Mapping and Modeling of Variable Source Areas in a Small Agricultural Watershed

by

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ABSTRACT

MAPPING AND MODELING OF VARIABLE SOURCE AREAS IN A SMALL AGRICULTURAL WATERSHED

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Modeling the spatiotemporal dynamics of Variable Source Areas (VSA) is challenging since VSAs depend on a number of factors such as soil properties, land use, water table, topography, geology and climatic conditions. In spite of these challenges, few encouraging attempts have been made to develop models for quantification and locating runoff generation areas based on VSA concepts. However, these approaches need to be validated with field tests for their feasibility and accuracy.

This research is divided into four main sections. The first section discusses how an advanced, low cost, remotely controlled digital Wireless Sensor Network (WSN) system was developed to monitor and acquire climatic and hydrological data from a distantly located watershed. The developed WSN system was installed in a small agricultural watershed near Elora, Ontario and watershed observations of 45 rainfall events from September 2011 to July 2013 were collected. In the second section, significance of various climatic and hydrological factors affecting the spatiotemporal variability of runoff generating areas are explored. Analysis showed that the runoff generating areas were strongly influenced by the seasons and that rainfall amoun
was the most dominant factor affecting these areas, followed by initial soil moisture and rainfall intensity.

The third section includes modification of an existing distributed CN-VSA method by incorporating seasonal variability of potential maximum soil moisture retention of the watershed. The simulations made with modified distributed CN-VSA predicted spatial extent of saturated areas more accurately in ways consistent with VSA hydrology. In the fourth section, an event based AGNPS model is reconceptualised based on VSA hydrology concept by incorporating the Topographic Wetness Index (TWI). This modeling approach demonstrates an easy method to predict the dynamics of VSAs by combining VSA hydrology with existing SCS-CN runoff equation. In this method, TWI was used in combination with land-use to define the CN values. The simulated results showed that in regions dominated by saturation excess runoff process, AGNPS-VSA model provides more realistic spatial distribution of runoff generating areas than the AGNPS model based on traditional SCS–CN method. This research will help to locate VSAs for applying targeted BMPs to control non-point source pollution.
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<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>$A_f$</td>
<td>Fractional area</td>
</tr>
<tr>
<td>AGNPS</td>
<td>Agricultural Non-Point Source Pollution Model</td>
</tr>
<tr>
<td>AWC</td>
<td>Antecedent wetness condition</td>
</tr>
<tr>
<td>BMP</td>
<td>Best Management Practices</td>
</tr>
<tr>
<td>C</td>
<td>Runoff coefficient</td>
</tr>
<tr>
<td>CN</td>
<td>Curve Number</td>
</tr>
<tr>
<td>CREAMS</td>
<td>Chemicals, Runoff and Erosion from Agricultural Management Systems model</td>
</tr>
<tr>
<td>CSA</td>
<td>Critical Source Area</td>
</tr>
<tr>
<td>D</td>
<td>Duration of Rainfall</td>
</tr>
<tr>
<td>d</td>
<td>Depth</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>E</td>
<td>Coefficient of efficiency (Nash-Sutcliffe)</td>
</tr>
<tr>
<td>EI</td>
<td>Erosion Index</td>
</tr>
<tr>
<td>EPIC</td>
<td>Erosion-Productivity Impact Calculator model</td>
</tr>
<tr>
<td>ERS</td>
<td>Elora Research Station</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GP</td>
<td>Guelph Permeameter</td>
</tr>
<tr>
<td>GRASS</td>
<td>Geographic Resources Analysis Support System</td>
</tr>
<tr>
<td>GWLF</td>
<td>General Watershed Loading Function model</td>
</tr>
<tr>
<td>HAA</td>
<td>Hydrologically Active Area</td>
</tr>
<tr>
<td>HSA</td>
<td>Hydrologically Sensitive Area</td>
</tr>
<tr>
<td>I</td>
<td>Rainfall intensity</td>
</tr>
<tr>
<td>Ia</td>
<td>Initial abstraction</td>
</tr>
<tr>
<td>I/O</td>
<td>Input / Output</td>
</tr>
<tr>
<td>IMC</td>
<td>Initial moisture content</td>
</tr>
<tr>
<td>Ks</td>
<td>Saturated hydrologic conductivity</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>Lidar</td>
<td>Light Detection And Ranging</td>
</tr>
<tr>
<td>m</td>
<td>rank of position</td>
</tr>
<tr>
<td>MFD</td>
<td>Multiple Flow Direction</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>MOE</td>
<td>Ministry of the Environment</td>
</tr>
<tr>
<td>MVLR</td>
<td>Multi Variable Linear Regression</td>
</tr>
<tr>
<td>n</td>
<td>Number of samples</td>
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<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
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<tr>
<td>NIR</td>
<td>Near infra-red</td>
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</table>
NPS  Nonpoint source pollution
NRCS  Natural Resources Conservation Service
NWRI  National Water Research Institute
Q    Runoff
ON   Ontario
p    Probability
P    Rainfall amount
$P_e$ Effective precipitation
PCB  Printed circuit board
r    Product-moment correlation coefficient
$R^2$ Coefficient of Determination
RGA  Runoff generating area
RL   Reduced level
RMSE Root-mean-squared error
S    Potential maximum retention
SAS  Statistical Analysis System
SCS-CN Soil Conservation Service curve number
SFD  Single Flow Direction
SI   Storm index
SMDR Soil Moisture Distribution and Routing model
SAR  Synthetic-aperture radar
SMoRMMod Soil Moisture-based Runoff Model
SWAT Soil & Water Assessment Tool
SWAT-VSA VSA-based Soil and Water Assessment Tool
SWAT-WB Water Balance-based Soil and Water Assessment Tool
tan$\beta$ Local gradient
TDR  Time-domain reflectometry.
TI   Topographic Index
TIN  Triangular Irregular Network
Tp   Time of ponding
TOPMODEL Rainfall-runoff model based on topography
TRCA Toronto Regional Conservation Authority
TVA  Tennessee Valley Authority
TWI  Topographic Wetness Index
USDA United States Department of Agriculture
US EPA United States Environmental Protection Agency
VSA Variable Source Area
VSAS1 VSA Simulator model 1
VSLF Variable Source Loading Function model
WSN  Wireless Sensor Network
CHAPTER 1

INTRODUCTION

1.1 Runoff generation mechanisms

Surface runoff due to excess rainfall and/or snowmelt constitutes an important part of the water cycle and a dominant pathway of nonpoint source pollution. Therefore, identifying the location of high runoff generating areas is very important for the application of best management practices (Hoover 1990; Leh et al. 2008; Singh and Woolhiser 2002).

The location of runoff generating areas (RGAs) in a landscape depends on the runoff generating mechanism. Infiltration excess and saturation excess are the two primary hydrological mechanisms of runoff generation. Infiltration excess is also called Hortonian overland flow, and occurs when the application of water to the soil surface exceeds the infiltration capacity of the soil (Horton 1933, 1940). The infiltration rate depends on soil properties, land use and landscape conditions (Hewlett and Hibbert 1963; Hornbeck and Reinhart 1964; Whipkey 1965). Infiltration excess runoff depends on magnitude of the rainfall intensity and often low rainfall intensity does not generate any runoff. With some exceptions, the infiltration excess is often assumed to take place uniformly over the landscape under arid and semi-arid conditions.

In contrast, saturation excess runoff occurs when soil becomes saturated from below as the water table rises to the land surface either from excess rainfall or from lateral subsurface flow. Precipitation over these saturated areas results in runoff (Dunne and
Leopold 1978). The portions of the landscape generating saturation excess runoff varies seasonally as well as within a storm, thus, they are generally termed as variable source areas (VSA) or hydrologically active areas (Frankenberger et al. 1999, Walter et al. 2000). Saturation excess runoff generally occurs in humid and thickly vegetated regions with permeable shallow soils underlain by an impervious layer (Dunne and Black 1970; Merwin et al. 1994).

In watersheds both infiltration excess and saturation excess runoff generating mechanisms may contribute to overland flow; however, often only one of the processes dominates (Betson 1964; Dickinson et al. 1970). The infiltration excess approach can be useful at a field scale but may not be good enough to simulate hydrologic processes at a watershed scale. Consequently, appropriate spatial and temporal representation of infiltration excess and saturation excess runoff in a watershed is the most significant task in hydrological modeling studies (Mehta et al. 2003, 2004).

1.2 Variable source areas

Variable Source Area (VSA) hydrology is a watershed runoff process where runoff during the precipitation event is generated on saturated surface areas of the landscape. In other words, precipitation on saturated areas becomes “saturation excess” overland flow. Runoff from these areas is generated by saturation excess after the water table rises and saturates the landscape.

The expansion and contraction of VSAs during and following a storm are generally influenced by the subsurface flow. Once the top layer of soil becomes saturated,
continuation of rainfall increases the interflow delivering water to the base of slopes and near stream areas, resulting in expansion of the runoff generating areas. After the cessation of rainfall, reduced downstream moisture movement results in the contraction of VSAs (Loganathan et al. 1989).

In the VSA hydrology runoff generating areas are not uniformly distributed over the landscape but is concentrated in specific saturated areas (Garen et al. 2005). Many researchers have suggested that relatively small portions of a watershed contribute to direct runoff whereas remaining regions rarely generate runoff. (Arteaga et al. 1973; Betson 1964; Moldenhauer et al. 1960). VSAs generally develop along the lower portions of hillslopes, topographically converging or concave areas; valley floors; shallow water table areas; and adjoining the streams (Amerman 1965).

VSAs contributing to overland flow are very active, sensitive and dynamic in nature and may vary significantly spatially and temporarily within the storm or seasonally. As an extension of the saturation excess process, VSAs within a watershed develop within hours or days and expand or contract depending on the landscape wetness and rainfall amount (Dunne and Black 1970; Hewlett and Nutter 1970; Walter et al. 2000). The spatial and temporal variability of VSAs depend upon the rainfall amount, rainfall intensity, landscape wetness, soil characteristics, land use, topography, water table depth and its geographical location (Sivapalan et al. 1987).

Field research has concluded that VSAs often originate from small but identifiable or at least interpretable fractions of a watershed and produce most of the watershed runoff (Gburek and Sharpley 1998; Srinivasan et al. 2000). Dickinson et al. (1970)
observed that the variable source areas in the Blue Springs Creek watershed (ON) having sub-humid continental climate ranged from 1 % to 21 % of the watershed area. Jordan (1994) reported that about 10 to 20 % of the catchment generate saturation excess runoff while the remaining areas infiltrate and does not contribute to any runoff.

1.3 VSAs related to water quality

Contamination of freshwater is a chronic problem worldwide that has serious consequences on ecosystem and human health. Nonpoint source (NPS) pollution from agriculture “is the leading source of water quality impacts in rivers and lakes, the second largest source of impairments to wetlands, and a major contributor to contamination of estuaries and groundwater” (US EPA, 2005).

The development of large amounts of storm runoff in a watershed has many implications on the environment and surface water contamination (Gregor and Johnson 1980). In watersheds dominated by saturation excess runoff generating mechanism, some fractional areas are more susceptible of generating surface runoff than others.

Walter et al. (2000) suggested that VSAs are associated with enhanced hydrologic sensitivity compared to other non-runoff generating areas and hence are called as Hydrologically Sensitive Areas (HSAs). Runoff from HSAs poses the risk of quickly delivering potential pollutants to surface water bodies. When these areas intersect with land use that can possibly contribute pollutants, they are termed Critical Source Areas (CSAs) (Gburek et al. 2002). The CSAs constitute a comparatively small area
of the watershed, but are responsible for contributing a large fraction of pollution loads to the surface waters (Sen et al. 2008).

Agricultural runoff is responsible for polluting rivers and lakes as well as impairing wetlands. Pollutants resulting from farming activities include sediment, fertilizers, pesticides, pathogens, metals, and salts (Miller et al. 1982). Farming activities result in contamination and degradation of the environment and pose the greatest threat to the world's drinking water supplies. Hydrologically, runoff from agricultural areas primarily originates from HSAs rather than from the entire watershed, therefore the studies dealing with agricultural pollution of surface waters need to be cognizant of the role of VSA hydrology (Govindaraju 1996; Qiu 2003, 2010).

In recent times, protection of local drinking water sources is a major environmental challenge (Davidson et al. 2005). Protecting sources of water and taking the necessary measures to restore water quality is vital for human, aquatic and ecosystem health. Therefore, identification of VSAs is crucial for application of BMPs for managing a wide range of water quality problems and reducing the loads of sediment, nutrients and bacteria to streams, lakes and reservoirs.

1.4 Variable Source Area modeling

Modeling spatial and temporal variability of VSA is very challenging since the development of a VSA depends on multiple factors such as soil properties, water table depth, topography, land use, geology, climatic conditions and topographic position in the landscape. In spite of difficulties and challenges, few encouraging
attempts have been made to develop models for quantification and locating runoff generation areas based on VSA concepts.

During the last two decades, the increase in computational power, advancement in Geographic Information System (GIS) and widespread availability of digital geographic data have led to the development of complex distributed deterministic models. A number of models such as TOPMODEL (Beven and Kirkby 1979), DHSVM (Wigmosta et al. 1994), SMDR (Steenhuis and Molen 1986), SMoRMod (Zollweg et al. 1996) have some capability to include variable source area concepts. These models, having variable degree of complexity are based on distributed moisture accounting within the segments of a watershed, are rarely used because they require copious calibration and large amount of input data (Pradhan et al. 2010).

Recently, there have been some re-conceptualizations of widely-used water quality models to account for VSA hydrology. The Soil and Water Assessment Tool (SWAT) and the Generalized Watershed Loading Function (GWLF) have both been successfully re-conceptualized to integrate VSA hydrology in SWAT-VSA (Easton et al. 2008) and Variable Source Loading Function (VSLF) (Schneiderman et al. 2007). However, these models are validated largely on long-term average simulations and not by rigorous field tests. Moreover, these models are somewhat more complicated and computationally intensive than most engineering applications warrant (Mills 2008).

In a new attempt, a modified version of SWAT called Water Balance-Based Soil and Water Assessment Tool (SWAT-WB) has been developed (White 2009). SWAT-WB
uses a physically-based soil water balance technique to model surface runoff instead of using the traditional Soil Conservation Service curve number (SCS-CN) method (USDA-SCS 1972). However, this approach needs to be tested with observed field data for its feasibility and accuracy of mapping VSAs in a watershed.

The majority of present water quality protection strategies, assessment methods and best management practices are based on conventional infiltration excess runoff concept and water quality management approaches still rely on popular water quality models based on infiltration excess runoff generating mechanism, since these are well established and user-friendly with their proven nutrient transport and soil erosion sub routines. However, for the areas dominated by saturated excess runoff mechanism, these models may not be able to predict the correct locations of runoff generating areas (Chapi 2009; Pradhan 2010). At present, VSA hydrology is not usually used for water quality protection (Qui et al. 2007) hence, there is a need to develop new approaches for monitoring and modeling to identify critical management areas from VSAs.

1.5 Problem statement

Field observations and repeated field mapping during and after rainfall events can be effectively used for mapping the size, magnitude, location and variability of runoff generating areas. Runoff generating areas during and after storm events can easily be observed and identified as VSAs by monitoring the watershed because these areas are wetter than other areas and need more time to dry after a storm event (Qiu 2003).
The traditional analog type hydrological monitoring systems lack resolution and scalability. In addition, cabling requirements in the field restricts the spatial size of the monitoring area (Oliveria et al. 2011). Rapid development in digital technology, wireless communication and low power micro sensing technologies has made Wireless Sensor Networks (WSNs) economically feasible to use in hydrologic research (Song et al. 2008). Unlike other networks, WSNs are designed for specific applications in hydrology (Verma 2013). During last few decades, substantial advancements have been made in the field of WSN’s technology but the development of WSNs for hydrological and environmental research is still in the relatively primitive stages. During the last decade, a number of research studies have focused on the field of WSN technology for environmental monitoring but very few of them are supported by actual field evaluation (Szewczyk et al. 2004). At present no simple or low cost off-the-shelf solution exists for hydrological monitoring applications. Hence, there is a need to develop a low cost, efficient and remotely operated WSN system for monitoring climatic and hydrologic variables in a watershed.

VSA hydrology has been universally acknowledged as a basic principle of hydrological science since 1970, but it has been noted that the quantitative understanding of the VSA concept is far from complete and its application to hydrologic calculations is not fully developed. Another poorly understood process is saturation overland flow. Further, very limited field data is available to physically verify or support the various theories of VSA hydrology and its governing factors. There is still ambiguity among the scientific community about the dominating factors affecting the development and variability of the VSAs. Therefore, there is a need for field
research to investigate the significance of various factors responsible for spatiotemporal variability of runoff generating areas in a watershed.

Many studies have shown that the theoretical basis of the SCS-CN method is valid for both Hortonian and saturation excess runoff generating mechanisms (Hjelmfelt 1980; Steenhuis et al. 1995). However, the majority of current water quality models use CN-values computed on the basis of soil infiltration capacity and land use to estimate storm runoff (Walter and Shaw 2005). These models implicitly presume that the runoff is generated by Hortonian runoff mechanism and hence fail to account for the effects of topography and moisture distribution, which are very important factors in the watersheds dominated by saturation excess runoff generating mechanism (Schneiderman et al. 2007; Srinivasan et al. 2002).

The Distributed CN–VSA method developed by Lyon et al. (2004) is one of the promising newer methods that incorporates VSA concept to simulate the aerial distribution of saturation excess runoff. This physically-based method uses a traditional SCS-CN approach to predict runoff volume and spatial extent of saturated areas and distributes runoff source areas within the watershed using a Topographic Wetness Index (TWI) approach. This simple method can be easily integrated with existing hydrological models for predicting the locations of runoff generating areas based on VSA concept. However, it needs to be validated with observed field data to ensure its feasibility and accuracy of mapping the VSAs in a watershed.

It is an established fact that a very high percentage of nonpoint source pollution loads from rural agricultural watersheds are generated by few intense rainfall events due to
high amount of generated runoff (McBroom et al. 2003). The rainfall events are also the main contributor in establishing hydrological connectivity between agricultural land and streams, and transporting NPS pollution loads (Kim et al. 2006). Hence, there is a need to develop a distributed event based model based on VSA hydrologic concept, to simulate overland flow and accurately identify runoff generating areas within a watershed. Such a model would aid in the identification, quantification and modeling of runoff generation mechanisms and runoff generating areas that are vital for best management practices applications in agricultural watersheds. Moreover, these models would help to develop strategies to minimize pollutant loads in surface waters by accurately predicting the locations of runoff generating areas.

1.6 Research objectives

The overall objective of this study is to investigate the spatial and temporal variability of the variable source areas in small agricultural watershed in the climatic conditions of Ontario. The specific objectives of this research are:

1) To develop a low cost, robust and remotely operated WSN system for monitoring and collecting climatic and hydrological data from a distantly located agricultural watershed.

2) To investigate the significance of factors affecting the spatial and temporal variability of runoff generating areas in a watershed by field experimentation and to identify VSAs.
3) To evaluate and improve the performance of an existing variable source area modeling approach (distributed CN-VSA) for mapping the variable source areas in a watershed with field observed data.

4) To develop and evaluate the performance of an event based distributed hydrological model for simulation of the dynamics of variable source area.

1.7 Expected outcome, impacts and benefits

The outcome of this research would provide a methodology to map sources of surface runoff in a field/watershed. The result of this comprehensive monitoring and modeling study on VSA hydrology concept would help in locating hot spots of runoff generation. Mapping of such source areas would result in selection of specific and targeted best management practices for the development of economically efficient and environmentally sustainable water quality and NPS pollution management strategies. In addition, for areas where monitoring is not possible the developed VSA modeling approach will allow to understand the hydrological behavior of headwater areas of a watershed, the process of soil erosion and sediment transport. Therefore, this is a major step towards development and implementation of best management practices (BMPs) on potential pollution generating areas in a watershed to reduce the loads of sediment, nutrients, pollutants and bacteria to streams, lakes and reservoirs.

1.8 Thesis organization

This thesis is organized into seven chapters as shown in Fig. 1.4. Chapters two, three, four, five and six are written as separate papers in a journal article format.
These individual papers describe different aspects of the research and include an introduction, methodology, results, discussion, and conclusion.

Figure 1.1: Flow chart showing organization of thesis

The thesis begins with Chapter 1 which includes introduction of the topic, problem statement, objectives and expected outcome.
Chapter 2 includes a literature review of past research, an explanation of the present situation and an outline of the future of variable source area hydrology including the use of emerging technologies for delineating and modeling VSAs.

Chapter 3 discusses the development and field evaluation of a low cost WSN system for hydrological monitoring in a small agricultural watershed.

Chapter 4 describes the field monitoring, data collection and statistical analysis of rainfall and runoff data from a study watershed.

Chapter 5 includes development and evaluation of the modified distributed CN-VSA approach for predicting VSAs of runoff generation.

Chapter 6 is devoted to development and evaluation of an event-based distributed model for modeling and mapping variable source areas in a watershed.

Chapter 7 wraps up the thesis by describing the conclusions and future recommendations pertaining to this research. Lastly, details of the study watershed and climatic and hydrological characteristics of three randomly selected rainfall-runoff events are included in the appendices.

1.9 References


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CHAPTER 2

Variable Source Area Hydrology: Past, Present and Future

Abstract

Variable Source Area hydrology is a watershed runoff process where surface runoff generates on saturated surface areas. In other words, the rain that falls on saturated areas results in “saturation excess” overland flow. Variable source areas develop when a soil profile becomes saturated from below after the water table rises to the land surface either from excess rainfall or from shallow lateral subsurface flow. This paper presents a review of the past and present research developments in the field of variable source area hydrology. Existing methods and approaches for monitoring, delineating, and modeling the VSAs are presented. Further, the advances in remote sensing technology, higher resolution satellites, and aerial photography for delineating saturated areas are discussed for the future of monitoring and modeling variable source areas.

Keywords: Variable source area, Hydrological modeling, SCS Curve Number, Topographic index, Nonpoint Source Pollution.

2.1 Introduction

The concept of Variable Source Area (VSA) was first developed by the U.S. Forest Service (1961) but the term "variable source area" is credited to Hewlett and Hibbert (1967). Dunne and Black (1970) and Hewlett and Nutter (1970) are also known to be
foundational contributors to the VSA hydrology concept. During the 1960s and 1970s, intensive field experiments in small catchments were conducted to map the spatial patterns of runoff generating areas and their seasonal variations. These studies supported the VSA concept and since then many efforts have been made to explain and predict the spatial patterns of VSAs (Barling et al. 1994; Beven and Kirkby 1979; Sivapalan et al. 1987).

VSAs develop when a soil profile becomes saturated from below after the water table rises to the land surface. This can happen due to either excess rainfall or shallow lateral subsurface flow from upslope catchment areas (Dunne and Black 1970; Dunne and Leopold 1978; Beven 2001; Srinivasan et al. 2002; Needelman et al. 2004). However, this is contrary to the long standing Hortonian theory, which assumes that runoff takes place when the rainfall intensity exceeds the infiltration capacity of the soil (Horton 1933). Hortonian overland flow does not happen at low rainfall intensities and is often assumed to take place uniformly over the landscape. However, many studies have shown that the fraction of the watershed susceptible to saturation excess runoff varies seasonally and within the rainfall event, thus these runoff generating areas are generally termed as VSAs or hydrologically active areas (Frankenberger et al. 1999; Walter et al. 2000).

VSAs are generally influenced by the rainfall amount and shallow lateral subsurface flow. Their spatial and temporal variability are different depending upon the rainfall amount, depth of the water table, antecedent wetness condition, soil characteristics, landscape topography and the geographical location of the area (Sivapalan et al. 1987). VSAs commonly develop along the lower portions of hillslopes, topographically
converging or concave areas; valley floors; shallow water table areas; and adjoining the streams (Amerman 1965).

Over the years, a number of physically-based distributed models based on VSA hydrology concept have been developed (Knapp 1974; Kirkby et al. 1975; Beven and Kirkby 1979; Frankenberger et al. 1999; Takeuchi et al. 1999; Ogden and Watts 2000). However, the requirement of a large amount of input data and the necessity of copious calibration often restricts practical application of these models in ungauged basins (Pradhan et al. 2010). During the last decade, few re-conceptualizations of widely-used hydrological models have been developed to include the VSA hydrology. However, these process-based models are also computationally intensive and complicated for engineering applications and need to be validated or supported by rigorous field tests (Mills 2008; Chapi 2009).

Even though the concept of VSA hydrology has become popular during the last two decades, it is not usually used in water quality protection procedures due to the lack of user-friendly watershed models based on VSA hydrological processes (Qiu et al. 2007). The majority of current water quality protection procedures assessment methods and Best Management Practices (BMPs) are based on conventional infiltration excess runoff theory (Walter et al. 2000). Water quality managers still rely on the water quality models to establish the sources and fates of nonpoint source pollutant fluxes because they are well documented and user-friendly with proven nutrient transport and soil erosion transport components (Wellen et al. 2014). These models primarily assume infiltration excess as the principal runoff producing mechanism and fail to correctly locate the runoff generating areas as the dominant
factors affecting the infiltration excess runoff generation mechanism are different than the factors that control saturation excess process (Schneideman et al. 2007).

Advancements in digital technology, wireless communication and embedded microsensing technologies have created a good potential for hydrological and environmental monitoring (Poret 2009). Recent developments in the field of Wireless Sensors Network (WSN) and communication systems have further revolutionized the field of hydrological monitoring. These are substantial improvements over traditional monitoring systems and are promising new technologies for studying hydrological responses of watershed headwaters in order to model the spatial-temporal variability of VSAs (Trubilowicz et al. 2009). Moreover, increasingly available computational power and new innovations in remote sensing, higher resolution satellites, and aerial photography are promising future technologies for monitoring, and for paving the way for formulating standard modeling methods for identification and quantification of VSAs (Pizurica et al. 2000).

The main objectives of this study are to: (1) provide an overview of the past and present research related to developments of VSA hydrology (2) describe present methods and approaches for monitoring, delineating, and modeling the VSAs and (3) discuss the monitoring and modeling of VSAs in the light of advancements in digital technology, remote sensing, higher resolution satellites and aerial photography.

2.2 Historical overview

The earlier concept of overland flow was that storm runoff is primarily the result of overland flow generated by an excess of rainfall that exceeds the infiltration capacity
of the soil. The infiltration excess runoff known as Hortonian flow (Horton 1933; 1937; 1940), occurs when the application of water to the soil surface exceeds the rate at which water can infiltrate into the soil. The infiltration rate depends on soil type, land use, vegetation and landscape wetness (Hewlett and Hibbert 1963; Hornbeck and Reinhart 1964; Whipkey 1965). Infiltration excess runoff does not happen at low intensities and is often assumed to take place uniformly over the landscape. Pilgrim et al. (1978); Jordan (1994); Perrin et al. (2001); Wetzel (2003) and Godsey et al. (2004) reported that the variability of soils in a watershed may allow both infiltration excess and saturation excess runoff generating mechanisms simultaneously in humid areas. However, Scherrer et al. (2007) observed that one or more of these mechanisms often dominate depending on the characteristics of watershed such as vegetation, slope, soil clay content and antecedent soil moisture condition.

