EXPLORING THE RESPONSE OF URBAN STORM SEWER SYSTEM TO THE IMPLEMENTATION OF GREEN ROOFS

BY

YUN TANG

THESIS

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Adviser:

Research Assistant Professor Arthur R. Schmidt, P.E.
ABSTRACT

With the increasing popularity of Best Management Practices (BMPs), research about the effect of BMP implementation on the hydrologic response of urban watersheds has become a hot topic. Green roofs, which have been reported as an effective means of reducing urban storm water runoff, have been widely used in Europe and are gaining increasing attention in the US. This thesis presents a method to study the changes of urban catchment runoff behavior from green roof implementation. The proposed method takes into account the thresholds in green roof response and abrupt changes in areal characteristics for better understanding of urban catchments. This allows the method to correctly scale various types of green roofs, and ultimately other BMPs, for a range of storm characteristics and BMP implementation.

This study used the Illinois Urban Hydrologic model (IUHM) as a base model for urban sewer system, except that the IUHM model was modified to allow the overland flow to be routed from impervious to pervious areas. A mathematical model was developed to simulate the major processes affecting the hydrologic response of green roofs (ponding, infiltration, drainage, and recession). The green roof model was calibrated to match the runoff observed from the green roof on the Business Instructional Facility (BIF) at the University of Illinois campus. The green roof model was incorporated into the probabilistic IUHM model by coupling the hydrologic response of the green roof from the green roof model with the probability of rain falling on a green roof and the probability of the green-roof runoff following different possible paths to the watershed outlet. The modified IUHM model, herein named Combined IUHM-Green Roof Model
(CIGM) was used to test green roof impact on hydrologic response at the catchment scale, with the green roof coverage ranging from 10% to 40% of the impervious area of the whole watershed. Two hypothetical storms (a uniform storm with an intensity of 7.62 mm/hr for 2 hours, and a 5yr Average Return Interval storm for 2 hours,) and two real storms (a January 2008 storm, and a July 2007 storm) were used in the model to test green roof performance under different rainfall types. A SWMM model was also developed and used for comparison purpose.

Results indicate that the implementation of green roofs has a distinct effect on decreasing the volume and peak of storm water runoff and postponing the time to peak runoff. The volume and peak discharge reduction depends on the temporal distribution of rainfall as well as the volume of rainfall and green roof coverage. The model also shows that routing overland flow from impervious to pervious areas can significantly reduce the catchment outflow and postpone the time to peak discharge. This overland flow routing alteration shows an even bigger effect on catchment outflow response than the change of green roof coverage does. In addition, catchment outflow can be further decreased by routing green roof runoff to pervious areas rather than impervious areas.
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# TABLE OF CONTENTS

LIST OF FIGURES ................................................................. vi
LIST OF TABLES ................................................................. viii
LIST OF SYMBOLS ............................................................... ix

CHAPTER 1: INTRODUCTION ...................................................... 1
  1.1 Background ........................................................................ 1
  1.2 Motivation ......................................................................... 2
  1.3 Thesis Objective and Scope of Research ......................... 5
  1.4 Outline of Thesis ............................................................ 6

CHAPTER 2: LITERATURE REVIEW .............................................. 7
  2.1 Green Roofs ................................................................. 7
  2.1.1 Working Mechanisms in Green Roofs ......................... 8
  2.1.2 Previous hydrologic/hydraulic modeling of Green Roofs ...... 9
  2.2 Previous Research about other BMP Implementation ........ 14
  2.3 Illinois Urban Hydrologic Model (IUHM) ......................... 17

CHAPTER 3: METHODOLOGY .................................................... 23
  3.1 Physical Mechanisms ...................................................... 23
  3.2 Modeling Approach ....................................................... 29
  3.2.1 Green Roof Modeling .................................................. 31
  3.2.2 IUHM Modification for Overland Flow Routing ............ 42
  3.3 SWMM Comparison ....................................................... 44

CHAPTER 4: CASE STUDY ......................................................... 47
  4.1 BIF Green Roof ............................................................ 47
  4.2 Rainfall Events ............................................................. 48
  4.3 Calumet Drop Shaft 51 Catchment (CDS-51) .................. 52
  4.4 Simulation of CDS-51 .................................................... 56
  4.5 SWMM set up for CDS-51 ............................................... 60
  4.6 Result Analysis ............................................................. 64
  4.6.1 Green Roof Model ..................................................... 65
  4.6.2 Effect of Overland Flow Routing ................................. 72
  4.6.3 Catchment Response under Different Green Roof Scenarios ... 76
  4.6.4 SWMM Comparison ................................................... 91

CHAPTER 5: CONCLUSION AND FUTURE WORK ....................... 98
  5.1 Conclusion ..................................................................... 98
  5.2 Limitation and Future Work ........................................... 98

REFERENCES ........................................................................ 101

Appendix A ............................................................................. 104
LIST OF FIGURES

FIGURE 1. A TYPICAL EXAMPLE STRUCTURE OF GREEN ROOFS (DRIVE2.SUBARU.COM, 2011) .......................................................... 7
FIGURE 2. SCHEMATIC OF FLOW DIAGRAM WITH INCORPORATION OF GREEN ROOF MODEL WITHIN IUHM MODEL .......................................................... 25
FIGURE 3. PHOTOGRAPH SHOWING THE GREEN ROOF ON BIF BUILDING IN UIUC (HOLLOWAY, 2009) .......................................................... 32
FIGURE 4. PLAN VIEW OF GREEN ROOF ON BIF BUILDING IN UIUC (NOT TO SCALE) (HOLLOWAY, 2009) .......................................................... 33
FIGURE 5. CROSS SECTION OF GREEN ROOF ON BIF BUILDING IN UIUC (NOT TO SCALE) (HOLLOWAY, 2009) .......................................................... 33
FIGURE 6. FLOW CHART OF THE GREEN ROOF MODEL .......................................................... 41
FIGURE 7. SCREEN SHOT OF THE SWMM MODEL FOR CDS-51 .......................................................... 45
FIGURE 8. SCREEN SHOT OF LID TOOLS IN SWMM5 (UNITS ARE MM AND MM/HR) .......................................................... 46
FIGURE 9. A UNIFORM RAINFALL EVENT WITH AN INTENSITY OF 7.62 MM/HR FOR 2HRS (YEN AND CHOW, 1980) .......................................................... 49
FIGURE 10. A 5YR ARI STORM, 2HRS (YEN AND CHOW, 1980) .......................................................... 49
FIGURE 11. JANUARY STORM, 2008 (DOLTON, IL) .......................................................... 51
FIGURE 12. JULY STORM, 2007 (DOLTON, IL) .......................................................... 51
FIGURE 13. PIPE SYSTEM PLAN VIEW OF CDS-51 CATCHMENT (CANTONE, 2010) .......................................................... 53
FIGURE 14. LAND FEATURES OF CDS51 CATCHMENT (GOOGLE MAP, 2011) .......................................................... 57
FIGURE 15. LAND LAYOUT OF A TYPICAL NEIGHBORHOOD IN CDS 51 CATCHMENT (GOOGLE MAP, 2011) .......................................................... 58
FIGURE 16. PARAMETERS OF SUBCATCHMENT 1 IN SWMM .......................................................... 63
FIGURE 17. LID SETTINGS OF SUBCATCHMENT 1 IN SWMM (20% GREEN ROOF COVERAGE) .......................................................... 63
FIGURE 18. LID SETTINGS OF SUBCATCHMENT 1 IN SWMM (20% GREEN ROOF COVERAGE) .......................................................... 64
FIGURE 19. CALIBRATION FOR SEPTEMBER 22 STORM, 2010 .......................................................... 67
FIGURE 20. CALIBRATION FOR AUGUST 20-21 STORM, 2010 .......................................................... 67
FIGURE 21. MODELED GREEN ROOF RUNOFF UNDER UNIFORM STORM .......................................................... 68
FIGURE 22. MODELED GREEN ROOF RUNOFF UNDER 5YR ARI STORM .......................................................... 69
FIGURE 23. MODELED GREEN ROOF RUNOFF UNDER JANUARY 2008 STORM .......................................................... 71
FIGURE 24. MODELED GREEN ROOF RUNOFF UNDER JULY 2007 STORM .......................................................... 71
FIGURE 25. OUTFLOW COMPARISON BETWEEN PERV_IMP AND IMP_PERV UNDER NON-GREEN ROOF SCENARIO .......................................................... 73
FIGURE 26. OUTFLOW COMPARISON BETWEEN PERV_IMP AND IMP_PERV UNDER NON-GREEN ROOF SCENARIO .......................................................... 73
FIGURE 27. OUTFLOW COMPARISON BETWEEN PERV_IMP AND IMP_PERV UNDER NON-GREEN ROOF SCENARIO (JAN STORM) .......................................................... 74
FIGURE 28. OUTFLOW COMPARISON BETWEEN PERV_IMP AND IMP_PERV UNDER NON-GREEN ROOF SCENARIO (JULY STORM) .......................................................... 74
FIGURE 29. CIGM OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE UNDER PERV_IMP OVERL AND FLOW ROUTING OPTION (UNIFORM STORM) .......................................................... 76
FIGURE 30. CIGM OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE UNDER PERV_IMP OVERL AND FLOW ROUTING OPTION (5YR ARI STORM) .......................................................... 77
FIGURE 31. CIGM OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE UNDER PERV_IMP OVERL AND FLOW ROUTING OPTION (JAN STORM) .......................................................... 77
FIGURE 32. CIGM OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE UNDER PERV_IMP OVERL AND FLOW ROUTING OPTION (JULY STORM) .......................................................... 78
FIGURE 33. OUTFLOW VOLUME REDUCTION RATE VERSUS DIFFERENT GREEN ROOF COVERAGE UNDER PERVIOUS-IMPERVIOUS OVERLAND RUNOFF ROUTING OPTION 79
LIST OF TABLES

TABLE 1. WATER MASS BALANCE FOR GREEN ROOF IMPLEMENTATION ........................................28
TABLE 2. INPUT PARAMETERS FOR THE GREEN ROOF MODEL .................................................48
TABLE 3. INPUT PARAMETERS FOR ONE SCENARIO OF CDS51 CATCHMENT ..............................55
TABLE 4. ALL SCENARIOS RUN IN CIGM ..............................................................................60
TABLE 5. INPUT PARAMETERS OF GREEN ROOF IN SWMM MODEL .......................................61
TABLE 6. CALIBRATION PARAMETERS IN GREEN ROOF MODEL ............................................66
TABLE 7. GREEN ROOF RESPONSE UNDER THE UNIFORM STORM AND THE 5YR ARI STORM ..................................................................................................................70
TABLE 8. GREEN ROOF RESPONSE UNDER THE JAN 2008 STORM AND THE JULY 2007 STORM .........................................................................................................................72
TABLE 9. OUTFLOW COMPARISON BETWEEN THE TWO OVERLAND FLOW ROUTING OPTIONS .......................................................................................................................75
TABLE 10. OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE CONDITIONS UNDER PERVIOUS-IMPERVIOUS OVERLAND RUNOFF ROUTING OPTION ............................................................................................................79
TABLE 11. OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF RUNOFF ROUTING OPTIONS (20% GREEN ROOF COVERAGE, PERVIOUS-IMPERVIOUS OVERLAND RUNOFF ROUTING) ....................................................................................................................85
TABLE 12. OUTFLOW COMPARISON BETWEEN DIFFERENT GREEN ROOF COVERAGE CONDITIONS UNDER IMPERVIOUS-PERVIOUS OVERLAND RUNOFF ROUTING OPTION ..................................................................................................................88
TABLE 13. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER NON-GREEN ROOF SCENARIO FOR JAN 2008 STORM .................................................................92
TABLE 14. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER NON-GREEN ROOF SCENARIO FOR JULY 2007 STORM ........................................................................92
TABLE 15. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER 20% GREEN ROOF SCENARIO FOR JAN 2008 STORM .................................................................94
TABLE 16. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER 20% GREEN ROOF SCENARIO FOR JULY 2007 STORM ........................................................................94
TABLE 17. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER 40% GREEN ROOF SCENARIO FOR JAN 2008 STORM ........................................................................96
TABLE 18. OUTFLOW COMPARISON BETWEEN CIGM AND SWMM UNDER 40% GREEN ROOF SCENARIO FOR JULY 2007 STORM ........................................................................96
LIST OF SYMBOLS

\[ A \]  total area of the catchment

\[ A_{hs}(h) \]  area of the cross section

\[ A_{oi} \]  original area of impervious area

\[ A_p \]  area of pervious area

\[ A_s \]  green roof area

\[ A_{in} \]  new impervious area

\[ A_v \]  area of the vegetated bed, square inch

\[ a \]  drain coefficient for pre-saturated drainage from the green roof

\[ a_i \]  scaling factor for the travel time within a successive \( i \)th-order conduit

\[ B_{hs}(h) \]  surface width of the channel

\[ b \]  drain exponent for pre-saturated drainage from the green roof

\[ c \]  drain coefficient for flow through the gravel layer to the drain

\[ C_d \]  weir coefficient, \( C_d = 3.33 \)

\[ D \]  depth of growth medium, inch

\[ d \]  drain coefficient for flow through the gravel layer to the drain

\[ F \]  cumulative infiltration

\[ f_{x_k}(t') \]  travel time probability-density-function (PDF) in state \( x_k \)

\[ f(t) \]  actual infiltration capacity at time \( t \), inch/hr;

\[ f_p(t) \]  potential infiltration capacity at time \( t \), inch;
\( F(t) \)  
accumulated infiltration at time \( t \), inch/hr

\( G_r \)  
volume of water retained by green roofs

\( G_f \)  
volume of green roof runoff

\( h \)  
flow depth

\( h_v \)  
height difference between vegetated bed surface and the wall, inch

\( h(t) \)  
ponding depth at time \( t \), inch

\( I_a \)  
initial abstractions

\( i(t) \)  
rainfall intensity at time \( t \), inch/hr

\( K \)  
saturated hydraulic conductivity of the growth medium, inch/hour;

\( L \)  
weir length, inch

\( N \)  
number of successive \( i \) th-order conduits

\( p\% \)  
percentage of the green roof runoff routed to impervious area

\( P(\omega) \)  
probability of a drop of water following this path

\( P_{OAi} \)  
initial state probability

\( P_{x_{oi}, perv} \)  
probability that a drop of rainfall will fall on a pervious region

\( P_{x_{oi}, imp} \)  
probability that a drop of rainfall will fall on an impervious region

\( P_{x_{oi}, perv, x_{oi}, imp} \)  
probability that a drop of rainfall transits from a pervious area to an impervious area

\( P_{x_{oi}, imp, x_{oi}, imp} \)  
probability that a drop of rainfall transits from an impervious area to an \( i \) th-order conduit
\( P_{x_i^c x_j} \) probability that a drop of water transits from an \( i \) th-order conduit to a \( j \) th-order conduit

\( P_{x_i^c x} \) probability that a drop of water travels through \( n \) successive \( i \) th-order conduits

\( Q(t) \) direct runoff hydrograph for the catchment

\( q_{L_w}(t) \) equivalent pervious excess rainfall

\( q_o(t) \) overflow runoff intensity at time \( t \), inch/hr

\( q_u(t) \) underflow intensity at time \( t \), inch/hour

\( q_{gr}(t) \) equivalent green roof runoff intensity at time \( t \), inch/hour

\( q(t) \) runoff intensity from gravel bucket, inch/hour

\( R_{io} \) volume of rainfall falling on impervious area

\( R_p \) volume of rainfall falling on pervious area

\( R_t \) total volume of rainfall

\( R_g \) volume of rainfall falling on green roofs

\( R_{in} \) volume of rainfall falling on the new reduced impervious area

\( R_{h} \) hydraulic radius

\( S_A(t) \) soil water storage per unit area in green roof bucket at time \( t \), inch

\( S_B(t) \) soil water storage per unit area in gravel bucket at time \( t \), inch

\( S_f \) suction head, inch

\( sc \) scaling factor, equal to Area of vegetated beds/Area of gravel zone
\( \bar{T}_w(t) \) total travel time of a raindrop moving through path \( w \) to the outlet

\( \bar{T}_{x_k} \) mean travel time

\( t \) time associated to the rainfall intensity

\( t' \) time associated with the ravel time PDF.

