0.434</td>
<td>0.090</td>
<td>1.220</td>
<td>16.32</td>
<td></td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.015</td>
<td>0.486</td>
<td>0.048</td>
<td>1.211</td>
<td>31.68</td>
<td></td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>0.068</td>
<td>0.330</td>
<td>0.036</td>
<td>1.250</td>
<td>10.32</td>
<td></td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.075</td>
<td>0.390</td>
<td>0.039</td>
<td>1.194</td>
<td>5.52</td>
<td></td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.040</td>
<td>0.432</td>
<td>0.031</td>
<td>1.115</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>Sandy clay</td>
<td>0.109</td>
<td>0.321</td>
<td>0.034</td>
<td>1.168</td>
<td>2.88</td>
<td></td>
</tr>
<tr>
<td>Silty clay</td>
<td>0.056</td>
<td>0.423</td>
<td>0.029</td>
<td>1.127</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>0.090</td>
<td>0.385</td>
<td>0.027</td>
<td>1.131</td>
<td>1.44</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 Van Genuchten average values for soil water retention and hydraulic conductivity according to Carsel and Parrish (1988)

<table>
<thead>
<tr>
<th>Texture</th>
<th>$\theta_c$</th>
<th>$\theta_s$</th>
<th>$\alpha$</th>
<th>n</th>
<th>$K_s$</th>
<th>cm/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.045</td>
<td>0.43</td>
<td>0.145</td>
<td>2.68</td>
<td>712.80</td>
<td></td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.057</td>
<td>0.41</td>
<td>0.124</td>
<td>2.28</td>
<td>350.20</td>
<td></td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.065</td>
<td>0.41</td>
<td>0.075</td>
<td>1.89</td>
<td>106.10</td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td>0.078</td>
<td>0.43</td>
<td>0.036</td>
<td>1.56</td>
<td>24.96</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>0.034</td>
<td>0.46</td>
<td>0.016</td>
<td>1.37</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.067</td>
<td>0.45</td>
<td>0.020</td>
<td>1.41</td>
<td>10.80</td>
<td></td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>0.100</td>
<td>0.39</td>
<td>0.059</td>
<td>1.48</td>
<td>3144.00</td>
<td></td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.095</td>
<td>0.41</td>
<td>0.019</td>
<td>1.31</td>
<td>6.24</td>
<td></td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.890</td>
<td>0.43</td>
<td>0.010</td>
<td>1.23</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>Sandy clay</td>
<td>0.100</td>
<td>0.38</td>
<td>0.027</td>
<td>1.23</td>
<td>2.88</td>
<td></td>
</tr>
<tr>
<td>Silty clay</td>
<td>0.070</td>
<td>0.36</td>
<td>0.005</td>
<td>1.09</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>0.068</td>
<td>0.38</td>
<td>0.008</td>
<td>1.09</td>
<td>4.8</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.3 gives an example of a different soil profile definition assigned to two different integers.

<table>
<thead>
<tr>
<th>Grid code = 1</th>
<th>Depth (m)</th>
<th>Grid code = 2</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Texture</td>
<td>From</td>
<td>To</td>
<td>Soil Texture</td>
</tr>
<tr>
<td>Clay</td>
<td>0</td>
<td>0.02</td>
<td>Sand</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>0.02</td>
<td>0.15</td>
<td>Loam</td>
</tr>
<tr>
<td>Silt Loam</td>
<td>0.15</td>
<td>0.2</td>
<td>Silt</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>0.2</td>
<td>0.25</td>
<td>Sandy Loam</td>
</tr>
</tbody>
</table>

Figure 4.3 Soil profile definition example.

4.2.1.4 Initial Soil Water Content Conditions

Initial conditions of soil water content are very important for infiltration based models. The initial conditions of soil moisture indicate if the soil is saturated, dry or an intermediate water content condition at the time the simulation starts. Mike SHE provides the option to specify the initial water content as an input value if the monitored data are available. Soil moisture monitored data provided by USGS were used to assign the initial water content of the soil as input values before the simulation starts. The user can specify if the soil initial water content is uniform or varies spatially and how deep the measurement was taken. Uniform soil moisture means that the initial water content value is the same in the model domain. If the initial water content varies spatially, a grid code file used for vegetation or soil grid code previously explained has to be created in order to assign different initial water contents values through the model domain.

The initial conditions can be specified by depth which means the initial condition of soil moisture can be specify by layers. They could be uniform or they could vary spatially. The initial conditions in this research were assigned varying spatially on the rain garden model domain for a uniform depth.
4.2.2 Sensitivity Analysis

Physical distributed models commonly have many input parameter values which can be modified during the calibration process (Refsgaard, 1997). As consequence calibration of these models can be difficult. A sensitivity analysis can be useful in model calibration. The sensitivity analysis helps to identify how the output varies (quantitatively and qualitatively) with different sources of variation in the model parameters. A simple sensitivity analysis was performed in order to identify the parameters that have the largest effects on the soil moisture, pond depth and actual evapotranspiration. These processes were chosen in this analysis because they are related to each other in the mass balance computation. For example if the time period is dry (not precipitation) it is expected that the soil moisture and actual evapotranspiration are going to decrease, and there is not pond depth is zero. Parameters considered in this analysis were divided into three groups (vegetation parameters, evapotranspiration parameters and soil parameters). As mentioned above tables 4.1 and 4.2 show the vegetation and evapotranspiration parameters. Table 4.3 and 4.4 give the soil parameters.

The sensitivity analysis was performed as follows:

Christensen (2008) calibrated the native/prairie Old Sauk and Owen rain gardens models for a single storm event. The Old Sauk single rain garden model calibrated by Christensen (2008) was the only model used for the sensitivity analysis because each model has the same input parameters. The Christensen (2008) calibrated model was used in this research to provided the default starting parameters for calibration. Evapotranspiration parameters used by Christensen (2008) were the Mike SHE default values. These starting parameters were varied plus and minus fifty percent. The purpose of this exercise was to run the model for extreme values of each parameter (low and high values) and to see how much the outputs change.
As mentioned above, the main parameters of the vegetation properties file are the \( \text{LAI} \), \( K_c \) and root depth. \( \text{LAI} \) has a range of values according to the literature. \( \text{LAI} \) varies from 0 to 7 (Mike SHE, 2008). In this case, the sensitivity analysis for \( \text{LAI} \) was done using a value of 0.5 as the minimum and 7 as the maximum in order to use values between this range. \( K_c \) can be below 1 for early crop stages and above 1 during the periods where the \( \text{LAI} \) is at its maximum (Mike SHE 2008). This parameter does not have a specific range of values. In this case the Christensen (2008) calibrated value of \( K_c \) was changed plus and minus fifty percent for the sensitivity analysis. On the other hand, the root depth depends on the type of vegetation. In this case the Christensen (2008) calibrated value of root depth was changed plus and minus fifty percent for the sensitivity analysis.

Soil parameters are shown above in tables 4.3 and 4.4. Table 4.3 shows the input parameters required by Van Genuchten method and table 4.4 gives the input parameters to estimate the wilting point and field capacity. Christensen (2008) used the typical Van Genuchten parameters values given by Dane et al. (2002) for calibration. Those typical values are the same values given by table 4.6. Table 4.5 shows typical Van Genuchten parameters values according to Raws et al. (1982). In this case, Christensen (2008) calibrated model was ran using the estimated values given in table 4.5 and then the results were compared. Wilting point and field capacity input values used by Christensen (2008) were the same as Mike SHE default values. In this case, these values were changed plus and minus fifty percent for the sensitivity analysis.

Total percent change of actual evapotranspiration, pond depth and soil moisture were calculated for maximum and minimum values of each parameter. The total change of actual evapotranspiration, pond depth and soil moisture are given by equations 3.1, 3.2 and 3.3.
\[ A_{ET} \% \Delta = \frac{\sum_{t=1}^{T} A_{ET_{mo}}(t) - \sum_{t=1}^{T} A_{ET_{c}}(t)}{\sum_{t=1}^{T} A_{ET_{c}}(t)} \cdot 100\% \]  

(3.1)

where \( A_{ET} \% \Delta \) is the actual evapotranspiration total change between the modified value and the calibrated value, \( A_{ET_{mo}} \) is the actual evapotranspiration of the modified value and the \( A_{ET_{c}} \) is the actual evapotranspiration of the calibrated value, \( t \) is the initial time and \( T \) is the total time.

\[ h_{d} \% \Delta = \frac{\sum_{t=1}^{T} h_{d_{mo}}(t) - \sum_{t=1}^{T} h_{d_{c}}(t)}{\sum_{t=1}^{T} h_{d_{c}}(t)} \cdot 100\% \]  

(3.2)

where \( h_{d} \% \Delta \) is the pond depth total change between the modified value and the calibrated value, \( h_{d_{mo}} \) is the pond depth of the modified value and the \( h_{d_{c}} \) is the pond depth of the calibrated value, \( t \) is the initial time and \( T \) is the total time.

\[ \theta \% \Delta = \frac{\sum_{t=1}^{T} \theta_{mo}(t) - \sum_{t=1}^{T} \theta_{c}(t)}{\sum_{t=1}^{T} \theta_{c}(t)} \cdot 100\% \]  

(3.3)

where \( \theta \% \Delta \) is the soil moisture total change between the modified value and the calibrated value, \( \theta_{mo} \) is the soil moisture content of the modified value, \( \theta_{c} \) is the soil moisture of the calibrated value, \( t \) is the initial time, and \( T \) is the total time.

