RUNOFF GENERATION IN PASTURES OF THE APPALACHIAN PLATEAU REGION OF NORTH ALABAMA

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RUNOFF GENERATION IN PASTURES OF THE APPALACHIAN PLATEAU REGION OF NORTH ALABAMA

Sumit Sen

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RUNOFF GENERATION IN PASTURES OF THE APPALACHIAN PLATEAU REGION OF NORTH ALABAMA

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VITA

Sumit Sen, son of Sushil and Shirin Sen was born on October 20, 1978 in Roorkee, Uttaranchal, India. He received his Bachelor of Technology degree in Agricultural Engineering from Allahabad Agriculture Institute, India. He moved to Fayetteville, Arkansas in August 2002 and earned a Master's degree in Agricultural & Biological Engineering from University of Arkansas. He joined the doctoral program in Biosystems and Civil Engineering Department at Auburn University in Spring 2005. He was recognized and awarded the Outstanding International Graduate Student award for the year 2009. During his doctoral studies he got married to Jaitika and they are expecting their first child in October 2009.

DISSERTATION ABSTRACT

RUNOFF GENERATION IN PASTURES OF THE APPALACHIAN PLATEAU REGION OF NORTH ALABAMA

Sumit Sen

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A detailed hillslope-scale hydrologic study was conducted in a pasture at the Sand Mountain region of north Alabama, USA. A 0.12 ha hillslope was intensively instrumented using 31 distributed surface and subsurface runoff sensors, a tipping-bucket rain gage, and a 0.31 m HS-flume. Data sets were collected during several rainfall events occurred in 2006 and 2007. This data was used in the hydrologic modeling part of this study.

Results from three rainfall events of differing characteristics, which occurred in 2006, using sensor data at four locations with different soil hydraulic properties along the hillslope showed that the main surface runoff generation mechanism in pastures of this region is infiltration excess. Rainfall intensity and soil hydraulic conductivity were found to play a dominant role in the surface runoff generation process. Furthermore, it was observed that only periods of high intensity rainfall (relative to saturated hydraulic conductivity) produced surface runoff.

Data analysis for six rainfall events in 2007 showed that the maximum runoff generation area that contributed to runoff at the outlet of the hillslope, varied between 67 and 100%. Furthermore, the data showed that as the rainfall intensity changed during a rainfall event, the runoff generation areas expanded or contracted. During rainfall events of high-intensity short- to medium-duration, 4 to 8% of total rainfall was converted to runoff at the outlet. Rainfall events with medium- to low-intensity, medium duration were found less likely to generate runoff at the outlet.

A physically-based, distributed hydrological model, $HIRO_2$, which considers infiltration-excess (Hortonian overland flow) runoff generation as the dominant mechanism, and incorporates most of the hydrologic processes occurring over a hillslope, was found to be applicable at a hillslope-scale. The model showed agreement with the observed spatial and temporal variability of runoff generation areas. The model results helped explain the interaction among hydrologic characteristics such as topography, soil parameters, and rainfall characteristics and their relation to surface runoff mechanisms.

The study demonstrates that only the areas of low hydraulic conductivity zones that are connected generate surface runoff during high intensity rainfall events. Since only high intensity periods of a few rainfall events generated runoff and also because less than about 10% of the rainfall was converted to runoff, this study indicates that subsurface flow is more important in the pastures of this region.

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TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

CHAPTER 2. RUNOFF GENERATION MECHANISMS IN PASTURES OF THE SAND MOUNTAIN REGION OF ALABAMA – A FIELD INVESTIGATION

CHAPTER 3. SPATIAL-TEMPORAL VARIABILITY AND HYDROLOGIC CONNECTIVITY OF RUNOFF GENERATION AREAS IN A NORTH ALABAMA PASTURE

CHAPTER 4. APPLICATION OF HIRO$_2$ HYDROLOGIC MODEL FOR SIMULATING HORTONIAN OVERLAND FLOW ON A PASTURE HILLSLOPE IN NORTH ALABAMA

