COMPARING THE EFFECTIVENESS OF RAIN BARRELS AND DETENTION PONDS ON PEAK FLOW REDUCTION IN A SEMI-URBAN WATERSHED

by

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ABSTRACT

Author: Lyu, Zhenglyu. MSCE
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Title: Comparing the Effectiveness of Rain Barrels and Detention Ponds on Peak Flow Reduction in a Semi-Urban Watershed
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Rain barrels are useful for stormwater management where conditions of on-site space are limited for retrofitting techniques. This paper aims at determining the scope of the effectiveness of rain barrels on reduction of direct runoff peak flow and volume. The Sugar Creek Watershed in the northwest of Illinois is simulated with a historical storm and design storms of 2-, 10-, 25-, 50-, and 100-year return periods for three different scenarios: only rain barrels, only detention ponds, and the combination of these two. For a storm with the return period less than 3 years, harvesting all rainfall volume received by rooftops, rain barrels are sufficient for flood control. In individual design to achieve the same flood control goal, compared with detention ponds, desired number of rain barrels need to harvest 10% to 15% more of the runoff volume of 2- to 100-year storms, and occupy up to 0.22% larger surface area of the watershed in case of a 100-year storm and as low as 0.13% less for a 5-year storm, which are 0.18 km2 and 0.11 km2, respectively. In combined design of capacity number of rain barrels with detention ponds, the overall combined area is slightly larger than the area of detention ponds in individual design, but the area of detention ponds in combined design is greatly reduced by more than 67% compared with the area of detention ponds in individual design.

1. INTRODUCTION

1.1 Introduction

Global modernization has resulted in city expansion in terms of urban area and population which poses challenges for urban stormwater management. City development inevitably increases the imperviousness of land and transforms large amounts of agricultural land and wetland into urban or built-up land, which has detrimental effects on hydrology (Harbor, 1994; Moscrip and Montgomery 1997; Shuster, 2005). In surface hydrology, adverse effects include an increase in runoff volume and peak discharge, and decrease in time of concentration; in subsurface hydrology, they include a decrease in infiltration and baseflow recharge. Excess direct runoff in cities has higher magnitude and likelihood of flooding compared with agricultural lands. Conventional approaches, man-made structures, including detention ponds and reservoirs, are designed for peak flow reduction, but have adverse effects on water quality and ecology (Coffman, 2000; Damodaram et. al., 2010). These disturbances of pre-development conditions necessitate the requirement for more efficient and adaptive stormwater management tools for urban areas (Ghimire, 2016).

Low-Impact-Development (LID) has gained public attention recently, as an innovative approach to manage stormwater. The fundamental principle of LID is to minimize the influence of post-development and mimic the hydrology of pre-development natural conditions. (USEPA 2000a). Prince George's County in Maryland was the one of the first counties to implement LID, where different actions were taken to reduce impervious area; utilize natural water channels that can be adapted for paving, curb, gutter, pipe system (Coffman, 2002). Current LID practices include rain gardens, rain barrels, green roofs, porous pavements, etc. Many studies have focused on the advantages of porous pavement and rain gardens (e.g., Dietz, 2007; Davis, 2008; Roy-Poirier et al., 2010; DeBusk and Wynn 2011).

Rain barrels are connected with rooftop areas via downspouts, which route overflowing rainfall to rain gardens or urban drainage networks; they are cheap, easy to install, and can be implemented and managed more flexibly in highly developed urban area. Frequent emptying of a rain barrel is necessary, because a single rain barrel which fills up quickly during a storm event has a marginal impact on the reduction of rainfall volume, which requires high level and scale of participation and execution of residents to achieve the expected performance on watershed-scale scenario. In addition to serving as a stormwater control practice, a rain barrel can be used by homeowners for gardening, which further place restrictions on outright implementation and utilization of rain barrel for water quality must also be accounted for (Jennings, 2013).

Earlier studies on LID often examined the improvement of post-development hydrology at garden scale and lot scale using a single storm, including frequency storms, and continuous storms. Gilroy and McCuen (2009) used 1- and 2-year design storms to examine reduction on peak flow rate and runoff volume at the scale of a single-family and commercial lots by implementing stormwater harvesting practices. A study in Cleveland Heights, Ohio showed that one rain barrel with the capacity of 189 L modeled on a 14 m2 garden would produce total retrospective reduction on annual roof runoff volume by 3.2%, 2.1%, and 1.4%, for the 1-, 2-, and 3-day barrel-emptying frequencies (Jennings et al., 2013). Although results show N×189 L rain barrel or N×14 m^2 would enhance the runoff reduction by a factor of N, it only tested the maximum effect of rain barrels when N=4.

A study by the District of Columbia Water and Sewer Authority concluded significant long-term reduction of combined sewer overflow (CSO) is impractical. Despite strong verbal and written recommendation for the implementation, in reality, 284-L rain barrels were each emptied 2.7 times per month, which was far below the recommended instruction to empty after each rainfall. Overall, 30% of residents were dissatisfied with overall rain barrel performances. (Trieu et al., 2001).

Recently, more studies have shifted from lot scale to watershed scale, from a single event to continuous events, from a single LID practice to the combination of several practices. The LID effectiveness for flood control was assessed at watershed scale for 30 years by using different scenarios, e.g. combination of different LID practices and various implementation rate; results showed the combination of implementation level of 50%-100% porous pavements and 100% rain gardens was the most effective for mitigating flood events in the Sugar Creek Watershed (Ahiablame and Shakya 2016).

Distributed hydrologic models, e.g. in SWMM (Huber and Dickson, 1988; Rossman, 2004), PCSWMM (James et al., 2010; Rossman, 2008), MUSIC (Wong et al., 2002), and SUSTAIN (USEPA 2009), have been developed to simulate the effects of on-site LID practices on hydrology and water quality. Distributed hydrologic models are data-intensive which use node-link drainage network to route node component (individual sub-catchment) through drainage component (channels, sewers). Lumped hydrologic models, e.g. in HEC-HMS (USACE 2000), L-THIA-LID (Hunter et al., 2010; Engel and Ahiablame, 2011), are not broadly adopted in current researches on LID modeling, which simulate catchments in a lumped approach by aggregating the effects of practices in one parameter (Elliot 2007; Ghimire 2016). While distributed modeling of LID practices is more accurate, it is prone to higher cost and thus impractical for long-term evaluation. Lumped models provide a preliminary demonstration of the benefits of LIDs before more elaborate modeling. Therefore, scaling up the modeling of LID practices from lot scale to watershed scale is important to accurately representing LID practices at watershed scale (Ahiablame and Engel, 2012).

Previous researches into the effectiveness of rain barrels adopted either a constant storage or limited choices of commercially available storage to simulate their impact on runoff peak flow (e.g. Ahiablame and Shakya 2016; Litofsky and Jennings 2014). A study showed water harvesting facilities, e.g. rain barrels and rain gardens, can effectively reduce flooding for storms with small rainfall intensity, but are incapable of mitigating storms with high magnitude (e.g. Damodaram et al., 2010). However, the best stormwater management plan varies with the specific watershed, which need to take into consideration both the cost and efficiency factors.

1.2 Problem Statement and Objectives

Previous studies on rain barrels used barrels with a single constant storage, or adapted rain barrels with several commercially available storage volumes to determine their effect on runoff peak flow and volume. Furthermore, it was found that rain barrels are impractical to achieve flood reduction in the long term, but can be useful for reducing runoff peak for a single storm event. Rooftops are the primary source for rain barrels to harvest rainfall and the effectiveness of rain barrels is restricted by the rooftop surface area. Because a rooftop can only direct the amount of rainfall it receives, just increasing the number of barrels per house will not achieve the expected reduction in storm water volume if not enough water is received by the rooftops. Thus, there is a need to determine how many rain barrels are really needed to store all the rooftop water, and whether these barrels are sufficient to produce any reduction in the streamflow volume and peak flow rate. In addition, the performance of rain barrels in conjunction with other traditional storm water control practices, e.g., detention ponds, needs to be explored.

This study aims to explore the effectiveness of rain barrels on stormwater management through the following objectives:

1. Quantify the change in runoff hydrograph in terms of volume and the peak flow by implementing incremental rain barrel storage per building.

2. Determine the required number of rain barrels and their effectiveness to maintain acceptable flow rate for an historical event and frequency storms with different return periods.

3. Compare the difference of the required storage volume and the surface area between rain barrels at household scale and detention ponds at community scale as to achieve the same flood mitigation objective.

4. Determine the effect of the combinative design of rain barrels and detention ponds in terms of the change of minimum required surface area in comparison with results from individual designs of detention ponds or rain barrels.

The study objectives are accomplished by using an urban watershed in central Illinois, which covers two cities and has high percentage of developed land use. The role of the effectiveness of rain barrels and other storm water reduction measures are simulated by using Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), a commonly used hydrologic modeling software for historical and frequency storms.

1.3 Thesis Organization

This thesis is divided into five chapters. This chapter introduces previous researches on rain barrels and sets up objectives for this study. The second chapter gives a description of the study area and an overview of the data used in this study. The third chapter explains the modeling of rain barrels and detention ponds in HEC-HMS, and an overview of the scenarios used to examine and compare their effects. The fourth chapter presents and discusses model results. The fifth chapter gives a summary of this study and provides opportunities for future work.

2. DATA AND STUDY AREA

2.1 Study Area

The City of Normal-Sugar Creek Watershed (HUC 071300090701) is located in central Illinois covering the two major cities of Normal and Bloomington, referred to SCW below (see Figure 2.1). The total drainage area of SCW is 85.14 km2 with one streamflow gage at its outlet (Sugar Creek near Bloomington, IL) and one rainfall gage at its centroid (Bloomington Waterworks). This watershed is selected based on its land cover of diverse types, from highly developed residential area to grassland and ponds, and the readily availability of all required data for hydrologic modeling. The highest percentage of land use in the watershed is low-intensity residential use at 43%, followed by high-intensity residential area at 38%, and agricultural use at 12%. Soils are dominated by Hydrologic Soil Group C, which has moderately low infiltration potential (see Figure 2.2). The average total percentage of impervious area is 40%. The average monthly precipitation varies between 50 mm in February and 112 mm in May, which accounts for 5% and 11% for total annual precipitation.

