

# Exploring the Response of Combined Urban Sewer System to the Implementation of Green Roof

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**Abstract.** In order to find an efficient and reliable method for assessing the impact of green roofs on runoff in urban areas, IUHM-GreenRoof combination model is established via Matlab. Taking CDS-51 catchment located in Dolton, Illinois as a case, and considering different green roof coverage ratios as well as runoff conditions, the influence on the catchment outlet runoff because of the application of green roofs is analysed by running the model in two typical storms. The results show that green roofs have good water storage capacity, which can effectively decrease the catchment runoff in terms of peak discharge and volume. Moreover, the green roof coverage ratio has more influence on runoff than green roof runoff conditions.

## 1. Introduction

With the high-speed development of urbanization, urban landscapes are constantly changing, with far more impervious surfaces than natural watersheds. The sealing effects of impervious surface result in a series of environmental problems within urban catchments, such as storm water flooding, which has become an issue of major concerns in the US, especially in some big cities with dense population and frequent rainfall events[1].

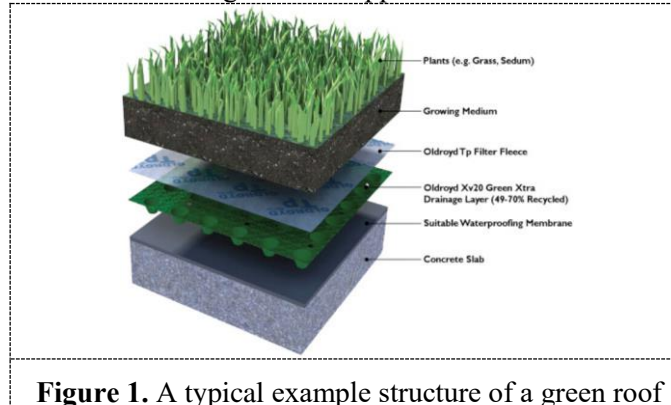
Due to the side effects brought by urban expansion, various sustainable development strategies has appeared, such as rain gardens, green roofs and permeable pavements, to help manage storm water. Green roof technology has become a popular strategy for retaining rainfall and reducing storm runoff, especially in ultra-urban areas where space is too limited to implement other best management practices (BMPs). Green roof is a relatively independent vegetation system built on building roofs, which is conventionally composed of six components: (1) plants; (2) a growing media; (3) a geotextile filter fabric; (4) a drainage layer; (5) a waterproofing; (6) the roof deck[2] (Figure 1). Green roofs have many environmental and financial benefits for urban catchment, focusing on managing stormwater, green roofs can: postpone the starting time of runoff; mitigate stormwater runoff; distribute the runoff over a longer period. Thus green roofs make urban hydrological cycle tend to approach the natural one, and lower urban flooding risk as well.

Up to now, various models have been developed for the hydrological process of green roofs. Hilten et al.[1] conducted a study on the effectiveness of green roofs to mitigate stormwater runoff by using HYDRUS-1D. Kasmin et al.[3] built a simple conceptual model composed of a substrate moisture storage component and a transient storage component, in order to find a robust method to identify monthly evapotranspiration values. Versini et al.[4] developed a conceptual model and integrated it into SWMM to reproduce the hydrological behavior of green roofs from building scale to basin scale. A commonality among these methods is that they are not physically based in their representation of



the underlying hydrologic and hydraulic processes of green roofs, meanwhile require burdensome input data, which restrict their use.

The scope of this paper is to develop a mathematical model for green roofs, incorporate it into IUHM appropriately to explore the influence of green roof application on urban runoff.



**Figure 1.** A typical example structure of a green roof

## 2. Modeling

### 2.1. Illinois Urban Hydrologic Model (IUHM)

The Illinois Urban Hydrologic Model (IUHM) is a mathematical model built by Cantone and Schmidt (2010) for simulating complex urban sewer system. It is rooted in the initial concept of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) developed by Rodriguez-Iturbe and Valdes (1979)[5]. By using the Strahler ordering procedure, an urban catchment of order,  $\Omega$ , can be defined into either overland state or conduit state. In each state, the travel times are calculated based on the kinematic wave assumption. When a drop of water falls on the catchment, it will flow from lower order to higher order, until reaches the outlet of the sewer system[6]. With the overland area being sub-divided into pervious and impervious regions, the total number of water possible flow path would be  $2^\Omega$ . For each path there is a corresponding exponential distribution of travel time in each state. Combining the travel time probability-density-function with the probability of a drop of water taking a certain pathway, the network impulse response function could be derived. The catchment runoff hydrograph is then determined by combining the network impulse response function and the excess runoff for all possible paths.