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Understanding hillslope hydrologic processes occurring during and after a rainfall event is an essential element of watershed management. In the last few decades, many experimental hillslope studies have been conducted to understand rainfall and runoff processes. Over the years, researchers (e.g., Hewlett and Hibbert, 1963; Whipkey, 1965; Kirkby, 1978, 1988; and O'Loughlin, 1990) have recognized the importance of hillslope hydrology not just for hillslope or watershed-scale hydrological studies but also because of its applicability to environmental, water quality, hydroecology and hydrogeomorphology studies at the watershed-scale (Bronstert and Pate, 1997; Loague *et al.*, 2006). Although, there has been a plethora of hydrologic studies completed all over the world to understand different hydrologic processes, there is still a need to develop methods to characterize runoff generation mechanisms occurring over hillslopes. Furthermore, data are needed to test available hydrologic models at hillslope-scales. Therefore, in this study, hillslope hydrology experiments were conducted to:

a) understand the runoff generation mechanisms, b) relate the effect of hydrologic characteristics of a hillslope with the runoff generation mechanisms, and c) use a hydrologic model to simulate the effect of hydrologic characteristics on runoff generation mechanisms.

1.2 SURFACE RUNOFF GENERATION MECHANISMS

Hillslope hydrology is concerned with the differentiation of rainfall water passing through vegetation into the soil profile and surface runoff (Kirkby, 1988). The two primary hydrologic mechanisms which are believed to generate surface runoff are infiltration excess (IE) and saturation excess (SE). Infiltration excess surface runoff occurs when rainfall rate exceeds soil infiltration rate. This infiltration process was described by Horton, and has been termed as Hortonian or IE surface runoff (Horton, 1933). In contrast, SE surface runoff occurs when the water table rises, saturating the whole soil profile and creating a seepage face (Dunne and Black 1970; Govindaraju and Kavvas, 1991; Walter *et al.*, 2003). This type of surface runoff occurs particularly along or near-stream areas and tends to expand and contract during and between rainfall events. Another type of surface runoff, known as return flow, occurs when the subsurface flow emerges at the surface due to profile concavity, or in areas where there are soil horizons of low permeability (Bevan, 1987; Kirkby, 1988). Hursh and Fletcher (1942) first discovered that subsurface flow can also contribute to flood peak, which was further validated by the work of Hewlett and Hibbert (1963) and Whipkey (1965). In 1964, Betson presented the “partial contributing area” concept, explaining that in certain geographic areas surface runoff occurs from only a small distinct portion of the watershed. Other scientists have also described SE surface runoff in terms of variable source areas (VSAs). Hewlett and Hibbert (1967) proposed the VSA concept of surface runoff generation, suggesting that IE surface runoff is seldom a limiting factor in forested environments. Furthermore, Freeze (1974) suggested that the VSA concept could transport flow due to three mechanisms: 1) VSA – saturation surface runoff, 2) VSA – subsurface flow, and 3) partial area – surface runoff. Generally, in most watersheds, all of these types of runoff mechanisms occur. However, one or more of these mechanisms often dominate depending on the hydrologic characteristics of a watershed (Scherrer *et al.,* 2007).

1.2.1 SURFACE RUNOFF RELATED TO WATER QUALITY

Given that the surface runoff is the primary mechanism of pollutant transport (especially for particulate-bound pollutants), consideration of hydrologically active areas (HAAs) is critical to effectively address water quality issues associated with land-applied animal manure. Earlier work has shown that controlling the HAAs having high phosphorus (P) levels within the watershed provides the greatest opportunity to alleviate water quality problems because runoff during storm periods dominate P export (Pionke *et al.,* 1996). Using a VSA model, Zollweg *et al.* (1995) demonstrated that land use and management changes on HAAs (comprising only 1% of the total watershed area) can reduce dissolved P export to surface waters by 24%. Identification of HAAs and understanding surface runoff generation mechanisms are challenging issues, yet they are fundamental to controlling non-point losses of nutrients and pathogens. In fact, because of the poor understanding of the transport component of P-Index, the National

Phosphorus Runoff Project (NPRP) was initiated efforts to address the lack of understanding of dominant hydrologic variables that control surface runoff and P transport (Sharpley *et al.,* 2002). Environmental managers are recognizing that they cannot effectively address non-point source (NPS) pollution without a firm understanding of surface runoff generation processes. Therefore, there is a need to quantify the interactions of NPS with static (e.g., topography, depth to bedrock, land uses) and dynamic (e.g., soil moisture, soil conductivity, rainfall intensity, water table) properties of watershed that control the extent of HAAs (Wolock, 1993; Wood *et al.,* 1990) and influence the quality of surface runoff. Identification of critical HAAs also has implications for managing a wide range of hydrologic/water quality problems related to nutrient, sediment and pathogen transport (Srinivasan *et al.,* 2002).

