Spring 4-13-2018

Rainwater Harvesting System Scenario Analysis on Runoff Reduction Potential in Surabaya, Indonesia: A Geospatial Analysis for Brantas Hilir Watershed

Putri Sukmahartati
University of Nebraska - Lincoln, putri21@huskers.unl.edu

RAINWATER HARVESTING SYSTEM SCENARIO ANALYSIS ON RUNOFF REDUCTION POTENTIAL IN SURABAYA, INDONESIA: A GEOSPATIAL ANALYSIS FOR BRANTAS HILIR WATERSHED

By

Putri B. Sukmahartati

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Environmental Engineering

Under the Supervision of Professor Ayse Kilic

Lincoln, Nebraska

April, 2018

RAINWATER HARVESTING SYSTEM SCENARIO ANALYSIS ON RUNOFF REDUCTION POTENTIAL IN SURABAYA, INDONESIA: A GEOSPATIAL ANALYSIS FOR BRANTAS HILIR WATERSHED

Putri Brikke Sukmahartati, M.S.

University of Nebraska, 2018

Advisor: Ayse Kilic

Global warming has become an environmental concern over the past several decades and its impact on the water cycle is very crucial to the well-being of the human population. In the hydrological cycle, water evaporates by the heat of the sun and atmosphere, where it is accumulated in the atmosphere via clouds and it then falls as rain. With warmer temperatures, more intensive evaporation and downpours occur. In addition, impervious surfaces are increasing as a result of urban development. Those surfaces cause more water to flow faster into open water bodies, creating more extensive flooding, and additionally reducing water quality. In this study, the amount of runoff volume (streamflow) that can be reduced by harvesting rainfall in residential systems is explored. Rainfall harvesting can be accomplished by installing storage tanks under roofs of residential homes. The harvested rainwater can be later used to augment domestic water demands. It also reduces the peaks of storm runoff, thereby reducing downstream flooding. The investigation on the impact of rainfall storage has been done using the USDA-Soil Conservation Service Curve Number (SCS-CN) method that estimates rainfall-runoff as a function of the imperviousness of the land surface, including structures. Soil maps, land use/land cover, and precipitation data were used as input to the

process. Surabaya is the second largest city in Indonesia, with a 2.843 million population based on 2017 demographics. The city has large residential areas as noted from land use/land cover maps. The buildings that cover this city can be a promising opportunity to harvest the rainfall, and supports water management in Surabaya. One of the objectives of this study was to develop and assign rainfall-runoff curve numbers based on fractions of lawn, buildings and other impervious systems to residential, government and commercial buildings with and without rainfall harvesting practices. These developments can help to model suitable rainwater harvesting potentials for the future.

Acknowledgement

I would first like to thank my thesis advisor Dr. Ayse Kilic for the support and research guidance through this thesis analysis. I would also like to thank Dr. Richard Allen who also contributed advice and ideas for improving my analyses and the thesis.

I would like to acknowledge Dr. Bruce Dvorak and Dr. Suat Irmak as the members of my thesis committee. I am gratefully indebted to their valuable input on this thesis.

I would also like to acknowledge Fulbright program to support my two-year program at UNL. I would thank Philip Blankenau and Samuel Ortega who shared information about gridded data, and Noordiah Helda who helped me a lot with hydrology problems.

Finally, I would like to thank my parents, my friends and especially my boyfriend, Ben Hage, for the continuous support and encouragement through the process of completing this thesis. This accomplishment would not have been possible without them.

Table of Contents

Table of Figures

List of Tables

CHAPTER 1: INTRODUCTION

1.1 Background

One of the biggest environmental threats in the future is the impact of climate change on the hydrologic cycle, as the result of human activities. Climate change is considered to be an external forcing to the hydrologic cycle that governs the occurrence and flows of water on planet Earth (NASA, n/d). Climate change from the greenhouse effect due to an increased emission of CO_2 (a greenhouse gas) alters the normal hydrologic cycle. The hydrologic cycle is quite sensitive to a warmer temperature at the Earth's surface and in the atmosphere.

Under these warmer conditions, the processes of evaporation and precipitation are expected to increase, and therefore the rates of runoff will increase. Following the hydrologic cycle, the increasing runoff will result in greater amounts of flooding (CA WALUP, 2006). As part of mitigation efforts to climate change, capturing and temporarily storing water from rain is becoming part of a potential effort to reduce streamflow. Rainfall harvesting can also be a benefit in reducing municipal demands for domestic water supply, and to reduce infiltration of potentially contaminated water into groundwater, from contaminated surface soil.

Geographical Information Systems (GIS) play an important role in modeling and monitoring various projects including environmental assessment (João and Fonseca 1996) because of their ability to describe spatial variation in natural systems. In a rainfall harvesting project and analyses, data input are mostly spatial in nature. These spatial inputs include rainfall distribution, slope, soil maps, streamflow networks, and land cover/use. Integration of these inputs with tool features in ArcMap can help to analyze the rainwater harvesting potential within a study area.

The study area for this research is the river basin containing Surabaya, Indonesia. Surabaya is the second largest city in Indonesia with population around 2.8 million and has a rapid urban development. As a result, Surabaya is populated with high and large buildings, roads and pavements, thus providing a small capacity to store rainfall. Under natural conditions, water from rain can be stored on vegetation, in the soil, and in surface depressions, with runoff occurring when the storage is filled. However, in urban areas where land is covered with construction and buildings, storage capacity becomes less and with reduced infiltration, creating higher runoff to streams and larger floods (Konrad, 2003).

The water supply in Surabaya is mainly operated by the Perusahaan Daerah Air Minum (PDAM) Surya Sembada Kota Surabaya. This company is still using major water sources from Kali Surabaya river that has an average flow rate of 40 m^3/s in the rainy season, and 20 m^3/s in the dry season (Sumantri et al. 2016). Surabaya is where the final outflow of the river to the ocean occurs. Frequently, flooding occurs during the rainy season due to low elevations in the city, leading to inundation and damage by the flooding.

Higher rainfall and runoff rates under future climate change, coupled with less infiltration caused by urban development, is the main issue that may lead to increased flooding and disasters. Collecting water from rainfall could be one of the least costly solutions since the harvested water could be reused for daily domestic water needs

(Garrison et al, 2011). Thus, rainwater harvesting systems are a promising technique to preserve water resources sustainability in the future.

The main objective of this study was to identify runoff volumes from rain and how they can be reduced by applying rainwater harvesting in residential and urban areas in Surabaya, Indonesia. The specific objectives for this study were:

1. gather data and create a spatial GIS repository for the study area to support data preprocessing,
2. determine the potential rainfall amounts that can be collected in each single dwelling (low density) and for high density residences in urban areas (government buildings, apartments, roadways, etc.), and
3. estimate reductions in basin-wide runoff depths for several extreme precipitation events under different scenarios.

1.2 Thesis Overview

This thesis is organized into five associated chapters. Chapter 1 is the introduction of the thesis and explains why conducting research related to collecting rainwater is needed in reducing municipal demands for domestic water supply, and in decreasing rainfall runoff from flooding events, and chapter 2 presents a literature review relevant to the research. Chapter 3 describes the essential methods that have been used in the research, while Chapter 4 discusses and presents the results. Lastly, Chapter 5 outlines the conclusions and some suggestions for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The main purpose of this chapter is to provide the reader with a general overview of rainwater harvesting and its analysis within a geographical information system (GIS) platform. The first part of this chapter is a brief description of rainwater harvesting and its potential to be applied to support environmental needs for reduced flooding and increased water supply. Next, a brief overview of GIS applications including the application to this research is presented. Then, several methods that can be implemented with a GIS model are described, and the last part provides a general overview of rainwater harvesting potential on runoff reduction.

2.2 Rainwater Harvesting

Rainwater harvesting can be used to capture and store runoff water from precipitation for daily human needs. Rainwater harvesting could be constructed using three basic elements: rainfall catchment area (roof), supporting collection system (gutter, screen/roof washer, and flushing system), and storage tank (Biswas and Mandal 2014). It has been reported by a few researchers that the use of rainwater in different countries to augment water supplies has a benefit to improve water savings in houses and buildings (Ghisi et al. 2006).

2.2.1 Potential of Rainwater Harvesting in Indonesia

Indonesia is located in a tropical region with large quantities of rainfall during nearly every year. It is therefore an ideal place for collecting rainfall due to its geographic location. Instead of letting all excess rainfall run off to the ocean, collecting the rainwater will help people in Indonesia since there is an essential need of water for daily consumption, and it can reduce the magnitude of flood damage. It can also support sanitation improvement for a healthier life.

2.2.2 Rainwater Harvesting Basic Components

The principal model for rainwater harvesting is collecting rainwater from roofs and storing the water temporarily in a tank (Saidan et al, 2015). Based on the Texas Manual on Rainwater Harvesting (2005), there are a variety of components considered and used for rainwater collection.

(1) Catchment Area

For all building types, the perfect choice to catch the rainwater is from the roof. The quality of the harvested rainwater from roof can be influenced by the materials of roof, climate condition, and environment (Vasudevan, 2012 as cited in Texas Manual 2005). In addition to this, water quantity from a rainwater harvesting system can be influenced by roof texture: smoother roof textures may result in more water captured.

(2) Gutters and Downspouts

Gutters function as a media to capture the rainwater once it leaves the roof, and rainwater can then be delivered by installing downspouts that lead to a storage tank. The low-cost gutters and downspout are usually made from PVC. Additionally, after the gutters and downspout have been installed, the next step is installing a drop outlet with an approximately 45 degrees angle to drain the water from the side of the house and into a tank or series of tanks.

(3) Rain Storage

Rain storage stores the harvested water and is most effective if it is empty before the rainfall period. Rain barrels can be obtained by purchasing from local stores or they can be built (Homeowner's Guide to Stormwater Management, 2016).

According to the Philadelphia Water Management (2006), rain barrels provide the following benefits:

a. They can help to reduce water pollution from the ground by minimizing stormwater runoff.
b. They can help home owners to lower their monthly water costs by recycling the harvested water to irrigate lawns and for sanitation purposes, including toilet flushing for example.
c. They can support natural groundwater recharge by using the stored water for later lawn and garden irrigation.

2.2.3 Water Quality

Rainwater that falls from above is often a very good source of high quality water, since it is not contaminated from ground pollution. However, because the collection systems that are used occupy roofs of residential houses, there are some factors that will affect the quality of the water that has been harvested, as summarized in Table 2-1.

Table 2-1 Types of contaminants, as well as their sources and risks, that are commonly found in rainwater system (Mosley 2005)

Contaminant	**Sources**	**Risk / mitigations**
Dust, ash and debris	1. Surrounding dirt and vegetation 2. Volcanic activity	Moderate: Can be minimized by doing maintenance on regular roof and gutter, also using a first-flush device and screens.
Pathogenic Bacteria	Bird and other animal droppings on roof, attached to dust	Moderate: Bacteria may be attached to dust or in animal droppings falling on the roof. Impacts can be minimized by use of a first-flush device and good roof and tank maintenance. Using chlorine to disinfect may also be useful.
Heavy metals	Dust, particularly in urban and industrialized areas, roof materials	Low: Unless downwind of industrial activity such as a metal smelter and/or rainfall is very acidic (this may occur in volcanic islands)
Other Inorganic Contaminants (e.g. salt from sea spray)	Sea spray, certain industrial discharges to air, use of unsuitable tank and/or roof materials	Low: Unless very close to the ocean or downwind of large-scale industrial activity
Mosquito Larvae	Mosquitos laying eggs in guttering and/or tank	Moderate: If tank inlet is screened and there are no gaps, risks can be minimized

2.3 Geographical Information Systems (GIS) Applications

Geographical Information Systems (GIS) have recently become one of the most powerful tools for analyzing spatial and non-spatial data (Adham et al. 2016). (Adham et al. 2016). GIS is a method created to capture, store, manipulate, analyze, manage, and present all types of geographical data (Research Guide 2017). Tools that have been provided within the software can be used to integrate various input layers such as the curve number that relates to runoff to rainfall, to analyze rainfall-runoff characteristics, and ultimately to determine the impact of rainwater harvesting for reducing flooding. The first important step for this research is the integration of watershed boundaries, soil maps and land use/land cover maps for the study area. The runoff depth can be then estimated by implementing spatial data layers into the basin wide analysis. This helps to determine the best possible rainwater harvesting systems for the study location, including impacts of sizes of harvesting systems on reducing flooding.

2.4 Rainfall Intensity

Rainfall intensity is measured and reported by the Tropical Rainfall Measuring Mission (TRMM) and its follow-on system named Global Precipitation Mapping (GPM). The Tropical Rainfall Measuring Mission is a joint NASA and Japanese Space Agency satellite that provides datasets of rainfall distribution in tropical and subtropical areas. Five instruments have been used in the TRMM satellite with four of them focused on precipitation: Visible and Infrared Scanner (VIRS), TRMM Microwave Imager (TMI), Precipitation Radar (PR), and Lightning Imaging Sensor (LIS) (Liu et al. 2012).

In this study, the TRMM dataset was retrieved at the GES-DISC Interactive Online Visualization and Analysis Infrastructure website (https://giovanni.gsfc.nasa.gov/giovanni/). Giovanni provides a quick data search, analysis, simple visualization and download using a normal web browser (Leptoukh 2007). Based on the study by (Shen et al. 2005), the implemented features of Giovanni are:

- Data from multiple remote sites as well as local sites are easy to be accessed.
- Server-side temporal and spatial subsetting.
- Server-side data processing.
- No need to download and preprocess the data manually.

• Support for multiple data formats: Hierarchical Data Format (HDF), HDF-EOS, network Common Data Form (netCDF), GRIdded Binary (GRIB), binary, and station data format.

• Multiple plot types like area, time, Hovmoller, and image animation are supported.

• Helps to process data output in ASCII format in multiple resolutions.

• Provides parameter inter-comparisons with functions, for example difference, scatter plot, and correlation coefficient.

• Easy to configure customized portals support for some project measurements.

• Runs on Linux, SGI, and Sun platforms.

2.5 Rainfall-Runoff Potential Assessments Techniques

Assessing the potential of rainwater harvesting can be done by utilizing the estimated production of runoff from rainfall events. Surface runoff occurs once the rainfall intensity exceeds the soil infiltration capacity (Critchley and Siegert 1991). The runoff will increase during high rainfall rates and when the soil infiltration capacity is lower (Lalitha Muthu and Helen Santhi 2015). There are some popular methods to analyze rainfall-runoff correlations including SCS CN, Green-Ampt, and Lumped methods.

2.5.1 Soil Conservation Service Curve Number (SCS CN)

The SCS CN method has been widely used as an accepted and popular model for estimating runoff depth due to its simplicity (Soulis and Valiantzas 2012). This method can generate an estimation of runoff depth, Q (mm), as a function of precipitation, P (mm), and a potential storage, S which is a function of curve number (CN) that can be estimated using soil type (Hydrologic Soil Group) and a Land Use/Land Cover map (Nearing et al. 1996).

In Indonesia, there are several studies on identifying runoff depth using the SCS CN method because it is relatively easy to be implemented. Cahyolestari (2010) used the SCS CN method for a study to reduce the surface runoff in the Samin watershed using different land use methods. Cahyolestari (2010) implemented the curve number from USDA as described in TR-55. For curve numbers of paddy fields, the study adopted information for small grains as reported in TR-55 as shown below in Table 2-2.

Table 2-2 Landuse Reclassification for Land Treatment (From Cahyolestari, 2010)

Nr.	Land Cover		Land Treatment/ Management	Hydrological Condition	
	from image interpretation	US-SCS Classification		Class	Explanation
1	Reservoir	Reservoir	-	-	-
2	Forest	Woodlands	-	Good	Protected from grazing so that litter and shrubs cover the soil
3	Rubber plantation	Woodlands	-	Fair	Grazed but not burned; there may be some litter
4	Mix garden	Farm woodlots	-	Fair	Grazed but not burned; there may be some litter
5	Paddy field	Small grains	Contoured and terraced	Poor	Contain a high proportion of row crops, small grains and fallow
6	Sugarcane plantation	Rotational meadow	Contoured	Poor	Heavily grazed or having plant cover on less than 50% of the area
7	Fruit and vegetable agricultural	Row crops	Straight row	Poor	Contain a high proportion of row crops, small grains and fallow
			Contoured	Poor	Contain a high proportion of row crops, small grains and fallow
8	Settlement	Farmsteads	-	-	-

The assignment of curve number for paddy fields can be seen through Table 2-3. In the table, the curve numbers for paddy field based on Hydrological Soil Group (HSG) are within the range of small grains curve numbers as presented in TR-55 (referenced in **Appendix E**).

Table 2-3 Curve Numbers for Each Land Cover Based on Hydrological Soil Group (From Cahyolestari, 2010)

Nr.	Land Cover	Land Treatment/ Management	Hydrological Condition	Hydrological Soil Groups			
				A	B	C	D
1	Reservoir	-	-	0	5	8	10
2	Woodlands	-	Good	25	55	70	77
3	Woodlands	-	Fair	36	60	73	79
4	Farm woodlots	-	Fair	36	60	73	79
5	Small grains	Contoured and terraced	Poor	61	72	79	82
6	Rotational meadow	Contoured	Poor	64	75	83	85
7	Row crops	Straight row	Poor	72	81	88	91
		Contoured	Poor	70	79	81	88
8	Farmsteads	-	-	59	74	82	86

Another research has been performed by Widiyati and Sudibyakto (2010) using the SCS CN method to study appropriate land cover to reduce surface runoff in the Pakuwojo Sub-watershed. The study found that areas covered by forest had the highest percentage of runoff reduction, relative to cultivated land, followed by carica papaya fields.

Those studies demonstrated that the SCS CN method can be a powerful procedure to analyze surface runoff from precipitation (rain). Researchers from around the world benefit from using this method especially because it can consider the impact of soil types based on geographical information.

2.5.2 Green-Ampt

SCS CN method is a popular method to estimate the runoff depth as a product of rainfall, however several other more theoretical methods have been used in hydrologic models to determine runoff depth, including the Green-Ampt infiltration equation. In hydrologic models, the Green-Ampt equation is based on Darcy's law for infiltration through soil (Nearing et al. 1996). There have been a number of studies that have focused on prediction of infiltration from rainfall events using the Green-Ampt method that have related parameters to soil properties (Van Mullem 1991).

The Green-Ampt model for infiltration can be described as:

$$f_{(t)} = K_e \left(1 + \frac{\psi \, \Delta\Theta}{F_{(t)}}\right) \tag{2-1}$$

Where:

$f_{(t)}$ = Infiltration rate (mm/hour)

K_e = Hydraulic conductivity (mm/hour)

ψ = Wetting front depth (mm)

$\Delta\Theta$ = Initial soil-water deficit (dimensionless)

$F_{(t)}$ = Cumulative infiltration (mm)

In the Green-Ampt equation, the capillary suction at the wetting front influences the hydraulic conductivity and the total hydraulic gradient that pulls water into soil (Mein and Farrell 1974). In applications with the equation it is often assumed that all rainfall infiltrated is processed into stored soil water content on the next day (for a wet condition), and that once the rainfall intensity exceeds the infiltration rates, the excess will become runoff (King, Arnold, and Bingner 1999). Furthermore, according to the

(Chen and Young 2006) study, the Green-Ampt equation can be implemented on sloping areas where the runoff amounts can be estimated by considering slope-surface storage relationships and therefore slope and infiltration relationships.

2.5.3 Lumped Model

In a lumped model, each watershed is considered to be a single aggregate unit using model parameters and input that is applied to each entire watershed area. One such lumped model is the Sacramento soil moisture model of the US National Weather Service (NWS) (Burnash et al. (1973) as cited in Carpenter and Georgakakos 2006). The lumped model concept is to simulate a watershed as a soil vertical column that has the upper and lower parts expressed as lengths of units where the moisture storage capacity, withdrawal rates, percolation, and the watershed outlet locations are considered in estimating total runoff. Products of lumped models can be used to determine curve numbers (Carpenter and Georgakakos 2006). Based on Vansteenkiste et al. (2014), the impacts of evapotranspiration in estimating soil storage dynamics, infiltration and runoff can be evaluated as one of the products of and parameters in a lumped model.

2.6 Rainwater Harvesting on Runoff Reduction

Rainwater harvesting is one of water conservation techniques that is recognized as a Low Impact Development (LID) for stormwater management, where storing runoff from stormwater for on-site use can reduce the runoff volume and pollutant amounts entering stormwater collection systems (Harvesting 2013).

In the past few years, rainwater harvesting has been used in humid and well-developed regions to reduce drought concerns, fulfilling increasing water demands, for stormwater runoff awareness, and as part of increased green building practices that support smart water use (Jones and Hunt 2010). Moreover, a recent study by (Campisano et al. 2017) showed that there were more Asian countries like Japan introducing rainwater harvesting as an essential water supply and runoff mitigation and as an effective tool for reducing flood problems in large cities.

Rainwater harvesting system implementation on buildings requires the setting up of appropriate size tanks to store the collected rainwater from rooftops or terraces. After the stored rainwater has been treated to eliminate pathogens and heavy metals, it can be used for local use for both internal and external non-potable consumption like toilet flushing, garden irrigation, terrace cleaning, etc. (Campisano and Modica 2016). However, there is one issue related to harvesting rainwater: the lack of control on available volumes of uncontrolled tanks, where available, useable volumes of tanks depend on the current demands for and use of water. This is a disadvantage that can result in a limited efficiency of rainwater tanks on runoff reduction. (Petrucci et al. 2012)

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

This chapter gives details of methods that were followed in this research. It provides information on the criteria of the data selection, where and how to obtain the data, and analysis of the data. First, the study area on which the research would be focused was determined. Then, the data to support the research were collected and afterwards, the process of analyzing the data was performed using ArcGIS 10.4 with implementation of the Soil Conservation Service Curve Number (SCS CN) method.

3.2 Study Area

The area of study is in Surabaya which is the capital of the East Java province and is Indonesia's second largest city. As is usual in Indonesia as a capital city, Surabaya has a dense population. With an area of around 330 km^2, the population that has settled in Surabaya is 3.2 million people. Figure 3.1 shows the general location of Surabaya in Indonesia.