4.2.3 Calibration and Validation

After the sensitivity analysis, it is easy to see which parameters change soil moisture the most. Calibration was done by adjusting those parameters to which the soil moisture is most sensitive. As part of this research the statistical criteria proposed by Yen (2002) and the Pearson correlation coefficient were used to guide calibration of models. The calibration was performed comparing quantitatively and qualitatively the observed soil moisture data with the soil moisture estimated by
Mike SHE. Mike SHE estimations are considered optimal if $R^2$, $R$ and $RMSE$ are close to 1, 1, and 0, respectively.

The following equations are proposed by Yen 2002:

Nash Sutcliffe coefficient ($R^2$):

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (\theta_o(t) - \theta_m(t))^2}{\sum_{i=1}^{T} (\theta_o(t) - \overline{\theta_o})^2}$$

(3.4)

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\theta_o - \theta_m)^2}$$

(3.5)

The following equation is proposed by Pearson:

Correlation Coefficient ($R$):

$$R = \frac{N \sum_{i=1}^{N} \theta_o \theta_m - \sum_{i=1}^{N} \theta_o \sum_{i=1}^{N} \theta_m}{\sqrt{N \sum_{i=1}^{N} \theta_o^2 - \left(\sum_{i=1}^{N} \theta_o\right)^2} \sqrt{N \sum_{i=1}^{N} \theta_m^2 - \left(\sum_{i=1}^{N} \theta_m\right)^2}}$$

(3.6)

where, $\theta_o$ is the soil moisture from the observed data and $\theta_m$ is the soil moisture from the model, $\overline{\theta_o}$ is the average of the observed soil moisture data, $R^2$ is the Nash-Sutcliffe coefficient, $RMSE$ is the root mean square error, $R$ is the correlation coefficient, $t$ is the initial time, $T$ is the total time, $i$ is the initial series value, and $N$ is the total number of samples.
After the calibration of the models, a validation exercise is performed in order to see how good the models estimated soil moisture under different continuous rainfall periods. The models are calibrated for the most intense continuous rainfall period and then are validated for a moderate and low intensity continuous rainfall period. More detail about calibration and validation exercises will be provide in the next chapter.

4.3 OAKDALE AVENUE WATERSHED MODELING

The lumped modeling approach is typically used to simulate large scale model by simplifying the parameter sets required to simulate several hydrologic processes occurring in large areas. Urban watersheds normally contain topography with designed flow paths that concentrate runoff spatially including streets, pipes, gutters and downspouts. Christensen (2008) proposed a physically based model methodology to simulate stormwater runoff of urban watershed at fine resolutions while including rain gardens in the watershed. The methodology was developed to examine the effect of rain gardens in an urban watershed model where the model of Oakdale urban watershed without rain gardens was calibrated at fine resolutions and then rain gardens were merged later in the calibrated watershed model. This methodology has been used in this research as reference to implement rain gardens in the same urban watershed.

The calibrated model is validated by generating an initial condition file for each calibrated storms by using precipitation data from NOAA from a nearby site: (41° 58' 0.012" N; 87° 45' 0" W NOAA, 2009).

This research is focused on simulating the Oakdale urban watershed model for continual rainfall events. The features and parameters that are merged in the urban watershed model come from the calibrated models of single rain gardens described in Chapter 5. Christensen (2008) performed simulations for several storm events with different return periods and assumed that excluding the evapotranspiration
from the analysis should have a negligible effect on the results because the short duration storms that were used in the analysis. In this study, the evapotranspiration was not excluded because the analysis was performed for long period of multiple rainfall events.

4.3.1 Mike SHE Model Description

The purpose of modeling Oakdale urban watershed is to analyze the hydrologic effects of rain gardens in a large scale model under a series of storm events. The hydrologic effects of rain gardens are quantified by estimating the reduction in the peak flow and volume of runoff at the outlet of the watershed. The reduction is estimated by comparing the peak flow and volume of runoff at the outlet of the watershed without rain gardens with the results of two different scenarios of rain gardens of different quantities dispersed throughout the watershed.

4.3.1.1 Rain Garden Modeling

Mike SHE is a physically distributed model able to simulate physical processes in a broad range of spatial scales. This modeling approach allows the incorporation of small stormwater management practices in urban watersheds. Rain gardens can be incorporate in a larger model by defining their topography and their soil and vegetation properties. Christensen (2008) configured six sets of scenarios consisting of layouts of randomly distributed rain gardens receiving water from the roof of houses. Two of those scenarios were chosen to simulate the Oakdale urban watershed model with rain gardens for continuous rainfall simulations. Each scenario is represented by a density of rain gardens in the watershed and a percentage of houses that have a rain garden. The percentages chosen in this research are 15% and 86%.
Figure 4.4 House IDs for rain garden placement in random scenarios (Christensen 2008).
The random layouts for each density were constructed using the random number generator in Microsoft Excel © (Christensen, 2008). The Oakdale urban watershed has 86 houses. Figure 4.4 shows the house IDs for rain gardens placement. The 15% scenario of rain gardens means that 13 of 86 houses have a rain garden. The 86% scenario of rain gardens means that 74 of 86 houses have a rain garden. Furthermore, the same size of rain gardens was applied to the two layouts chosen. The size of each rain garden is 15% the roof area. Each rain garden has a depth of 0.5 feet. Table 4.7 gives the house IDs with rain gardens for the 15% random scenario. Table 4.8 gives the house IDs without rain gardens for the 86% random scenario.

<table>
<thead>
<tr>
<th>Table 4.7 Random scenario of 15% rain gardens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>15%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4.8 Random scenario of 86% rain gardens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>86%</td>
</tr>
</tbody>
</table>

4.3.1.2 Mike SHE Input Files

The input files of the Oakdale urban watershed model are basically created like the input files described in the single rain garden modeling section. The vegetation grid code and properties input files were incorporated in the Oakdale model. The evapotranspiration process was included in the analysis because the long period of continual storm events that was used in the analysis. Potential evapotranspiration data from Argonne Lab (41°42′33″N, 87°58′55″W) were used in this analysis as reference evapotranspiration in the area. These data were provided by Elizabeth A. Murphy from the USGS. Calibrated evapotranspiration and vegetation parameters from Madison native rain gardens were used to describe the rain garden vegetation in the Oakdale urban watershed. The time period used for calibration of the Madison native rain gardens was during the summer season. Vegetation parameters
including the $LAI$, $K_e$ and root depth change according to the season. It was assumed that the highest values of $LAI$ and $K_e$ occur during the spring and summer seasons because the weather condition promotes the vegetation development. These parameters should be lower for the fall and winter seasons. More details about the vegetation setup will be described in Chapter 6.

The topography file was prepared by using the LIDAR data available. The street’s slopes were assigned using the gutter slopes provided by Chow and Yen (1976). The roof of the buildings was lowered to the ground surface elevation (the same technique used in the single rain garden models). The houses in Oakdale watershed have direct connection to the sewer by downspouts. This physical characteristic was defined in the model as a channel with a small berm on both sides.

The topography files with rain gardens are the main change to the actual watershed. The original topography is altered to define the depressions on the land that represent a rain garden. The houses without a rain garden have a small yard channel that acts like a downspout connected to the sewer. The houses with rain gardens do not have a channel connected to the sewer. In this case, the topography is altered in order to define the rain garden on the land.

The predominant soil in Oakdale avenue watershed is loamy and silty clay (Cantone, 2007). This soil was applied to pervious areas. The soil profiles of all rain gardens have the same soil properties as the calibrated Old Sauk native rain garden. This rain garden is a good representation of a typical rain garden design. A soil with a very low hydraulic conductivity was assigned to impervious areas. Manning $M$ values larger than 100 were assigned to impervious areas because the water moves fast on these surfaces water and values less than 10 were assigned to pervious areas because the water moves slowly on these surfaces. Initial values of detention storage were assigned to impervious and pervious areas.
A Mike 11 1-D model was used for sewer hydraulic calculations. The branches of the pipe network are specified by the user. User defined Mike 11 branches were linked to Mike SHE, and received water from Mike SHE either by using a modified weir approach or by manning calculation. Physical properties of the sewer pipe network given by Chow and Yen (1976) were assigned to the pipes in Mike 11. The Manning n number of 0.015 was assigned to the pipes and 0.013 to the gutter respectively.

4.3.2 Validation of the Model

The Oakdale urban watershed model was built and calibrated by Christensen (2008). Christensen (2008) used monitored from 1959 to 1964 to calibrate the model. The calibration was performed for three different storms: May 19, 1959, September 18, 1960 and August 24, 1963. The initial conditions for each storm were estimated by Christensen (2008). Precipitation data from NOAA from the site with the following coordinates: 41° 58' 0.012" N; 87° 45' 0" W were used to create a hot start data file for each storm. The files then were used to initialize each simulation. The Nash Sutcliffe coefficient ($R^2$) and the root mean square error ($RMSE$) were calculated in order to compare Christensen’s results and the new results with the observed data.
CHAPTER 5: SINGLE RAIN GARDENS SIMULATIONS

This chapter describes the procedure used to build Mike SHE models of Madison native rain gardens. Input files details and specifications of each model are provided. Results of sensitivity analysis, calibration and pond depth volume calculation are included and discussed in this chapter as well. The purpose of these exercises is to validate the effectiveness of Mike SHE estimating hydrologic processes occurring in a rain garden. Calibrated parameters of rain gardens are the used to implement them inside a watershed scale model.