Horton (1943) recognized that surface runoff rarely occurs on soils well protected by forest cover due to “somewhat unusual conditions”. The term “unusual condition” can be seen as the first concept on VSAs in a watershed. Subsequently Hoover and Hursh (1943) and Hursh (1944) described a “dynamic form of subsurface flow” contributing to storm flow generation in forested areas. Subsequently, Roessel (1950) emphasized the importance of subsurface flow and groundwater contributions to streamside outflow. Cappus (1960) based on the study in a watershed dominated by sandy soils, provided clear field evidence of subsurface storm flow within the context of the VSA concept. He divided the watershed into “runoff areas” and “infiltration areas”. The runoff generating areas were completely water-saturated terrains; while in the infiltration areas, the saturated hydraulic conductivity of soils was so high that
the rain falling onto these areas was absorbed and no runoff was generated (Ambroise 2004).

Hursh and Fletcher (1942) discovered that subsurface flows and groundwater depletion can also contribute to stream flow in humid regions. This was further confirmed by Hewlett and Hibbert (1963), Reinhart et al. (1963) and Whipkey (1965). Many researchers contributed the VSA concept between 1961 and 1975, but Hewlett had the honor of describing the significance of the VSA concept (Jackson 2005).

The Tennessee Valley Authority (TVA) (TVA 1964, 1965) investigated eight rainfall events in two gauged watersheds and found that runoff is first generated from the low lands while slopes and ridges gradually contribute as soil moisture increases during the storm. TVA called these areas "partial watershed areas" and "dynamic watershed concept". Zavodchikov (1965) referred to these areas as “effective areas”. In a study conducted on an agricultural research watershed, Amerman (1965) concluded that runoff generating areas are randomly distributed on ridge tops, valley slopes and valley bottoms.

Betson (1964) proposed the partial area concept, suggesting that only certain fixed regions of a watershed contribute to runoff whereas remaining regions rarely generate runoff. The partial areas result from variability in infiltration rate and intensity of rainfall in time and space that generate Hortonian overland flow. The main difference between VSA and the partial area concept is that variable source areas are produced by saturation excess runoff as a result of the soil's inability to transmit
interflow further downslope and expand and contract spatially and temporally, whereas partial areas in a watershed remain spatially static (Freeze 1974).

The paper by Hewlett and Hibbert’s (1967) ‘Factors affecting the response of small watersheds to precipitation in humid areas’ is a benchmark research in the field of VSA hydrology. Their research proved to be a well-accepted alternative to the previous concept of Hortonian overland flow. Later on Kirkby and Chorley (1967) introduced slope concavities and areas with thinner surface soil as locations where surface saturation may occur, leading to the development of VSAs. Based on the field investigations and analysis of a number of rainfall events, Ragan (1967) revealed that a small fractional area of a watershed contributed significant flow to the storm hydrograph. Similarly, Arteaga and Rantz (1973) analyzed eleven rainfall events also reported that only certain areas in a watershed contribute runoff while the remaining areas did not contribute.

Hewlett (1969) carried out experiments on mountainous watersheds of the southern Appalachians within the Coweeta hydrologic laboratory. This area consists of steep slopes, highly infiltrative surface soils, small valley aquifers, pathways, and turnover rates of water in forested or well-vegetated environments. He concluded that the interflow and VSA runoff were the main drivers of storm flow with interflow delivering water to the base of slopes and temporary expansion and contraction of the VSAs around the stream channel (Dunne 1970; Dunne and Black 1970; Troendle 1985; Loganathan et al. 1989).
Whipkey (1969) measured the outflow from various horizons of a forest soil and found that the first layer of the soil was the main source of runoff due to its saturation by a perched water table over an impeding layer. This was further validated by Betson and Marius's (1969) studies on the runoff generation mechanism and observations that a shallow A horizon of the soil was frequently saturated. From this observation, they concluded that a thin A horizon of the soil is a primary source of runoff and this soil layer causes a heterogeneous runoff generation pattern within the watershed.

Dunne and Black (1970a, 1970b) used the water table information to define the saturated areas in a forested watershed to investigate the saturation excess runoff generation process. From this study they concluded that a major portion of the storm runoff was generated by small parts of the watershed saturated by subsurface flow and direct precipitation. They also indicated that the top soil profile becomes saturated due to a rise in the water table and rainfall over these wet areas results in saturated excess overland flow. This type of saturated areas generally develops in valley floors and close to the streams.

Pearce (1976) observed that both the Hortonian runoff and saturation excess runoff generation mechanisms occur concurrently in humid forest areas and a small part of the watershed produces runoff. Later, Freeze (1980) supported this theory and Mosley (1979) also drew similar conclusion after monitoring a small forest watershed with steep (35°) slopes and shallow (average 0.55 m) soils on impermeable strata. Mosley (1979) observed that only 3 % of net precipitation became overland flow while the subsurface flow was dominant during rainfall events and quick flows indicating the importance of saturated excess mechanisms for stream flow generation. Steenhuis
and Muck (1988) also observed that the rainfall intensities rarely exceed the infiltration capacity of shallow hillside soils and these observations were later supported by Merwin et al. (1994).

Many studies have shown that VSAs often occur across the small but predictable fractional areas of a watershed (Srinivasan et al. 2000; 2002). Gburek (1990, 1998) described the VSAs as areas consisting of the stream surface and the area of surface saturation caused by the groundwater table intersection within the land surface above the elevation of a stream.

Walter et al. (2000) suggested the concept of Hydrologically Active Areas (HAAs). They observed that in the VSA hydrology dominant watersheds, some areas are more prone of generating runoff for all rainfall events. These areas are also named as hydrologically sensitive areas (HSAs) when connected to the primary surface bodies of water. Hydrologically sensitive areas coinciding with potential pollutant loading areas are defined as Critical Source Areas (CSAs) or referred as "Critical Management Zones" (Gburek et al. 2002).

Joel et al. (2002) indicated that the Horton’s concept of runoff generation does not provide an adequate description of hydrological processes at the hillslope level. He observed that on average, the larger plots of 50 m² area generate more runoff per unit areas than smaller plots (0.25 m²) and supported the observations of Chorley (1980) that the Horton’s theory becomes less accurate with increase in catchment size.
Srinivasan et al. (2000), Hernandez et al. (2003) and McGuire et al. (2007) observed that the interaction between static characteristics (topography, soil, land cover) and dynamic characteristics (time varying rainfall characteristics, soil moisture conditions, hydraulic conductivity of soil and depth to the water table) affects variability of VSAs. Latron and Gallart (2007, 2008) suggested that the VSAs can be classified into two categories according to the process of soil saturation. The VSAs developed due to the rising of the water table to the surface was termed as A type VSAs and the areas with top upper layer saturated due to the perched water table were classified as B type VSAs.

Lastly, Buda et al. (2009) demonstrated the influence of subsurface soil properties on surface runoff generation in agricultural watersheds with VSA hydrology, which could be useful for improving the accuracy of existing VSA prediction models.

2.3 Factors affecting Variable Source Areas

Knowledge of the factors affecting the development and variability of VSAs is critical for developing a better understanding of the response of a watershed to rainfall event. The main factors affecting the spatial and temporal variability of VSAs are watershed characteristics, topography, water table depth, soil type, land use, rainfall characteristics, surface and groundwater hydrology, geology and climatic conditions (Walter et al. 2000).

Dickinson and Whiteley (1970) were the first to evaluate VSAs and concluded that the most important factors affecting VSAs were stream surface area, pre-event soil moisture, rainfall intensity, and depletion of soil moisture storage as the storm
progresses. Moore et al. (1976) indicated that topography, soil type, vegetation, and antecedent moisture index are key factors affecting the saturated areas in small watersheds. Lee and Delleur (1976) concluded that the drainage basin, slope and roughness of landscape are the controlling factors of the VSAs. Dunne and Leopold (1978) emphasised the importance of storm size, phreatic zone and the subsurface flow system for runoff generation. Beven (1978) suggested that soil type, topography and basin size play an important role in the hydrological response of headwaters. Beven and Wood (1983) concluded that the storm rainfall, initial moisture deficit and geomorphologic structure of the watershed are critical factors affecting the variability of VSAs. Hernandez et al. (2003) reported that hill sides with concave and low relief areas are more susceptible and create large VSAs compared to steep slope hillsides.

Pearce et al. (1986) reported antecedent wetness, physical properties of soil, water table depth and storm magnitude are the most important factors in seasonal expansion and contraction of VSAs. Kwaad (1991) analyzed summer and winter runoff generation mechanisms and observed that summer runoff follows the Horton model of runoff generation process and is controlled by the rainfall intensity, whereas, winter runoff follows the saturated excess mechanism and is affected by the amount of rainfall rather than the rainfall intensity. Verhoest et al. (1998) suggested the need for soil moisture properties, groundwater seepage and topography to map the spatial variability of variable source areas. Troch et al. (2000) explained that the development of VSAs in a watershed depends on land relief and wetness of the landscape. Elsenbeer and Vertessy (2000) reported that the hydrological response of
a watershed can be controlled by lithological properties of soils and their interactions with rainfall characteristics.

Kirkby et al. (2002) examined the effects of several factors on surface runoff generation using a Variable Bucket Model and concluded that the slope, storm size, and storm duration are the important factors affecting the runoff generation. Gupta (2002) reported that saturated hydraulic conductivity, bulk density of soil, elevation and field slope are dominant factors affecting runoff generation during the summer months. Hernandez et al. (2003) suggested that topography, soil hydraulic properties, and depth of the water table show good correlation with the variability of VSAs. Nachabe (2006) related soil type, topography, rainfall, vegetation cover, and depth of the water table to the expansion and contraction of VSAs. Gomi et al. (2008) observed that the delivery of surface runoff from hill slopes to stream channels depends upon the timing and size of rainfall events, surface vegetation and soil conditions.

Literature review indicates that the development and variability of VSAs depends on many factors; however, depending upon the objective, many researchers have considered different factors as primordial for mapping variable source areas at different scales (Kirkby et al. 2002; Leh et al. 2008). Despite substantial research conducted during the last five decades, there is still knowledge to be gained concerning the main factors affecting development and variability of variable source areas.
2.4 Dynamics of Variable Source Areas

The VSAs contributing to surface runoff are very dynamic in nature and significantly vary spatially and temporarily within a storm as well as seasonally. VSAs within the watershed expand or shrink depending on subsurface flow, landscape wetness and rainfall amount (Hewlett and Nutter 1970; Dunne and Black 1970; Walter et al. 2000).

Riddle (1969) summarized the magnitude of variable source areas in a watershed from the literature suggested that the distributions of the runoff generating area were very similar despite the variable characteristics of the basins. The majority of stream flow producing event were generated by less than 10 % of the watershed areas.

Dickinson and Whiteley (1970) studied twenty three rainfall events between the months of October and November and found that VSAs in the watersheds ranged between 1 to 21 %. They also indicated that the VSAs were relatively small at the beginning of the storm depending on stream surface area and soil moisture near the streams. Moreover, they observed that the minimum contributing areas ranged from 0 to 59 % with a mean of 20 % and a median value of 10 %.

Freeze (1972, 1974) revealed after experimenting in the Reynolds Creek Watershed near Boise (Idaho) that storm flow originates from 1 to 3 % of the landscape and generally does not exceed 10 % of the watershed area. A field survey during spring season by Shibatani (1988) showed that the extent of the saturated surface near a stream zone ranged from 8 % of the total watershed area at low flow to 20 % at high flow. Jordan (1994) suggested that about 10 % of the catchment generated saturation excess runoff. In a modeling study, Zollweg et al. (1995) observed that 98 % of the
runoff volume was generated from 14 % of the watershed. Pionke et al. (1997) reported that in hilly watersheds 90 % of the annual phosphorus loads are transported by storm runoff from less than 10 % of the watershed area.

Leh et al. (2008) used sensor data and field-scale approach to study the dynamics of the spatial extent of runoff source areas in a pasture hillslope by incorporating sensor data into a geographic information-based system and concluded that both infiltration excess runoff and saturation excess runoff occur simultaneously. Infiltration excess areas vary from 0 to 58 % and saturation excess from 0 to 26 %.

2.5 Monitoring of Variable Source Areas

Monitoring is the most reliable approach for delineating VSAs in a watershed. Although this approach is time consuming and expensive, it is accurate and trustworthy. There are numerous field monitoring techniques used to identify critical areas within a watershed. These techniques can be broadly categorized as either active or passive methods (Anderson and Burt 1978b). Active methods are data collection techniques that are implemented in the field during storm events and immediately after the cessation of the storm. In contrast, passive methods include automatic field measurements and sampling by means of probes or sensors.

2.5.1 Active methods of monitoring

Field observations (Anderson and Burt 1978b; Qiu 2003) and repeated field mapping (Dunne et al. 1975; Moore et al. 1976) can be effectively used for delineating the size, magnitude, location, and variability of runoff generating areas. Accumulated runoff
areas during and after storm events can be easily observed and identified as VSAs, since they are wetter than other areas and need more time to dry after a storm event.

Engman and Arnett (1977) suggested high-altitude photography and Landsat data to map VSAs with the backing of ancillary information when vegetation is present. Ishaq and Huff (1979a,1979b) used infrared images for the identification of VSAs, and found that their locations were in good agreement with soil moisture samples taken from the field.

Verhoest et al. (1998) analysed European Remote Sensing (ERS) Synthetic Aperture Radar images and determined that the observations of soil moisture patterns occurring in the vicinity of the river network were consistent with the rainfall-runoff dynamics of VSAs. Pizurica et al. (2000) applied a Wavelet-based image de-noising technique to Synthetic Aperture Radar images for mapping VSAs in a watershed on the basis of spatial variations of soil moisture.

Application of natural tracers and isotopes is another way of mapping the VSAs. Pearce et al. (1986) successfully quantified saturated areas by using deuterium and oxygen tracers in eight small forested watersheds in New Zealand. Sklash et al. (1986) analyzed isotope data to differentiate old water (stored water) from new water (surface runoff) and their respective contributions to flow at the outlet of a small watershed. Subsequently, Tetzlaff et al. (2005) obtained encouraging results for application of a hydrometric and natural tracer technique to assess the significance of VSAs and their influence to surface and subsurface runoff to stream hydrograph.
2.5.2 Passive methods of monitoring

Passive methods involve in-field sampling using probes, sensors, and shallow wells automated for data collection. Passive methods usually involve minimal soil disturbance. However, high costs associated with the installation of shallow wells and the limited availability of appropriate probes and sensors are the limiting factors in the application of these methods (Srinivasan et al. 2000).

During the last two decades, analog and digital probes have been used for monitoring various climatic and hydrological research studies (Vivoni and Camilli 2003; Hart and Martinez 2006). Recently Wireless Sensor Network (WSN) systems have been used for monitoring soil moisture, runoff and other hydrological parameters (Chapi 2009). Zollweg (1996) developed a non-automated sensor application for VSA research to identify saturated areas. Later on the sensors designed by Zollweg (1996) were automated by Srinivasan et al. (2000, 2002) to detect runoff generating areas from a 26 ha watershed. Chaubey et al. (2006) and Leh et al. (2008) also applied the same sensors for identification of VSAs from a 1250 ha watershed. Sen et al. (2008) also deployed surface and subsurface sensors at 31 locations to investigate VSAs in a small (0.12 ha) pasture watershed.

In recent years, widespread adoption of WSNs, particularly for industrial applications, have made them extremely cost effective (Song et al. 2008) and hence these devices can be deployed in large numbers across a study watershed with less human intervention. Currently WSNs are used extensively in many real world applications due to their deployment flexibility (Phillip et al. 2012; Langendoen et al. 2013). Chapi
(2009) successfully developed a low cost WSN system to measure soil moisture and overland flow from an 8 ha watershed to investigate the runoff generating areas.

### 2.6 Modeling Variable Source Areas

Betson (1964) was the first among many researchers to define a scaling factor for modeling runoff generating areas using a reanalysis of Horton’s infiltration capacity equation. Lane et al. (1978) represented an index similar to Betson’s scaling factor to identify the portion of the watershed contributing runoff to the outlet. Dickinson and Whiteley (1970) evaluated the minimum contributing area in Ontario and found a nonlinear relationship between minimum contributing area and the moisture index.

The Topographic Index (TI), a simple concept requiring minimal computing resources was developed by Kirkby and Weyman (1974) as a means of identifying areas with the greatest propensity to saturate. This concept was later applied to the TOPMODEL (Beven and Kirkby 1979), a conceptual semi distributed watershed model based on the variable source area concept for simulating hydrologic fluxes of water through a watershed. TOPMODEL determines saturated areas by simulating interactions of ground and surface water by estimating the movement of the water table (Lamb et al. 1997 and 1998; Franks et al. 1998; Güntner et al. 1999).

Engman and Rogowski (1974) introduced a storm hydrograph technique for the quantification of partial contributing areas on the basis of infiltration capacity distribution for excess precipitation computation. Lee and Delleur (1976) developed a dynamic runoff contributing area model for a storm based on excess precipitation and
B horizon permeability. Engman (1981) validated the application of Lee and Delleur’s model to large watersheds. Kirkby et al. (1976) developed a fully distributed model (SHAM) to locate saturated areas within small watersheds.

The first generation of the VSA Simulator model VSAS1 was developed by Troendle (1979) for identification of dynamic zones in watersheds. A newer version of the same model, VSAS2, was introduced by Bernier (1982). The second generation VSAS2 is a physical storm flow model based on saturation excess mechanism of runoff generation.

O’Loughlin (1981, 1986) introduced a criterion to locate the surface saturated areas on draining hillslopes in natural watersheds based on soil transmissivity, hillslope gradient and its wetness state characterized by base flow discharge from the watershed. Heerdegen and Beran (1982) introduced a regression technique for identifying VSAs in a watershed using convergent flow paths and retarding overland slope as independent variable and the speed of flood response as dependent variable. Gburek (1983) presented a simple physically-based distributed storm hydrograph generation model. This model is based on the recurrence interval’s relationship to watershed contributing areas in order to simulate VSAs and thereby the potential delivery of NPS pollution to the stream. Boughton (1987) developed a conceptual model named the “elementary bucket model” of watershed behavior representing the surface storage capacity of the watershed to evaluate the partial areas of saturation overland flow.
Steenhuis et al. (1995) developed a simple technique to predict watershed runoff by modifying the SCS Curve Number (SCS-CN) method for variable source areas. Spatially distributed Soil Moisture-based Runoff Model (SMoRMod) was developed by Zollweg et al. (1996) to simulate hydrological processes of VSAs. Abraham and Tiwari (1999) developed a mathematical model to predict the position of the water table and streamflow based on rainfall and spatial variability of topography, soil moisture, and initial water table. Frankenberger et al. (1999) developed a daily water balance model called Soil Moisture Routing (SMR) to simulate the hydrology of shallow sloping watershed by using the Geographic Resources Analysis Support System (GRASS). Walter et al. (2000) developed a simple conceptual model to show the extent of VSAs based on the probability of an area to saturate during a rainfall event. Subsequently, Agnew et al. (2006) used this concept along with topographic index and “distance from a stream” to develop a model to locate the hydrologically sensitive areas in a watershed. Kim and Steenhuis (2001b) developed a grid-based VSA model GRISTORM to simulate event storm runoff.

The distributed CN–VSA approach developed by Lyon et al. (2004) simulates the distribution of saturated areas within the watershed based on VSA hydrology concept. This method uses SCS-CN approach to estimate runoff amount and Topographic Wetness Index (TWI) to spatially distribute runoff generating areas within the watershed. This simple method can be easily integrated with existing hydrological models for predicting the locations of runoff generating areas. Recently, the relative saturation of a watershed has been modeled for humid areas using the concept of water balance dynamics (Manfreda and Fiorentino 2008; Manfreda 2008). This model
is based on a stochastic differential equation that allows climatic and physical characteristics of the watershed to derive a probability density function of surface runoff.

### 2.7 Present status

Over the years, a number of modeling efforts have been made to understand and delineate spatial patterns of VSAs. During the last two decades, increasingly available computational power has made greater advancements in GIS. The widespread availability of digital geographic data has led to the development of complex distributed deterministic models. These models are based on the distributed moisture accounting within parts of the landscape for predicting saturation excess runoff generating areas. However, the data and computing requirements of these models restrict their practical application to research studies. None of these models are validated / supported by rigorous field tests (Chapi 2009; Pradhan et al. 2010).

During the last decade, some encouraging attempts have been made to introduce VSA hydrology into watershed-scale water quality models such as the Soil and Water Assessment Tool (SWAT) (Easton et al. 2008) and Generalized Watershed Loading Function (GWLF) (Schneiderman et al. 2007). However, even these process-based models are too intricate and computationally intensive for field applications (Mills 2008).

In another attempt, a water balance-based modified version of the USDA's Soil & Water Assessment Tool watershed model SWAT-WB has been developed (Eric 2009). Instead of using the traditional Curve Number method to model surface runoff,
SWAT-WB uses a physically-based soil water balance. In this approach, a daily soil water balance was used to determine the saturation deficit of each hydrologic response unit (HRU) in SWAT, which was then used, instead of the CN method, to determine daily runoff volume. SWAT-WB model predicts runoff generated from saturated areas, contrary to the traditional SWAT approach. However, the performance of this approach needs to be evaluated with field data under various types of soils, land use, topography and climatic conditions.

Pradhan et al. (2010) developed a one-parameter model of saturated source area dynamics and the spatial distribution of soil moisture. The single required parameter is the maximum soil moisture deficit within the watershed. The advantage of this model is that the required parameter is independent of topographic index distribution and its associated scaling effects. This parameter can easily be measured manually or by remote sensing. The maximum soil moisture deficit of the watershed is a physical characteristic of the basin and therefore, this parameter avoids regionalization and parameter transferability problems.

The majority of present water quality protection procedures, assessment methods and BMPs are developed using the infiltration excess runoff generating theory (Walter et al. 2000). Water quality managers still rely upon popular water quality models such as the SWAT, AGNPS, HSPF, GWLF etc. since these are well established and user-friendly with their proven nutrient transport and soil erosion transport sub routines. These water quality models are widely used because they are based on the traditionally acceptable engineering rainfall-runoff approaches (i.e., the Rational Method and Curve Number equation) which require little input data. Most of these
models are primarily based on infiltration excess runoff response mechanism where soil type and land use are the controlling factors. Since dominant factors that affect variable source area are different than the factors affecting the infiltration excess runoff generating mechanism, models based on infiltration-excess runoff generating mechanism will show the locations of runoff source areas differently (Schneiderman et al. 2007).

At present, VSA hydrology is not widely recognized in the water quality protection procedures due to the lack of user-friendly water quality models for simulating the VSA hydrological processes. Therefore, there is a need to develop new tools to guide watershed managers in predicting the runoff and correctly locating the critical runoff generating areas within the watershed for application of BMPs to control non-point source pollution.

2.8 Towards future developments

The literature shows that there are currently no clearly defined approaches or specific procedures for monitoring and modeling variable source areas in a watershed. Given that very little data exists on hydrologic processes and their interactions with runoff generating areas, further research is needed to develop a thorough understanding of this area of hydrology. Detailed and extensive fieldwork is required for delineating and identification of VSAs in watersheds with different types of topography, soils, climatic conditions, antecedent moisture conditions and land use characteristics.
Current GIS capabilities can be used at different stages of development of a hydrologic application. Especially important among these is the capability to derive spatial attributes from various sources such as remote sensing, sampling, interpolation, digitizing existing maps, and the capability to store these attributes in a geographic database. GIS simplifies the collection of climatic and hydrologic input for use in a model and is easier to apply to a variety of scales, from a small field to a large watershed (Khatami et al. 2014). GIS greatly simplifies model setup, and that the use of GIS actually improves model performance (Savabi et al. 1995). During the last two decades, the hydrologic community has started moving into a new era of using GIS-based distributed models. Furthermore, the GIS platform can be used for developing models consistent with VSA concept of hydrology for the identification and quantification of runoff generating areas.

Topographic indices derived from Digital Elevation Models are employed to generate spatially continuous soil water information as an alternative to point measurements of soil water content. Due to their simplicity and physically-based nature, these have become an integral part of VSA-based hydrological models to predict saturated areas within a watershed.

Current monitoring methods of VSAs using digital and analog sensors are limited in spatial and temporal resolution partly due to the inability of sensors to measure the temporal variability of surface runoff and partly due to cost and lack of autonomy of the systems. Visits to the field sites are required to collect data and maintain the sensors (Freiberger et al. 2007). Therefore, it is necessary to develop new reliable
and robust systems for monitoring the spatial and temporal variability of hydrological parameters and runoff generating areas in a watershed.

Recent advances in digital and sensing technology, particularly in the area of WSN systems have enabled real time environmental monitoring at unprecedented spatial and temporal scales (Mainwaring et al. 2002; Trubilowicz et al. 2009). These WSNs have great potential for a wide range of applications including climatic and hydrological monitoring. These WSNs present a significant improvement over traditional sensors, and can be a promising new technology for studying hydrological response of watersheds in order to monitor spatial-temporal variability of VSAs (Hughes et al. 2006; Chapi 2009).

Information on spatial and temporal distribution of soil moisture is important to identify VSAs in a watershed. Point measurements of soil moisture by conventional soil sampling and laboratory analysis are slow, laborious, and expensive (Lingli et al. 2009). Furthermore, the point measurements of soil moisture are restricted to describe soil moisture at a small and specific location as spatial distribution of soil moisture is highly variable over time and space (Stefania 2012; Wood et al. 1992).

A non-intrusive geophysical method using Ground Penetrating Radar (GPR) has been used as a potential alternative method to measure the volumetric water content (VWC) of shallow soil (Huisman et al. 2002). The soil moisture under a range of soil saturation conditions is estimated with GPR by measuring the reflection travel time of an electromagnetic wave traveling between a radar transmitter and receiver. Soil
water content measurements taken with surface GPR reflection methods have shown good agreement with soil moisture measurements taken by time domain reflectometry method (Klenk et al. 2014) and soil moisture content measured with capacitance sensors (Van et al. 1997; Bradford et al. 2014).

Recent technological advances in satellite remote sensing have shown that soil moisture can be measured by a variety of remote sensing techniques. Remotely sensed data is an important source of spatial information and could be used for modeling purposes. Recent developments in remote sensing technologies are capable of conducting soil moisture mapping at the regional scale. Improvements in image resolution technology, as well as airborne or satellite borne passive and active radar instruments have potential for monitoring soil water content over large areas. These methods are useful for monitoring soil moisture content for future environmental and hydrological studies (Chen 2014).