Unlike traditional deterministic models, IUHM can still give a highly accurate output without detailed parameters of all pipes and overland signatures which are not always available. Also, IUHM has been setup to allow the incorporation of other hydrologic and hydraulic processes, for example, the best management practices (BMPs), which makes the subsequent integration easy to implement.

### 2.2 Green Roof Model

Green-Ampt method was used to calculate infiltration capacity in the model. This model divided the whole rainfall-runoff process into four states.

**2.2.1. Initial state.** At the beginning of a precipitation event, soil water content keeps increasing, but does not reaches field capacity. All rainfall is infiltrated and stored in soil. The runoff intensity is 0.

**2.2.2. Pre-saturated state.** In this phase, soil moisture content exceeds field capacity but soil is not saturated yet. As rainfall continues infiltrating, water flow out of the soil layer and runoff occurs. Green roof was assumed to be a linear reservoir in this state, thus discharge rate would be proportional to the realtime water storage in the soil column. The runoff intensity is calculated by equation 2.1.

$$q(t) = a * S(t) / dt \quad (2.1)$$

$$S(t + \Delta t) = S(t) + f(t) * dt - q(t) * dt \quad (2.2)$$

$q(t)$ : runoff intensity at time  $t$ , inch/hour;  $S$ : real-time soil water storage, inch;  $a$ : calibration factor;  $dt$ : time step, hour;  $f$ : infiltration rate, inch/hour.

**2.2.3. Saturated state.** Runoff at the second state is much smaller compared with water infiltrated in, so soil water storage continues increasing. When soil water content reaches saturated moisture content,

soil becomes saturated. In this state, the whole system reaches a relative balanced state. Darcy's Law is used to calculate runoff intensity.

$$q(t) = K * \frac{D + h(t)}{D} \quad (2.3)$$

$K$ : saturated hydraulic conductivity, inch/hour;  $D$ : soil depth, inch;  $h$ : ponding depth, inch.

**2.2.4. Recession state.** In this state, rainfall stops and ponding water is also consumed up by infiltration or evapotranspiration, but runoff still continues because of the water stored in the soil column in previous phases. However, the discharge rate will decrease as time goes. In this study, runoff was assumed to follow an exponential decay. The runoff intensity is calculated by equation 2.4.

$$q(t + \Delta t) = q(t) * e^{-\lambda} \quad (2.4)$$

$\lambda$ : calibration factor.

### 2.3. Combined IUHM-GreenRoof Model

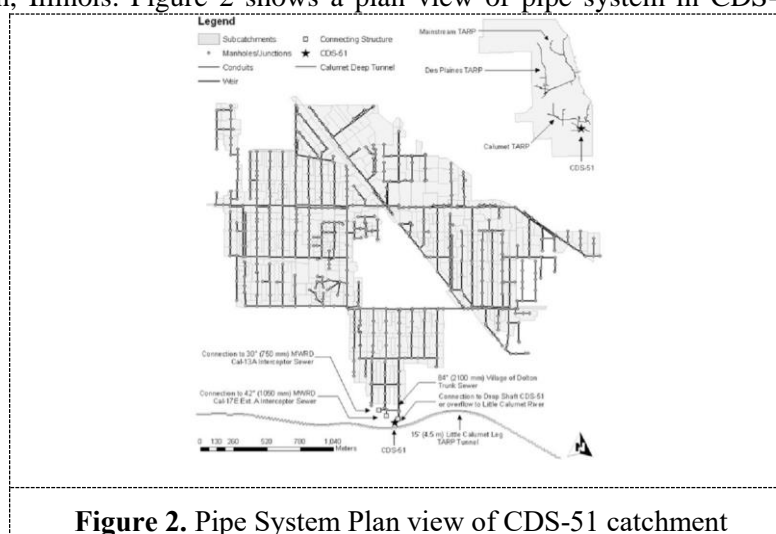
Green roof model was embedded into IUHM as a function without changing the IUHM code too much. Important changes of the original code are listed as follows compared with the original IUHM:

- (1) A variable of green roof coverage ratio is defined based on the impervious area, denoted as "grratio". In other words, if it is given a value of 20%, then 20% of the impervious area will be replaced by green roof. Users can change its value to test the effect of different green roof coverage.
- (2) A variable of routing part of green roof runoff to impervious area is introduced into the model, with a value ranging from 0 to 1, denoted as "grimp". If its value is set to 0, that means all green roof runoff will be routed to pervious area; if indicated as 1, then all green roof runoff will be routed to impervious area. Users can alter its value for testing the difference of various routing ways.
- (3) Due to the introduction of green roof coverage, the original impervious area will be correspondingly decreased by the same ratio. Meanwhile, the average impervious overland flow length will be decreased due to the reduction of impervious area. The excess runoff on both impervious and pervious overland regions will also be changed due to the inflow of green roof runoff

## 3. Case Study

### 3.1. Calumet Drop Shaft 51 catchment (CDS-51)

The CDS-51 catchment is a 5th-order complex urban system with an area of 782 acre, located in the Village of Dolton, Illinois. Figure 2 shows a plan view of pipe system in CDS-51. The catchment



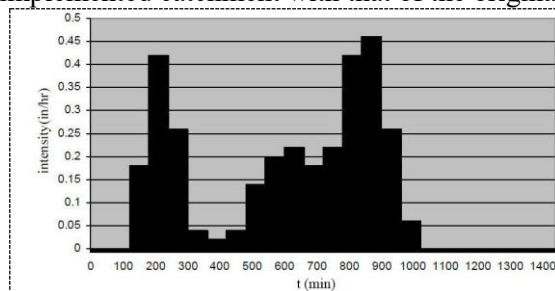
**Figure 2.** Pipe System Plan view of CDS-51 catchment

captures combined storm and sanitary flows and delivers them to Calumet system of Chicago's Tunnel and Reservoir Plan (TARP)[6]. The combined sewers flow from lower-order pipes to higher-order ones until end up in a 5th order pipe with a diameter of 2150mm. In this study, catchment outlet runoff will be used as the comparing variable to testify the effect of green roof application.

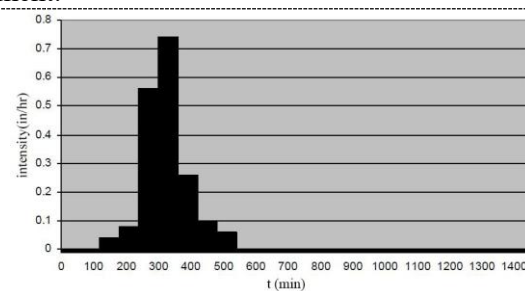
### 3.2. Rainfall Events

Two typical rainfall storms were chosen to test the behavior of the combined IUHM-GreenRoof Model: (1) January storm in 2008, a low intensity, long duration event, started at 18:00 and lasted 15 hours, with a peak intensity of 0.46 in/h and a total precipitation is 3.12 in.; (2) July storm in 2007, a high intensity, short duration event, started at 02:00 and was 7 hours long, with a peak intensity of 0.74 in/h and a total precipitation of 1.84 in. Figure 3 and 4 shows the rainfall intensity of January 2008 storm and July 2007 storm respectively.

The reason for choosing these two storms is that Cantone (2010) has simulated the same rainfall events using IUHM, and proved that IUHM-derived runoff matching the actual flow data for CDS-51 well, which ensures the credibility of the comparison between the runoff behavior of green-roof-implemented catchment with that of the original catchment.