5.1 MIKE SHE MODEL DESCRIPTION OF USGS MADISON RAIN GARDENS

Mike SHE models were built to represent the physical design of the Old Sauk and Owen native rain garden sites as closely as possible. Native rain garden models were calibrated and validated comparing the results qualitatively and quantitatively with observed data. Calibrated rain gardens models validate the Mike SHE accuracy simulating rain garden’s hydrologic processes. Calibrated input parameters for rain gardens were used to represent a rain garden that could be merged into the larger scale site model called Oakdale Avenue.

Rain garden models have a grid size of 1 meter (Christensen 2008). This grid size is good enough to represent the rain gardens sites. Precipitation data from 2004 to 2007 were used to perform a cumulative rainfall analysis of each site. The purpose of this exercise was to determine the most extreme rainfall period per year. Figures 5.1 and 5.2 show the cumulative rainfall plots from 2004 to 2007 of Old Sauk and Owen sites. According with these figures the most extreme cumulative rainfall period is between July and August, 2007 where over 371 millimeters (15 inches) of rain were recorded in
38 days. This intense period was used to calibrate the Old Sauk and Owen rain garden models respectively.

Figure 5.1 Old Sauk rain garden cumulative rainfall from 2004 to 2007.

Figure 5.2 Owen rain garden cumulative rainfall from 2004 to 2007.
The main Mike SHE inputs files are the following:

- Model Domain
- Topography
- Manning M (Strickler)
- Soil Grid Code
- Detention Storage
- Vegetation Code
- Initial Water Content

As mentioned in Chapter 4, the model domain defines the model spatial coverage. The topography file was done using survey data which define the spatial elevations of the sites and is used for overland flow 2-D calculations. Manning $M$ file defines the Manning $M$ (Strickler) value that is equal to $\frac{1}{n}$ over Manning $n (1/n)$. High values of Manning $M$ are used to describe surfaces where water runs quickly out of the surface and low values are used to describe surfaces where the water runs slowly. Manning $M$ values of 100 and 10 were assigned to the roof and rain gardens (Christensen 2008).

Three soil profiles were assigned to Old Sauk and Owen native rain gardens (native, grass and impervious) respectively. The soil layer depth and soil textures of the native rain garden soil profiles were assigned using a bore-hole data file provided by the USGS (Appendix). The vegetation input file is required to estimate the actual evapotranspiration of native vegetation. Values of $LAI$, root depth and $K_c$ which are the main parameters of the vegetation file were found in the literature. The initial water content was assigned using monitored soil moisture data from the site. The soil moisture data have been monitored by using seven sensors at different depths. Data monitored by the first sensor (the sensor closer to the surface) were used to set the initial soil moisture condition in the model.
Old Sauk and Owen native rain gardens were calibrated using a continuous rainfall period between July 25 and August 20, 2007. The rain gardens were designed with enough storage capacity to retain runoff coming from the roof. The sensitivity analysis was performed for vegetation, evapotranspiration and soil input parameters using an individual parameter perturbation method (Christiaens and Feyen, 2002). This method is based on changing one parameter per run and compares the output of the model with the output obtained by using the original set of parameters. While there are other methods to perform a sensitivity analysis that maybe could be more accurate, the purpose of this analysis was to provide a general idea about which parameters should be modified during calibration rather than to examine the procedure used to perform this analysis. After the sensitivity analysis, the models were calibrated to the observed data using the methods explained in Chapter 4. The parameters that showed more sensitivity in the soil moisture and pond depth were adjusted in order to get the closest match possible between the simulated soil moisture data and the observed soil moisture data. The models were validated for a moderate and low intensity cumulative rainfall periods.

The models of Madison rain gardens were calibrated to obtain input parameter files that can be used later to implement rain gardens into a larger scale model. As mentioned before, the Oakdale Avenue watershed was used in this research as an example of a large scale model to implement rain gardens.

The soil profile and vegetation input files from the Old Sauk rain garden were used to represent the group of rain gardens that will be merged later into the Oakdale Avenue watershed model to quantify their hydrological effects.
5.2 SENSITIVITY ANALYSIS RESULTS

A sensitivity analysis was done before the Mike SHE model calibration. The main purpose of this exercise was to identify the group of parameters that show more sensitivity in soil moisture and pond depth. The sensitivity analysis was performed for the period between July 25 and August 20, 2007 (the most extreme continuous rainfall time period between 2004 and 2007). The same period was used to calibrate Old Sauk and Owen Mike SHE models. Table 5.1, 5.2, 5.3, and 5.4 show the total percent change between the Christensen (2008) calibrated model results and the outputs after the input parameter perturbation. Three different outputs (pond depth, actual evapotranspiration and soil moisture) are considered in this analysis respectively. The first soil layer of the Old Sauk native rain garden has a loamy texture. The soil moisture was estimated in this soil layer at 0.3m depth (depth of the first layer).

Table 5.1 Total percent change of vegetation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>Min Value (-)</th>
<th>Max Value (+)</th>
<th>h % Δ (-)</th>
<th>h% Δ (+)</th>
<th>A_ET Δ% (-)</th>
<th>A_ET Δ% (+)</th>
<th>θ% Δ (-)</th>
<th>θ% Δ (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAI</td>
<td>[-]</td>
<td>6</td>
<td>0.5</td>
<td>7</td>
<td>-0.454</td>
<td>-0.041</td>
<td>-24.636</td>
<td>0.002</td>
<td>1.688</td>
<td>0.004</td>
</tr>
<tr>
<td>Kc</td>
<td>[-]</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4.136</td>
<td>2.259</td>
<td>-94.589</td>
<td>-46.028</td>
<td>4.623</td>
<td>2.333</td>
</tr>
<tr>
<td>Root</td>
<td>mm</td>
<td>500</td>
<td>250</td>
<td>750</td>
<td>-1.713</td>
<td>0.589</td>
<td>-5.860</td>
<td>0.431</td>
<td>0.292</td>
<td>0.648</td>
</tr>
</tbody>
</table>
Table 5.2 Total percent change of evapotranspiration parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>h% Δ (-50%)</th>
<th>h% Δ (+50%)</th>
<th>A_ET % Δ (-50%)</th>
<th>A_ET % Δ (+50%)</th>
<th>θ % Δ (-50%)</th>
<th>θ % Δ (+50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_ROOT</td>
<td>[-]</td>
<td>0.25</td>
<td>-0.081</td>
<td>0.075</td>
<td>-0.207</td>
<td>0.218</td>
<td>-0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>C_1</td>
<td>[-]</td>
<td>0.3</td>
<td>-0.075</td>
<td>0.000</td>
<td>-0.218</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>C_2</td>
<td>[-]</td>
<td>0.2</td>
<td>0.518</td>
<td>-0.533</td>
<td>0.016</td>
<td>0.005</td>
<td>-0.150</td>
<td>0.155</td>
</tr>
<tr>
<td>C_3</td>
<td>mm/day</td>
<td>20</td>
<td>0.218</td>
<td>-0.090</td>
<td>-2.536</td>
<td>1.196</td>
<td>0.159</td>
<td>-0.065</td>
</tr>
<tr>
<td>Canopy Interception</td>
<td>mm</td>
<td>0.05</td>
<td>0.127</td>
<td>0.118</td>
<td>0.004</td>
<td>0.003</td>
<td>0.008</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 5.3 Total percent change of Van Genuchten soil parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>New Value</th>
<th>h % Δ</th>
<th>A_ET % Δ</th>
<th>θ % Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ_s</td>
<td>[-]</td>
<td>0.43</td>
<td>0.440</td>
<td>3.060</td>
<td>0.186</td>
<td>2.460</td>
</tr>
<tr>
<td>θ_r</td>
<td>[-]</td>
<td>0.078</td>
<td>0.027</td>
<td>0.431</td>
<td>0.844</td>
<td>-3.336</td>
</tr>
<tr>
<td>α</td>
<td>1/cm</td>
<td>0.036</td>
<td>0.090</td>
<td>3.801</td>
<td>0.163</td>
<td>-5.800</td>
</tr>
<tr>
<td>n</td>
<td>[-]</td>
<td>1.56</td>
<td>1.220</td>
<td>200.955</td>
<td>-2.680</td>
<td>15.409</td>
</tr>
<tr>
<td>K_s</td>
<td>cm/d</td>
<td>25</td>
<td>16.320</td>
<td>334.786</td>
<td>0.957</td>
<td>6.206</td>
</tr>
</tbody>
</table>

Table 5.4 Total percent change of wilting point and field capacity parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>h% Δ (-50%)</th>
<th>h% Δ (+50%)</th>
<th>A_ET % Δ (-50%)</th>
<th>A_ET % Δ (+50%)</th>
<th>θ % Δ (-50%)</th>
<th>θ % Δ (+50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pF_{fc}</td>
<td>[-]</td>
<td>2</td>
<td>6.720</td>
<td>3.296</td>
<td>-18.407</td>
<td>3.303</td>
<td>3.058</td>
<td>-0.098</td>
</tr>
<tr>
<td>pF_{w}</td>
<td>[-]</td>
<td>4.2</td>
<td>4.349</td>
<td>3.584</td>
<td>-7.926</td>
<td>0.578</td>
<td>0.371</td>
<td>0.031</td>
</tr>
</tbody>
</table>

According with the tabulated results, LAI and K_c show high sensitivity on the actual evapotranspiration.