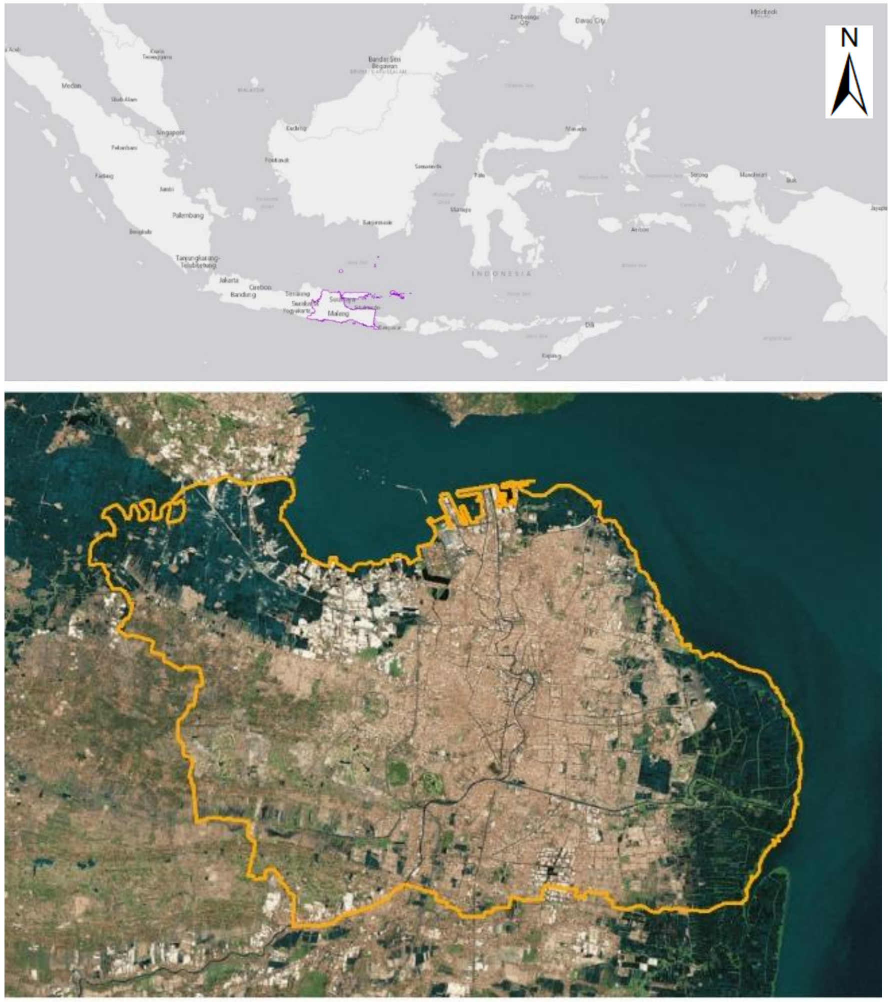


Figure 3-1 Study area location map showing all of Indonesia (top), and the aerial imagery of Surabaya city (bottom) through ESRI ArcGIS Online-ArcMap 10.4.

Surabaya is located within a tropical area that has two major seasons: dry and rainy seasons. The dry season ranges from May-September, while the rainy season ranges from October-April. Total amounts of rainfall in this city area vary from approximately 2000 – 4000 mm per year, and air temperature in Surabaya is around 23 – 34^{0}C all year (BPS, 2016).

The city of Surabaya resides primarily on a river delta and is mostly flat, about 3 – 6 m above sea level, making it vulnerable to flooding. In addition, most of the sewers in Surabaya are all generally filled to capacity both in rainy and dry seasons (Susetyo, 2008). Thus, flooding is something that cannot be avoided.

3.3 Runoff Modeling Approach

The Soil Conservation Service Curve Number (SCS CN) method (TR-55, 1986) is very useful to quantify rainfall-runoff relationships for evaluating rainwater harvesting. According to (Soulis and Valiantzas 2012), the SCS CN method has been popular among engineers because it is simple to use and is well-developed. The parameters of the equation are relatively easy to obtain and are well-documented. In addition, the many factors that influence the runoff generation are generally incorporated into a single CN parameter. The form of the SCS Runoff Equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{3-1}$$

where

Q = direct runoff (mm)

P = precipitation (mm)

S = potential maximum retention prior to when full runoff begins (mm)

Ia = Initial abstraction (mm)

Initial abstraction can be estimated using the standard equation:

$$I_a = 0.2\,S \tag{3-2}$$

With Equations (3-1) and (3-2), Q becomes:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8\,S)} \tag{3-3}$$

where S is related to the curve number for all land use/land cover and the soil conditions within an area by:

$$\boldsymbol{S = \frac{1000}{CN} - 10} \quad (3\text{-}4)$$

for S in inches, and for S in mm as:

$$\boldsymbol{S = \frac{25400}{CN} - 254} \quad (3\text{-}5)$$

The curve number calculation is typically applied using daily precipitation totals. When applied to a day having prior rain, an antecedent moisture condition (AMC) of III is typically used to assign the CN value, as opposed to the standard AMC II condition (TR-55, 1986 and Hawkins et al., 2003).

A flowchart of the data layers and the major steps that are important to conducting the required analysis is illustrated in Figure 3-2. Three input layers have been processed to create curve number that was critical in runoff production. The input data as presented in Figure 3-2 were soil map, landcover map, and digital elevation model (DEM) from SRTM. After the curve number has been assigned, the rainfall data was added to determine the runoff depth as the final product to be analyzed.

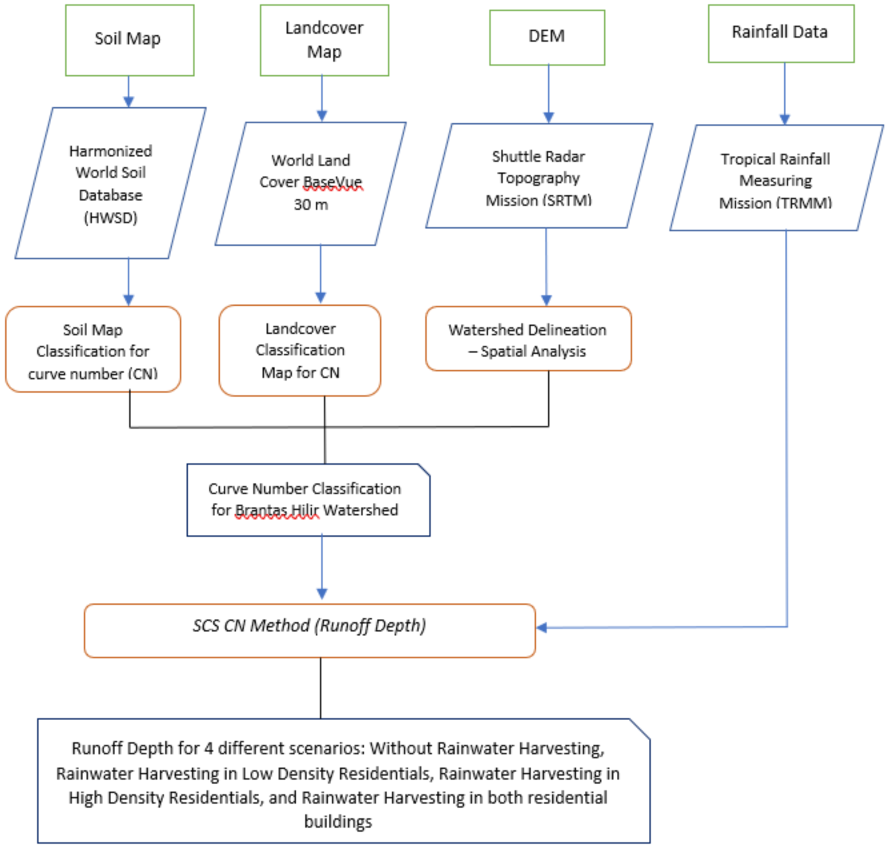


Figure 3-2 Framework of the study showing the data sources and computation steps.

There were a total of four major spatial GIS data layers employed for the analysis. The Digital Elevation Model (DEM) is important to delineate a watershed boundary, while soil and land cover data layers were used to produce the spatial distribution of curve number for the newly delineated watershed area. Soil maps are essential in this process because the soil properties within the area of watershed determine the Hydrological Soil Group (HSG) that in turn impacts the value for CN. The next step is to overlay the HSG map with a landcover map, that can then be processed to create the CN generation. After the curve number has been generated, the precipitation data from TRMM were used in the SCS-CN method to produce the runoff depth values.

This thesis has four types of runoff depths generated from residential area classifications to investigate the influence of rainwater harvesting applications on the runoff volume reduction within the entire basin. The residential area is a land use in which single-dwelling housing predominates, as opposed to industrial and commercial areas and high density residential areas. Runoff evaluations were chosen based on the landcover map of Surabaya.

(1) without rainwater harvesting (RWH),

(2) applying rainwater harvesting in low density residential areas,

(3) applying rainwater harvesting in high density residential areas, and

(4) applying rainwater harvesting in both low and high density areas.

3.4 Primary Data Sets

A number of readily available GIS data layers from global and national data repositories were collected to characterize the watershed characteristics and to develop a rainfall runoff procedure associated with rainwater harvesting within the GIS framework. These data were entered into the ArcMap software (ArcGIS Desktop 10.4.2., 1999-2007 ESRI Inc.). All the data layers were converted to an Indonesian Datum 1974 projection and WGS 1984 coordinate system within ArcGIS. The spatial resolution was set to 30 m for the soil map which had been resampled into a raster format using cubic convolution. The TRMM grid size was 0.25º x 0.25º (27.8 km x 27.8 km).

3.3.1 Elevation

The SRTM 1-Arc Second Global (SRTM1) data having approximately 30-meter resolution have been used to provide elevation information used to delineate the watershed boundary for the study area (Fig 3-3). The Shuttle Radar Topography Mission

(SRTM) is a collaboration effort of the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) and provides elevation data for the globe (USGS, n/d) using an active remote sensing radar. SRTM1 data were obtained through Earth Explorer at https://earthexplorer.usgs.gov/ on April 26, 2017.

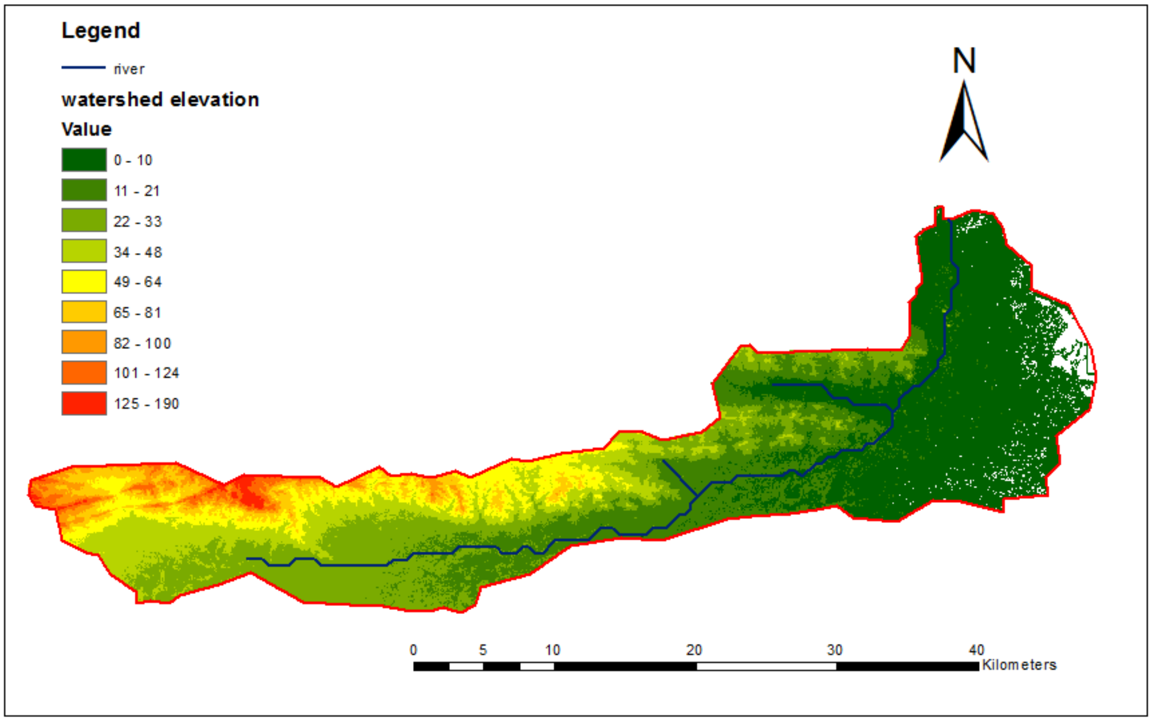


Figure 3-3 SRTM1 elevation data (meters) for the research study area. The blue line represents the major stream network that has a flow direction towards East.

The watershed and streams were delineated using the Arc-GIS-based procedures as outlined in Exercise 4 of the UNL CIVE 853 course titled GIS in Water Resources, as described at http://snr.unl.edu/kilic/giswr/2016/. The delineated watershed is known as Brantas Hilir Watershed and which influences the runoff towards the city of Surabaya. This watershed boundary was used as the outline for the study area to determine the runoff volume reduction associated with rainwater harvesting applications. The primary river in this watershed is the Kali Surabaya River which has a length of 42 kilometers. The watershed in the west is mostly agricultural and with scrublands high in the watershed, and to the east, is covered by city (lower elevation), near the ocean.

The urban areas are located in a delta region with low elevation, ±10 m based on DEM SRTM in Figure 3-3. Because of this low elevation level, it is possible that the runoff depths may be affected by gravitational tides (Suprijanto 2004). From the Wassmann et al. (2004) study, the large flooding because of tidal effects mostly happens during the rainy season when the rates of rainfall are higher.

3.3.2 Tropical Rainfall Measuring Mission (TRMM)

TRMM, as described in Chapter 2 Section 2.4, provides detailed precipitation data for tropical areas that has been used very often among scientists worldwide. TRMM data for the 10-year period from 2007 to 2016 were obtained through the Giovanni Web Interface by accessing the variable of near-real-time precipitation rate for a daily accumulation. Data were obtained for the 112.152^{o} to 112.837^{o} longitude, -7.457^{o} to -7.195^{o} latitude covering the Surabaya area. After the data were obtained, average total amounts of rainfall rate for each month were summarized to characterize the year to year variations, as shown in Figure 3-4.

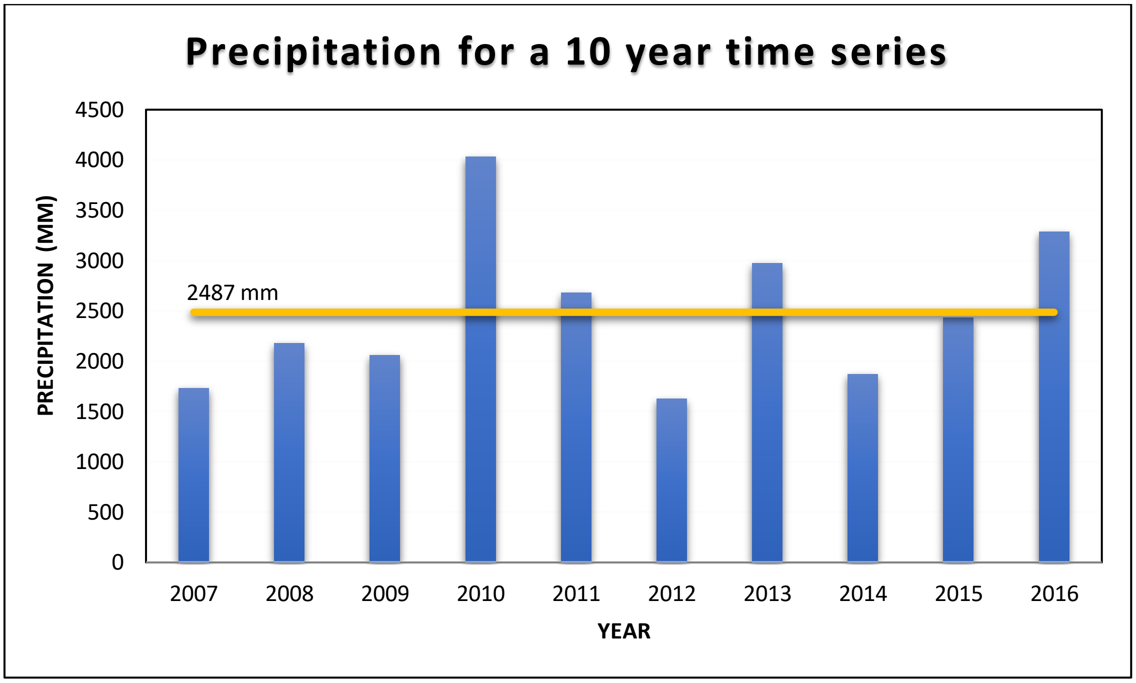


Figure 3-4. Average annual precipitation amounts (mm) over a 10-year period.

The average annual precipitation over the last 10 year period in Surabaya is around 2487 mm (Figure 3-4). The rainfall amounts from the two extreme rainfall events in 2010 and 2016 were used to develop rainwater harvest scenarios due to the possibility of their reoccurring in the future. One event was a 5 day storm between November 4 to 8, 2010. The second event was a 5 day storm between February 24, 2016 and February 28, 2016.

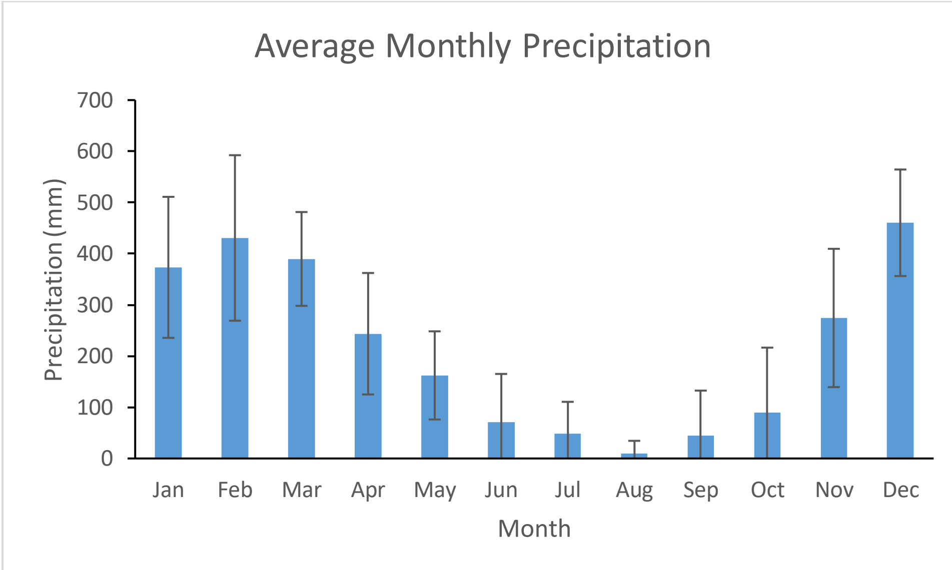


Figure 3-5 Average monthly precipitation amounts (mm) with error bars showing standard deviations

Figure 3-5 presents the average precipitation amount in each month over a 10 year period. It is shown that the high amount of rainfall happened in the wet season (November – April). There are two peaks of rainfall (double maxima) that occurred: February and December, which represents the rainfall pattern in tropical areas in response to vertical sun (Singh 2010). The double maxima rainfall characterized the tropical areas (close to equator) precipitation due to the equatorial type effect (Sutherland-Addy 2013).

The second step in precipitation data analysis was retrieving TRMM in a GIS format at ftp://trmmopen.gsfc.nasa.gov/pub/gis/ for two extreme rainfall events in the 10-year period. TRMM data was converted to a GIS format using the help document within the downloaded URL, which explained how to use the TRMM data within ESRI ArcGIS/ArcMap (Kelley, 2017).

There were two large multi-day storm events that occurred in 2010 and 2016 that resulted in flooding in the city. The highest precipitation was 107 mm in November for year 2010, and 77 mm in February for year 2016 (Table 3-1). After the precipitation data had been processed through ArcMap, there were 6 TRMM pixels that represented the rainfall amount within the two peak events. These pixels are presented below in Figure 3-6 and Figure 3-7 with more climate information presented in Table 3-1.