\( WI \) water input to the overland area.

\( W \) path space

\( x_{oi} \) an overland state

\( x_{ci} \) a conduit state

\( \theta_s \) saturated volumetric water content, decimal fraction

\( \theta_i \) initial volumetric water content, decimal fraction

\( \Delta t \) time step, hour.

\( \lambda \) recession coefficient for recovery of infiltration capacity of the green roof

\( \omega \) a specific path

\( \mu_{x_k} \) kinematic wave celerity of a flood wave
CHAPTER 1: INTRODUCTION

1.1 Background

As cities continue to grow, urban landscapes are constantly changing to have far more impervious area than natural watersheds. Typical impervious area in cities includes buildings, roads, and parking lots. Their sealing effects result in several environmental problems within urban catchments, such as storm water flooding and heat island effect. Storm water flooding has become an issue of major concern in the U.S., and worldwide, especially in large cities with dense population and frequent rainfall events (Hilten et al, 2008). Since an impervious area does not allow water to penetrate into the soil, the increase of impervious regions from urban sprawl leads directly to considerable increase of storm water volume reaching municipal storm sewers, and ultimately local waterways. For example, when large storm events occur in Chicago, the combined sewer system in the city cannot handle the volume of water, resulting in ponding, inlet surge, basement flooding, combined-sewer overflow into the waterways, and during some extreme events, into Lake Michigan. The pollutants carried in the sewers directly threaten the health of local water resources.

Due to these side effects brought by urban expansion, various sustainable development strategies, such as rain gardens, rain barrels, vegetated swales, green roofs and permeable pavements, have been researched to help manage storm water (USEPA, 2000). Green roof technology has become a popular strategy for retaining rainfall and reducing storm runoff peak flows, especially in ultra-urban areas where space is too limited to implement
other best management practices (BMPs) (Hilten et al, 2008). Storm water runoff can be retained and mitigated by green roofs because the growth medium can hold water and slowly release it later, either as subsurface drainage or by evapotranspiration. Many incentive programs have been implemented in the United States to encourage application of green technology to help control the impact of storm water runoff. For example, home owners in the city of Seattle can get an exemption from storm water management tax, or receive credits of flow control if they implement green roofs in their properties (She and Pang, 2010).

1.2 Motivation

Because of the increasing popularity of green roof technology, the impact of green roof implementation in urban watersheds has become a hot research topic. Several studies examined the hydrologic response of a single green roof (Hilten et al, 2008; Kasmin et al, 2010; She and Pang, 2010). The effect of green roofs on a larger scale has also been studied by various methods. For example, Cater and Jackson (2006) used the Soil Conservation Service (SCS) Curve Number (CN) method as the infiltration and runoff model to test green roof impact at multiple spatial scales. Sherrard (2007) built a simple bucket model for a single green roof and extrapolated it to an urban scale to test its stormwater reduction effects. Details about the existing work are provided in Chapter 2 “Literature Review”.

Most of the existing research about BMP implementation typically used a lumped modeling approach. The lumped modeling approach uses average coefficients to represent a relatively large area as a single homogeneous area. While the size of the area
depends on the decisions of the model developer, the area is large enough that multiple heterogeneous components (e.g., pervious and impervious areas) are lumped together with a coefficient such as percent imperviousness. This process diminishes the ability of the model to discern the effects of the heterogeneity and discontinuity of land surfaces in different spatial scales.

Another issue is that existing research has given little consideration about the thresholds existing in green roof performance. For small storms, green roofs behave as pervious area. However, once the soil is saturated green roofs behave as impervious. A threshold exists between these two behaviors and it will have an impact on the hydrologic response of the catchment. Accounting for these thresholds of green roof performance and how these affect the hydrologic response of an urban watershed is another important aspect of green roof performance that will be examined in this thesis.

The motivation for this thesis is to present a method to better understand the issues discussed above. How to effectively and correctly evaluate the effects of green roofs on the hydrologic response of urban catchments, giving full consideration to scaling, heterogeneity and thresholds, is the primary focus of this study. The approach of this study is to develop tools to simulate the hydrologic response of small-scale BMPs—specifically, green roofs—and incorporate these into an urban watershed model that can effectively solve the heterogeneity problem of land surfaces. The urban watershed model chosen for this study is the Illinois Urban Hydrologic Model (IUHM).
Unlike a lumped modeling approach which resorts to assumptions about averaging or changing areal coefficients, the approach in this study allows the modeler to subdivide an urban catchment into representative homogeneous areas. IUHM simulates the response of those areas (hence accounting for thresholds) and combines these responses probabilistically to simulate the catchment response. IUHM takes account of heterogeneity and areal characteristics efficiently because of the following reasons. First, it uses probabilistic techniques to quantify the relation between variables at different scales. This enables the model to describe complex heterogeneity within sub-catchments in different scales. Second, the geomorphologic dispersion due to the heterogeneity of path length in the network is taken into consideration by the travel time distribution. Third, IUHM was designed in a way that “it could be used in such situations under the hypothesis that the mean and variance of the input parameters could be determined using only a sub-set of the full deterministic dataset” (Cantone, 2010). Thus by changing categorizing/subdividing the watershed, modelers can reduce the heterogeneity within subcatchments. Therefore, due to the effective consideration of scaling and heterogeneity, IUHM provides a perfect platform to describe the effect at the catchment scale of incorporation of small-scale hydrologic processes, like BMPs.

Most existing catchment modeling approaches, including IUHM, are built with an assumption that the overland flow is routed from pervious area to impervious area. This assumption was made based on the fact that most cities were built this way. However, the increasing popularity of various green technologies, (e.g. rain gardens, grass swales, etc.), begins to change this situation. Many green stormwater technologies route runoff from
impervious area to pervious area, thus the real overland flow routing includes two conditions: (1) from pervious area to impervious area, and (2) from impervious area to pervious area. In this study, IUHM will be modified to release the restriction that the overland flow can only be routed from pervious area to impervious area. It will allow both of those two routing methods in the same simulation.

1.3 Thesis Objective and Scope of Research

The purpose of this thesis is to develop a method to research and quantify the changes of urban catchment runoff behavior from implementing green roofs. This method will explicitly account for thresholds in green roof response and abrupt changes in areal characteristics rather than resort to assumptions such as averaging or changing model coefficients. This will allow the method to correctly scale various types of green roofs and ultimately other BMPs for a range of storms and BMP implementation.

The scope of this thesis is limited to green roofs and disconnection of impervious areas. A mathematical model for green roofs was developed and calibrated by the observed rainfall-runoff data from the green roof on the Business Instructional Facility (BIF) building, which is located on campus of University of Illinois at Urbana-Champaign (UIUC). The original IUHM model was modified to account for both pervious-impervious and impervious-pervious overland flow routing. The green roof model was then incorporated into the modified IUHM model to test the impact of green roof implementation hydrologic response at the catchment scale. A case study was done by using the Calumet Drop Shaft 51 (CDS-51) catchment (located in the Village of Dolton, IL) as an example. A SWMM model for CDS-51 was also developed, including the
integration of green roofs through LID control tool. This SWMM model was used for the purpose of comparing with the results obtained with the IUHM model.

1.4 Outline of Thesis

Chapter 2 provides a literature review of previous research available that is pertinent to the scope of this thesis, including IUHM, modeling green roofs and implementation of other BMPs. Chapter 3 discusses in detail the methodology used in developing the green roof model, modifying the original IUHM, and incorporating the green roof model within modified IUHM. Chapter 4 gives a case study by using CDS-51 as an example. Chapter 5 presents the conclusion, limitation and future research.
CHAPTER 2: LITERATURE REVIEW

2.1 Green Roofs

A green roof is a vegetated soil system built on the roof of a building. Its structure may vary but almost always has six basic components: (1) the roof deck, (2) a waterproofing/root barrier/roof membrane, (3) a drainage layer, (4) a geotextile filter fabric, (5) a growing media or substrate, and (6) plants or vegetation (Liu, 2006; Mentens et al., 2006; Cantor, 2008; Bliss et al., 2009). It may also include additional layers such as insulation, vapor control or support panels. Figure 1 shows the green roof structure with the basic six components described above.

Figure 1. A typical example structure of green roofs (drive2.subaru.com, 2011)
2.1.1 Working Mechanisms in Green Roofs

Green roofs can partially or completely cover the roof area. Pioneering researchers usually divide green roofs into two categories based on the depth of the growing medium and the need of maintenance:

(1) Extensive green roofs, with shallow soil depth and minimum maintenance needs. They are relatively self-sustaining, and the plant types are usually sedum species.

(2) Intensive green roofs, with greater depths of growing medium and bigger plants such as shrub and trees. They are more labor-intensive and usually can be accessed for maintenance (Peck and Kuhn, 2004; Mentens et al., 2006; Cantor, 2008).

Green roofs have many environmental and financial benefits for urban catchments, like reducing heat-island effect and providing insulation, but in this study we only focus on the advantage they bring along for stormwater management. Green roofs can help with the following aspects of managing stormwater: (1) postponing the starting time of runoff because green roofs can store a certain amount of water; (2) decreasing the peak and total runoff by retaining part of rainfall in the soil medium; (3) distributing the runoff over a longer period due to a relative slow release of the excess water (Mentens et al, 2006; Hollander, 2007; Holloway, 2009).

Green roofs have been a popular form of sustainable storm water management in European countries, such as Germany, Switzerland and Austria for several decades
(USEPA, 2000; Mentens et al., 2006). They are relatively new to the US but are gaining more attention recently because of their special advantage over other BMPs, space efficiency. This is especially important for older cities that have been developed for a long time. The space in the urban area, especially in downtown areas, is very limited for implementation of other BMPs, such as retention ponds and grassed swales (Hilten et al., 2008). Green roofs, on the other hand, simply use the current roof area without occupying additional space. This directly converts the impervious area covered by green roofs to a stormwater management area. Green roofs have been reported to be quite effective in reducing combined sewer overflows, even in older urban areas (USEPA, 2000; Bliss et al., 2009).

2.1.2 Previous hydrologic/hydraulic modeling of Green Roofs

Literature review suggests that current modeling methods for green roofs mainly fall into four categories: (1) curve number (CN) methods that rely on statistical analysis of runoff collected at experiment stations; (2) physical models developed for groundwater applications that solve the field equations for unsaturated flow; (3) analytical models that treat green roofs as a combination of linear storage reservoirs; (4) water-balance models that treat green roofs as simple reservoirs with restricted outlets (Zimmer and Geiger 1997; Jarrett et al. 2007; Hilten et al. 2008; She, 2010). There are also some other modeling methods. For example, Hollander (2007) used a modified Green-Ampt method and a physical model to research the effect of green roof implementations; She and Pang (2010) constructed a physics-based model in FORTRAN to simulate rain water movement with green roof medium. Details will be given in the following paragraphs.
Carter and Jackson (2006) used the Soil Conservation Service (SCS) CN method as the infiltration and runoff model to test green roof impact at multiple spatial scales in Athens, Georgia. The modeling was performed using StormNet Builder, a stormwater modeling software package, which uses EPAs SWMM5.0 analysis engine and CN infiltration method for routing runoff through a watershed (BOSS International, 2005; Cater and Jackson, 2006). Green roofs were implemented in the model by assigning a CN of 86 to green roofs while giving a CN of 98 to impervious area and 84 to pervious area. Model storms were a Type II rainfall distribution for various 24h design storms. They found that for large storms (storms that are greater than the 2-year-24-h event) the stormwater reduction was minimal even if vegetated roofs were widely implemented. On the other hand, for rainfall events smaller than 2.54cm (1in), green roofs had a noticeable effect on reducing stormwater runoff across the watershed (Cater and Jackson, 2006).

Hollander (2007) proposed a mathematical rainfall/runoff modeling method for green roofs and researched the effect of green roof implementations. The main objective of the study was to develop a simple, well-understood and widely available method to estimate the hydrologic benefits of green roofs. In this study, the hydrologic effects of green roofs were modeled at a roof scale using both a modified Green-Ampt method and the Illinois Urban Drainage Simulator (ILLUDAS) model. The results from the modified Green-Ampt model were used to optimize the parameters used in the ILLUDAS model to provide the best simulations of the effect of a single green roof over a range of storm conditions. The resulting optimized parameters were then used to apply ILLUDAS to simulate the effects of green roofs at a watershed scale. The modeling process used a set
of 24-minute-triangular hyetograph storms with total rainfall ranging from 0.76 to 3.81cm (0.3in to 1.5in) and a set of NRCS Type II 24 hour storms with total rainfall varying from 2.54 to 12.7cm (1in to 5in). The green roof coverages ranged from 0% to 100%, with the increments being 0%, 9%, 18%, 27%, 50% and 100% of the entire basin. The ILLUDAS modeling results indicated that green roofs resulted in reductions in both the volume and peak discharge of runoff for all storms and intensities, and with the largest effect happening during small storms and large green roof coverage scenarios. The model also showed that for a neighborhood-block scale, the volume and peak discharge (expressed as a percentage of the runoff volume and peak discharge for the scenario with no green roofs) decreased with the increase of green roof coverage at almost identical rates for the smallest 2.54cm storm, but the volume decreased at a much greater rate than the peak discharge did in a larger storm (e.g., for an increase in green roof coverage from 18% to 27%, the percent reduction of volume was three times greater than the reduction in peak discharge for a 12.7cm storm).

Sherrard (2007) built a simple bucket model for a single green roof and extrapolated it to an urban scale to test its stormwater runoff reduction effects. In this study the single green roof model result was extrapolated to the urban catchment by simply combining the volume reduction of stormwater from a single green roof and the available roof area of the urban watershed. The model was run for an 8-year period (January 2002 through December 2009) using atmospheric data from two nearby weather stations for that period. Sherrard found that the city of Portsmouth, NH, could expect approximately 15,000 m³
of stormwater volume reduction per year if all flat rooftops were covered with vegetated roofs.

Hilten et al. (2008) conducted a study on the effectiveness of green roofs to mitigate stormwater runoff by using HYDRUS-1D, which is a modeling environment for analysis of water flow and solute transport in variably saturated porous media. In this study, the stormwater performance was simulated for a modular block green roof with simulation results verified by study site data. The total area of the study site was 37 m², which was composed of 100 square aluminum green roof blocks, and the dimensions of each block were 60×60×10 cm. Three 1.0 cm diameter drains were located along each side of all the individual blocks approximately 1.0 cm above the base of the block. Simulations were run using HYDRUS-1D for SCS 24-h design storms to determine peak flow, retention and detention time for runoff. The study revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation, providing complete retention of small storms (<2.54 cm) and detention for larger storms, assuming initial soil moisture content as 0.1.

She and Pang (2010) constructed a physics-based green roof model in FORTRAN to simulate rain water movement within the medium of green roof. The objective of their study was to develop a physically based model that can capture the primary hydrologic and hydraulic processes of a single green roof. The hydrologic and hydraulic processes of green roofs were modeled using three submodules: an evapotranspiration module, an infiltration module, and a flow routing module. The evapotranspiration module simply
sets evapotranspiration to zero during rainfall period and takes the form of an exponential decay with moisture content during dry periods. The infiltration module was composed of three components: drainage and advance of wetting front (based on modified Green-Ampt equations (Mein and Larson 1973; Chow et al. 1988)); medium saturation (based on Darcy’s law); and recession (based on exponential decay). The evapotranspiration and infiltration modules were written in FORTRAN and output a text file in SWMM5 format, which was then imported to the SWMM5 RUNOFF module to generate runoff. The model was calibrated using more than three years of data from the green roof of Hamilton Building of Portland, Oregon. The study site green roof has an area of about 243.4 s m\(^2\) (2,620 sq ft) and a slope of 2.1% (Hutchinson et al. 2003). The precipitation data used were from a 5-min precipitation record collected by a rain gauge on the top of Hamilton Building from 12/27/2001 to 01/04/2005. Two events from this record were chosen and simulated, and also the whole series was simulated. Results showed that the absolute error between simulated and observed total flow volume is about 10% for the entire record, which She and Pang (2010) indicated was acceptable for simulating both events and continuous records.