Moreover, vegetation parameters and evapotranspiration parameters show a low sensitivity on the soil moisture and pond depth. Probably these parameters do not show sensitivity because the layer is very
deep. The first layer should be discretized in several thin layers and estimate the soil moisture close to the surface in order to see how sensitive the soil moisture is to the vegetation and evapotranspiration parameters. On the other hand, soil moisture and pond depth are sensitive to the saturated hydraulic conductivity and the empirical constant $n$. At the same time wilting point and field capacity parameters show some sensitivity in the soil moisture and pond depth as well. Soil parameters in general were adjusted during calibration because they showed greatest sensitivity in the soil moisture results. Typical values from the literature were used as reference to perform the calibration.

**5.3 CALIBRATION AND VALIDATION RESULTS**

Mike SHE models of single rain gardens were calibrated and validated to observed data from the Old Sauk and Owen sites. Old Sauk and Owen rain garden models were calibrated to the continuous rainfall period between July 25 and August 20, 2007. Figure 5.3 show the Old Sauk calibrated and monitored soil moisture at 0.18m depth (the closest depth to the surface) where the first sensor was located. Old Sauk and Owen rain garden models were validated for moderate and low rainfall intensity periods. The moderate intensity period chosen is between August 19 and August 31, 2006. This period produced 144 millimeters (6 inches) of rain in 12 days. The low intensity period chosen is between July 11 and August 1, 2006. This period produced 77 millimeters (3 inches) of rain in 21 days. Figure 5.4 and 5.5 show the validation of Old Sauk model for soil moisture at 0.18m. In the validation of the models, the observed soil moisture was compared with the simulated soil moisture as it was done for calibration. Figures 5.6 gives the Owen native rain garden calibrated soil moisture at 0.18m. Figures 5.7 and 5.8 illustrate the validation of Owen native rain garden model for moderate and low intensity continuous rainfall periods.
Figure 5.3 Old Sauk calibrated soil moisture.

Figure 5.4 Old Sauk soil moisture during the moderate intensity period.
Figure 5.5 Old Sauk soil moisture during the low intensity period.

Figure 5.6 Owen calibrated soil moisture.
Figure 5.7 Owen soil moisture during the moderate intensity period.

Figure 5.8 Owen soil moisture during the low intensity period.
Tables 5.5 and 5.6 give the error measurements for Nash-Sutcliffe, correlation coefficient and RMSE of Old Sauk and Owen native rain gardens models. These error measurements were estimated for the calibrated and validated continuous rainfall time periods.

**Table 5.5 Old Sauk native rain garden simulation performance**

<table>
<thead>
<tr>
<th>Case</th>
<th>$R^2$</th>
<th>$R$</th>
<th>RMSE ($m^3/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.902</td>
<td>0.955</td>
<td>0.0325</td>
</tr>
<tr>
<td>Validation (Moderated Intensity time period)</td>
<td>0.873</td>
<td>0.962</td>
<td>0.0507</td>
</tr>
<tr>
<td>Validation (Low Intensity time period)</td>
<td>0.636</td>
<td>0.835</td>
<td>0.0553</td>
</tr>
</tbody>
</table>

**Table 5.6 Owen native rain garden simulation performance**

<table>
<thead>
<tr>
<th>Case</th>
<th>$R^2$</th>
<th>$R$</th>
<th>RMSE ($m^3/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.801</td>
<td>0.845</td>
<td>0.0580</td>
</tr>
<tr>
<td>Validation (Moderated Intensity time period)</td>
<td>0.747</td>
<td>0.940</td>
<td>0.0457</td>
</tr>
<tr>
<td>Validation (Low Intensity time period)</td>
<td>0.729</td>
<td>0.858</td>
<td>0.0486</td>
</tr>
</tbody>
</table>

Table 5.7 shows the calibrated input parameters for Old Sauk and Owen native rain gardens. Tables 5.8 and 5.9 give the soil profile for each native rain garden.
### Table 5.7 Calibrated parameters for Old Sauk and Owen native rain gardens

<table>
<thead>
<tr>
<th>Native Rain Garden</th>
<th>Manning M</th>
<th>Detention (mm)</th>
<th>Ground Water Table (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roof</td>
<td>Ground</td>
<td>Roof</td>
</tr>
<tr>
<td>Old Sauk</td>
<td>100</td>
<td>10</td>
<td>0.65</td>
</tr>
<tr>
<td>Owen</td>
<td>110</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 5.8 Old Sauk native rain garden calibrated soil profile description

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>From Depth</th>
<th>To Depth</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
<td>A Horizon</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.72</td>
<td>Sandy Loam</td>
<td></td>
</tr>
<tr>
<td>0.72</td>
<td>1.02</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>1.02</td>
<td>1.25</td>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>1.32</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>1.32</td>
<td>3.01</td>
<td>Clay</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.9 Owen native rain garden calibrated soil profile description

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>From Depth</th>
<th>To Depth</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.18</td>
<td>A Horizon</td>
<td></td>
</tr>
<tr>
<td>0.18</td>
<td>0.25</td>
<td>Clay Loam</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>2.4</td>
<td>Loamy Sand</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>2.5</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>Loamy Sand</td>
<td></td>
</tr>
</tbody>
</table>

Tables 5.10 and 5.11 show calibrated Van Genuchten, vegetation and evapotranspiration parameters.

### Table 5.10 Van Genuchten values for calibrated Old Sauk and Owen native rain gardens

<table>
<thead>
<tr>
<th>Texture</th>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$\alpha \text{ cm}^{-1}$</th>
<th>n</th>
<th>$K_s \text{ cm/d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Horizon</td>
<td>0.03</td>
<td>0.48</td>
<td>0.047</td>
<td>1.51</td>
<td>3.4</td>
</tr>
<tr>
<td>Sand</td>
<td>0.045</td>
<td>0.43</td>
<td>0.145</td>
<td>1.59</td>
<td>712.8</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>0.041</td>
<td>0.41</td>
<td>0.068</td>
<td>1.32</td>
<td>106.1</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>0.057</td>
<td>0.41</td>
<td>0.124</td>
<td>2.28</td>
<td>350</td>
</tr>
<tr>
<td>Clay Loam</td>
<td>0.07</td>
<td>0.41</td>
<td>0.04</td>
<td>1.31</td>
<td>6.2</td>
</tr>
<tr>
<td>Clay</td>
<td>0.068</td>
<td>0.43</td>
<td>0.145</td>
<td>1.59</td>
<td>712.8</td>
</tr>
</tbody>
</table>
Table 5.11 Old Sauk and Owen native vegetation and ET parameters

<table>
<thead>
<tr>
<th>Time period</th>
<th>LAI</th>
<th>Root Depth (mm)</th>
<th>$K_c$</th>
<th>$C_{int}$ (mm)</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$ mm/day</th>
<th>$AROOT$ (1/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June - August</td>
<td>2</td>
<td>950</td>
<td>0.9</td>
<td>0.05</td>
<td>0.3</td>
<td>0.2</td>
<td>20</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The soil profiles were built using the bore-hole data given in tables A1 and A2 in the appendix. Soil parameters, mainly from the first soil layer of each rain garden (Old Sauk and Owen) were adjusted to calibrate the soil moisture to the observed data at 0.18 meters depth. According to the bore-hole data, the first soil layer of each rain garden is composed of the organic soil called A Horizon. This upper layer is capable of holding nutrients to sustaining plant growth. Van Genuchten soil parameter values estimated by Ippisch et al. (2006) were used as reference in this research to assign parameters to the A Horizon organic soil. Tables 4.5 and 4.6 were used as reference to assign Van Genuchten values to the other soil textures.

It was found that the first soil layer has a great influence in the infiltration rate of the rain garden. This finding was expected because of the application of Richards’s equation to estimate the infiltration. The vertical discretization of the first soil layer showed a great sensibility to the soil moisture. The first soil layer of Old Sauk and Owen native rain gardens were discretized in several very thin layer in order to estimate the soil moisture as accurate as possible.

The soil profile shown in tables 5.8 represents the native soil of the Old Sauk site. Old Sauk native rain garden soil profile is close to an engineered rain garden soil profile because of the soils properties and distribution. As mentioned above the first layer of Old Sauk gardens is composed of A horizon organic soil, which provide nutrient to the plants. The second soil layer provides storage because of the sandy loam soil properties. The rest of the soil profile contains sand and clay soil textures.
The soil profile shown in table 5.9 represents the native soil of Owen site. Owen native rain garden soil profile has a clay Loam soil layer between the organic soil and sandy soil. The soil profile does not match with a typical rain garden design because of the soil texture distribution.

5.4 WATER VOLUME CALCULATION RESULTS

As mentioned in the previous section, Old Sauk and Owen native rain gardens were calibrated and validate to observed soil moisture data at 0.18m depth. Observed pond depth data from Old Sauk and Owen native rain gardens sites were provided by the USGS. Volume calculations of observed and simulated pond depth were performed in order to compare the volume of pond depth with the volume of cumulative rainwater draining into each rain garden. This exercise gives an idea if there are inconsistencies with the data or numerical errors from the model.