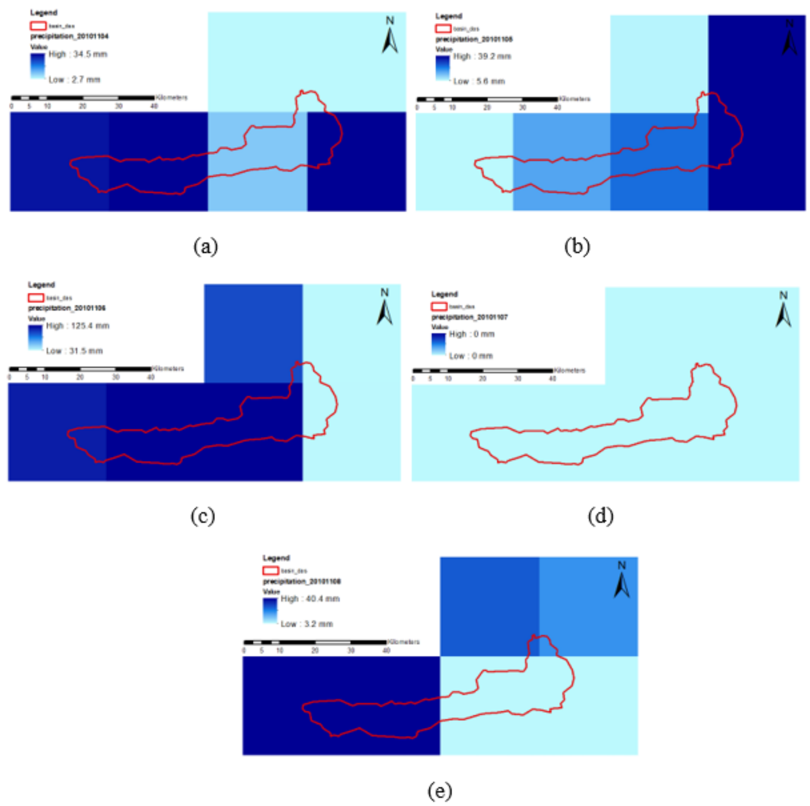


Figure 3-6 Precipitation data for the first event: Nov. 4 (a), Nov. 5 (b), Nov. 6 (c), Nov. 7 (d), and Nov. 8, 2010 (e) overlaid onto the study river basin

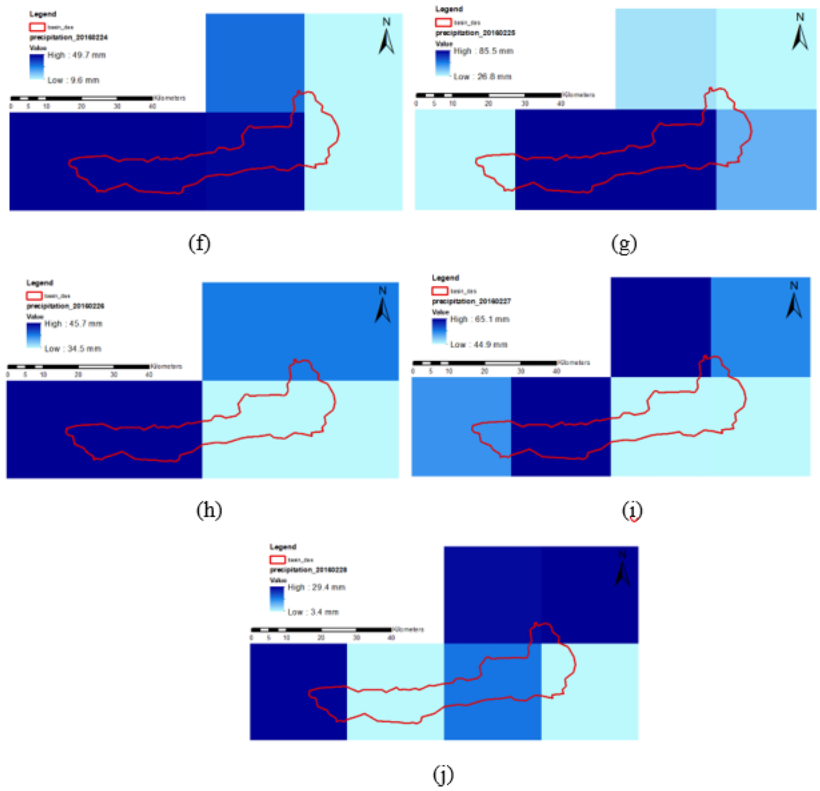


Figure 3-7 Precipitation data for 2016: Feb. 24 (f), Feb. 25 (g), Feb. 26 (h), Feb. 27 (i), and Feb. 28 (j) overlaid on the study river basin

Table 3-1 Climate data in the City of Surabaya within 24-hour period

Date	Precipitation (mm)	Peak Rainfall Intensity (mm/hour)	Temperature (°C)
11/4/2010	22	5	28
11/5/2010	16	4	28
11/6/2010	107	24	28
11/7/2010	0	0	28
11/8/2010	16	4	29
2/24/2016	33	7	25
2/25/2016	77	17	25
2/26/2016	40	9	25
2/27/2016	55	12	25
2/28/2016	17	4	25

The data from the two multiday storm events were used as a basis to determine the possibility of how much water could be harvested under extreme events similar to when typical flooding occurs. Additionally, the model results can help inform storm water management and policy-making in Surabaya for similar events occurring in the future.

3.3.3 FAO Global Soil Data

The soil map used for this research was obtained through ArcGIS online from the Harmonized World Soil Database (HWSD), which is in 3 arc-second spatial resolution. This map was generated from the partnership between FAO (Food and Agriculture Organization) and International Soil Reference and Information Centre (ISRIC) – World Soil Information who had been charged with developing regional Soil and Terrain databases (as cited in HWSD; Nachtergaele et al., 2009).

There are over 16,000 soil map units in the HWSD and each has attribute data. The attributes of each soil data component are beneficial for assigning Hydrological Soil Groups (HSG) for selected locations. The HWSD soils map for Brantas Hilir watershed is shown in Figure 3-6 where the west part of the watershed is dominated by Gleysols that have high clay content while the central part of the watershed is mostly fluvisols with alluvial characteristics (stratification). The spatial resolution of the HWSD soils map is 1 km by 1 km.

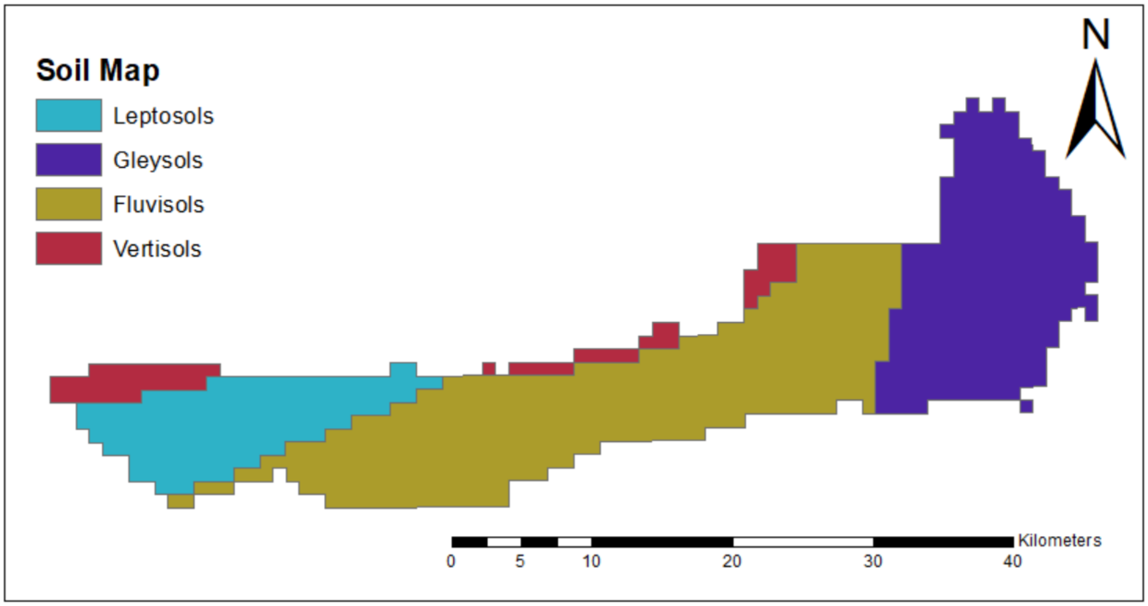


Figure 3-8 The Harmonized World Soil Database showing major soil types across Brantas Hilir Watershed.

There are four dominant different soil types across the watershed based on the Harmonized World Soil Database (Fig 3-8). The percentages of silt, sand, and clay content for the topsoil (0 – 30 cm) is given in Table 3-2 and this soil information is used to determine the Hydrologic Soil Group (HSG) to produce Curve Number (CN) and associated runoff depth (Q) production. For example, the dominant soil content from the Table 3-2 is clay (high percentage) which has small particle size, producing lower rates of infiltration. Thus, higher runoff depths can be expected.

Table 3-2 Soil type information

Soil Mapping Unit	% Sand	% Silt	% Clay
Gleysols	17	31	52
Leptosols	28	25	47
Fluvisols	39	41	20
Vertisols	20	24	56

3.3.4 Global Land Use and Land Cover

Land Use/Land Cover data were obtained from the World Land Cover BaseVue 30 m data set developed by MDA (MacDonald, Dettwiler and Associates Ltd., 2013) which is available through the ESRI ArcGIS map server. The Land cover data show characteristics for the material cover across the earth's surface that can impact infiltration and the curve number derivation. From Figure 3-9, there are two major land use types that cover the watershed area: urban and agriculture areas. The urban areas, which cover the most eastern part of the watershed, comprise 21% of the watershed: 9% for low density areas and 12% for high density areas. By comparison, the agricultural landuse, shown with representative colors which are visible in figure 3-9, have 53% of coverage for the watershed. These features affect the estimation of the curve number to the interaction of different land cover characteristics when combined with the soil types.

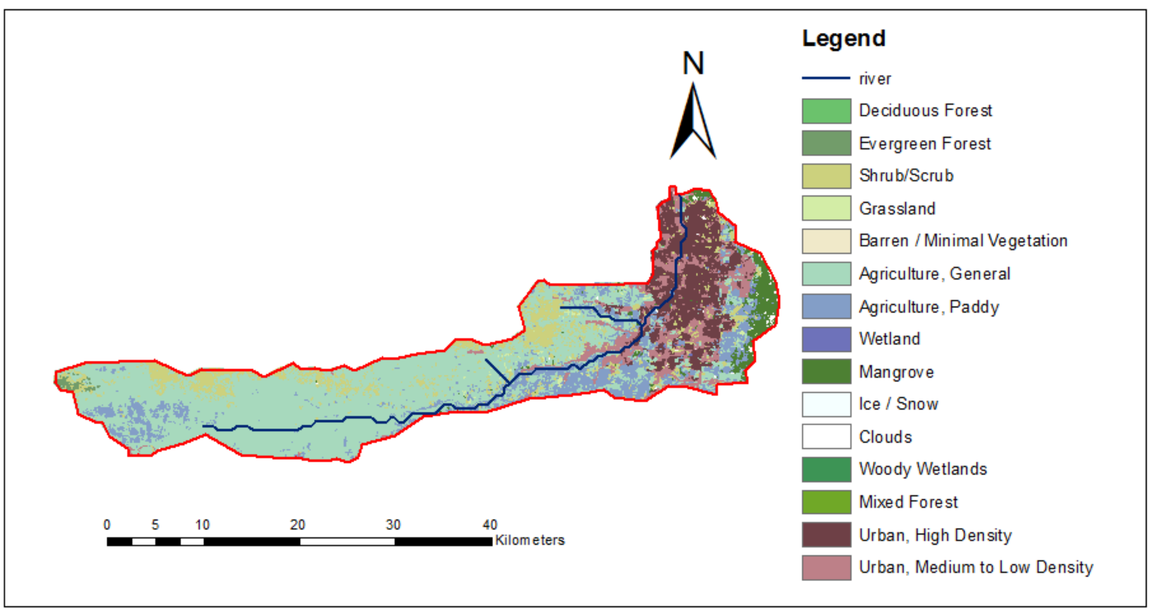


Figure 3-9 World Land Cover BaseVue 30 m Classifications for Brantas Hilir Watershed. The blue line represents the major stream network that has a flow direction toward the urban areas.

Figure 3-10 shows a closeup view of the urban area which are the focus of the runoff reduction due to rainfall harvesting. Urban areas are where many people settle, and where there is much human activity.

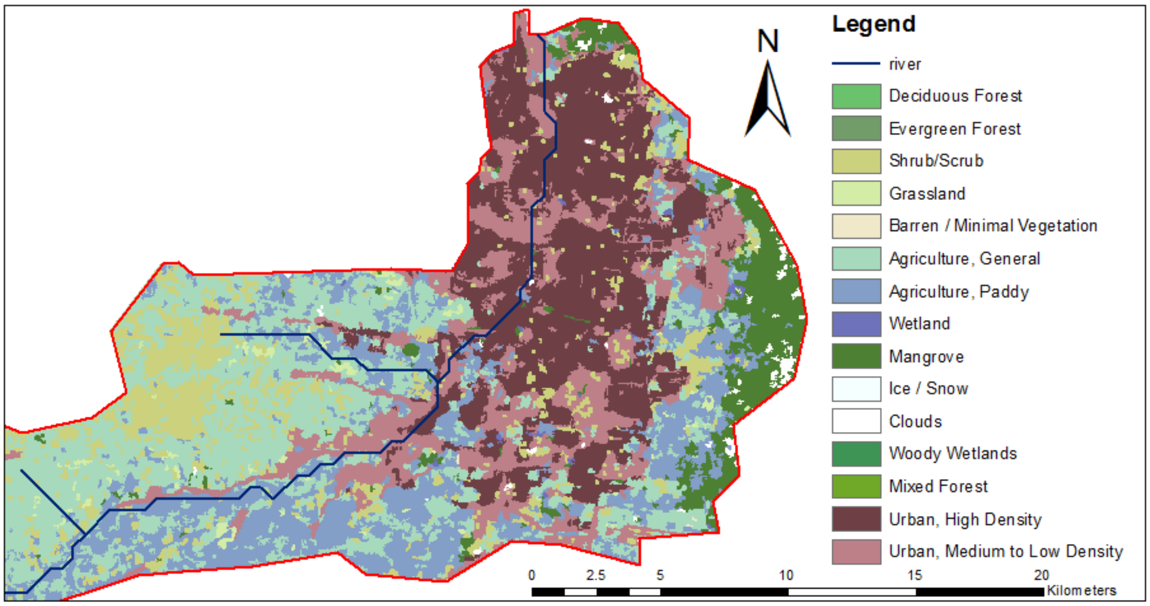


Figure 3-10 Land Cover Map Detail for Urban Areas

3.5 Hydrologic Soil Group (HSG)

The hydrologic soil group is important for deriving the value for the rainfall-runoff curve number, including the impact of soil type on infiltration properties. According to the National Engineering Handbook Chapter 7 (NRCS -USDA, 2009), there are four hydrologic soil groups which are classified based on infiltration rates and drainage class with more descriptions given in Table 3-3.

Most of the soils in the study area have high clay contents and fall within HSG D due to their lower infiltration rates. Because HSG D is poor in absorbing the water, and this type of soil that dominates the watershed area is not well-drained.

Table 3-3 Descriptions of Hydrologic Soil Groups (NRCS - USDA, 2009)

Hydrologic Soil Group	Description
A	Soil classifications for this group contain < 10% of clay, and > 90% of sand or gravel and the textures are gravel or sand.
	Soils in this group have high infiltration rate and low runoff potential when thoroughly wet.
B	Soil classifications for this group contain between 10 - 20% of clay, and 50 - 90% of sand and the textures are loamy sand or sandy loam.
	Soils in this group have a moderate infiltration rate and moderately low runoff potential when thoroughly wet.
C	Soil classifications for this group contain between 20 - 40% of clay, and < 50% of sand and the textures are loam, silt loam, sandy clay loam, clay loam, and silty clay loam.
	Soils in this group have a low infiltration rate and moderately high runoff potential when thoroughly wet.
D	Soil classifications for this group contain > 40% of clay, and < 50% of sand and the texture is clayey.
	Soils in this group have a very low infiltration rate and high runoff potential when thoroughly wet.

3.6 Generating Curve Numbers

To estimate rainfall runoff in Eq.1, the user should first calculate CN values associated with each soil and land use type. The curve number was determined by using an assigned hydrology soil group and land use/land cover as input data.

3.5.1 Overlay analysis

Combination of soil types and land use types was done using an overlay analysis in ArcMap. To enable the use of the overlay analyst tool in ArcMap through the intersect tool, raster data of land use/land cover were converted into polygons according to groupings of common land use types. The conversion of raster data into polygons was necessary because the runoff volumes and percentage reductions from rainfall harvesting were summarized and grouped according to land use type.

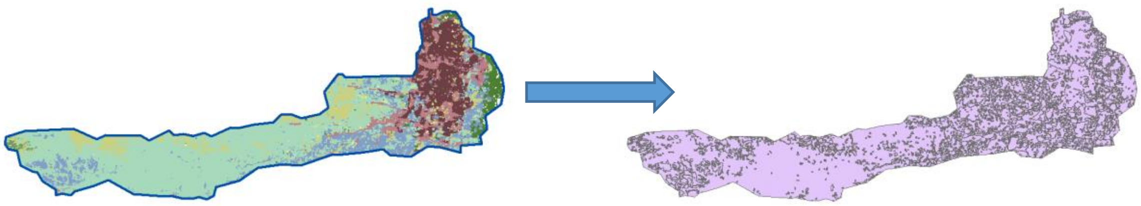


Figure 3-11 Conversion of raster data to polygons for the land use/land cover for the study area.

The soil map was clipped to the watershed boundary for use in the analyses. The curve number was based on both land cover/land use and soil map with hydrologic soil group (HSG). Table 3-4 shows the determination of HSG using the soil information from HWSD viewer.

Table 3-4 Hydrologic Soil Group (HSG) determined for each soil type detail

Soil Mapping Unit Symbol	% Topsoil Sand	% Topsoil Silt	% Topsoil Clay	HSG
Gleysols	17	31	52	D
Leptosols	28	25	47	D
Fluvisols	39	41	20	C
Vertisols	20	24	56	D

The HSG D class has percentages of clay more than 40%. Therefore, Gleysols, Leptosols, and Vertisols are assigned a D class while Fluvisols have adequate amounts of sand and silt, and are registered as C class.

The intersect tool combines the influence of the land cover/land use classification with type of soil, which is overlaid into one new layer prior to assignment of the curve number as represented in Figure 3-12.

OBJECTID *	Shape *	SU_NAME	HSG	gridcode	Description	Shape_Length	Shape_Area
1	Polygon	Vertisols	D	7	Agriculture, General	123.7	956.2
2	Polygon	Vertisols	D	7	Agriculture, General	321.3	3614.1
3	Polygon	Vertisols	D	3	Shrub/Scrub	333.3	3241.3
4	Polygon	Vertisols	D	8	Agriculture, Paddy	1075.5	23483.2
5	Polygon	Vertisols	D	7	Agriculture, General	1620	31343.2
6	Polygon	Vertisols	D	7	Agriculture, General	123.7	956.2
7	Polygon	Vertisols	D	3	Shrub/Scrub	804	21992
8	Polygon	Vertisols	D	8	Agriculture, Paddy	1175	46852.6
9	Polygon	Vertisols	D	7	Agriculture, General	309.2	3824.7
10	Polygon	Vertisols	D	3	Shrub/Scrub	63.9	32.2
11	Polygon	Vertisols	D	8	Agriculture, Paddy	1669.8	51633.5
12	Polygon	Vertisols	D	3	Shrub/Scrub	1484.3	32510
13	Polygon	Vertisols	D	3	Shrub/Scrub	7136.2	421835.4
14	Polygon	Vertisols	D	3	Shrub/Scrub	307.1	4748.7
15	Polygon	Vertisols	D	7	Agriculture, General	927.7	21035.9
16	Polygon	Vertisols	D	3	Shrub/Scrub	3092.2	144382.4
17	Polygon	Vertisols	D	8	Agriculture, Paddy	4024	220371.4
18	Polygon	Vertisols	D	7	Agriculture, General	1484.3	64063.7
19	Polygon	Vertisols	D	8	Agriculture, Paddy	1113.2	21035.9
20	Polygon	Vertisols	D	8	Agriculture, Paddy	678.2	12269.2
21	Polygon	Vertisols	D	8	Agriculture, Paddy	247.4	2868.5
22	Polygon	Vertisols	D	8	Agriculture, Paddy	1298.7	32510
23	Polygon	Vertisols	D	3	Shrub/Scrub	1548.2	49817.8
24	Polygon	Vertisols	D	3	Shrub/Scrub	5811.3	282705.6
25	Polygon	Vertisols	D	3	Shrub/Scrub	1360.6	33466.1
26	Polygon	Vertisols	D	21	Urban, Medium to Low De	2286.1	128922.5

Figure 3-12 Intersect attribute table for Land Cover and Soil Maps

3.5.2 Look Up Tables

The function of a look up table is to simplify the effort to find a curve number value based on the hydrologic soil group. Values in the Look Up table for this study were generated from TR-55 NEH-4 tables.

The curve number (CN) condition that is assigned to irrigated paddy fields should, in principle, be different from NEH-4 tables for small grains. This is due to the fact that paddy fields are often already flooded with water prior to a storm event, and the edges of the paddy fields can function to retain substantial depths of rainfall prior to any discharge from the field. The amount of storage depends on the prior depth of inundation and heights of control structures on the paddies. However, many studies have practiced using the same CN value for paddy and small grains.

According to Im et al. (2007), the differences between paddy and small grains are: (1) paddy fields will retain water at 20-50 mm depth during the growing season, (2) lower percolation rates occur on paddy fields due to puddling practices, (3) the surface drainage is controlled by the individual gates, (4) the flooding depth is influenced by antecedent rainfall and time during the irrigation system. However, Im et al (2007) found that the paddy field curve numbers tend to be in the ranges that appear in NEH-4 tables for small grains. For this study, a different curve number was assigned to paddy than for general agriculture as shown in Table 3-5.

Table 3-5 Look Up Table from NEH-4 tables for assigning the curve number

gridcode	Description	A	B	C	D
1	Deciduous Forest	36	60	73	79
2	Evergreen Forest	40	66	77	85
3	Shrub/Scrub	35	56	70	77
4	Grassland	49	69	79	84
5	Barren / Minimal Vegetation	77	86	91	94
7	Agriculture, General	67	78	85	89
8	Agriculture, Paddy	61	73	81	84
9	Wetland	100	100	100	100
10	Mangrove	98	98	98	98
11	Water	100	100	100	100
20	Urban, High Density	89	92	94	95
21	Urban, Medium to Low Density	77	85	90	92

Paddy curve numbers as seen in Table 3-5 are a little bit different from those in Table 2-3 because as presented in **Appendix E**, the paddy field area within the study area is considered to have poor infiltration rates due to the soil properties.

The Look Up table was joined with the land use/land cover and soil map intersect layer inside ArcMap to assign appropriate curve numbers for each grid code. Figure 3-13 shows that the LookUp Table followed the landcover classification, and the next step, which is generating the curve numbers, could then be processed, as described below.

Table

intersect_lc_soil_lookup

OBJECTID *	Shape *	SU_NAME	HSG	gridcode	Description	A	B	C	D	Shape_Length	Shape_Area *
1	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	123.7	956.2
2	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	321.3	3614.1
3	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	333.3	3241.3
4	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	1075.5	23483.2
5	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	1620	31343.2
6	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	123.7	956.2
7	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	804	21992
8	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	1175	46852.6
9	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	309.2	3824.7
10	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	63.9	32.2
11	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	1669.8	51633.5
12	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	1484.3	32510
13	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	7136.2	421835.4
14	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	307.1	4748.7
15	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	927.7	21035.9
16	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	3092.2	144382.4
17	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	4024	220371.4
18	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	1484.3	64063.7
19	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	1113.2	21035.9
20	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	678.2	12269.2
21	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	247.4	2868.5
22	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	1298.7	32510
23	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	1548.2	49817.8
24	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	5811.3	282705.6
25	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	1360.6	33466.1
26	Polygon	Vertisols	D	21	Urban, Medium to Low Density	77	85	90	92	2286.1	128922.5

0 (0 out of 2026 Selected)

intersect_lc_soil_lookup

Figure 3-13 Attribute table after joining the intersect layer with the Lookup table

The curve number layer was produced by using a field calculator in ArcGIS for each land use/land cover class and HSG. As a result, the CN layer has a unique curve number for each land use/soil combination which is shown in Figure 3-14.