Kasmin H. et al. (2010) built a simple conceptual model for green roof hydrological processes to reproduce monitored data for both single storm events and a long-term simulation period. The model comprises a substrate moisture storage component and a transient storage component. Storage within the substrate represents the roof’s overall storm water retention capacity. Following a storm event the retention capacity is restored by evapotranspiration (ET). The model was calibrated by comparing modeled and
monitored runoff under a large storm event that happened in June 13-16, 2007. The study mainly concentrated on finding a robust method to identify monthly ET values. Analysis suggested that ET falls below 1mm/day for much of the year under UK climatic conditions.

2.2 Previous Research about other BMP Implementation

Villarreal et al (2004) investigated the effect of disconnecting impervious areas from a combined sewer in favor of a new open stormwater system. In the system, several kinds of BMPs, including green roofs, open channels and detention ponds were researched both individually and together. The objective was to find the best coupling of BMPs to achieve the best use of available space and to maximize water handling. The system was tested by comparing a number of design-storms (recurrence intervals: 1/2, 2, 5 and 10-years) assuming wet and dry initial conditions. The time-area method was used to simulate direct runoff, and PondPack (Haestad Methods, 2002) was used to route water through the BMPs. A composite runoff coefficient was defined for each area contributing to the BMPs based on areal weightings. For the non-green roof scenario this coefficient was estimated by measuring the retention capacity of the green roofs. By changing the composite runoff coefficient to simulate the absence of green roofs and comparing the amount of runoff to the scenario with green roofs for each recurrence interval, the effect of green roofs were studied. This simple analysis found that green roofs are effective at lowering the total runoff. For the 0.5 year return period, the greatest percent retention achieved by green roofs was 34%, while for the 10 year storm produced this effect was 15%.
Zhen et al (2006) developed a land-use based BMP analysis model to identify the most cost-effective combinations of management practices to help minimize combined sewer overflow (CSO) by simulating various BMPs, including bio-retention basins, green roofs, filters, swales, and rain barrel systems. The major components of this model included an ArcGIS interface that could provide GIS-based visualization and support for developing a catchment network, a process-based BMP simulation module that provided a technique that was sensitive to local climate and rainfall patterns, and an optimization component that used a meta-heuristic optimization technique. The BMP module can process infiltration, orifice outflow, controlled orifice release, weir-controlled overflow spillway, under-drain outflow, bottom slope influence, bottom roughness influence, general loss or decay of pollutant, pollutant filtration through soil medium, and evapotranspiration. Users can choose each type of BMPs by defining the processes described above. A case study was done for a highly developed residential area of two city blocks draining to Anacostia River, located in Washington, DC. The case study showed that green roofs were not preferred due to relatively high cost and low efficiency for reducing runoff, and rain barrels may not be a good choice for a site with substantial area to apply infiltration practices, such as bio-retention cells.

Hollander et al (2006) developed a tool to compare the benefits of different BMPs in terms of runoff and discharge levels, detention requirements, and economics on both the lot and 40-acre area scales. The BMPs explored in this study included roadside swales, green roofs, porous pavement, rain gardens, trees, and street and sidewalk reductions.
The tool was made into a website where users can configure a neighborhood by giving values to some defined parameters and also choose any combination of the BMPs. For the individual lot, the curve number (CN) method was used to calculate total runoff; pre-defined values for CN were built into the on-line model for lots with and without various BMPs. The NRCS graphical peak discharge method was used to calculate the peak discharge; the average rational method coefficient was used to calculate other parameters. For the 40ac scale analysis, the Kerby equation (Kerby, 1959) was used to calculate the time of concentration of the overland flow; the rational method for pipe routing (Mays, 2001) was used to route flow from each lot to the detention basin through the pipe network. Results were presented in terms of five parameters, which are total discharge and peak discharge for lot scale results and peak discharge, average decrease in required pipe diameter, and detention Area required for neighborhood scale results. The scenarios using all the five BMPs and the default lot layout values were run and showed that all the scenarios benefit from BMP techniques, with a given parameter reducing by 10%-30%. Furthermore, the benefits increase as a neighborhood becomes more developed.

Christensen (2008) developed a methodology to explore the hydrologic effects of rain gardens at different sizes, quantities, and distributions in an urban catchment over a range of return period storms. Mike-SHE (DHI Software) was used to simulate the hydrologic processes of rain gardens. Christensen calibrated a Mike-SHE model for an individual rain garden to observed data collected by the USGS for a rain garden in Madison, WI. The calibrated parameters were then used in a Mike-SHE model of a 13-acre urban catchment. The calibrated parameters allowed simulation of the effect of identical rain
garden size, number, layout, and return interval in the catchment with 86 houses were simulated. The storms used were for a range of recurrence interval storm events ranging from 6 months to 100 year events. Results revealed that rain gardens can reduce peak discharge and runoff volume and time to peak significantly. However, compared with the size and number of rain gardens and the return interval of the storm, the location of the rain gardens was not important. Reductions ranges for both volume and peak flow ranged from 10% to 50% for the catchment simulated, and the maximum time to peak differences were about 3.5 minutes. Results also showed that rain gardens also had substantial influences on peak flow and volume reduction for larger storms (10 year to 50 year events).

2.3 Illinois Urban Hydrologic Model (IUHM)

The Illinois Urban Hydrologic Model (IUHM) is a mathematical model developed by Cantone and Schmidt (2010) for simulating complex urban sewer systems. It is rooted in the initial concept of the Geomorphologic Instantaneous Unit Hydrograph (GIUH), which was developed by Rodriguez-Iturbe and Valdes (1979). The basic idea of GIUH is that, for a natural watershed, the hydrologic response is essentially related to the topological structure of the basin, and could be determined by using the Strahler ordering scheme and Horton’s Laws with no need of observed data. Cantone and Schmidt (2010) proposed that this theory could be modified for modeling urban sewer systems. By using the Strahler ordering procedure, an urban catchment of order, $\Omega$, can be considered as a collection of paths that are defined by a sequence of states, either overland state or conduit state. The
adoption of these two states provides simulated infiltration excess overland flow and channel flow, which Cantone and Schmidt identify as the most significant hydrologic processes at the scales of interest for urban catchments.

In IUHM, the overland area is divided into pervious and impervious regions. IUHM assumes that the overland flow is routed from pervious area to impervious area. Thus the total number of possible paths would be $2^\Omega$, which is considerably smaller than the number of pathways that a deterministic approach must model (Cantone, 2010). When a drop of water falls on the catchment, it will follow one of the finite numbers of pre-defined paths, from lower order to higher order, until it reaches the outlet of the sewer system. The probability of following any given path is determined by combining the initial state probabilities (i.e. the probability of a drop of water falling in an overland contributing area) and the probabilities of a drop of water transitioning from one conduit to another which is inherently based upon the topological structure of the network (Cantone, 2010). In each overland and conduit state, the travel times are calculated based on the expanded kinematic wave assumption following the theory proposed by Yen and Lee (1997) and expanded upon by Saco and Kumar (2002). For each path there is a corresponding distribution of travel time, which was assumed to be exponential. Combining the travel time probability-density-function with the probability of a drop of water following a certain path, the network impulse response function for the catchment can be derived. The direct runoff hydrograph for the catchment is then determined by combining the network impulse response function and the excess runoff for all possible paths.
The detailed mathematics of this approach is presented by Cantone (2010) and can be summarized as follows. Consider a specific path \( \omega \)

\[ x_{i,\text{perv}} \rightarrow x_{i,\text{imp}} \rightarrow x_i \rightarrow x_{j} \cdots \rightarrow x_c \rightarrow \text{outlet} \]

Where \( x_{O,l} \) denotes an overland state, \( x_{C,i} \) denotes a conduit state, \( i=1,2,\ldots,\Omega \).

The probability of a drop of water following this path is \( P(\omega) \), which is calculated by multiplying the initial overland state and the probabilities of making successive transitions to conduits of higher order along the path:

\[
P(w) = \begin{cases} 
P_{i,\text{perv}} \cdot P_{x_{i,\text{perv}} \rightarrow x_{i,\text{imp}}} \cdot P_{x_{i,\text{imp}} \rightarrow x_i} \cdots P_{x_i \rightarrow x_j} \cdot P_{x_j \rightarrow x_c} & \text{for path starting from pervious area} \\
P_{i,\text{imp}} \cdot P_{x_{i,\text{imp}} \rightarrow x_{i,\text{perv}}} \cdot P_{x_{i,\text{perv}} \rightarrow x_i} \cdots P_{x_i \rightarrow x_j} \cdot P_{x_j \rightarrow x_c} & \text{for path starting from impervious area} 
\end{cases}
\]

(1)

Where \( i=1,2,\ldots,\Omega \). \( P_{i,\text{perv}} \) is the initial state probability, which means the probability that a drop of rainfall will fall on an \( i \)-th order overland region. \( P_{x_{i,\text{perv}}} \) is the probability that a drop of rainfall will fall on a pervious region which is equal to the perviousness of the catchment. \( P_{x_{i,\text{imp}}} \) is the probability that a drop of rainfall will fall on a impervious region which is equal to the imperviousness of the catchment. \( P_{x_{i,\text{perv}} \rightarrow x_{i,\text{imp}}} \) is the probability that a drop of rainfall transits from a pervious area to a impervious region, which is equal to 1 in current version of this model. \( P_{x_{i,\text{imp}} \rightarrow x_i} \) is the probability that a drop of rainfall transits from an impervious area to an \( i \)-th order conduit. \( P_{x_i \rightarrow x_j} \) is the probability that a drop of water transits from an \( i \)-th order conduit to a \( j \)-th-order conduit.
A scaling factor, $a_i$, is generated for the travel time within a successive $i$ th-order conduit:

$$a_i = \sum_{n=1}^{N} nP_{x_i,n}$$  \hspace{1cm} (2)

where $n = 1, 2, \ldots, N$ is the number of successive $i$ th-order conduits, and $P_{x_i,n}$ is the probability that a drop of water travels through $n$ successive $i$ th-order conduits.

The kinematic wave celerity, $\mu_{x_i}$, of a flood wave based on the flow depth, $h$, is calculated by the following equation (Cappelaere, 1997):

$$\mu_{x_i} = \frac{Q_{x_i} K_{x_i}(h)}{B_{x_i}(h) K_{x_i}(h)}$$  \hspace{1cm} (3)

where $B_{x_i}(h)$ is the surface width of the channel, $K_{x_i}(h)$ is calculated by

$$K_{x_i}(h) = \frac{1}{n_{x_i}} A_{x_i}(h) R_{x_i}(h)^{2/3}$$  \hspace{1cm} (for S.I. units) with $A_{x_i}(h)$ and $R_{x_i}(h)$ being the area and hydraulic radius respectively, and the celerity $K_{x_i}'(h) = \frac{\partial K_{x_i}(h)}{\partial h}$. Using this celerity the mean travel time for a flood wave in a given state $x_i$ can be calculated by the following equation:

$$T_{x_i} = \frac{L_{x_i}}{\mu_{x_i}}$$  \hspace{1cm} (4)
The total travel time of a raindrop of intensity, \(i(t)\), moving through path \(w\) to the outlet, \(T_w(t)\) is given by:

\[
T_w(t) = T_{x_{oi, perv}}(t) + T_{x_{oi, perv, imp}}(t) + a_i T_{x_{oi}}(t) + a_j T_{x_{ij}}(t) + ... + a_{iW} T_{x_{iW}}(t)
\]  

(5)

IUHM assumes the travel time for both overland flow and conduit flow follows an exponential distribution with a mean travel time \(T_{x_k}\). In this way the catchment is conceptualized as linear reservoirs in series and/or parallel (Gupta et al., 1980), and is written as:

\[
f_{x_k}(t') = \frac{1}{T_{x_k}(t)} \exp\left(-\frac{t'}{T_{x_k}(t)}\right); \quad t'
\]  

(6)

where \(f_{x_k}(t')\) is the travel time probability-density-function (PDF) in state \(x_k\), \(t\) relates to the rainfall intensity and \(t'\) is the time associated with the ravel time PDF.

The network impulse response function of the catchment is calculated by the following equation:

\[
u(t',t) = \prod_{w} \left[ f_{x_{oi, perv}}(t') * f_{x_{oi, perv, imp}}(t') * f_{x_{oi}}(t') * f_{x_{ij}}(t') * ... * f_{x_{iW}}(t') \right] \times P(w)
\]  

(7)

where "\(*\)" denotes a convolution integral, and \(W\) is the path space.

The direct runoff hydrograph for the catchment, \(Q(t)\) is then given by

\[
Q(t) = \sum_{r=1}^{\infty} \left[ u(t',t) \cdot q_{L_r}(t) \right] \cdot A
\]  

(8)
where $A$ is the total area of the catchment, and $q_Lw(t)$ is the equivalent pervious excess rainfall, $q_{Lw,per}(t)$, for the paths starting from pervious area, and equal to the equivalent impervious excess rainfall, $q_{Lw,imp}(t)$, for the paths starting from impervious area.

IUHM is driven by a user-defined rainfall intensity series. It requires the input of the mean and variance of parameters including overland slope, conduit slope, subcatchment area and imperviousness. This is a very powerful approach because it doesn’t require detailed parameters of all pipes and overland which are not always available in reality. It can give a highly accurate output even just by using a sub-set of the full deterministic dataset of the catchment signatures. As testified by Cantone and Schmidt (2010) in the Calumet Drop Shaft 51 (CDS-51) catchment (located in the Village of Dolton, IL), a random sample constituted by as little as 30% of the subcatchments and conduits can be used to generate the input for IUHM without considerably decreasing the accuracy or increasing the uncertainty of the predicted hydrologic response.
CHAPTER 3: METHODOLOGY

3.1 Physical Mechanisms

In IUHM, urban development is characterized by two types of surfaces: pervious and impervious. When green roofs are implemented into an urban system, they represent a third type of surface area which behaves as pervious before saturation and impervious after saturation. Although nominally these three types of surfaces seem to operate in parallel, green roofs actually work in a sequential way with the other two types of overland areas. In IUHM, when rain falls on a green roof, part of the water is evaporated or stored for vegetation use, and part becomes runoff. Green roof runoff usually passes through an overland area before entering into the sewer system. In contrast, excess flow from overland areas can enter the sewer system directly or after passing another overland area. Once the green roof runoff is routed to an overland area, it then combines with the precipitation that falls on that overland area, and then follows the overland flow paths. Because runoff passes the green roof and overland areas sequentially, green roof runoff can be regarded as a delayed rainfall process that supplements the precipitation falling on the receiving overland surface.