5.4.1 Pond Depth and Soil Moisture Results

Mike SHE is able to estimate the pond depth inside a rain garden. The pond depth of the two rain gardens (Old Sauk and Owen) was estimated by using the model and then compared with the observed pond depth of each site. Figure 5.9 shows the precipitation, pond depth and soil moisture at 0.18m depth from July 25, 2007 to August 20, 2007. The pond depth is under and over estimated by the model in some cases. For example, the first peak of pond depth is estimated by the model and it is around 0.04 meters (0.13 feet). However, the observed pond depth is zero at the same time period. According to the observed soil moisture data, there was a significant increment in the soil moisture because of a rainfall event. The simulated soil moisture also showed the response to the rainfall event. It is shown that the soil was saturated at the time when the ponding occurred according to the observed and simulated soil moisture data. In this case, observed pond depth data could have errors or maybe the real pond depth
was very small compared with the pond depth estimated by the model and the instrument could not record the measurement.

The pond depth is overestimated by the model in the next peaks excluding the last peak where the model underestimated the pond depth. The simulated soil moisture decreases faster than the observed soil moisture from the second peak forward as it is shown in figure 5.9. In addition, the simulated soil moisture at the last pond depth peak shows variability while the observed soil moisture is the same during the period. The simulated soil moisture increase and decrease during the rainfall event while the monitored soil moisture is basically the same for the entire period. The last simulated pond depth peak is much smaller than the observed pond depth peak and occurred before the highest observed pond depth. The simulated pond depth at this peak drains much faster than the observed pond depth. The reduction of simulated pond depth at this point is due to the reduction in the soil moisture.

![Rainfall, Pond Depth, Soil Moisture Graphs](image)

*Figure 5.9 Old Sauk pond depth and soil moisture from 07/25/07 to 08/20/07.*
Figure 5.10 illustrates the rainfall, pond depth (simulated and observed) and the soil moisture (simulated and observed) from August 19 to August 31, 2006. The pond depth is overestimated by the model in the first peak and underestimated in the second peak. The simulated pond depth drains faster than the observed pond depth because the simulated soil moisture decreases more rapidly than the observed soil moisture. It is expected that the soil moisture varies continuously because the infiltration process and the rain intensity. The observed soil moisture is basically constant during the rainfall event. The simulated soil moisture of the second pond depth peak responds to the rainfall variability while the observed soil moisture is basically the same during the time period when the peak occurs. The simulated soil moisture is higher than the observed soil moisture before the first peak of pond depth and is practically lower than the observed soil moisture after the second peak of pond depth. This tendency explains why the pond depth is underestimated by the model after the first pond depth peak.

Figure 5.10 Old Sauk pond depth and soil moisture from 08/19/06 to 08/31/06.
Figure 5.11 gives the rainfall, pond depth (simulated and observed), and the soil moisture (simulated and observed) from July 11 to August 1, 2006. Observed pond depth is zero during the whole time period. The observed soil moisture responds to the rainfall events during this period showing that the soil is saturated during the three rainfall events. On the other hand, the model estimated three pond depth peaks for each rainfall event during the simulation period. The simulated soil moisture also shows that the soil is saturated during the rainfall periods. The simulated soil moisture drains faster than the observed soil moisture after reach the saturated soil moisture value.

Figure 5.11 Old Sauk pond depth and soil moisture from 07/11/06 to 08/01/06.

Figure 5.12, 5.13 and 5.14 show the Owen native rain garden rainfall, pond depth (simulated and observed), and soil moisture for the intense, moderate and low rainfall intensity periods used for calibration and validation of the model. These figures show a similar behavior to the figures of the Old Sauk native rain garden discussed above. According to the calibration and validation results, the model estimates well the soil moisture for each period. However, the pond depth is not that close to the
observed pond depth for some cases. It could be because of several reasons such as: error in data collection, precision of the instrument, description of the soil textures of the site and limitations of the model estimating this particular parameter. The simulations also were performed for continuous rainfall events. The error could have been spread due to the long time of the simulations.

Figure 5.12 Owen pond depth and soil moisture from 07/25/07 to 08/20/07.
Figure 5.13 Owen pond depth and soil moisture from 08/19/06 to 08/31/06.

Figure 5.14 Owen pond depth and soil moisture from 07/11/06 to 08/01/06.
5.4.2 Volume Estimation of Pond Depth and Cumulative Rainfall

As mentioned in Chapter 3, the area of Old Sauk native rain garden is approximately 28 square meters (300 square feet). The walls of the rain garden are approximately vertical. The volume of pond depth was calculated by multiplying the pond water depth with the rain garden area. Approximately 140 square meters (1500 feet) of the roof area drains into the rain garden. Cumulative rainfall volume is then calculated multiplying the cumulative rainwater times the area of the roof that drains into the rain garden (140 square meters).

The area of Owen native rain garden is approximately 9 square meters (100 square feet). Approximately 46 square meters (500 square feet) of the roof area drains into the rain garden. Additionaly this rain garden is approximately cubic shaped. The volume of pond water was calculated by multiplying the pond water depth with the rain garden area. Cumulative rainfall volume is then calculated multiplying the cumulative rainwater times the area of the roof that drains into the rain garden (46 square meters).

5.4.2.1 Old Sauk native rain garden

The pond water and cumulative rainfall volume calculations were performed for the period used for the calibration of each rain garden. Figure 5.15 shows the volume of pond depth (observed and simulated), cumulative rainfall and the soil moisture (observed and simulated) of peak of pond depth on August 5, 2007. This figure shows clearly that when there is an increment in the volume of cumulative rainfall the volume of pond depth increase as well. The volume of cumulative rainfall remains constant during periods without rain. When it is not raining, the pond depth decreases as it is shown in figure 5.15.
Figure 5.15 Volume of pond depth and rainfall and soil moisture on 08/05/07.

Figure 5.16 illustrates the volume of pond water (observed and simulated), volume of cumulative rainfall and the soil moisture (observed and simulated) for the peak of pond depth on August 14, 2007.

According to this figure, there is an increment in rainfall at 2:30 am. At this time, there is an increment in the volume of simulated pond depth but while the volume of observed pond water is close to zero. The simulated and observed soil moisture are saturated at the same time. The saturated soil moisture is around 0.48 m$^3$m$^{-3}$. The second peak of simulated pond on figure 5.16 drains faster than the peak of observed pond depth volume. When the volume of simulated pond depth drains completely, there is a reduction in the simulated soil moisture. The volume of observed pond depth drains slower than the simulated pond depth. The observed soil moisture remains saturated after the volume of observed pond depth drains completely. It could be possible because the soil setting in the model drains a little faster than the soil from the site.
Figure 5.16 Volume of pond depth and rainfall and soil moisture on 08/14/07.

Figure 5.17 shows the volume of pond depth (simulated and observed), the volume of cumulative rainfall and the soil moisture (simulated and observed) for the peak of pond depth between August 18 and 19, 2007. This plot shows a large difference between the volume of simulated pond depth and the volume of observed pond depth. The simulated soil moisture increase and decrease very fast.
5.4.2.2 Owen native rain Garden

The pond water and cumulative rainfall volume calculations were performed for the period used for the calibration of each rain garden. Figure 5.18 shows the volume of pond depth (observed and simulated), cumulative rainfall and the soil moisture (observed and simulated) of the peak of pond depth on July 26, 2007. In this case the model overestimated the pond depth while the simulated soil moisture is very similar to the observed soil moisture.

Figure 5.17 Volume of pond depth and rainfall and soil moisture between 08/18/07 and 08/19/07.
Figure 5.18 Volume of pond depth and rainfall and soil moisture between 07/26/07 and 07/27/07.

Figure 5.19 gives the volume of pond depth (observed and simulated), cumulative rainfall and the soil moisture (observed and simulated) of peak of pond depth on August 14, 2007. The plot shows that there was an increment in the simulated pond depth volume when the volume of cumulative rainfall increased. The soil moisture estimated by the model and the observed soil moisture reach the saturation point ($0.48 \text{m}^3/\text{m}^3$) at the same time. Also the peak of observed pond depth is smaller than the peak of simulated pond depth. In this particular case, the observed soil moisture decrease faster than the simulated soil moisture.
Figure 5.19 Volume of pond depth and rainfall and soil moisture on 08/14/07.

Figure 5.20 illustrates the volume of pond depth (simulated and observed), the volume of cumulative rainfall and the soil moisture of the pond depth peak on August 19, 2007. The volume of simulated pond depth increases faster than the volume of observed pond depth. The volume of simulated and observed pond depth respond very well to the increment in rainfall. The observed soil moisture decreases faster than the simulated soil moisture. It could be a reason why the observed pond depth drains faster than the simulated pond depth. The simulated soil moisture remained saturated and decreased a little when the pond depth drains completely.
The model overestimated the pond depth in all three cases. The soil moisture was used in this analysis to compare its relation with the rainfall and pond depth. Mike SHE does a complex water balance calculation. The soil moisture does not explain entirely the missing mass but it gives an idea about the moisture condition of the soil. It was expected that pond depth could occur during a rainfall event when the antecedent soil moisture conditions were saturated.