Synthetic-aperture radar (SAR) techniques have the ability to monitor soil parameters under various weather conditions. In the case of unembellished agricultural soils, the reflected radar signal depends strongly on the composition, roughness, and moisture content of the soil. Many studies have shown the potential of radar data to retrieve information concerning soil properties using data collected by space and airborne scatterometers and model simulations (Chan et al. 2008; Ouchi 2013). However, water content estimates show limited penetration depth in soils (Lakshmi 2004) and require a minimal vegetation cover to reduce interference of the radar signal (Jackson et al. 1996). Pizurica et al. (2000) observed that temporal radar imagery technique is very effective for the identification of saturated areas in a watershed.
The other promising new method of determining soil moisture level is using the thermal emissions and reflected spectral radiance from soils in the microwave range from remotely sensed information. Thermal emissions from the landscape are sensitive to soil moisture levels in the upper layer of soil. Soil surfaces with higher moisture content emit lower level of microwave radiation than dry soils (De Jeu et al. 2008). Thermal images are generally acquired by aircrafts flying at low altitudes or can be obtained from high resolution satellites. This technique of identifying wet landscape areas is a promising technology for monitoring VSAs.

Another approach to determine soil moisture is to remotely sense the greenness of the vegetation (DeAlwis et al. 2007). Spatial and temporal patterns of vegetation greenness indices can be derived by measurements taken from a space platform. One such index, the Normalized Difference Vegetation Index (NDVI) provides a direct measurement of the density of green vegetation. This index uses strong absorption by plant leaf pigment (chlorophyll) in the red (R) and contrast between the strong reflectance measurements of vegetation in the near infra-red (NIR) spectrum (Petropoulos 2013).

2.9 Concluding Remarks

VSA hydrology has been universally acknowledged as a basic principle in the hydrological sciences since 1970, but quantitative understanding of VSA concept is far from complete and its applications to hydrologic calculations are not fully developed. Very little data exists to physically verify or support different theories/hydrologic processes and their interactions with runoff generating areas.
Modeling spatial and temporal variability of VSAs is challenging due to the involvement of a large number of factors and complex physical processes. In spite of these difficulties and challenges, few encouraging attempts have been made to develop models for quantification and locating runoff generation areas in a watershed. These approaches need to be validated with rigorous field tests to assure their feasibility and accuracy.

At present, VSA hydrology is not popular among water quality managers due to a lack of user-friendly water quality models for simulating VSA hydrologic processes. The majority of current water quality protection practices, assessment procedures and management policies are based on conventional infiltration excess runoff generating theory. Water quality managers still rely on popular water quality models based on infiltration excess runoff generating mechanism, since these are well established and user-friendly with their proven nutrient transport and soil erosion transport subroutines. However, for the areas dominated by saturated excess runoff mechanism, these models may not be able to predict the correct locations of runoff generating areas.

Information concerning saturated areas and spatial soil moisture variations in a watershed are essential to identify VSAs. Advancements in digital WSNs, remote sensing, higher resolution satellites, aerial photography and increased computational power may be promising new technologies to monitor spatial and temporal variability of VSAs. Emerging technologies and improved GIS capabilities can be promising
tools for the development of new hydrologic applications and VSA-based hydrological models.

2.10 References


2.11 Transition to Chapter 3

Watershed monitoring is the most reliable approach for any hydrological or environmental research. Though this approach is time consuming and expensive, it is accurate and trustworthy. During last few decades, analog type sensor networks have been used to monitor watersheds for various hydrological and environmental studies. However, recent developments in digital and micro sensing technologies and improved industrial manufacturing processes have made it possible to build small automatic multi-functional sensors. These sensor devices can be used to collect, store and transmit the observations.

At present, no simple or low cost off-the-shelf solution exists for hydrological monitoring applications. Therefore, there is a need for adopting modern technologies in order to develop an efficient and reliable wireless sensor network system to gather real-time climatic and hydrological information from remotely located watersheds.

Chapter 3 describes the development of a remotely controlled digital wireless sensor network system for the monitoring and acquisition of climatic and hydrological data from a distantly located watershed. This is the first objective of this research thesis.
CHAPTER 3

Development and field evaluation of a low cost wireless sensor network system for hydrological monitoring of a small agricultural watershed

Abstract

Hydrological monitoring and real time access to data are valuable for hydrological research and water resources management. Traditional hydrological monitoring systems based on analog measurements are prone to noise and cabling requirements in the field restricts the size of the monitoring area. Rapid developments in digital technology, micro-electro-mechanical systems, low power micro sensing technologies and improved industrial manufacturing processes have made Wireless Sensor Network (WSNs) systems more economical to use. This study developed a remotely operated, low cost and robust wireless sensor network system to monitor and collect climatic and hydrologic data from a small agricultural watershed in harsh weather conditions near Elora, southern Ontario. The developed system was rigorously tested in the laboratory and field and was proven to be accurate and reliable for monitoring climatic and hydrologic parameters of the watershed.

Keywords: Hydrological monitoring, Wireless Sensor Network, Field data collection, Watershed, Real-time

3.1 Introduction

Long-term, high quality climatic and hydrological data is essential for hydrological research and for the implementation of effective water management strategies from
field to basin scale. Field monitoring and repeated field mapping can be used effectively for understanding the relationships and interactions between various soil and environmental parameters of the complex hydrological process (Anderson and Burt 1978). Monitoring and collection of long-term data from remotely located sites is time consuming and expensive due to the need for frequent visits to the sites for maintaining and monitoring the instruments and for downloading data (Freiberger et al. 2007). Although this approach is time consuming and expensive; it is accurate and trustworthy (Chapi 2009). Currently a number of technologies are being used to acquire hydrological data. Accuracy, resolution and scalability are some of the major problems confronting current hydrological monitoring systems. These issues need to be examined and addressed in order to develop an efficient and accurate hydrological monitoring system.

In earlier methods, analog type network nodes connected to each other by cables and number of sensors wired to data loggers were used for hydrological monitoring. The need for this cabling in the field increases cost and restricts the spatial size of the monitoring area (Oliveira et al. 2011). In analog systems, converting signals from one form to another always incurs signal losses. Another great disadvantage is that even with the most careful manufacturing process is that no two analog devices are exactly the same, making the exact duplication of the signal impossible. In digital systems, data is converted into binary code and then reassembled back to its original form at the reception point. Since these binary codes can be easily manipulated, this method offers a wider range of options. Compared to analog systems, digital networks can collect long-term data at larger scales (Mainwaring et al. 2002; Trubilowicz et al. 2009).
A digital WSN system comprised of spatially distributed nodes connected to sensors communicates bi-directionally to a main location (Jue 2010). As the WSNs do not require cabling, these are cheaper and easier to install in addition to requiring low maintenance. The WSN is built of few to several "nodes" (known as mote in North America) where each node is connected to one or more sensors (Sarade et al. 2012). Each sensor network node has four key components: (1) The microprocessor & ADC (analog to digital converter), (2) Transceiver & Antenna, (3) Memory Unit, and (4) External sensors (Karl and Willig 2005). The individual sensor node consists of a number of hard wired sensors. Each node is wirelessly connected to other nodes, and finally to a central base station (Fig. 3.1).

The WSN possesses great potential for a broad range of applications including hydrological and environmental monitoring (Cardell et al. 2005; Hart et al. 2006; Bogena et al. 2007; Poret 2009). Recent developments in the field of automatic sensors and communication systems have further revolutionized the field of hydrological monitoring. The widespread adoption of these devices, particularly for industrial applications, has made them extremely cost effective (Song et al. 2008). Because of this, these devices can be deployed in large numbers across a watershed with less human intervention. The WSNs are extensively used in many real-world applications due to their cost effectiveness and deployment flexibility (Philipp et al. 2012; Langendoen et al. 2013)
Sensors used in WSN systems convert physical parameters to electrical signals. WSNs can be used with many diverse types of sensors such as thermal, optical, acoustic, seismic, magnetic, infrared and radar. These sensors are able to monitor a wide variety of conditions such as temperature, pressure, humidity, light, noise level, movement, speed direction and size of an object (Jennifer et al. 2008). Sensor nodes can be used for different purposes including event detection, continuous tracking, location sensing etc. (Lewis et al. 2004; Akyildiz et al. 2002).

Unlike other systems, WSNs are designed for specific requirements and applications (Verma 2013). The WSN systems for environmental monitoring are specially designed to acquire the necessary data at specific time intervals. Details of importance, the accuracy of the data and the physical environment of deployment should be considered while designing the WSN system. The WSN system must be
designed to withstand weather conditions, such as temperature, winds, rain, snow, and pressure or vibration (Hart et al. 2006).

During the last decade, a number of studies have focused on the field of WSN technology for environmental monitoring but very few of them are validated by field tests beyond a few sensor nodes (Szewczyk et al. 2004). At present, no simple or low cost off-the-shelf solution exists for hydrological monitoring applications. Hence, there is a need for adopting modern technologies to develop efficient and reliable wireless network systems to gather real-time hydrological information in the present complex environment.

The specific objective of this research is to develop a low cost, efficient, and remotely operated WSN system to monitor and collect hydrologic and climatic data from a watershed. The main goal of this study is to acquire real-time hydrologic and climatic data from a small rural agricultural watershed situated near Elora (Ontario).

3.2 Design and development of WSN

The design and development of the WSN took place over a four year period from 2007 to 2011. During this period, a number of designs with different types of components were developed and tested. Various designs and deployment issues were identified and resolved during the development process of the WSN.

The WSN development took place in three phases. In the first phase, a WSN system was designed using hardware from Texas Instruments (TI). The nodes were based on TI-MSP-TRF6903 boards with a TRF6903 RF transceiver and a MSP430
microcontroller. The transceiver operates in the 902-MHz to 928-MHz ISM frequency band and the microcontroller was a 16-Bit ultra-low-power MCU with 60 kB of Flash memory for data storage.

The MPXV70002 vacuum pressure sensor from Freescale was used to capture the water height and was connected to the ADC port of the TI board. The board was programmed via the MSP430 JTAG connector. The MCU Flash memory was erased and reprogrammed. The IAR System’s Workbench EW430 software package in combination with the MSP430 JTAG allowed real-time debugging of the code (Poret 2009). The developed WSN with three nodes was tested and evaluated in the laboratory and the field but it was observed that the communication range of the nodes was limited and the wireless communication was sensitive to metal fences and electrical power lines. These problems caused noise in pressure readings. The large size of the node boards needed a large waterproof housing unit and antenna which were difficult to maintain in the field.

The WSN system was modified in phase 2 to overcome these problems (Chapi 2009). The hardware components from Crossbow (Xbow) were used to build a new WSN. This system was based on XM2110 motes with built in control and communication functions. Each platform includes an ATmega1281 low-power microcontroller with a 10-bit ADC and 512 kB of memory and an AT86RF230 RF front end IEEE 802.15.4 compliant, and a ZigBee transceiver with 300 m line-of-sight transmission range.
The network gateway consisted of an IRIS mote connected to a USB MIB520CA interface. The Freescale MPXV7002 pressure sensor and the ICT ECH₂O soil moisture sensor were connected to the 51-pin expansion slot through a printed circuit board (PCB). The interface board passed the sensor data onto a PC. The software tool Mote-View, which was designed specifically for the WSN, uses XML files to convert the data from its simple binary input form from the gateway into decimal values and so these values could be displayed in real-time and saved in a database. The program allowed database dumping, whereby collected sensor data is exported into a text file. The text file can be read in Excel and modified with custom calibration equations.

This modified WSN system was tested in the field for communication between nodes and between nodes and gateway. The range of the WSN node as per the Crossbow IRIS reference manual was greater than 300 m for outdoor conditions and greater than 50 m for indoor conditions. The transmission range of the nodes in the field was found to be about 250 m at the optimal battery voltage, with the range decreasing in accordance with drops in the battery voltage. This system was installed in the study watershed at the Guelph Turfgrass Institute on the University of Guelph campus, where it performed satisfactorily under a small height of vegetation and level ground surface conditions. The study watershed was monitored and necessary data was collected from July 2008 to April 2009 for modeling the spatial variability of runoff generating areas.

Despite successful application of this WSN system, it still required further improvements due to its short battery life and interruption of the signal from
depressions and tall vegetation. Considering this, the WSN system was further modified in phase 3 based on these issues, with the objective of improving the efficiency of WSN system.

3.2.1 Modification of WSN system (Phase 3)

For further modification of the WSN system in phase 3, updated third generation MICA2 IRIS 2.4 GHz nodes XM2110CA were used (Fig. 3.2(1)). This node featured several new capabilities that enhanced the overall functionality of the WSN system. The communication range of this node was three times better than the previous node, and it has twice as much program memory than previous MICA nodes. A Printed Circuit Board (PCB) was designed and fabricated in order to connect a maximum of six different kinds of sensors to the 51-pin expansion slot on the node. The interface unit MIB510CA, shown in Fig. 3.2 (2), allowed the user to reprogram any node by plugging the node directly into the base and operating it as part of the root node interface, giving the PC a data conduit of the radio-based sensor network.

3.2.1.1 Sensors

The pressure sensor used for the phase 3 WSN system shown in Fig. 3.2(3) is a new series of the sensor called the Freescale MPXV7007DP. The MPXV7007DP is a piezo-resistive monolithic silicon dual port pressure sensor. It has an output range of (-2) to 2 kPa with an accuracy of ± 2.5 %, with 0.5 to 4.5 V proportional output voltage.
The (E240-40761) 10 cm long (Decagon Devices, Inc.), 10HS high-frequency soil moisture sensor (Fig. 3.2(4)) was selected for monitoring soil moisture. This capacitance type sensor has a large sphere of influence to accurately measure the dielectric permittivity of the soil. The electric circuit inside 10HS changes the capacitance measurement into a proportional millivolt output. The high frequency oscillator removes the soil type sensitivity of the sensor and thus improves its ability to measure soil moisture in any type of soil.

3.2.1.2 Power supply

The third generation MICA2 nodes require a power range of 1.7 to 4.3 V DC supply for communication within its wireless network. After rigorous testing of various conventional and rechargeable batteries, 4.0 V (4.5 Ah) lead-acid batteries were found to be the most reliable for this application. This battery lasted for about 30 days in the field under normal climatic conditions (Fig. 3.2(6)). Solar panels of 14 × 4 × 0.5 cm with 6 V DC open circuit voltage and a short circuit current output of 100 mA were used to recharge the battery. These panels have 2 solder tabs with 7.5 cm long insulated leads to be connected to the batteries and weighs only 27 g. Each WSN node was connected to two solar panels to charge the batteries and maintain the supply voltage within a specified range to extend the battery life and the WSN operation as shown in Fig. 3.2(5).

3.2.1.3 Sturdiness of node assembly

The nodes were made watertight and sturdy to withstand the harsh temperatures, winds and rain for an extended period of time in the field. Each wireless node was
housed in water tight PVC housing and was attached onto a 3.0 m. long and 25 mm dia. PVC pipe. This pipe was attached to a $45 \times 45 \times 10$ cm wooden pedestal. The wooden pedestal was secured in the field by four 29 cm long PVC plugs. A glow sign cone was attached on top of the node for prominent visibility and to protect the PVC housing from rain and snow. A pair of solar panel was attached to this cone. This modified node setup was found to be very sturdy and resistant to harsh climatic conditions in the field. The overall assembly of components of the node in the field is shown in Fig. 3.2(7).

![Components of the developed WSN system.](image)

**Figure 3.2:** Components of the developed WSN system. (1) IRIS Mote XM2110CA (2) gateway unit MIB510CA (3) pressure sensor “Freescale” MPXV7007DP (4) soil moisture sensor (E240-40761) 10HS (5) 6V DC 100 mA solar panel (6) 4.0 V (4.5 Ah) lead acid battery (7) assembly of node in field

### 3.2.1.4 Communication connectivity

The nodes were elevated 3.0 m above ground level to increase communication connectivity so that the crop height and the depressed areas did not interfere with the line of sight connectivity between the nodes. This increase in the height of the nodes
and improved connectivity between them resulted in a decreased number of required nodes and of the overall cost of the WSN system.

Commercial out-of-the-box kits for WSNs were commercially available; however, the requirements of reliability and cost-effectiveness for this application led to using specific hardware and available off the shelf components. The hardware components were purchased directly from the distributors, and data acquisition boards for the IRIS Mote were designed and fabricated in the laboratory in order to increase cost effectiveness. The assembling of WSN components was carried out in the university workshop to minimize the overall cost of the network.

3.2.1.5 Data visualization tool for WSN

The Mote-View Monitoring Software is developed by Crossbow as a visualization tool for WSN. It allows the users to visualize the data and monitor the status of the wireless sensor network. Each individual node collects data through its sensors and transmits this data to the base station. The data packets received by the base station are stored in the connected computer in which Mote-View is running. Mote-View uses XML files to convert the data from its simple byte input form from the base station into decimal values. These values are displayed real-time in a window and saved in a database. The program allows for database dumping which exports the collected sensor data into a text file. The text file can be read into Excel and modified with custom calibration equations.

The Mote-View interface has four main tab sections. The toolbar tab allows the user to specify activities and initiate various commands. The second tab displays a list of
the nodes, their health and their deployment status. The third visualization tab has four sub tabs and shows the sensor data as data view, command view, chart view and topology view. The forth server tab shows incoming messages and a log of the events.

3.3 Laboratory calibration of nodes

The calibration of soil moisture and pressure sensors was performed in the laboratory. The soil from the experiment field was used to calibrate the soil moisture sensors. Three sensors from a group of sensors were randomly selected for calibration. An oven dry soil with bulk density similar to field conditions was packed into multiple containers. The soil was evenly packed in the containers and the sensor was inserted in the container during the packing of soil. The sensor reading was noted and the gravimetric method was used to determine the volumetric water content ($\theta_v$ % by volume) of the soil sample. Water was added to the container to raise its water content, the sensor reading was recorded and again the water content was measured by the gravimetric method. This procedure was repeated until soil saturation was achieved. The data obtained from the sensor reading and soil water content was plotted as shown in Fig. 3.3. The following equation fitted to the data with a determination coefficient ($R^2$) of 0.9299.

$$\theta_y = 0.001x^2 - 0.2063x + 12.226$$

(3.1)

Where, $\theta_y$= soil moisture content in % by volume and $x$ = sensor reading in mV.

Similarly, three pressure sensors were randomly selected for calibration to determine the depth of the water. A plastic tube was attached to the pressure sensor and placed
in a graduated glass cylinder. Water was gradually added to this graduated cylinder to increase the water level from 0.0 to 20 cm, and corresponding sensor readings were recorded. The data collected from this calibration is shown in Fig. 3.4. The linear equation fitted to this data is presented below, and it has a determination coefficient ($R^2$) of 0.9891

$$H = 0.6072x - 292.48$$

(3.2)

Where, $H$= depth of water and $x$ stands for sensor reading in mV.

![Figure 3.3: Calibration diagram of soil moisture sensor](image-url)
Figure 3.4: Calibration diagram of pressure sensor

3.4 Field testing of WSN

The field testing of the WSN's performance was carried out at three different locations: (1) Turf-grass Institute Guelph (ON), (2) Elora Research Station (ERS) located south of Elora (ON), and (3) Kettle-Creek paired watersheds located within the southern boundary of the city of London (ON).

The soil moisture and pressure sensor readings obtained by the WSN were verified by taking manual measurements in the field. The height of water above V-notch was measured manually and soil moisture level of top layer of soil (20 cm) was measured using digital VG-200 soil moisture meter. Fig. 3.5 and Fig. 3.6 show surface runoff depth and soil moisture readings of node # 5 recorded by the WSN and manually for the storm occurred on 12 September 2011. Similarly, WSN readings of node # 4
were verified manually on 27 December 2011 (Fig. 3.7 and 3.8). The comparison confirmed the proper functioning of the WSN system during field deployment.

Figure 3.5: WSN and manual readings of soil sensor on September 12, 2011

Figure 3.6: WSN and manual readings of pressure sensor on September 12, 2011
Figure 3.7: WSN and manual readings of soil sensor on December 27, 2011

Figure 3.8: WSN and manual readings of pressure sensor on December 27, 2011
3.5 Field data collection

After successfully testing the WSN system at three different locations (Guelph University campus, Turf Grass Institute, Guelph and Kettle Creek paired watershed near London (ON)) the data collection from a small study watershed of 21.62 ha situated in Elora Research Station (ERS) was carried out from September 2011 to July 2013. The ERS is located at 43° 39’ N and 80° 25’ W and is about 20 km from Guelph (ON). The climate in Elora is temperate humid with average annual precipitation of 875 mm of which about 150 mm falls as snow. The elevation of this agricultural watershed ranges from RL 357 to 378 m with gentle slopes to slopes as steep as 22 %. The soil of the study watershed is sandy loam belonging to hydrological soil group B with soil depth ranging from 0.60 to 0.90 m underlain by a restrictive layer. The entire watershed was under the cultivation of hay crop during the process of data collection.

Figure 3.9: Layout of the study watershed at Elora (Ontario)
The study watershed at ERS was divided into 8 sub-watersheds with the help of the watershed delineating tool of ArcGIS. At the outlet of each sub-watershed, a V-notch weir with pressure sensor was installed to measure overland runoff. Soil moisture sensors were installed at the centroids of the sub-watersheds and near all 8 outlet points. A total of 16 soil moisture sensors, 8 V-notch weirs with pressure sensors, and 6 hopper nodes were installed in this study watershed. The watershed at ERS and the locations of soil moisture sensors and V-notch weirs are shown in Fig. 3.9. A base station node was attached to a laptop with internet connection and stationed in a nearby private property in order to power the laptop. During spring and fall, batteries lasted for 40 to 45 days, depending on weather conditions. In the summer, batteries lasted for more than 60 days.

Real time access to the field laptop offered the advantage of remotely monitoring the health and battery level of each node in the field. This helped to reduce the number of site visits, as they were only made when the nodes needed to be replaced or repaired. These visits ensured that the WSN was continuously working, and that no data was lost due the repairs/replacement of non-functional nodes. Furthermore, this system enabled the user to remotely put the WSN on sleep mode to conserve the battery power. Real time access also enabled the user to adjust the data sampling interval accordingly to rainy or dry periods. Since relevant data was to be collected during rainy periods, the sampling interval was shortened remotely compared to the sampling interval during dry weather. This not only helped to conserve the battery life, but also helped to avoid the collection of unnecessary data.
The soil moisture sensor’s readings were converted from mV to soil moisture percentage by using the calibration equation 3.1. Similarly, the pressure sensor’s readings collected by the WSN system were converted to water depth by using calibration equation 3.2. A flow hydrograph of each field segment was developed to compute the total flow generated by the field. Rainfall and temperature data were collected from ERS weather station located about 500 m from the study watershed. Surface runoff and soil moisture monitoring started in September 2011 and continued until July 2013. Soil moisture levels and runoff generated from eight sub-watersheds was monitored for 45 rainfall events for simulation and mapping of runoff generating areas in the study watershed.

The field measurements of a rainfall event dated 01 June 2012 are plotted in Fig. 3.10. Rainfall started at 5.00 a.m. and total rainfall for the event was 46.03 mm. The maximum daytime temperature was 13.7 °C. The average soil moisture of the watershed at the beginning of the rainfall (θ) was 0.14 (by volume) and runoff initiated after 43 minutes when soil moisture (θ) reached 0.43 (saturation). This indicated that the initial abstraction (Ia) of this rainfall event was 6.1 mm. The peak discharges of 0.041 m³/s, 0.013 m³/s and 0.161 m³/s were recorded at 7.00 p.m. at the outlets of sub-watershed 4 and 6 as well as at the end of the watershed. By analysing the runoff hydrograph data, it was calculated that this rainfall event generated 2456 m³ of overland flow and the coefficient of runoff was 29.28 %.
Figure 3.10: Field observations of rainfall and runoff event dated June 01, 2012

The continuously recorded field data of soil moisture, rainfall, and temperature during the month September 2012, is shown in Fig. 3.11. There were 6 major rainfall events and a maximum of 25.76 mm of rain recorded on 08 September 2012. The average soil moisture of the study watershed was about 14 % (by volume) at the beginning of the month and increased to 42-45 % during rainfall events. The graph also shows daily maximum and minimum temperatures during the month. The maximum temperature of 28.8 °C was recorded on 03 September and the minimum of 0.6 °C on 24 September 2012. Field observations of precipitation, soil moisture and temperature during the year 2012 are shown in Fig. 3.12.
**Figure 3.11:** Field observations of precipitation, soil moisture and temperature during September 2012

**Figure 3.12:** Field observations of precipitation, soil moisture and temperature during year 2012
The field data of soil moisture and discharge for 10 rainfall events in the fall of 2011 were successfully recorded. During the year 2012, data for 4 spring events, 10 summer events, and 10 fall events were collected. During the year of 2013, field data for 3 spring and 8 summer rainfall events were recorded for simulating and mapping of runoff generating areas in the study watershed. It was observed that the installed WSN system worked accurately with minimum maintenance for extended periods of time.

### 3.6 Summary and Conclusions

This research has provided an overview of the development of an integrated WSN system for monitoring climatic and hydrologic parameters of a remotely located agricultural watershed. This system was designed to acquire, store and transmit climatic and hydrological data from a remotely situated agricultural watershed. The designed WSN system was comprised of an advanced wireless network technology which together with the internet facilitates the communication of field data between the study site and client in real time. This WSN system was calibrated in the laboratory and tested at three locations in southwestern Ontario, Canada. Field scale testing demonstrated that the system was robust enough to work under adverse weather conditions such as high winds, rain and snow. The developed WSN system was reliable and accurate in monitoring the climatic and hydrologic data of the watershed. This system was installed in a remote agricultural field near Elora (ON), where it worked satisfactorily with minimum maintenance and enabled continuous data collection for two years.
The advantage of this system is that it can be accessed from anywhere by any computer connected to the internet. Remote data collection and maintenance considerably reduced the need for site visits, which significantly reduced the monitoring cost. Although this WSN system was specifically tailored for a project focused on mapping the VSAs in a small rural agricultural watershed, it is still flexible to use in a variety of contexts. Thus, this WSN system will prove to be a useful and flexible tool for future hydrological research.

3.7 References


Dropbox

https://www.dropbox.com/business?home=true&tk=sem_goog_b&kw=dropbox|xje&net=g&ad=39420846102|1t1&camp=sem_goog_b_ca_eng_top_exact&mwid=s4ZfKezUs|pcrid|39420846102|pmt|e|pkw|dropbox|pdv|c&kw=dropbox|e&muid


LogMeIn

https://secure.logmein.com/welcome/freeremotecontrola/?destination=/welcome/freeremotecontrola/\&wt.srch=1\&utpk=logmein\&originid=345693\&mcomb


3.8 Transition to Chapter 4

In the preceding chapter, an innovative remotely operated, low cost and robust WSN system was developed to monitor and collect the climatic and hydrologic parameters from an agricultural watershed. Chapter 4 describes the second objective of this research, to conduct an experimental field study to investigate the significance of the climatic and hydrological factors affecting the spatiotemporal variability of runoff generating areas. For this analysis the climatic and hydrological data was collected using the WSN system developed in the previous chapter.
CHAPTER 4

Field investigation of the runoff generating areas in a small agricultural watershed in southern Ontario

Abstract

Prediction and identification of runoff generating areas is important for developing watershed management strategies to mitigate non-point source pollution. Spatial and temporal variability of runoff generating areas are very complex and depend on multiple climatic and hydrological factors. The majority of the previous research studies describe great variability in the dominant factors responsible for runoff generation. Furthermore, very limited field data is available to physically verify the dominance of various controlling factors.