An assumption of spatial uniformity is made for green roof runoff routing in this case (the effect of this assumption will be analyzed in Chapter 5). This assumption means that the inflow from the green roof is assumed to be equally distributed over the area receiving the green roof runoff. This allows the green roof runoff to be received as additional rainfall by scaling it by the ratio of the green roof area to the area of the
overland region receiving this flow. By superimposing the rainfall intensity and the scaled synchronized green roof runoff, an equivalent rainfall event can be derived for the overland area where green roof runoff is routed. In this process, the green roof is considered as an “implemented filter” that alters the features of the original rainfall event. This altered rainfall, which starts at a later time with a lower peak and longer tail, is precipitated into the overland area. Figure 2 shows a sketch map of this approach.
Figure 2. Schematic of flow diagram with incorporation of green roof model within IUHM model
As shown in Figure 2, part of the impervious area is replaced by green roofs. The original rainfall (labeled in green) precipitates on the three types of urban surfaces. For this rainfall event, the green roofs generate a runoff series (labeled in blue color). Then \( p\% \) of the green roof runoff is routed to impervious area, and \( 1 - p\% \) is routed to pervious area (\( p \) can be decided by users). Now for both pervious and impervious overland area, there is an input from the original rainfall event and also green roof runoff. By superimposing these two, an equivalent rainfall event can be derived for pervious and impervious area.

It should be noticed that different equivalent rainfall series can be derived for impervious and pervious area by changing the value of “\( p \)”, the ratio of green roof runoff routed to impervious area. The derived equivalent rainfall series is then imposed to the impervious area and the pervious area.

In this approach, mass balance is achieved by ensuring that the total volume of water input to the catchment remains constant. For a catchment without green roofs, assuming the volume of rainfall falling on impervious area is \( R_{io} \), and the rainfall on pervious area is \( R_p \). Then the total volume of rainfall \( R_t \) is calculated in equation 9:

\[
R_t = R_{io} + R_p
\]  

(9)

Assuming the original area of the impervious area is \( A_{io} \), the pervious area is \( A_p \), and the total area of the catchment is \( A \), equation 10 shows the summation:

\[
A = A_{io} + A_p
\]  

(10)

Now assuming that part of the impervious area, \( A_g \), is replaced by the green roofs, then the new impervious area \( A_{ig} \) is shown in equation 11:
\[ A_{in} = A_{io} - A_g \] \hspace{1cm} (11)

Combining equation (2) and (3), the total area of the catchment can be represented by equation 12:

\[ A = A_g + A_p + A_{in} \] \hspace{1cm} (12)

Green roofs take up some area in the impervious area; they will retain some amount of water, which is how green roof implementation affects the catchment outlet runoff.

Assuming the amount of rainfall falling on green roofs is \( R_g \), and on the new reduced impervious area is \( R_{in} \). Then we get the relationship shown in equation 13:

\[ R_{io} = R_{in} + R_g \] \hspace{1cm} (13)

Combining equations (9) and (13) yields the total amount of rainfall \( R_t \) falling on the catchment (equation 14):

\[ R_t = R_{in} + R_p + R_g \] \hspace{1cm} (14)

Assuming the volume of water retained by the green roofs is \( G_r \), and the volume of green roof runoff is \( G_f \), then according to mass balance, we have equation 15:

\[ R_g = G_r + G_f \] \hspace{1cm} (15)

Assuming \( p\% \) of green roof runoff is routed to the impervious area (\( p\% \) is referred to later as the “green roof routing ratio”), and \((1 - p\%)\) is routed to the pervious area. As a result, water input to to the impervious area \( A_{in} \) is \( (R_{in} + G_f \times p\%) \), and for pervious area \( A_p \), water input will be \( (R_{in} + G_f \times (1 - p\%)) \). Table 1 shows the water mass balance for this approach, where \( F \) is the cumulative infiltration, \( I_a \) is the initial abstractions, and
WI is the water input to the overland area. It should be noted that the explanation here is for a given order, and this is repeated for each order.

Table 1. Water mass balance for green roof implementation

[Aᵢₒ, Aᵢᵢ, Aᵢᵢᵢ, Gᵢ, Gᵢᵢ, Rᵢᵢ, Rᵢᵢᵢ and Rᵢᵢᵢᵢ are defined in the previous paragraphs; F is the cumulative infiltration, Iᵢ is the initial abstractions, and WI is the water input to the overland area; N/A means ‘not applicable’]
Table 1 shows that for both cases, total water input is the same $R_r$. When green roofs are implemented, part of the water ($G_r$) is retained in green roofs. Thus the water mass balance in this approach is fulfilled.

### 3.2 Modeling Approach

This study uses the volumetric approach described above to explore the impact of green roof implementation in a complex urban catchment. The modeling approach includes three parts: (1) green roof model development; (2) IUHM modification for releasing the restriction that overland flow must be routed from pervious area to impervious area (3) incorporation of the green roof model within the modified IUHM model. The incorporated model will be referred as the Combined IUHM-GreenRoof Model (CIGM).

Three new variables are introduced into CIGM for purposes of this study:

- The overland flow routing ratio (“PI”), which gives the fraction (percentage) of flow which is routed from pervious area to impervious area. The overland flow routing ratio changes the routing method, but does not alter the percent imperviousness of the catchment. For example, if users set the overland flow routing ratio as 60%, then 60% of the overland flow will be routed from pervious areas to impervious areas, and 40% of flow will be routed in the opposite way.

- The green roof coverage ratio (“grratio”), which gives the fraction (percentage) of the impervious area replaced by green roofs ($A_g / A_{io}$). It should be noted that the green roof area cannot exceed the available roof area of the catchment.
• The green roof runoff routing ratio \((p\%)\), which gives that fraction (percentage) of green roof runoff that is routed to impervious areas. For example, if users determine this ratio to be 40\%, then 40\% of green roof runoff is routed to impervious area, and the other 60\% will be routed to pervious area.

Introduction of these three variables enables CIGM to test how different green roof coverage, green roof runoff routing directions, and overland runoff routing directions can affect the catchment outlet runoff during a given storm. The variable values can be decided by users depending on local conditions for case studies regarding specific urban catchments. By changing these three variables, hydrologic response of an urban catchment to different scenarios of green roof coverage and flow routing can be researched.

The green roof model constructed in this study can represent multiple kinds of green roofs. By changing corresponding parameters (these parameters will be specified in section 3.2.1 Green Roof Modeling), the green roof model can simulate green roofs with both overdrain and underdrain, green roofs with only overdrain, and green roofs with varying storage capacity. Through changing the settings of green roofs, the effect of different green roof characteristics on urban catchment runoff can also be studied. The results of these scenarios can be analyzed to find out how green roofs can best serve an urban catchment.
3.2.1 Green Roof Modeling

The numerical green roof model developed in this study can be used independently to study the behavior of a single green roof without considering other urban facilities, but when incorporated into IUHM it serves as a part of the whole system (as shown in Figure 2).

There is no standard way to model hydrological process of green roofs. For incorporation within IUHM, a mathematical model for a single green roof was constructed in Matlab. This model was used to generate a rainfall-runoff relationship for a single green roof. The work here is not to develop a physics-based model that can be applied generally, but rather empirical descriptions of the processes that can be calibrated with observed data. For calibration purposes, the green roof on the Business Instruction Facility (BIF) on the UIUC campus is used as a prototype to build this model. The BIF green roof was installed by American Hydrotech, Inc. in summer 2008 and has been monitored ever since its installation (Holloway, 2009). Figure 3 is a photograph showing the green roof on the BIF building; Figure 4 shows a plan view of the green roof (not to scale), and Figure 5 shows a cross-section view of the green roof. Modeling a site with a single monitored green roof helps to ensure that the physics-based model is accurately simulating the hydrologic processes in green roofs. The monitored data also help to provide calibrated input parameters that can be used to model the effect of placing such green roofs into a larger catchment.
As shown in Figure 4, the green roof is composed of four vegetated beds that are surrounded by a non-vegetated gravel zone. Three sets of drains are equally distributed spatially along one side of the roof in the gravel zone. When water drains out of the growing medium, it first flows to the gravel, and then to the drains. The whole process can be regarded as a two-bucket model. The first bucket is the green roof, and the second one is the gravel bucket. Water coming out from the green roof bucket will first go to the gravel bucket, and then become runoff to an overland area.

Figure 3. Photograph showing the green roof on BIF building in UIUC (Holloway, 2009)
Details of the modeling method for the infiltration process within a single green roof are explained in the following paragraphs. The modeling approach uses well-documented theories to calculate the whole infiltration process. As mentioned before, the emphasis of
this thesis is to develop a method to research and quantify the changes of urban
catchment runoff behavior from implementing green roofs. Green roof modeling in this
study just provides a tool to explore the results of the method proposed in section 3.1
“Physical Mechanisms”.

It should be noted that in this study we did not consider evapotranspiration. Although
evapotranspiration plays an important role in green roof working process for a long term,
in the process of a single rainfall storm its value is minimal enough to be neglected. A
study of evapotraspiration done by Rezaei et al in 2005 revealed that a long-term
evapotranspiration rate was measured as approximately 0.00467 cm/hour (0.0018
inch/hour) for extensive green roofs. Since this study involves only single rainfall events,
evapotranspiration is regarded as null in the whole process of a storm.

In the following calculation, all runoff units are in inch/hour, portraying the runoff
intensity for a unit area. Runoff intensity should be multiplied by the area of the
vegetated bed to calculate runoff volume per hour.

I. Green roof

The conceptual model of the green roof is comprised of three processes: ponding,
overflow, and underflow. These will be described in the following paragraphs.

A. Ponding

The vegetated bed of the green roof on the BIF building is separated from the gravel
zone by an impermeable wall. The wall is approximately 3mm higher than the
surface of the vegetated bed. When the rainfall intensity is larger than the infiltration capacity, water will begin to accumulate on the vegetated surface. The accumulated water will either infiltrate later when the soil is capable to absorb more water or become over flow when the ponding depth exceeds the limit of the wall. Ponding depth is calculated at every time step by the following equation.

\[ h(t + \Delta t) = h(t) + i(t) \Delta t - f(t) \Delta t \]

where \( f(t) \) means the actual infiltration capacity at time \( t \), and is calculated by the equation 17.

\[ f(t) = \text{min}(i(t), f_p(t)) \]

where \( f_p(t) \) signifies the potential infiltration capacity at time \( t \), and is calculated by the Green-Ampt equation (Mays, 2001).

\[ f_p(t) = K \left( \frac{S_f \cdot (\theta_s - \theta_i)}{F(t)} + 1 \right) \]

\( h(t) \): ponding depth at time \( t \), inch;

\( i(t) \): rainfall intensity at time \( t \), inch/hr;

\( f(t) \): actual infiltration capacity at time \( t \), inch/hr;

\( f_p(t) \): potential infiltration capacity at time \( t \), inch;

\( F(t) \): accumulated infiltration at time \( t \), inch;

\( K \): saturated hydraulic conductivity of the growth medium, inch/hour;

\( S_f \): suction head, inch;

\( \theta_s \): saturated volumetric water content, decimal fraction

\( \theta_i \): initial volumetric water content, decimal fraction
\( \Delta t \): time step, hour.

B. Overflow

When ponding depth exceeds the limit of the wall, there will be overflow from vegetated bed to the surrounding gravel zone. The surface level of the gravel zone is around 10cm lower than the surface of the vegetated bed. This elevation difference allows overflow from the vegetated bed to be regarded as weir flow. For simplification, we assume that the overflow is distributed uniformly over the planted area of the green roof. Then the overflow intensity can be calculated by the following weir equation:

\[
q_o(t) = C_d * L * \left[ h(t) - h_c \right]^{3/2} / A_v
\]

\( q_o(t) \): overflow runoff intensity at time \( t \), inch/hr;

\( C_d \): weir coefficient, \( C_d = 3.33 \);

\( L \): weir length, inch;

\( h(t) \): ponding depth at time \( t \), inch;

\( h_c \): height difference between vegetated bed surface and the wall, inch;

\( A_v \): area of the vegetated bed, square inch.

C. Underflow

Underflow comes from the water infiltrated through the growth medium, and its intensity largely depends on the infiltration process. The typical infiltration process can be divided into four steps, illustrated in detail as follows. In every calculation
step, we first evaluate which one of the four states the soil is in by comparing the current soil moisture content with field capacity and saturated soil moisture content. The four states are described below.

1. Initial state

The initial state happens at the beginning of a precipitation event. This state involves in the field capacity, which is defined as the maximum amount of water that the growth medium can hold within its structure against gravity (Chorley 1984; Lindeburg 2003; She 2010). In the initial state, soil water content keeps increasing as rain falls, but does not reach field capacity. Water just infiltrates and advances the wetting front; no water drains out from the growth medium. Therefore in this state, all rainfall is infiltrated and stored in the growth medium; no underflow occurs. The underflow intensity in this phase is 0.

\[ q_u(t) = 0 \]

\( q_u(t) \): underflow intensity at time \( t \), inch/hour.

2. Non-saturated state

This state is the second phase in which soil moisture content exceeds field capacity but the soil is not saturated. In this state, the wetting front has reached the bottom of growth medium, rainfall continues to infiltrate, some water drains through the bottom of the soil medium, and underflow occurs. In this study, the green roof is assumed to be represented as a non-linear reservoir in this state. The discharge rate is calculated by equation 21, in which \( a \) and \( b \) are
calibration factors that determined the non-linear relationship between discharge rate and the real-time water storage in the soil column. Equation 22 is used to calculate real-time water storage for a unit area in the green roof bucket which equals the water storage in last time step plus infiltration and minus underflow.

\[
q_u(t) = a \cdot S_A(t)^b / \Delta t
\]  
\[
S_A(t + \Delta t) = S_A(t) + f(t) \cdot \Delta t - q_u(t) \cdot \Delta t
\]  

\(q_u(t)\) : underflow intensity at time \(t\), inch/hour.

\(S_A(t)\) : soil water storage per unit area in green roof bucket at time \(t\), inch;

\(f(t)\) : infiltration rate at time \(t\), inch/hr;

\(a\) : calibration factor, determined by calibration with real observed data;

\(b\) : calibration factor, determined by calibration with real observed data;

\(\Delta t\) : time step, hour.

3. Saturated state

Although runoff occurs at the second non-saturated state, it is much smaller compared to the water volume infiltrated into the soil. As rainfall continues, soil water storage continues increasing. When soil water content reaches the saturated moisture content, the growth medium becomes saturated. In this phase, Darcy’s Law is used to calculate underflow intensity. The soil system reaches a relative balanced state as equal rates of water flow in and out. The runoff intensity in the saturated phase is calculated by equation 23. In the saturated state, if the infiltration rate becomes smaller than the underflow
discharge rate (most likely due to a decrease in rainfall intensity), the soil moisture content will drop below the saturated moisture content and the system will revert to state 2. In contrast, if rainfall keeps increasing, ponding accumulates and eventually we will get overflow.

\[ q_u(t) = K \times \frac{D + h(t)}{D} \]  (23)

- \( q_u(t) \): underflow intensity at time \( t \), inch/hour.
- \( K \): saturated hydraulic conductivity of the growth medium, inch/hour;
- \( D \): depth of growth medium, inch;
- \( h(t) \): ponding depth at time \( t \), inch;

4. Recession state

In this state, rainfall stops and ponding water is also consumed up by infiltration or evapotranspiration, but underflow still continues because of the water stored in the soil column at previous phases. However, the discharge rate will decrease with time. In this study, runoff was assumed to follow an exponential decay until soil moisture content falls back to initial moisture content (She et al, 2010). The runoff intensity in the recession state is calculated by equation 24.

\[ q_u(t + dt) = q_u(t) \times e^{-\lambda dt} \]  (24)

- \( q_u(t) \): underflow intensity at time \( t \), inch/hour;
- \( dt \): time step, hour;
- \( \lambda \): calibration factor,
II. Gravel

The surrounding gravel zone accepts both overflow and underflow from the vegetation zone. As the water volume stored in the gravel zone increases, runoff from the gravel zone also increases, and vice versa. Assuming the gravel bucket is also a nonlinear reservoir, runoff from the gravel bucket can be calculated by equation 25:

\[ q(t) = c \times S_b(t)^d / \Delta t \]  

\[ S_b(t + \Delta t) = S_b(t) + q_u(t) \times \Delta t \times sc + q_o(t) \times \Delta t \times sc - q(t) \times \Delta t \]  

\( q(t) \): runoff intensity from gravel bucket, inch/hour;

\( q_u(t) \): green roof underflow intensity at time \( t \), inch/hour.