Figure 5.20 Volume of pond depth and rainfall and soil moisture on 08/19/07.
As mentioned in previous chapters, the Oakdale Avenue urban watershed has been selected to simulate rain gardens and analyze its response to these stormwater management practices. Calibrated parameters from the Old Sauk rain garden were used as input parameters to describe rain gardens inside Oakdale Avenue watershed. The Old Sauk rain garden was chosen for this analysis because of its compatibility to the soil of the watershed.

The Oakdale Avenue Mike SHE model was built and calibrated by Christensen (2008). Christensen (2008) calibrated the model for three different storms. The initial conditions for each storm were assumed in his analysis. Precipitation data from the NOAA site with the following coordinates: 41° 58' 0.012" N; 87° 45' 0" W (NOAA 2009) were used in this research with the Mike SHE model to produce hot start data files representing the conditions leading up to the events being simulated. These are described in greater details before. The hot start data files were later used to initialize each simulation. Results from Christensen (2008) were compared with the results using the hot start data file to initialize the simulations.

Christensen (2008) did not include evapotranspiration in his model because he analyzed the effects of rain gardens for individual storm events. He assumed that the evapotranspiration was negligible in his analysis because of the short time of the simulations. A continuous rainfall analysis was performed in this research. Evapotranspiration was added to the Christensen (2008) Oakdale model to look at the effect of evapotranspiration in the rain garden recovery and the antecedent moisture conditions. The evapotranspiration in this case is not negligible and has to be considered in the model. Potential evapotranspiration data from Argonne Lab (41°42'33"N, 87°58'55"W) were used in this analysis as
reference evapotranspiration in the watershed. The potential evapotranspiration data were provided by Elizabeth A. Murphy from the USGS.

Rain garden scenarios (15% and 86% rain gardens) were analyzed in this research. The difference between the scenarios is the quantity of rain gardens. The size (15% the roof area) and the storage depth (0.5 ft) of each rain garden are the same. The Oakdale urban watershed model was simulated with and without rain gardens in order to analyze the hydrologic effects of these stormwater management practices. The reduction in peak discharge and volume were estimated for each rain garden scenario.

6.1 PRECIPITATION FREQUENCY ANALYSIS

As mentioned early in this chapter, precipitation data from the NOAA site with the following coordinates: 41° 58' 0.012" N; 87° 45' 0" W were used in this research to perform the simulations. A hourly precipitation record of 33 years (from 1948 to 1980) was used to perform a precipitation frequency analysis. The annual maximum hourly precipitation was used to perform this analysis. The Log normal and Gumbel distributions were fit to the annual maximum series in order to determine which distribution matched better with the data. Figures 6.1 and 6.2 show the relation between the rainfall and the probability of non-exceedance for a log normal and Gumbel distributions respectively. The distributions match very well with the precipitation data. Table 6.2 gives the tabulated results of the precipitation frequency analysis.
Figure 6.1 Log normal distribution fit to 33-year annual maximum series of hourly precipitation.

Figure 6.2 Gumbel distribution fit to 33-year annual maximum series of hourly precipitation.
<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfall (mm)</th>
<th>rank</th>
<th>Probability</th>
<th>Normal Z</th>
<th>Log10(rain)</th>
<th>Gumbel K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>68.580</td>
<td>1</td>
<td>0.029</td>
<td>1.89</td>
<td>1.836</td>
<td>2.288</td>
</tr>
<tr>
<td>1957</td>
<td>54.356</td>
<td>2</td>
<td>0.059</td>
<td>1.565</td>
<td>1.735</td>
<td>1.735</td>
</tr>
<tr>
<td>1961</td>
<td>52.832</td>
<td>3</td>
<td>0.088</td>
<td>1.352</td>
<td>1.723</td>
<td>1.407</td>
</tr>
<tr>
<td>1958</td>
<td>50.800</td>
<td>4</td>
<td>0.118</td>
<td>1.187</td>
<td>1.706</td>
<td>1.17</td>
</tr>
<tr>
<td>1960</td>
<td>43.434</td>
<td>5</td>
<td>0.147</td>
<td>1.049</td>
<td>1.638</td>
<td>0.983</td>
</tr>
<tr>
<td>1968</td>
<td>42.926</td>
<td>6</td>
<td>0.176</td>
<td>0.929</td>
<td>1.633</td>
<td>0.828</td>
</tr>
<tr>
<td>1954</td>
<td>42.672</td>
<td>7</td>
<td>0.206</td>
<td>0.821</td>
<td>1.630</td>
<td>0.694</td>
</tr>
<tr>
<td>1969</td>
<td>42.418</td>
<td>8</td>
<td>0.235</td>
<td>0.722</td>
<td>1.628</td>
<td>0.576</td>
</tr>
<tr>
<td>1959</td>
<td>40.640</td>
<td>9</td>
<td>0.265</td>
<td>0.629</td>
<td>1.609</td>
<td>0.469</td>
</tr>
<tr>
<td>1949</td>
<td>39.370</td>
<td>10</td>
<td>0.294</td>
<td>0.541</td>
<td>1.595</td>
<td>0.372</td>
</tr>
<tr>
<td>1971</td>
<td>36.322</td>
<td>11</td>
<td>0.324</td>
<td>0.458</td>
<td>1.560</td>
<td>0.282</td>
</tr>
<tr>
<td>1950</td>
<td>35.306</td>
<td>12</td>
<td>0.353</td>
<td>0.377</td>
<td>1.548</td>
<td>0.198</td>
</tr>
<tr>
<td>1972</td>
<td>33.020</td>
<td>13</td>
<td>0.382</td>
<td>0.299</td>
<td>1.519</td>
<td>0.119</td>
</tr>
<tr>
<td>1977</td>
<td>33.020</td>
<td>14</td>
<td>0.412</td>
<td>0.223</td>
<td>1.519</td>
<td>0.044</td>
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<tr>
<td>1975</td>
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<td>15</td>
<td>0.441</td>
<td>0.148</td>
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<tr>
<td>1956</td>
<td>30.480</td>
<td>16</td>
<td>0.471</td>
<td>0.074</td>
<td>1.484</td>
<td>-0.097</td>
</tr>
<tr>
<td>1948</td>
<td>29.972</td>
<td>17</td>
<td>0.5</td>
<td>0</td>
<td>1.477</td>
<td>-0.164</td>
</tr>
<tr>
<td>1960</td>
<td>29.718</td>
<td>18</td>
<td>0.529</td>
<td>-0.074</td>
<td>1.473</td>
<td>-0.23</td>
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<tr>
<td>1953</td>
<td>29.464</td>
<td>19</td>
<td>0.559</td>
<td>-0.148</td>
<td>1.469</td>
<td>-0.294</td>
</tr>
<tr>
<td>1951</td>
<td>28.194</td>
<td>20</td>
<td>0.588</td>
<td>-0.223</td>
<td>1.450</td>
<td>-0.357</td>
</tr>
<tr>
<td>1967</td>
<td>27.178</td>
<td>21</td>
<td>0.618</td>
<td>-0.299</td>
<td>1.434</td>
<td>-0.419</td>
</tr>
<tr>
<td>1979</td>
<td>26.416</td>
<td>22</td>
<td>0.647</td>
<td>-0.377</td>
<td>1.422</td>
<td>-0.482</td>
</tr>
<tr>
<td>1974</td>
<td>25.146</td>
<td>23</td>
<td>0.676</td>
<td>-0.458</td>
<td>1.400</td>
<td>-0.544</td>
</tr>
<tr>
<td>1965</td>
<td>24.638</td>
<td>24</td>
<td>0.706</td>
<td>-0.541</td>
<td>1.392</td>
<td>-0.607</td>
</tr>
<tr>
<td>1970</td>
<td>23.622</td>
<td>25</td>
<td>0.735</td>
<td>-0.629</td>
<td>1.373</td>
<td>-0.672</td>
</tr>
<tr>
<td>1964</td>
<td>22.860</td>
<td>26</td>
<td>0.765</td>
<td>-0.722</td>
<td>1.359</td>
<td>-0.738</td>
</tr>
<tr>
<td>1973</td>
<td>21.082</td>
<td>27</td>
<td>0.794</td>
<td>-0.821</td>
<td>1.324</td>
<td>-0.807</td>
</tr>
<tr>
<td>1952</td>
<td>20.574</td>
<td>28</td>
<td>0.824</td>
<td>-0.929</td>
<td>1.313</td>
<td>-0.879</td>
</tr>
<tr>
<td>1963</td>
<td>20.320</td>
<td>29</td>
<td>0.853</td>
<td>-1.049</td>
<td>1.308</td>
<td>-0.957</td>
</tr>
<tr>
<td>1976</td>
<td>15.494</td>
<td>30</td>
<td>0.882</td>
<td>-1.187</td>
<td>1.190</td>
<td>-1.043</td>
</tr>
<tr>
<td>1966</td>
<td>15.240</td>
<td>31</td>
<td>0.912</td>
<td>-1.352</td>
<td>1.183</td>
<td>-1.142</td>
</tr>
<tr>
<td>1978</td>
<td>14.732</td>
<td>32</td>
<td>0.941</td>
<td>-1.565</td>
<td>1.168</td>
<td>-1.262</td>
</tr>
<tr>
<td>1980</td>
<td>12.700</td>
<td>33</td>
<td>0.971</td>
<td>-1.89</td>
<td>1.104</td>
<td>-1.433</td>
</tr>
</tbody>
</table>
The Gumbel distribution fit was used to estimate the probability of exceedance and the return period for several storms. The probability of exceedance is estimated by 1 minus the probability of non-exceedance. The return period is the reciprocal of the probability of exceedance. For example, a rainfall depth of 30mm per hour has a probability of non-exceedance of 0.5. The probability of exceedance is 0.5 and the return period is 2 years.