1.3 EFFECT OF HYDROLOGIC CHARACTERISTICS ON SURFACE RUNOFF GENERATION AND THE DYNAMICS OF HYDROLOGICALLY ACTIVE AREAS

Hydrologic characteristics play an important role in converting the rainfall into surface runoff within a watershed. Surface runoff generation is a highly nonlinear and spatially-variable process (Pilgrim *et al.*, 1978; Hoover, 1990). The interaction between the static characteristics such as topography, soil and land cover, and dynamic characteristics such as time-varying rainfall characteristics, antecedent soil moisture conditions, infiltration rates, soil hydraulic properties and depth to water table affect the surface runoff generation process within a watershed (Hernandez *et al.*, 2003). Dunne *et al.* (1991) showed that on grassland hillslopes, effective infiltration rates vary with rainfall intensity and flow depth due to the interaction between rainfall, runoff, and vegetated microtopography. This study concluded that for short hillslopes or plots, effective infiltration rates are simply the spatial average of the saturated and unsaturated conductivities. However, for longer hillslopes, infiltration rates depend on hillslope length. Hillsides with flat terrain are more susceptible to large VSA than terrain with steep slopes (Hernandez *et al.*, 2003). Further, scientists have shown that infiltration and surface runoff generated by infiltration excess mechanism is highly sensitive to rainfall intensity (Walter *et al.*, 2003), whereas surface runoff generated by saturation excess mechanism is less sensitive to rainfall characteristics (Hernandez *et al.*, 2003). Kirkby *et al.* (2002) studied the effect of changing storm condition over time on the dynamics of runoff producing areas and showed that the topography, land use and geology play important roles in hillslope runoff generation processes. Ticehurst *et al.* (2007) showed that understanding the soil morphology and soil properties over the hillslope helps to identify the importance of hydrological flow paths in runoff generation processes.

1.4 IMPORTANCE OF HYDROLOGIC CONNECTIVITY

Hydrologic connectivity refers to the water movement from one location to another on a landscape that can generate surface runoff. The surface-runoff contributing areas on a hillslope are spatially and temporally dynamic during (and after) a rainfall event. To understand the overall hydrologic response of a natural landscape, it is important to understand the hydrologic connectivity of surface-runoff contributing areas. The complexity of the hydrological processes occurring within a watershed depend on the interaction between runoff generation mechanisms, hydrologic connectivity of runoff generation areas, and infiltration of runoff further down slope (Reaney *et al.*, 2007).

Even though a number of studies have suggested that runoff generation is spatially and temporally variable and hydrologic connectivity of runoff generation areas is important for overall hillslope response, only a few recent studies have shown this through hillslope studies under natural rainfall conditions.

1.5 IMPORTANCE OF HILLSLOPE HYDROLOGIC MODELING

Hillslope hydrologic modeling is an essential element of watershed modeling to understand different hydrological processes occurring during and after a rainfall event. Kirkby (1988) suggested that more than 95% of the stream water passes through the soil or over a hillside before reaching a channel network. Recently, many hydrological models have been developed for simulating hydrological processes at field- and watershed-scales. Meng *et al.* (2008) reviewed various models and classified them with distributed infiltration models and runoff as fully three-dimensional (3D) models and flow-path based models. Examples of these models include InHM, CAS2D, GSSHA, and KINEROS. These distributed models were determined to be computationally intensive. However, other models that use hydrologic response units (HRU) (e.g., SWAT, PRMS, SWIM) do not take into account the spatial and temporal variability of hydrologic processes and hence as computationally more efficient.