\( q_o(t) \): overflow intensity at time \( t \), inch/hour.

\( S_b(t) \): soil water storage per unit area in gravel bucket at time \( t \), inch;

\( c \): calibration factor, determined by calibration with real observed data;

\( d \): calibration factor, determined by calibration with real observed data;

\( sc \): scaling factor, \( sc = \text{Area of vegetated beds}/\text{Area of gravel zone} \);

\( \Delta t \): time step, hour.

Runoff from the gravel bucket is scaled to the vegetated beds to get the total runoff from the green roof, which means the runoff per unit area of the green roof is calculated by the equation 27:

\[ q_{gr}(t) = q(t) / sc \]
\( q_{gr}(t) \): equivalent green roof runoff intensity at time \( t \), inch/hour

\( q(t) \): gravel bucket runoff intensity at time \( t \), inch/hour

\( sc \): scaling factor, \( sc = \text{Area of vegetated beds}/\text{Area of gravel zone} \)

Figure 6 shows a flowchart of the working mechanism of the green roof model, and detailed code is attached in Appendix A.

Figure 6. Flow chart of the green roof model
The modeling method described above can represent multiple types of green roofs by changing the values of some parameters. For example, if users set $a = 0, K = 0$ in equation 21 and 23 respectively, then the model simulates a green roof with overdrain only. But if $a$ and $K$ are given nonzero values, the model represents a green roof with both underdrain and overdrain. Users can also define the storage of the green roof by changing the growth medium depth. By allowing the simulation of multiple types of green roofs, this model enables CIGM to scale different kinds of green roofs. Users can therefore analyze the impact of certain green roof characteristics on urban watershed runoff.

3.2.2 IUHM Modification for Overland Flow Routing

The original IUHM model allows overland flow routing only from pervious areas to impervious areas (this routing method is referred to as pervious-impervious in later context). In this study, we also consider overland runoff to be directed from impervious areas to pervious areas (this is referred to as impervious-pervious in later context).

For the proposed impervious-pervious routing method, the approach of calculating catchment outlet runoff is slightly different from the original IUHM method. The catchment outflow is still derived by combining the excess runoff and the network impulse response function, but excess runoff in this case will only include the runoff from pervious areas, because all runoff from impervious areas is routed to pervious area. In this overland flow routing method, all water falling on impervious areas will be scaled to pervious area based on the ratio of impervious to pervious areas. Once the flows have
been scaled appropriately, they will be uniformly superimposed on the rainfall falling on the pervious areas. The flow travel time within impervious areas is considered as zero in this study, which means that the rainfall falling on impervious areas is instantly scaled to pervious areas. Another difference is that the network impulse function will be changed due to the opposite overland flow routing, which leads to different flow paths (details refer to equation 29 in later context). But the central idea and calculation method are still the same.

For impervious-pervious overland flow routing, rain falling on impervious areas will follow a path such as the following:

\[x_{oi, imp} \rightarrow x_{oi, perv} \rightarrow x_{ci} \rightarrow x_{cj} \ldots \rightarrow x_{c\Omega} \rightarrow \text{outlet}\]

And rain falling on pervious areas will follow a path such as:

\[x_{oi, perv} \rightarrow x_{ci} \rightarrow x_{cj} \ldots \rightarrow x_{c\Omega} \rightarrow \text{outlet}\]

Where \(x_{oi}\) denotes an overland state, \(x_{ci}\) denotes a conduit state, \(i=1,2,\ldots, \Omega\).

The probability of a drop of water following these paths will be:

\[
P(w) = P_{oi} * P_{\text{scaling}} * P_{\text{imp}} * P_{\text{imp-perv}} * P_{\text{perv-ci}} * P_{\text{ci-cj}} * \ldots * P_{\text{ci-cW}} \quad \text{for path starting from impervious area}
\]

\[
P(w) = P_{oi} * P_{\text{scaling}} * P_{\text{perv-imp}} * P_{\text{perv-ci}} * P_{\text{ci-cj}} * \ldots * P_{\text{ci-cW}} \quad \text{for path starting from pervious area}
\]

(28)

The scaling factor, the travel time for a raindrop, and travel time distribution still follow equations (2) to (6).
The network impulse response function of the catchment follows the following equation:

\[
u(t',t) = \sum_{w} \left[ f_{x_{i,\text{imp}}}(t') \ast f_{x_{i,\text{imp prev}}}(t') \ast f_{x_{i,\text{imp prev}}}(t') \ast f_{x_{i,\text{imp prev}}}(t') \ast f_{x_{i,\text{imp prev}}}(t') \ast P(w) \right]
\] (29)

where \( \ast \) denotes a convolution integral, \( W \) is the path space.

The direct runoff hydrograph for the catchment, \( Q(t) \), is derived by:

\[
Q(T) = \sum_{t' \geq T} \left[ u(t',t) \cdot q_{L,\text{w}}(t) \right] \cdot A
\] (30)

It should be noted here that \( q_{L,\text{w}}(t) \) refers to the equivalent pervious excess rainfall, \( q_{L,\text{w prev}}(t) \), which is calculated through the superimposition of the original pervious excess rainfall and the scaled impervious excess rainfall to pervious area.

### 3.3 SWMM Comparison

The results from CIGM were compared with the well-accepted SWMM5 model. In this thesis, a case study was done for the area draining to dropshaft CDS-51 in the Calumet-TARP system by using CIGM (details will be given in Chapter 4 Case Study).

Correspondingly, a detailed high resolution SWMM model for CDS-51 was also constructed. The detailed SWMM model included 723 subcatchments, 722 conduits, 722 junctions and 1 outfall. This included a subcatchment for every pipe in the sewer system.

The average subcatchment size in this detailed model was 1.08 acres. As a result, assumptions still had to be made to incorporate the effect of multiple green roofs in a single subcatchment. Figure 7 shows a screen shot of this model. Identical green roof implementation scenarios were set up in this SWMM model, and results were compared with the CIGM output.
Green roofs can be added to the SWMM model by using the LID control tools. For SWMM5, the LID tools include five options: Bio-Retention Cell, Infiltration Trench, Porous Pavement, Rain Barrel, and Vegetative Swale. SWMM 5 can incorporate these simplistic models within a catchment. Figure 8 shows a screen shot of the LID control editor in SWMM5. Compared with the other four LID types, the conceptual model used to describe a bio-retention cell is the most similar to the process of green roofs. Therefore, the Bio-Retention Cell was chosen as the LID type to simulate green roofs. The green roof parameters in SWMM 5 were set up to match what were used in CIGM. Thus the SWMM output could become comparable to the results derived in CIGM. Details would be provided in Chapter 4.
Figure 8. Screen shot of LID tools in SWMM5 (units are mm and mm/hr)
CHAPTER 4: CASE STUDY

A case study for the CDS-51 drop shaft catchment (Dolton, IL) has been done by running CIGM with various scenarios of green roofs and rainfall series. The CDS-51 catchment was chosen as a sample study because most of the data for this catchment are available, which is very important for modeling and comparison. These data include land use, soil, and observed flow. The original developer of IUHM, Joshua Cantone (2010), has simulated CDS-51 using IUHM and SWMM, and proved that IUHM-derived runoff has a good match with the observed flow data. In this study, we keep using this catchment for exploring the effect of green roof implementation.

4.1 BIF Green Roof

As mentioned before, the green roof on BIF building on UIUC campus has been used as a prototype for the green roof modeling in this study. Therefore, the basic data describing the BIF green roof have been used as input parameters in the green roof modeling. It is an extensive green roof with 8 inch deep growing medium. The growth medium is an engineered soil that is comprised of approximately 88% sand, 10% silt, and 2% clay. Most hydraulic parameters for the growth medium were determined by observed data (Holloway, 2009) or Table 4.15 in Stormwater Collection Systems Design Handbook (Mays, 2001). Field capacity was set as 0.2 (www.terragis.bees, 2011). Detailed input parameters are listed in Table 2.
Table 2. Input parameters for the green roof model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing medium depth</td>
<td>203</td>
<td>mm</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>38</td>
<td>mm/hr</td>
</tr>
<tr>
<td>Soil water suction head</td>
<td>110</td>
<td>mm</td>
</tr>
<tr>
<td>Initial soil moisture content</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Field capacity</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Saturated soil moisture content</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Overflow collar height</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Evapotranspiration rate</td>
<td>0</td>
<td>mm/hr</td>
</tr>
<tr>
<td>Depression storage</td>
<td>0</td>
<td>mm</td>
</tr>
<tr>
<td>The ratio of green roof area to gravel area</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Rainfall Events

The rainfall series used in this study include: (1) a hypothetical uniform rainfall event with an intensity of 7.62 mm/hr for 2 hours; (2) a 5yr ARI (Average Return Interval) triangular storm generated by the methodology proposed by Yen and Chow (1980); (3) a January storm in 2008; (4) a July storm in 2007.

The reason for choosing uniform and triangular storms is that it is easier to capture the response characteristics of green roofs by using simple rainfall series. Besides, such rainfall series can rule out any doubts that the watershed response may be a function of rainfall. Figure 9 shows the uniform storm described above, which is a low-intensity/short-duration event; Figure 10 shows the 5yr ARI storm with a peak intensity of 54.9mm/hr and a duration of 2 hours, which represents a high-intensity/short-duration storm. The duration of the ARI storm was decided as 2 hours because we wanted to test how green roofs respond to short rainfall events, especially the ones with high intensity. While most storms will be of longer duration and smaller intensity than the two-hour storm, the two-hour storm represents a typical design storm for calculating the peak
discharge for the storm-drainage system. Hence, this provides an estimation of the effect
of green roofs on the drainage for the design storm. The time length of these two storms
both fall into “short” term, but they represent very different rainfall series with unique
rainfall intensity distribution which may lead to different hydrologic response from the
green roof model, and eventually the CIGM model.

Figure 9. A Uniform rainfall event with an intensity of 7.62 mm/hr for 2hrs

Figure 10. A 5yr ARI storm, 2hrs (Yen and Chow, 1980)
While hypothetical storms with typical rainfall distributions can help to identify the characteristics of the hydrological response of green roofs more easily, testing the green roof model with real storms is more physically meaningful. Therefore in this study, two rainfall storms from Dolton, IL were chosen to test CIGM, a January 2008 storm and a July 2007 storm. The reason for choosing these two storms is that their characteristic represents two distinct conditions of real rainfall events. The January storm is featured as low-intensity long-duration, and the July storm has the characteristic of high-intensity long-duration. Their distinct characteristics may result in different hydrologic responses from an urban watershed. The January 2008 storm also caused one of the largest combined sewer overflow events for CDS-51 in the period of April 2007 to April 2009 (Cantone, 2010).

Figures 11 and 12 show the rainfall intensity of January 2008 storm and July 2007 storm respectively. The January storm started at 18:00 on January 7, 2008 and lasted 15 hours, with a peak intensity of 11.7 mm/hr; the total precipitation is 79.2mm. The July 2007 storm started at 02:00 on 26 July 2007 and was 7 hours long, with a peak intensity of 18.8 mm/hr and a total precipitation of 46.7mm.

These four storms were all tested in the green roof model and the CIGM model to study the hydrologic response of the catchment. However, they were not the storms used for calibrating the green roof model. Instead, the weather data for two rainfall events observed at the BIF building was used for the calibration of the green roof model. Details are provided in section 4.6.1 “Green Roof Model”.
Figure 11. January Storm, 2008 (Dolton, IL)

Figure 12. July Storm, 2007 (Dolton, IL)
4.3 Calumet Drop Shaft 51 Catchment (CDS-51)

The CDS-51 catchment is a 5th-order complex urban system with an area of 782 acres, located in the Village of Dolton, IL. Figure 13 shows a plan view of the pipe system in this catchment. The catchment captures combined storm and sanitary flows and delivers them to the Calumet system of Chicago’s Tunnel and Reservoir Plan (TARP) (MWRDGC, 1999, Cantone 2010). The combined sewers flow from lower-order pipes to higher-order ones, and end up in a 5th order pipe with a diameter of 215 cm. From here, flow either goes to drop shaft 51, to an interceptor, or overflows to Little Calumet River depending on whether TARP’s capacity is exceeded (see Figure 13). This 5th order pipe could be considered as the outlet of the catchment. Better understanding of the catchment outflow would provide more insight to how the catchment runoff affects the Tunnel and Reservoir Plan (TARP) system and the natural environmental system. In this study, we analyzed the effect of green roof implementation by comparing the catchment outflow graph in different green roof and rainfall scenarios.
Table 3 is an example of the input parameters for one CIGM scenario. This scenario is with 20% of green roof coverage, all green roof runoff routing to pervious area, and the percentage of overland flow routing from pervious to impervious area is 60%. It should be noted that the overland flow routing ratio from pervious to impervious area, the green roof coverage ratio, and the routing ratio of green roof runoff to impervious area are three
variables (italicized in Table 3) whose values users can change in different scenarios. Correspondingly, average green roof coverage and average imperviousness will also change with the green roof coverage ratio. Other parameters remain the same in different scenarios. The parameters of the catchment are determined based on various sources, like the Village of Dolton sewer atlas and Cook County’s LiDAR data (See Cantone, 2010, for more details).
Table 3. Input parameters for one scenario of CDS51 catchment

<table>
<thead>
<tr>
<th>parameters</th>
<th>Value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>order ((i))</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>manning's (n) for impervious area</td>
<td>0.015</td>
<td></td>
</tr>
<tr>
<td>manning's (n) for pervious area</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>kinematic wave parameter for wide rectangular planes/channels</td>
<td>5/3</td>
<td></td>
</tr>
<tr>
<td>area</td>
<td>782</td>
<td>acre</td>
</tr>
<tr>
<td>green roof coverage ratio (denoted as &quot;grratio&quot;)</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>ratio of green roof runoff to impervious area (&quot;grimp&quot;)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ratio of overland flow from pervious to impervious area (&quot;opi&quot;)</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>number of pipes in order ((i)) of catchment</td>
<td>449</td>
<td>157</td>
</tr>
<tr>
<td>1st order</td>
<td>57</td>
<td>51</td>
</tr>
<tr>
<td>2nd order</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>3rd order</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th order</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5th order</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average channel length of (i)-th order pipes</td>
<td>61570</td>
<td>59741</td>
</tr>
<tr>
<td>variance in channel length of (i)-th order pipes</td>
<td>769330074.2</td>
<td>892240796.2</td>
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<tr>
<td>1st order</td>
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<td>2nd order</td>
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<tr>
<td>average channel slope of (i)-th order pipes</td>
<td>0.00485</td>
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<tr>
<td>variance in channel slope of (i)-th order pipes</td>
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<tr>
<td>1st order</td>
<td>9.4864E-06</td>
<td>2.1316E-06</td>
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<td>2nd order</td>
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<tr>
<td>average diameter of (i)-th order pipes</td>
<td>329.184</td>
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<tr>
<td>variance in diameter of (i)-th order pipes</td>
<td>10866.3117</td>
<td>29762.04628</td>
</tr>
<tr>
<td>average upstream area contributing to (i)-th order pipes</td>
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<td>46664281315</td>
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<tr>
<td>variance in upstream area contributing to (i)-th order pipes</td>
<td>1.32929E+20</td>
<td>1.50679E+21</td>
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<td>average overland slope contributing to (i)-th order pipes</td>
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<td>average impervious ness of overland area contributing to (i)-th order</td>
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<tr>
<td>variance in impervious ness of overland area contributing to (i)-order</td>
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<td>scaling factor to account for transitions in (i)-th order pipes</td>
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<td>initial state probability</td>
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<td>0.247</td>
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<table>
<thead>
<tr>
<th>transition probability matrix</th>
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<tr>
<td>\begin{bmatrix} 0 &amp; 0.737 &amp; 0.151 &amp; 0.112 &amp; 0 \ 0 &amp; 0 &amp; 0.722 &amp; 0.194 &amp; 0.083 \ 0 &amp; 0 &amp; 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 &amp; 1 \ 0 &amp; 0 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix}</td>
</tr>
</tbody>
</table>
4.4 Simulation of CDS-51

This section describes the scenarios simulated in CIGM. As mentioned before, one parameter introduced here is the fraction of overland flow routed from pervious to impervious area. In a watershed, the overland flow routing is a combination of both pervious-impervious and impervious-pervious cases. In our study we want to examine what difference these two overland flow routing methods can lead to. Therefore, we tested three cases in terms of overland flow routing: (1) All the overland flow is routed from pervious areas to impervious areas; (2) All the overland flow is routed from impervious areas to pervious areas; (3) 70% overland flow is routed from pervious areas to impervious areas, and the other 30% is routed from impervious areas to pervious areas.