**Figure 3.** Rainfall intensity of January Storm



**Figure 4.** Rainfall intensity of July Storm

### 3.3. Extensive Green Roof

**Table 1.** Input parameters for green roof.

parameter	value	unit
growing medium depth	8	in
saturated hydraulic conductivity	0.43	in/h
soil water suction head	4.33	in
initial soil moisture content	0.041	
field capacity	0.18	
saturated soil moisture content	0.453	
overflow collar height	4.72	in
evapotranspiration rate	0.0018	in/h
depression storage	0.15	in
linear reservoir calibration factor "a"	0.0025	
recession state calibration factor "λ"	0.002	

An extensive green roof with 8 in deep sandy loam was simulated. Most hydraulic parameters for the growing medium are listed in Table 1. For effective comparison, depression storage of 0.15 in was assumed for green roof as it was the same in IUHM. Evapotranspiration rate was set as 0.0018 inch/hour according to a study done by Rezaei (2005). This value was used in recession state.

### 3.4. Simulation

As mentioned before, there are two kinds of routing method for overland flow in IUHM, one is routing overland runoff from pervious regions to impervious regions (referred as the pervious-impervious case), and the other is inverted (referred as impervious- pervious case). For both of these two cases, the original IUHM has first been run for later comparison.

In pervious-impervious case: (1) To research the influence from different green roof coverage, assuming all green roof runoff would be routed to previous area, green roof coverage ratio was set for

20%, 30%, 40%, and 50%, respectively. (2) To research the effect of altering green roof runoff routing method, a simulation of routing all green roof runoff to impervious area, or pervious area, or 50% to each, has all been run respectively, with 20% green roof coverage.

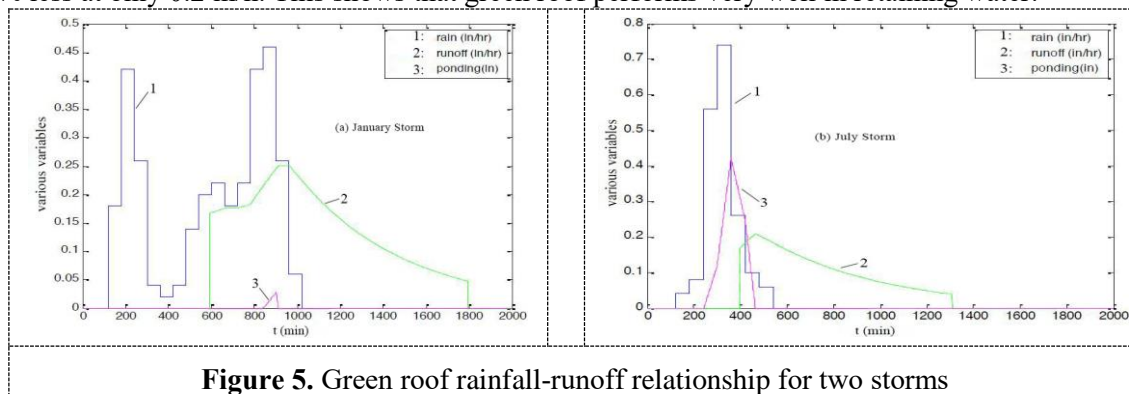
In impervious-pervious case: only different green roof coverage (20%, 30%, 40%, and 50%) would be explored for the catchment to test for different impact to catchment outlet runoff.

Combination case: the pre-proposed methods are extreme conditions, the combination of these two conditions can be realized by simply giving a percentage based on the actual situation.