2.2 Data

To develop a hydrologic model used for this study, geospatial data are processed in ArcMap 10.3.1 using HEC-GeoHMS, and then imported in to HEC-HMS. A HEC-HMS model is calibrated using historical rainfall and streamflow data. Address points in the study area are used to set different scenarios for the number of rain barrels per individual building, and calculate the total storage volume of rain barrels in each sub-basin.

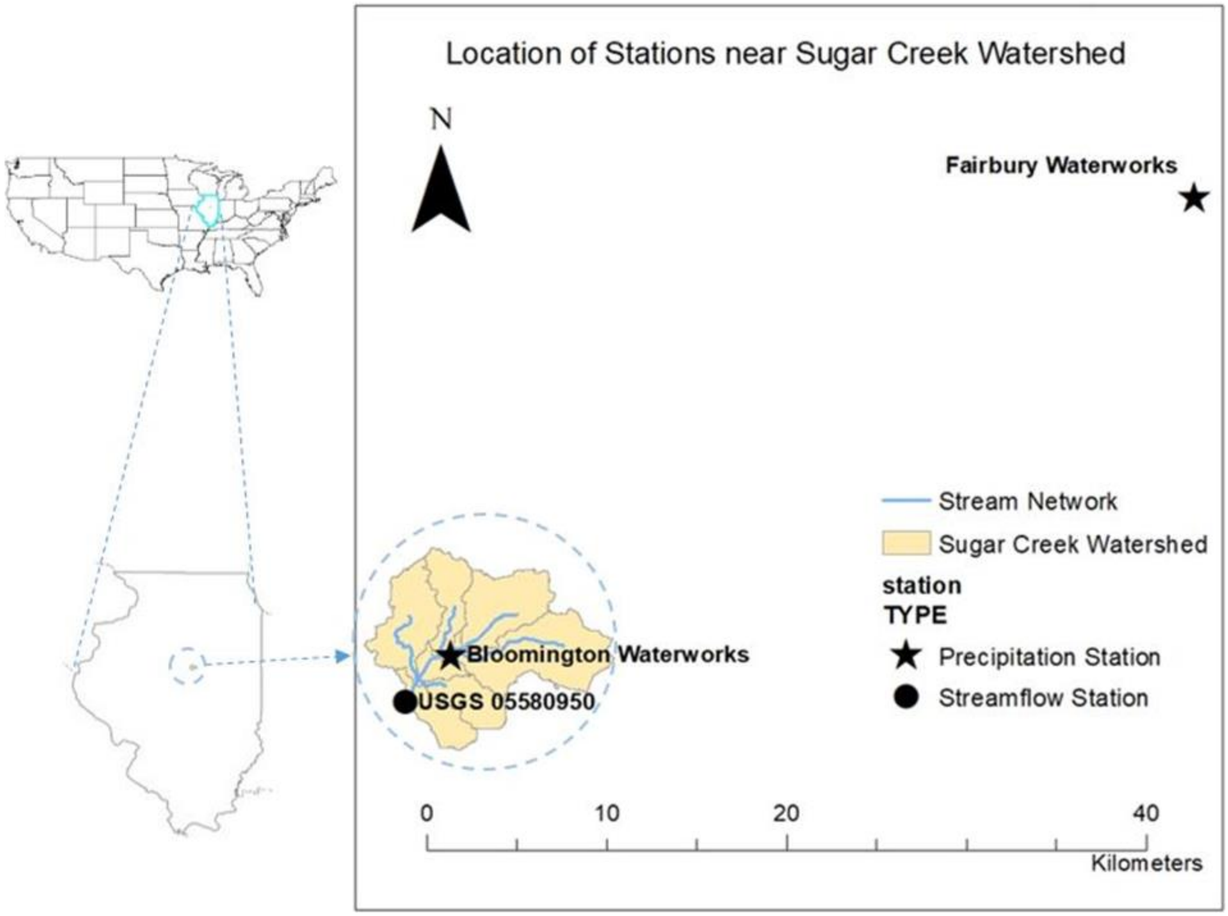


Figure 2.1 Study Area with Sugar Creek Boundary and Gage Locations

The 30-m horizontal resolution Digital Elevation Model (DEMs) are used for this study and obtained from the National Map Viewer in 2017. The DEM for the study area is reconditioned by using the stream network from the National Hydrography Dataset (NHD). The Gridded Soil Survey Geographic (gSSURGO) Database are used to obtain hydrologic soil groups (HSG) information, and the National Land Cover Database (NLCD) 2011 are used in this study to get the 30-m resolution land cover and impervious surface area percentage data. (Figure 2.2)

Historical 15-min streamflow data are obtained from the United States Geological Survey's streamflow gauge at Sugar Creek Near Bloomington, IL (USGS 05580950). Similarly, historical 15-min precipitation data are obtained from Fairbury Waterworks Station, which is located about

50 km northeast of the SCW centroid. Frequency precipitation data, which are used to generate frequency storms in HEC-HMS, are obtained from Precipitation Frequency Data Server maintained by NOAA. Building information in Normal and Bloomington city is obtained from McLean County GIS Consortium, which contains information on individual building address in point features (see Figure 2.3).