Although there has been a significant progress in understanding the processes governing the rainfall-runoff processes (Stomph *et al.,* 2002), researchers have continuously mentioned the need of experimental data from hillslope studies for testing hydrologic models (Loague and VanderKwaak, 2004). Due to the high spatial and temporal variability in many hydrological parameters in nature, some physical laws which are scale dependent cannot express these variabilities. Morbidelli *et al.* (2006) illustrated the importance of spatial variability of soil hydraulic conductivity for the infiltration-excess runoff generation mechanism through numerical simulation. Therefore, there is a need to develop and test a robust physically-based hydrological model which can be applied at different climate zones and most importantly can be applied at different scales, such as hillslope and watershed scale (Kirkby, 1988; Loague and VanderKwaak, 2004).

1.6 OBJECTIVES AND HYPOTHESES

The overall goal of this study is to develop a field-scale hydrological dataset which enhance a better understanding of hillslope flow and contaminant transport processes. Our study site was located in the Sand Mountain region of north Alabama. The specific reason for selecting this was that this area is in the highest broiler producing county (DeKalb county). At this site poultry litter is used on agricultural fields and pastures as a cheap alternative to commercial fertilizers, and this has caused build-up of soil P. Thus, the overall objective of this study was to identify the characteristics of surface runoff generation mechanisms which can be controlled using watershed management practices to improve water quality monitoring. Specific objectives of this study are:

1) Identify the runoff-generation mechanisms at a hillslope field site using distributed sensors. Hydrologic properties of the site were collected during and after several rainfall events.

2) (a) Delineate the spatial and temporal variability of runoff generation areas under multiple rainfall conditions,

   (b) Demonstrate the importance of hydrologic connectivity for generating runoff from a hillslope on which infiltration-excess is the dominant flow process.

3) Test the applicability of the $HIRO_2$ model for the Sand Mountain region of north Alabama

The specific research hypotheses were:

Objective 1:

- Infiltration excess is the main mechanism that produces surface runoff from the pastures of the Sand Mountain region.

Objective 2:

- Spatial and temporal distribution of runoff-contributing areas can be characterized by quantifying a few key hydrologic variables.

Objective 3:

- A physically-based model, such as $HIRO_2$, can simulate hydrologic processes occurring in the pastures of the Sand Mountain region.

1.7 ORGANIZATION OF THE STUDY

This study focuses on the above mentioned three objectives and hypotheses, and each of the objectives is covered in a separate chapter. Since the chapters are written in a journal format, the literature review pertaining to each objective is provided at the beginning of each chapter.

Chapter 2 presents the details of hillslope instrumentation used to measure surface runoff, and subsurface flow, during three rainfall events that occurred in 2006. It identifies the main surface runoff generation mechanism occurring in a pasture of the Sand Mountain region of North Alabama, which was our first objective. This chapter has already been published in Hydrological Processes (Sen *et al.*, 2008).

Chapter 3 presents the rainfall-runoff dynamics data collected using surface runoff and subsurface sensors for three rainfall events of different characteristics in 2007. Data used to characterize the spatial and temporal distribution of runoff contributing areas and their hydrologic connectivity, which was our second objective. This chapter has been accepted, pending correction, for publication in Hydrological Processes (Sen *et al.*, 2009).

Chapter 4 presents the application of the $HIRO_2$ model for simulating the runoff generation mechanisms occurring at the study site. The model was also used for delineating spatial and temporal distribution of runoff generation areas and their connectivity to the outlet at different rainfall events. This chapter addresses the third objective of this study. This chapter will be submitted in Hydrological Processes for publication.

Chapter 5 presents the conclusions of the study and provides recommendations for future research.