6.2 OAKDALE URBAN WATERSHED MODELING RESULTS

This chapter presents the results obtained from the Oakdale urban watershed model. The Oakdale urban watershed model was used to simulate continuous rainfall periods. Two different scenarios of rain gardens have been implemented in the watershed model in order to analyze the hydrologic effects of these sustainable stormwater management practices. The discharge at the outlet of the watershed was estimated by the model with and without rain gardens. The percent of reduction in peak flow and volume of runoff were estimated for each rain garden scenario and the results were compared. The soil moisture also was estimated for one of the rain gardens during the continuous time of simulation. It was assumed that the soil moisture was the same for all of the rain gardens under the same storm events because the spatial distribution of the rainfall is uniform.

6.2.1 Validation of Oakdale Avenue Watershed Model

The Oakdale urban watershed model was built and calibrated by Christensen (2008). As mentioned in Chapter 3, Oakdale Avenue was monitored from 1959 to 1964. Rainfall and discharge data were recorded during this period. Christensen (2008) used the rainfall and discharge data to calibrate the model. The calibration was performed for three different storms: May 19, 1959, September 18, 1960 and August 24, 1963. The initial discharge value for each storm was estimated by Christensen (2008). Precipitation data from NOAA from the site with the following coordinates: 41° 58' 0.012" N; 87° 45' 0"
W were used with the Mike SHE model to create a hot start data file for each storm. A hot start data file is a folder with results of a previous simulation and is commonly used to start a new simulation. The initial values of discharge, soil moisture and other variables at the end of simulations performed before the simulation of each calibrated storm was used to initialize the calibrated storm simulations. This exercise was performed to compare the model performance with assumed initial conditions and initial conditions estimated by the model. Table 6.1 shows the comparison between the discharge at the outlet of the Oakdale Avenue watershed estimated by Christensen (2008) and the discharge estimated by using initial conditions (IC) from a hot start data file for each calibrated storm. The Nash Sutcliffe coefficient ($R^2$) and the root mean square error (RMSE) were calculated in order to compare Christensen’s results and the new results with the observed data.

<table>
<thead>
<tr>
<th>Storm</th>
<th>$R^2$ Christensen (2008)</th>
<th>$R^2$ New IC</th>
<th>RMSE Christensen (2008) (m³/s)</th>
<th>RMSE New IC (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/19/1959</td>
<td>0.961</td>
<td>0.954</td>
<td>0.00865</td>
<td>0.00868</td>
</tr>
<tr>
<td>9/18/1960</td>
<td>0.824</td>
<td>0.802</td>
<td>0.01</td>
<td>0.0112</td>
</tr>
<tr>
<td>8/24/1963</td>
<td>0.806</td>
<td>0.849</td>
<td>0.0087</td>
<td>0.00703</td>
</tr>
</tbody>
</table>

According to table 6.1, there is a small difference between the performance of Christensen (2008) simulation and the simulation with new initial conditions. The reason why the values are very close is because the discharge estimated by the model is very close to the baseflow discharge for the three storms. It means that the initial conditions estimated by Christensen (2008) are similar to the initial conditions from the hot start data file. The comparison between results shows that it is not necessary to calibrate the model again because of the small difference between the simulation performances.
6.2.2 Continuous Rainfall Modeling Results

Two scenarios of rain gardens were simulated using continuous rainfall data. “Wet” and “dry” years were picked from a 33 year precipitation record to perform the simulations. The local slope of the plot of cumulative rainfall versus time was estimated in order to identify “wet” and “dry” years in the precipitation record. Large slope values represent wet periods and small slope values represent dry periods. Figure 6.3 shows the estimated slope of the cumulative rainfall versus time.

![Figure 6.3 Slope of the cumulative rainfall versus time.](image)

The continuous rainfall analysis was performed for a “wet” and a “dry” year. According to figure 6.4, 1961 is one of the wetter years from the precipitation record. This year is considered a “wet” year because of the large slope of the cumulative rainfall and it was picked to perform the continuous simulation analysis. On the other hand, 1974 is one of the driest years from the precipitation record. This year is considered a “dry” year because of the small slope value and it also was selected to perform the continuous simulation analysis.
The continuous rainfall analysis was performed for 1961 and 1974. Precipitation data from April to November of each year were used in this analysis. Precipitation data from December to March were not used in this analysis because the effect of the snow is beyond the scope of this research.

The response of the Oakdale Avenue urban watershed was simulated using data from April to November from 1961 and 1974. First, the watershed was simulated without rain gardens. A hot start data file was created and used to initialize the simulation. The model then was modified to simulate the watershed with rain gardens. As mentioned in Chapter 4, two different scenarios of rain gardens (15% and 86% rain gardens) were used to estimate their hydrologic effects in urban watersheds. The simulation of each rain garden scenario was initialized by using a hot start data file created with data before the time of simulation. The difference between each scenario is the quantity of rain gardens. The area and storage capacity of each rain garden is the same. The discharge at the outlet of the watershed with and without rain gardens was estimated by the Oakdale Avenue Mike SHE model. The soil moisture of one rain garden was estimated by the model as well. It was assumed that the soil moisture of the rest of the rain gardens is very similar because the spatial distribution of the rainfall is uniform.

During a period of continuous storm rainfall events, there are possible situations such as: a group of storms or single storms with different magnitudes occurring between a short period of time (a day or less) and a group of storms or single storms with different magnitudes occurring between a long period of time (one week or more). The situations described above and other possible situations, make challenging the analysis of continuous rainfall events. In addition, the soil moisture variability depends on the frequency and magnitude of the storms. Because of the complexity of this analysis, single 60-min storms (one or more days between storms) were picked from the data file and analyzed. Single storms of different magnitudes were selected to analyze the effect of the rain garden scenarios in the peak
discharge and volume at the outlet of the watershed. Figure 6.4 shows the reduction in peak discharge for single storms of different magnitudes.

![Figure 6.4 Reduction in peak discharge for 15% and 86% rain garden scenarios.](image)

According to figure 6.4, the peak discharge reduction is larger for the 86% rain garden scenario than the 15% rain garden scenario. The results of the model show that the peak discharge reduction depends on the quantity of rain gardens. The reduction of peak discharge increased when the quantity of rain gardens increased. However, the peak discharge reduction for the 86% rain garden scenario and the 15% rain garden scenario is almost the same for large storms events (more than 50 mm per hour). In accordance with figure 6.2, a storm of 50 millimeters per hours is equivalent to a 10 year storm. In base on this analysis, the peak discharge reduction will be relative small for storms larger than a 10 year storm.
The antecedent moisture conditions are important to analyze the hydrologic effects of rain gardens. Rain gardens have a larger runoff retention capacity when the soil is dry than when the soil is saturated. When the rain garden soil reaches the saturation point, the storm water starts to pond inside the rain garden depression. Rainfall runoff comes out the rain garden depression when the water level exceeds the storage capacity. In this case, the rain garden is working like an impervious surface. Figure 6.4 illustrates that sometimes a greater reduction in peak discharge is achieve for storms with larger rainfall intensity than other storms that showed a smaller reduction in peak discharge. These cases happened because the antecedent moisture conditions were drier for some storm than others before the storm event occurred. For example, according to figure 6.4, the reduction in peak discharge for 43 millimeters is smaller than the reduction in peak discharge for 53 millimeters. The soil moisture before the 43 millimeters of rainfall was 0.35 m$^3$ and the soil moisture before the 53 millimeters of rainfall was 0.29 m$^3$. Rain gardens can provide greater reduction in runoff when the soil is dry than when the soil is wet or saturated.

In general, rain gardens have the capacity to reduce the peak discharge of stormwater runoff. According to the trendline for each rain garden scenario, the 86% rain garden scenario can reduce the peak discharge approximately 45% for a 2 year storm and 12% for a 10 year storm. The 15% rain garden scenario can reduce the peak discharge approximately 18% for a 2 year storm and 8% for a 10 year storm.

Figure 6.5 shows the volume reduction for the 86% and 15% rain garden scenarios. The results of the model show that the volume reduction depends on the quantity of rain gardens. The reduction of volume increase when the quantity of rain gardens increase. However, the volume reduction for the
86% rain garden scenario and the 15% rain garden scenario is almost the same for large storms events (more than 50 mm per hour) such as the peak discharge reduction.

![Graph showing reduction in volume for 15% and 86% rain garden scenarios.](image)

**Figure 6.5 Reduction in volume for 15% and 86% rain garden scenarios.**

Rain gardens have the capacity to reduce the volume of storm with different magnitude. The reduction of volume decrease when the magnitude of the storm increases. According to the trendline for each rain garden scenario, the 86% rain garden scenario can reduce the volume approximately 40% for a 2 year storm and 8% for a 10 year storm. The 15% rain garden scenario can reduce the volume approximately 16% for a 2 year storm and 3% for a 10 year storm.
Table 6.3 gives the single storm, date, ARI, peak discharge (Qp) and volume for no rain gardens, 15% rain gardens and 86% rain gardens.