Table

intersect_lc_soil_CN

OBJECTID *	Shape *	SU_NAME	HSG	gridcode	Description	A	B	C	D	CN	Shape_Length	Shape_Area
1	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	123.7	956.2
2	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	321.3	3614.1
3	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	333.3	3241.3
4	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	1075.5	23483.2
5	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	1620	31343.2
6	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	123.7	956.2
7	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	804	21992
8	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	1175	46852.6
9	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	309.2	3824.7
10	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	63.9	32.2
11	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	1669.8	51633.5
12	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	1484.3	32510
13	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	7136.2	421835.4
14	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	307.1	4748.7
15	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	927.7	21035.9
16	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	3092.2	144382.4
17	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	4024	220371.4
18	Polygon	Vertisols	D	7	Agriculture, General	67	78	85	89	89	1484.3	64063.7
19	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	1113.2	21035.9
20	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	678.2	12269.2
21	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	247.4	2868.5
22	Polygon	Vertisols	D	8	Agriculture, Paddy	61	73	81	84	84	1298.7	32510
23	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	1548.2	49817.8
24	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	5811.3	282705.6
25	Polygon	Vertisols	D	3	Shrub/Scrub	35	56	70	77	77	1360.6	33466.1
26	Polygon	Vertisols	D	21	Urban, Medium to Low De	77	85	90	92	92	2286.1	128922.5

1 (0 out of 2026 Selected)

intersect_lc_soil_CN

Figure 3-14 Attribute table results after applying a CN for each classification

After the CN was produced, the CN map was generated. The CN map is presented below in Figure 3-15, and the CN value detail for urban areas is shown in Figure 3-16.

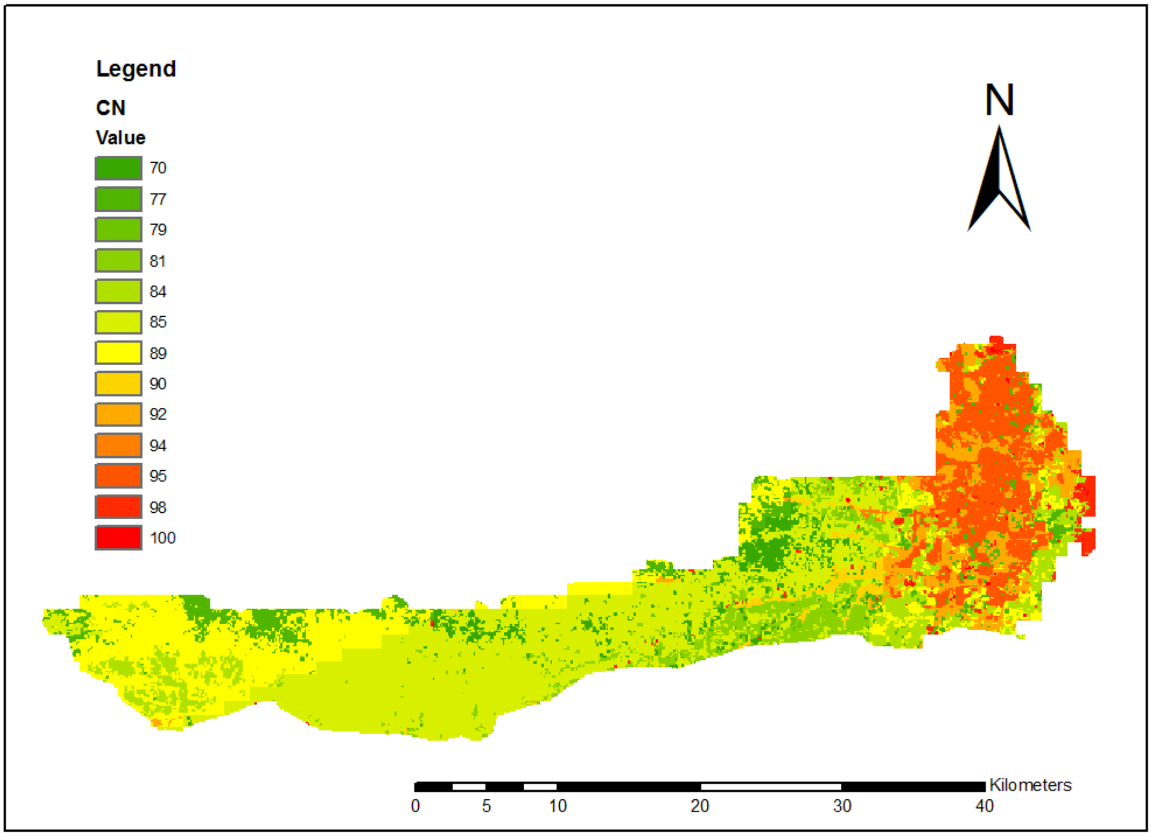


Figure 3-15 Curve Number distributions within the Brantas Hilir Watershed map

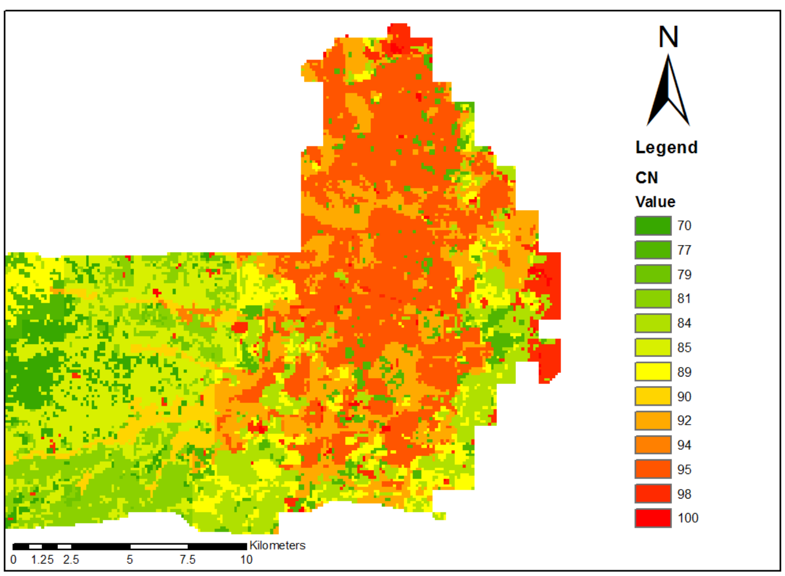


Figure 3-16 Close up of Curve Number distributions in urban areas of the watershed.

The CN values over the entire watershed range from 70 – 100 as generated using landcover and soil maps. Figures 3-15 and 3-16 show the higher values for CN lie on the urban areas near the delta that delivers water to the sea. This information reflects that the urban areas have more impervious areas that influence runoff rates. Hence, the higher runoff depths can be expected in the results for Brantas Hilir watershed.

CN values in the attribute table mostly followed the hydrological soil group. This result is supported by comparing soil map classification and the generated CN map. Figure 3-17 shows that the lines of soil boundaries separate the CN values. This indicates that the soil type has a controlling influence, along with land use type, on runoff rates.

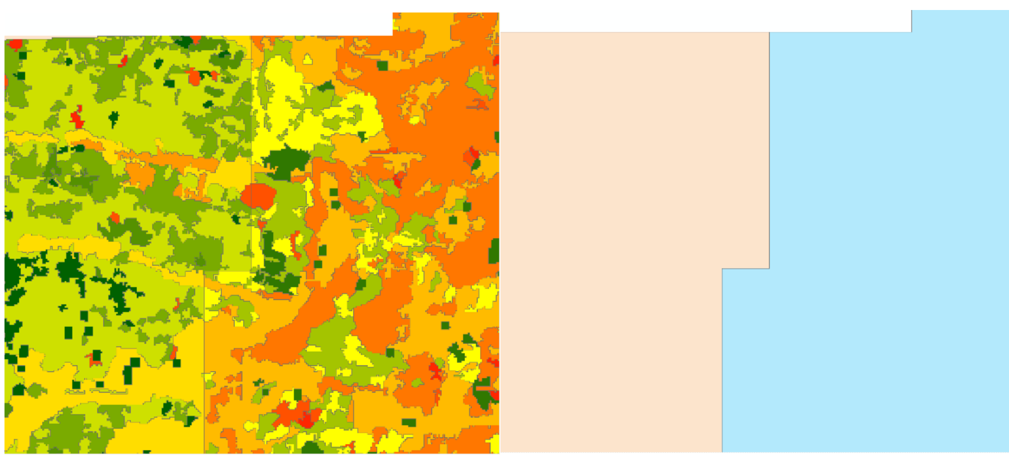


Figure 3-17 Curve Numbers in a closeup that show influence of soil type (two soil types are shown for the area on the right as brown and blue colors).

3.7 Rainwater Harvesting Scenarios

The basis of the rainwater harvesting scenarios is runoff depth without harvesting. Differences from the basis indicate the benefits of harvesting in residential and urban areas. Therefore, four scenarios were applied to quantify the influence of rainwater harvesting application within the study area:

1. Runoff volume without rainwater harvesting (Scenario 1)
2. Runoff volume with rainwater harvesting in low residential areas (Scenario 2)
3. Runoff volume with rainwater harvesting in high residential areas (Scenario 3)
4. Runoff volume with rainwater harvesting in low and high residential areas (Scenario 4)

Scenario 1 was applied during processing curve number values without applying any rainwater harvesting applications. This serves as a baseline condition for estimating runoff volumes and by which to compare with runoff volumes determined from additional computations where rainwater harvesting was employed.

For Scenario 2, the average 'tank' volume which commonly has been used by a single dwelling to capture and hold rain water was calculated from average water usage for single family dwellings in Indonesia. In this calculation, the average size and layout for one single house was denoted as 84/70 which means 84 m^2 area for the whole property and 70 m^2 for the building area. The other areas remained are for the grass (lawn) and impervious areas like walkways and driveways. The fraction (f) for roof, lawn/grass, and other impervious area (driveway) are 0.83, 0.10, and 0.07 respectively.

The estimated typical tank size was 1.1 m^3, which came from average water usage per person, 180 l/day, and assuming that there are 5 people in one family within one house. The depth of retention for the entire property area was calculated by dividing the average tank size by the area of the entire property: $(1.1\ m^3 / 84\ m^2) \times 1000$ mm/m = 13 mm. Therefore, the expected S for low density areas is increased by 13 mm with tanks.

The number of the water usage seems high because the climate in Indonesia is tropic and humid. For these reasons, people tend to take a bath two times per day.

Additionally, the majority of people in Indonesia are Muslims, causing them to use more water for cleaning their body before praying (wudhu). The typical tank that is used usually is cylindrical in shape. This tank size can be purchased in the local market or can be constructed as well. The detail of steps for the calculation of adjustments to the CN retention term S was as follows:

a. First step is calculating the S (retention) using one average tank size per single dwelling.
b. S in this research is weighted based on S for roof and S for non-roof areas.
c. S for roof areas is assumed to equal 3 mm, assuming that some of the initial precipitation adheres to the roof material and is later evaporated.
d. S for non-roof areas that contain grass areas / lawn or other impervious areas (driveways), are calculated using the following equation:

$$S\ for\ non-roof = \frac{(S\ grass * f\ grass) + (S\ other * f\ other)}{f\ grass + f\ other} \quad (3\text{-}6)$$

Calculation Result:

Variable	CN	S(mm)	fraction
Roof	98	3.00	0.83
Grass	84	48.38	0.10
Other	98	5.18	0.07

Storage (S) for non-roof area : 31.10 mm

S for non-roof = retention depth for non-roof area, expressed for the total property area (mm)

S grass = maximum retention depth for lawn (mm)

f grass = fraction of the lawn over the entire property (dimensionless)

S other = maximum retention for driveways (mm)

f other = fraction of the driveways over the entire property (dimensionless)

e. Data that will be used for this calculation are: curve number (CN), S for each detail within one property and the fraction for each detail.

f. The water tank size was determined by calculating water daily usage in one family by assuming that there are 5 people live in one house.

g. There are two final S values in this calculation which are S without rainwater harvesting (without tank) and S with rainwater harvesting (with tank):

(i) S without tank for low density can be calculated using this equation:

$$S_{\text{without tank}} = \frac{S_{\text{roof}} \cdot A_{\text{roof}} + S_{\text{non-roof}} \cdot A_{\text{non-roof}}}{\text{Total Area}} \quad (3\text{-}7)$$

Where:

S roof = retention depth for roof area over the entire property (mm)

A roof = area of the entire roof (m^2)

S for non-roof = retention depth for non-roof area, expressed for the total property area (mm)

A non-roof = the non-roof area (m^2)

Total Area= the entire property area (m^2)

(ii) S with tank for low density residences can be calculated using this equation and noted that V is volume:

$$S_{\text{with tank}} = \frac{V_{\text{tank}} + S_{\text{roof}} \cdot A_{\text{roof}} + S_{\text{non-roof}} \cdot A_{\text{non-roof}}}{\text{Total Area}} \quad (3\text{-}8)$$

Where:

V tank = volume of the average tank size (m^3)

S for non-roof = retention depth for non-roof area, expressed for the total property area (mm)

A non-roof = the non-roof area (m^2)

Total Area= the entire property area (m^2)

Calculation Result:

Average water usage	:	180	liter/day/person
Number of people in family	:	5	people
Water usage in 1 family	:	900	liter/day
Tank size that is used	:	1100	liter
S without tank	**:**	7.68	mm
S with tank	**:**	20.78	mm

After the final S has been calculated, using Equation (3) with the precipitation depth from TRMM, the runoff volume is determined. **Appendix B1** can be referenced for this procedure.

Scenario 3 estimates the runoff volume with rainwater harvesting in high density urban areas using the steps as detailed above. Scenario 3 has been applied to this research due to its feasibility of rainwater harvesting application in areas having rise buildings as demonstrated in some studies in Australia (Zhang et al. 2009), Malaysia (LAU et al. 2005), Tokyo, Singapore, Berlin, Thailand, Bangladesh, Africa, Brazil, and the USA (UNEP n/d). High density urban areas in this study contain government building, offices, small apartment and large apartment buildings where each building has a typical underground tank (reservoir) size of ±200 m^3 (for more details see **Appendix B2**). The tank size in Scenario 3 was based on the calculation of the number of people residing in the building which also has been applied to the calculation for Scenario 2. The area of each building is defined as the average size of the high density land use area in the City of Surabaya.

Scenario 4 evaluated the runoff volume with rainwater harvesting in both low and high density residential areas: In this scenario, the calculations implemented final S values for low and high density areas. This scenario was conducted to compare the benefit of rainwater harvesting performance when all city areas were equipped with rainwater harvesting, relative to the other scenarios.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter describes the results of data analyses followed by a discussion of the research findings. The first section provides the results of spatial analysis comparisons for the four different scenarios. The second section is the result of runoff depth comparisons for each scenario. The third and fourth section conduct an optimization of the rainwater harvesting (RWH) performance and the factors that influence its performance.

4.2 Runoff Depth Comparisons for Four Rainwater Harvesting Scenarios

In this section, the results of runoff depth estimation are presented with spatial analyses and tabulations for the four rainwater harvesting scenarios that were implemented to evaluate the differences of runoff depth between low density and high density dwelling systems. The main results show how much the rainwater harvesting can reduce the amounts of runoff.

4.2.1 Spatial Analysis

This section discusses the result of the runoff depth that has been produced within ArcGIS for the Brantas Hilir watershed.

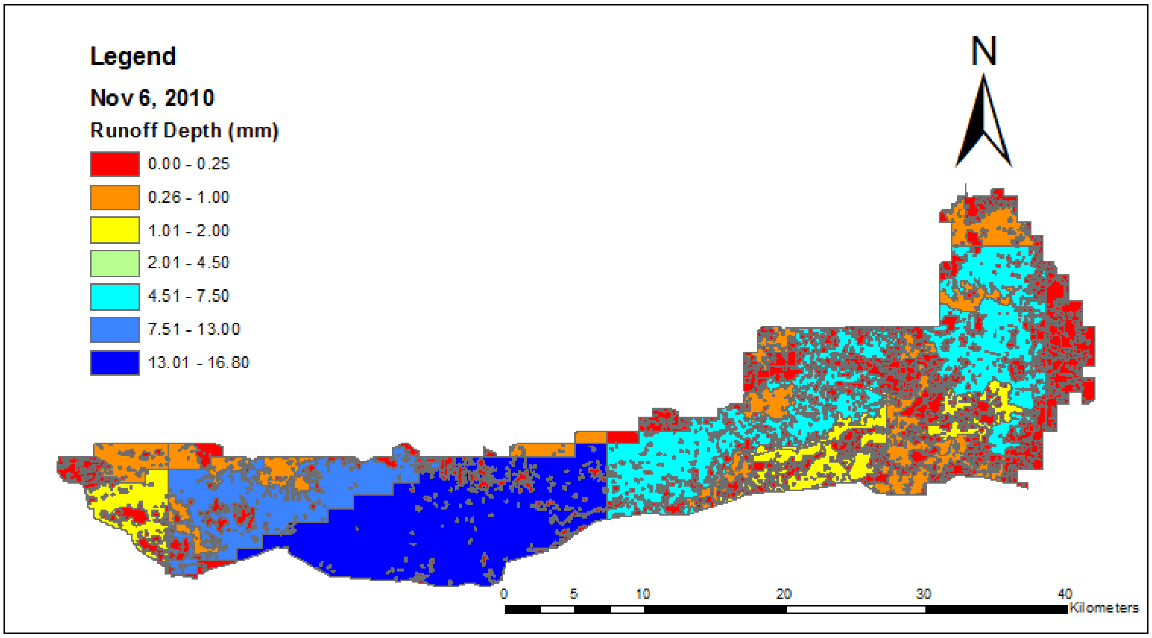


Figure 4-1 The Result of Runoff Depth over Watershed Area Before RWH for November 6, 2010

Figure 4-1 shows the spatial distribution of runoff depth in Brantas Hilir Watershed without applying rainwater harvesting. The values of the runoff depth over the watershed area are in range of the lowest, ±0.25 mm, to the highest, 16.80 mm. These spatial distribution values were influenced by gridded spatial precipitation (*Figure 3-6 and Figure 3-7*). For example, the higher runoff depth was depicted in the central part of the watershed area, which based on landcover map (*Figure 3-9*) is agricultural land. Based on the pixel detail of the precipitation data, the highest rainfall rate occurred on the agriculture areas. Although it was expected that the runoff depth in urban areas, which is covered by most of the impervious areas, should have higher value, actually, it was not higher than the agriculture areas due to the different precipitation distribution. This is because the more precipitation happens, then the more runoff will be produced as the direct response.

However, the higher runoff depth in agricultural land will bring more benefits to farmers because paddy rice is the main crops that usually is planted during the wet season. Paddy field needs to be inundated to grow at 2 – 5 cm (Im et al. 2007), and with runoff depth 1 – 2 mm (*Figure 4-1*), a rain fed irrigation will help the farmers work.

Figure 4-2 displays the runoff depths for comparing four different scenarios that are focused on urban areas. The urban areas: low and high density residentials, were selected for applying the rainwater harvesting system based on the rooftop that could be employed as rainfall catchment areas.

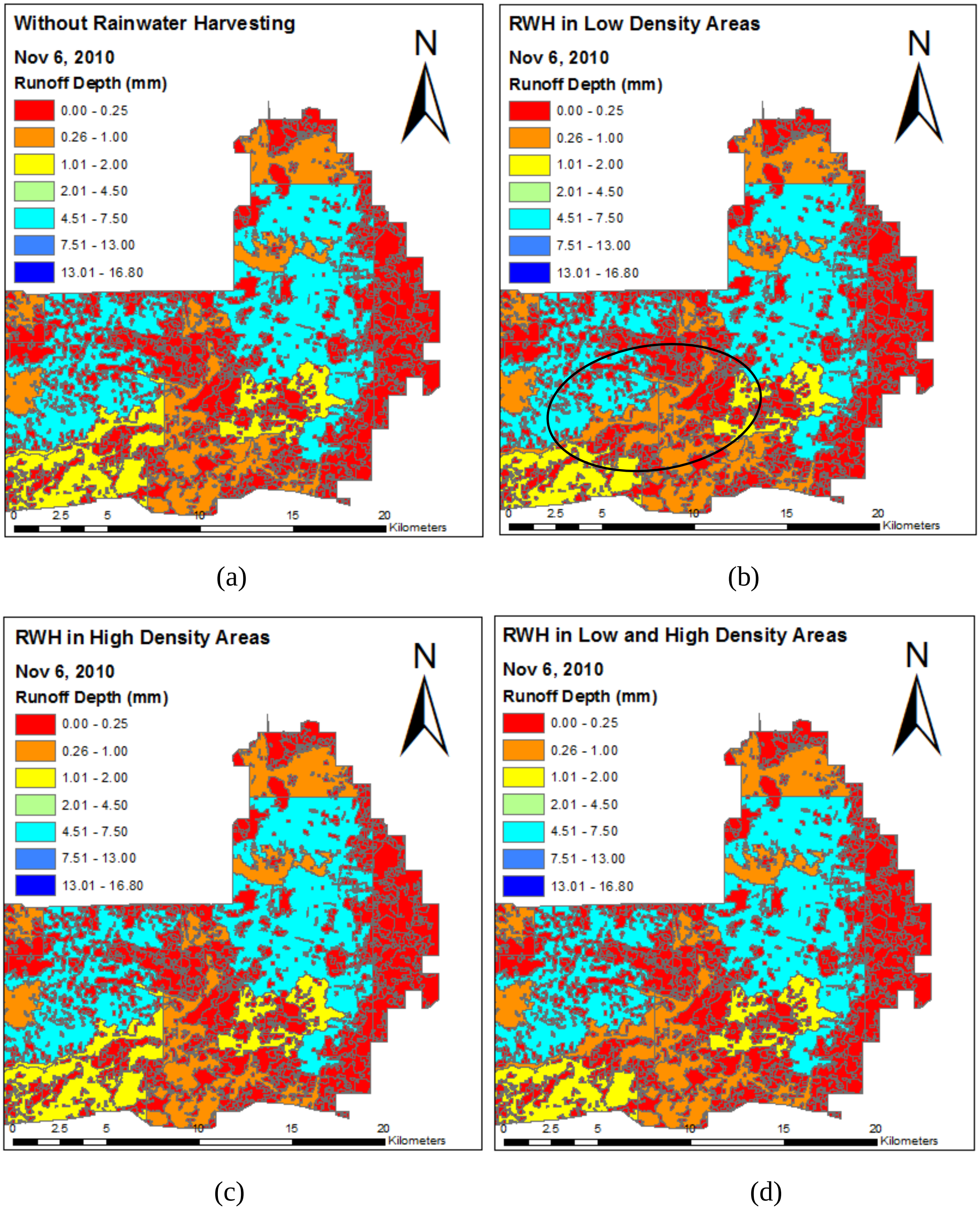


Figure 4-2 Spatial Distribution of Runoff Depth for Four RWH Scenarios: Without RWH (a), RWH in Low Density Area (b), RWH in High Density Area (c), and RWH in Both Urban Areas (d)

In the first scenario Figure 4-2 (a), the runoff depth in urban areas had a range in values from ±0.25 mm to 7.50 mm. After applying rainwater harvesting in low density areas, the spatial distribution was changed for the low density areas (referring to the Landcover map in *Figure 3-9*). From Figure 4-2 (b), showing the second scenario, there is one highlighted region (black oval) showing a significant overall change in runoff depth, from 1 – 2 mm range to 0.26 – 1 mm range.