CHAPTER 2

RUNOFF GENERATION MECHANISMS IN PASTURES OF THE SAND MOUNTAIN REGION OF ALABAMA – A FIELD INVESTIGATION

2.1 INTRODUCTION

Alabama consistently ranks in the top three U.S. states in confined poultry (broiler) production. Confined broiler production results in about 1.8 million tons of litter each year containing high levels of nitrogen (N), phosphorus (P), pathogens, and other potential contaminants (e.g., Arsenic, Copper, and Zinc) (Kingery *et al.*, 1994). Land application of litter to pastures, as a cheap alternative to commercial fertilizer, has resulted in P contamination of surface water bodies and excessive buildup of P in soils of major poultry producing counties (e.g., Cullman, Marshall, Dekalb, and Blount) of the Sand Mountain region of north Alabama (Figure 2.1). Even though P is an essential nutrient for plant growth, runoff of P can accelerate eutrophication, resulting in severe impairment of water bodies that support aquatic, recreational and drinking water uses (Carpenter *et al.*, 1998; Daniel *et al.*, 1998). In addition to P, other water quality issues (e.g., pathogens) associated with massive amount of litter produced each year threatens the sustainability of the poultry industry in this region. In agricultural watersheds, surface runoff is recognized as the primary mechanism of transport of particulate-bound pollutants (e.g., P and pathogens) to nearby water bodies (Wetzel, 1983; Fleming and Cox, 1998). Studies have shown that nonpoint source (NPS) pollutants can be effectively managed by identifying the hydrologically active areas (HAAs; areas generating surface runoff) and controlling pollutant losses from those areas (Pionke *et al.*, 1996; Gburek and Sharpley, 1998; Gburek *et al.*, 2002; Heathwaite *et al.*, 2005). For accurate identification of HAAs, a thorough understanding of hillslope-scale surface runoff generation mechanisms is crucial. Thus, knowledge of surface runoff generation mechanisms is an important first step for reducing transport of NPS pollutants (especially those that are particulate bound) from hillslopes.

In the past, due to distinct variations in hydrologic behavior of a watershed, it has been difficult to identify and delineate HAAs (Pilgrim *et al.* (1978). However, recently, it has been recognized that there is a great need to use innovative approaches to: (a) test new and existing runoff generation theories and (b) test different hydrologic models that incorporate hydrologic properties (Hopmans and Pasternack, 2006). A few field-scale studies (e.g., Srinivasan *et al.*, 2001; Hernandez *et al.*, 2003; McGuire *et al.*, 2007) have been conducted to understand how static characteristics such as topography, depth to bedrock, and land cover, and dynamic characteristics such as time-varying rainfall characteristics, antecedent soil moisture conditions, soil hydraulic properties, and water levels in the soil profile affect surface runoff generation mechanisms. The objective of this study was to identify the primary mechanism responsible for surface runoff generation in pastures of the Sand Mountain region of north Alabama. Identification of runoff generation mechanism will lead to accurate delineation of HAAs and effective control of NPS pollutants in this region.

2.1.1 THEORETICAL CONSIDERATIONS

Hillslope hydrology is concerned with differentiation of rainfall water passing through vegetation into the soil profile and surface runoff (Kirkby, 1988). Infiltration excess (IE) and saturation excess (SE) are the two primary hydrologic mechanisms that are believed to generate surface runoff. Infiltration excess surface runoff occurs when rainfall rate exceeds soil infiltration rate. This infiltration process was described by Horton, and has been termed as Hortonian or IE surface runoff (Horton, 1933). In this type of mechanism, as the rainfall proceeds, water infiltrates into the soil profile increasing the moisture content at the soil surface. As the soil surface gets saturated, infiltration rate of water decreases, and if the rainfall intensity is higher than the infiltration rate, overland flow occurs (Figure 2.2). Usually this type of overland flow occurs in a deep water table environment and is influenced by soil type, slope, land use, and temporal variability of rainfall. Studies in the northeastern United States have shown that it is often improper to apply the Hortonian model, since during majority of the rainfall events, the infiltration rates are not exceeded by the rainfall rates (Ogden and Watts, 2000).

In contrast, SE surface runoff occurs when the perched water table rises, saturating the whole soil profile and creating a seepage face (Walter *et al.,* 2003; Dunne and Black 1970; Govindaraju and Kavvas, 1991) (Figure 2.2). This type of surface runoff occurs particularly along or near-stream areas and tends to expand and contract during and between rainfall events. Thus, this mechanism occurs mainly in soils with a restrictive layer below the surface, and is influenced by local topography, soil depth, and landscape position. Another type of surface runoff, known as return flow, occurs when the subsurface flow emerges out on the surface due to profile concavity, or in areas where there are soil horizons of low permeability (Kirkby, 1988; Beven, 1987).