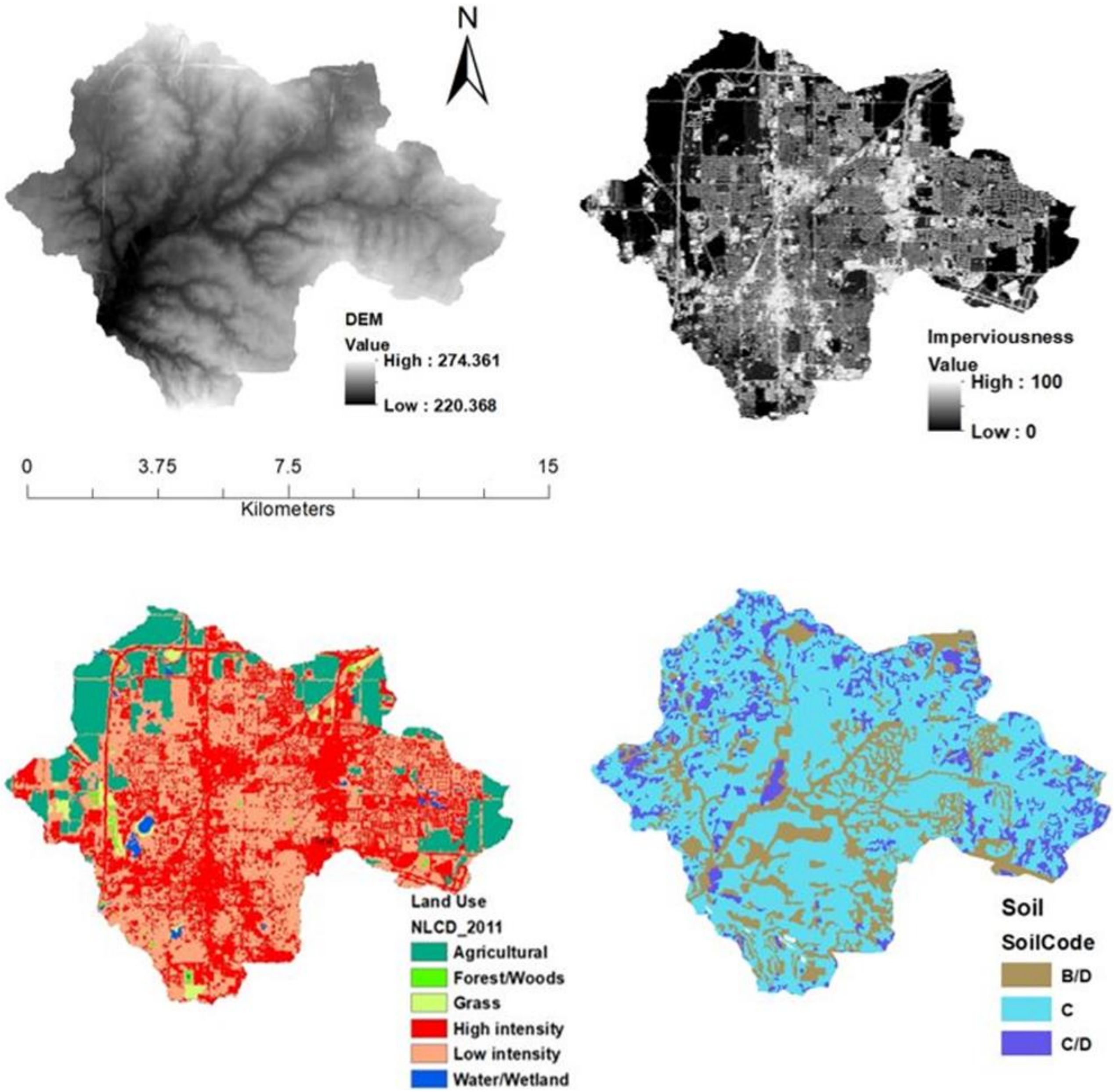


Figure 2.2 DEM, Imperviousness, Land Use, and Soil of Study Area

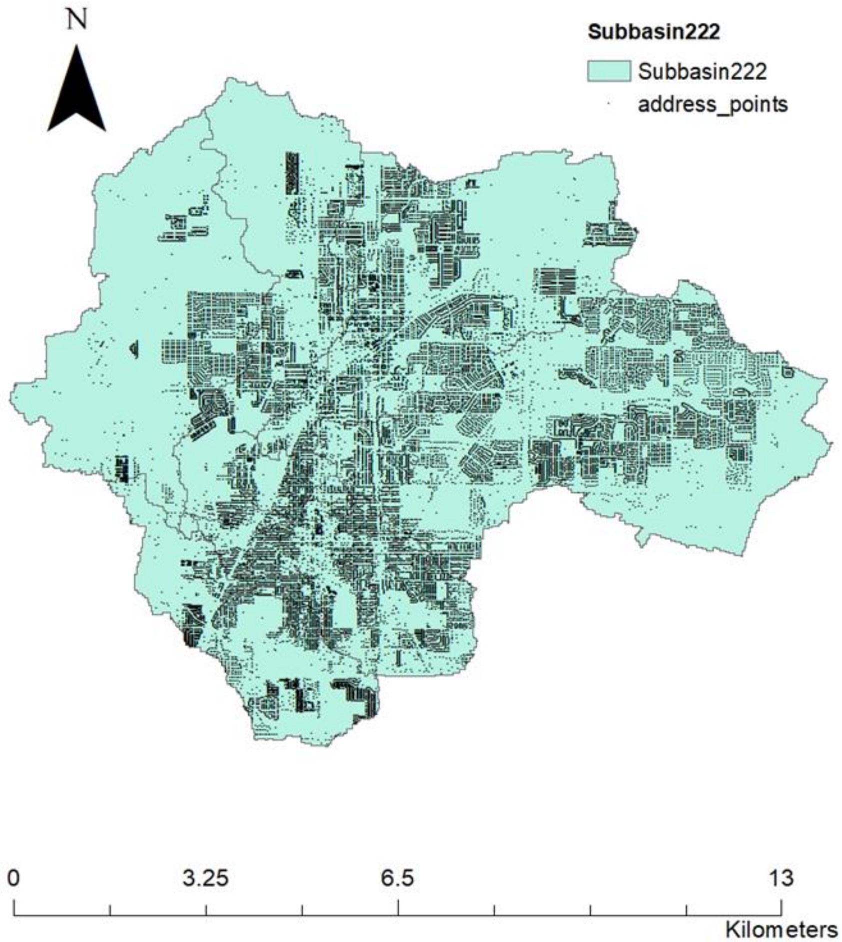


Figure 2.3 Address Points in Study Area

3. METHODOLOGY

This chapter includes information regarding the tools and scenarios to simulate and compare the effect of rain barrels and detention ponds in HEC-HMS.

3.1 Methodology Overview

This study examines the suitability of rain barrels to impact direct runoff for a single storm event. In past studies, the number and storage volume of rain barrels selected were limited per house and fixed in case of various storm events, which does not provide full potential of rain barrels on direct runoff control. In order to investigate the scope of the event-specific flood reduction that rain barrels can achieve, a methodology is developed in HEC-HMS for SCW to include three models: only rain barrels (RB-based), only detention ponds (DP-based), and a combination of rain barrels and detention ponds (RB-DP-based). Because HEC-HMS does not specifically simulate the effect of rain barrels, reservoirs are used to simulate this effect. In this study, the goal of flood control is to reduce the peak flow at the outlet of watershed below acceptable level. In summary, the methodology is divided into five steps: (1) create and calibrate a basic HEC-HMS model without reservoirs using a selected historical storm event; (2) create a RB-based model and determine the scope of the effectiveness of rain barrels on peak flow reduction for a historical event and different design storms and compare their surface areas; (3) create a DP-based model and determine the minimum required surface area of detention ponds for individual design storms; (4) create a combined model for rain barrels and detention ponds (RB-DP-based) and determine the minimum required surface area in case of individual design storms; (5) compare the results of the basic, RB-based, DP-based and RB-DP-based models.

3.2 HEC-HMS Overview

HEC-HMS is a rainfall-runoff modelling software developed by the US Army Corps of Engineering's Hydrologic Engineering Center, which uses different methods to simulate different hydrologic processes. The Loss methods in HEC-HMS compute the loss of rainfall volume due to infiltration. The Transform methods transform excess precipitation into direct runoff. The Baseflow methods compute the portion of baseflow in streamflow. The Route Methods route the flow from each sub-basin through open channels towards watershed outlet.

3.3 HEC-HMS Modeling

3.3.1 *Data pre-processing*

Hydrologic Engineering Center's Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a Geographic Information System (GIS) extension that pre-processes geospatial data to create a HEC-HMS model. In this study, a DEM is pre-processed to delineate the stream network and create the basic HEC-HMS model. Considering that rain barrels are simulated using a reservoir for each sub-basin in the watershed, 7% of total watershed area is chosen as the stream delineation threshold to create nine sub-basins, which is a manageable number for manual input of storage-discharge relationships. Table 3.1 shows the characteristics of sub-basins.

Table 3.1 Characteristics of Sub-basins

Sub-basin	Sub-basin Area (km^2)	Number of houses per sub-basin	House Density ($1/km^2$)
W100	9.17	3674	400.9
W110	16.20	9458	583.7
W120	15.46	3155	204.1
W130	23.99	10000	416.9
W140	0.99	782	790.5
W150	3.29	1706	518.1
W160	0.10	5	51.4
W170	8.34	6086	730.0
W180	7.60	3220	423.7
Sum	85.14	38086	447.4

3.3.2 *HEC-HMS calibration*

In this study, the basic HEC-HMS model is calibrated using a historical storm event. To calibrate a model for good prediction accuracy, the selection of an eligible storm is crucial. It is recommended by Viessman et al. (1989, p.186) that an ideal storm for calibrating a hydrologic model should meet the following criteria: (1) A simple-storm structure, resulting in well-defined hydrograph with distinct peaks; (2) Uniform temporal rainfall distribution over the whole rainfall event; (3) Uniform spatial rainfall distribution over the entire watershed; and (4) Direct runoff volume in range of 0.5 to 1.75 in. It is not easy to meet the criteria due to the missing records and the malfunction of gages. In this study, historical data dating back to last 30 years are used to pick an eligible storm event, and the event on May 12, 1990 meets the standards. The characteristics of this event including the rainfall histogram and streamflow hydrograph are presented in Table 3.2 and Figure 3.1.

Table 3.2 A Selected Storm Event for Calibration

Date	Observed Rainfall Data				Observed Runoff Data		
	Precipitation	Maximum intensity	Storm duration		Runoff Volume		Peak Discharge
	(in)	(in/15min)	(hr)	(min)	(ac-ft)	(in)	(cfs)
May 12, 1990	0.8	0.4	2	45	1771.3	1.01	2370

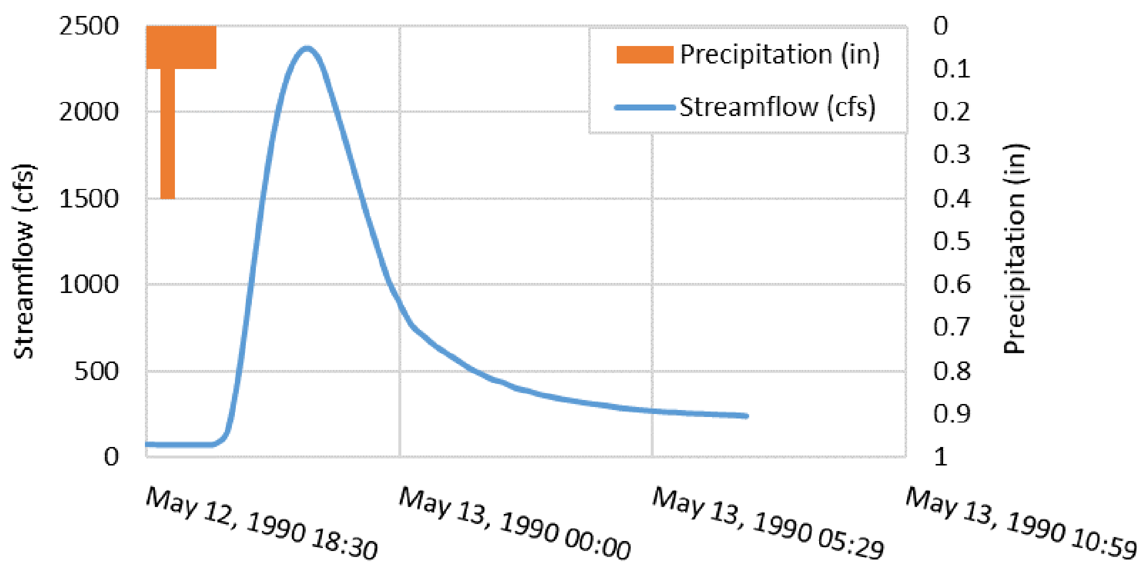


Figure 3.1 Rainfall Histogram and Streamflow Hydrograph on May 12, 1990

In this study, the basic HEC-HMS model is created by using the SCS CN method for accounting rainfall losses, Clark Unit Hydrograph method to transform excess rainfall to direct runoff, and Muskingum method to route flow in open channels. Baseflow is not incorporated because rain barrels can only impact direct runoff, and baseflow existing in the observed streamflow data was separated using the recursive digital filter method within the Web-based Hydrologic Analysis Tool (WHAT) (Eckhardt 2005; Kyoung et al., 2005; Ahiablame et al., 2016). The Clark Unit Hydrograph method is chosen because it has parameters related to time of concentration and storage, which can simulate the effect of the low-slope topography and depression storage in SCW.

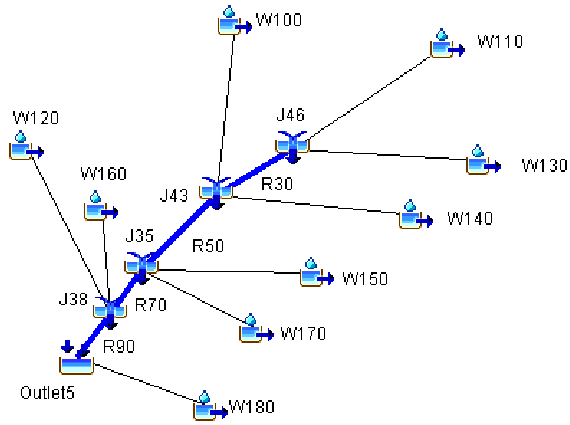
The calibrated basic HEC-HMS model provides a good prediction of direct runoff in Sugar Creek Watershed, indicated by the Nash–Sutcliffe coefficient of 0.86. The average values of calibrated parameters are listed in Table 3.3.