In this study a small watershed, divided into eight sub-watersheds, was monitored for two years by using a remotely operated Wireless Sensor Network (WSN) system. Soil moisture and runoff data for 7 spring, 18 summer and 20 fall season rainfall events were collected to identify the significance of factors affecting the spatial and temporal variability of runoff generating areas. The results showed strong seasonal influence on runoff generating areas. Rainfall amount, initial soil moisture conditions and rainfall intensity were found to be the most significant factors affecting the runoff generating areas.

Keywords: Runoff coefficient, Runoff generating areas, Spatial and temporal variability, Saturation excess runoff, Nonpoint source pollution.
4.1 Introduction

Management of Non-point Source Pollution (NPS) necessitates accurate modeling of the rainfall-runoff process in the humid and well-vegetated rural watersheds. The rainfall–runoff transformation is a nonlinear and very complex process as it depends on a number of climatic and hydrologic parameters. Even though a wide variety of different approaches and a large number of models have been developed to understand the spatial and temporal dynamics of rainfall-runoff relationships, a unified approach is still missing (Ponce 2014).

Rainfall properties, soil characteristics, land use, climatic conditions, topography, surface/subsurface/groundwater hydrology and geology are the main factors involved in controlling the spatial-temporal variability of runoff generation (Das 2009). Moreover, the factors that influence the spatial and temporal variability of runoff also depend on the dominant runoff generating mechanism as the main factors that control infiltration excess runoff generation are different than the factors that affect saturated excess runoff process (Vertessy et al. 2000; Schneiderman et al. 2007).

In case of infiltration excess mechanism, runoff depends mainly on rainfall intensity and total rainfall amount is not an important parameter. Further, when rainfall intensities are much larger or smaller than the infiltration capacity of soils, the initial soil moisture conditions are also not critical. Contrary to this, for regions where saturation excess runoff generation is the dominant process, total rainfall amount is a controlling factor and rainfall intensity does not play major role (Kostka et al. 2003; Castillo et al. 2003).
Runoff coefficient is one of the most widely used key concepts in engineering hydrology to describe rainfall-runoff relationships. Analysis of runoff coefficients is useful in understanding the transformation of rainfall into event-based runoff. The concept of event runoff coefficient dates back to the beginning of the 20th century (Sherman, 1932) but it is still an existing research issue in hydrology (Ralf et al. 2009). The majority of previous research studies indicate great variability in the dominant factors responsible for runoff generation process (Weiler et al. 2003). The main limitation on the analysis of runoff generation research has been the lack of field data on rainfall-runoff events to evaluate the impact of various factors affecting runoff generating areas (Kuang et al. 2012).

During the last decade, researchers have investigated the significance of the soil moisture dynamic on runoff generation by monitoring small experimental watersheds and have observed that the wetness condition of the landscape before the rainfall event is an important factor in the runoff generation (Longobardia et al. 2003; Zehe and Bloschl 2004; Aronica and Candela 2004). A study by Brocca et al. (2009) suggests that the rainfall amount, rainfall intensity, and the antecedent wetness condition (AWC) are the most significant factors affecting the runoff generation and out of these three factors, AWC is the most important one.

In this study, a remotely operated Wireless Sensor Network (WSN) system was used in a small rural agricultural watershed to continuously monitor soil moisture conditions and runoff generated by different parts of the watershed. Climatic and hydrologic data for 7 spring, 18 summer and 20 fall events from September 2011 to July 2013 were collected. The main objective of the study was to investigate the significance level of
the correlation of runoff coefficient with rainfall amount, initial soil moisture content, rainfall intensity, five day antecedent rainfall and rainfall duration to describe the annual and seasonal variability of runoff generating areas.

4.2 Materials and Methods

4.2.1 Study area

The experimental field study was conducted in a 21.62 ha agricultural watershed in the Elora Research Station (ERS) of University of Guelph, located at 43° 39' N and 80° 25' W in Ontario Canada (Fig. 4.1). Elora has a humid continental climate with warm summers and no dry season. The temperature typically varies between -13.9 °C to 21.4 °C and is rarely below -18 °C or above 28 °C. The average annual precipitation in the study region is about 875 mm of which about 150 mm falls as snow. The elevation of the watershed ranged from RL 357 to 378 m with gentle to slopes as steep as 22 %. The general slope of the watershed is towards northwest side, where it outlets in to a small creek.

Figure 4.1: Layout of study watershed and sub-watersheds in Elora Research Centre
Soil samples collected from fifteen locations in the study watershed were used to determine the physical properties as given in Table 4.1. The surface soil (0 to 20 cm) was classified as sandy loam texture (Hydrologic Soil Group B) based on the particle size distribution. The procedure outlined by Black et al. (1965) was used for the mechanical analysis of the soil. Bulk density was determined using undisturbed core samples. A Guelph Permeameter (GP) was used to obtain in-situ measurements of field saturated hydraulic conductivity (Ks). The depth of the restrictive layer was determined by using an auger and ranged from 60 to 90 cm. During the study period the experimental watershed was under the cultivation of hay crop.

Table 4.1: Characteristics of field soil

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Bulk density (kg/m³)</th>
<th>Ks (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy loam</td>
<td>61</td>
<td>29</td>
<td>10</td>
<td>1190</td>
<td>318 x 10⁻⁸</td>
</tr>
</tbody>
</table>

4.2.2 Monitoring the climatic and hydrologic variables

The Digital Elevation Model (DEM) of the study watershed was developed by the Lidar (Light Detection and Ranging) survey. This DEM was used to obtain principal geomorphic features, such as hill slope and drainage channels in the study watershed. The watershed was divided into 8 sub-watersheds using the flow path pattern. A remotely operated Wireless Sensor Network (WSN) system was installed in the watershed to continuously monitor soil moisture and runoff sensors. Soil moisture sensors were installed at two locations in each sub-watershed and runoff
was monitored at the outlet of each sub-watershed. A base station node was attached to a laptop with internet connection and stationed in a nearby shelter to store and communicate the collected data. At the outlet of each sub-watershed, a V-notch weir with pressure sensor was installed to measure overland runoff. A total of 16 soil moisture sensors, 8 V-notch weirs with pressure sensors, and 6 hopper nodes were installed in this study watershed. The detailed layout of the monitoring locations of soil moisture sensors and V-notch weirs are shown in Fig. 4.2

Figure 4.2: Monitoring locations of soil moisture sensors and V-notch weirs

The (E240-40761) 10HS high-frequency 10 cm long soil moisture sensor was selected and used for monitoring the soil moisture. This capacitance type sensor has a large sphere of influence to accurately measure the dielectric permittivity of the soil.
The electric circuit inside 10HS changes the capacitance measurement into a proportional millivolt output. The high frequency oscillator of this sensor removes the soil type sensitivity of the sensor and thus improves its ability to measure soil moisture in any type of soil. V-notch weirs were used to measure flow at the outlet of each sub-watersheds. The head of water over the V-notch crest was measured with piezo-resistive monolithic silicon dual port Freescale MPXV7007DP pressure sensors.

Rainfall and temperature data were collected from the ERS weather station located 500 m from the experimental watershed. Rainfall data collected using tipping bucket rain gauge permitted the characterization of each event in terms of rainfall intensity, duration and rainfall amount. Storms were defined as events with more than 5 mm of precipitation. Events were considered distinct if they were separated by at least 12 hours. The rainfall events were generally characterized by relatively short and intense convective storms, although few long duration rainfall events were also recorded.

Surface runoff and soil moisture monitoring started in September 2011 and continued until July 2013. Soil moisture levels and runoff generated from eight sub-watersheds was monitored for 45 rainfall events. This includes 7 events during spring, 18 during summer and 20 during the fall season. Observed runoff was considered as saturated excess surface runoff when the rainfall intensity was less than the saturated hydraulic conductivity of soil (Ks) and infiltration excess type when the rainfall intensity exceeded the Ks.
4.2.3 Analysis procedure

The data collected during the field observation were used to determine the dominant factors affecting the runoff generating areas. The runoff coefficient was used as an index of runoff generating areas and the time of ponding was used as an index to identify the time when the sub-watershed started runoff contributing runoff to the outlet of the watershed. The factors evaluated include rainfall amount, initial soil moisture, rainfall intensity, 5-day antecedent rainfall and rainfall duration. The factors affecting seasonal variability in runoff coefficient due to seasonal variations were also investigated. Spring season covered the period from February 1 to May 31, summer season from June 1 to September 31 and fall from October 1 to January 31 (Dickinson et al. 2007).

The influence of the factors affecting runoff generating area was evaluated by using various statistical tests. Statistical Analysis System (SAS) software (SAS Institute, 2004) was used to perform correlation and multi-variable regression analysis. The appropriateness of the multiple regression model as a whole was tested by the F-test. The statistical tools used include linear regression coefficient of determination ($R^2$), root mean square error (RMSE), Pearson product-moment correlation coefficient ($r$) test and p-test. Coefficient of determination is a statistical measure of how close the data are to the fitted regression line. The root mean square error (RMSE) was used as an indicator of the differences between the values predicted by a model or an estimator and the actual observed values. Pearson product-moment correlation coefficient ($r$) is an indication of strength and direction of the linear relationship between two sets of data. It is defined as the sample covariance of the variables
divided by the product of their (sample) standard deviations. A correlation greater than ± 0.8 is generally described as strong, whereas, a correlation less than ± 0.5 is generally described as weak (Masaaki 2013). The p-test is a statistical method used for testing a hypothesis within a population or a proportion within a large population.

4.3 Results and Discussion

Ontario hydrology exhibits seasonal patterns that strongly influence the rainfall-runoff process. The physical condition of a watershed varies spatially and temporally due to number of climatic and hydrologic factors. Therefore, the rainfall, soil moisture at the beginning of runoff event, rainfall intensity, rainfall during the last five-day, rainfall duration and runoff generated at the watershed outlet for 45 rainfall events are presented in Table 4.2. Runoff co-efficient is considered as minimum runoff generating area (MRGA) for this analysis and the probability of exceedance of the storms (return period) is calculated by using equation (4.1) suggested by Weibull (1951):

\[ P = \frac{m}{(n+1)} \]  

(4.1)

Where:

\( P \) = probability of exceedance in years, \( m \) = rank of position and \( n \) = number of samples.
Table 4.2: Main characteristics of 45 observed rainfall-runoff events

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Initial soil moisture (m³/m³)</th>
<th>Rainfall during last 5-day (mm)</th>
<th>Rainfall (mm)</th>
<th>Max. rainfall intensity (mm/h)</th>
<th>Time of ponding (min)</th>
<th>Rainfall duration (min)</th>
<th>Runoff (mm)</th>
<th>Minimum runoff generating area (MRGA) (%)</th>
<th>Return period (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
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<td>12.7</td>
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<td>3</td>
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<td>0.331</td>
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<td>16</td>
<td>240</td>
<td>14.86</td>
<td>50.0</td>
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<td>27.7</td>
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<td>33</td>
<td>120</td>
<td>2.44</td>
<td>8.8</td>
<td>3.5</td>
</tr>
<tr>
<td>26</td>
<td>31-Jul-13</td>
<td>0.246</td>
<td>27.7</td>
<td>35.7</td>
<td>10.6</td>
<td>151</td>
<td>720</td>
<td>4.88</td>
<td>13.7</td>
<td>6.6</td>
</tr>
<tr>
<td>27</td>
<td>12-Sep-11</td>
<td>0.104</td>
<td>0.0</td>
<td>12.0</td>
<td>6.7</td>
<td>28</td>
<td>120</td>
<td>0.26</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>13-Oct-11</td>
<td>0.339</td>
<td>22.2</td>
<td>28.3</td>
<td>8.7</td>
<td>69</td>
<td>480</td>
<td>5.41</td>
<td>19.2</td>
<td>4.2</td>
</tr>
<tr>
<td>29</td>
<td>14-Oct-11</td>
<td>0.295</td>
<td>28.3</td>
<td>47.2</td>
<td>8.7</td>
<td>31</td>
<td>600</td>
<td>16.63</td>
<td>35.3</td>
<td>23.0</td>
</tr>
<tr>
<td>30</td>
<td>19-Oct-11</td>
<td>0.212</td>
<td>47.2</td>
<td>17.9</td>
<td>4.5</td>
<td>72</td>
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<td>1.57</td>
<td>8.8</td>
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<td>22-Nov-11</td>
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<td>0.6</td>
<td>9.5</td>
<td>2.1</td>
<td>192</td>
<td>480</td>
<td>0.26</td>
<td>2.7</td>
<td>1.2</td>
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<td>32</td>
<td>27-Nov-11</td>
<td>0.254</td>
<td>9.5</td>
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<td>3.0</td>
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<td>17.6</td>
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<tr>
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<td>0.325</td>
<td>15.4</td>
<td>48.4</td>
<td>6.3</td>
<td>85</td>
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<td>13.48</td>
<td>27.9</td>
<td>46.0</td>
</tr>
<tr>
<td>Event</td>
<td>Date</td>
<td>Initial soil moisture</td>
<td>Rainfall during last 5-day</td>
<td>Rainfall</td>
<td>Max. rainfall intensity</td>
<td>Time of ponding</td>
<td>Rainfall duration</td>
<td>Runoff</td>
<td>Minimum runoff generating area (MRGA)</td>
<td>Return period</td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
<td>-----------------------</td>
<td>---------------------------</td>
<td>----------</td>
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<td>--------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m³/m²)</td>
<td>(mm)</td>
<td>(mm)</td>
<td>(mm/h)</td>
<td>(min)</td>
<td>(min)</td>
<td>(mm)</td>
<td>(%)</td>
<td>(Year)</td>
</tr>
<tr>
<td>34</td>
<td>04-Dec-11</td>
<td>0.336</td>
<td>48.4</td>
<td>26.5</td>
<td>6.4</td>
<td>48</td>
<td>360</td>
<td>5.48</td>
<td>20.7</td>
<td>3.1</td>
</tr>
<tr>
<td>35</td>
<td>14-Dec-11</td>
<td>0.237</td>
<td>0.0</td>
<td>21.5</td>
<td>5.3</td>
<td>39</td>
<td>420</td>
<td>1.99</td>
<td>9.3</td>
<td>2.3</td>
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<td>36</td>
<td>27-Dec-11</td>
<td>0.228</td>
<td>2.1</td>
<td>8.2</td>
<td>4.0</td>
<td>62</td>
<td>180</td>
<td>0.38</td>
<td>4.6</td>
<td>1.1</td>
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<tr>
<td>37</td>
<td>13-Oct-12</td>
<td>0.167</td>
<td>0.0</td>
<td>28.8</td>
<td>13.1</td>
<td>182</td>
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<td>3.51</td>
<td>12.2</td>
<td>4.6</td>
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<tr>
<td>38</td>
<td>20-Oct-12</td>
<td>0.196</td>
<td>0.0</td>
<td>12.2</td>
<td>5.3</td>
<td>112</td>
<td>300</td>
<td>0.70</td>
<td>5.7</td>
<td>1.4</td>
</tr>
<tr>
<td>39</td>
<td>23-Oct-12</td>
<td>0.274</td>
<td>12.2</td>
<td>24.5</td>
<td>7.1</td>
<td>104</td>
<td>1020</td>
<td>3.45</td>
<td>14.1</td>
<td>2.7</td>
</tr>
<tr>
<td>40</td>
<td>26-Oct-12</td>
<td>0.317</td>
<td>24.5</td>
<td>27.1</td>
<td>2.4</td>
<td>418</td>
<td>1500</td>
<td>5.98</td>
<td>22.1</td>
<td>3.3</td>
</tr>
<tr>
<td>41</td>
<td>28-Oct-12</td>
<td>0.332</td>
<td>51.6</td>
<td>19.7</td>
<td>5.5</td>
<td>67</td>
<td>600</td>
<td>2.26</td>
<td>11.5</td>
<td>2.0</td>
</tr>
<tr>
<td>42</td>
<td>12-Nov-12</td>
<td>0.285</td>
<td>7.2</td>
<td>9.8</td>
<td>2.6</td>
<td>89</td>
<td>360</td>
<td>0.31</td>
<td>3.2</td>
<td>1.2</td>
</tr>
<tr>
<td>43</td>
<td>02-Dec-12</td>
<td>0.238</td>
<td>7.6</td>
<td>21.6</td>
<td>9.2</td>
<td>29</td>
<td>180</td>
<td>4.93</td>
<td>22.8</td>
<td>2.4</td>
</tr>
<tr>
<td>44</td>
<td>16-Dec-12</td>
<td>0.257</td>
<td>6.6</td>
<td>12.0</td>
<td>3.3</td>
<td>244</td>
<td>900</td>
<td>0.57</td>
<td>4.8</td>
<td>1.4</td>
</tr>
<tr>
<td>45</td>
<td>20-Dec-12</td>
<td>0.211</td>
<td>12.0</td>
<td>10.8</td>
<td>3.1</td>
<td>142</td>
<td>600</td>
<td>0.33</td>
<td>3.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Runoff from the majority of the rainfall events was generated by saturated excess runoff generating mechanism because the rainfall intensity for only 8 events exceeded the saturated infiltration capacity of the soil.

The data show that the event rainfall amount ranged from 5.32 mm to 48.40 mm. Maximum rainfall of 48.40 mm occurred on 29-Nov-11. The maximum rainfall intensity of this event was 6.31 mm/hr, producing 13.48 mm of runoff resulting in a 28 % of MRGA. The rain event with the least rain (5.32 mm) occurred on 27-Aug-12. This three-hour long rain event with rainfall intensity of 2.32 mm/hr with relatively dry initial soil moisture conditions generated 0.23 mm (49.72 m³) of runoff and registered 4 % value of MRGA. In the spring season, the maximum amount of rainfall occurred on 21-May-13. A total of 40.9 mm of rainfall was recorded within 5 hour time span with a maximum intensity of 9.37 mm/hr. This event generated 18.82 mm (4069 m³) of runoff and resulted 46 % of MRGA. The maximum rainfall during the summer
season was measured on 31-July-13, when 35.68 mm of rainfall with a rainfall intensity of 10.61 mm/hr generated 4.88 mm (1055 m$^3$) of runoff with 14 % of MRGA.

The soil moisture content before the rain events during spring, summer and fall seasons ranged from 0.20 to 0.36, 0.09 to 0.33 and 0.17 to 0.34 m$^3$/m$^3$ respectively. The maximum 5-day antecedent rainfall amount of 51.63 mm measured on 28-Oct-12 was the result of two successive storms on 23-Oct-12 and 26-Oct-12. This pre-event rainfall increased the soil moisture content of the watershed to 0.33 m$^3$/m$^3$. The summary statistics of 45 observed rainfall events is given in Table 4.3.

Table 4.3: Statistical summary of 45 observed rainfall-runoff events

<table>
<thead>
<tr>
<th></th>
<th>Rainfall (mm)</th>
<th>Initial soil moisture (m$^3$/m$^3$)</th>
<th>Max. rainfall intensity (mm/h)</th>
<th>Rainfall during last 5-day (mm)</th>
<th>Rainfall Duration (min)</th>
<th>Runoff generating area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>5.32</td>
<td>0.09</td>
<td>2.14</td>
<td>0.00</td>
<td>60</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum</td>
<td>48.40</td>
<td>0.34</td>
<td>18.20</td>
<td>51.63</td>
<td>1500</td>
<td>50.0</td>
</tr>
<tr>
<td>Mean</td>
<td>21.56</td>
<td>0.22</td>
<td>7.28</td>
<td>12.11</td>
<td>503</td>
<td>14.3</td>
</tr>
<tr>
<td>Median</td>
<td>19.69</td>
<td>0.22</td>
<td>6.57</td>
<td>7.61</td>
<td>420</td>
<td>8.8</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>11.85</td>
<td>0.07</td>
<td>3.88</td>
<td>14.02</td>
<td>335</td>
<td>13.0</td>
</tr>
</tbody>
</table>

These data also show a large variability in MRGA due to variations in the climatic and hydrologic conditions of the watershed. The summary statistics of seasonal variation of MRGAs is given in Table 4.4.
Table 4.4: Seasonal statistics of minimum runoff generating area

<table>
<thead>
<tr>
<th></th>
<th>Minimum runoff generating areas (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spring</td>
</tr>
<tr>
<td>Minimum</td>
<td>12.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>50.0</td>
</tr>
<tr>
<td>Mean</td>
<td>34.4</td>
</tr>
<tr>
<td>Median</td>
<td>38.3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>15.2</td>
</tr>
</tbody>
</table>

The data show that the runoff generating area is strongly influenced by seasons. MRGA during the spring season were maximum and varied from 12.7 % to 50.0 %. The highest MRGA of 50.0 % occurred during a rain event on dated 3-May-12 with rainfall amount of 29.7 mm and maximum rainfall intensity of 9.67 mm/hr. The initial soil moisture at the beginning of this event was 0.33 m³/m³ and 5-day antecedent rainfall was 10.5 mm. The MRGA of 12.7 % was registered during the rainfall event dated 30-Apr-12. The low value of MRGA was due to small rainfall amount and lower pre-event soil moisture content.

The MRGA during summer varied from 1.3 % to 25.6 % with the average of 8 %. During this season about 75 percent of rainfall events exhibited MRGAs less than 10 % and 40 percent of the events had MRGA less than 5 %. Four rainfall events for which the runoff generating area was greater than 10 % were storms with high rainfall intensity and large rainfall amount. Two rainfall events that produced MRGA of about 25 % were large events with rainfall amount of more than 45 mm. Maximum MRGA of 25.6 % was produced by a severe rainfall event on 10-June-13 with rainfall amount of 45.71 mm and maximum rainfall intensity of 9.62 mm/hr. The lowest MRGA of 1.33 % was recorded for a 9 hour long rain event dated 31-July-12 with rainfall of 8.29 mm.
and maximum rainfall intensity of 2.27 mm/hr. The watershed before the start of this rain event was relatively dry with soil moisture content of 0.16 m$^3$/m$^3$.

For fall events, the MRGA ranged from 2.7 % to 35.3 % with an average value of 13.6 %. The minimum MRGA of 2.7 % occurred on 22-Nov-11. This was due to very low initial soil moisture content (0.14 m$^3$/m$^3$) at the beginning of the event. During this event 9.53 mm of rain fell over eight hours with maximum rainfall intensity of 2.14 mm/hr. The rainfall event producing the largest MRGA of 35.3 % occurred on 14-Oct-11 with rainfall depth of 47.16 mm. During this event, the landscape was relatively wet with soil moisture content of 0.29 m$^3$/m$^3$ and 5-day antecedent rainfall of 28.3 mm. The maximum rainfall intensity during this event was relatively high (8.74 mm/hr).
4.3.1 Factors affecting the variability of runoff generating area

In this study, seasonal and annual variability of runoff generating areas was further explored by means of investigating the possible effect of rainfall amount, initial soil moisture, rainfall intensity, five day antecedent rainfall and rainfall duration on runoff coefficient (minimum runoff generating area).

4.3.1.1 Effect of rainfall amount

The annual and seasonal variation of minimum runoff generating areas with rainfall amount is presented in Fig. 4.3.

![Figure 4.3: Relationship between minimum runoff generating area and rainfall amount](image)

These data show that over the year MRGAs increase with an increase in rainfall amount. The relationship between MRGA and rainfall amount is the strongest for the summer season ($R^2=0.81$) followed by fall ($R^2=0.73$) and spring ($R^2=0.26$). During the
spring season, the MRGA did not show strong relationship with rainfall amount. This was due to high initial soil moisture conditions. The evapotranspiration losses during this season were relatively small. These conditions resulted in low infiltration. During summer, relatively dry soil profile in the watershed due to low soil water content at the beginning of the rainfall resulted high infiltration and low MRGA. An increase in rainfall amount resulted more runoff, high runoff coefficient and strongest relationship between MRGA and rainfall amount. For the fall season, the relationship between MRGA and rainfall amount is strong but weaker than summer. The MRGA for a particular rainfall amount during fall season is about 8 % less than during summer season. The variability within this season is due to variability in the initial soil moisture conditions at the beginning of rainfall event.

4.3.1.2 Effect of initial soil moisture content

The variability in the MRGA with initial soil moisture content over the years and for various seasons is shown in Fig. 4.4.

These data shows that MRGA increases in proportion to the increase in initial soil moisture at the beginning of a rainfall event. However during the spring, the MRGA did not show any relationship with initial soil water content. During early part of this season, all the rainfall events generated high value of MRGA. This was due to high initial soil moisture conditions and impeded infiltration due to presence of frost layer at a shallow depth in the soil profile.
During late spring period the absence of frost layer in the soil profile enhanced infiltration and reduction in MRGA. For summer events, there is a strong positive relationship ($R^2 = 0.78$) between MRGA and initial soil water content. For most of the rainfall events during this season the initial soil conditions were relatively dry, ranged from 0.09 to 0.28 m$^3$/m$^3$ resulted in less runoff amount and reduced MRGA. For majority of rainfall events the MRGA did not exceed greater than 15 %.

For the fall season, the MRGA again showed strong positive relationship with initial soil water content but the temporal variability was more than summer’s variability. These results show that during the summer and fall seasons, initial soil moisture content plays an important role on the magnitude of minimum runoff generating area. These results also agree with the observations of Castillo et al. (2003) that the runoff
response for the saturation excess type of runoff generating mechanism depends on the wetness condition of the landscape.

### 4.3.1.3 Effect of rainfall intensity

Figure 4.5 shows annual and seasonal change in MRGA with rainfall intensity.

![Figure 4.5: Relationship between minimum runoff generating area and maximum rainfall intensity](image)

These data show that the MRGA increases with rainfall intensity: however, the trends are stronger for summer and fall seasons than the spring season. The maximum rainfall intensity for the spring and fall events did not exceed 10.5 mm/hr and for majority of events it was less than 8 mm/h, whereas the MRGA of 5 out of 7 events were more than 35%. The low value of the determination coefficient ($R^2$) suggests that rainfall intensity does not have any significant effect on MRGA for spring rainfall.
events. For all the summer events with maximum rainfall intensity is less than 10 mm/hr and MRGA is less than 10 %. Only two events with maximum rainfall intensity of about 13.5 mm/hr generated 25 % value of MRGA. For the fall season the MRGA showed mixed trend with maximum rainfall intensity. Majority of the rainfall events with maximum rainfall intensity is less than 9 mm/hr generated less than 20% values of MRGA. However, for three events with maximum rainfall intensity of 6 mm/hr the MRGA was more than 20% and for one event close to 30%. This was due to either high initial soil water content or high rainfall amount.