We chose the third scenario above because it is the most likely scenario happening in CDS-51 drop shaft area. In urban watershed, it may be difficult to route water from non-roof impervious areas to pervious areas, but it would be applicable to route all the roof runoff to pervious area, which is a case of routing water from impervious area to pervious area. Thus if we route all roof runoff to pervious area and disregard other impervious-pervious routing conditions (e.g. impervious-pervious routing due to other BMPs), the percentage of impervious-pervious routing will be equal to the ratio of roof area to the whole watershed. This is also an optimal scenario to get rid of as much roof runoff as possible before it enters into the urban sewer system.

Figure 14 shows a plan view of the land features in CDS-51 catchment. We can see that residential area occupies the largest portion of the catchment. There are also a few green
lands. A typical neighborhood area was extracted from this catchment and is shown in Figure 15. This neighborhood layout was then drawn in AutoCAD, and by using the calculation tools in AutoCAD we estimated that the ratio of roof area to the whole area was roughly 35%. Due to the presence of the green lands in this catchment, we lowered this ratio to 30%. This was also how the third scenario was decided.
In the pervious-impervious case, different green roof coverage and different green-roof-runoff routing methods were researched. First, assume all green roof runoff is routed to pervious area (which is environmentally wise because more water can be infiltrated), set green roof coverage as 10% to 40% with a step of 10% rise each time, from which the influence from different green roof coverage could be investigated. Second, assume 20% of impervious area is replaced by green roof, a simulation of routing all green roof runoff...
to impervious area, or pervious area, or 50% to each, will be run respectively. By doing this, the effect of altering green roof runoff routing method can be studied.

In the impervious-pervious case, only different green roof coverage will be explored for the catchment; all green roof runoff will be routed to pervious area because in this overland flow routing condition, all water routed to impervious area will go to pervious area eventually. Just as the pervious-impervious case, green roof coverage ratios of 10%, 20%, 30% and 40% have been tested for different impact to catchment outlet runoff.

For the combined case (70% pervious-impervious and 30% impervious-pervious), the setting of green roof coverage will be also from 10% to 40% with an increase step of 10%, the routing of green roof runoff will also be set as 100% to impervious area, or 100% to pervious area, or 50% to each, but it should be noted that the green roof runoff setting will only affect the 60% overland flow which is routed from pervious area to impervious area because of the reason explained earlier. All scenarios run by CIGM were summarized in Table 4.
Table 4. All scenarios run in CIGM

<table>
<thead>
<tr>
<th></th>
<th>scenario 1</th>
<th>scenario 2</th>
<th>scenario 3</th>
<th>scenario 4</th>
<th>scenario 5</th>
<th>scenario 6</th>
<th>scenario 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>pervious-impervious</td>
<td>green roof coverage</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>ratio of routing green roof runoff to pervious area</td>
<td>100%</td>
<td>50%</td>
<td>0</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>impervious-pervious</td>
<td>green roof coverage</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ratio of routing green roof runoff to pervious area</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>combined case</td>
<td>green roof coverage</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>ratio of routing green roof runoff to pervious area</td>
<td>100%</td>
<td>50%</td>
<td>0</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

4.5 SWMM set up for CDS-51

In the CDS-51 SWMM model, green roof implementation was set up as a LID control with the input data of surface, soil, storage, and under drains. For matching the hydraulics of green roofs we used in CIGM, the available BIF green roof data presented in Table 2 were used here. Table 5 shows the input data for green roof model in SWMM.
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>storage depth</td>
<td>0.254</td>
<td>mm</td>
</tr>
<tr>
<td>vegetation volume fraction</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>surface roughness(manning's n)</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>surface slope(percent)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>thickness</td>
<td>203</td>
<td>mm</td>
</tr>
<tr>
<td>porosity</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>field capacity</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>wilting point</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>conductivity</td>
<td>38</td>
<td>mm/hr</td>
</tr>
<tr>
<td>conductivity slope</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>suction head</td>
<td>110</td>
<td>mm</td>
</tr>
<tr>
<td>height</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>void ratio</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>conductivity</td>
<td>110</td>
<td>mm/hr</td>
</tr>
<tr>
<td>clogging factor</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>drain coefficient</td>
<td>1.524</td>
<td>mm/hr</td>
</tr>
<tr>
<td>drain exponent</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>drain offset height</td>
<td>0</td>
<td>mm</td>
</tr>
</tbody>
</table>

In the SWMM model, the subcatchment was divided based on the contributing area for each junction, giving a very detailed high-resolution model, which could provide more accuracy regarding lumped modeling techniques. This could also help to get a better comparison result with the CIGM model.

In SWMM, there are two different approaches to add LID controls within a subcatchment: (1) add LID controls into each sub-catchment; (2) create a new sub-catchment for each original sub-catchment to represent a proposed LID control. These two ways work differently and may make a difference in the final results of catchment runoff. Under the first approach, all LID controls work in parallel. But under the second approach, LID
controls can work in series and runoff from different upstream subcatchments can be routed onto the LID subcatchment. Due to the working mechanism of green roofs (working in parallel and not allowing overland flow being routed to green roofs), the first approach was chosen in this study.

Figures 16 to 18 show the LID settings for subcatchment 1. Take the scenario of 20% of green roof coverage as an example. As shown in Figure 16, the imperviousness of subcatchment 1 is 52.76%, thus the green roof coverage is 52.76% *20%=10.7%. Figure 17 and 18 show the parameter settings used to enter the green roofs to SWMM. We can see that the green roof covered 10.7% of the subcatchment1 area, and 20% of impervious area is treated as green roofs. The same setting of parameters needs to be done for every subcatchment, with values specific to each subcatchment.

Developing the parameter set to describe every subcatchment and every scenario in SWMM is relatively more time-consuming in SWMM than in CIGM. Therefore, if the results from both models have a good match, we can conclude that CIGM is capable of analyzing the effect of green roofs in a simpler way.
Figure 16. Parameters of Subcatchment 1 in SWMM

Figure 17. LID settings of Subcatchment 1 in SWMM (20% green roof coverage)
Figure 18. LID settings of Subcatchment 1 in SWMM (20% green roof coverage)

4.6 Result Analysis

Multiple simulations have been done for CDS-51 by using both the CIGM and SWMM models. Green roofs were implemented in these two models in such a way that the parameters describing the areas of the different models are equivalent. The simulation results for the similar scenarios were compared and analyzed in this chapter. Discussions presented in this section include the performance of the green roof model, the effects of
changing overland flow routing options, the CIGM model performance under different green roof and rainfall scenarios, and the output comparison between SWMM and CIGM.

4.6.1 Green Roof Model

1. Model Calibration

As stated in section 3.2.1 “Green Roof Modeling”, several calibration parameters are required for the green roof model. In equation 21, “α” is a drain coefficient, and “b” is a drain exponent for pre-saturated drainage from the green roof. In equation 24, “λ” is a recession coefficient for recovery of infiltration capacity of the green roof. In equation 25, “c” and “d” are a drain coefficient and a drain exponent, respectively, for flow through the gravel layer to the drain. All five of these parameters need to be calibrated with observed rainfall-runoff data so that they can be used to predict the behavior of the green roof modeled in future rainfall events.

Observed rainfall data from August 20-21, 2010 and September 22, 2010 and data describing the corresponding runoff from the BIF green roof were used to calibrate the two-bucket green roof model. Random initial values were given to the five calibration parameters, and after processing the two storms above, runoff output from the model were compared with observed runoff data. If the two series didn’t have a good match, the values for the five parameters were modified until the modeled runoff and the observed runoff series match each other. Final calibrated values for the five parameters are presented in Table 6 below.
Table 6. Calibration parameters in Green Roof Model

<table>
<thead>
<tr>
<th>calibration parameter</th>
<th>calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.06</td>
</tr>
<tr>
<td>b</td>
<td>14</td>
</tr>
<tr>
<td>c</td>
<td>0.2</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
</tr>
<tr>
<td>λ</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figures 19 and 20 show the calibrated results for the green roof model under the two storms described above. With the calibrated values listed in Table 6, we can see that the modeled runoff statistics generally represent the characteristics of the observed data; the runoff volume and peak closely follow what happened in the real condition. But the runoff starting time from the model is generally after the timing of real observed data. This calibration result is not perfect due to the limitation of accessed data and also the limitation of the modeling method. It does provide a tool to explore the effects of green roof implementation in urban catchment, which is the main objective of this study.
Figure 19. Calibration for September 22 Storm, 2010

Figure 20. Calibration for August 20-21 Storm, 2010
2. Model Response under Different Rainfall Scenarios

The calibration above was just for the green roof on the BIF building, which has both overdrain and underdrain. If there were observed rainfall-runoff data for a green roof with only overdrain, then the calibration parameters should have different values. Due to the lack of such data, in this section we only simulated the green roof type with both overdrain and underdrain. But it should be noted that other green roof types can also be simulated by this green roof model as described in section 3.2.1. Using the calibrated values presented in Table 6, the green roof model was run to predict the runoff behavior under four rainfall events.

![Modeled Green Roof Runoff under Uniform Storm](image)

*Figure 21. Modeled Green Roof Runoff under Uniform Storm*
Figures 21 and 22 show the green roof response under the uniform storm with an intensity of 7.62 mm/hr for 2 hours and the 5yr ARI triangular storm, respectively. The uniform event represents a short-duration low-intensity storm, and the 5yr ARI storm characterizes a short-duration high-intensity event. From the graphs above, we can see that green roof runoff starts at a later time and has a lower peak and longer tail compared with the rainfall series. The characteristics of the green roof runoff for the two storms are concluded in Table 7.
Table 7  Green roof response under the uniform storm and the 5yr ARI storm

<table>
<thead>
<tr>
<th></th>
<th>Time to Peak (min)</th>
<th>Peak Runoff (mm/hr)</th>
<th>Total Runoff (mm)</th>
<th>Total Rainfall (mm)</th>
<th>Green Roof Retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform storm</td>
<td>120</td>
<td>0.063</td>
<td>0.11</td>
<td>15.24</td>
<td>99.25%</td>
</tr>
<tr>
<td>5yr ARI Storm</td>
<td>61</td>
<td>38.68</td>
<td>44.75</td>
<td>54.9</td>
<td>18.50%</td>
</tr>
</tbody>
</table>

Runoff corresponding to the uniform storm shows two phases (as labeled in Figure 21). Phase 1 shows an increasing trend to a peak of 0.063 mm/hr, phase 2 shows runoff decreasing from the peak until reaching zero. In the entire process, the green roof did not reach saturation state. Runoff in phase 1 is generated in Non-Saturated state (details please refer to section 3.2.1), and phase 2 shows the recession state.

Unlike the uniform storm, the runoff graph corresponding to the 5yr ARI storm shows 4 distinct states (as labeled in Figure 22). Phase 1 is the pre-saturated state which shows an increasing trend; phase 2 features a fairly constant runoff rate around 38mm/hr which is the saturated hydraulic conductivity of the soil medium, but the actual runoff rate is slightly bigger than 38mm/hr with a peak of 38.68mm. This means that in this state the green roof soil medium is saturated, and also there is a slight overflow. In phase 3, rainfall decreases to such an extent that it cannot keep the saturation state of the soil medium, which makes the green roof return to non-saturated state. Phase 4 shows the recession state.

The comparison above indicates that the green roof runoff generated by the uniform storm and the 5yr ARI storm have quite different shapes. Combined with the feature of these two storms, we can see that green roof works better on postponing time to peak,
decreasing peak runoff, and retaining water for low-intensity short-duration storms rather than high-intensity short-duration storms.

Figure 23. Modeled Green Roof Runoff under January 2008 Storm

Figure 24. Modeled Green Roof Runoff under July 2007 Storm
Figures 23 and 24 show runoff corresponding to the two real rainfall events. The characteristics of the green roof runoff for these two storms are summarized in Table 8.

For the January 2008 storm, we can find that at the green roof runoff almost follows the hyetograph after about 800min. This means that for the January 2008 storm the green roof reaches saturation threshold at this point, and behaves like impervious area afterward. For the July 2007 storm, the water retention volume is about 34.6% percent, and runoff peak is almost the same as the rainfall peak, 18.5mm/hr. After the runoff reaches the peak intensity, the runoff graph almost follows the hyetograph, this indicates that the green roof is saturated around the time that runoff reaches the peak value. Calculation of both the January storm and the July storm show that the green roof can hold a volume of around 15.7-15.9 mm of water. Once this volume is reached, the green roof is saturated.

### 4.6.2 Effect of Overland Flow Routing

Overland flow routing has significant impact on the catchment runoff. Figures 25 to 28 show a comparison of the catchment outflow between different overland runoff routing options for the four storms. In the following figures, “CIGM_perv_imp” indicates overland flow routing is from pervious area to impervious area, and “CIGM_imp_perv” indicates overland flow routing is from impervious area to pervious area.
Figure 25. Outflow comparison between perv_imp and imp_perv under non-green roof scenario (Uniform Storm)

Figure 26. Outflow comparison between perv_imp and imp_perv under non-green roof scenario (5yr ARI Storm)
Figure 27. Outflow comparison between perv_imp and imp_perv under non-green roof scenario (Jan storm)

Figure 28. Outflow Comparison between perv_imp and imp_perv under non-green roof scenario (July storm)
These graphs show that the impervious-pervious overland runoff routing method can significantly decrease the volume and peak of the catchment outflow compared with the pervious-impervious routing option. The time to peak is also approximately 8-10 minutes longer than the pervious-impervious case. The outflow characteristics of both the impervious-pervious and pervious-impervious overland flow routing options are listed in Table 9. For the uniform 7.62 mm/hr storm, the outflow is totally eliminated by routing the overland flow from impervious to pervious areas. The reduction of the total outflow volume is 100% for the uniform storm, 8.23% for the 5yr ARI storm, 75.28% for the January 2008 storm, and 59.92% for the July storm. This demonstrates that except for a high-intensity short duration storm, impervious-pervious overland routing can effectively use pervious areas to capture runoff from the impervious areas. As overland runoff is routed from impervious area to pervious area, water is infiltrated into the soil and less excess runoff enters the pipe system.