Table 3.3 Average Calibrated Parameters

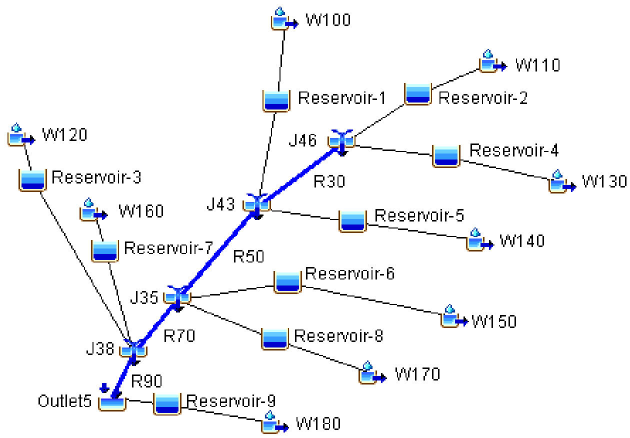
<table>
<tr><td colspan="6">Loss Method: SCS Curve Number</td></tr>
<tr><td colspan="2">Initial Abstraction</td><td colspan="2">Curve Number</td><td colspan="2">Imperviousness</td></tr>
<tr><td colspan="2"></td><td colspan="2">82.06</td><td colspan="2">25.82</td></tr>
<tr><td colspan="6">Transform Method: Clark SUH</td></tr>
<tr><td colspan="3">Time of Concentration (hr)</td><td colspan="3">Storage Coefficient (hr)</td></tr>
<tr><td colspan="3">2.90</td><td colspan="3">0.43</td></tr>
<tr><td colspan="6">Routing: Muskingum</td></tr>
<tr><td colspan="2">Muskingum K</td><td colspan="2">Muskingum X</td><td colspan="2">Number of sub-reaches</td></tr>
<tr><td colspan="2">0.35</td><td colspan="2">0.40</td><td colspan="2">1</td></tr>
</table>

3.3.3 *Incorporating rain barrels in HEC-HMS*

HEC-HMS cannot simulate the distributed effect of rain barrels, which are small on-site LID practices. Therefore, the representation of rain barrels is achieved by aggregating the effect of total rain barrels in the form of a reservoir (RB-reservoir) for each sub-basin in HEC-HMS as shown in Figure 3.3 (B), in comparison to the no-reservoir model in Figure 3.2 (A). The initial storage of each RB-reservoir before each simulation is set to zero.



(A) No-reservoir HEC-HMS Model



(B) RB-based HEC-HMS Model

Figure 3.2 HEC-HMS Models

3.3.4 *Effect of rain barrels on a historical event*

The National Weather Service has defined different flood warning stages for each United States Geological Survey's (USGS) gauge in the United States, and it regularly produces forecasts for each station to identify whether the stage is at safe level or requires action related to flooding. Accordingly, the streamflow gauge at the SCW outlet (USGS number: 05580950; SUGAR CREEK NEAR BLOOMINGTON, IL) has its action stage at the gage height of 7 ft (discharge at 1985.7 cfs), and flood stage at 11 ft (discharge at 3652 cfs) as shown in Figure 3.3. In this study, all HEC-HMS models are aimed at reducing peak discharge below the action flood stage at the SCW outlet.

(http://water.weather.gov/ahps2/hydrograph.php?wfo=ilx&gage=bmii2&hydro_type=2)

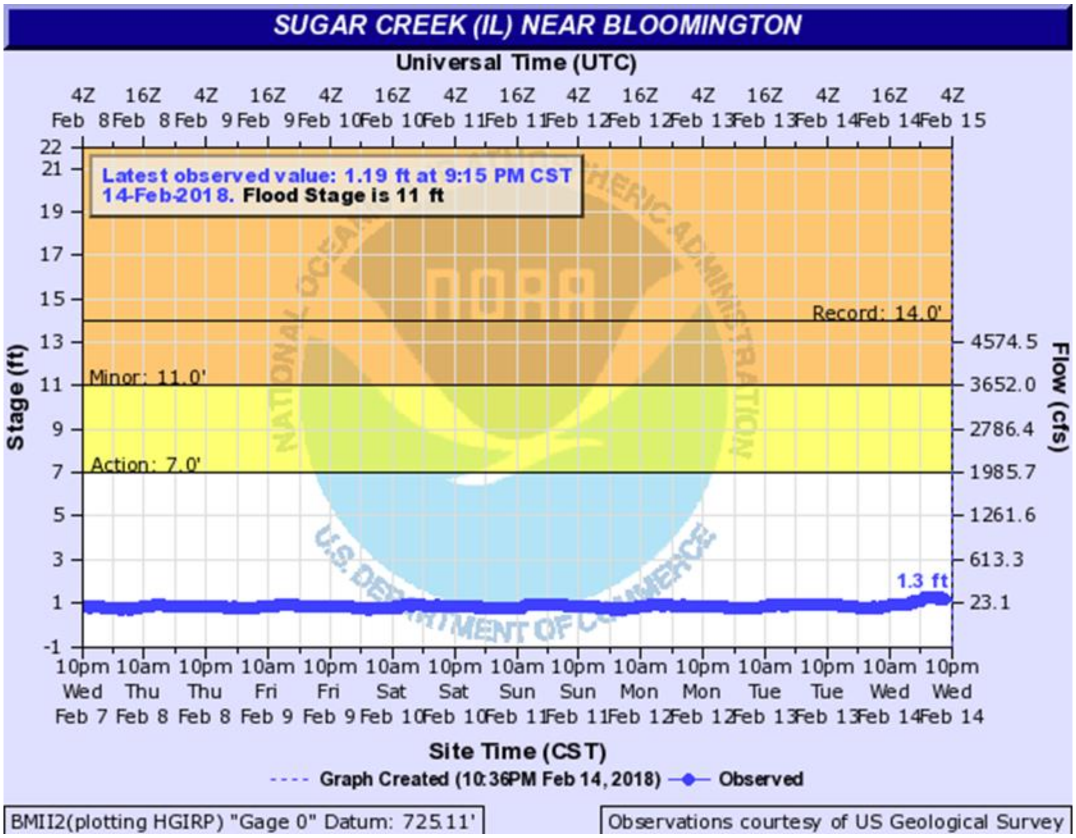


Figure 3.3 Flood Stage at Sugar Creek (IL) Near Bloomington

The effectiveness of rain barrels is evaluated by incremental number of rain barrels assigned per building in the study area. The rain barrel used in this study is assumed as 1.22 m high and has the storage volume of 340 L. Considering that rainfall draining from a rooftop can only fill up a limited number of rain barrels, it is necessary to determine the capacity number of rain barrels per building for the storm. The volume of rainfall received by rooftops varies depending on rooftop area, rainfall intensity, and duration. In this study, the rooftop area of an individual building is assumed as 139.35 m2. Thus, for the storm event on May 12, 1990, the rainfall volume received by a rooftop is equivalent to eight 340-L rain barrels covering a footprint of 2.3 m2.

Reservoir modeling in HEC-HMS requires the input of a storage-discharge relationship. The storage for each RB-reservoir is computed by summing up the storage volume of all rain barrels in each sub-basin using Equation 3.1. The storage-discharge relationship is then developed by assuming a broad-crested weir using Equation 3.2. The weir length is the square root of the RB-reservoir surface area which is the footprint of total rain barrels in a sub-basin; the weir crest height is the same as the height of a rain barrel, which is 1.22 m. It is assumed that rain barrels will not be emptied during the storm and water will overflow after the barrel is full.

$$RB\ reservoir\ storage = Single\ Rain\ Barrel\ Storage\ \times Number\ of\ Rain\ Rarrels\ per\ House \times Total\ Number\ of\ Houses\ in\ a\ Subbasin \qquad Equation\ 3.1$$

$$Q = C_{bcw} \times L \times H^{3/2} \qquad Equation\ 3.2$$

where:

Q = discharge, m3/s (ft3/s)

Cbcw = broad-crested weir coefficient, 1.44 – 1.70 (2.61 – 3.08), metric system (U.S. Customary)

L = broad-crested weir length, m

H = height of the water above weir crest, m

The adopted broad crested weir coefficient is 1.7 (metric system).

3.3.5 *Effect of Rain Barrels on Design Storms*

After investigating the effectiveness of rain barrels on a historical storm event, the same RB-based model is used to investigate the effectiveness of rain barrels in case of design frequency storms. Frequency storms data for SCW are obtained from the NOAA Precipitation Frequency Storm Server. In this study, 24-hour duration frequency storms with 5-min intensity and return period of 2, 5, 10, 25, 50, and 100 years are selected for input of meteorological data into HEC-HMS. To validate the peak discharge simulated in basic HEC-HMS model using data from NOAA, observed annual maximum discharge series at the SCW outlet are used to perform flood frequency analysis using Log Pearson Type III distribution as shown in Table 3.4. Comparison shows simulated hydrograph in HEC-HMS using data from NOAA is of peak discharge far higher than the result from the analysis of Log Pearson Type III distribution. Therefore, the precipitation data of design frequency storms from NOAA are modified by multiplying with different factors to make the basic HEC-HMS model produce hydrographs with peaks close to the result of Log-Pearson Type III flood frequency analysis; the precipitation data of the design storms used in this study are presented in Table 3.5.

Table 3.4 Log-Pearson Type III Flood Frequency Analysis

USGS 05580950 (period of record 1975 - 2016)		
Return Period	Skew Coefficient	Discharge
(years)	K (-0.196)	Q (cfs)
2	0.032	2509
5	0.849	3597
10	1.258	4307
25	1.681	5189
50	1.947	5834
100	2.181	6466
200	2.392	7096

Table 3.5 Design Frequency Storms
(precipitation in inch)

Return Period / Duration	2	5	10	25	50	100
5-min:	0.22	0.27	0.29	0.31	0.32	0.33
15-min:	0.43	0.51	0.55	0.58	0.60	0.61
60-min:	0.70	0.88	0.97	1.07	1.13	1.18
2-hr:	0.84	1.03	1.15	1.28	1.37	1.45
3-hr:	0.89	1.11	1.24	1.39	1.49	1.58
6-hr:	1.05	1.30	1.46	1.64	1.76	1.87
12-hr:	1.21	1.49	1.66	1.86	1.98	2.10
24-hr:	1.39	1.70	1.89	2.12	2.30	2.48

The effectiveness of rain barrels on frequency storms is evaluated by comparing the results between simulations using desired number and capacity number of rain barrels per house. The desired number is the number of rain barrels needed to keep the surface water level below action flood stage; the capacity number is the number of rain barrels that can actually be filled up during a specific storm. Table 3.6 shows the capacity number and the desired number of rain barrels per house and their respective footprint for the storm event on May 12, 1990. It is assumed that rain barrels will not be emptied during a storm and the water will overflow after barrels are full. The outflow structure of a RB-reservoir in the case of design frequency storms is a broad-crested weir with the weir height same as the height of a rain barrel, and the reservoir storage is calculated by summing up the total rain barrel storage in each sub-basin (Equation 3.1). If the peak runoff discharge rate routed through RB-reservoirs is above action flood level, then a new simulation is performed using larger reservoir storage volume, which is achieved by increasing reservoir surface area. For each frequency storm, once the simulated peak runoff discharge is reduced to below action flood stage, the minimum reservoir surface area and the equivalent desired number of rain barrels per house are recorded.