4.3.1.4 Effect of five-day antecedent rainfall amount

Figure 4.6 shows the temporal variations in MRGA with five-day antecedent rainfall amount. Over the annual time frame, the relationship between MRGA and five-day antecedent rainfall amount is very weak or practically insignificant with a coefficient of determination of 0.16. The MRGA showed relatively higher correlation with 5-day antecedent rainfall amounts during summer and fall seasons than spring with $R^2$ value of 0.64 and 0.53 respectively. For spring events the MRGA varies in a very narrow range and more than 35%, though the maximum five-day antecedent rainfall amount does not exceed 10 mm. This was due to very wet soil moisture condition and five-day rainfall has no significant effect on the pre-event wetness conditions. During late spring, summer and early fall period the five-day antecedent rainfall amount affects the MRGA area by affecting the initial soil moisture condition. During winter period five-day antecedent rainfall amount has minimum effect on soil wetness and MRGA.
4.3.1.5 Effect of rainfall duration

The effect of rainfall duration on the MRGA over the year and during spring, summer and fall seasons is presented in Fig. 4.7.

These data show relatively weak relationship between MRCA and rainfall amount relative to other factors affecting MRGA. Over the annual time frame virtually no relationship ($R^2=0.10$) exists between the MRGA and rainfall duration. During the spring season, for majority of the rainfall events the MRGA is greater than 30 %. Two events for which MRGA is less than 15 % occurred during late spring period when the soil was relatively dry. For the summer and fall events, the MRGA increases with rainfall duration but the relationship was moderately positive with ($R^2$) of 0.52 and
0.41 respectively. During summer and early fall periods the rainfall intensities were generally high and an increase in rainfall duration resulted an increase in RGA.

![Figure 4.7: Relationship between minimum runoff generating area and rainfall duration](image)

The summary statistics of the relationship of MRGA with rainfall amount, initial soil water content, maximum rainfall intensity, 5-day antecedent rainfall and rainfall duration is given in Table 4.5. These data show that over the annual time frame rainfall amount and initial soil moisture conditions are the most important factors. For spring period the MRGA is controlled by rainfall amount and maximum rainfall intensity. For summer and fall period, all the factors are important to describe the magnitude of MRGA.
Table 4.5: Summary of correlation of various factors with minimum runoff generating area

<table>
<thead>
<tr>
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<th>Minimum runoff generating area</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Spring (R²)</td>
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<tr>
<td>Rainfall amount (mm)</td>
<td>0.26</td>
</tr>
<tr>
<td>Initial soil moisture (m³/m³)</td>
<td>0.01</td>
</tr>
<tr>
<td>Rainfall intensity (mm/h)</td>
<td>0.36</td>
</tr>
<tr>
<td>5-day antecedent rainfall (mm)</td>
<td>0.07</td>
</tr>
<tr>
<td>Rainfall duration (min)</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The variability of the MRGA was further investigated by means of Pearson product-moment correlation coefficient statistics and the results are presented in Table 4.6.

Table 4.6: Statistical correlation of various factors with minimum runoff generating area

<table>
<thead>
<tr>
<th></th>
<th>MRGA</th>
<th>P</th>
<th>IMC</th>
<th>I</th>
<th>5-DAR</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RC</td>
<td>P</td>
<td>IMC</td>
<td>I</td>
<td>5-DAR</td>
</tr>
<tr>
<td>MRGA</td>
<td>[r]</td>
<td>p-value</td>
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<td>0.6856</td>
<td>0.5657</td>
<td>0.4243</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt;.0001</td>
<td>0.0181</td>
<td>0.0389</td>
<td>0.7997</td>
<td>0.4391</td>
</tr>
<tr>
<td>P</td>
<td>[r]</td>
<td>p-value</td>
<td>0.6856</td>
<td>1</td>
<td>0.0389</td>
<td>0.4391</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
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<td>0.0181</td>
<td>0.7997</td>
<td>1</td>
<td>-0.2848</td>
</tr>
<tr>
<td>IMC</td>
<td>[r]</td>
<td>p-value</td>
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<td>0.0389</td>
<td>0.7997</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>0.0181</td>
<td>0.7997</td>
<td>1</td>
<td>-0.2848</td>
<td>0.058</td>
</tr>
<tr>
<td>I</td>
<td>[r]</td>
<td>p-value</td>
<td>0.4243</td>
<td>0.0389</td>
<td>0.4391</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
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<td>0.0025</td>
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</tr>
<tr>
<td>5-DAR</td>
<td>[r]</td>
<td>p-value</td>
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<td>0.5825</td>
<td>0.0109</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>0.6783</td>
<td>0.2593</td>
<td>0.5825</td>
<td>0.0109</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>[r]</td>
<td>p-value</td>
<td>0.3162</td>
<td>0.4999</td>
<td>0.1730</td>
<td>-0.2168</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>0.0398</td>
<td>0.0005</td>
<td>0.2557</td>
<td>0.1525</td>
<td>0.0725</td>
</tr>
</tbody>
</table>

MRGA=Minimum runoff generating area, P= Rainfall (mm); IMC= Initial soil moisture content (m³/m³) ; I= Rainfall intensity (mm/h); 5-DAR= 5 day antecedent rainfall (mm); D= Duration of event (min)
This correlation matrix shows that the rainfall amount, initial soil moisture, rainfall intensity and rainfall duration exhibit Pearson's coefficients of correlation $|r|$ of 0.6856, 0.5657, 0.4243 and 0.3162 respectively with p-values < 0.05. This means that there is sufficient evidence to believe that these factors have significant positive correlation with the MRGA. Contrarily, the p-value of the five-day antecedent rainfall factor is 0.6783 with $|r|$ value of 0.4000 suggests that this factor does not have an effect on MRGA. Ranking of these factors based on the strength of $|r|$ indicates that rainfall amount is the most significant factor followed by initial soil moisture content and maximum rainfall intensity.

4.3.2 Multivariable Linear Regression analysis

To develop a possible relationship between the MRGA and the factors affecting it, a Multi Variable Linear Regression (MVLR) analysis was performed over the annual and seasonal data. The relationship obtained is presented in Table 4.7. The regression results show that MRGA can be estimated with very good accuracy during summer season, good accuracy during spring season and fall winter season and with reasonable accuracy over annual time frame using rainfall amount, initial soil moisture content, rainfall intensity, five-day antecedent rainfall and rainfall duration parameters. The data also show that the MRGA has strong seasonal dependency.
Table 4.7: Simulated multivariable linear regression equations and their descriptive statistics

<table>
<thead>
<tr>
<th>Season</th>
<th>Equation</th>
<th>n</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>F-value</th>
<th>Pr&gt;F value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>$\text{MRGA} = 0.25189 - 0.00732(P) + 0.07504(IMC) + 0.07484(I) - 0.0144(5\text{-DAR}) - 0.00030(D)$</td>
<td>7</td>
<td>0.7554</td>
<td>0.1811</td>
<td>0.62</td>
<td>0.7408</td>
</tr>
<tr>
<td>Summer</td>
<td>$\text{MRGA} = -0.07990 + 0.00273(P) + 0.31853(IMC) + 0.00135(I) - 0.00225(5\text{-DAR}) + 0.00013(D)$</td>
<td>18</td>
<td>0.9051</td>
<td>0.0258</td>
<td>22.88</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fall</td>
<td>$\text{MRGA} = -0.08397 + 0.00628(P) + 0.38510(IMC) - 0.00168(I) - 0.00021(5\text{-DAR}) - 0.00001(D)$</td>
<td>20</td>
<td>0.7851</td>
<td>0.0501</td>
<td>10.35</td>
<td>0.0003</td>
</tr>
<tr>
<td>Annual</td>
<td>$\text{MRGA} = -0.12978 + 0.00853(P) + 0.91420(IMC) - 0.00545(I) - 0.00326(5\text{-DAR}) - 0.00007(D)$</td>
<td>45</td>
<td>0.5415</td>
<td>0.0931</td>
<td>9.21</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

$P$ = Rainfall (mm); IMC = Initial soil moisture content (m$^3$/m$^3$); $I$ = Rainfall intensity (mm/h); 5-DAR = 5-day antecedent rainfall (mm); $D$ = Duration of event (min); n = Number of observation; RMSE = Root mean square error.

The developed MLRV model for the summer season with a p-value of <0.0001 and $R^2$ of 0.90 shows a statistically best fit regression model between MRGA with rainfall amount, initial soil water content, maximum rainfall intensity, 5-day antecedent rainfall amount and rainfall duration. The regression analysis for spring and fall seasons shows $R^2$ values of 0.75 and 0.78 and RMSE values of 0.18 and 0.05 respectively. The higher RMSE associated with spring season can be attributed to large standard deviation of the unexplained variance of the response variable. The developed regression model incorporating all 45 observed events for the prediction of MRGA over the annual time frame with a $R^2$ value of 0.54 and p-value of <0.0001 demonstrates a statistically significant relationship (Table 4.7).
Multivariable regression analysis between time of ponding (Tp) and rainfall amount, initial soil water content, maximum rainfall intensity, five-day antecedent rainfall and rainfall duration for spring, summer and fall showed no significant correlation (Table 4.8). However, the developed regression equation using all 45 observed events exhibited a R^2 value of 0.45 and p-value of <0.05. The developed annual equation and their descriptive statistics are presented in Table 4.8.

Table 4.8: Simulated multivariable regression equation for time of ponding and descriptive statistics

<table>
<thead>
<tr>
<th>Equation</th>
<th>n</th>
<th>R^2</th>
<th>RMSE</th>
<th>F-value</th>
<th>Pr&gt;F value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>45</td>
<td>0.4546</td>
<td>0.1811</td>
<td>60.85</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

4.3.3 Relation of minimum contributing areas with basin moisture index and storm index

The concept of basin moisture index (Dickinson and Whiteley 1970) and storm index (Arteaga et al. 1973) and their relationship with runoff contributing areas were also investigated using the data obtained from observed events. Again the runoff coefficient was used as an index of minimum contributing area.

Dickinson and Whiteley (1970) studied effect of antecedent wetness conditions and rainfall amount on minimum contributing area. Their study reveals that the minimum contributing area varies from 1 to 50 percent and the majority of events have minimum contributing areas below 10 percent with a median value of 5 percent. The
relationship for the basin moisture index in Eq. 4.2 proposed by Dickinson and Whiteley is given as:

\[ M = Ma + \frac{P}{2} \]  \hspace{1cm} (4.2)

Where \( M \) = the basin moisture index at the beginning of the storm in cm.

\( Ma \) = the soil moisture stored in the upper 70 cm of soil and

\( P \) = the precipitation depth (cm).

The basin moisture index computed by using the relationship described above is shown in Fig. 4.8. The shape of this relationship is similar to the one proposed by Dickinson and Whiteley (1970).

![Figure 4.8: Relationship between minimum contributing area and basin moisture index](image)

**Figure 4.8: Relationship between minimum contributing area and basin moisture index**
The data suggest that the relationship between the minimum contributing area and the basin moisture index is nonlinear in nature and that the basin moisture index value of approximately 25 cm behaves as a threshold value. The minimum contributing area is relatively constant up to 25 cm value of basin moisture index and less than 10 % of the area contributes runoff for more than 80 % of rainfall events. The minimum contributing area showed a marked and rapid increase in basin moisture index greater than the threshold value. These data also show that all the spring events have a basin moisture index greater than the threshold value and a minimum contributing area greater than 16 %. Most of the summer and spring season events have minimum contributing areas less than 12 %.

Figure 4.9 presents the relationship between the minimum contributing area and the storm index proposed by Arteaga et al. (1973). The storm index (Eq. 4.3) is defined as:

\[ SI = A + \frac{P}{2} \]  \hspace{1cm} (4.3)

Where SI is storm index (inch), A is antecedent rainfall (inch), and P is total storm rainfall (inch).

The relationship between the minimum contributing area and the storm index is similar in form to the relationship between minimum contributing area and basin moisture index.
These data show that the storm index up to 2.5 inches exhibits a linear relationship with minimum contributing area. After the threshold values an increase in SI values results a rapid increase in the minimum contributing area. The data also show all of the spring events have SI indices greater than the threshold value of 2.5 inch with minimum contributing area between 15 to 45 %. Most of the summer and fall season events constitute runoff contributing area of less than 10 % of the total watershed area.

4.3.4 Description of spatial and seasonal minimum runoff generating areas

To investigate seasonal and spatial variability in minimum runoff generating areas, three median rainfall events one each from spring, summer and fall were selected for analysis. The summary of various climatic characteristics and hydrological responses
of the eight sub-watersheds for this rain event are shown in Table 4.9. The spring rain event dated 10-May-13 was four hours long with a rainfall amount of 15.01 mm and maximum rainfall intensity of 5.76 mm/hr. The maximum and minimum temperatures on this spring day were 17.6°C and 6.9°C respectively.

**Table 4.9: Summary of climatic and hydrological data for spring event dated 10-May-13**

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-watershed area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.5</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>Five-day antecedent rainfall (mm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Initial soil moisture (m³/m³)</td>
<td>0.23</td>
<td>0.21</td>
<td>0.24</td>
<td>0.2</td>
<td>0.18</td>
<td>0.19</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
<td>15.01</td>
</tr>
<tr>
<td>Max. rainfall intensity (mm/hr)</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
<td>5.76</td>
</tr>
<tr>
<td>Runoff (m³)</td>
<td>186</td>
<td>181</td>
<td>170</td>
<td>214</td>
<td>104</td>
<td>74</td>
<td>168</td>
<td>82</td>
</tr>
<tr>
<td>Peak runoff (m³/s)</td>
<td>140 X 10⁻²</td>
<td>115 X 10⁻²</td>
<td>94 X 10⁻³</td>
<td>217 X 10⁻³</td>
<td>64 X 10⁻³</td>
<td>33 X 10⁻³</td>
<td>150 X 10⁻³</td>
<td>94 X 10⁻³</td>
</tr>
<tr>
<td>Runoff generating area (%)</td>
<td>41.03</td>
<td>39.41</td>
<td>41.79</td>
<td>32.26</td>
<td>33.63</td>
<td>32.87</td>
<td>31.44</td>
<td>42.35</td>
</tr>
<tr>
<td>Runoff contribution to the watershed (%)</td>
<td>15.78</td>
<td>15.35</td>
<td>14.42</td>
<td>18.15</td>
<td>8.82</td>
<td>6.28</td>
<td>14.25</td>
<td>6.96</td>
</tr>
</tbody>
</table>

These data show that for 10-May-13 rainfall event the runoff generating area of sub-watersheds ranged from 31.44 % to 42.35 %. During this rainfall event, all parts of the watershed contribute to the runoff at the outlet. The reason is that pre-event soil moisture of sub-watershed 8 was the wettest among all eight sub-watersheds (0.26 m³/m³) and it contributed 6.96 % of the total watershed runoff with a runoff generating area of 42.35 %. Sub-watersheds 3 and 1 were second and third in the ranking with runoff generating areas 41.79 % and 41.03 %, respectively. The runoff generating area of sub-watershed 7 was minimum (31.44 %) and it generated 168 m³ of runoff and contributed 14.25 % of the total watershed runoff. This shows that the areas with
higher soil moisture or the wetter areas within the watershed generated the larger amount of runoff.

The summer event dated 05-July-13 was six hours long with a rainfall amount of 28.13 mm and a maximum rainfall intensity of 12.7 mm/hr. The five-day antecedent rainfall for this event was 23.1 mm and the maximum and minimum temperatures for this summer day were 23.7°C and 16.5°C respectively. The summary of various climatic characteristics and the hydrological responses of the eight sub-watersheds for this rain event is shown in Table 4.10.

Table 4.10: Summary of climatic and hydrological data for summer event dated 05-July-13

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-watershed area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.5</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>Five-day antecedent rainfall (mm)</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
<td>22.8</td>
</tr>
<tr>
<td>Initial soil moisture (m³/m³)</td>
<td>0.19</td>
<td>0.16</td>
<td>0.18</td>
<td>0.15</td>
<td>0.16</td>
<td>0.17</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>Max. rainfall intensity (mm/hr)</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
</tr>
<tr>
<td>Runoff (m³)</td>
<td>76</td>
<td>66</td>
<td>61</td>
<td>65</td>
<td>38</td>
<td>27</td>
<td>40</td>
<td>37</td>
</tr>
<tr>
<td>Peak runoff (m³/s)</td>
<td>84 X 10⁻⁴</td>
<td>73 X 10⁻⁴</td>
<td>60 X 10⁻⁴</td>
<td>127 X 10⁻⁴</td>
<td>42 X 10⁻⁴</td>
<td>23 X 10⁻⁴</td>
<td>92 X 10⁻⁴</td>
<td>43 X 10⁻⁴</td>
</tr>
<tr>
<td>Runoff generating area (%)</td>
<td>8.95</td>
<td>7.67</td>
<td>8.00</td>
<td>5.23</td>
<td>6.56</td>
<td>6.40</td>
<td>3.99</td>
<td>10.20</td>
</tr>
<tr>
<td>Runoff contribution to the watershed (%)</td>
<td>18.54</td>
<td>16.10</td>
<td>14.88</td>
<td>15.85</td>
<td>9.27</td>
<td>6.59</td>
<td>9.76</td>
<td>9.02</td>
</tr>
</tbody>
</table>

These data show that the runoff generating areas of sub-watersheds varies from 3.99 % to 10.20 %. The soil moisture of the sub-watersheds before the rainfall event of ranged from 0.14 to 0.21 m³/m³. Sub-watershed 8 was the wettest among all sub-watersheds with a soil moisture content of 0.21 m³/m³ and contribution 9.02 % to the total watershed runoff with a MRGA of 10.20 %. The lower initial soil water content of
0.14 m³/m³ of sub-watershed 7 resulted in the least MRGA of 3.99 %. During this event this sub-watershed generated 40 m³ of runoff and contributed 9.76 % of the total runoff.

A fall rain event dated 13-Oct-12 lasted for five hours with a rainfall amount of 28.84 mm and maximum rainfall intensity of 13.10 mm/hr. The summary of various climatic characteristics and hydrological responses of the eight sub-watersheds for this rain event are shown in Table 4.11.

**Table 4.11: Summary of climatic and hydrological data for fall event dated 13-Oct-12**

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-watershed area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.5</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>Five-day antecedent rainfall (mm)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Initial soil moisture (m³/m³)</td>
<td>0.21</td>
<td>0.18</td>
<td>0.19</td>
<td>0.15</td>
<td>0.17</td>
<td>0.16</td>
<td>0.14</td>
<td>0.23</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
<td>28.84</td>
</tr>
<tr>
<td>Max. rainfall intensity (mm/hr)</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
<td>13.10</td>
</tr>
<tr>
<td>Runoff (m³)</td>
<td>130</td>
<td>114</td>
<td>105</td>
<td>124</td>
<td>66</td>
<td>47</td>
<td>90</td>
<td>64</td>
</tr>
<tr>
<td>Peak runoff (m³/s)</td>
<td>69 X 10⁻⁴</td>
<td>64 X 10⁻⁴</td>
<td>56 X 10⁻⁴</td>
<td>95 X 10⁻⁴</td>
<td>43 X 10⁻⁴</td>
<td>29 X 10⁻⁴</td>
<td>74 X 10⁻⁴</td>
<td>36 X 10⁻⁴</td>
</tr>
<tr>
<td>Runoff generating area (%)</td>
<td>14.93</td>
<td>12.92</td>
<td>13.43</td>
<td>9.73</td>
<td>11.11</td>
<td>10.86</td>
<td>8.77</td>
<td>17.20</td>
</tr>
<tr>
<td>Runoff contribution to the watershed (%)</td>
<td>17.57</td>
<td>15.41</td>
<td>14.19</td>
<td>16.76</td>
<td>8.92</td>
<td>6.35</td>
<td>12.16</td>
<td>8.65</td>
</tr>
</tbody>
</table>

The data Table 4.11 show that the average minimum area generating runoff is 12.4 % and the sub-watershed area generating runoff ranges from 8.77 to 17.20 %. Prior to the initiation of the rainfall event, the soil moisture content of the sub-watersheds ranged from 0.14 to 0.23 m³/m³. The peak runoff discharges at the outlet of sub-watersheds was between 29 x 10⁻⁴ to 95 x 10⁻⁴ m³/s. Sub watershed 1 produced the highest amount of runoff (130 m³) and contributed 17.57 % of total watershed runoff.
followed by watershed 4 with runoff of 124 m$^3$ and a contribution of 16.76 % of the total runoff. Sub-watersheds 2 and 3 ranked third and fourth and sub-watershed 6 contributed the least amount (47 m$^3$) of runoff and contributed 6.35 % of total watershed runoff.

Comparison of the results in Tables 4.9, 4.10 and 4.11 also show that sub-watershed 8 has the maximum MRGA and sub-watershed 7 has the minimum MRGA for any event during the study period. These results also show that rainfall intensity during the spring does not have any significance effect on runoff generating areas whereas higher rainfall intensity results in larger MRGA during the summer and fall. The data also shows that MRGA increases with an increase in initial soil water content. Due to wetness conditions of the watershed, the MRGA are large during spring season compared to summer and fall seasons. These result also suggest that though the soil and land use of sub-watersheds were same, the minimum runoff generating area also exhibits seasonal and spatial variability.

4.4 Conclusions

Based on the results reported in this study, the following conclusions can be drawn:

Runoff generating areas exhibits strong seasonal variability. Rainfall amount is the most significant factor affecting minimum runoff generating areas, followed by initial soil moisture and rainfall intensity. Five-day antecedent rainfall and rainfall duration have minimum impact on the minimum runoff generating area. Rainfall amount and maximum rainfall intensity are the dominant factors affecting minimum runoff generating areas during spring period. During summer and fall period dominant
factors affecting minimum runoff generating area includes rainfall amount and initial soil water content followed by maximum rainfall intensity, five-day antecedent rainfall and rainfall duration. There are threshold basin soil moisture index and storm index, below which the minimum contributing area is relatively insignificant. Above these indices the minimum contributing area exhibits an exponential increase.

4.5 References


4.6 Transition to Chapter 5

The third objective of this research study was to appraise the existing methods and models to assess their strength and gaps in quantification and delineating the VSAs. The literature suggests that very few models have been developed to simulate hydrological processes based on VSA concepts. Recently, there has been some re-conceptualization of widely-used water quality models to account for VSA hydrology. The majority of these models are continuous, long-term hydrologic simulation models.

The distributed CN–VSA approach developed by Lyon et al. (2004) is one of the promising new methods to simulate the distribution of saturated areas within the watershed based on VSA hydrology concepts. This method was selected for detailed evaluation as it is an event-based method. This is a physically-based method and uses SCS-CN approach to predict runoff amount and spatial extent of saturated areas. This method distributes runoff generating areas by using topographic wetness index approach.

In chapter 5, the distributed CN-VSA method was evaluated and modified to account for seasonal changes in potential maximum retention (S). The modified distributed CN-VSA method was applied to the study watershed to simulate runoff amount and spatial extent of saturated areas using observed data presented in the preceding chapter to evaluate its feasibility and accuracy of mapping the VSAs.
CHAPTER 5

Development and evaluation of modified distributed CN-VSA method for estimation of spatial distribution of Variable Source Areas

Abstract

Many of the current watershed models employ Soil Conservation Service Curve Number (SCS-CN) approach based on soil and land use for runoff simulation. These models implicitly assume that runoff is generated by the Hortonian process and therefore they are unable to correctly account for the effects of topography or moisture distribution in a watershed.

The distributed CN-VSA method is based on SCS-CN approach to estimate runoff amount and uses the Topographic Wetness Index (TWI) to spatially distribute runoff generating areas within the watershed. The size of the saturated watershed areas and their spatial locations are simulated by assuming an average annual value of potential maximum retention. However, the literature indicates large seasonal variation in the value of potential maximum retention.

This paper focuses on the evaluation and modification of the distributed CN-VSA method to account for the seasonal changes in the potential maximum retention. Simulated results indicate that the modified distributed CN-VSA method performed better than the distributed CN-VSA method to predict runoff amount as well as size and spatial distribution of runoff generating areas. This method is simple and can be incorporated into non-point source pollution models.
Keywords: Saturation excess runoff, Variable source area, SCS runoff curve number, Topographic wetness index, Nonpoint Source Pollution.

5.1 Introduction

Saturation excess is one of the dominant mechanisms of overland flow generation in humid and well-vegetated regions (Dunne 1978; Ward 1984). Predicting the locations of saturated areas and the corresponding risks of generating surface runoff is important for developing watershed management strategies to mitigate non-point source pollution and its impacts.

Saturation excess runoff occurs when soil becomes saturated from below after the water table rises to the land surface either from excess rainfall or from shallow lateral subsurface flow. Precipitation over these saturated areas results in overland flow (Dunne and Leopold 1978). This is opposed to the Hortonian theory, which assumes that runoff occurs when the precipitation rate exceeds the maximum soil infiltration capacity (Horton 1933). Furthermore, Hortonian overland flow does not occur at low rainfall intensities and it is often assumed to take place uniformly over the landscape. However, the portion of the watershed susceptible to saturation excess runoff varies seasonally as well as within a storm, thus these areas are generally termed as variable source areas (VSA) or hydrologically active areas (Frankenberger et al. 1999, Walter et al. 2000). VSAs generally develop along the lower portions of hillslopes, topographically converging or concave areas; valley floors; shallow water table areas; and adjoining the streams (Amerman 1965).
The number of models based on the VSA concept of watershed response are reported in the literature including TOPMODEL (Beven and Kirkby 1979), DHSVM (Wigmosta et al. 1994), SMDR (Steenhuis and Molen 1986), SMoRMod (Zollweg et al. 1996) etc. These models have varying degrees of complexity and are based on distributed moisture accounting within the segments of a watershed, but these models are rarely used as they require copious calibration and large amount of input data (Pradhan et al. 2010). Over the last decade, some encouraging attempts have been made to introduce VSA hydrology in the watershed scale water quality models such as the Soil and Water Assessment Tool SWAT-VSA (Easton et al. 2008) and the Generalized Watershed Loading Function (GWLF) (Schneiderman et al. 2007). However, these models need to be validated with rigorous field tests. Moreover, these models are somewhat more complicated and computationally intensive than most engineering applications warrant (Mills 2008).

The majority of hydrologic and non-point source pollution models have the option of using the SCS-CN method for estimating surface runoff from a storm rainfall. The main advantage of this method is that it incorporates most of the factors affecting runoff generation such as soil class, land use, surface condition, and antecedent soil moisture amount (Ponce and Hawkins 1996; Mishra and Singh 2003a; Mishra et al. 2004(b); Mishra et al. 2005). Despite several identified problems such as lumping the watershed parameters in a single parameter, a lack of peer reviewed justification and uncertainty in runoff estimates, the CN method is extensively used to estimate surface runoff (Soulis et al. 2009) from ungauged watersheds. Steenhuis et al. (1995) suggested that the theoretical basis of the SCS-CN method is valid for both Hortorian
and saturation excess runoff generating mechanisms (Hjelmfelt 1980). However, the majority of water quality models use the SCS-CN method based on soil infiltration characteristics and land use for runoff simulation. Therefore these models are not able to correctly locate the runoff generating areas as the main factors that control infiltration excess runoff generation mechanism are different from the factors that control VSAs (Schneiderman et al. 2007).