In 1964, Betson (1964) presented the “partial area” or “contributing area” concept, explaining that in certain geographic areas surface runoff occurs from only a small distinct portion of the watershed. Other scientists have also described SE surface runoff in terms of variable source areas (VSAs). Hewlett and Hibbert (1963) proposed the VSA concept of surface runoff generation, suggesting that IE surface runoff is seldom a limiting factor in forested environments. Furthermore, Freeze (1974) suggested that VSA concept could transport flow due to three mechanisms: 1) VSA – saturation surface runoff, 2) VSA – subsurface flow, and 3) partial area – surface runoff. In most watersheds, all of these types of runoff mechanisms occur during storms. However, depending on the hydrologic characteristics of a watershed, one or more of these mechanisms often dominate.

More recently, several studies (e.g., Gburek and Sharpley, 1998; Srinivasan *et al.*, 2001; Srinivasan *et al.*, 2002) have suggested that surface runoff often occurs across small, identifiable portions of a landscape (called HAAs). Zollweg *et al.* (1995) termed these HAAs as ‘critical source areas’ and found that surface runoff from these areas contributes disproportionately to the overall watershed response. Furthermore, scientists have reported that storm flow (stream) originates from small but consistent portions of upstream areas that constitute less than 10% (usually 1-3%) of the watershed area, and even in these areas, only 10-30% of the rainfall causes surface runoff (Freeze, 1974). In another study, Walter *et al.* (2000) reported that approximately 10% of their watershed area was designated as hydrologically sensitive, which in turn accounted for about 20% of the total annual runoff. Several other field studies have attempted to map the HAAs due to SE and IE mechanisms by comparing the streamflow response to rainfall intensities using the soil moisture data collected by manual and automated tensiometers (Rogowski *et al.,* 1974; Anderson and Burt, 1978).

2.2 EXPERIMENTAL HILLSLOPE

2.2.1 GENERAL DESCRIPTION OF THE STUDY AREA

The study area lies in the eastern part of the Sand Mountain area of the Cumberland Plateau section of the Appalachian Plateaus physiographic province (Baker and Osborne, 1994). Elevation of the study area is 330 m above mean sea level. The study area receives approximately 137 cm of precipitation annually. Occurring mainly as rainfall, a significant portion of annual precipitation falls during winter and early spring months. The study was conducted on a 0.12 ha hillslope pasture field at the Sand Mountain Research and Extension Center (SMREC) located in DeKalb County, Alabama (Figure 2.1). The SMREC is one of the field research and extension units of the Alabama Agricultural Experiment Station. The hillslope represents a typical pasture in this region. A cool season grass (Kentucky 31 Tall Fescue) has been grown for many years on this site. The study site was extensively surveyed using a Real-Time Kinematic GPS (Trimble Navigation Limited, Sunnyvale, CA) unit to generate detailed microtopography

(Figure 2.1). Microtopography data from GPS unit was used to develop 0.5 m resolution digital elevation model (DEM) using ArcGIS 9.x software (ESRI, Redland, CA). The site has an average slope of 3.3%. Elevation differences in the middle are less as compared to upper and lower sections of the hillslope.

The main soils on the hillslope are Hartsells (fine-loamy, siliceous, subactive, thermic Typic Hapludults) and Wynnville (Fine-loamy, siliceous, subactive, thermic Glossic Fragiudults). The Hartsells series consists of moderately deep (sandstone at 50-100 cm), well-drained, moderately permeable soils that are formed from acid sandstone. These soils are found on nearly level to moderately steep ridges and upper slopes of hills and mountains. The Wynnville soils are moderately well drained, slowly permeable soils also formed from sandstone. The Wynnville soils have fragipans in the subsoils which are slowly permeable. Because both the sandstone layer and the fragipans are slowly permeable, short durations of water perching occurs above these restrictive layers. Soils were described and sampled at two locations within the study hillslope. Table 2.1 shows the soil horizonation and physical properties at both locations. Surface horizons were fine sandy loam in texture, had a moderate granular structure, and were very friable. Subsurface horizons were loamy textured with subangular blocky structure and firm consistency. Redox concentration and depletions features were observed at both locations. At the upslope location, these features were observed from 25-125+ cm, whereas at the downslope location, these features were observed from 76-159+ cm. The presence of these features suggests the occurrence of short-term perched water table in the soil profile.

Fragic characteristics (Btx) were found at both locations. Soft bedrock (Cr) was classified as a multicolored weathered sandstone, and moderately firm in place (Table 2.1).