Table 3.6 Capacity Number of Rain Barrels and Footprint per Building

Storm Frequencies	0.5	0.2	0.1	0.04	0.02	0.01
Storm Return Period (year)	2	5	10	25	50	100
Number of RB	45	51	56	66	78	93
Footprint (m^2)	12.6	14.2	15.7	18.4	21.8	26.0

3.3.6 *An alternative rainfall harvesting practice – detention pond*

As the rooftop area limits the rainfall volume that can be harvested in rain barrels, only using the capacity number of rain barrels may be insufficient for flood control. Thus, an alternative rainfall harvesting practice – detention pond – is designed to achieve the flood reduction goal. Detention ponds can be implemented as small on-site storage tanks, or as large regional facilities for a sub-basin. Regional detention ponds outperform on-site ponds, in terms of lower maintenance and better peak flow control (Hartigan 1986).

In this study, the goal of designing detention ponds is to determine their total minimum surface area to achieve flood control goal without causing roadway overtopping in case of individual design frequency storm. In previous section, reservoirs in HEC-HMS model were set up to mimic the behavior of overflowing barrels. Thus, a RB-reservoir only releases outflow when the water level rises above the rain barrel height. In this section, detentions ponds are also modeled as broad-crested reservoirs (referred to as DP-reservoir) with crest height equal to the height of a rain barrel, but the storage-discharge relationship of a DP-reservoir is different from a RB-reservoir. A DP-reservoir may have outlet structures that allow outflow below the crest height at different rate. The initial storage of each DP-reservoir before each simulation is set to zero.

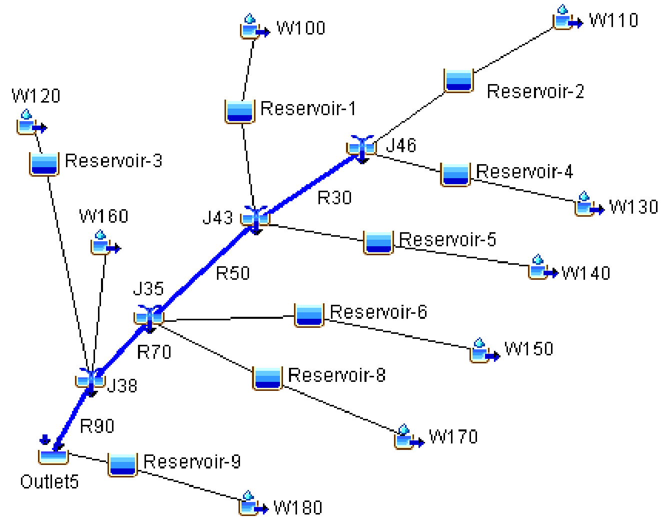


Figure 3.4 Diagram of Detention Pond-based HEC-HMS model

An individual detention pond is designed for each sub-basin except for one that has a very small area and contributes very little runoff (W160 in Figure 3.4). A detention pond consists of an impoundment area, a principle spillway, and an emergency spillway. A principle spillway consists of a riser and culvert. A riser is a structure upstream of a reservoir which has the shape of a cylinder with an open top and orifices opening on lateral surface area at different height, which can control the flow through it by acting as a weir or an orifice. A culvert is a conduit that route the water from the riser to the downstream of a reservoir. The design of a multi-stage riser is frequently adopted, which allows water flow at different flow rate at different height. However, the design of a multi-stage riser is based on a single-stage riser. The mechanism of a single-stage riser is the fundamental hydraulics for orifices, weirs, and culverts.

In this study, the design discharge for the outlet of each sub-basin in DP-based model is the weighted assignment of the acceptable discharge at the outlet of the watershed according to the weight of the natural peak discharge of the outlet of each sub-basin in the no-reservoir model. There are six design storms used in this study, and each design storm is simulated with no-reservoir model to obtain its set of design discharges for the outlet of each sub-basin in the DP-based model. For each detention pond, a culvert is designed with the capacity to route the design discharge, which is preceded by one or several multi-stage risers to regulate the flow. The design of the culvert capacity is performed using the HY-8 program, which is suggested by the Land Development Handbook Third Edition (Dewberry, 2008), and the design of multi-stage riser is performed in Excel.

3.3.7 *Combined effect of rain barrels and detention ponds*

In order to explore the combined effect of rain barrels and detention ponds in terms of total surface area in case of design frequency storms, a HEC-HMS model is developed in which the flow from each sub-basin is first routed through a RB-reservoir, and then routed through a DP-reservoir, as shown in Figure 3.5. The idea is to use capacity number of rain barrels to set up the behavior of RB-reservoirs and then design a unique elevation-storage-discharge relationship for each DP-reservoir to continue the task of peak flow reduction which is partially achieved by RB-reservoirs. Design storms, including 100-, 50-, 25-, 10-, and 5-year storm, are used to determine the total minimum surface area of rain barrels and detention ponds to reduce peak flow at the outlet of the watershed under acceptable level. For each design storm, risers and culverts of each detention pond are designed individually because the design discharges vary with sub-basins.

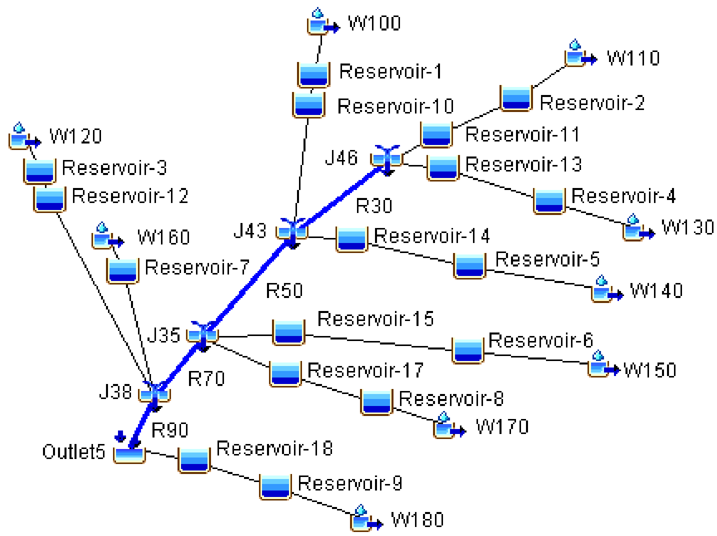


Figure 3.5 Diagram of Combination of Rain Barrels and Detention Ponds

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter explains the results of the study on the effectiveness of rain barrels on the reduction of peak flow and runoff volume, and compares the minimum required surface area of rainfall harvesting pratices between RB-based, DP-based, and RB-DP-based models. The first part of this chapter presents the results of the RB-based model that explores the scope of the effectiveness of rain barrels on storms with different rainfall characteristics, e.g. a historical event and several design frequency storms. The second part of this chapter explains the results of the DP-based model which determines the minimum required surface area of detention ponds to cope with different design frequency storms. The third part is the set of results of the RB-DP-based model, which is a combination of rain barrels and detention ponds; the total minimum required surface area of rain barrels and detention ponds are presented and compared with the results from the RB-based and DP-based models.

4.2 Effectiveness of Rain Barrels on a Historical Event and Design Storms

The effectiveness of rain barrels during the storm event on May 12, 1990 is evaluated by assigning an incremental number of rain barrels per building in the study area. Results on the historical storm are presented in terms of the peak flow change, and the percentage of runoff volume that is stored in the RB-reservoir in each sub-basin. The effectiveness of rain barrels on design frequency storms is evaluated by comparing the results of using the capacity number and the desired number of rain barrels. Results on design frequency storms are presented in two ways: the capacity and the desired number of rain barrels of each design storm, their surface area per house, and their individual effect on hydrographs.

4.2.1 *On a historical event: peak discharge decrease*

Figure 4.1 shows the effect of the incremental quantity of rain barrels on the runoff peak flow for the event on May 12, 1990. In Figure 4.1, it can be observed that the runoff peak discharge does not show any noticeable decline until the number of rain barrels per house reaches above four, with a reduction of approximately 20 cfs. Starting with four rain barrels per house, with an increment of 2 in each simulation, it can be observed that the peak rate decreases very little before 8 rain barrels per house and shows a steady decline around 60 cfs with 10 and more rain barrels per house. For peak flow to be reduced to below action flood stage, 14 rain barrels per building are desired. However, based on the characteristics of the storm, and assuming that an individual rooftop area is 139.35 m2, only 8 rain barrels can be filled up by the rainfall volume received by a rooftop, which only reduces the peak flow by 100 cfs as shown in Figure 4.2.