<table>
<thead>
<tr>
<th></th>
<th>Time to Peak (min)</th>
<th>Peak Outflow (m³/s)</th>
<th>Total Outflow (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform Storm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>perv-imp</td>
<td>120</td>
<td>3.71</td>
<td>21140</td>
</tr>
<tr>
<td>imp-perv</td>
<td>n/a</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5yr ARI Storm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>perv-imp</td>
<td>81</td>
<td>22.6</td>
<td>104129</td>
</tr>
<tr>
<td>imp-perv</td>
<td>90</td>
<td>22.1</td>
<td>95560</td>
</tr>
<tr>
<td>Jan 2008 Storm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>perv-imp</td>
<td>902</td>
<td>6.06</td>
<td>141096</td>
</tr>
<tr>
<td>imp-perv</td>
<td>912</td>
<td>4.7</td>
<td>34872</td>
</tr>
<tr>
<td>July 2007 Storm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>perv-imp</td>
<td>362</td>
<td>9.59</td>
<td>80380</td>
</tr>
<tr>
<td>imp-perv</td>
<td>376</td>
<td>7.54</td>
<td>32218</td>
</tr>
</tbody>
</table>
4.6.3 Catchment Response under Different Green Roof Scenarios

1. 100% Pervious-Impervious Overland Flow Routing

1). Different green roof coverage

Pervious-impervious overland flow routing is the prevalent condition in the real world. Understanding the impact of green roof implementation in this circumstance is an important concern of this study. Figures 29 to 32 show the comparison of catchment runoff with different green roof coverage under pervious-impervious overland runoff routing condition in the four storms. In the following figures, “gr” indicates the percentage of impervious area occupied by green roofs, and “rimp” indicates the ratio of green roof runoff that is routed to impervious area. For example, “gr 0.1_rimp0” indicates 10% of the impervious area is occupied by green roofs and 0 percent of green roof runoff routing to impervious area.

![Figure 29. CIGM Outflow Comparison between Different Green Roof Coverage under perv_imp Overland Flow Routing Option (Uniform Storm)](image-url)
Figure 30. CIGM Outflow Comparison between Different Green Roof Coverage under perv_imp Overland Flow Routing Option (5yr ARI Storm)

Figure 31. CIGM Outflow Comparison between Different Green Roof Coverage under perv_imp Overland Flow Routing Option (Jan Storm)
Table 10 lists the detailed volume and peak reduction rate of the catchment outflow corresponding to different green roof coverage percentages under the pervious-impervious overland runoff routing option. Figures 33 and 34 show the content of Table 10 in graphical form.
Table 10 Outflow comparison between different green roof coverage conditions under pervious-impervious overland runoff routing option

<table>
<thead>
<tr>
<th></th>
<th>10% coverage</th>
<th>20% coverage</th>
<th>30% coverage</th>
<th>40% coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform Storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>10.00%</td>
<td>20.00%</td>
<td>30.00%</td>
<td>40.00%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>10.00%</td>
<td>20.00%</td>
<td>30.00%</td>
<td>40.00%</td>
</tr>
<tr>
<td>5yr ARI Storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>5.30%</td>
<td>10.46%</td>
<td>15.92%</td>
<td>21.61%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>6.61%</td>
<td>13.22%</td>
<td>19.70%</td>
<td>25.90%</td>
</tr>
<tr>
<td>Jan 2008 Storm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>10.00%</td>
<td>20.00%</td>
<td>29.98%</td>
<td>39.02%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>10.03%</td>
<td>20.00%</td>
<td>29.95%</td>
<td>34.49%</td>
</tr>
<tr>
<td>July 2007 Storm</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>10.00%</td>
<td>20.00%</td>
<td>29.56%</td>
<td>38.48%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>10.00%</td>
<td>20.00%</td>
<td>29.52%</td>
<td>37.23%</td>
</tr>
</tbody>
</table>

Figure 33 Outflow volume reduction rate versus different green roof coverage under pervious-impervious overland runoff routing option
Figure 34 Outflow peak reduction rate versus different green roof coverage under pervious-impervious overland runoff routing option

From the graphs above, it can be seen that except for the 5yr ARI storm, 10% of green roof coverage can generally decrease catchment outflow volume and peak by 10%. Also, with every 10% increase of green roof coverage, catchment outflow can be decreased 10% further. However, for the January 2008 storm and the July 2007 storm, when green roof coverage increases from 30% to 40%, the volume and peak of the catchment outflow further decreases by 5% - 8% instead of 10%. This indicates that when green roof coverage exceeds 30% the catchment outflow no longer maintains a linear relationship with the green roof coverage. Green roof coverage results in less reduction of catchment outflow volume and peak for the 5yr ARI storm than with other rainfall events (around 5% of reduction for every 10% of green roof coverage). The 5yr ARI storm is representative of the stormwater design storm. While other storms occur more frequently, the 5yr ARI
storm represents the condition that stormwater infrastructure is typically designed to convey, and hence provides a good representation of the benefits of green roofs at reducing the size and cost of stormwater infrastructure. The results highlight that green roofs are more effective during low-intensity, long-duration storms than they are during high-intensity, short-duration storms.

2). Different green roof runoff routings

In addition to the overland flow routing methods, the type of surface to which green roof runoff is routed will affect catchment runoff. Figures 35 to 38 show the comparison of catchment outflow under different green roof runoff routing options for the four storms. In this comparison, it is assumed that 20% of impervious area is replaced by green roofs. Overland runoff is routed from pervious to impervious area as before.

![Figure 35. CIGM Outflow Comparison between Different Green Roof Runoff Routing Options under 20% Green Roof Coverage and perv_imp Overland Flow Routing Condition (Uniform Storm)](image)

81
Figures 35 and 36 show an almost identical catchment outflow under different green roof runoff routing options. This indicates that the green roof runoff routing condition does not have a noticeable effect during very small or very large short-term storms. A possible explanation is for small storms, green roof runoff is not big enough for its routing to have an influence on catchment response, and for very large storms, precipitation rate exceeds infiltration rate, causing flow routed from green roofs to directly flow out of pervious areas to impervious areas with little infiltration. During a large storm scenario, the pervious area behaves more like an impervious area for green roof runoff, resulting in a decreased impact of the location to which green roof runoff is routed.
Figure 37. CIGM Outflow Comparison between Different Green Roof Runoff Routing Options under 20% Green Roof Coverage and perv_imp Overland Flow Routing Condition (Jan Storm)

Figure 38. CIGM Outflow Comparison between Different Green Roof Runoff Routing Options under 20% Green Roof Coverage and perv_imp Overland Flow Routing Condition (July Storm)
Figures 37 and 38 show a noticeable decrease of catchment outflow when more runoff from green roof is routed to pervious areas. The difference between the two real storms and the two hypothesized storms is that the duration of the real storms is much longer, and the intensity of the real storms falls between the values represented by the two hypothetical storms. Since the soil has a longer time to absorb water during the real storms more water is infiltrated for the real storms than for the two hypothetical storms.

For the January storm, the first peak discharge remains relatively constant with the green roof runoff routing options while the second peak discharge decreases when more runoff from green roofs is routed to the pervious area. Furthermore, the entire catchment runoff graphs overlap with each other in the beginning part of the rainfall, but differ later. This difference is due to the retention effect of the green roofs. Initially, all water is stored in the green roof, so it does not matter where the green-roof runoff is routed. However, when green roofs begin to release water, excess runoff from both the impervious and pervious area begins to change, which in turn affects catchment outflow.

The detailed reduction rate of catchment outflow volume and peak under the January and July storms are listed in Table 11. With 20% of green roof coverage and all overland flow routing from pervious to impervious area, catchment outflow decreases by 20% if all the green roof runoff is routed to pervious area, but this reduction rate is only around 6-8% if all the green roof runoff is routed to impervious area. Based on this result, it should be encouraged that the green roof runoff is routed to pervious area.
Table 11 Outflow comparison between different green roof runoff routing options (20% green roof coverage, pervious-impervious overland runoff routing)

<table>
<thead>
<tr>
<th></th>
<th>rout all green roof runoff to impervious area</th>
<th>50% to each</th>
<th>rout all green roof runoff to pervious area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jan 2008 storm</strong></td>
<td>volume reduction 6.59%</td>
<td>13.30%</td>
<td>20.00%</td>
</tr>
<tr>
<td></td>
<td>peak reduction 4.08%</td>
<td>12.04%</td>
<td>20.00%</td>
</tr>
<tr>
<td><strong>July 2007 Storm</strong></td>
<td>volume reduction 8.77%</td>
<td>14.41%</td>
<td>20.00%</td>
</tr>
<tr>
<td></td>
<td>peak reduction 6.87%</td>
<td>13.51%</td>
<td>20.00%</td>
</tr>
</tbody>
</table>

2. 100% Impervious-Pervious Overland Flow Routing

Green roof impact in impervious-pervious overland flow routing condition is an important issue in this research due to the increasing application of green technology in urban construction. Figures 39 to 42 display the comparison of catchment runoff between different green roof coverage, 10% to 40% with an increasing step of 10%, under impervious-pervious overland flow routing method in the four storms.
Figure 39. CIGM Outflow Comparison between Different Green Roof Coverage under imp-perv Overland Flow Routing Condition (Uniform Storm)

Figure 40. CIGM Outflow Comparison between Different Green Roof Coverage under imp-perv Overland Flow Routing Option (5yr ARI Storm)
Figure 41. CIGM Outflow Comparison between Different Green Roof Coverage under imp-perv Overland Flow Routing Option (Jan Storm)

Figure 42. CIGM Outflow Comparison between Different Green Roof Coverage under imp-perv Overland Flow Routing Option (July storm)
As shown in Figure 39, there is no outflow for the uniform 7.62 mm/hr storm in the impervious-pervious overland flow routing condition; therefore, different green roof coverage does not make any difference here. However, for the 5yr ARI storm, the volume and peak of catchment outflow both decrease as green roof coverage increases. The same results are seen for the July storm. Detailed reduction rates are shown in Table 12.

<table>
<thead>
<tr>
<th></th>
<th>10% coverage</th>
<th>20% coverage</th>
<th>30% coverage</th>
<th>40% coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5yr ARI Storm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>3.46%</td>
<td>6.84%</td>
<td>10.22%</td>
<td>13.55%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>4.27%</td>
<td>8.19%</td>
<td>11.70%</td>
<td>14.71%</td>
</tr>
<tr>
<td><strong>July 2007 Storm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume reduction</td>
<td>7.95%</td>
<td>15.08%</td>
<td>21.06%</td>
<td>26.52%</td>
</tr>
<tr>
<td>peak reduction</td>
<td>5.21%</td>
<td>10.27%</td>
<td>18.10%</td>
<td>24.14%</td>
</tr>
</tbody>
</table>

The 5yr ARI storm is a typical high-intensity/short-duration event. The July storm is relatively mild with a longer duration. By comparing these two storms in Table 12, it is seen that green roofs have a better retention effect in terms of catchment outflow volume and peak reduction for the July storm than for the 5yr ARI storm when the green roof coverage ratio is at the same level. Table 12 shows that under a 5yr ARI storm, peak discharge and total volume are reduced by about 3%-4% for every 10% of green roof application. For the July storm, Table 12 shows a greater reduction rate, with a volume decrease of around 7% and a peak discharge decrease of 5% with a 10% green roof coverage. This result shows that green roofs have better retention effect for lower-intensity and longer-duration storms.
Comparing Table 12 with Table 10, it can be seen that the same green roof coverage can have a better retention effect when overland flow is routed from pervious area to impervious area. For example, for the July 2007 storm, 10% of green roof coverage can decrease catchment peak outflow by 10% when overland flow is routed from pervious area to impervious area; however, catchment peak outflow is only reduced by 5% when overland flow is routed from impervious area to pervious area. A similar conclusion can be drawn for other storms. This shows that the overland flow routing has a greater impact on on the catchment outflow than green roof coverage.

For the January storm, there is not a big change in catchment outflow under different green roof coverage scenarios, as is shown in Figure 41. The reason is that in this rainfall event, the green roof is saturated before the peak rainfall arrives; it behaves like impervious area afterward. With impervious-pervious overland routing method, catchment outflow starts at a time close to the peak time of rainfall, when the green roof is already saturated. Therefore, regardless of the coverage of green roofs, they all behave like impervious areas at this time, and thus lead to invariance of the catchment outflow.

3. Combination of the Two Overland Flow Routing Options

As mentioned before, in urban catchments, overland runoff routing is neither 100% from impervious areas to pervious areas, nor 100% from pervious areas to impervious areas. The actual condition is usually a combination of both. As described in section 4.4, 20% green roofs were tested on an urban catchment with 70% overland flow routing from pervious to impervious area and 30% overland flow routing from impervious to pervious.
Figures 43 and 44 show the results of this scenario in the January and July storm, respectively (all green roof runoff is routed into pervious area).

Figure 43. CIGM Outflow under the Scenario of 20% Green Roof Coverage, 70% perv-imp and 30% imp-perv Overland Flow Routing Condition (Jan Storm)

Figure 44. CIGM Outflow under the Scenario of 20% Green Roof Coverage, 70% perv-imp and 30% imp-perv Overland Flow Routing Condition (July Storm)
In the January storm, the first and second runoff peak decreased 22% and 18.6% respectively. The first peak declined more than the second peak because the green roof held water at the beginning of the rainfall event offering a greater dampening capacity during this time. When the second rainfall peak arrived, the green roofs had already begun to release flow, resulting in a higher catchment discharge during the second peak time. This resulted in a smaller decrease of peak discharge. In the July storm, peak reduction was around 17%.

4.6.4 SWMM Comparison

As mentioned in section 4.5, several green roof scenarios were also simulated in SWMM. Figures 45 and 46 show a comparison of the catchment outflow between SWMM and CIGM for a non-green roof scenario under the January 2008 storm and the July 2007 storm, respectively.

![Figure 45. Catchment outflow comparison between CIGM and SWMM under non-green roof scenario for January 2008 storm](image)
The peak discharges, time to peak, and outflow volume for both storms under the non-green-roof scenario, are summarized in Table 13 and 14. For the January 2008 storm, the first peak discharge from CIGM is 8% smaller than from SWMM, and the second peak discharge values from the two models are almost identical. The time to first peak from
CIGM is 9 minutes later than from SWMM, but the time to second peak from both models is the same. The volume of catchment outflow from CIGM is 2.2% larger than that from SWMM. For the July 2007 storm, the peak discharges from the two models are almost the same; the time to peak from CIGM is 2 minutes later; and the volume of catchment outflow from CIGM is 2.5% larger. From these data, it can be determined that the catchment outflows from the two models display a good agreement.

Now consider the following scenario: 20% green roof coverage, all green roof runoff routing to impervious area, and overland flow routing from pervious area to impervious area. Figures 47 and 48 show a comparison of catchment outflow between CIGM and SWMM for this scenario. Catchment outflow results are shown in Figure 49 and 50 for a green roof coverage increased to 40%.

Figure 47. Catchment outflow comparison between CIGM and SWMM under 20% green roof scenario for January 2008 storm.
Figure 48. Catchment outflow comparison between CIGM and SWMM under 20% green roof scenario for the July 2007 storm

Table 15 Outflow comparison between CIGM and SWMM under 20% green roof scenario for Jan 2008 storm

<table>
<thead>
<tr>
<th>January 2008 Storm</th>
<th>first peak discharge (m³/s)</th>
<th>second peak discharge (m³/s)</th>
<th>time to first peak (min)</th>
<th>time to second peak (min)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWMM</td>
<td>4.66</td>
<td>5.37</td>
<td>242</td>
<td>902</td>
<td>2107.73</td>
</tr>
<tr>
<td>CIGM</td>
<td>3.91</td>
<td>5.81</td>
<td>250</td>
<td>902</td>
<td>2193.88</td>
</tr>
</tbody>
</table>

Table 16 Outflow comparison between CIGM and SWMM under 20% green roof scenario for July 2007 storm

<table>
<thead>
<tr>
<th>July 2007 Storm</th>
<th>peak discharge (m³/s)</th>
<th>time to peak (min)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWMM</td>
<td>8.39</td>
<td>361</td>
<td>1141.13</td>
</tr>
<tr>
<td>CIGM</td>
<td>8.93</td>
<td>364</td>
<td>1223.68</td>
</tr>
</tbody>
</table>

Tables 15 and 16 summarize the outflow characteristics for both storms under the 20% green roof scenarios. For the January 2008 storm, when green roof coverage is 20%, the
first peak discharge from CIGM is 8% smaller than from SWMM, and the second peak discharge values from the two models are almost identical. The time to first peak from CIGM is 10 minutes later than that from SWMM, and the time to second peak from both models is the same. The volume of catchment outflow from CIGM is 2.2% larger than that from SWMM. For the July 2007 storm, the peak discharge from CIGM is 6% larger; the time to peak from CIGM is 3 minutes later; and the volume of catchment outflow from CIGM is 6.7% larger.