2.2.2 INSTRUMENTATION

The hillslope was intensively instrumented with surface runoff and subsurface sensors, a rain gauge, an H-flume and shallow wells. In particular, pairs of surface runoff and subsurface sensors were installed at 27 points initially (until July 2006). In August 2006, four additional pairs of surface runoff and subsurface sensors were installed. The surface runoff sensors were miniature v-notch weirs made of 2-mm thick galvanized sheet metal with a sensor pin and a ground pin set 2 cm apart and 3 cm away from the v-notch and located on the upslope side of the sensor. The subsurface sensors, installed up to 42 cm depth, recorded the fluctuation in water table near the surface. Details of the surface runoff and subsurface sensors can be found in Srinivasan *et al.* (2001). The surface runoff and subsurface sensors were powered using 12-volt DC batteries. All sensors were connected to a series of multiplexers and dataloggers (model CR10X, Campbell Scientific, Inc. Logan, UT). A tipping bucket rain gauge measured the rainfall at 5-min intervals. Two shallow water wells with pressure transducers were installed to monitor the depth of water table when the water table was more than 42 cm deep. One well was located near the upslope end of the hillslope, while the other one was located near the downslope end of the hillslope. The site was instrumented such that the hillslope drained to a point where an H-flume recorded the overland flow from the entire instrumented hillslope. Since the total surface runoff recorded from January to mid-August, 2006 was very small, the 0.46 m of H-flume was replaced by a 0.31 m HS-flume to record discharges from the hillslope. All 31 surface runoff and subsurface sensors were installed in pairs to study the interaction between water table and surface runoff for the characterization of HAAs and runoff generation mechanisms.

At the initiation of a rainfall event, the rain gauge activated the surface runoff and subsurface sensors and the pressure transducers (in shallow wells and HS-flume) and the data was collected during and two hours after a rainfall event had seized. Rainfall, water table level (at subsurface sensor and shallow well locations), and occurrence of runoff at surface and subsurface sensor locations were collected at 5 min intervals. The data collection began in January 2006 and so far data for more than 30 rainfall events have been collected. However, for addressing the objective of this paper, three rainfall events were considered for detailed analysis.

2.3 DATA COLLECTION

2.3.1 IN-SITU SOIL HYDRAULIC CONDUCTIVITY MEASUREMENTS

Heterogeneity in soil hydraulic conductivity (k) may strongly influence the hydrologic characteristics of a hillslope (Corradini *et al.,* 1998). Thus, in-situ k measurements were obtained on December 5, 2006 to estimate the spatial variability of k in the study area. A disk infiltrometer (Decagon Devices, Inc., Pullman, WA) with 2.0 cm suction was used to perform the hydraulic conductivity measurements at the 31 sampling points (Table 2.2). Prior to the data collection a rainfall event of 0.45 cm occurred on December 1, 2006. Since this rainfall was small, it was assumed that there was no significant effect on the k values. At each sampling point, as the water infiltrated, the volume of water in the disk infiltrometer was recorded at regular time intervals. To calculate the hydraulic conductivity, van Genuchten parameters (van Genuchten, 1980) for a sandy loam soil were used ($\alpha = 0.075\ \text{cm}^{-1}$; $n = 1.89$). The nondimensional coefficient (A) was equal to 5.2 and the area was equal to 7.94 cm^2 for the disk infiltrometer. Hydraulic conductivity was calculated using the Zhang (1997) method, which is given by:

$$I = (C_1 t + C_2 \sqrt{t}) \qquad (1)$$

where, I is the cumulative infiltration (cm), t is the time (s), and C_1 (cm.s^{-1}) and C_2 ($\text{cm.s}^{-1/2}$) are the parameters related to sorptivity and hydraulic conductivity. The hydraulic conductivity of the soil was then computed using

$$k = \frac{C_1}{A} \qquad (2)$$

and A was computed using

$$A = \frac{11.65(n^{0.1} - 1)e^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}} \quad \text{where, } n \geq 1.9 \qquad (3)$$

where, n and α are the van Genuchten parameters for the soil, r_o is the disk radius, and h_o is the suction at the disk surface. The soil hydraulic conductivity given by the disk infiltrometer is about two-third of the true saturated hydraulic conductivity (Koorevaar *et al.,* 1983).