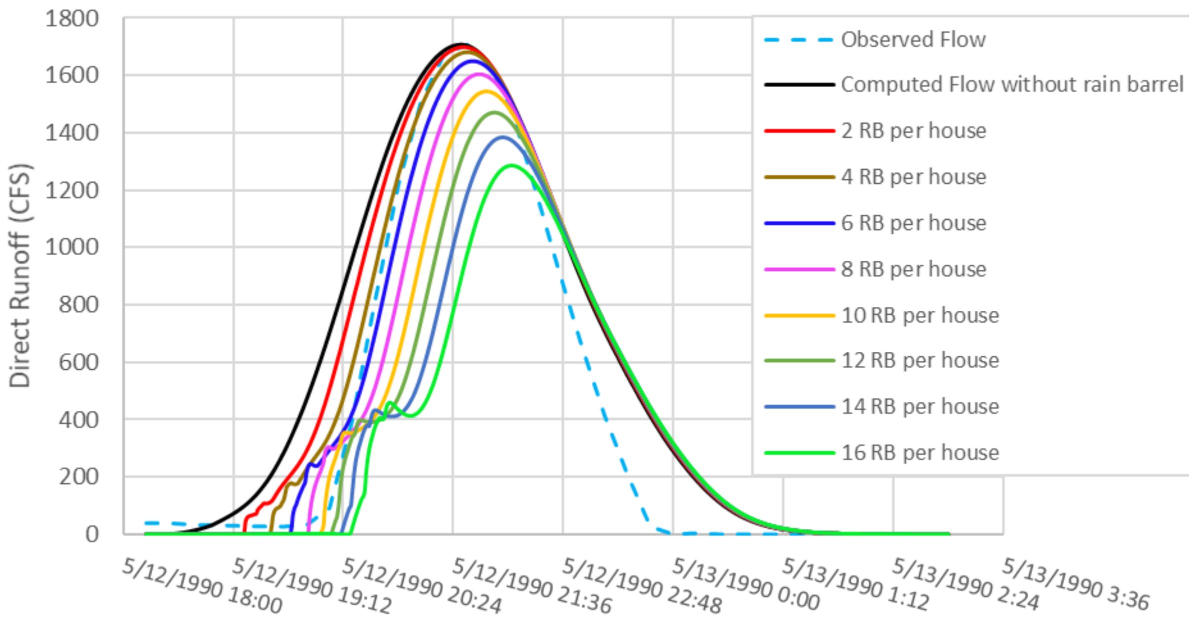


Figure 4.1 Hydrograph of May 12, 1990 with Incremental Number of Rain Barrels

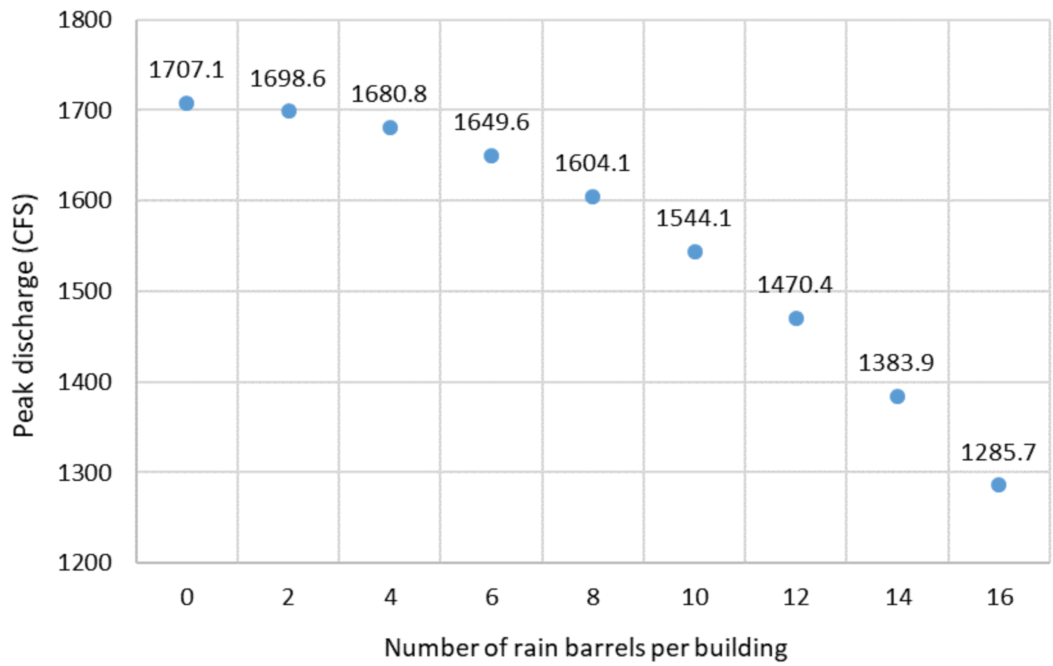


Figure 4.2 Peak Discharge Change with Incremental Number of Rain Barrels

4.2.2 *On a historical event: runoff volume stored in rain barrels*

Rain barrels control the outflow by storing excess runoff volume. Thus, it is important to analyze the behavior of the reservoir storage representing rain barrels (RB-reservoir) when peak flow is reduced. Although the desired performance of 16 rain barrels cannot be achieved, it can be used to demonstrate this behavior. Table 4.1 shows the RB-reservoirs inflow and outflow volume, and the peak and final percentage of the runoff volume stored in reservoirs, in the scenario of 16 rain barrels assigned per house. At the outlet of SCW without RB-reservoirs, the peak flow rate and direct runoff volume are 1708 cfs and 893 ac-ft, respectively. By assigning 16 rain barrels per house, the peak flow rate can be reduced by 318 cfs, and the total runoff volume that the rain barrels in SCW are needed to harvest is 176.1 ac-ft. The average peak and final percentage of the runoff volume stored in RB-reservoirs are 19.72% and 18.81%, which are 176.1 and 168.0 ac-ft, respectively; the difference might be due to infiltration and evaporation. It is also noted that, for sub-basin W160, its RB-reservoir's inflow volume is equal to outflow volume. By comparing the house density of sub-basin W160 with other sub-basins, it is found that, for a sub-basin with low house density, rain barrels have negligible impact on runoff volume.

Table 4.1 Statistics of RB-Reservoirs for the Storm on May 12, 1990 (16 RB per House)

Reservoir # (Sub-basin)	Reservoir Inflow Volume (ac-ft)	Reservoir Outflow Volume (ac-ft)	Peak Reservoir Storage (ac-ft)	Peak Storage Percentage	Final Storage Percentage	House Density (1/km^2)
Reservoir 1 (W100)	92.5	76.3	16.8	18.16%	17.51%	401
Reservoir 2 (W110)	173.6	131.9	43.1	24.83%	24.02%	584
Reservoir 3 (W120)	130.1	116.2	15.4	11.84%	10.68%	204
Reservoir 4 (W130)	260.6	216.5	46.7	17.92%	16.92%	417
Reservoir 5 (W140)	12.5	9.0	3.5	28.00%	28.00%	791
Reservoir 6 (W150)	37.4	29.9	7.7	20.59%	20.05%	518
Reservoir 7 (W160)	1.2	1.2	0	0.00%	0.00%	51
Reservoir 8 (W170)	105.9	79.0	28.0	26.44%	25.40%	730
Reservoir 9 (W180)	79.2	65.0	14.9	18.81%	17.93%	424

4.2.3 *On design storms: scope of the effectiveness of rain barrels*

The effectiveness of rain barrels in case of different design storms is investigated by comparing the results of the simulations using the desired number and the capacity number of rain barrels separately. Figure 4.3 presents the comparison of the desired number and the capacity number of rain barrels per house for individual design storms and their footprint per house. For instance, for a 1% storm (a storm with the return period of 100 years), the RB-reservoirs representing desired number of rain barrels (D-RB-reservoirs) can be translated into 156 rain barrels per house.

However, in practice, only 96 rain barrels per house can be filled up during a 1% (100-year) frequency storm. Thus, the desired peak flow reduction cannot be achieved; the same is true for a 2% (50-year), 4% (25-year), 10% (10-year), and 20% (5-year) storm. As the storm frequency increase, the gap between the desired number and the capacity number of rain barrels narrows down. For a 50% (2-year) storm, the capacity number of rain barrels achieves lower peak flow than that of the desired number. Furthermore, a smooth interpolation shows that the capacity number meets the desired number of rain barrels at frequency of 33% (a 3-year storm) where the number and the footprint of rain barrels per house are 49 and 14 m2, respectively. Thus, for a storm with return period less than 3 years, harvesting all rainwater volume received by rooftops, rain barrels can provide enough reduction on peak flow to maintain safe discharge rate at the outlet of SCW.

However, for storms with return periods longer than 3 years, stormwater management cannot rely exclusively on rain barrels; it is necessary to consider other stormwater management practices.

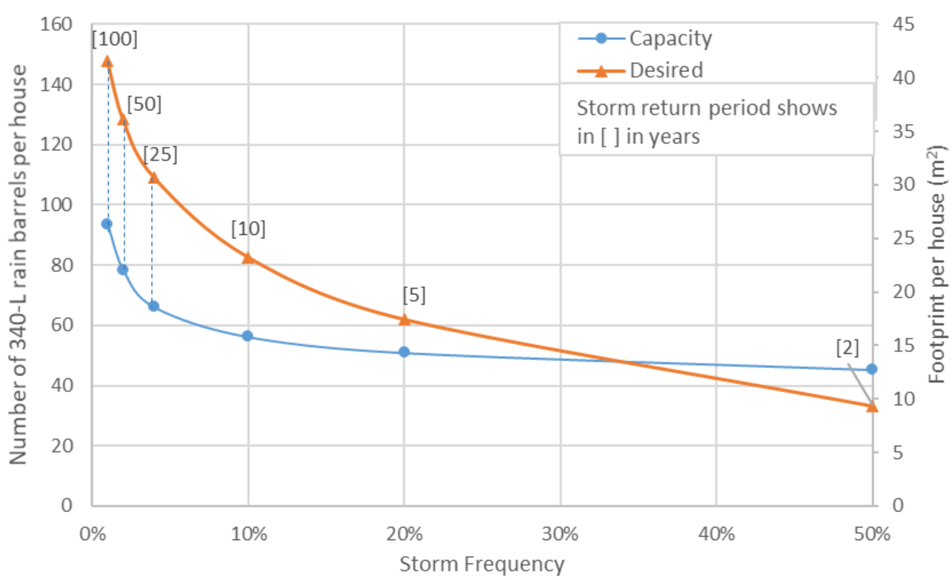


Figure 4.3 Number and Footprint of Capacity and Desired Rain Barrels Scenarios

Figure 4.4 shows the hydrographs of the design storms simulated with the desired number and the capacity number of rain barrels per house separately. As storm frequency decreases, the gap of peak flow rate between scenarios using the capacity number and the desired number of rain barrels widens, but the acceleration slows down. From a 2% (50-year) to a 1% (100-year) storm, without rain barrels, the peak flow rate increases from 5834 to 6466 cfs; by harvesting all rainfall volume received by rooftops in rain barrels, rain barrels make peak flow rate increase from 3887 to 3932 cfs.