### Table 6.3 ARI, peak discharge and volume for single storms

<table>
<thead>
<tr>
<th>Date (m/dd/yy)</th>
<th>60-min Storm (mm)</th>
<th>ARI (years)</th>
<th>Days since last storm</th>
<th>No rain gardens Qp (m³/s)</th>
<th>No rain gardens Volume (m³)</th>
<th>15% rain gardens Qp (m³/s)</th>
<th>15% rain gardens Volume (m³)</th>
<th>86% rain gardens Qp (m³/s)</th>
<th>86% rain gardens Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/31/61</td>
<td>9.652</td>
<td>1</td>
<td>6</td>
<td>0.063</td>
<td>0.067</td>
<td>0.047</td>
<td>0.050</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>5/25/61</td>
<td>13.208</td>
<td>1.04</td>
<td>4</td>
<td>0.095</td>
<td>0.099</td>
<td>0.076</td>
<td>0.078</td>
<td>0.042</td>
<td>0.043</td>
</tr>
<tr>
<td>4/28/74</td>
<td>25.146</td>
<td>1.5</td>
<td>7</td>
<td>0.202</td>
<td>0.205</td>
<td>0.172</td>
<td>0.169</td>
<td>0.106</td>
<td>0.103</td>
</tr>
<tr>
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<td>1</td>
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<td>0.383</td>
<td>0.362</td>
<td>0.368</td>
<td>0.354</td>
<td>0.356</td>
</tr>
<tr>
<td>8/4/61</td>
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<td>10</td>
<td>3</td>
<td>0.482</td>
<td>0.241</td>
<td>0.446</td>
<td>0.223</td>
<td>0.431</td>
<td>0.216</td>
</tr>
</tbody>
</table>

Figure 6.6 Peak discharge coefficient for 15% and 86% rain garden scenarios.
Figure 6.6 illustrate the relation between the peak discharge coefficient and the rainfall intensity for the Oakdale Avenue watershed with (15% and 86% rain garden scenarios) and without rain gardens. The discharge coefficient is defined as the ratio between the peak discharge and the rainfall intensity. This figure shows that the peak discharge coefficient is directly proportional to the rainfall intensity. Peak discharge coefficient increases when the rainfall intensity increases. In addition, rain gardens are able to reduce the peak runoff coefficient. According to figure 6.6, the 86% rain garden scenario reduces the peak discharge coefficient approximately from 0.20 to 0.13 for 30 millimeters of rainfall in one hour. This storm is equivalent to a 2 year storm according to figure 6.2. The 15% rain garden scenario reduces the peak discharge coefficient of the same storm from 0.20 to 0.17. The difference between the 15% and 86% rain garden scenarios in the peak discharge reduction become small for large storms. Figure 6.6 gives an idea about how much the peak discharge can be reduced after the implementation of rain gardens and helps to identify what storm is large enough to see no difference between the original watershed and the watershed with rain gardens.

Figure 6.7 illustrates the relation between the peak discharge coefficient and the soil moisture for the 15% and 86% rain garden scenarios. The saturated soil moisture is $0.48\text{m}^3\text{m}^{-3}$. 

This figure shows that the peak discharge coefficient increases when the soil moisture increases. Figure 6.7 also shows that when the soil moisture increases, the difference of peak discharge coefficient between each rain garden scenario decreases. The antecedent moisture condition of the soil has an important effect in the effectiveness of rain gardens. When the soil is saturated, rainwater starts to fill the rain garden depression. If the storm is extreme, the water could come out of the rain garden. At this point, the rain garden acts like an impervious surface. The rain garden has more infiltration capacity when the soil moisture is dry.

In summary, 15% and 86% rain garden scenarios are able to reduce the peak discharged and volume for ARI storms from 1 year to 10 years. The reduction of peak discharge and volume depend on the quantity
of rain gardens. The reduction increase when the rain garden quantity increases. Rain gardens also can reduce the peak discharge coefficient for ARI storms from 1 year to 10 years. The antecedent moisture condition of rain garden soil has an impact in the rain gardens performance. The infiltration capacity of runoff changes if the soil is dry, wet or saturated.
CHAPTER 7: CONCLUSION AND FUTURE WORK

This chapter presents the conclusions about the results presented in the previous chapters and the possible applications that could benefit from the findings of this research. Future research recommendations that could help improve the methodologies using in this research are also included in this chapter.

The purpose of this research is to describe relations among the percentage of a watershed served by rain gardens, the number of those rain gardens, the effect of antecedent conditions, and the peak discharge of runoff from the watershed for continuous rainfall simulations. This analysis will be performed following a predictive methodology proposed by Christensen 2008. The methodology is implemented by using a physically distributed hydrologic model (Mike SHE) at fine resolution. Mike SHE (MIKE by DHI 2008) is able to simulate the main hydrologic processes of several rain gardens at fine resolution since the model covers the major processes in the hydrologic cycle and their interactions.

Two separate rain gardens site with native vegetation from Madison, Wisconsin with monitored data were simulated at 1m resolution using Mike SHE was able to estimate the main hydrologic processes of rain gardens. The models were calibrated to observed soil moisture data for a long period. The calibration results showed that Mike SHE was able to accurately simulate the soil moisture these rain gardens. In addition, the pond depth’s data estimated by the model were compared to the observed pond depth data. Volume calculations of pond water and cumulative rainfall were also performed. Continuous rainfall simulations were performed to calibrate the single rain garden model.
By comparing simulated results with observed data, was found that Mike SHE provided a reasonable estimate of soil moisture and infiltration processes occurring in these rain gardens.

Results from the two rain garden scenarios incorporated into the Oakdale Avenue watershed model show that rain garden have a relative significant impact on the reduction of peak discharge and runoff volume depending on the magnitude of the storm and the quantity of rain gardens. The peak discharge reduction ranges from 100% to 10% for the 86% rain garden scenario and from 32% to 5% for the 15% scenario. The volume reduction ranges from 100% to 10% for the 86% rain garden scenario and from 30% to 5% for the 15% rain garden scenario. Rain garden scenarios have an impact on reducing the peak discharge coefficient of the watershed. The antecedent moisture condition of rain garden soil has an impact on the rain gardens performance. The infiltration capacity of runoff changes if the soil is dry, wet or saturated.

An important finding from the model is that the 15% and 86% rain garden scenarios produced noticeable peak discharge and volume reductions for ARI storms from 1 year to 10 years. The reduction of peak discharge and volume is small after ARI storms larger than 10 years and the reduction by each scenario is almost the same.

In general, the results show that small scale, distributed stormwater management practices like rain gardens can reduce peak discharge and volume for a range of storm events. This research provides results that demonstrate both, the effectiveness of rain gardens in mitigating runoff and also the danger of relying on them for runoff control for large storms. Also, the effectiveness of rain gardens showed to be inversely proportional to the soil moisture, when it reflects recent history of precipitation. This study was performed in the Oakdale urban watersheds in Chicago, IL. Generalization of these results cannot
be made but, it is possible get an idea of the benefits of rain gardens implemented in urban watershed similar to the Oakdale urban watershed.

The effect of rain gardens and other BMPs such as, green roofs, bioswales, and porous pavement can be implemented in urban watershed by using the same methodology used in this research. Soil profiles representing bioswales, porous pavement or green roofs can be created by using Mike SHE and their effects in urban hydrology can be estimated. Different scenarios and quantities of these BMPs can be made and simulated by using this methodology.

Other research topics could be: to perform an uncertainty analysis of the results estimated by a Mike SHE model, to compare results of different models such as Hec-HMS or SWMM with Mike SHE results, study the performance of BMPs during the winter season, and test different engineered soils to compare which could be more efficient for runoff retention.

Monitoring of BMPs and other physical characteristics on urban watershed should be monitored. The monitored data can be very useful to validate models for a range of different cases and facilitate the development of new researches topics.
REFERENCES


Kristensen, K. J. and Jensen, S. E. (1975). “A model for estimating actual evapotranspiration from potential evapotranspiration.” Royal Veterinary and Agricultural University, Nordic Hydrology 6, pp. 170-188.


Yan J. and Zhang J. (1998)."Evaluation of the MIKE SHE modeling system” *American Society of Agricultural Engineers (ASAE) conference.*


### Table A1. Old Sauk native vegetation soil description

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<th>Comments (brief)</th>
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### Table A2. Owen native vegetation soil description

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### Table A4. Sewer network data (Chow and Yen 1976)

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### Table A5. Alley drainage data (Chow and Yen 1976)

#### Alleys between Welling and Oakdale

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#### Alleys between Oakdale and George

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### Table A6. Inlet data (Chow and Yen 1976)

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**Figure A1.** Example of flow data from recorder (Tucker 1968).
Figure A2. Schematic of flow vault and recording system (Tucker 1968).
Figure A3. Flow measurement vault details (Tucker 1968).
Figure A4. Vault pipe details (Tucker 1968).
RAINFALL AND RUNOFF FROM STORM OF
MAY 19, 1959

(* For additional details on runoff see Figure B1.)

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<th>Runoff, cfs</th>
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