The third scenario applied rainwater harvesting systems in high residential areas (*Figure 4-2 (c)*). Based on Figure 4-2 (c), the runoff changes for this scenario were not able to be presented in spatial distribution due to the small changes (Table 4-2 could be referred). So, the runoff depth range was remained the same from before the RWH was applied (±0.25 mm to 7.50 mm).

The fourth scenario as presented in Figure 4-2 (d) was the combination of rainwater harvesting application in low residential and high residential areas. RWH application for both residential systems reduced the runoff depth although there is not much changes in the spatial distribution where the runoff depth ranged from ±0.25 to 7.50 mm, before and after RWH. However, the RWH performance will reach maximum stage when the combination of low and high residential are applied (3% for event on November 6, 2010).

4.2.2 Runoff Depth Result

In this section, the results of the runoff depth estimation using SCS-CN are presented. The runoff depth (Q) was obtained from CN aggregation using ArcGIS 10.4.

First, the CN values were assigned from the soil map and land cover map combinations. Runoff depth values were estimated using the CN for five different TRMM grid cells, and these values were distributed inside the ArcGIS system according to the overlay of TRMM, soil and land use data. Then, the weighted average runoff depth (Q) was calculated for the entire watershed based on the spatial distribution of estimated runoff results as presented in Table 4-1 (see **Appendix C** for the runoff details in each landcover class).

Table 4-1 Results of different runoff depth estimation based on four different scenarios

Date	Precipitation (mm)	Q (mm)			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
11/04/2010	22	5.6	5.2	5.4	5.0
11/05/2010	16	2.7	2.3	2.4	2.0
11/06/2010	107	73.7	72.6	72.4	71.3
11/07/2010	0	0	0	0	0
11/08/2010	16	3.2	3.0	3.1	2.9
2/24/2016	33	12.3	11.6	11.8	11.1
2/25/2016	77	45.8	44.7	44.7	43.6
2/26/2016	40	16.2	15.4	15.4	14.6
2/27/2016	55	27.5	26.6	26.6	25.6
2/28/2016	17	3.3	2.8	2.9	2.4

The result that has been presented above shows that the runoff depth was only slightly decreased when applying the rainwater harvesting. This is because the rainwater harvesting was applied only in urban areas: low and high density areas, and from Chapter 3 Section 3.3.4, the percentage of the urban areas within Brantas Hilir watershed is only around 20%. Therefore, the results represent what can be expected.

To make the results easier to visualize, Figure 4-3 and Figure 4-4 are presented below which have a peak runoff on November 6, 2010 due to its large amount of precipitation on that day (Table 4-1). The outcome of the chart is the decreasing values of the runoff depth for each scenario.

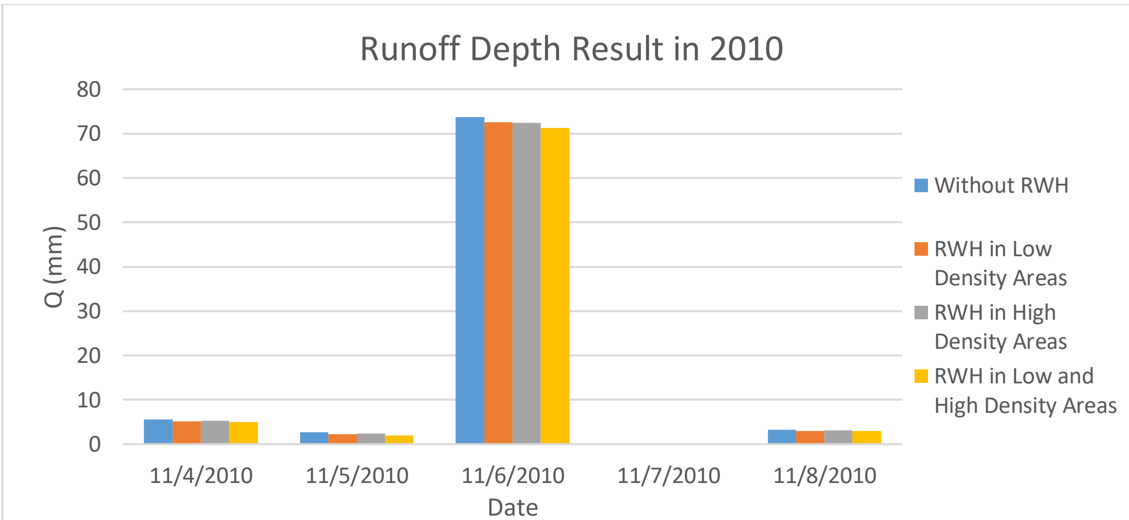


Figure 4-3 Runoff depth result for four scenarios in 2010

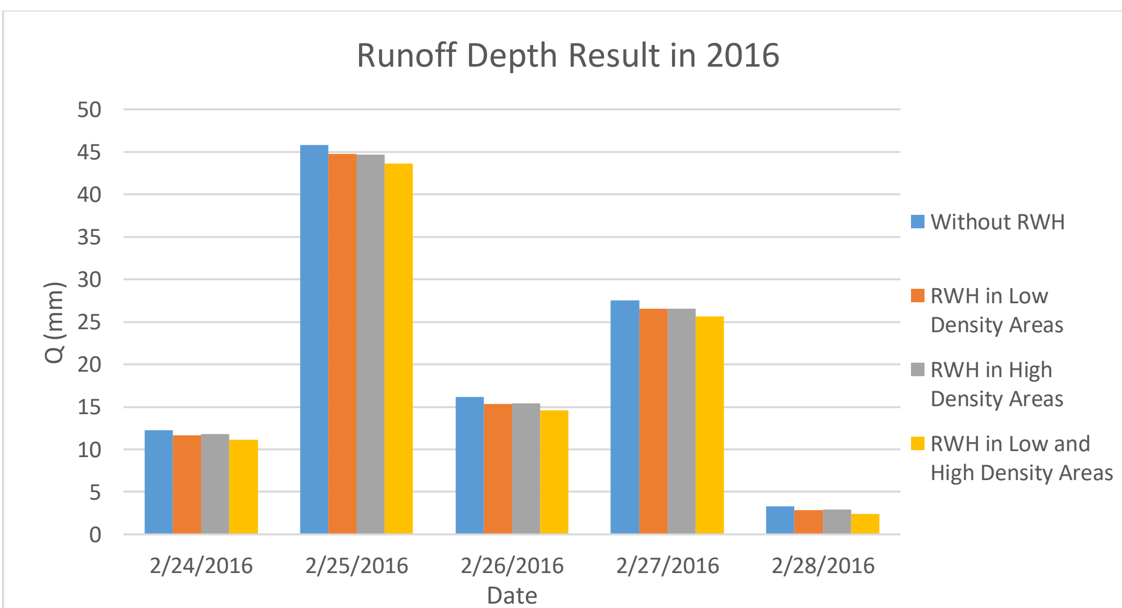


Figure 4-4 Runoff depth result for four scenarios in 2016

The percentages of the runoff reduction as presented in Table 4-2 was based on a baseline condition of no harvesting (Scenario 1). The percentages for Scenario 2 and 3 are additive, so the third column represents the total of the first two columns.

Table 4-2 Runoff Reduction Percentages from Rainwater Harvesting Scenarios

Date	Precipitation (mm)	% Runoff Reduction		
		Scenario 2	Scenario 3	Scenario 4
11/04/2010	22	7.2	3.7	10.9
11/05/2010	16	17.6	11.1	28.7
11/06/2010	107	1.5	1.7	3.2
11/07/2010	0	0.0	0.0	0.0
11/08/2010	16	6.5	3.1	9.6
2/24/2016	33	5.2	4.2	9.4
2/25/2016	77	2.3	2.4	4.7
2/26/2016	40	5.0	4.5	9.5
2/27/2016	55	3.4	3.4	6.8
2/28/2016	17	15.0	11.5	26.6

The highest percentage of the runoff reduction was presented by Scenario 4 (RWH in both urban areas) on November 5, 2010 which reach 28.7%. The high percentage value could be reached because on this day the precipitation was also higher than the day before and also because on the second day the rainfall catchment was more optimal than the following days due to the unsaturation condition.

Unfortunately, the reduction decreased for November 6, 2010. This happened because the tanks were likely to be already filled and the additional rainfall cannot be stored in tanks anymore (tanks are “saturated”). The average tank size that has been used was 1.1 m^3 based on the average water usage of 180 l/day per person.

It can be concluded from Figure 4-2 that the typical range in reduction of runoff amounts when employed in low density residential areas was from 1.5 to 17.6% for large rain events. For runoff amounts when employed in high density residential areas, the reduction percentages range from 1.7 to 11.5% for large rain events. Lastly, runoff reduction percentages when employed in both low and high density residential areas was range from 3.2 to 28.7% for large rain events.

4.3 Optimizing Rainwater Harvesting Tank Sizing in Each Single Dwellings

Rainwater harvesting result can be improved by increasing the tank volume to be able to catch more water. In this study, the impact of tank volume was evaluated by adding multiple tanks to single unit dwellings. The additional tanks were added only to single unit dwellings because it is easier to add tanks to single unit dwellings, compared to adding tanks to the high density buildings that are assumed to use underground tanks (reservoirs), which are usually made from concrete and are more expensive than small plastic tanks. The water that is stored in the additional tanks would be useful for people in daily usage such as toilet flushing and garden irrigation.

The results show that by increasing the tank volume, the runoff depth could be reduced significantly, as presented in Table 4-3. The rainwater harvesting in high residentials were also included for these additional scenarios.

Table 4-3 Percentage of Runoff Reduction with Additional Tank

Date	Precipitation (mm)	% Runoff Reduction		
		Scenario 4 with one-tank size	Scenario 4 with two-tank size	Scenario 4 with three-tank size
11/04/2010	22	10.9	14.1	15.6
11/05/2010	16	28.7	37.3	41.9

11/06/2010	107	3.2	4.4	5.5
11/07/2010	0	0	0	0
11/08/2010	16	9.6	11.1	11.2
2/24/2016	33	9.4	12.2	14.0
2/25/2016	77	4.7	6.5	7.9
2/26/2016	40	9.5	12.8	15.0
2/27/2016	55	6.8	9.2	11.1
2/28/2016	17	26.6	33.0	38.2

The percentages of the runoff reduction with different tank sizes as presented above was relative to a baseline condition of no harvesting as described in the previous section (4.1.2, Table 4-2).

The highest percentage of the runoff reduction was presented by Scenario 4 with three tanks on November 5, 2010 which had a 41.9% reduction. The high percentage value was reached because on this day the precipitation was also higher than the day before, but lower than on November 6. The other high percentage of runoff reduction occurred on February 28 with three tanks in one single house.

Most of the higher values of runoff reduction percentage were obtained with rainwater harvesting using three tanks. The results suggest that the more tanks that are provided, the more rainwater could be collected. The limit for this study was adding tanks up to three items due to economic concerns, the size of average houses in Surabaya, and the ability for a household to consume that larger volume of water.

4.4 Runoff Reduction Sensitivity to Precipitation (Rainfall)

This section will discuss about how the rainfall intensity influenced the rainwater harvesting performance in reducing direct surface runoff (rainfall – runoff model) which is shown by Figure 4-5 and 4-6, as one important element for hydraulic system design

(Deletic & Maksimovic 1998). Figures 4-5 and 4-6 were created to identify the effectivity of the RWH runoff reduction behavior in different rainfall quantities in different RWH scenarios. These figures were based on the RWH runoff reduction percentages results which have been presented in Tables 4-2 and 4-3 where the rainfall quantity ranges were represented two storm events in 10-year of period.

Figure 4-5 shows the RWH runoff reduction performance within a set of rainfall ranges for three different RWH applications: RWH in Low Density, High Density and Low and High Density areas. While Figure 4-6 depicts the performance of RWH runoff reduction within the rainfall range for RWH with one tank, two tank and three tank sizing.

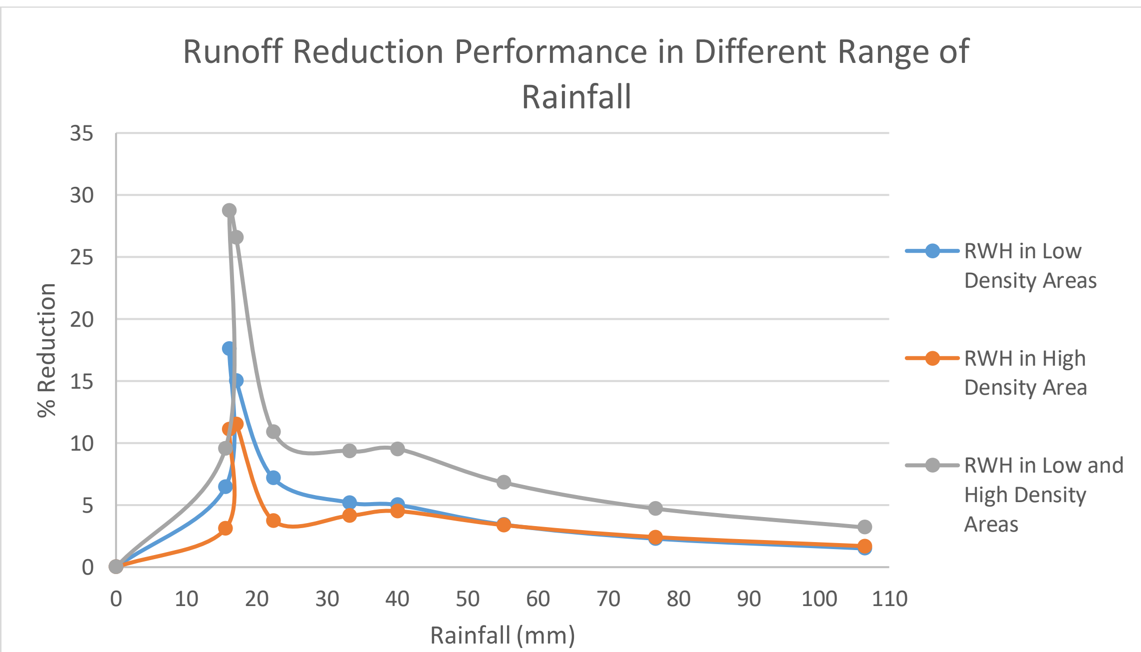


Figure 4-5 Runoff Reduction performance with Different Rainwater Harvesting Scenarios

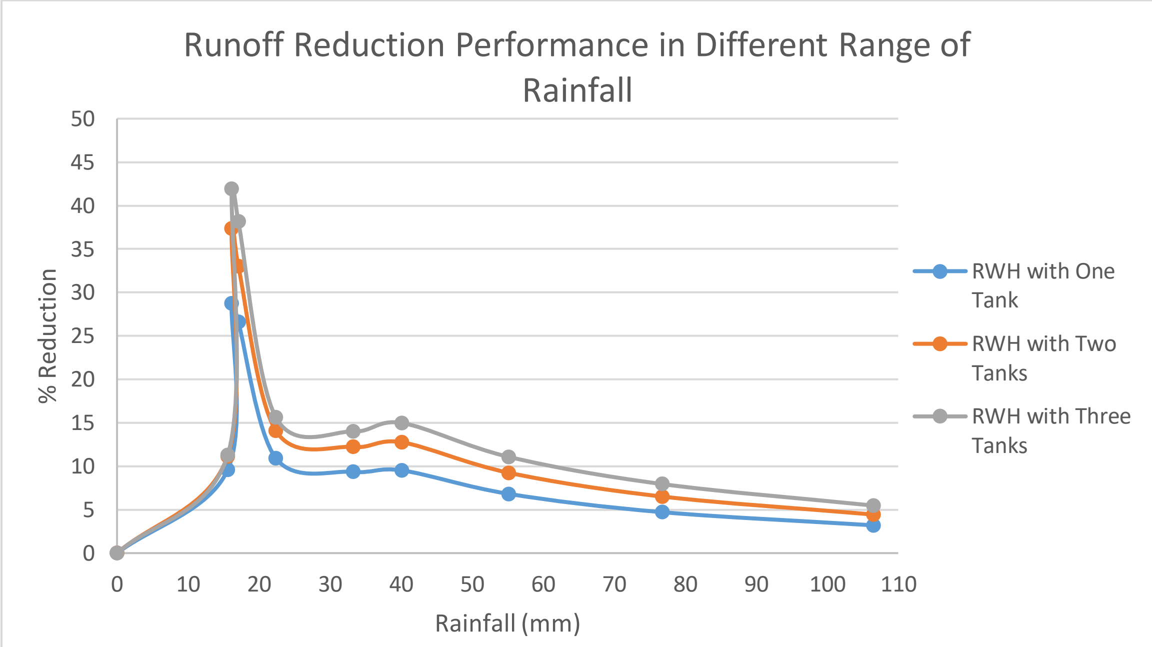


Figure 4-6 Runoff Reduction performance in Rainwater Harvesting System with Different Additional Tank Volumes

As shown in Figures 4-5 and 4-6, the rainwater harvesting performance in reducing the runoff was high on smaller rainfall events due to the relative depth of retention by tanks. Due to limited capacity of the rainwater tanks, once they are full, the impact of the harvesting would likely be less during multiple days of rainfall having higher rainfall amounts. Therefore, the benefit of rainfall harvesting during high precipitation may not be very beneficial to reduce the chances of flooding even by increasing the number of additional tanks. The best possible way to implement rainwater collection and flood reduction may be to increase management of paddy fields in rainfed agriculture areas, where the paddy fields could be managed to begin a forecast rainy period with nearly empty capacity.

According to (Ursino 2016), there may no significant improvement to the rainwater harvesting performance by increasing the tank size and cost when the optimum storage capacity is achieved. Furthermore, Jones and Hunt (2010) found the rain barrels may give small effect to limit runoff due to its inadequate storage, and overflow that frequently happened in storm events. They concluded that additional tanks that are needed to upgrade the rainwater system performance would still be affected by the rainfall amount that goes into the tank.

However, there is a possible situation where the rainwater harvesting may be most useful. For example, rainwater harvesting may significantly reduce minor flooding during frequent smaller precipitation events especially along the roadways in rural areas (soil bunds) where farmers could receive the benefits from it. Even though there is some flood control, the major floods over the past two decades are becoming more frequent in Indonesia (Suripin et al. 2017).

The other possible reason that may cause lower performance of the rainwater harvesting is the sewer conditions over the Surabaya area. As previously discussed, the sewer type in Surabaya is open channel and it always is filled in both seasons: rainy and dry season (Section 3.1 would be referred). Usually, domestic wastewater will flow into the same sewer where the rainfall is flowing and interferes with the local water balance. For this case, the rainwater harvesting may not be a best approach to manage flooding, and instead it may be more suitable to areas with water scarcity and with moderate rainfall intensity.

One possible recommendation for the infrastructure that can be considered to help the flooding event in Surabaya is creating diversion channels from rivers or dams to control the flood discharge peak by capturing the flood pulse and releasing it into available ponds or lakes (Ding and Wang 2006). By applying several integral dams to divert the channel system, it would reduce the frequency and volume of the flows (Kingsford 2000). From a study that Kondolf (1997) conducted, an engineering solution might be addressed to manage debris that may become stuck in the outlets and decrease the performance of the diversion system. One technology to prevent this is by implementing trash racks upstream of the outlet and low level outlet gate structures (Kondolf 1997).

CHAPTER 5: CONCLUSION

5.1 Conclusion

This study evaluated the rainwater harvesting potential on runoff reduction from rainfall events with four different scenarios which were applied in residential areas in Surabaya, Indonesia. The scenarios have been conducted by producing and analyzing curve numbers as the direct runoff parameter through an ArcGIS 10.4 system using satellite data collections from TRMM, SRTM, FAO Global Soil Data, and Global Land Use and Land Cover as input. Based on two modeled storm events, the following conclusions were reached:

1. Several factors are important in determining how much runoff reduction occurs with the use of rainfall harvesting: precipitation (mm), type of residential area where the rainwater harvesting was implemented, the maximum tank size capacity, and wetness of the soil.
2. The percentages of runoff reduction varied based on the factors that are mentioned above. The reduction was largest for smaller storm events (10 – 20 mm precipitation) and the percent runoff reduction become relatively small for large storm events (3 - 10%). Thus, rainwater harvesting may reduce the frequency of flooding from small storm events, but will have relatively little impact on reducing flooding from large storm events. Approximately, 3-5% of reduction occurred for precipitation more than 100 mm.
3. Rainwater collection will be a good approach to be proposed in small communities in developing countries like Indonesia for water scarcity mitigation, however

because of the limits of tank storage it may not have a significant effect to help reduce impacts of flooding events.

5.2 Future Research

The future work for analyzing flood system management can be conducted with ArcGIS due to its powerful platform especially in urban planning. Recommended additional features in the future might include the diversion channel system with dams control for flood management and additional ponds which can be utilized for water recharge purpose. The addition of channel routing of hydrographs from remote parts of the river basin would help to better evaluate the cumulative impact of multi-day rain events. Another future research that can be done is applying rainwater harvesting in places with water scarcity to promote better sanitation. For example, in some mountainous areas, water supply systems may not provide adequate water for people's daily needs and would benefit from rainfall harvesting.