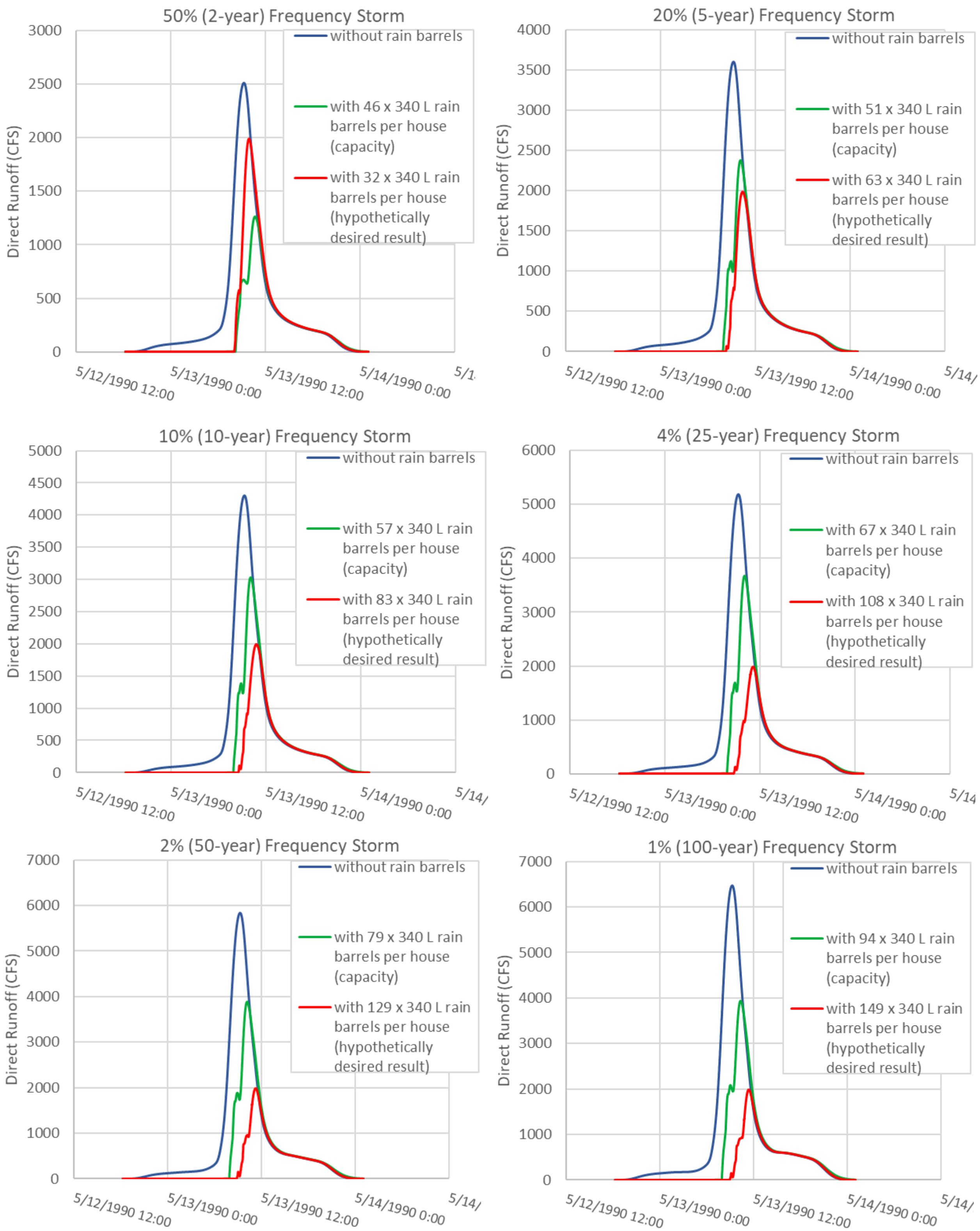


Figure 4.4 Hydrographs of Design Frequency Storms with Rain Barrels

4.3 Effectiveness of Detention Ponds on Design Storms

The effect of detention ponds on design storms is tested on the DP-based model for each design storm individually. The goal is to design detention ponds wherever sub-basins need them, to reduce the peak flow at the outlet of the watershed to below the flood discharge. Results from the DP-based model are compared with the results from the RB-based model of desired number of rain barrels, which are analyzed from two perspectives: design storms, and detention ponds. From the perspective of each design storm, the peak percentage of its runoff volume that needs to be stored in detention ponds to achieve the flood control goal is compared with the peak percentage if the desired number of rain barrels are used to achieve the same goal. From the perspective of detention ponds, the minimum surface area of all detention ponds in Sugar Creek Watershed that needs to be occupied by detention ponds to achieve the flood control goal is compared with the area that is needed by desired number of rain barrels.

4.3.1 *Runoff Volume stored in Detention Ponds*

To compare the difference of the required storage volume between rain barrels and detention ponds to achieve same flood control goal, it is necessary to determine the peak percentage of runoff volume of each design storm that needs to be harvested in rain barrels or in detention ponds.

It is natural that a longer-return-period storm generates larger-volume runoff and requires the rainfall harvesting practices to store more of the runoff volume to achieve the flood control goal. However, the storage requirements of rain barrels and detention pond are different. As shown in Figure 4.5, rain barrels need to harvest 15% more runoff volume of a 2-year storm than detentions ponds, 12% more of a 4-year storm, and around 10% more of a 10-, 25-, 50-, and 100-year storm. Although the desired number of rain barrels per house exceeds the capacity number of rain barrels, this comparison shows the intrinsic difference in the required storage volume between rain barrels and detention ponds, assuming that the rooftops are large enough and place no restriction on the desired performance of rain barrels on harvesting rainfall volume.

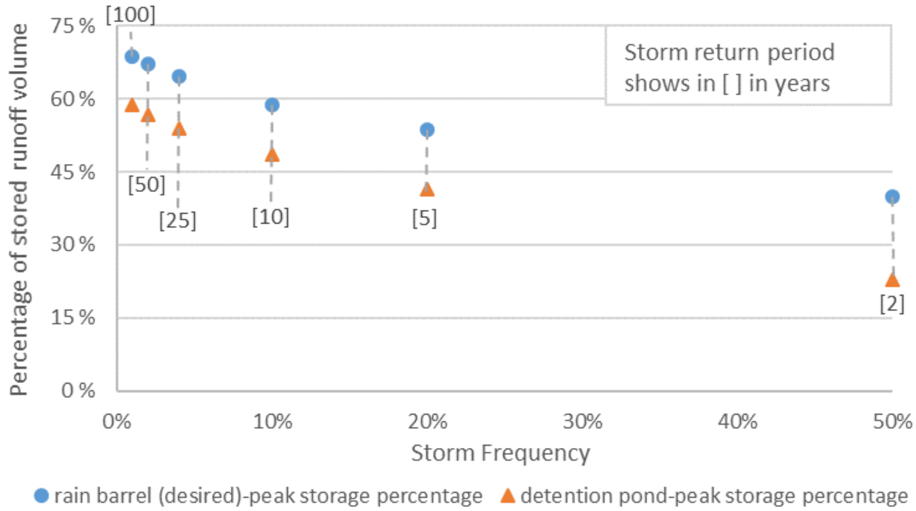


Figure 4.5 Comparison of Peak Storage Percentages

4.3.2 *Surface Area of Detention Ponds*

In addition to the comparison of the differences of the peak percentage of runoff volume of each design storm that is stored in rain barrels or detention ponds, the differences in the surface area requirements between both rainfall harvesting practices for each design storm are also explored. Figure 4.6 shows the percentages of the surface area of SCW that are needed to be occupied by the desired number of rain barrels or detention ponds to control individual design storms. It can be observed that detention ponds need up to 0.22% smaller surface area of SCW than rain barrels in case of a 100-year storm, and as low as 0.13% less for a 5-year storm, which can be interpreted as smaller surface area by 0.18 km2 and 0.11 km2, respectively.

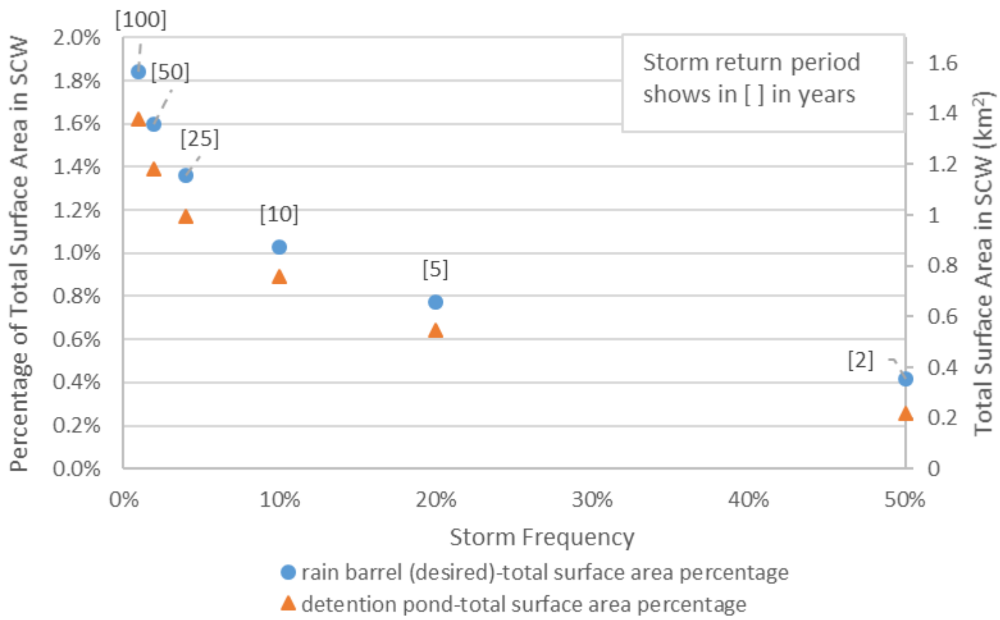


Figure 4.6 Comparison of Surface Area Percentages

4.4 Combinative Effect of Rain Barrels and Detention Ponds on Design Storms

The combinative effect of capacity number of rain barrels with detention ponds is evaluated using the RB-DP-model. The results are presented in terms of the reduction of the quantity and surface area of detention ponds in the combinative scenario compared with detention ponds in the individual scenario.