Figure 49. Catchment outflow comparison between CIGM and SWMM under 40% green roof scenario for January 2008 storm
Table 17 Outflow comparison between CIGM and SWMM under 40% green roof scenario for Jan 2008 storm

<table>
<thead>
<tr>
<th>January 2008 Storm</th>
<th>first peak discharge (m³/s)</th>
<th>second peak discharge (m³/s)</th>
<th>time to first peak (min)</th>
<th>time to second peak (min)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWMM</td>
<td>3.98</td>
<td>4.66</td>
<td>242</td>
<td>902</td>
<td>1736.16</td>
</tr>
<tr>
<td>CIGM</td>
<td>2.93</td>
<td>5.08</td>
<td>251</td>
<td>902</td>
<td>1881</td>
</tr>
</tbody>
</table>

Table 18 Outflow comparison between CIGM and SWMM under 40% green roof scenario for July 2007 storm

<table>
<thead>
<tr>
<th>July 2007 Storm</th>
<th>peak discharge (m³/s)</th>
<th>time to peak (min)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWMM</td>
<td>7.18</td>
<td>361</td>
<td>976.95</td>
</tr>
<tr>
<td>CIGM</td>
<td>7.67</td>
<td>365</td>
<td>1032.05</td>
</tr>
</tbody>
</table>

The outflow characteristics for both storms under the 40% green roof scenarios were listed in Table 17 and 18. When green roof coverage is 40%, for the January 2008 storm, the first peak discharge from CIGM is 26% smaller than from SWMM, and the second peak discharge is 9% larger. The time to first peak from CIGM is 10 minutes later than that from SWMM, and the time to second peak from both models are the same. The
volume of catchment outflow from CIGM is 7.7% larger than that from SWMM. For the July 2007 storm, the peak discharge from CIGM is 6.3% larger; the time to peak from CIGM is 4 minutes later; and the volume of catchment outflow from CIGM is 5.3% larger.

Comparing the three green roof scenarios above between CIGM and SWMM, several characteristic behaviors can be identified. Regarding the January 2008 storm, for 20% green roof coverage scenario, both models show approximately an 8% decrease in outflow volume, but CIGM shows a larger decrease in the first peak discharge and smaller decrease in the second peak discharge compared with SWMM. For the 40% green roof scenario, both models show approximately a 15% decrease in volume, and CIGM shows a larger decrease in first peak charge than SWMM, but the decrease in second discharge is almost the same for the two models (around 13%). Regarding the July 2007 storm, for the 20% green roof coverage scenario, both models show approximately a 50% decrease in outflow volume, but CIGM shows a 7% decrease in peak discharge while SWMM shows a 12% decrease in peak discharge. For the 40% green roof scenario, both models show approximately a 14% decrease in peak discharge and a 57% decrease in outflow volume. The differences between the decrease amounts from the two models may result from the inaccuracy of green roof implementation methods in the SWMM model, or the limitation of green roof modeling method in this study. But generally the two models show similar results. The results from CIGM and SWMM show that CIGM, as a probabilistically based approach, can confidently be used in place of SWMM.
CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

The results analysis in section 4 can lead to the following conclusions:

1) The impervious-pervious overland runoff routing method can significantly decrease the volume and peak of the catchment outflow. The time to peak is also postponed when compared with the pervious-impervious overland flow routing condition.

2) Green roofs do not have as good retention effect in high-intensity short-duration storm as in low-intensity short-duration storms. Green roofs have better retention effect for low-intensity long-duration storms than high-intensity long-duration events.

3) Catchment outflow can be further decreased by routing more of the green-roof runoff to pervious area. It should be encouraged that all the green roof runoff is routed to pervious area.

4) Routing overland flow from impervious area to pervious area has a bigger effect to decrease catchment outflow volume than implementing 40% green roofs.

5) The changing of green roof coverage has a bigger influence to catchment outflow than the changing of green roof runoff routing.

5.2 Limitation and Future Work

The green roof model used in this study was built based on theoretical hydrologic mechanisms. Although it was calibrated with the observed data from the green roof on
BIF building in UIUC campus, the calibration results are still not good enough to give an accurate prediction of runoff behavior during storms due to the limitation of the modeling methods. This model could only provide a tool for understanding how the implementation of green roofs can affect urban catchment under different conditions, which is the main objective of this study. In future work, more accurate method could be developed for deriving rainfall-runoff relationship for green roofs. With modification, the incorporation method of IUHM and green roof developed in this study could be extended to more BMPs, like rain gardens, vegetated swales, and permeable pavements. This would provide a tool for studying impact from various BMPs implemented in urban catchment. The framework of adapting IUHM to take account of multiple kinds of BMPs could also be a future research topic.

In the green roof and IUHM incorporation section, green roof runoff was assumed to be applied uniformly to the region where it is routed. This is not what happens under real conditions: green roof runoff is routed to impervious or pervious area through pipes, which means water will flow only on its path and not on the whole region. However, this assumption won’t have an effect on the excess runoff from impervious area because all the water arriving will become excess runoff regardless of how it is transported. For the permeable area, this assumption may have some impact. Spatial distribution of water is more helpful for infiltration than concentrated runoff, especially in high-intensity rainfall event. Green roof pipe inflow may not be infiltrated as well as when it is distributed on a larger area, thus maybe more excess runoff will come out from pervious area in reality while in the model this additional runoff is ignored because it is considered as having
infiltrated. The influence of this assumption was beyond the scope of this study, but it could provide a topic for future research.
REFERENCES


Hilten, Roger N. et al. (2008). Modeling stormwater runoff from green roofs with Hydrus-1D.


Metropolitan Water Reclamation District of Greater Chicago (MWRDGC), Tunnel and reservoir lan (TARP), 1999.


Appendix A

% Yun Tang
% Feb 17, 2011

% This simple model is for generating rainfall-runoff relationship on green roof.
% All the unit here is in water depth, in or in/hr
% simulation starts from the 1st rainfall event

rain=xlsread('\130.126.242.76\tarp\USER_FOLDERS\yuntang1\MasterThesis\Rainfall\Rainfall_Jan.xls','Rain','j2:j182');

dt=1/60; % time steps in hrs.
nr=length(rain);
De=8;% depth of growing media (sandy loam), inch
K=1.5;% hydraulic conductivity, inch/hr
Sw=4.33;% soil water suction head, inch
theta_i=0.17;% initial soil moisture content(residual moisture content)
theta_s=0.55;% saturated soil moisture content, porosity
theta_f=0.2;% field capacity
RF=1;% recovery factor
hc=0.2;% height of overflow collar, inch
Cd=3.33;% weir coefficient
L=622;% length of weir, inch
sc=5;% the ratio of green roof area to gravel area
A=96.38;% area of green roof, square inch
AG=19.12;% area of gravel, square inch

a=1;% gravel bucket, calibration factor for green roof runoff
b=0.06;% green roof bucket, calibration factor for underdrain when soil moisture between field capacity and saturation
c=0.2;% gravel bucket, calibration factor for green roof runoff
alpha=14;% green roof bucket
lamda=0.01;% calibration factor for runoff occured in recession submodule

beta=1;

%=== parameters

theta=zeros(length(t),1);% moisture content
f=zeros(length(t),1);% infiltration rate calculated by Green-Ampt Method
F=zeros(length(t),1);% cumulative infiltration calculated by Green-Ampt Method
q=zeros(length(t),1);% green roof run off, inch/hr
u=zeros(length(t),1);% underdrain, inch/hr
o=zeros(length(t),1);% overflow, inch/hr
% ponding depth
p_f=zeros(length(t),1);
% potential infiltration rate
SA=zeros(length(t),1);
% Water storage in green roof soil, inch
SB=zeros(length(t),1);
% Water storage in gravel, inch
ac_f=zeros(length(t),1);
% actual infiltration rate
excess_rain=zeros(length(t),1);
% rainfall which could not be infiltrated
Q=zeros(length(t),1);
% cumulative runoff, inch
qo=zeros(length(t),1);
% overflow on green roof, inch/hr
Crain=zeros(length(t),1);
% cumulative rainfall on green roof, inch

theta(1)=theta_i;
for i=1:length(t)
    rng(1) = K*t(i);
    rng(2) = K*t(i) + Sw*log(1 + 10*K*t(length(t)) /
                                (Sw*(theta_s-
                                 theta_i)));
    F_func = @(x)(x/K - (Sw-h(i))*(theta_s-
                         theta_i)/K*log(1+x/((Sw-h(i))*(theta_s-
                         theta_i)))) - t(i);
    F(i)=fzero(F_func,rng);
    f(i)=K*K*(Sw-h(i))*(theta_s-
                 theta_i)/F(i);
end
j=1;
for i=1:length(t)-1
    if rain(i)~=0 % enter rainfall event,
        event_start=i;
        if theta(i)<theta_f;
        % infiltration submodule, Green-Ampt Method
            excess_rain(i)=rain(i)-f(j);
            ac_f(i)=f(j);
            SA(i+1)=SA(i)+ac_f(i)*dt-u(i)*dt;
            theta(i+1)=theta_i+SA(i+1)/De;
            h(i+1)=h(i)+rain(i)*dt-ac_f(i)*dt;
            u(i+1)=0;
            o(i+1)=0;
            if h(i+1)>hc
                o(i+1)=Cd*L*(h(i+1)-hc)^(3/2)/A;
                h(i+1)=h(i+1)-o(i+1)*dt;
            end
            SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-
                      q(i)*dt*(sc);
            q(i+1)=c*SB(i+1)^a/dt;
        end
        if excess_rain(i)<0
            if h(i)>0;
                ac_f(i)=f(j);
                SA(i+1)=SA(i)+ac_f(i)*dt-u(i)*dt;
                theta(i+1)=theta_i+SA(i+1)/De;
                h(i+1)=max(0,h(i)+rain(i)*dt-ac_f(i)*dt);
                u(i+1)=0;
            end
        end
    end
end
o(i+1)=0;
if h(i+1)>hc
    o(i+1)=Cd*L*(h(i+1)-hc)^3/2)/A;
    h(i+1)=h(i+1)-o(i+1)*dt;
end
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
else
    ac_f(i)=rain(i);
    SA(i+1)=SA(i)+ac_f(i)*dt-u(i)*dt;
    theta(i+1)=theta+i+SA(i+1)/De;
    h(i+1)=h(i);
    u(i+1)=0;
    o(i+1)=0;
end
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
end
q(i+1)=c*SB(i+1)^a/dt;

elseif theta(i)>=theta_f&&theta(i)<theta_s %field capacity is exceeded, but not saturated yet, runoff occurs

    excess_rain(i)=rain(i)-f(j);
    ac_f(i)=f(j);
    SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
    theta(i+1)=theta_i+SA(i+1)/De;
    h(i+1)=h(i)+rain(i)*dt-ac_f(i)*dt;
    u(i+1)=b*SA(i+1)^alpha/dt;
    o(i+1)=0;
    if h(i+1)>hc
        o(i+1)=Cd*L*(h(i+1)-hc)^3/2)/A;
        h(i+1)=h(i+1)-o(i+1)*dt;
    end
end
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
q(i+1)=c*SB(i+1)^a/dt;

if excess_rain(i)<0
    if h(i)>0
        ac_f(i)=f(j);
        SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
        theta(i+1)=theta_i+SA(i+1)/De;
        h(i+1)=max(0,h(i)+rain(i)*dt-ac_f(i)*dt);
        u(i+1)=b*SA(i+1)^alpha/dt;
        o(i+1)=0;
        if h(i+1)>hc
            o(i+1)=Cd*L*(h(i+1)-hc)^3/2)/A;
            h(i+1)=h(i+1)-o(i+1)*dt;
        end
    else
        ac_f(i)=rain(i);
        SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
        theta(i+1)=theta_i+SA(i+1)/De;
        h(i+1)=h(i);
        u(i+1)=b*SA(i+1)^alpha/dt;
        o(i+1)=0;
    end

106
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
end
q(i+1)=c*SB(i+1)^a/dt;
end

elseif % saturated submodule,
  if h(i)>0
    u(i)=K*(De+h(i))/De;
    ac_f(i)=f(j);
    SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
    if SA(i+1)>De*theta_s
      SA(i+1)=De*theta_s;
    end
    theta(i+1)=theta_i+SA(i+1)/De;
    h(i+1)=max(0,h(i)+rain(i)*dt-ac_f(i)*dt);
    u(i+1)=K*(De+h(i+1))/De;
    o(i+1)=0;
    if h(i+1)>hc
      o(i+1)=Cd*L*(h(i+1)-hc)^3/2/A;
      h(i+1)=h(i+1)-o(i+1)*dt;
    end
    SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
    q(i+1)=c*SB(i+1)^a/dt;
  end
else
  u(i)=K*(De+h(i))/De;
  ac_f(i)=f(j);
  SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
  if SA(i+1)>De*theta_s
    SA(i+1)=De*theta_s;
  end
  theta(i+1)=theta_i+SA(i+1)/De;
  h(i+1)=max(0,h(i)+rain(i)*dt-ac_f(i)*dt);
  u(i+1)=K*(De+h(i+1))/De;
  o(i+1)=0;
  if h(i+1)>hc
    o(i+1)=Cd*L*(h(i+1)-hc)^3/2/A;
    h(i+1)=h(i+1)-o(i+1)*dt;
  end
  SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
  q(i+1)=c*SB(i+1)^a/dt;
end
elseif rain(i)==0&&h(i)>0%enter interenvent time, but still ponding
  if theta(i)<theta_s
    ac_f(i)=f(j);
    SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
    theta(i+1)=theta_i+S(i+1)/De;
    h(i+1)=max(0,h(i)-ac_f(i)*dt);
    u(i+1)=b*SA(i+1)^alpha/dt;
    o(i+1)=0;
    if h(i+1)>hc
      o(i+1)=Cd*L*(h(i+1)-hc)^3/2/A;
      h(i+1)=h(i+1)-o(i+1)*dt;
    end
    SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
    q(i+1)=c*SB(i+1)^a/dt;
  end
end
end
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
q(i+1)=c*SB(i+1)^a/dt;

else
ac_f(i)=min(f(j),q(i));
SA(i+1)=max(0,SA(i)+ac_f(i)*dt-u(i)*dt);
if SA(i)>De*theta_s
   SA(i)=De*theta_s;
end
theta(i+1)=theta_i+SA(i+1)/De;
h(i+1)=max(0,h(i)-ac_f(i)*dt);
u(i+1)=K*(De+h(i+1))/De;
o(i+1)=0;
if h(i+1)>hc
   o(i+1)=Cd*L*(h(i+1)-hc)^3/2/A;
h(i+1)=h(i+1)-o(i+1)*dt;
end
SB(i+1)=SB(i)+u(i)*dt*sc+o(i)*dt*sc-q(i)*dt*(sc);
q(i+1)=c*SB(i+1)^a/dt;
end % Recession submodule
ac_f(i)=0;
SA(i+1)=max(0,SA(i)-u(i)*dt);
if SA(i+1)>De*theta_s
   SA(i+1)=De*theta_s;
end
theta(i+1)=theta_i+SA(i+1)/De;
h(i+1)=0;
u(i+1)=u(i)*exp(-lamda);
o(i+1)=0;
SB(i+1)=SB(i)+u(i)*dt*sc-q(i)*dt*(sc);
q(i+1)=c*SB(i+1)^a/dt;

end
j=j+1;
end

Q(1)=0.5*dt*q(1);
for i=2:nr
   Q(i)=Q(i-1)+q(i-1)*dt+0.5*(q(i)-q(i-1))*dt;
end