#### 4. Results and Discussion

##### 4.1. Green Roof Rainfall-Runoff Relationship

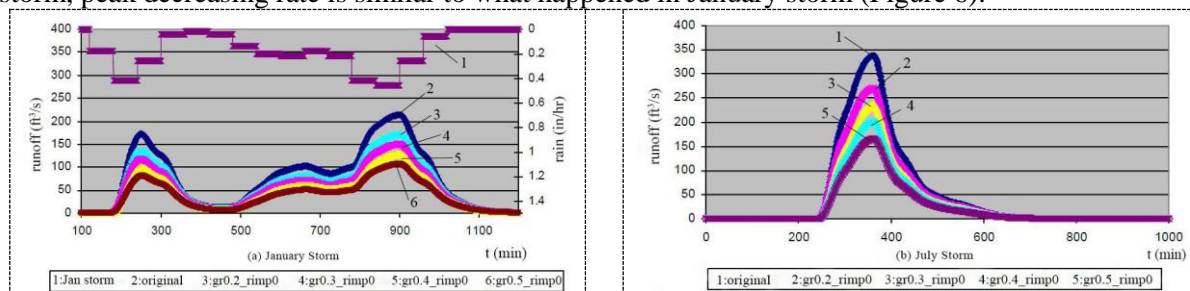
The infiltration mechanism of green roofs leads to a unique rainfall-runoff relationship (Figure 5). Compared with rainfall, green roof runoff starts at a later time with a lower peak. For the January storm, green roof peak discharge is about 0.25 in/h, which is 45.7% less than peak rainfall intensity. This retention effect is even better during the July storm, in which green roof peak discharge is about 73% less at only 0.2 in/h. This shows that green roof performs very well in retaining water.



**Figure 5.** Green roof rainfall-runoff relationship for two storms

##### 4.2. Green Roof Impact in Pervious-Impervious Condition

Pervious-impervious condition is more prevalent in urban areas. In January storm, for every 10% increase in green roof coverage, the first and second peak runoff is decreased by nearly 10%. For July storm, peak decreasing rate is similar to what happened in January storm (Figure 6).

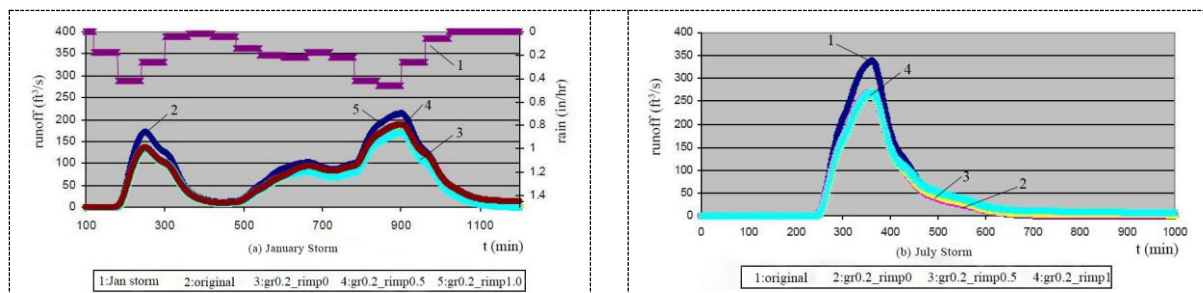


**Figure 6.** Catchment runoff comparison with different green roof coverage for two storms

This shows that green roofs have a similar retention effect for both two types of storm under pervious-impervious case.

Except for the overland flow routing method, the green roof runoff routing condition would also affect catchment outlet runoff (Figure 7). For the January storm, peak discharge tends to be smaller when more green roof runoff is routed to the permeable area. This is reasonable because permeable area can absorb and allow more water infiltration. However, it should be noted that the first peak discharge almost doesn't change while the second peak apparently decreases. This reflects the retention effect of the green roof. At the beginning of a rainfall event, the green roof stores all water infiltrated and slowly releases it after the soil capacity is exceeded. At the time of the first rainfall peak, the green roof still holds all water falling on it, but when the second rainfall peak comes, it has already begun to release flow.