References

Adham, Ammar, Michel Riksen, Mohamed Ouessar, and Coen Ritsema. 2016. "A Methodology to Assess and Evaluate Rainwater Harvesting Techniques in (Semi-) Arid Regions." *Water* 8 (5):198. https://doi.org/10.3390/w8050198.

Al-Seekh, Saleh H., and Ayed G. Mohammad. 2009. "The Effect of Water Harvesting Techniques on Runoff, Sedimentation, and Soil Properties." *Environmental Management* 44 (1):37–45. https://doi.org/10.1007/s00267-009-9310-z.

"An Environmentally Sound Approach for Sustainable Urban Water Management: An Introductory Guide for Decision-Makers." Examples of Rainwater Harvesting and Utilisation Around the World. Accessed January 04, 2018. http://www.unep.or.jp/ietc/publications/urban/urbanenv-2/9.asp.

Biswas, Biplob Kumar, and Bablu Hira Mandal. 2014. "Construction and Evaluation of Rainwater Harvesting System for Domestic Use in a Remote and Rural Area of Khulna, Bangladesh." *International Scholarly Research Notices* 2014:1–6. https://doi.org/10.1155/2014/751952.

Cahyolestari, Diah P. "Proposing an appropriate land use based on hydrological analysis and in accordance with state regulations A case study of Samin Watershed Central Java Indonesia." PhD diss., Thesis / Dissertation ETD, 2010. Accessed December 4, 2017. http://www.itc.nl/library/papers_2010/msc/aes/cahyolestari.pdf.]

Cal. Water & Land Use Partnership, How Urbanization Affects the Water Cycle, (2006), available at http://www.coastal.ca.gov/nps/watercyclefacts.pdf (retrieved on May 2, 2017)

Campisano, Alberto, David Butler, Sarah Ward, Matthew J. Burns, Eran Friedler, Kathy DeBusk, Lloyd N. Fisher-Jeffes, et al. 2017. "Urban Rainwater Harvesting Systems: Research, Implementation and Future Perspectives." *Water Research* 115 (May):195–209. https://doi.org/10.1016/j.watres.2017.02.056.

Campisano, Alberto, and Carlo Modica. 2016. "Rain Water Harvesting as Source Control Option to Reduce Roof Runoff Peaks to Downstream Drainage Systems." *Journal of Hydroinformatics*, jh2015133. https://doi.org/10.2166/hydro.2015.133.

Carpenter, Theresa M., and Konstantine P. Georgakakos. 2006. "Intercomparison of Lumped versus Distributed Hydrologic Model Ensemble Simulations on Operational Forecast Scales." *Journal of Hydrology* 329 (1–2):174–85. https://doi.org/10.1016/j.jhydrol.2006.02.013.

Chen, Li, and Michael H. Young. 2006. "Green-Ampt Infiltration Model for Sloping Surfaces: GREEN-AMPT INFILTRATION MODEL FOR SLOPING SURFACES." *Water Resources Research* 42 (7). https://doi.org/10.1029/2005WR004468.

Critchley, Will, Klaus Siegert, and C. Chapman. "Water harvesting (AGL/MISC/17/91)." Water harvesting. Accessed December 20, 2017. http://www.fao.org/docrep/u3160e/u3160e00.htm#Contents.

Deletic, Ana B., and C. T. Maksimovic. "Evaluation of Water Quality Factors in Storm Runoff from Paved Areas." *Journal of Environmental Engineering* 124, no. 9

(1998): 869-79. Accessed December 14, 2017. doi:10.1061/(asce)0733-9372(1998)124:9(869).

Ding, Yan, and Sam SY Wang. 2006. "Optimal Control of Open-Channel Flow Using Adjoint Sensitivity Analysis." *Journal of Hydraulic Engineering* 132 (11):1215–1228.

Dingman, S.L. (2002). Physical Hydrology (2nd ed). Upper Saddle River, NJ: Prentice Hall.

Ghisi, Enedir, Andreza Montibeller, and Richard W. Schmidt. 2006. "Potential for Potable Water Savings by Using Rainwater: An Analysis over 62 Cities in Southern Brazil." *Building and Environment* 41 (2):204–10. https://doi.org/10.1016/j.buildenv.2005.01.014.

Harvesting, Rainwater. 2013. "Literature Review and Case Studies."

Im, Sangjun, Seungwoo Park, and Taeil Jang. 2007. "Application of SCS Curve Number Method for Irrigated Paddy Field." *KSCE Journal of Civil Engineering* 11 (1):51–56.

"Infiltration - The Water Cycle." Infiltration - The Water Cycle, from USGS Water-Science School. Accessed December 27, 2017. https://water.usgs.gov/edu/watercycleinfiltration.html.

João, Elsa, and Alexandra Fonseca. 1996. "THE ROLE OF GIS IN IMPROVING ENVIRONMENTAL ASSESSMENT EFFECTIVENESS: THEORY VS. PRACTICE." *Impact Assessment* 14 (4):371–87. https://doi.org/10.1080/07349165.1996.9725913.

Jones, Matthew P., and William F. Hunt. 2010. "Performance of Rainwater Harvesting Systems in the Southeastern United States." *Resources, Conservation and Recycling* 54 (10):623–29. https://doi.org/10.1016/j.resconrec.2009.11.002.

King, Kevin W., J. G. Arnold, and R. L. Bingner. 1999. "Comparison of Green-Ampt and Curve Number Methods on Goodwin Creek Watershed Using SWAT." *Transactions of the ASAE* 42 (4):919.

Kingsford, Richard Tennant. 2000. "Ecological Impacts of Dams, Water Diversions and River Management on Floodplain Wetlands in Australia." *Austral Ecology* 25 (2):109–127.

Kondolf, G. Mathias. 1997. "PROFILE: Hungry Water: Effects of Dams and Gravel Mining on River Channels." *Environmental Management* 21 (4):533–551.

Konrad, C. P. Effects of Urban Development on Floods. Accessed December 14, 2017. https://pubs.usgs.gov/fs/fs07603/.

Lalitha Muthu, A. C., and M. Helen Santhi. 2015. "Estimation of Surface Runoff Potential Using SCS-CN Method Integrated with GIS." *Indian Journal of Science and Technology* 8 (28). https://doi.org/10.17485/ijst/2015/v8i28/83324.

LAU, Tze Liang, Taksiah A. Majid, K. K. Choong, Nor Azazi Zakaria, and Aminuddin Ab Ghani. 2005. "Study on a High Rise Building Incorporated with Rainwater Harvesting Storage Tank towards Building a Sustainable Urban Environment in Malaysia." In *The 2005 World Sustainable Building Conference in Tokyo (SB05Tokyo)*, 3312–3319.

Leptoukh, Gregory. 2007. “Exploring NASA and ESA Atmospheric Data Using Giovanni, the Online Visualization and Analysis Tool.” https://ntrs.nasa.gov/search.jsp?R=20070032732.

Liu, Zhong, Dana Ostrenga, William Teng, and Steven Kempler. 2012. “Tropical Rainfall Measuring Mission (TRMM) Precipitation Data and Services for Research and Applications.” *Bulletin of the American Meteorological Society* 93 (9):1317–25. https://doi.org/10.1175/BAMS-D-11-00152.1.

Maidment, D. R. (2008). Arc hydro: GIS for water resources. Redlands, CA: ESRI Press.

Mein, R. G., and D. A. Farrell. 1974. “Determination of Wetting Front Suction in the Green-Ampt Equation.” *Soil Science Society of America Journal* 38 (6):872–876.

Mosley, Luke. 2005. *Water Quality of Rainwater Harvesting Systems*. South Pacific Applied Geoscience Commission. http://www.pacificwater.org/userfiles/file/mr0579.pdf.

Nearing, M. A., B. Y. Liu, L. M. Risse, and X. Zhang. 1996. “Curve Numbers and Green-Ampt Effective Hydraulic Conductivities.” *JAWRA Journal of the American Water Resources Association* 32 (1):125–136

Noah Garrison, Christopher Kloss, and Robb Lukes,”Capturing Rainwater from Rooftops: An Efficient Water Resource Management Strategy That Increases Supply and Reduces Pollution,” Natural Resources Defense Council, November 2011, www.nrdc.org/sites/default/files/rooftoprainwatercapture.pdf (accessed July 7, 2017).

NRCS (2009). National Engineering Handbook, Part 630, Chapter 7: Hydrologic Soil Groups. Available at: https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22526.wba (accessed July 30, 2017)

Petrucci, Guido, José-Frédéric Deroubaix, Bernard De Gouvello, Jean-Claude Deutsch, Philippe Bompard, and Bruno Tassin. 2012. “Rainwater Harvesting to Control Stormwater Runoff in Suburban Areas. An Experimental Case-Study.” *Urban Water Journal* 9 (1):45–55.

Prasad, H. C., Bhalla, P., & Palria, S. (2014). Site Suitability Analysis of Water Harvesting Structures Using Remote Sensing and GIS: A Case Study of Pisangan Watershed, Ajmer District, Rajasthan. *The International Archives of the Photorammetry, Remote Sensing and Spatial Information Services, XL-8*, 1471-1482.

"Research Guides: Mapping and Geographic Information Systems (GIS): What is GIS?" What is GIS? - Mapping and Geographic Information Systems (GIS) - Research Guides at University of Wisconsin-Madison. Accessed December 19, 2017. https://researchguides.library.wisc.edu/GIS.

Schiariti, Paul. *Basic Hydrology Runoff Curve Numbers*. PPT. Mercer County Soil Conservation District. n/d. http://njscdea.ncdea.org/CurveNumbers.pdf.

Shen, Suhung, H. Rui, Z. Liu, T. Zhu, L. Lu, S. Berrick, G. Leptoukh, et al. 2005. “Giovanni: A System for Rapid Access, Visualization and Analysis of Earth Science Data Online.” http://www.academia.edu/download/43862205/103971.pdf.

Silveira, L., F. Charbonnier, and J. L. Genta. 2000. “The Antecedent Soil Moisture Condition of the Curve Number Procedure.” *Hydrological Sciences Journal* 45 (1):3–12. https://doi.org/10.1080/02626660009492302.

Singh, Surender. *Geography For the UPSC Civil Services Preliminary Examination*. New Delhi: Tata McGraw-Hill Publishing Co. Ltd., 2010.

Soulis, K. X., and J. D. Valiantzas. 2012. “SCS-CN Parameter Determination Using Rainfall-Runoff Data in Heterogeneous Watersheds – the Two-CN System Approach.” *Hydrology and Earth System Sciences* 16 (3):1001–15. https://doi.org/10.5194/hess-16-1001-2012.

Sumantri, Siswo Hadi, Imam Hanafi, Ratno Bagus Edi Wibowo, and others. 2016. “Maintaining Availability of Raw Drinking Water in Surabaya under the System Dynamics Approach.” *Resources and Environment* 6 (5):95–103.

Suprijanto, Iwan. 2004. “Kerentanan Kawasan Tepi Air Terhadap Kenaikan Permukaan Air Laut Kasus Kawasan Tepi Air Kota Surabaya.” *DIMENSI (Journal of Architecture and Built Environment)* 31 (1).

Suripin, Ratih Pujiastuti, and Widjonarko. "The Initial Step for Developing Sustainable Urban Drainage System in Semarang City-Indonesia." *Procedia Engineering*171 (2017): 1486-494. Accessed March 23, 2018. doi:10.1016/j.proeng.2017.01.478.

Sutherland-Addy, Esi, and Takyiwaa Manuh. *Africa in contemporary perspective: a textbook for undergraduate students*. Legon-Accra, Ghana: Sub-Saharan Publishers, 2013.

Ursino, Nadia. 2016. “Risk Analysis Approach to Rainwater Harvesting Systems.” *Water* 8 (8):337. https://doi.org/10.3390/w8080337.

Van Mullem, J. A. 1991. “Runoff and Peak Discharges Using Green-Ampt Infiltration Model.” *Journal of Hydraulic Engineering* 117 (3):354–370.

Vansteenkiste, Thomas, Mohsen Tavakoli, Niels Van Steenbergen, Florimond De Smedt, Okke Batelaan, Fernando Pereira, and Patrick Willems. 2014. “Intercomparison of Five Lumped and Distributed Models for Catchment Runoff and Extreme Flow Simulation.” *Journal of Hydrology* 511 (April):335–49. https://doi.org/10.1016/j.jhydrol.2014.01.050.

Wassmann, Reiner, Nguyen Xuan Hien, Chu Thai Hoanh, and To Phuc Tuong. 2004. “Sea Level Rise Affecting the Vietnamese Mekong Delta: Water Elevation in the Flood Season and Implications for Rice Production.” *Climatic Change* 66 (1):89–107.

Widiyati, Christanti N., and Sudibyakto. "Application of US-SCS Curve Number Method and GIS for Determining Suitable Land Cover of Small Watershed." *Indonesian Journal of Geography* 42, no. 1 (January 1, 2010): 67-90. Accessed December 4, 2017. doi:https://doi.org/10.22146/indo.j.geog,1578.

USDA Soil Conservation Service (1986) Urban Hydrology for Small Watersheds, Technical Release 55, 2nd ed., NTIS PB87-101580, Springfield, VA.

Zhang, Yan, Donghui Chen, Liang Chen, and Stephanie Ashbolt. 2009. “Potential for Rainwater Use in High-Rise Buildings in Australian Cities.” *Journal of Environmental Management* 91 (1):222–26. https://doi.org/10.1016/j.jenvman.2009.08.008.

Appendices

Appendix A List of Abbreviations and Acronyms

CN Curve Number

DEM Digital Elevation Model

F

GIS Geographic Information System

HSG Hydrological Soil Group

P Precipitation

Q Runoff

RWH Rainwater Harvesting

S

SCS Soil Conservation Service

Appendix B Retention (S) Calculations

B1 Low Density

a. Maximum retention calculation for rainwater harvesting with single tank usage.

Part 1

Variable	CN	S(mm)	fraction
Roof	98	3.00	0.83
Grass	84	48.38	0.10
Other	98	5.18	0.07

Weighted S non roof: : 31.10 mm

Part 1

Variable	CN	S(mm)	fraction
Roof	98	3.00	0.83
Grass	84	48.38	0.10
Other	98	5.18	0.07

Weighted S non roof: : 31.10 mm

Part 2

Average water usage	:	180	liter/day/person
Number of people in family	:	5	people
Water usage in 1 family	:	900	liter/day
Tank size that is used	:	1100	liter
S for low density	**:**	7.68	mm
S_adjusted for low density	**:**	18.28	mm

b. Rainwater harvesting with two tanks in one single dwelling

Part 1

Variable	CN	S(mm)	fraction
Roof	98	3.00	0.83

Grass	84	48.38	0.10
Other	98	5.18	0.07

Weighted S non roof: : 31.10 mm

Part 2

Average water usage : 180 liter/day/person
Number of people in family : 5 people

Water usage in 1 family : 900 liter/day

Tank size that is used : 2200 liter

S for low density **:** 7.68 mm
S_adjusted for low density **:** 33.87 mm

c. Rainwater harvesting with three tanks in one single dwelling

Part 1

Variable	CN	S(mm)	fraction
Roof	98	3.00	0.83
Grass	84	48.38	0.10
Other	98	5.18	0.07

Weighted S non roof: : 31.10 mm

Part 2

Average water usage : 180 liter/day/person
Number of people in family : 5 people

Water usage in 1 family : 900 liter/day

Tank size that is used : 3300 liter

S for low density	**:**	7.68	mm
S_adjusted for low density	**:**	46.97	mm

B2 High Density

Type of building	Area of building/roof (m^2)	Total Area (m^2)	Average Tank Volume (m^3)
Government	1938	42000	200
Office	3000	5000	200
Small Apartment	5655	8700	200
Big Apartement	4000	8400	300

Part 1: Government Building

Variable	CN	S(mm)	fraction
Roof	98	98.00	0.4
Grass	84	84.00	0.25
Other	98	98.00	0.35

Weighted S non roof: : 23.18 mm

S for high density **:** 23.31 mm
S_adjusted for high density **:** 26.87 mm

Part 2: Office Building

Variable	CN	S(mm)	fraction
Roof	98	5.18	0.60
Grass	84	48.38	0.13
Other	98	5.18	0.27

Weighted S non roof: : 19.22 mm

S for high density **:** 9.49 mm
S_adjusted for high density **:** 47.69 mm

Part 3: Small Apartment

Variable	CN	S(mm)	fraction
Roof	98	5.18	0.65
Grass	84	48.38	0.25
Other	98	5.18	0.1

Weighted S non roof:	:	36.04	mm
S for high density	**:**	14.56	mm
S_adjusted for high density	**:**	35.60	mm

Part 4: Big Apartment

Variable	CN	S(mm)	fraction
Roof	98	5.18	0.48
Grass	84	48.38	0.10
Other	98	5.18	0.42

Weighted S non roof:	:	13.43	mm
S for high density	**:**	8.46	mm
S_adjusted for high density	**:**	42.75	mm

Storage (S) for high residential can be calculated using this equation:

$$S_W = \frac{(S_1 * A_1) + (S_2 * A_2) + (S_3 * A_3) + (S_4 * A_4)}{Total\ Area}$$

S before using tank	:	19.10	mm
S with tank	:	31.76	mm

Appendix C Runoff Depth Comparison for Four Different Scenarios

C1 Runoff depth without RWH

First Event

Date	Precipitation (mm)	Landcover class	Q (mm)
11/4/2010	30.8	Evergreen Forest	0.03
	21.5	Shrub/Scrub	0.15
	14.7	Grassland	0.00
	13.1	Barren / Minimal Vegetation	0.00
	26.3	Agriculture, General	3.59
	19.3	Agriculture, Paddy	0.31
	20.1	Wetland	0.15
	22.7	Mangrove	0.26
	15.1	Water	0.02
	12.6	Urban, High Density	0.40
	14.6	Urban, Medium to Low Density	0.77
11/5/2010	5.6	Evergreen Forest	0.00
	15.3	Shrub/Scrub	0.05
	17.8	Grassland	0.01
	16.0	Barren / Minimal Vegetation	0.00
	13.9	Agriculture, General	0.52
	16.8	Agriculture, Paddy	0.17
	23.7	Wetland	0.05
	27.5	Mangrove	0.32
	16.9	Water	0.02
	16.3	Urban, High Density	0.62
	17.8	Urban, Medium to Low Density	1.00
11/6/2010	96.5	Evergreen Forest	0.26
	109.4	Shrub/Scrub	4.82
	100.2	Grassland	0.30
	105.5	Barren / Minimal Vegetation	0.01
	115.9	Agriculture, General	41.63
	102.7	Agriculture, Paddy	7.70
	81.8	Wetland	4.82
	64.8	Mangrove	0.85

Date	Precipitation (mm)	Landcover class	Q (mm)
	93.8	Water	0.14
	100.0	Urban, High Density	9.81
	97.8	Urban, Medium to Low Density	8.05
11/7/2010			
11/8/2010	40.4	Evergreen Forest	0.06
	15.2	Shrub/Scrub	0.16
	7.3	Grassland	0.00
	7.6	Barren / Minimal Vegetation	0.00
	20.2	Agriculture, General	2.30
	12.3	Agriculture, Paddy	0.20
	6.3	Wetland	0.16
	7.0	Mangrove	0.05
	12.0	Water	0.02
	8.7	Urban, High Density	0.15
	8.1	Urban, Medium to Low Density	0.29

Second Event

Date	Precipitation (mm)	Landcover class	Q (mm)
2/24/2016	27.3	Evergreen Forest	0.02
	34.0	Shrub/Scrub	0.38
	25.3	Grassland	0.01
	26.5	Barren / Minimal Vegetation	0.00
	40.1	Agriculture, General	7.95
	29.2	Agriculture, Paddy	0.74
	20.9	Wetland	0.38
	16.5	Mangrove	0.17
	25.3	Water	0.04
	24.8	Urban, High Density	1.36
	24.7	Urban, Medium to Low Density	1.58

Date	Precipitation (mm)	Landcover class	Q (mm)
2/25/2016	49.4	Evergreen Forest	0.09
	78.3	Shrub/Scrub	2.54
	76.7	Grassland	0.19
	78.4	Barren / Minimal Vegetation	0.00
	80.0	Agriculture, General	24.54
	75.9	Agriculture, Paddy	4.71
	70.5	Wetland	2.54
	62.0	Mangrove	0.81
	69.1	Water	0.10
	74.1	Urban, High Density	6.75
	74.6	Urban, Medium to Low Density	5.96
2/26/2016	44.8	Evergreen Forest	0.07
	40.0	Shrub/Scrub	0.50
	36.2	Grassland	0.04
	36.3	Barren / Minimal Vegetation	0.00
	42.5	Agriculture, General	8.60
	38.4	Agriculture, Paddy	1.26
	35.8	Wetland	0.50
	36.1	Mangrove	0.44
	38.5	Water	0.06
	36.8	Urban, High Density	2.55
	36.5	Urban, Medium to Low Density	2.59
2/27/2016	55.3	Evergreen Forest	0.11
	55.1	Shrub/Scrub	1.17

Date	Precipitation (mm)	Landcover class	Q (mm)
	50.8	Grassland	0.09
	51.3	Barren / Minimal Vegetation	0.00
	57.7	Agriculture, General	14.65
	52.9	Agriculture, Paddy	2.46
	49.5	Wetland	1.17
	50.4	Mangrove	0.64
	55.9	Water	0.08
	52.8	Urban, High Density	4.31
	51.8	Urban, Medium to Low Density	3.93
2/28/2016	22.2	Evergreen Forest	0.01
	17.9	Shrub/Scrub	0.02
	18.2	Grassland	0.00
	19.4	Barren / Minimal Vegetation	0.00
	17.5	Agriculture, General	1.08
	17.7	Agriculture, Paddy	0.15
	14.1	Wetland	0.02
	11.3	Mangrove	0.11
	17.9	Water	0.03
	19.1	Urban, High Density	0.85
	18.1	Urban, Medium to Low Density	1.04