Ever since the inception of the VSA concept of runoff generation, topography has been considered as an important factor affecting the hydrological processes in watershed hydrology (Hewlett and Hibbert 1967). In hilly watersheds with moderate to steep topography, the gravity component dominates the hydraulic potential, and the characteristics of the terrain are vital variables to determine the watershed response and distribution of water to rainfall inputs (Rodriguez et al. 1979; Beven and Kirkby 1979; O’Loughlin 1986; Anderson et al. 1992). Various topographic indices of wetness are being used to generate spatially continuous soil water information for identifying saturation excess areas as an alternative to point measurements of soil water content (Hassan et al. 2007; Moore et al. 1993; Western et al. 1999). Moreover, due to their simplicity and physically-based nature, topographic indices have become an integral part of VSA-based hydrological models (Yong et al. 2012).

The Distributed CN–VSA method developed by Lyon et al. (2004) is one of the promising new methods based on VSA concept to simulate the aerial distribution of saturation excess runoff. This is a physically-based method and uses a traditional SCS-CN approach to predict runoff volume and spatial extent of saturated areas and distributes runoff source areas within the watershed using a Topographic Wetness
Index (TWI) approach. This simple method can be integrated with existing hydrological models for predicting the locations of runoff generating areas based on the VSA concept. In the distributed CN-VSA method, potential maximum retention is assumed to be constant throughout the year. However, field observations indicate a large variation between the annual average potential storage and potential maximum retention value for spring, summer and fall seasons. Therefore the distributed CN-VSA method needs modification in order to move from a constant potential maximum retention to a seasonal variable potential maximum retention.

The main objectives of this study are to modify and evaluate the distributed CN-VSA method. Both distributed CN-VSA method and the modified distributed CN-VSA method were applied to a small agricultural watershed. Simulated results of runoff and its aerial distribution in the watershed for spring, summer and fall rainfall events were compared with observed field data to evaluate their feasibility and accuracy of mapping the VSAs in a watershed.

5.2 **Description of distributed CN–VSA method**

The distributed CN–VSA method divides a watershed into two parts. The saturated part generating runoff and the remaining unsaturated part infiltrates and do not contribute to runoff. This method estimates the saturated fraction of watershed by using the SCS runoff curve number method and aerially distributes runoff source areas through the watersheds by application of TWI approach.
5.2.1 Predicting the saturated fractional area of watershed

The rainfall-runoff equation used by the SCS–CN method (USDA-SCS 1972) for estimating the depth of direct runoff from storm rainfall is given as:

\[ Q = \frac{(P-Ia)^2}{(P-Ia+S)} \]  \hspace{1cm} \text{Which is valid for } P > Ia \text{ and } Q = 0 \text{ for } P \leq Ia \tag{5.1} \]

Where,

\( Q = \) Runoff in mm, \( P = \) Rainfall in mm, \( Ia = \) Initial abstraction in mm and \( S = \) Potential maximum retention in mm

This form of CN equation was proposed by Mockus (1949) after reviewing results from many small experimental watersheds (Wildermuth et al. 2009; Rallison 1980). This equation is widely used in hydrological engineering in spite of its empirical nature. The effective precipitation \( P_e \) is the part of precipitation that contributes to surface runoff and is defined as:

\[ P_e = P - Ia \tag{5.2} \]

Eq. (5.1) can be rewritten as

\[ Q = \frac{P_e^2}{P_e+S} \tag{5.3} \]

Steenhuis et al. (1995) suggested that Eq. (5.3) can be used to determine saturation excess runoff that results from saturated soils. The underlying principle of this VSA interpretation of the SCS-CN equation is that the fractional area \( A_f \) of the watershed
generating runoff can be estimated from the ratio of runoff depth ($\Delta Q$) to precipitation depth ($\Delta Pe$) given by the following equation.

$$Af = \frac{\Delta Q}{\Delta Pe}$$  \hspace{1cm} (5.4)

The runoff generating area, according to Eq. (5.4) is equal to the derivative of $Q$ with respect to $Pe$. Differentiating Eq. (5.3) with respect to $Pe$ using partial fraction decomposition, the fraction of watershed generating area can be computed:

$$Q = Pe - S + \frac{S^2}{Pe + S}$$  \hspace{1cm} (5.5)

The differentiation results in:

$$Af = 1 - \frac{S^2}{(Pe + S)^2}$$  \hspace{1cm} (5.6)

Eq. (5.6) is in agreement with the natural VSA process that when $Pe = 0$, the runoff generating area is zero and when $Pe$ approaches $\infty$, the runoff generating area is equal to 1. The application of this equation can be used for watersheds where the $S$ value is known.

The parameter $S$ describes how fast a soil saturates and starts producing runoff. The runoff generated during storm events is largely dependent on available soil water storage $S$ prior to the rainfall event. Generally $S$ is computed either using CN value for average soil and land use conditions or from observed data on effective precipitation and runoff amount in gauged watersheds (Shaw and Walter 2009).
In terms of VSA hydrology, initial abstraction is the amount of water required to initiate the runoff. It is the amount of water that infiltrates the soil before complete saturation of the soil. The universal default for the initial abstraction given by the SCS-CN methodology is \( I_a = 0.20 \) \((S)\). Many researchers have indicated that \( I_a = 0.20 \) \((S)\) is unacceptably high and it depends on individual watershed characteristics (Ling et al. 2014). Therefore it should be carefully selected and employed with caution. Steenhuis et al. (1995) indicated that according to the definitions of \( I_a \) and \( S \), modified SCS-CN method gives good results for humid, well-vegetated and rural regions.

### 5.2.2 Spatial location of the Runoff Generating Areas

Topography exerts major controls on spatial distribution of saturated areas and also affects the spatial variability of soil moisture related to hydrological processes (Sorensen et al. 2006). The Topographic Wetness Index (TWI) was first introduced by Beven and Kirkby (1979). It is a physically-based index that can be used to quantify the effect of topography and moisture content on runoff generation and for predicting the location of surface saturation zones within a watershed (O’Loughlin 1986; Barling et al. 1994). TWI is an important terrain attribute as it describes the spatial pattern of soil saturation and indicates the accumulated water flow at any point in a watershed. It controls soil moisture, flow accumulation, distribution of saturated zones and thickness of soil horizons (Florinsky 2012). The fractional portions in a watershed having similar TWI value are assumed to have a similar hydrological response to rainfall when other factors such as soil type, land use and antecedent soil moisture
are the same or can be treated as being the same (Quinn et al. 1995). A large upslope drainage area and low terrain slope results in a higher TWI. The region with a higher value of TWI indicates a high probability of occurrence of soil saturation (Beven and Kirkby 1979). The TWI is defined as:

\[
\text{TWI}(\lambda) = \ln\left(\frac{a}{\tan \beta \cdot D \cdot \text{Ksat}}\right)
\]

(5.7)

Where,

\( a = \) local upslope area draining through a certain point per unit contour length in m\(^2\)

\( \tan \beta = \) local gradient at the point

\( D = \) depth of soil in m and

\( \text{Ksat} = \) average saturated hydraulic conductivity in m/day.

Usually, the Digital Elevation Model (DEM) is used to calculate the TWI. It is preferable to compute “a” using the Multiple Flow Direction (MFD) algorithm as it gives more accurate flow distribution patterns (Wolock et al. 1995; Buchanan et al. 2012; Alberto 2014). The MFD algorithm assumes that water from a current position could flow into more than one neighbouring cells (Cheng et al. 2011).

The fractional area of watershed that will generate the runoff for a given storm event is calculated by Eq. (5.6). This area is used to determine the threshold TWI (\( \lambda \)) value. It is assumed that the areas above this threshold \( \lambda \) are generating runoff and that areas below the threshold TWI (\( \lambda \)) are infiltrating.
5.3 Material and Methods

5.3.1 Description of the Watershed

The study was conducted in a 21.62 ha agricultural watershed situated in the Elora Research Station of University of Guelph, located at 43° 39' N and 80° 25' W, in Ontario Canada (Fig. 5.1). The elevation of the watershed ranges from RL 357 to 378 m with gentle slopes and slopes as steep as 22 %. The general slope of the watershed is towards the northwest side, where it outlets in to a small creek. The dominant soil is sandy loam belonging to hydrological soil group B. The average saturated hydraulic conductivity of the soil, measured by Guelph permeameter was 11.45 X 10^{-3} m/hr. The soil depth ranged from 0.60 to 0.90 m underlain by a restrictive layer. The climate of Elora is temperate humid with an average annual precipitation of 875 mm of which about 150 mm falls as snow. The entire watershed was under the cultivation of hay crop during the study period.

A remotely operated low cost Wireless Sensor Network (WSN) system was developed and tested (Panjabi et al. 2015) and was installed in the study area to monitor the soil moisture and runoff from eight sub-watersheds in the study watershed. A total of 16 soil moisture sensors were installed in the field to monitor soil moisture. Surface runoff was measured using 8 V-notch weirs fitted with a pressure sensor. Rainfall was monitored using a tipping bucket rain gauge installed at ERS weather station located 500 m from experimental site. Continuous soil moisture and surface runoff of 45 runoff producing events were sampled during the study period. This included 7 spring, 18 summer and 20 fall season events. In this study,
spring covers period 1\textsuperscript{st} February to May 31\textsuperscript{st}, summer from June 1\textsuperscript{st} to September 30\textsuperscript{th} and fall from 1\textsuperscript{st} October to January 31\textsuperscript{st}.

![Figure 5.1: Layout of the study watershed in Elora Research Centre, Elora Ontario](image)

A Lidar (Light Detection and Ranging) survey of the study watershed was conducted to obtain a high resolution Digital Elevation Model (DEM) of 1.0 m × 1.0 m horizontal and 0.01 m vertical resolution. Land use and soil layers were prepared using ArcMap 10. The upslope contributing area per unit length of contour (a) values were determined using Whitebox Geospatial Analysis Tool (Lindsay 2014). This software uses a multi directional flow path algorithm for more realistic flow and wetness distributions (Buchanan et al. 2012; Alberto 2014). Soil depth at various locations in the field were obtained by using an auger and a constant head Guelph permeameter was used to measure in-situ field saturated hydraulic conductivity. The Topographic
Wetness Index (TWI) map of 1 m grid cell resolution (Fig. 5.2) was created using Eq. (5.7).

![Topographic Wetness Index map](image)

**Figure 5.2: Topographic Wetness Index map of study watershed**

### 5.3.2 Distributed CN-VSA method

The distributed CN–VSA method consists of four steps. To explain the method, a rainfall event dated 28-May-2013 is selected as an example. In the first step, a line graph was prepared using the observed event data of $P_e$ and $Q$ as shown in Fig. 5.3. The $S$ value of the watershed was computed by fitting Eq. 5.3 to $P_e$ and $Q$ data. The average annual $S$ value for the watershed computed was 112 mm.
In the second step, a graph of \( P_e \) versus \( A_f \) was created using Eq. 5.6 and the \( S \) value obtained in step 1. In this step, the saturated fractional area \( A_f \) of the watershed is determined using the given \( P_e \) of the rainfall event. For the rainfall event of 28-May-2013, \( P_e = 36.14 \) mm and \( S \) value of 112 mm corresponds to a fraction of saturated area \( A_f = 37 \% \) of the total watershed area as shown in Fig. 5.4. The runoff volume of 2891 m\(^3\) for this event was calculated by multiplying the effective precipitation \( (P_e) \) 36.14 mm with the saturated area \( (A_f) = 7.99 \) ha.
In step three, a graph of $Af$ corresponding to the TWI was prepared using a TWI map of the study watershed as shown in Fig. 5.5. The threshold $\lambda$ was computed using the fraction of saturated area $Af$ computed in step two. The threshold $\lambda$ value corresponding to an $Af$ value of 37% (7.99 ha) was 5.7. This implies that the areas in the watershed with $\lambda$ value of 5.7 or higher were saturated by the rain event.
In the fourth step, the locations of saturated areas within the watershed are identified from the TWI map of the watershed using the threshold $\lambda$ value obtained in step three. The portions of the watershed having equal or higher $\lambda$ value than the threshold $\lambda$ are saturated and generate runoff, whereas the remaining areas do not contribute to surface runoff. Figure 5.6 shows the location of runoff generating areas within the watershed corresponding to the threshold $\lambda$ value of 5.7.

![Figure 5.6: Distributed CN-VSA method-Step 4 (rainfall event dated 28-May-2013)](image)

5.3.3 Application of Distributed CN-VSA method

The distributed CN–VSA method was applied to the study watershed and nine representative rainfall events (small, average and large) out of 45 monitored events were selected for detailed simulation. This included three events each for spring, three for summer and three for fall seasons. The initial abstraction for each rainfall event was determined using the observed data of accumulated rainfall from the beginning of the rainfall event to the time when direct runoff started. The effective
rainfall $P_e$ for each event was determined by subtracting initial abstraction from the total rainfall depth $P$. The steps to the simulation of these nine rainfall events are illustrated in Fig. 5.7.

Figure 5.7: Application of the distributed CN–VSA method using nine rainfall events
As an example, during a spring event on 3-May-12, 29.70 mm of rainfall $P$ resulted in 27.52 mm of $P_e$ (Table 5.1). The $S$ value of 112 mm was determined by fitting Eq. 5.3 to observed event runoff corresponding to event $P_e$ (Fig. 5.7 step 1). The $P_e$ value of 27.52 mm corresponds to an $Af$ of 33 % of the total watershed area as shown in step 2 of Fig. 5.7. The $Af$ value of 33 % (7.13 ha) as determined in step two corresponded to a threshold $\lambda$ value of 5.7 using graph of $\lambda$ versus $A_f$ for the study watershed (Fig. 5.7 step 3). This implies that 33 % of the watershed has a $\lambda$ value larger than 5.7. Therefore in response to this rain event, watershed areas with threshold values 5.7 or more were saturated. Effective precipitation depth of 27.52 mm over the saturated area of 7.13 ha results in a runoff volume of 1963 m$^3$. Step 4 of Fig. 5.7 shows the locations of runoff generating areas within the watershed corresponding to the threshold $\lambda$ value of 5.7.

5.3.4 Modified distributed CN-VSA method

The methodology used to compute modified distributed CN-VSA method is similar to the distributed CN-VSA method except that instead of using an annual average value of potential maximum retention, seasonal value of $S$ for spring, summer and fall are determined in step 1 by using plots for individual seasons. In the same way, individual graphs $Af$ versus $P_e$ of spring, summer and fall season is plotted in step 2 by using Eq. 5.6 and the seasonal $S$ values obtained in step 1. The procedure of calculating the fractional area of saturation $Af$, threshold values of TWI for a rainfall event in step 3 and the distribution of runoff in the watershed in step 4 remains the same as per the distributed CN-VSA method.
5.3.5 Application of the Modified Distributed CN-VSA method

The simulation of nine rainfall events is shown in Fig. 5.8.

Figure 5.8: Application of the modified distributed CN–VSA method using nine rainfall events
The average $S$ value for spring, summer and fall was obtained by applying Eq. 5.3 to the rainfall-runoff events according to their seasons by plotting three individual seasonal plots of $P_e$ versus $Q$ resulting in 48 mm, 104 mm and 184 mm respectively as shown in Fig. 5.8 step 1. These average seasonal $S$ values significantly different from annual average $S$ value of 112 mm.

For example, a spring rainfall event of 3-May-12 generated 27.52 mm of effective precipitation $P_e$ against a total rainfall of 29.70 mm. From the $P_e$ versus $Af$ for spring ($S=48$ mm) with $P_e$ value of 27.52 mm, the corresponding value of $Af$ is 58 % (12.54 ha of the watershed area) as shown in Fig. 5.8, step 2. The plot of $Af$ versus $\lambda$ (Fig. 5.8, step 3) designates the threshold $\lambda$ value of 4.3 corresponding to the 58 % fraction of saturated area. This indicates that 58 % of the watershed has a $\lambda$ value higher than 4.3. As a result, areas in the watershed with $\lambda$ value of 4.3 or higher were saturated by this rainfall event. The runoff volume of 3451 m$^3$ for this rain event was calculated by using the $P_e$ value of 27.52 mm and saturated area of 12.54 ha.

5.4 Results and Discussion

5.4.1 Comparison of runoff amounts estimated by distributed CN–VSA method and Modified distributed CN–VSA method

The comparison of the runoff simulated with distributed CN-VSA method and the modified CN-VSA method with the observed data is presented in Table 5.1.
Table 5.1: Comparison of the runoff simulated by distributed CN-VSA method and modified distributed CN-VSA method with observed runoff

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (P) (mm)</th>
<th>Effective Precipitation (P_e) (mm)</th>
<th>Observed Runoff (Q) (m³)</th>
<th>Distributed CN-VSA method</th>
<th>Modified CN-VSA method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(S) (Af) Simulated runoff (m³)</td>
<td>(S) (Af) Simulated runoff (m³)</td>
</tr>
<tr>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03-May-12</td>
<td>29.70</td>
<td>27.52</td>
<td>3214</td>
<td>112 33 1963</td>
<td>48 58 2951</td>
</tr>
<tr>
<td>10-May-13</td>
<td>15.01</td>
<td>12.37</td>
<td>1180</td>
<td>112 18 481</td>
<td>48 31 829</td>
</tr>
<tr>
<td>28-May-13</td>
<td>38.60</td>
<td>36.14</td>
<td>3196</td>
<td>112 37 2891</td>
<td>48 62 4844</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>08-Sep-12</td>
<td>25.76</td>
<td>20.65</td>
<td>784</td>
<td>112 27 1205</td>
<td>184 18 804</td>
</tr>
<tr>
<td>08-Jul-13</td>
<td>14.76</td>
<td>10.12</td>
<td>183</td>
<td>112 16 350</td>
<td>184 9 197</td>
</tr>
<tr>
<td>31-Jul-13</td>
<td>35.68</td>
<td>30.76</td>
<td>1056</td>
<td>112 39 2527</td>
<td>184 25 2112</td>
</tr>
<tr>
<td>Fall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-Oct-11</td>
<td>47.16</td>
<td>43.48</td>
<td>3596</td>
<td>112 44 4136</td>
<td>104 45 4230</td>
</tr>
<tr>
<td>27-Nov-11</td>
<td>15.41</td>
<td>11.89</td>
<td>586</td>
<td>112 17 437</td>
<td>104 18 463</td>
</tr>
<tr>
<td>23-Oct-12</td>
<td>24.52</td>
<td>20.85</td>
<td>745</td>
<td>112 29 1217</td>
<td>104 28 1262</td>
</tr>
</tbody>
</table>

These results indicate that the modified CN-VSA method simulates runoff much closer to observed runoff than the distributed CN-VSA method. For the spring season for the two out of three events the modified CN-VSA simulate runoff similar to observed runoff. For the third event the modified CN-VSA overestimated the simulated runoff. This may be due to the use of average seasonal value of S for individual rainfall event on 28-May-13. The analysis of the soil moisture data before the start of this event indicated that the soil moisture conditions were much dried than estimated by seasonal S. The distributed CN-VSA underestimated runoff for all the events and the difference from the observed runoff was greater than the modified CN-VSA method.
During summer season the distributed CN-VSA overestimated the runoff amount by more than 50% (35% to 59%). This may be due to the fact that the soil was drier than the assumed average annual potential maximum retention (S) value. The modified distributed CN-VSA also overestimated the runoff amount but the overestimation is less than 35% (3% to 50%). The use of monthly potential retention could further improve the agreement with the observed results. For the fall season the distributed CN-VSA and modified distributed CN-VSA the methods give similar results, an average variation of the runoff amount by 18% and 20% respectively. For two events both the methods overestimated the runoff amount and underestimated for one event. These results indicate that the modified distributed CN-VSA approach has the better capability to predict runoff amount (Coefficient of determination $R^2 = 0.76$ and Nash–Sutcliffe efficiency coefficient $E = 0.66$) than the distributed CN-VSA approach ($R^2 = 0.63$ and $E = 0.64$).

For further analysis the comparison of simulated runoff using distributed CN-VSA method and modified distributed CN-VSA method with 36 observed runoff events are presented in Figures 5.9 and 5.10 respectively.
The results given in Figure 5.9 clearly show that the distributed CN-VSA method underestimates the runoff amount during spring period and overestimates during summer period. This is due to the use of average annual value of S. Higher estimated annual average value of S will under estimate runoff during spring and overestimate period. For the fall period their results and mixed with combination of under and over estimation. The $R^2$ value between the simulated and observed runoff was 0.69 and $E=0.66$.

The Figure 5.10 shows the comparison of the runoff simulated by the modified CN-VSA with the observed runoff. These data show better agreement of simulated runoff with observed runoff. The predictions of runoff by the modified distributed CN-VSA method show no systematic bias or major deviation between observed and simulated
runoff which are evenly scattered around the 1:1 line as shown. The determination coefficient improved from 0.69 to 0.75 for modified distributed CN-VSA method and E from 0.66 to 0.71 for modified distributed CN-VSA method. This indicates that the modified distributed CN-VSA method is an improvement over the traditional distributed CN-VSA method.

![Figure 5.10: Comparison of the runoff simulated by the modified distributed CN–VSA method with the observed runoff](image)

Figure 5.10: Comparison of the runoff simulated by the modified distributed CN–VSA method with the observed runoff
5.4.2 Spatial distribution of runoff

To further evaluate the performance of these methods the percentage of the area generating runoff at the watershed outlet, the spatial distribution of runoff generating areas by both methods were estimated and the results are presented in Figures 5.11 to 5.13. Both the method uses similar approach to spatially distribute the runoff generating areas using TWI concept. It is assumed the areas with TWI greater than or equal to threshold λ value are saturated and generate the runoff and that the areas below this threshold λ are infiltrating.

Analysis of the results for these spring rainfall events indicate that for the three spring rainfall events the average area generating runoff estimated by the distributed CN–VSA method and modified distributed CN–VSA method were 29% (18 - 37%) and 50% (31 to 62%) respectively. The runoff generating area estimated by modified distributed CN-VSA looks more realistic because in Ontario during late winter and early spring season more area generates runoff due to wet soils close to saturation. Figure 5.11 displays the comparison of aerial distribution and locations of runoff generating areas for the three spring rainfall events simulated by distributed CN–VSA method and the modified distributed CN–VSA method respectively.
For the summer season the average area generating runoff by distributed CN-VSA method was 27% (16 to 39 %) and by modified distributed CN-VSA was 17% (9 to 25%). The In the same way, Figure 5.12 displays the aerial distribution of and the locations of runoff generating areas for the three summer rainfall events simulated by distributed CN–VSA method and the modified distributed CN–VSA method.
Figure 5.12: Comparison of spatial distribution of runoff estimated by distributed CN–VSA method and Modified distributed CN–VSA method of summer rainfall events

For the fall season both the distributed CN-VSA method and modified distributed CN-VSA method estimated 30% of the watershed area was generating the runoff. The range of area generating runoff and the areal distribution of runoff for the distributed CN-VSA method (17 to 44%) and modified distributed CN-VSA method (18 to 45%) was also similar.
5.5 Conclusions

The developed modified distributed CN-VSA method presented in this study is an extension of the distributed CN-VSA method used to predict runoff amount and spatial distribution of variable source area for watersheds where saturation excess is a dominant runoff generating process. The results of this study show that the modified distributed CN-VSA is an improvement over the distributed CN-VSA approach for the estimation of runoff amount and the magnitude and spatial distribution of runoff generating area. The new modified distributed CN–VSA method can be integrated with existing hydrological models for predicting and correctly
locating critical runoff generating areas for designing best management practices to effectively control non-point source pollution.

5.6 References


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5.7 Transition to Chapter 6

The fourth objective of this research study was to develop an event-based VSA model for simulation and mapping of runoff generating areas and to validate the model results with the observed field data. The next chapter describes the development of a new modeling approach by re-conceptualizing the event-based Agricultural Non-Point Source Pollution (AGNPS) model (Young et al. 1989) to identify and locate the runoff generating areas based on VSA hydrology concepts.
CHAPTER 6

Incorporation of Variable Source Area Runoff Generation Mechanism into the Hydrology of the AGNPS Model

Abstract

In this study a modeling approach was developed using an event-based distributed Agriculture Non-Point Source Pollution (AGNPS) model to simulate and locate the runoff generating areas based on VSA hydrology concepts. The modeling approach of the AGNPS model was modified to distribute runoff generating areas in a way consistent with VSA hydrology by incorporating the Topographic Wetness Index (TWI). The developed AGNPS-VSA model was validated on a small agricultural watershed in Ontario, Canada. The modified model, AGNPS-VSA showed good agreement with observed runoff and runoff source areas were correctly identified. The developed approach has good potential for applications in agricultural watersheds to develop strategies to minimize the pollutant loads to the surface water bodies by accurately predicting the locations of critical runoff generating areas for application of best management practices.

**Keywords:** Variable source area, Saturation excess runoff, SCS runoff curve number, Topographic wetness index, Nonpoint Source Pollution.

6.1 Introduction

Surface runoff is considered to be the main carrier of Non-Point Source (NPS) pollutants from watersheds to receiving water bodies. Therefore, accurate prediction
of runoff generating areas in a watershed is necessary for the placement of best management practices to effectively control the NPS pollution (Qui et al. 2007).

The two primary hydrological mechanisms that generate surface runoff are infiltration excess and saturation excess. Infiltration excess runoff (also referred as Hortonian overland flow) occurs when the application of water to the soil surface exceeds the infiltration capacity of the soil (Horton 1933, 1940). Hortonian overland flow depends on rainfall intensity and is often assumed to take place uniformly over the landscape. However, saturation excess runoff occurs when soil becomes saturated from below due to a rise in the local water table to the land surface, either from excess rainfall or by shallow lateral subsurface flow from upslope contributing areas (Dunne and Leopold 1978). The fraction of the watershed susceptible to saturation excess runoff varies in space and time with the variation in landscape wetness during the season, throughout the year and during individual rainfall events. Hence these fractions of watershed area are referred to as variable source areas (Hernandez et al. 2003; Dunne and Black, 1970a and 1970b; Hewlett and Nutter, 1970). Generally, VSAs are found in parts of the landscape with shallow, well-drained soils underlain by an impervious layer or locations where the topographic slope decreases, resulting in a convergence of surface and lateral shallow subsurface flows.

Topography plays an important role in hydrological processes and it has been a main focus since inception of the VSA concept (Hewlett and Hibbert 1967). Furthermore, it affects the spatial variation of soil moisture and watershed response to the precipitation inputs (Rodhe and Seibert, 1999; Seibert et al. 1997; Zinko et al. 2005). Kirkby (1975) proposed that the distributed nature of catchment responses could be
indexed on the basis of topographic analysis. Beven and Kirkby (1979) incorporated the concept of Topographic Index (TI) as a means of identifying areas with the greatest propensity to saturate into the TOPMODEL. Since then, topographic indices have been widely used to describe the variation of spatial soil moisture patterns (Moore et al. 1993; Burt and Butcher 1985) and have become an effective tool in the saturation excess runoff models to predict potential VSAs (Grabs et al. 2009; Agnew et al. 2006; Lyon et al. 2004; Western et al. 1999).