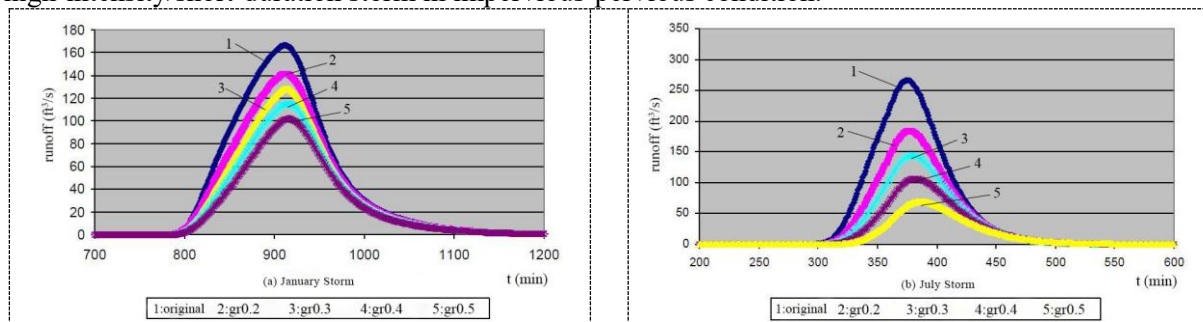


**Figure 7.** Catchment runoff comparison with different green roof runoff routing methods for two storms (20% green roof application).

For the July storm, the entire catchment runoff graphs seem to overlap with each other. Possible reason is that the storm intensity is too high compared with infiltration capacity, even if green roof runoff is routed to permeable regions, it still cannot be infiltrated and becomes the excess runoff. For both storms, the routing ratio of green roof runoff has a smaller effect to catchment runoff than green roof coverage does.

#### 4.3. Green Roof Impact in Impervious-Pervious Condition

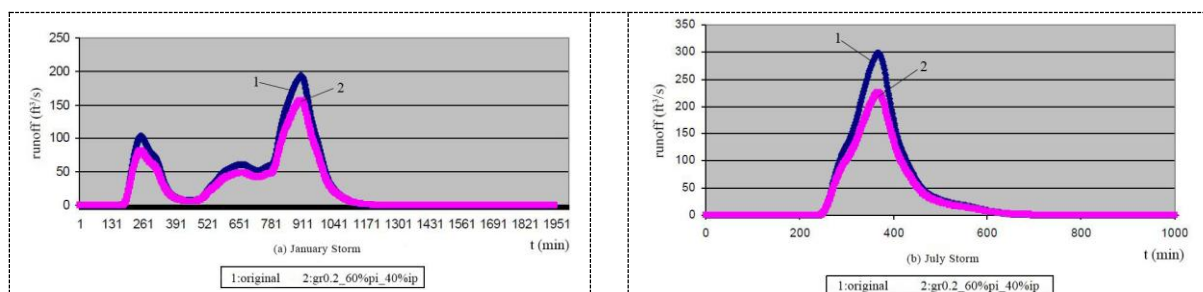
Under impervious-pervious condition, catchment runoff volume and peak both decrease as green roof coverage increases (Figure 8). However, the peak discharge decreasing rate of the July storm is almost twice than that of the January storm. This shows that green roofs have a better retention effect for the high-intensity/short-duration storm in impervious-pervious condition.



**Figure 8.** Catchment runoff comparison with different green roof coverage for two storms.

#### 4.4. Green Roof Impact in Combined Condition

Figure 9 shows how 20% green roof works on an urban catchment with 60% overland flow routing from pervious to impervious area and 40% in the inverted way. In January storm, the first and second runoff peak decreased 22% and 18.6%, respectively. In July storm, peak reduction was around 22%.



**Figure 9.** Catchment runoff comparison with combined condition for two storms

### 5. Conclusion and Future Work

Form the results analysis above, several conclusions can be drawn:

(1) Under pervious-impervious condition, green roofs have similar retention effect for both two types of storm. Catchment runoff tends to have higher peak if more green roof runoff is routed to impervious area. However, this effect diminishes for the high-intensity/short-duration rainfall event. In addition, green roof coverage has bigger effect to catchment runoff than green roof runoff routing ratio.

(2) Under impervious-pervious condition, catchment runoff volume and peak both decrease as green roof coverage increases. Meanwhile, green roofs have a better retention effect for high-intensity/short-duration storm than low-intensity/long-duration rainfall event.

(3) In combined condition, 20% green roof application could decrease catchment runoff peak by about 22% for both storm types. However, this value could change with the percentage of overland flow routing methods, resulting in a more complicated condition.

The incorporation method of IUHM and green roof developed in this study provide a tool for understanding how the implementation of green roofs can affect urban catchment under different conditions. With modification, it could be extended to more BMPs. The framework of adapting IUHM to kinds of BMPs could also be a research topic.

## 6. Reference

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