C2 Runoff depth with RWH in Low Density Areas

First Event

Date	Precipitation (mm)	Landcover class	Q (mm)
11/4/2010	30.8	Evergreen Forest	0.03
	21.5	Shrub/Scrub	0.15
	14.7	Grassland	0.00
	13.1	Barren / Minimal Vegetation	0.00
	26.3	Agriculture, General	3.59
	19.3	Agriculture, Paddy	0.31
	20.1	Wetland	0.15
	22.7	Mangrove	0.26
	15.1	Water	0.02
	12.6	Urban, High Density	0.40
	14.6	Urban, Medium to Low Density	0.37
11/5/2010	5.6	Evergreen Forest	0.00
	15.3	Shrub/Scrub	0.05
	17.8	Grassland	0.01
	16.0	Barren / Minimal Vegetation	0.00
	13.9	Agriculture, General	0.52
	16.8	Agriculture, Paddy	0.17
	23.7	Wetland	0.05
	27.5	Mangrove	0.32
	16.9	Water	0.02
	16.3	Urban, High Density	0.62
	17.8	Urban, Medium to Low Density	0.52
11/6/2010	96.5	Evergreen Forest	0.26
	109.4	Shrub/Scrub	4.82
	100.2	Grassland	0.30
	105.5	Barren / Minimal Vegetation	0.01
	115.9	Agriculture, General	41.63
	102.7	Agriculture, Paddy	7.70
	81.8	Wetland	4.82
	64.8	Mangrove	0.85
	93.8	Water	0.14
	100.0	Urban, High Density	9.81
	97.8	Urban, Medium to Low Density	6.94

Date	Precipitation (mm)	Landcover class	Q (mm)
11/7/2010			
11/8/2010	40.4	Evergreen Forest	0.06
	15.2	Shrub/Scrub	0.16
	7.3	Grassland	0.00
	7.6	Barren / Minimal Vegetation	0.00
	20.2	Agriculture, General	2.30
	12.3	Agriculture, Paddy	0.20
	6.3	Wetland	0.16
	7.0	Mangrove	0.05
	12.0	Water	0.02
	8.7	Urban, High Density	0.15
	8.1	Urban, Medium to Low Density	0.08

Second Event

Date	Precipitation (mm)	Landcover class	Q (mm)
2/24/2016	27.3	Evergreen Forest	0.02
	34.0	Shrub/Scrub	0.38
	25.3	Grassland	0.01
	26.5	Barren / Minimal Vegetation	0.00
	40.1	Agriculture, General	7.95
	29.2	Agriculture, Paddy	0.74
	20.9	Wetland	0.38
	16.5	Mangrove	0.17
	25.3	Water	0.04
	24.8	Urban, High Density	1.36
	24.7	Urban, Medium to Low Density	0.94
2/25/2016	49.4	Evergreen Forest	0.09
	78.3	Shrub/Scrub	2.54
	76.7	Grassland	0.19
	78.4	Barren / Minimal Vegetation	0.00
	80.0	Agriculture, General	24.54
	75.9	Agriculture, Paddy	4.71
	70.5	Wetland	2.54
	62.0	Mangrove	0.81
	69.1	Water	0.10
	74.1	Urban, High Density	6.75

Date	Precipitation (mm)	Landcover class	Q (mm)
	74.6	Urban, Medium to Low Density	4.91
2/26/2016	44.8	Evergreen Forest	0.07
	40.0	Shrub/Scrub	0.50
	36.2	Grassland	0.04
	36.3	Barren / Minimal Vegetation	0.00
	42.5	Agriculture, General	8.60
	38.4	Agriculture, Paddy	1.26
	35.8	Wetland	0.50
	36.1	Mangrove	0.44
	38.5	Water	0.06
	36.8	Urban, High Density	2.55
	36.5	Urban, Medium to Low Density	1.78
2/27/2016	55.3	Evergreen Forest	0.11
	55.1	Shrub/Scrub	1.17
	50.8	Grassland	0.09
	51.3	Barren / Minimal Vegetation	0.00
	57.7	Agriculture, General	14.65
	52.9	Agriculture, Paddy	2.46
	49.5	Wetland	1.17
	50.4	Mangrove	0.64
	55.9	Water	0.08
	52.8	Urban, High Density	4.31
	51.8	Urban, Medium to Low Density	2.99
2/28/2016	22.2	Evergreen Forest	0.01
	17.9	Shrub/Scrub	0.02
	18.2	Grassland	0.00
	19.4	Barren / Minimal Vegetation	0.00
	17.5	Agriculture, General	1.08
	17.7	Agriculture, Paddy	0.15
	14.1	Wetland	0.02
	11.3	Mangrove	0.11
	17.9	Water	0.03
	19.1	Urban, High Density	0.85
	18.1	Urban, Medium to Low Density	0.54

C3 Runoff depth with RWH in High Density Areas

First Event

Date	Precipitation (mm)	Landcover class	Q (mm)
11/4/2010	30.8	Evergreen Forest	0.03
	21.5	Shrub/Scrub	0.15
	14.7	Grassland	0.00
	13.1	Barren / Minimal Vegetation	0.00
	26.3	Agriculture, General	3.59
	19.3	Agriculture, Paddy	0.31
	20.1	Wetland	0.15
	22.7	Mangrove	0.26
	15.1	Water	0.02
	12.6	Urban, High Density	0.19
	14.6	Urban, Medium to Low Density	0.77
11/5/2010	5.6	Evergreen Forest	0.00
	15.3	Shrub/Scrub	0.05
	17.8	Grassland	0.01
	16.0	Barren / Minimal Vegetation	0.00
	13.9	Agriculture, General	0.52
	16.8	Agriculture, Paddy	0.17
	23.7	Wetland	0.05
	27.5	Mangrove	0.32
	16.9	Water	0.02
	16.3	Urban, High Density	0.32
	17.8	Urban, Medium to Low Density	1.00
11/6/2010	96.5	Evergreen Forest	0.26
	109.4	Shrub/Scrub	4.82
	100.2	Grassland	0.30
	105.5	Barren / Minimal Vegetation	0.01
	115.9	Agriculture, General	41.63
	102.7	Agriculture, Paddy	7.70
	81.8	Wetland	4.82
	64.8	Mangrove	0.85
	93.8	Water	0.14
	100.0	Urban, High Density	8.56
	97.8	Urban, Medium to Low Density	8.05

Date	Precipitation (mm)	Landcover class	Q (mm)
11/7/2010			
11/8/2010	40.4	Evergreen Forest	0.06
	15.2	Shrub/Scrub	0.16
	7.3	Grassland	0.00
	7.6	Barren / Minimal Vegetation	0.00
	20.2	Agriculture, General	2.30
	12.3	Agriculture, Paddy	0.20
	6.3	Wetland	0.16
	7.0	Mangrove	0.05
	12.0	Water	0.02
	8.7	Urban, High Density	0.05
	8.1	Urban, Medium to Low Density	0.29

Second Event

Date	Precipitation (mm)	Landcover class	Q (mm)
2/24/2016	27.3	Evergreen Forest	0.02
	34.0	Shrub/Scrub	0.38
	25.3	Grassland	0.01
	26.5	Barren / Minimal Vegetation	0.00
	40.1	Agriculture, General	7.95
	29.2	Agriculture, Paddy	0.74
	20.9	Wetland	0.38
	16.5	Mangrove	0.17
	25.3	Water	0.04
	24.8	Urban, High Density	0.85
	24.7	Urban, Medium to Low Density	1.58
2/25/2016	49.4	Evergreen Forest	0.09
	78.3	Shrub/Scrub	2.54
	76.7	Grassland	0.19
	78.4	Barren / Minimal Vegetation	0.00
	80.0	Agriculture, General	24.54
	75.9	Agriculture, Paddy	4.71
	70.5	Wetland	2.54
	62.0	Mangrove	0.81
	69.1	Water	0.10
	74.1	Urban, High Density	5.65

Date	Precipitation (mm)	Landcover class	Q (mm)
	74.6	Urban, Medium to Low Density	5.96
2/26/2016	44.8	Evergreen Forest	0.07
	40.0	Shrub/Scrub	0.50
	36.2	Grassland	0.04
	36.3	Barren / Minimal Vegetation	0.00
	42.5	Agriculture, General	8.60
	38.4	Agriculture, Paddy	1.26
	35.8	Wetland	0.50
	36.1	Mangrove	0.44
	38.5	Water	0.06
	36.8	Urban, High Density	1.82
	36.5	Urban, Medium to Low Density	2.59
2/27/2016	55.3	Evergreen Forest	0.11
	55.1	Shrub/Scrub	1.17
	50.8	Grassland	0.09
	51.3	Barren / Minimal Vegetation	0.00
	57.7	Agriculture, General	14.65
	52.9	Agriculture, Paddy	2.46
	49.5	Wetland	1.17
	50.4	Mangrove	0.64
	55.9	Water	0.08
	52.8	Urban, High Density	3.38
	51.8	Urban, Medium to Low Density	3.93
2/28/2016	22.2	Evergreen Forest	0.01
	17.9	Shrub/Scrub	0.02
	18.2	Grassland	0.00
	19.4	Barren / Minimal Vegetation	0.00
	17.5	Agriculture, General	1.08
	17.7	Agriculture, Paddy	0.15
	14.1	Wetland	0.02
	11.3	Mangrove	0.11
	17.9	Water	0.03
	19.1	Urban, High Density	0.47
	18.1	Urban, Medium to Low Density	1.04

C4 Runoff depth with RWH for Low and High Density Areas

First Event

Date	Precipitation (mm)	**Landcover class**	**Q (mm)**
11/4/2010	30.8	Evergreen Forest	0.03
	21.5	Shrub/Scrub	0.15
	14.7	Grassland	0.00
	13.1	Barren / Minimal Vegetation	0.00
	26.3	Agriculture, General	3.59
	19.3	Agriculture, Paddy	0.31
	20.1	Wetland	0.15
	22.7	Mangrove	0.26
	15.1	Water	0.02
	12.6	Urban, High Density	0.19
	14.6	Urban, Medium to Low Density	0.37
11/5/2010	5.6	Evergreen Forest	0.00
	15.3	Shrub/Scrub	0.05
	17.8	Grassland	0.01
	16.0	Barren / Minimal Vegetation	0.00
	13.9	Agriculture, General	0.52
	16.8	Agriculture, Paddy	0.17
	23.7	Wetland	0.05
	27.5	Mangrove	0.32
	16.9	Water	0.02
	16.3	Urban, High Density	0.32

Date	Precipitation (mm)	**Landcover class**	**Q (mm)**
	17.8	Urban, Medium to Low Density	0.52
11/6/2010	96.5	Evergreen Forest	0.26
	109.4	Shrub/Scrub	4.82
	100.2	Grassland	0.30
	105.5	Barren / Minimal Vegetation	0.01
	115.9	Agriculture, General	41.63
	102.7	Agriculture, Paddy	7.70
	81.8	Wetland	4.82
	64.8	Mangrove	0.85
	93.8	Water	0.14
	100.0	Urban, High Density	8.56
	97.8	Urban, Medium to Low Density	6.94
11/7/2010			
11/8/2010	40.4	Evergreen Forest	0.06
	15.2	Shrub/Scrub	0.16
	7.3	Grassland	0.00
	7.6	Barren / Minimal Vegetation	0.00
	20.2	Agriculture, General	2.30
	12.3	Agriculture, Paddy	0.20
	6.3	Wetland	0.16
	7.0	Mangrove	0.05
	12.0	Water	0.02
	8.7	Urban, High Density	0.05
	8.1	Urban, Medium to Low Density	0.08

Second Event

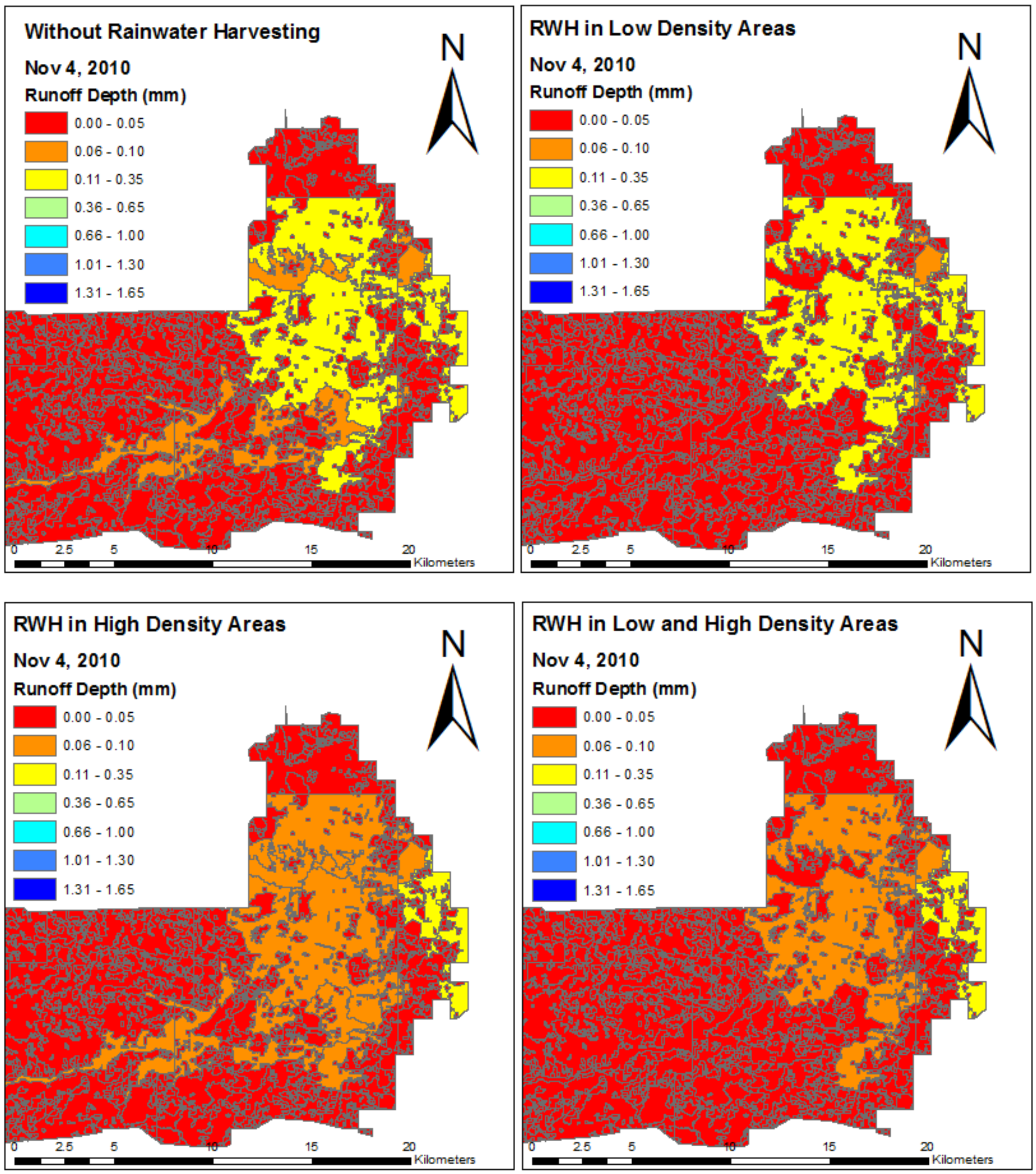
Date	Precipitation (mm)	Landcover class	Q (mm)
2/24/2016	27.3	Evergreen Forest	0.02
	34.0	Shrub/Scrub	0.38
	25.3	Grassland	0.01
	26.5	Barren / Minimal Vegetation	0.00
	40.1	Agriculture, General	7.95
	29.2	Agriculture, Paddy	0.74
	20.9	Wetland	0.38
	16.5	Mangrove	0.17
	25.3	Water	0.04
	24.8	Urban, High Density	0.85
	24.7	Urban, Medium to Low Density	0.94
2/25/2016	49.4	Evergreen Forest	0.09
	78.3	Shrub/Scrub	2.54
	76.7	Grassland	0.19
	78.4	Barren / Minimal Vegetation	0.00
	80.0	Agriculture, General	24.54
	75.9	Agriculture, Paddy	4.71
	70.5	Wetland	2.54
	62.0	Mangrove	0.81
	69.1	Water	0.10
	74.1	Urban, High Density	5.65
	74.6	Urban, Medium to Low Density	4.91
2/26/2016	44.8	Evergreen Forest	0.07

Date	Precipitation (mm)	Landcover class	Q (mm)
	40.0	Shrub/Scrub	0.50
	36.2	Grassland	0.04
	36.3	Barren / Minimal Vegetation	0.00
	42.5	Agriculture, General	8.60
	38.4	Agriculture, Paddy	1.26
	35.8	Wetland	0.50
	36.1	Mangrove	0.44
	38.5	Water	0.06
	36.8	Urban, High Density	1.82
	36.5	Urban, Medium to Low Density	1.78
2/27/2016	55.3	Evergreen Forest	0.11
	55.1	Shrub/Scrub	1.17
	50.8	Grassland	0.09
	51.3	Barren / Minimal Vegetation	0.00
	57.7	Agriculture, General	14.65
	52.9	Agriculture, Paddy	2.46
	49.5	Wetland	1.17
	50.4	Mangrove	0.64
	55.9	Water	0.08
	52.8	Urban, High Density	3.38
	51.8	Urban, Medium to Low Density	2.99
2/28/2016	22.2	Evergreen Forest	0.01
	17.9	Shrub/Scrub	0.02
	18.2	Grassland	0.00

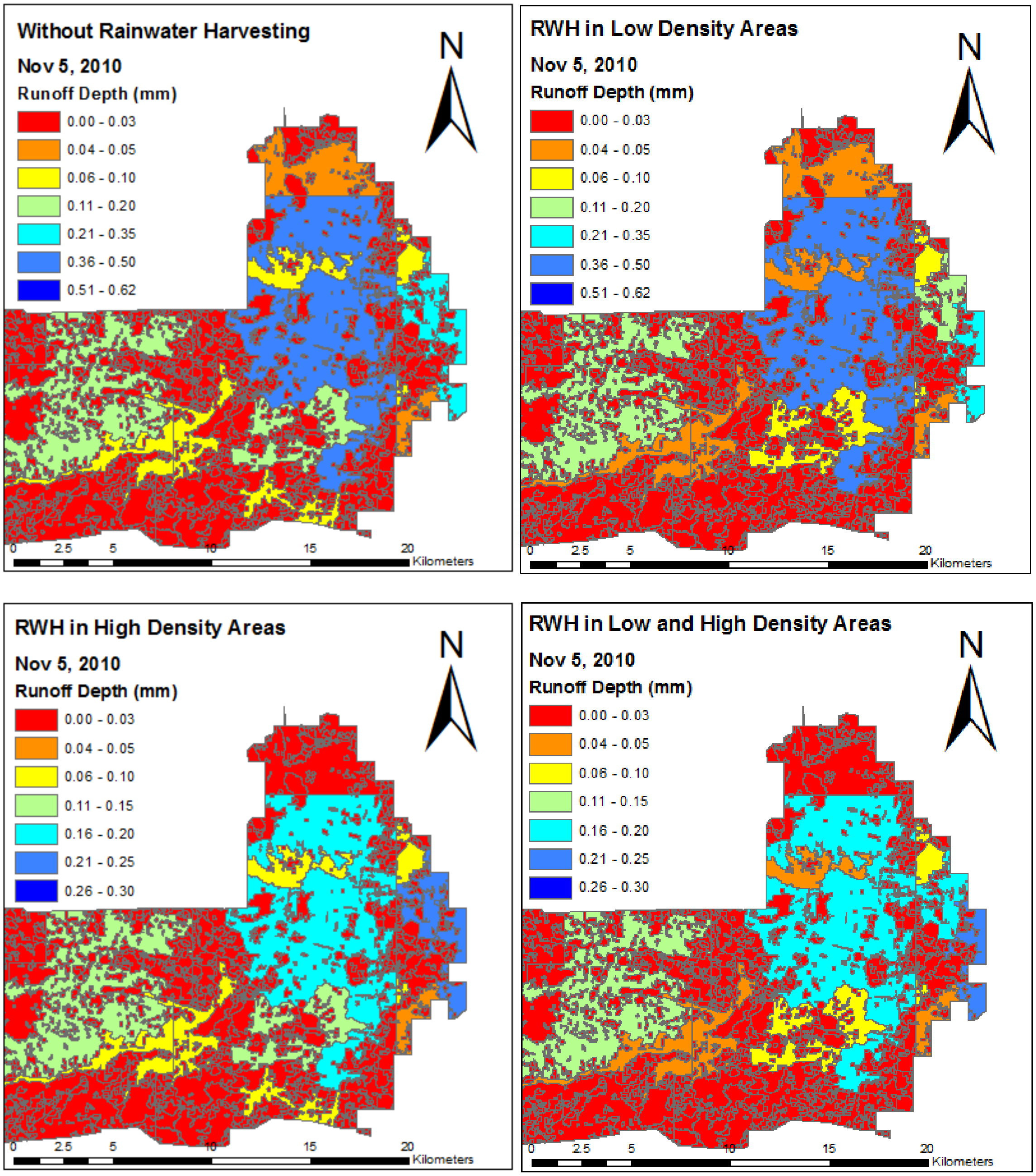
Date	Precipitation (mm)	Landcover class	Q (mm)
	19.4	Barren / Minimal Vegetation	0.00
	17.5	Agriculture, General	1.08
	17.7	Agriculture, Paddy	0.15
	14.1	Wetland	0.02
	11.3	Mangrove	0.11
	17.9	Water	0.03
	19.1	Urban, High Density	0.47
	18.1	Urban, Medium to Low Density	0.54