Modeling spatial and temporal variability of VSAs is very challenging since the development of a VSA depends on a number of factors such as topography, land use, soil properties, water table depth, watershed characteristics, geology, climatic conditions and topographic position in the landscape. In spite of such difficulties and challenges, a few encouraging attempts have been made to develop models for quantification of runoff and locating runoff generation areas based on VSA concepts. However, these models are somewhat more complicated and computationally intensive than most engineering applications warrant and none of them are validated by field studies under different hydrological conditions (Mills 2008). Most of the current water quality protection procedures, assessment methods and implementation of BMPs are based on conventional infiltration excess response to rainfall concept (Walter and Shaw 2005; Walter et al. 2000). Water quality managers mainly rely on popular water quality models based on infiltration excess runoff generating mechanism, since these are well established and user-friendly due to their proven nutrient transport and soil erosion sub routines. However, for the areas
dominated by a saturated excess runoff mechanism, these models may not be able to predict the correct locations of runoff generating areas (Pradhan 2010; Chapi 2009).

Recognizing the need for developing an event model for predicting and delineating VSAs, the methodology proposed in this paper is based on the concept developed by Easton et al (2008). In the present study, CN value for each cell is assigned according to its TWI class that categorises each cell based on its comparative susceptibility of becoming saturated and generating saturation excess surface runoff. Although there are a wide variety of hydrologic and pollutant routing models to choose, AGNPS was selected because it is an event model applicable to agricultural watersheds. Moreover, the AGNPS model was earlier evaluated and validated in the Ontario conditions by the Ontario Ministry of the Environment (MOE) and the National Water Research Institute (NWRI) of Canada (Leóna et al. 2004). The AGNPS model has also been considered to be suitable and useful watershed management tool to design and evaluate BMPs (TRCA, 2003).

AGNPS, a distributed single-event model is widely used for watershed management to evaluate best management practices (BMPs) due to its user-friendliness, flexibility, and relative accuracy (Bosch et al. 2004). The AGNPS model uses geographic cells of data units to describe watershed and channel conditions. Runoff characteristics and transport processes of sediments and nutrients are simulated for each square cell and routed to the watershed outlet in a step wise manner. The hydrology component of AGNPS uses the SCS curve number procedure developed by the USDA Soil Conservation Service to compute the surface runoff (Grunwald et al. 1999).
The main objective of this research is to re-conceptualize the event-based AGNPS model to predict runoff generating areas based on VSA hydrology concept. The simulated results of the AGNPS-VSA model are compared with the AGNPS model and validated with the observed data.

6.2 The AGNPS model

The Agricultural Non-Point Source Pollution (AGNPS) model (Young et al. 1989) is a distributed event-based model that has the capability to simulate surface runoff, sediment and nutrients transport from agricultural watersheds. The model divides the watershed into uniform rectangular equal size working areas classified as cells. This discretization concept allows the model to express all the watershed characteristics and inputs at the individual grid-cell level. To describe heterogeneity of the watershed, main grid cells are sub divided in to smaller sub cells. The cells are assigned identification numbers starting from north western corner of the watershed and proceeding by rows from west to east side. As per the model manual, the cell size can be selected from 0.4 to 16 ha depending on the area of the watershed at the discretion of the user. Smaller cell size can increase the accuracy of the results but will require more computer run time. On the other hand, considering larger areas as homogeneous units will reduce computation time but will result in loss of accuracy. For watersheds larger than 800 ha, it is suggested to use cell size of 16 ha.

The input of spatially distributed data is handled through the use of Geographical Information System (GIS). Basic databases required for the AGNPS model include the Digital Elevation Model (DEM), map files of watershed boundary, soil type, land
use, and water features (lakes, rivers and drain) layers. The DEM is used to derive slope properties, slope length, drainage network and other related parameters. The initial data requirements for the model are cell number, area of each cell, precipitation, storm duration and storm type. The four storm types I, IA, II and III are used to calculate the peak discharge, Erosion Index (EI) and sediment yield (Haregeweyn et al. 2002).

The AGNPS model uses the Curve Number method developed by USDA Natural Resources Conservation Service (USDA SCS 1972) to compute the runoff for each cell. The CN is the most sensitive parameter in the AGNPS and related to the hydrologic soil group, land use, antecedent soil moisture and hydrologic conditions of the watershed (Chaubey et al. 1999b). The surface runoff generated from each individual cell is calculated separately. Runoff from one cell becomes input to the next adjacent cell.

The response of the watershed to a storm is simulated by considering the storm duration as the modeling time step. The peak runoff rate $Q_{\text{max}}$ for each cell is calculated by using the following relationship given by Smith and Williams (1980).

$$Q_{\text{max}} = 3.79 \times (A)^{0.70} \times (J)^{0.16} \times \left( \frac{R}{25.4} \right)^{(0.903 \times A)^{0.017}} \times \left( \frac{L}{A} \right)^{-0.19}$$

(6.1)

Where,

$A$= drainage area (km$^2$).

$J$= channel slope (%).
R= runoff volume (mm) and  

L= flow path length in km.  

The runoff is routed from each cell to the next according to the flow direction from watershed divide to the outlet. This procedure allows examining the flow at any point in the discretized watershed. The model uses modified Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) that includes the effect of slope shape on soil erosion for calculating upland erosion. The model subdivides sediment yield into five particle size classes-clay, silt, small aggregates, large aggregates and sand.  

The computations in AGNPS are performed in three stages. Initial calculations for all cells such as surface runoff, time of concentration and estimates for upland erosion are carried out in the first stage. The second stage calculates the runoff volume and sediment yields. In the third stage, sediments and nutrients are routed to downstream of the watershed to calculate the actual sediment and nutrient flow rates (Jin-Hua et al. 2009). The strength of this model is its use of readily available input data and its process-based subroutines. The model provides output in tabular format as well as in spatial map file format.  

The AGNPS model is well suited for simulating surface runoff amount, peak flow and sediment/nutrient yields from single events at watershed outlet or at user-specified location in a watershed. The AGNPS model has been applied and validated at the sub-watershed and watershed scale in southern Ontario and has been considered to be suitable and a useful tool in watershed management to design and evaluate BMPs (TRCA, 2003).
6.3 The CN method and its application to VSA concept

The Soil Conservation Service Curve Number (SCS-CN) method is used for estimating direct runoff amount by using the following equation given by USDA-SCS (1972)

\[ Q = \frac{(P-Ia)^2}{(P-Ia+Se)} \]

Which is valid for \( P > Ia \); and \( Q = 0 \) for \( P \leq Ia \) \hspace{1cm} (6.2)

Where,

\( Q \) = Direct runoff in mm, \( P \) = Rainfall depth in mm, \( Ia \) = Initial abstraction in mm and \( Se \) = Potential maximum retention in mm

The effective precipitation \( Pe \), the part of precipitation that reaches stream channels as runoff is defined as:

\[ Pe = P - Ia \ (\text{mm per event}) \] \hspace{1cm} (6.3)

Eq. (6.2) can be rewritten in the form originally proposed by Mocus (1949)

\[ Q = \frac{Pe^2}{Pe+Se} \] \hspace{1cm} (6.4)

Effective rainfall (\( Pe \)) is the depth of rainfall after the initiation of runoff (total rainfall depth after subtracting the initial abstraction). The universal default for the initial abstraction given by the SCS CN methodology is \( Ia = 0.20 \ Se \) (USDA-SCS 1972). After reviewing results from many experimental watersheds, Rallison (1980) found that the main justification given by Mockus (1949) was that with a value of \( Ia = \)
Se the SCS-CN method produces rainfall-runoff characteristics similar to natural watersheds.

Several studies have suggested that the theoretical basis of the SCS-CN method is valid for both Hortorian and saturation excess runoff generating mechanisms (Hjelmfelt 1980). However, the majority of the current hydrologic models employ the SCS-CN method based on soil infiltration characteristics and land use for runoff simulation (Walter and Shaw 2005).

Steenhuis et al. (1995) suggested that Eq. (6.4) can be used to estimate saturation excess runoff resulting from saturated soils during a rainfall event. The effectively saturated area of the watershed can be expressed as:

\[ Af = \frac{\Delta Q}{\Delta Pe} \]

(6.5)

Where,

\( Af \) = saturated fraction of watershed area

\( \Delta Pe \) = incremental depth of precipitation and

\( \Delta Q \) = incremental saturation excess runoff

The runoff generating area, according to Eq. (6.5) is equal to the derivative of Q with respect to Pe. Differentiating Eq. (6.4) with respect to Pe using partial fraction decomposition, the fraction of runoff generating area for a rainfall event can be computed as (Steenhuis et al. 1995):
\[ Af = 1 - \frac{Se^2}{(Pe + Se)^2} \]  

(6.6)

This equation is in agreement with mathematical limits, when \( Pe = 0 \), the runoff generating area is zero and when \( Pe \) approaches \( \infty \), the runoff generating area is 1.

As per Eq. 6.6, surface runoff occurs from the fractional areas when local effective available storage ' \( \sigma_e \)' is less than effective rainfall (\( Pe \)). Hence replacing ' \( \sigma_e \)' for \( Pe \) and As for \( Af \) (%), and the watershed with average overall storage 'Se', the relationship can be expressed as (Schneiderman et al. 2007):

\[ As = 1 - \frac{Se^2}{(\sigma_e + Se)^2} \]  

(6.7)

The local effective soil moisture \( \sigma_e \) for any fractional area \( As \) of the watershed can be computed by re arranging terms in Eq. 6.7:

\[ \sigma_e = Se \left( \sqrt{\frac{1}{1-As}} - 1 \right) \]  

(6.8)

The Eq. 6.8 can be described for soil moisture storage \( \sigma \) at the beginning of rainfall event as:

\[ \sigma = Se \left( \sqrt{\frac{1}{1-As}} - 1 \right) + Ia \]  

(6.9)

### 6.4 Incorporation of Variable Source Area concept into AGNPS model

The AGNPS model calculates runoff separately for individual cells using the SCS CN method and assigns CN value according to soil class and land use. For the modified
AGNPS model with VSA concept (AGNPS-VSA), the estimation of runoff from cells is based on a topographic wetness index that categorises each cell of the watershed according to its comparative susceptibility for becoming saturated and generating saturation excess surface runoff. In this study, TWI is used to define the distribution of wetness indices (Beven and Kirkby 1979). The TWI map of the watershed is generated using following equation:

$$TWI = \ln\left( \frac{a}{D \cdot Ks \cdot \tan\beta} \right)$$ (6.10)

Where,

- $a =$ local upslope area draining through a certain point per unit contour length in m$^2$
- $\tan\beta =$ local gradient at the point
- $D =$ depth of soil in m and
- $Ks =$ average saturated hydraulic conductivity in m d$^{-1}$.

The areas within the watershed with larger TWI values are more susceptible to saturate than the areas with a small TWI. It has been noted that the landscape areas saturate in the order from highest to lowest TWI. The fractional areas within the watershed are ranked according to their TWI.

In the AGNPS-VSA modeling approach, the watershed is divided into unit areas of equal size called wetness classes at the discretion of the user. The AGNPS model divides soil type in 12 classes, therefore for convenience; the watershed in this study is also divided into 12 wetness index classes, each representing 8.33% of the
watershed area. Wetness class 12 has the highest value of TWI and wetness class 1 has lowest values. During a rainfall event, watershed areas with wetness class 12 saturate first and start generating runoff. As the rain continues, the watershed areas begin to saturate according to their relative storage (wetness class) and start generating runoff one after another. Each wetness class is characterized by a maximum effective storage ($\sigma_{e,i}$) above which the runoff is generated. Schneiderman et al. (2007) proposed a method for deriving maximum effective storage ($\sigma_{e,i}$) for each wetness class as:

$$\sigma_{e,i} = \int_{A_{s,i}}^{A_{s,i+1}} \sigma_e \ast (dA_{s,i})$$

(6.11)

$$\sigma_{e,i} = \left(\frac{2Se\left(\sqrt{1-A_{s,i}} - (\sqrt{1-A_{s,(i+1)}})\right)}{(A_{s,i+1} - (A_{s,i}))} - Se\right)$$

(6.12)

Where, $\sigma_{e,i}$ = maximum effective storage of a fraction i of the watershed. $Se$ = overall watershed storage and $A_{s,j}$ = percent of the watershed area with local effective soil water storage less than or equal to $\sigma_{e,i}$.

Schneiderman et al. (2007) suggested that runoff generating areas within the watershed are characterized by having maximum effective storage ($\sigma_{e,j}$) and the remaining infiltrating areas have larger maximum effective storage. Moreover, each wetness class area is bounded by wetter and drier fraction of wetness class areas. The wetness class area denoted by the term $A_{s,i+1}$ is bounded by wetter class area $A_{s,i+2}$ and drier $A_{s,i}$ on the other side.

Runoff depth $q_i$ in mm for each wetness class can also be described as:
\[ q_i = Pe - \sigma e, \text{ for } Pe > \sigma e \]  \hspace{1cm} (6.13)

The total runoff amount \( Q \) can be computed as:

\[ Q = \sum_{i=1}^{n} q_i (A_s, i + 1 - A_s, i) \]  \hspace{1cm} (6.14)

The major difference between the AGNPS and AGNPS-VSA models is the way in which the runoff is calculated. AGNPS model uses the SCS–CN method based on an infiltration excess runoff generating mechanism by assigning CN values based on soil type, land use and hydrologic condition. The AGNPS-VSA model, estimates runoff from saturated areas based on TWI classes and it is assumed that only saturated areas generate runoff and the dry areas does not contribute to any runoff. Thus the AGNPS-VSA takes into account saturation excess response to rainfall.

6.5 Study area

The revised modeling approach (AGNPS-VSA) and original AGNPS model were evaluated in a small agricultural watershed. The agricultural study watershed, 21.62 ha in area is situated in the Elora Research Station of the University of Guelph (Fig. 6.1) located at 43° 39' N and 80° 25' W in Ontario Canada. The study watershed of 21.62 ha has an elevation ranging from 357 to 378 m with gentle to steep 22 % slope. The general slope of the watershed is towards northwest side, where it outlets in to a small creek. The dominant soil is sandy loam belonging to hydrological soil group B. The average saturated hydraulic conductivity of the soil, measured by Guelph permeameter was \( 11.45 \times 10^{-3} \) m/hr. The soil depth ranged from 0.60 to 0.90 m underlain by a restrictive layer. The climate of Elora is temperate humid with an
average annual precipitation of 875 mm of which about 150 mm falls as snow. The entire watershed was under the cultivation of hay crop during the study period.

![Figure 6.1: Layout of the study watershed in Elora Research Centre, Elora Ontario](image)

6.6 Input data

A total of 16 soil moisture sensors were installed in the watershed to monitor soil moisture. Surface runoff at the watershed outlet was measured using a V-notch weir fitted with a pressure sensor. A remotely operated low cost wireless system network (WSN) was developed (Chapter 4) and used to monitor the sensors and to collect continuous data of soil moisture and runoff from 45 rainfall events from September 2011 to July 2013. It includes 10 rainfall events during fall 2011, 4 during spring 2012, 13 during summer 2012, 8 during fall 2012, 3 during spring 2013 and 7 during
summer 2013. Hourly rainfall data was obtained from Elora research centre weather station located at a distance of 500 m from the study site.

The Digital Elevation Model (DEM) of 1 m X 1 m horizontal and 0.01 m vertical resolution was obtained by a Lidar (Light Detection and Ranging) survey of the watershed. The upslope contributing area per unit length of contour values (a) was determined using the Whitebox Geospatial Analysis Tool (Lindsay 2014). This software uses a multi directional flow path algorithm for more realistic flow and wetness distributions (Buchanan et al. 2012; Alberto 2014). The soil depth at various locations in the field was measured using an auger and saturated conductivity was measured using the Guelph Permeameter. The TWI map of the study area was prepared by using equation 6.10.

The TWI map of the watershed shown in Fig. 6.2 was divided into 12 wetness index classes of equal size using GIS software ArcMap-10. The soil type lookup table in the AGNPS model database contains fields of various soil properties that link the code with data values of each soil type class to be used for hydrologic sub-routines. These associated soil properties were indexed and included in the attribute table of TWI map file corresponding to 12 wetness index classes. The soil map layer file was then substituted by the TWI map file. The land use layer file of the area was prepared according to the AGNPS land use lookup table. The watershed area was divided into 20 m X 20 m homogenous cells.
Figure 6.2: Topographic Wetness Index class map of the study watershed

6.7 Calibration of AGNPS and AGNPS-VSA models

Both the AGNPS-VSA and AGNPS models were calibrated using 26 events comprising of 3 spring, 13 summer and 10 fall events of 2012. The model calibration procedure was divided into two phases. In the first phase, the average (S) value obtained from observed data; 48 mm for spring; 184 mm for summer and 104 mm for fall season is distributed in to 12 wetness classes to calculate CN values based on \( \sigma_{e,i} \) for each wetness class using Eq. 6.12 for AGNPS-VSA model. Thus, for AGNPS-VSA model, the CN of higher wetness class cells are pushed up and lower wetness class cells are pulled down. The AGNPS model assigned same CN value to each cell
of the watershed based on average seasonal (S) value. Table 6.1 summaries Parameters of AGNPS-VSA and AGNPS models for fall season.

Table 6.1: Parameters of AGNPS-VSA and AGNPS models for fall season

<table>
<thead>
<tr>
<th>Wetness Index Class</th>
<th>AGNPS-VSA Method</th>
<th>AGNPS Model</th>
<th>Soil Hydrologic Group</th>
<th>Land Use</th>
<th>CNII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average TWI</td>
<td>σe in mm</td>
<td>CNII</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.48</td>
<td>521.34</td>
<td>32.8</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Short Grass</td>
<td>69.4</td>
</tr>
<tr>
<td>2</td>
<td>2.69</td>
<td>212.71</td>
<td>54.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3.31</td>
<td>140.73</td>
<td>64.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3.67</td>
<td>102.90</td>
<td>71.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.06</td>
<td>78.57</td>
<td>76.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4.47</td>
<td>61.21</td>
<td>80.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4.91</td>
<td>48.03</td>
<td>84.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>5.38</td>
<td>37.58</td>
<td>87.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5.87</td>
<td>29.02</td>
<td>89.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.43</td>
<td>21.85</td>
<td>92.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>7.84</td>
<td>15.73</td>
<td>94.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>11.86</td>
<td>10.43</td>
<td>96.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the second phase of calibration, the models were re-run by uniformly adjusting CN values to maximize the coefficient of determination ($R^2$) and the Nash–Sutcliffe model efficiency coefficient (E) between observed and simulated amount of runoff.

6.8 Discussion of Results

Two approaches are used to evaluate the performance of AGNPS-VSA model. In the first approach, the simulated runoff using the AGNPS-VSA model and the AGNPS model are compared with the observed runoff. In the second approach, the spatial distribution of the runoff generating areas according to the AGNPS-VSA method and AGNPS model are discussed.
6.8.1 Comparative evaluation of AGNPS-VSA and AGNPS approaches

As indicated earlier, 26 rainfall events were used to calibrate the AGNPS-VSA and AGNPS models and remaining 19 events were used to validate these models. The comparison of observed and simulated runoff volumes for calibration and validation phases by both the models are shown in Figs. 6.3 to 6.6.

![Graph showing comparison of simulated versus observed runoff for calibration phase.](image)

Figure 6.3: Comparison of the runoff simulated by the AGNPS-VSA model with the observed runoff for the calibration phase.
Figure 6.4: Comparison of the runoff simulated by the AGNPS-VSA model with the observed runoff for the validation phase.

Figure 6.5: Comparison of the runoff simulated by the AGNPS model with the observed runoff for the calibration phase.
Figure 6.6: Comparison of the runoff simulated by the AGNPS model with the observed runoff for the validation phase.

These results indicate that both the AGNPS-VSA and AGNPS models performed well for the simulation of runoff for all the seasons. The coefficient of determination ($R^2$) and Nash–Sutcliffe model efficiency coefficient (E) of AGNPS-VSA model for the calibration and validation phases were 0.79 and 0.82 and 0.78 and 0.71, respectively. The $R^2$ and E values of calibration and validation phases for the ANGPS models were 0.79 and 0.75 and 0.78 and 0.70, respectively. Thus, the AGNPS-VSA performed slightly better than the calibration phase and much better than the validation phase.

These data also show that around the 1:1 line was also similar for all the seasons indicating no systematic bias or major deviation. However, the simulated runoff volumes of the majority of spring events were under predicted by both models, which may be the weakness in the simulation of spring hydrology when the presence of a frost layer at a shallow depth could result in more runoff than simulated by both the
models. The results also indicate that the events generating small amount of runoff exhibit less variation as compared to the events generating large amount of runoff.

6.8.2 Comparative evaluation between AGNPS-VSA model and AGNPS model

Nine representative rainfall events (small, average and large) covering three seasons were randomly selected from the 45 events to further investigate the performance of AGNPS-VSA and AGNPS model. This included three events for spring, three for summer and three for fall seasons. Comparison of the simulated runoff by AGNPS-VSA and AGNPS model with the observed data is presented in Table 6.2.

<p>| Table 6.2: Comparison of the runoff simulated by AGNPS model and AGNPS-VSA model with observed runoff |
|--------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation (mm)</th>
<th>Observed runoff (m³)</th>
<th>AGNPS model Simulated runoff (m³)</th>
<th>AGNPS-VSA model Simulated runoff (m³)</th>
<th>Runoff generating area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>03-May-12</td>
<td>29.70</td>
<td>3214</td>
<td>2236</td>
<td>2536</td>
</tr>
<tr>
<td></td>
<td>10-May-13</td>
<td>15.01</td>
<td>1180</td>
<td>912</td>
<td>1142</td>
</tr>
<tr>
<td></td>
<td>28-May-13</td>
<td>38.60</td>
<td>3196</td>
<td>4178</td>
<td>4428</td>
</tr>
<tr>
<td>Summer</td>
<td>08-Sep-12</td>
<td>25.76</td>
<td>784</td>
<td>694</td>
<td>763</td>
</tr>
<tr>
<td></td>
<td>08-Jul-13</td>
<td>14.76</td>
<td>183</td>
<td>136</td>
<td>178</td>
</tr>
<tr>
<td></td>
<td>31-Jul-13</td>
<td>35.68</td>
<td>1056</td>
<td>724</td>
<td>834</td>
</tr>
<tr>
<td>Fall</td>
<td>14-Oct-11</td>
<td>47.16</td>
<td>3596</td>
<td>2188</td>
<td>2646</td>
</tr>
<tr>
<td></td>
<td>27-Nov-11</td>
<td>15.41</td>
<td>586</td>
<td>408</td>
<td>624</td>
</tr>
<tr>
<td></td>
<td>23-Oct-12</td>
<td>24.52</td>
<td>745</td>
<td>874</td>
<td>858</td>
</tr>
</tbody>
</table>
These results indicate that during spring season both the models under predicted two out of the three events and over predicted the third event. AGNPS-VSA model simulated runoff closer to observed runoff than AGNPS model for two under predicted events but for the third event on 28-May-13, it over predicted the runoff by 39 %. For this event AGNPS model over predicted observed runoff by 31 %.

During summer season, the AGNPS-VSA model simulated runoff much closer to observed runoff than AGNPS model. The difference between simulated runoff and observed runoff by AGNPS model was 23 % (11% to 31 %) whereas the difference by AGNPS-VSA model was 12 % (3 % to 21 %). During fall season, the AGNPS-VSA model also simulated runoff closer to observed runoff than AGNPS model. AGNPS model under predicted the runoff for two out of the three events, whereas, AGNPS-VSA model under predicted one rainfall event of dated 23-Oct-12. The difference between simulated runoff and observed runoff for the AGNPS model was 30 % (17% to 39 %) and for the AGNPS-VSA model was 16 % (15 % to 26 %). The result indicates that AGNPS-VSA model has better capability in predicting runoff than the AGNPS model. The performance of AGNPS-VSA was best during summer season followed by fall and spring season. Both the model showed large difference between simulated and observed runoff during spring season which may be due to presence of frost layer in the top soil layer.

The overall result indicate that the AGNPS-VSA model has the better capability of predicting the runoff amount ($R^2 = 0.77$ and Nash–Sutcliffe efficiency coefficient $E = 0.76$) than the AGNPS model ($R^2 = 0.75$ and $E = 0.70$).
The major difference between AGNPS model and AGNPS-VSA model is that the AGNPS model does not have the capability to predict runoff generating areas as it used infiltration-excess approach as the primary runoff-generating mechanism and assigns a CN value to each cell according to its soil type, land use and hydrological conditions. AGNPS-VSA model is based on saturation excess runoff generating mechanism and assigns CN value to each cell according to its topographic wetness index class. Different TWI class of the cell categorises its relative susceptibility of the becoming saturated and generating saturation excess surface runoff. AGNPS-VSA model assigns higher CN value to the cell having higher TWI index class and lower CN to cells having lower TWI class.

In this study, due to uniform dominant soil type and land use, the AGNPS model assigned a CN value of 69.4 to all the cells and the simulated results by AGNPS model predicted that the entire watershed was generating runoff for all the rainfall events. Whereas, the results of AGNPS-VSA model indicates that only saturated areas of the watershed were generating the runoff and for the rest of the areas, water was infiltrating during the rainfall event. The spatial pattern of runoff generating areas simulated by the AGNPS-VSA model for three spring events (SP-1, SP-2 and SP-3), three summer events (SU-1, SU-2 and SU-3) and three fall events (F-1, F-2 and F-3) are shown in Fig. 6.7.
These results show strong seasonal influence on the variability of runoff generating areas. During spring season, large portion of watershed generates runoff, followed by fall and summer season. This is due to high soil moisture content during spring than fall and summer seasons. Small saturated areas during summer season can be attributed to the dry conditions high temperatures and evaporation demand.

The simulation results by AGNPS-VSA model (Table 6.2) indicate that 55% (38-66%) of the watershed area generate runoff during spring, 21% during summer (14-27%) and 36% (26-49%) fall seasons. Comparing similar evens of 28-May-13 during
spring, 08-July-13 during summer and 27-Nov-11 during fall indicates that for almost similar magnitude of rainfall events the runoff generating area was 38% during spring, 26% during fall and 14% during summer season.

Two other similar rainfall events of summer and fall season dated 08-Jul-13 and 27-Nov-11 with rainfall of 14.76 mm and 15.41 mm resulted in runoff generating areas of 14 % (SU-2) and 26 % (F-2) respectively. Similar temporal pattern of runoff generating area is also visible for other rainfall events. During summer season a 25.76 mm of rainfall event on 08-Sep-12 resulted in 22 % (SU-1) of runoff generating area, whereas similar rainfall events of 24.52 mm on 23-Oct-12 resulted in 34 % (F-3) of runoff generating area. This indicates that for the same amount of rainfall, runoff generating area is more during fall season than summer season.

The AGNPS-VSA model predicts that the central and lower portions of the watershed generates most of the runoff where due to flattening of slope and the large upslope contributing area has higher probability of saturation. It is also evident from these results that the flow paths are the areas with high probability of saturation and generates most of the runoff during rainfall events.