4.4.1 *Reduction in the number of detention ponds*

Not all outflow routed through a RB-reservoir representing capacity number of rain barrels (C-RB-reservoirs) bears flooding risk on the sub-basin downstream. Thus, for the outlet of a sub-basins with safe discharge rate after being routed through a C-RB-reservoir, the design of a DP-reservoir is not necessary. Only those sub-basins that still bear hazardous discharge rate after being routed through a C-RB-reservoir needs to be complemented with a DP-reservoir immediately downstream. Inclusion of a DP-reservoir following a C-RB-reservoir applies to: for a 5-year storm, sub-basin W110; for a 10-year storm, sub-basin W110 and W130; for a 25-year storm, sub-basin W110, W120, and W130; for a 50 or 100-year storm, sub-basin W100, W110, W120, and W130.

4.4.2 *Reduction in the Total Surface Area*

In Figure 4.7, the minimum total surface area of the combinative design of capacity number of rain barrels and detention ponds to maintain safe discharge rate at the outlet of SCW is compared with the area of the individual design of desired number of rain barrels or detention ponds. Results in Figure 4.7 show that the total area of the combinative scenario is mostly larger than the area of the detention ponds in the individual design, e.g. 0.0319 km2 (2.3%) larger for a 100-year storm, 0.0348 km2 (2.9%) larger for a 50-year storm, 0.0201 km2 (2.0%) larger for a 25-year storm, 0.0106 km2 (1.4%) smaller for a 10-year storm, and 0.0351 km2 (6.4%) larger for a 5-year storm. In addition, the combinative scenario results in a significant reduction in the surface area of detention ponds, excluding rain barrels, compared with the detention ponds in individual design, that is, 0.96, 0.7964, 0.6811, 0.6075, and 0.5055 km2 smaller, by 69.4%, 67.2%, 68.2%, 80.1%, 92.6%, for a 100-, 50-, 25-, 10-, and 5-year storm, respectively. In addition, as storm frequency increases, a decreasing gap appears between the total area of combinative scenario and the area of desired rain barrels in individual design. The combinative scenario of capacity number of rain barrels and detention ponds needs 0.153, 0.1421, 0.1388, 0.1299, and 0.0777 km2 smaller total area than the individual design of desired number of rain barrels, for a 100-, 50-, 25-, 10-, and 5-year storm respectively.

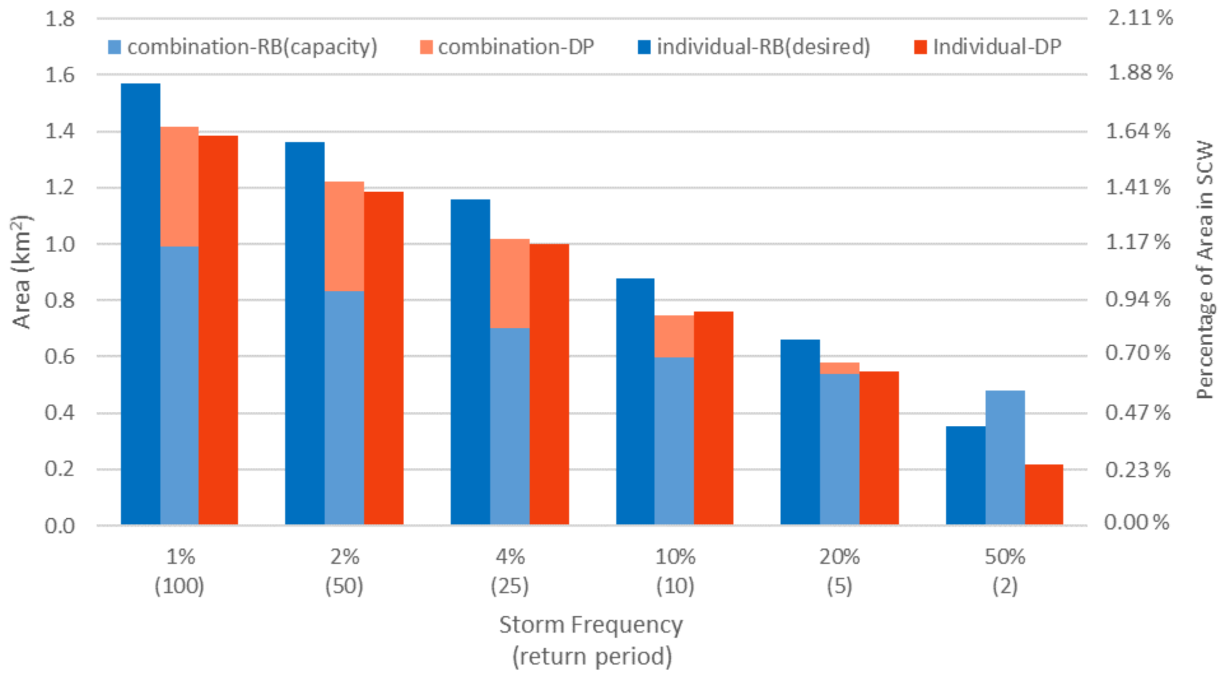


Figure 4.7 Area Comparison of Individual and Combinative Scenarios

5. SUMMARY AND CONCLUSION

5.1 Summary

Rain barrels, as a component of Low Impact Development (LID), can control urban stormwater in terms of reduction on runoff volume and peak flow rate. An overflowing rain barrel stores rainfall volume inside its storage, and releases outflow after it is full. The resulting discharge hydrograph has a different shape. In this study, the discharge hydrograph at the outlet of the watershed, without any rain barrels, features one peak. When rain barrels are included, the rising limb of the resulting hydrograph changed, featuring multiple low peaks. However, if the watershed is simulated through detention ponds with proper outlet structure that drains water constantly at different surface water level, the resulting hydrograph has a smooth rising limb with one limb.

The contributing factor to the difference in the shape of hydrograph from the rain barrel-based and the detention pond-based model is the inability of overflowing rain barrels to release low flow and the expedited time gap from low flow to high flow. By contrast, designed detention ponds with proper outlet structures allow outflow even at low discharge rate and drains water out completely eventually, which also can actively control the peak outflow rate below acceptable level. Thus, the minimum required storage volume of detention ponds is smaller than that of rain barrels; the peak percentage of the runoff volume of 2- to 100- year storms that detention ponds are needed to harvest is 10% to 15% smaller than that of the desired number of rain barrels. The total surface area of the watershed that is needed to be occupied by detention ponds in case of 5- to 100-year storms is 0.13% to 0.22% smaller compared with the area of desired number of rain barrels.

Overflowing rain barrels have certain but limited effect on peak flow reduction because the size of rooftop area restricts the achievement of desired performance. Rainwater volume falling on rooftops determines the effective storage volume of rain barrels. The maximum reduction on runoff peak flow is assessed by storing all rainfall received by rooftops inside rain barrels. In the study area, for a storm with the direct runoff peak flow at 1700 cfs, rain barrels at capacity can reduce peak flow rate by 100 cfs; for a 100-year storm, rain barrels at capacity can reduce peak flow rate from 6466 cfs to under 4000 cfs.

As rain barrels only use its storage volume to store runoff volume and indirectly reduce peak flow rate, detention ponds aim at releasing allowable peak flow rate by temporarily storing inflow that exceed outflow capacity and will finally drain out all runoff volume. The final storage of rain barrels has negligible change from its peak storage, but the final storage of detention ponds will eventually decrease to zero, which inevitably elongates the base time. The timing of emptying rain barrels should be chosen wisely as to not pose additional threat to flood control.

For the overall design of rainfall harvesting facilities, rain barrels should be designed as the complementary storage facilities in addition to detention ponds. Considering that 10% to 15% larger storage volume and 0.13% to 0.22% (0.18 km2 and 0.11 km2, respectively) larger surface area are needed for rain barrels to achieve the same stormwater management goal as detention ponds do in case of 2- to 100-year storms, rainfall harvesting facilities should feature a higher proportion of rain barrels and a lower proportion of detention ponds in a high-density residential area, and a lower proportion of rain barrels and a higher proportion of detention ponds in a low-density residential or agricultural area.

The combinative design of rain barrels at capacity number with detention ponds results in a substantial reduction in the surface area of detention ponds, compared with the detention ponds in the individual design, by 0.51 km2 and 0.96 km2, that is, 69.4% and 92.6%, for a 5- and 100-year storm, respectively. However, the total area of the combinative design is not much different from the area of detention ponds in the individual design; in most cases, the area of the combinative design is larger, e.g. 0.201 km2 (2%) larger for a 25-year storm, and 0.0351 km2 (6.4%) larger for a 5-year storm, but for a 10-year storm, 0.0106 km2 (1.4%) smaller.

Along with city development, the city size expands and the center moves. A detention pond that was in rural area when designed might become the new center for business or residential area. The retrofitting of rain barrels shows that more public land could be restored from detention ponds by the addition of rain barrels assigned to individual buildings in the watershed. However, the number of rain barrels per building needed to control a 2-year storm is 32; thus, an aboveground or underground storage tank, in lieu of 32 rain barrels, would be more practical.

5.2 Limitations

This study did not differentiate between residential or commercial buildings, or include the emptying of rain barrels, or the distributed on-site modeling of rain barrels. Future work will delve into scenarios of the combination of rain barrels with other LID practices designed specifically for buildings of different uses. It is also important to use a distributed hydrologic model that allows configuration of distinctive time delay of the emptying of rain barrels based on their spatial location. Continuous modeling should be adopted for evaluating long-term effectiveness of rain barrels using coarser time-scale data and simulated with larger time step, e.g. HEC-HMS continuous modeling using SMA method (Chu 2009), or SWAT modeling (Seo 2017).

In this study, the lumped approach to modeling the effect of all rain barrels in a sub-basin assumes a reservoir with a broad-crested weir which has a weir length calculated as the square root of the total surface area of all rain barrels. However, if the four sides of the square are used as the weir length, the outflow approximation of rain barrels can be improved.

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