Appendix D Spatial Distribution of Runoff Depth

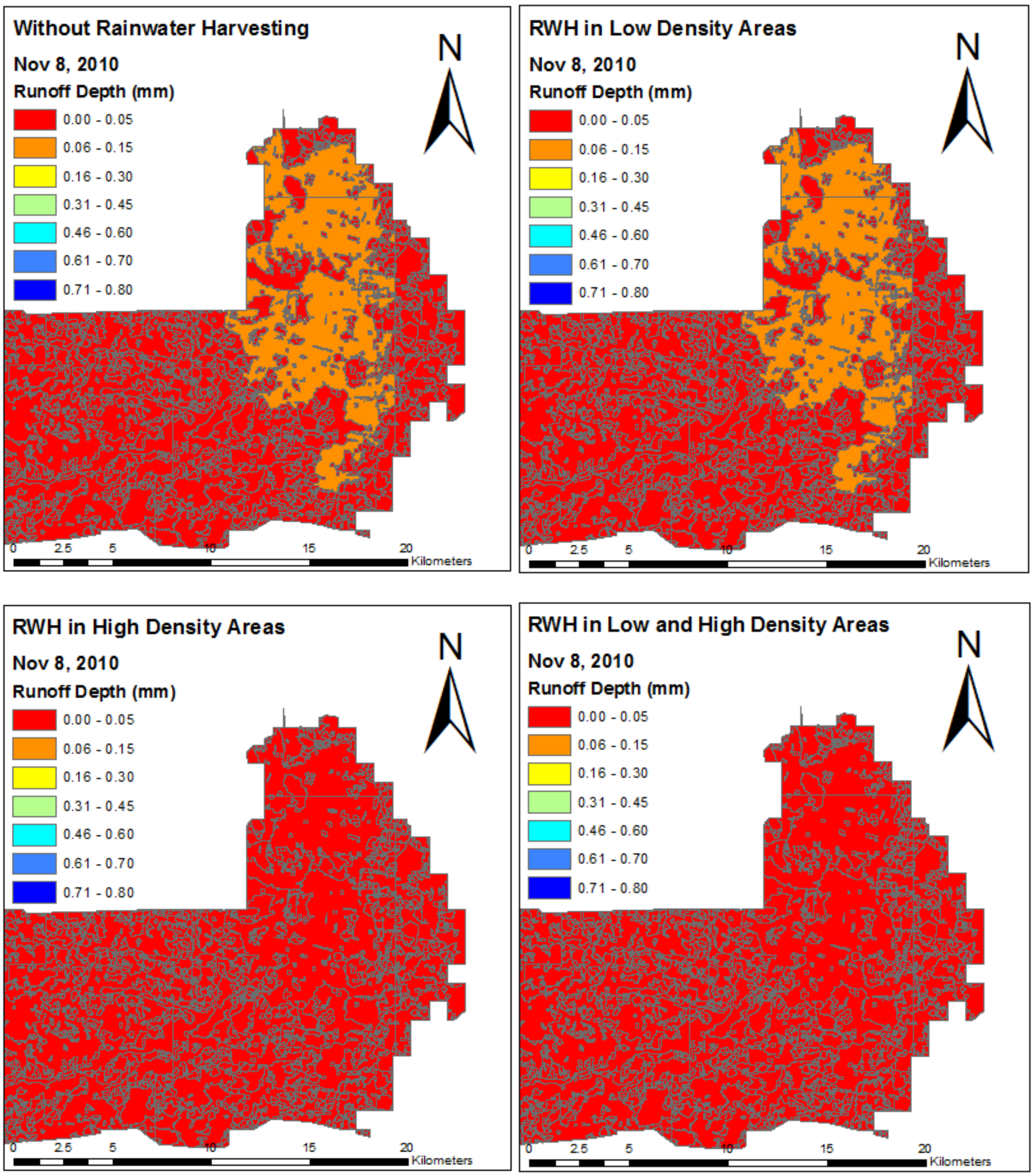
D1 Runoff Depth Spatial Distribution on November 4, 2010



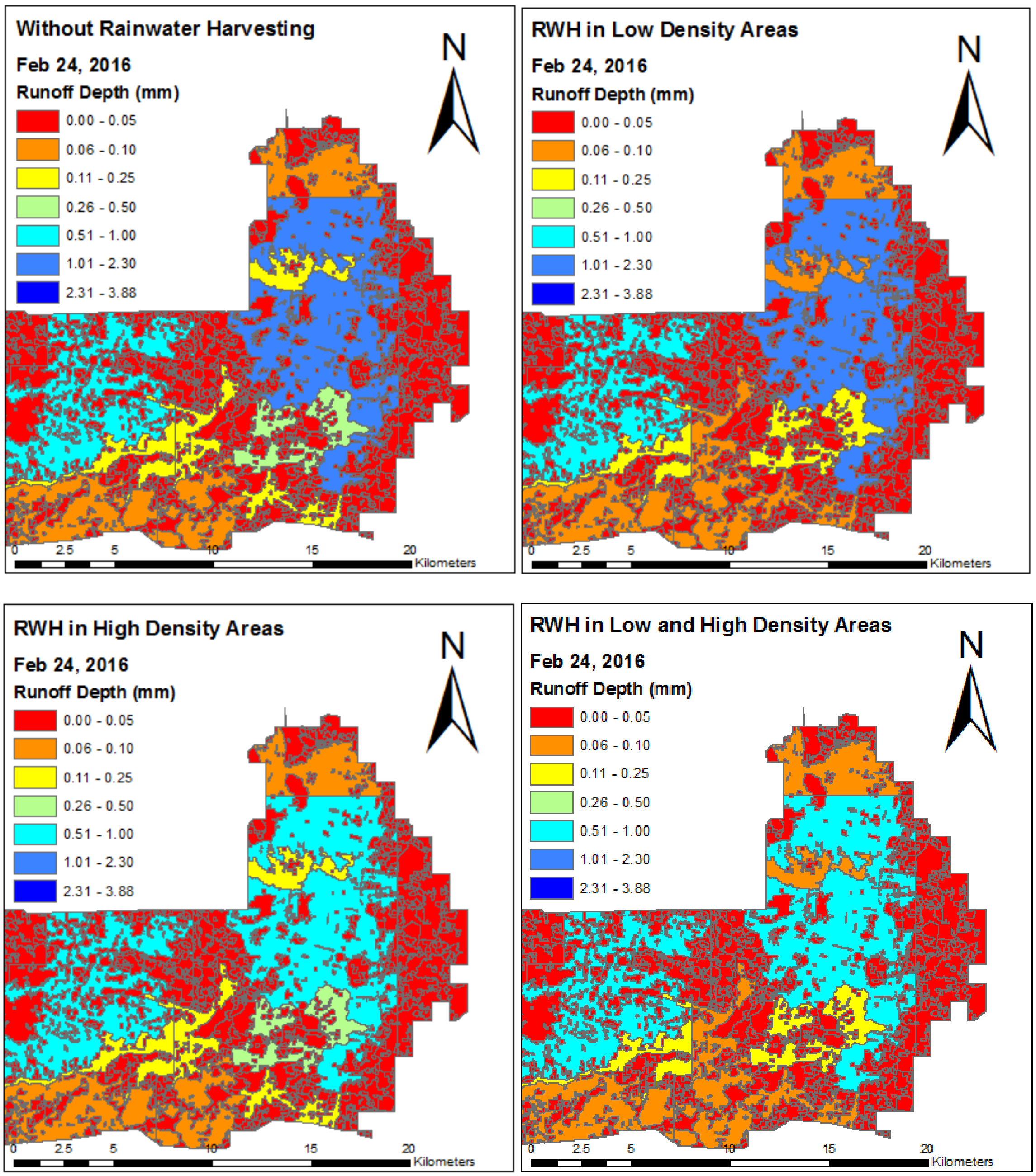
D2 Runoff Depth Spatial Distribution on November 5, 2010



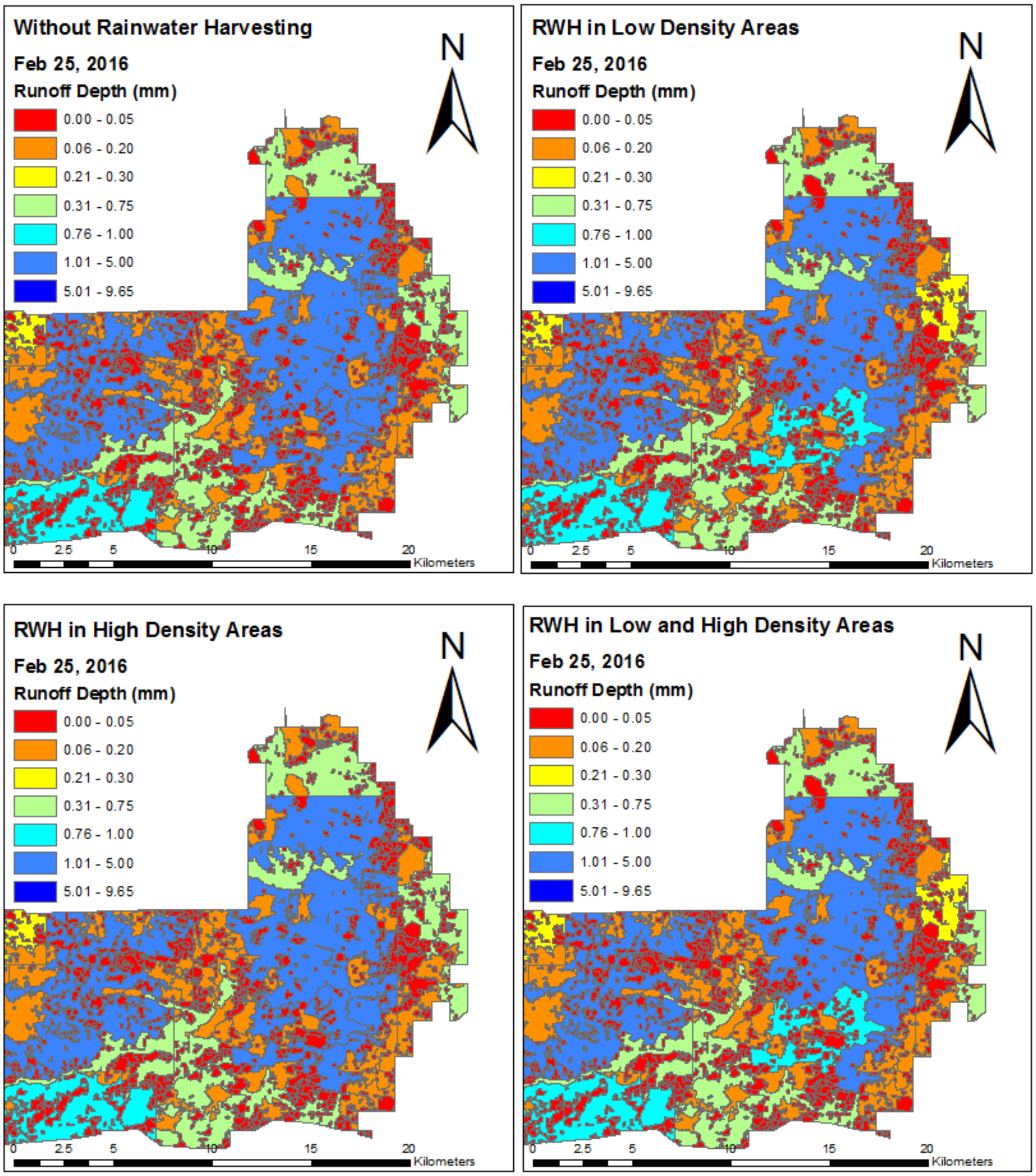
D3 Runoff Depth Spatial Distribution on November 8, 2010



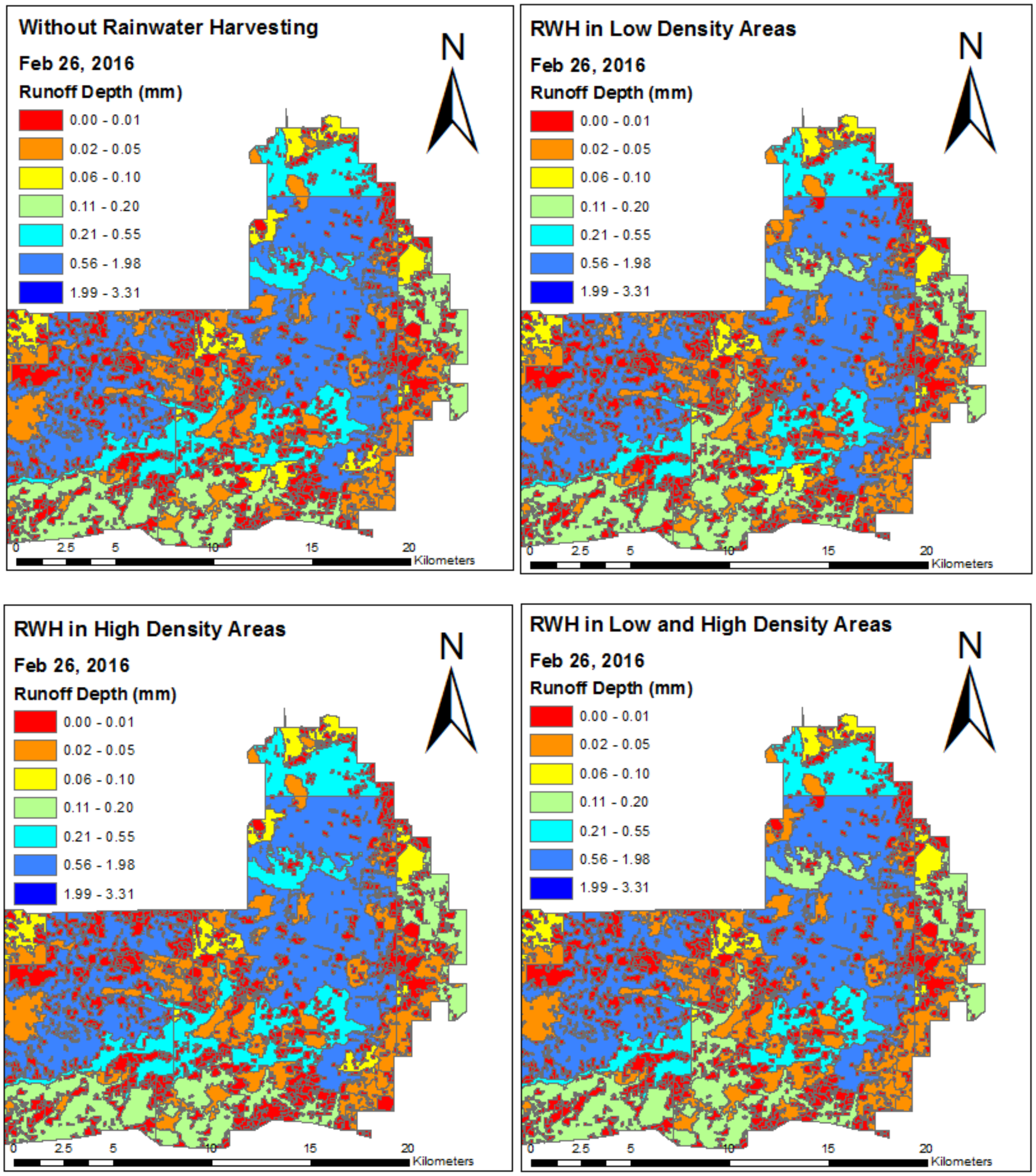
D4 Runoff Depth Spatial Distribution on February 24, 2016



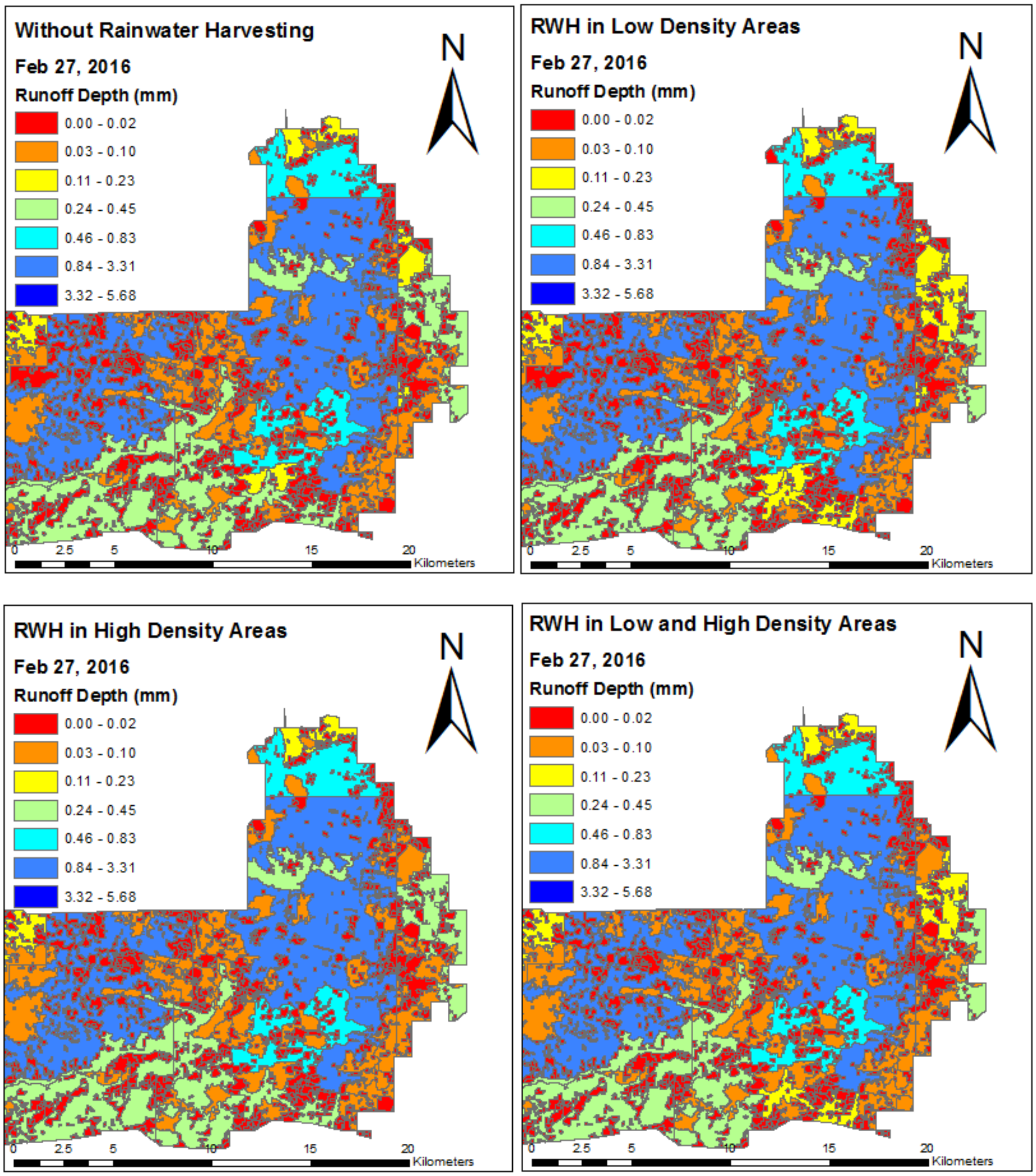
D5 Runoff Depth Spatial Distribution on February 25, 2016



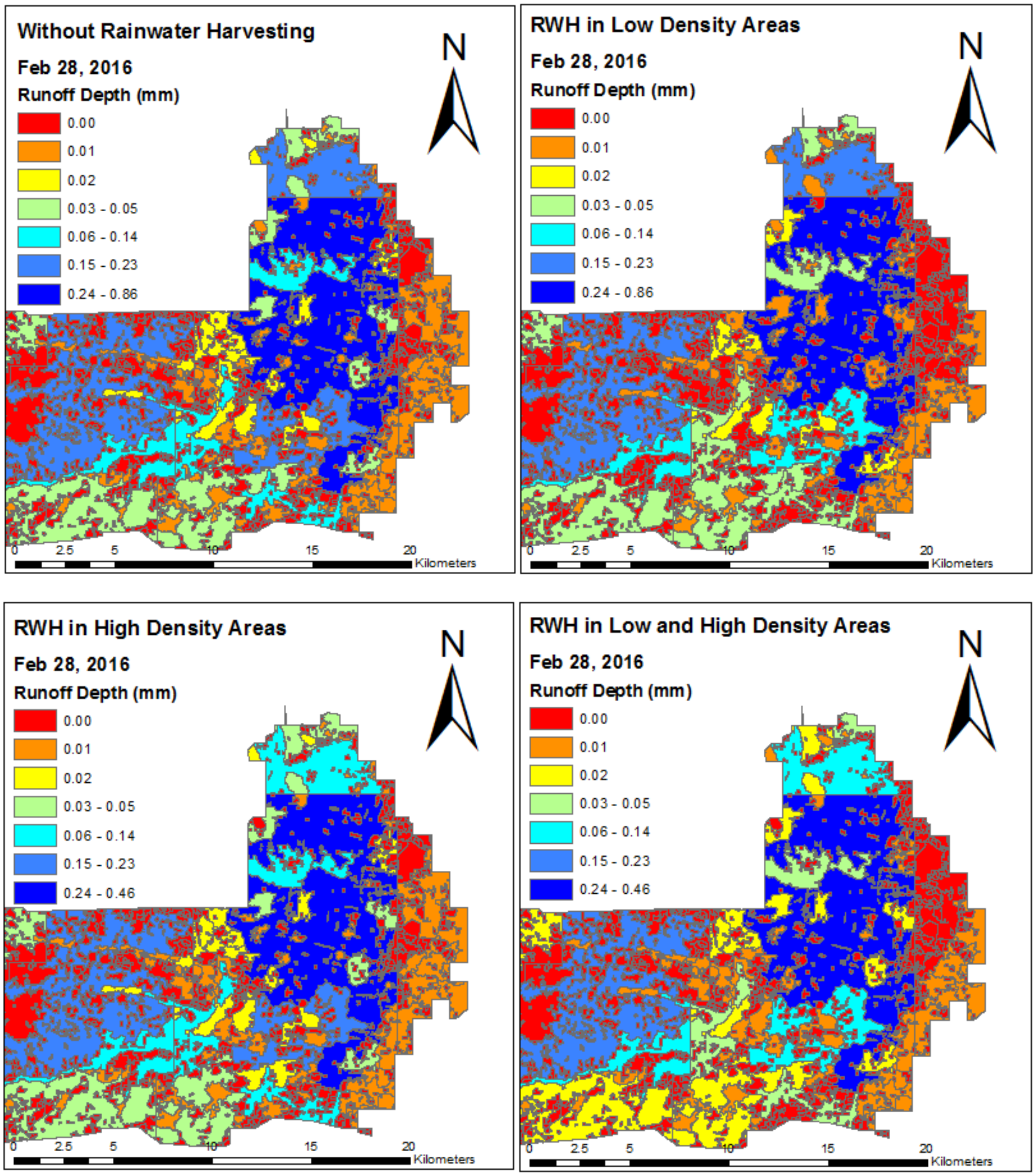
D6 Runoff Depth Spatial Distribution on February 26, 2016



D7 Runoff Depth Spatial Distribution on February 27, 2016



D8 Runoff Depth Spatial Distribution on February 28, 2016



Appendix E Runoff Curve Numbers for Agricultural Lands Based on TR-55

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and I_a=0.2S

[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.