These results suggest that the AGNPS-VSA model has the capability to predict the locations of runoff generation areas realistically in saturation excess dominated watersheds and is in consistent with the VSA concept. The AGNPS-VSA model represents the spatial hydrological patterns with a rational that the area adjoining to flow paths might be more logical locations for targeted water quality protection applications. Watersheds where saturation excess is the dominant runoff process, the
developed AGNPS-VSA approach provides a better approach to estimate realistic spatial distribution of runoff generation areas to formulate targeted management strategy to effectively manage nonpoint source pollution.

6.9 Conclusions

In this study, an alternative approach based on saturation excess runoff generating mechanism has been incorporated into the AGNPS model. The modified AGNPS-VSA approach assigns CN value to each cell according to its TWI class that categorises its relative susceptibility for becoming saturated and generating surface runoff. The developed approach has improved the capability of the AGNPS model to locate critical runoff generating areas in a watershed to develop economically feasible and environmentally sustainable water quality management strategies for agricultural for agricultural non-point source pollution management.

6.10 References


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CHAPTER 7

Conclusions and recommendations

This study focused on (1) development of a low cost, robust and remotely operated WSN system for collecting climatic and hydrological data from a distantly located agricultural watershed (2) conducting an experimental field study to investigate factors affecting spatiotemporal variability of runoff generating areas (3) modification and evaluation of distributed CN-VSA method using experimental field data and (4) development of an event-based hydrological model to simulate the dynamics of variable source areas.

7.1 Conclusions

The outcome of this research has provided a methodology to map sources of surface runoff and groundwater recharge in a watershed. The application of the results of this study will help in identification of source areas of runoff generation and associated pollutants. Identification of such source areas will lead to the selection of a specific and targeted BMPs for the development of economically feasible and environmentally sustainable non-point source pollution management strategies.

The following conclusions have been drawn from this study.

1. An efficient and robust WSN system comprised of advanced wireless network technology was developed for monitoring and collecting climatic and hydrologic data from a remotely situated agricultural watershed. The developed WSN system can be accessed from any computer connected to
the internet for real time collection of field hydrologic data. The developed remote data collection system reduced the number of site visits, efficient operation and maintenance of the system and has the potential for varieties of application in hydrologic research and resulted in lower monitoring and maintenance costs.

2. The result confirmed that the saturation excess runoff generation mechanism was the dominant runoff generating mechanism in the experimental watershed. Runoff was generated, even though the rainfall intensity hardly exceeded the saturated hydraulic conductivity of the soil.

3. In Ontario climatic conditions, the rainfall amount is the most significant factor affecting the magnitude of the runoff generating areas in a watershed followed by Initial soil moisture and rainfall intensity.

4. The topographic indices have strong and regionally consistent correlations with the probabilities of saturated areas. These indices can be used to identify hydrologically sensitive areas with higher relative propensities for runoff generation, within a watershed and can be easily incorporated into water quality models.

5. The modified distributed CN-VSA method, incorporating the seasonal changes in the potential maximum retention is a simple and better tool to estimate runoff and to locate critical runoff generating areas within a watershed.

6. The AGNPS-VSA model is better model than the AGNPS model for simulation of event runoff in regions dominated by saturation excess runoff.
process and has the capability to identify the spatial distribution of runoff generating areas in a watershed.

### 7.2 Recommendations for future research

1. Field monitoring of large size watersheds is required for quantification and delineating VSAs under different types of soil, land use, topography and climatic conditions.

2. Extensive field studies are required to verify various theories of variable source area hydrology and its governing factors.

3. This study focused on the development of AGNPS-VSA model for the prediction of runoff and identification of runoff generating areas based on VSA hydrology concept. Further research is needed to improve this modeling approach and make it user-friendly. The developed model has been evaluated on a 22 ha watershed and has given satisfactory results. There is a need to evaluate this model on a large watershed.

4. This research was conducted in humid and temperate climatic conditions of southern Ontario. There is a need for such field study in other climatic conditions to investigate the concept of variable source area hydrology.
Appendix - A

Historical weather data of the study watershed

Elora, Ontario has a humid continental climate with warm summers and no dry season. Over the course of a year, the temperature typically varies from -13.9 °C to 21.4 °C and is rarely below -18 °C or above 28 °C. The hottest day on record was in 1988 with high of 35.2 °C and coldest day was in 1994 with low of -30 °C. The warm season lasts from May 20 to September 15 and the cold season lasts from December 5 to March 4. The monthly climate data of temperatures is shown in Table A.1.

Table A.1: Monthly temperatures of Elora research site in 2011, 2012 and 2013 compared to 27 year normal temperatures

<table>
<thead>
<tr>
<th>Month</th>
<th>27 year normal</th>
<th>Temperature (°C)</th>
<th>2011 Monthly Average</th>
<th>2012 Monthly Average</th>
<th>2013 Monthly Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monthly Minimum</td>
<td>Monthly Maximum</td>
<td>Monthly Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>-23.5</td>
<td>7.7</td>
<td>-6.7</td>
<td>-10.2</td>
<td>-3.9</td>
</tr>
<tr>
<td>February</td>
<td>-22.2</td>
<td>6.1</td>
<td>-6.8</td>
<td>-7.9</td>
<td>-2.5</td>
</tr>
<tr>
<td>March</td>
<td>-17.9</td>
<td>17.2</td>
<td>-1.2</td>
<td>-3.4</td>
<td>5.6</td>
</tr>
<tr>
<td>April</td>
<td>-6.5</td>
<td>23.2</td>
<td>6.0</td>
<td>5.5</td>
<td>5.3</td>
</tr>
<tr>
<td>May</td>
<td>-1.4</td>
<td>28.3</td>
<td>12.4</td>
<td>12.6</td>
<td>14.7</td>
</tr>
<tr>
<td>June</td>
<td>4.1</td>
<td>30.9</td>
<td>17.3</td>
<td>16.5</td>
<td>18.3</td>
</tr>
<tr>
<td>July</td>
<td>7.2</td>
<td>31.0</td>
<td>19.7</td>
<td>21.4</td>
<td>21.3</td>
</tr>
<tr>
<td>August</td>
<td>5.8</td>
<td>30.2</td>
<td>18.4</td>
<td>19.0</td>
<td>18.5</td>
</tr>
<tr>
<td>September</td>
<td>0.5</td>
<td>28.4</td>
<td>14.6</td>
<td>15.0</td>
<td>13.8</td>
</tr>
<tr>
<td>October</td>
<td>-3.9</td>
<td>23.6</td>
<td>8.2</td>
<td>8.9</td>
<td>8.6</td>
</tr>
<tr>
<td>November</td>
<td>-10.0</td>
<td>16.2</td>
<td>2.3</td>
<td>4.8</td>
<td>1.5</td>
</tr>
<tr>
<td>December</td>
<td>-19.5</td>
<td>9.3</td>
<td>-3.7</td>
<td>-1.3</td>
<td>-0.7</td>
</tr>
</tbody>
</table>
The average annual precipitation in the region is 875 mm and the maximum precipitation was 1162.4 mm in the year 1992. The minimum rainfall of 679.2 mm was recorded during the year 2012. The monthly precipitation data is presented in Table A.2.

Table A.2: Monthly Precipitation of Elora research site in 2011, 2012 and 2013 compared to 27 year normal precipitation

<table>
<thead>
<tr>
<th>Month</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>27.2</td>
<td>114.9</td>
<td>67.5</td>
<td>47.6</td>
<td>46.8</td>
<td>80.5</td>
</tr>
<tr>
<td>February</td>
<td>14.8</td>
<td>91.6</td>
<td>47.3</td>
<td>58.2</td>
<td>32.0</td>
<td>71.2</td>
</tr>
<tr>
<td>March</td>
<td>28.7</td>
<td>86.9</td>
<td>56.2</td>
<td>68.1</td>
<td>31.0</td>
<td>40.6</td>
</tr>
<tr>
<td>April</td>
<td>30.0</td>
<td>131.4</td>
<td>72.4</td>
<td>90.7</td>
<td>30.0</td>
<td>123.8</td>
</tr>
<tr>
<td>May</td>
<td>0.0</td>
<td>129.6</td>
<td>77.8</td>
<td>113.3</td>
<td>28.2</td>
<td>102.0</td>
</tr>
<tr>
<td>June</td>
<td>22.6</td>
<td>184.1</td>
<td>89.6</td>
<td>87.0</td>
<td>64.6</td>
<td>122.3</td>
</tr>
<tr>
<td>July</td>
<td>8.9</td>
<td>182.1</td>
<td>88.1</td>
<td>31.9</td>
<td>30.4</td>
<td>130.9</td>
</tr>
<tr>
<td>August</td>
<td>12.1</td>
<td>198.3</td>
<td>79.5</td>
<td>158.6</td>
<td>62.6</td>
<td>69.5</td>
</tr>
<tr>
<td>September</td>
<td>25.8</td>
<td>142.9</td>
<td>80.2</td>
<td>76.1</td>
<td>106.2</td>
<td>142.9</td>
</tr>
<tr>
<td>October</td>
<td>15.4</td>
<td>138.4</td>
<td>78.4</td>
<td>128.9</td>
<td>127.3</td>
<td>133.6</td>
</tr>
<tr>
<td>November</td>
<td>33.7</td>
<td>157.6</td>
<td>74.6</td>
<td>90.5</td>
<td>40.2</td>
<td>33.7</td>
</tr>
<tr>
<td>December</td>
<td>0.2</td>
<td>104.1</td>
<td>60.7</td>
<td>85.5</td>
<td>79.9</td>
<td>43.2</td>
</tr>
<tr>
<td>Total yearly</td>
<td>872.3</td>
<td>1064.4</td>
<td>679.2</td>
<td>1094.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Precipitation, temperature and soil moisture data for fall season (2011), year 2012 and year 2013 are shown in Figures A.1, A.2 and A.3 respectively.

Figure A.1: Precipitation, temperature and soil moisture data of study watershed for fall 2011

Figure A.2: Precipitation, temperature and soil moisture data of study watershed for year 2012
Figure A.3: Precipitation, temperature and soil moisture data of study watershed for year 2013
Appendix - B

Soil and land use/cover of study watershed

Soil samples were collected from fifteen locations in the study watershed (Fig. A.4) for testing various attribute of soil. The soil testing analysis was carried out in the soil testing laboratory of the School of Engineering.

Figure A.4: Map showing locations of soil testing in study watershed

Textural analysis of the soil surface (0 to 20 cm) resulted in the surface soil being classified as sandy loam (Hydrologic Soil Group B). Table A.3 contains the
percentage range of the primary grain size analysis of 15 soil samples. The soil class was determined using a soil texture triangle as shown in Fig. A.5.

Table A.3: Percentages of the primary soil separates (0-20 cm)

<table>
<thead>
<tr>
<th>Soil Textural Class</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Loam</td>
<td>57 to 65</td>
<td>28 to 34</td>
<td>7 to 16</td>
<td>B</td>
</tr>
</tbody>
</table>

Figure A.5: Soil textural triangle (USDA)

The soil testing results of bulk density, porosity and field saturated hydraulic conductivity are presented in Table A.4. Constant head Guelph Permeameter (GP)
was used to obtain in-situ measurements of field saturated hydraulic conductivity. The soil depth in the study watershed varied from 0.60 to 0.90 m underlain by a restrictive layer.

Table A.4: Soil testing results of bulk density and field saturated hydraulic conductivity

<table>
<thead>
<tr>
<th>Sr.</th>
<th>Location ID</th>
<th>Northing</th>
<th>Easting</th>
<th>Soil depth</th>
<th>Bulk density</th>
<th>Saturated hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D-01</td>
<td>547737</td>
<td>4833451</td>
<td>0.82</td>
<td>1170</td>
<td>272</td>
</tr>
<tr>
<td>2</td>
<td>D-02</td>
<td>547666</td>
<td>4833380</td>
<td>0.87</td>
<td>1210</td>
<td>279</td>
</tr>
<tr>
<td>3</td>
<td>D-03</td>
<td>547616</td>
<td>4833331</td>
<td>0.84</td>
<td>1160</td>
<td>294</td>
</tr>
<tr>
<td>4</td>
<td>D-04</td>
<td>547536</td>
<td>4833251</td>
<td>0.78</td>
<td>1220</td>
<td>287</td>
</tr>
<tr>
<td>5</td>
<td>D-05</td>
<td>547460</td>
<td>4833175</td>
<td>0.81</td>
<td>1190</td>
<td>357</td>
</tr>
<tr>
<td>6</td>
<td>D-06</td>
<td>547433</td>
<td>4833149</td>
<td>0.83</td>
<td>1110</td>
<td>336</td>
</tr>
<tr>
<td>7</td>
<td>D-07</td>
<td>547378</td>
<td>4833094</td>
<td>0.86</td>
<td>1260</td>
<td>316</td>
</tr>
<tr>
<td>8</td>
<td>D-08</td>
<td>547603</td>
<td>4833577</td>
<td>0.76</td>
<td>1130</td>
<td>274</td>
</tr>
<tr>
<td>9</td>
<td>D-09</td>
<td>547481</td>
<td>4833531</td>
<td>0.71</td>
<td>1260</td>
<td>282</td>
</tr>
<tr>
<td>10</td>
<td>D-10</td>
<td>547391</td>
<td>4833502</td>
<td>0.69</td>
<td>1180</td>
<td>374</td>
</tr>
<tr>
<td>11</td>
<td>D-11</td>
<td>547323</td>
<td>4833442</td>
<td>0.69</td>
<td>1230</td>
<td>356</td>
</tr>
<tr>
<td>12</td>
<td>D-12</td>
<td>547266</td>
<td>4833391</td>
<td>0.74</td>
<td>1150</td>
<td>324</td>
</tr>
<tr>
<td>13</td>
<td>D-13</td>
<td>547229</td>
<td>4833358</td>
<td>0.66</td>
<td>1200</td>
<td>354</td>
</tr>
<tr>
<td>14</td>
<td>D-14</td>
<td>547202</td>
<td>4833333</td>
<td>0.64</td>
<td>1230</td>
<td>286</td>
</tr>
<tr>
<td>15</td>
<td>D-15</td>
<td>547158</td>
<td>4833295</td>
<td>0.71</td>
<td>1140</td>
<td>382</td>
</tr>
</tbody>
</table>

The entire study watershed was under the cultivation of hay crop during the study period. The area within 40 km of this study site was covered by croplands (45 %), grasslands (32 %), and forests (21 %).
Appendix - C

Lidar survey and topographical analysis of the study watershed

A professional surveying company, Triatic Imaging Inc. was hired to carry out the Lidar survey of the study watershed in order to develop a high resolution Digital Elevation Model (DEM). The DEM was used to obtain critical geomorphic features, such as hill slope angles, slopes and drainage channels of the study watershed.

Lidar is an acronym for Light Detection and Ranging. It is a device that uses laser pulses to measure the distance and other properties of a target. Lidar technology is one of the most important inventions in the field of optical Remote Sensing. The Lidar sensors emit 5,000 to 50,000 laser pulses per second and the information about the target objects are derived from the time interval of these laser pulses. The distance of an object is determined by the time difference of emitted and reflected signals.

Lidar technology is widely used for a variety of fields of application such as geometrics, geography, geology seismology, forestry, remote sensing, and atmospheric physics (Arthur, 1991). Lidar technology is also useful for three dimensional imaging such as Digital Elevation Models (DEM) and Triangular Irregular Network (TIN) for topographical analysis. A DEM is an assembly of distinct elevation points spaced at regular horizontal intervals. In the field of water resource engineering, DEM has proven to be helpful in creating topographic maps, contour maps, floodplain analysis and hydrological modeling.
For this study, the Lidar survey was carried out by using the very sophisticated instrument Leica Geo-systems Scan Station–C10 (Fig. A.6) with well-established photogrammetric techniques. The recorded point data was then processed by filtering vegetation, local spikes and noises to generate high resolution 200 mm grid size bare ground Digital Elevation raster files. The DEM of the study watershed is shown in Fig. A.7. The topographic cross section profile of the study watershed at sections X-X and Y-Y were created using ESRI’s ArcGIS program and are presented in Figures A.8 and A.9. The contour map and stream network of the study watershed were created from the Lidar DEM as shown in Figures A.10 and A.11.

Figure A.6: LiDar data acquiring instrument (Leica Geo systems Scan Station C–10)
Figure A.7: Lidar generated DEM of study watershed

Figure A.8: Cross Section profile at X-X of study watershed
Figure A.9: Cross Section profile at Y-Y of study watershed

Figure A.10: Topographic slope and contours of the study watershed
Figure A.11: Drainage lines and field outlet of study watershed
Appendix - D

Topographic wetness index of the study watershed

Topography has been a main focus since the inception of VSA concept for runoff generation (Hewlett and Hibbert 1967). It plays an important role in the spatial distribution of soil moisture, hydrological processes and watershed responses to the precipitation inputs. (Rodhe and Seibert 1999; Seibert et al. 1997). In hilly watersheds with moderate to steep topography, the gravity component dominates the hydraulic potential, and terrain characteristics is a vital variable in determining the watershed response and the distribution of water to rainfall inputs (Beven and Kirkby 1979; O’Loughlin 1986; Rodriguez et al. 1979).

Kirkby in 1975 proposed that the distributed nature of catchment responses could be indexed on the basis of topographic analysis. Field measurements of soil water content are insufficient to provide the continuous spatial coverage needed for land-management applications (Hassan et al. 2007). Therefore, as an alternative to field measurements of soil water content, topographic indices of wetness can be used to generate spatially continuous soil water information for identifying saturation excess areas within the watershed (Western et al. 1999). Beven and Kirkby in 1979 incorporated the concept of Topographic Index (TI) as a means of identifying areas with the greatest propensity to saturate into TOPMODEL. Since then various topographic indices have been commonly used to describe variation in spatial soil moisture patterns due to their simple and physically-based nature (Beven and Kirkby 1984; Burt and Butcher 1985; Moore et al. 1991). Nowadays, topographic indices are
widely used as an effective tool to predict potential VSAs by saturation excess runoff and have become an integral part of modern hydrological models (Agnew et al. 2006; Lyon et al. 2004; Western et al. 1999).

The topographic index used in TOPMODEL is expressed as $\ln \left( a / \tan \beta \right)$. In this equation, “$a$” represents the contributing area/unit contour length in $m^2$ and “$\tan \beta$” represents the local topographic gradient at the point. The digital elevation model (DEM) of the watershed is used to derive the Topographic index. The procedure of determining the Topographic Index using the DEM is presented in Fig. A.12

![Flow chart showing development of Topographic Index](image)

Figure A.12: Flow chart showing development of Topographic Index

Generally “$a$” is calculated by using a Single Flow Direction (SFD) or Multiple Flow Direction (MFD) algorithm. SFD algorithm assumes that water from a pixel drains into one of the neighbouring pixel having the lowest elevation (D8 algorithm) while MFD is
based on the assumption that water from the pixel could drain into more than one adjoining pixels (Quinn et al. 1991). Buchanan et al. 2012 suggested that the MFD algorithm provides more accurate flow and wetness distribution.

The general procedure for the calculation of TI from gridded DEM is described as below:

1. The DEM used should be assessed for sinks, and if appropriate, the sinks should be filled.
2. Flow direction should be calculated using the filled DEM.
3. Then, flow direction should be used to calculate flow accumulation.
4. In the above equation, “a” needs to be accounted for DEM resolution.
   \[ a = (\text{flow accumulation} + 1) \times \text{cell size} \]
5. Calculate slope (\( \beta \)) in degrees.
6. Convert slope (\( \beta \)) to radians = \( \beta \times \frac{1.570796}{90} \) (where \( \frac{\pi}{2} = 1.570796 \))
7. Run the final equation in the raster calculator: \( \ln \left( \frac{a}{\tan \beta \times T} \right) \)

The topographic index was extended by Beven (1986) to a soil topographic index in the form \( \ln \left( \frac{a}{\tan \beta \times T} \right) \) where T is the local transmissivity of the soil. This index incorporates the variability of soil characteristics of the landscape (Kulasova et al. 2014)

The Lidar DEM of the ERS study watershed was used to generate Topographic Wetness Index (TWI) map using ArcGIS 10 software. The upslope contributing area per unit length of contour (a) values were determined using the Whitebox Geospatial Analysis Tool (Lindsay 2014). This software uses multi directional flow path algorithm
(Alberto 2014) for more realistic flow and wetness distributions (Buchanan et al. 2012). The Topographic Wetness Index (TWI) map of 1 m grid cell resolution was made using following equation:

\[
TWI(\lambda) = \ln \left( \frac{a}{\tan \beta + D \cdot Ks} \right)
\]

Where \(D\) = Soil depth in m.

\(Ks\) = Average saturated hydraulic conductivity in m/day.

The TWI map of the study watershed is shown below in Fig. A.13.

![Topographic Wetness Index map of study watershed](image)

Figure A.13: Topographic Wetness Index map of study watershed
Appendix - E

Climatic and hydrological characteristics of randomly selected rainfall events from the spring, summer and fall seasons

Spring rainfall event dated 03-May-2012

Table A.5: Summary of climatic and hydrological characteristics of a spring event dated 03-May-12

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.50</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>5-day antecedent rainfall (mm)</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
<td>10.53</td>
</tr>
<tr>
<td>Initial soil moisture (% v/v)</td>
<td>33.0</td>
<td>30.5</td>
<td>30.4</td>
<td>33.6</td>
<td>30.2</td>
<td>28.6</td>
<td>31.4</td>
<td>35.1</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
<td>29.7</td>
</tr>
<tr>
<td>Initial abstraction (mm)</td>
<td>1.93</td>
<td>2.20</td>
<td>2.21</td>
<td>1.92</td>
<td>2.23</td>
<td>2.62</td>
<td>2.14</td>
<td>1.70</td>
</tr>
<tr>
<td>Obs. runoff (m$^3$)</td>
<td>507</td>
<td>414</td>
<td>397</td>
<td>744</td>
<td>293</td>
<td>185</td>
<td>539</td>
<td>246</td>
</tr>
<tr>
<td>Peak runoff (m$^3$/s)</td>
<td>456 X 10$^4$</td>
<td>409 X 10$^4$</td>
<td>349 X 10$^4$</td>
<td>689 X 10$^4$</td>
<td>248 X 10$^4$</td>
<td>141 X 10$^4$</td>
<td>513 X 10$^4$</td>
<td>237 X 10$^4$</td>
</tr>
<tr>
<td>Runoff Coefficient</td>
<td>0.5653</td>
<td>0.4558</td>
<td>0.4927</td>
<td>0.5666</td>
<td>0.4795</td>
<td>0.4160</td>
<td>0.5094</td>
<td>0.6411</td>
</tr>
</tbody>
</table>
Figure A.14: Runoff hydrograph at outlet of sub-watersheds 1 to 8 on dated 03-May-12

Figure A.15: Spatial distribution of runoff coefficients during rainfall event dated 03-May-12
Summer rainfall event dated 26-July-2012

Table A.6: Summary of climatic and hydrological characteristics of a summer event dated 26-July-12

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
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<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.50</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>5-day antecedent rainfall (mm)</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
<td>1.53</td>
</tr>
<tr>
<td>Initial soil moisture (% v/v)</td>
<td>13.3</td>
<td>13.0</td>
<td>12.8</td>
<td>13.4</td>
<td>12.6</td>
<td>11.7</td>
<td>13.2</td>
<td>14.1</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
<td>20.64</td>
</tr>
<tr>
<td>Max. rainfall intensity (mm/h)</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
<td>18.2</td>
</tr>
<tr>
<td>Initial abstraction (mm)</td>
<td>4.59</td>
<td>4.72</td>
<td>4.79</td>
<td>4.57</td>
<td>4.87</td>
<td>5.23</td>
<td>4.65</td>
<td>4.36</td>
</tr>
<tr>
<td>Obs. runoff (m³)</td>
<td>99</td>
<td>75</td>
<td>72</td>
<td>154</td>
<td>58</td>
<td>36</td>
<td>105</td>
<td>48</td>
</tr>
<tr>
<td>Peak runoff (m³/s)</td>
<td>141 X 10⁻⁵</td>
<td>115 X 10⁻⁵</td>
<td>93 X 10⁻⁵</td>
<td>217 X 10⁻⁵</td>
<td>64 X 10⁻⁵</td>
<td>32 X 10⁻⁵</td>
<td>150 X 10⁻⁵</td>
<td>95 X 10⁻⁵</td>
</tr>
<tr>
<td>Runoff Coefficient</td>
<td>0.1583</td>
<td>0.1188</td>
<td>0.1280</td>
<td>0.1686</td>
<td>0.1371</td>
<td>0.1165</td>
<td>0.1426</td>
<td>0.1795</td>
</tr>
</tbody>
</table>

Figure A.16: Runoff hydrograph at outlets of sub-watershed 1 to 8 on dated 26-July-12
Figure A.17: Spatial distribution of runoff coefficients during event dated 26-July-12

Fall rainfall event dated 02-Dec-2012

Table A.7: Summary of climatic and hydrological characteristics of a fall event dated 02-Dec-12

<table>
<thead>
<tr>
<th></th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field area (ha)</td>
<td>3.02</td>
<td>3.06</td>
<td>2.71</td>
<td>4.42</td>
<td>2.06</td>
<td>1.50</td>
<td>3.56</td>
<td>1.29</td>
</tr>
<tr>
<td>5-day antecedent rainfall (mm)</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
</tr>
<tr>
<td>Initial soil moisture (% v/v)</td>
<td>25.26</td>
<td>23.03</td>
<td>22.77</td>
<td>26.02</td>
<td>22.49</td>
<td>20.23</td>
<td>23.88</td>
<td>28.53</td>
</tr>
<tr>
<td>Max. rainfall intensity (mm/h)</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
<td>9.16</td>
</tr>
<tr>
<td>Initial abstraction (mm)</td>
<td>3.36</td>
<td>3.69</td>
<td>3.73</td>
<td>3.27</td>
<td>3.78</td>
<td>4.20</td>
<td>3.56</td>
<td>2.52</td>
</tr>
<tr>
<td>Obs. runoff (m$^3$)</td>
<td>171</td>
<td>133</td>
<td>128</td>
<td>238</td>
<td>96</td>
<td>63</td>
<td>184</td>
<td>90</td>
</tr>
<tr>
<td>Peak runoff (m$^3$/s)</td>
<td>$2.142 \times 10^3$</td>
<td>$1.933 \times 10^3$</td>
<td>$1.626 \times 10^3$</td>
<td>$3.217 \times 10^3$</td>
<td>$1.153 \times 10^3$</td>
<td>$6.53 \times 10^3$</td>
<td>$2.398 \times 10^3$</td>
<td>$1.083 \times 10^3$</td>
</tr>
<tr>
<td>Runoff Coefficient</td>
<td>0.2625</td>
<td>0.2011</td>
<td>0.2186</td>
<td>0.2498</td>
<td>0.2159</td>
<td>0.1942</td>
<td>0.2393</td>
<td>0.3239</td>
</tr>
</tbody>
</table>
Figure A.18: Runoff hydrograph at outlets of sub-watershed 1 to 8 on dated 02-Dec-12

Figure A.19: Spatial distribution of runoff coefficients during event dated 02-Dec-12