2.3.2 RAINFALL MEASUREMENTS

Figure 2.3 shows the amounts of rainfall for 26 rainfall events that occurred from January, 2006 to January, 2007. Rainfall events recorded during this period ranged from 0.33 to 7.40 cm producing a total of 55 cm of rainfall (which is well below 137 cm for average year). A few rainfall events, which occurred in early January, April, and November 2006, were missed because of power failure at the study site. To-date, very few rainfall events have generated surface runoff from the whole study area as recorded by the HS-flume at the outlet of the hillslope. Table 2.6 shows all the rainfall events collected during the sampling period. Out of 26 rainfall events, eight events generated runoff.

2.4 RESULTS AND DISCUSSION

2.4.1 RUNOFF GENERATION MECHANISM

Since it is not feasible to present detailed data for all rainfall events, data for three rainfall events with differing characteristics are presented in this paper. The first rainfall event, hereafter referred as event 1, occurred on June 23, 2006 and was a high-intensity, short duration event (Figure 2.4a). During event 1, 2.13 cm of rainfall occurred in 1 hour 45 minutes, with a maximum intensity of 76.2 mm/hr. The second rainfall occurred on September 7, 2006 (event 2), and was characterized as a medium-intensity, medium duration event (Figure 2.4b). The total rainfall amount was 3.43 cm and the rainfall duration was 3 hours 05 minutes, with a maximum intensity of 18.3 mm/hr. The third rainfall event occurred on October 27, 2006 (event 3), and was characterized as low-intensity, long duration event (Figure 2.4c). During event 3, 3.30 cm rainfall occurred in 19 hours 35 minutes, with a maximum intensity of 6.1 mm/hr.

Four different locations were randomly selected across the hillslope to analyze the data collected by the surface runoff and subsurface sensors for the three selected rainfall events. Location 4 (Figure 2.1) was selected from the upslope section because this area had a medium soil hydraulic conductivity value (11.1 mm/hr; Table 2.2). Location 16 (Figure 2.1) was selected from the middle section and also had a low soil hydraulic conductivity value (3.5 mm/hr; Table 2.2). Location 26 (Figure 2.1) was selected from the lower section and had a low soil hydraulic conductivity value (0.7 mm/hr; Table 2.2). Location 6 (Figure 2.1) was selected to evaluate the effect of a high soil hydraulic conductivity value (51.2 mm/hr) on the surface runoff generation mechanism.

During event 1 (Figure 2.4a), the first 20 minutes (from 1510 to 1530 hours) showed a higher rainfall intensity than the measured soil hydraulic conductivity (and most likely infiltration rate). At the same time, subsurface sensors showed the water table to be below the surface at locations 4, 6, 16, and 26. This suggests that surface runoff during that period was most likely due to the IE mechanism (Table 2.3 a, b, c, and d). The subsurface sensor at location 6 having high soil hydraulic conductivity showed an increase in perched water table. This suggested that at location 6, a restrictive layer exists on which a perched water table builds up when the rainfall amount and intensity is high enough. Location 16 also shows features of the presence of a restrictive layer near the surface. From 1530 to 1550 hours, although the rainfall intensity decreased, locations 4, 6, 16, and 26 continued to show runoff, which was attributed to residual runoff from the high intensity rainfall period.

Similar results were observed for event 2. The time period from 1620 to 1700 hours was selected to show the type of runoff generation mechanism that occurred during this storm (Table 2.4 a, b, c, and d). Analysis of the data shows that the rainfall intensity was within order of the measured soil hydraulic conductivities at location 4 and 16. Locations 4, 16, and 26 showed IE runoff during this period. Location 16 showed no runoff from 1620 to 1630 hours. The same location showed IE runoff from 1640 to 1700 hours (Table 2.4c). The subsurface sensor, however, showed an increase in perched water table at this location. This could be possibly due to the restrictive layer near the surface as discussed earlier. Considering that the rainfall intensity during this event was not orders of magnitude higher than the soil hydraulic conductivity estimated for this site, it is not surprising that no runoff was initially observed at this location 16. Location 6, which had a much higher hydraulic conductivity compared to the rainfall intensities for this event, showed no runoff. Furthermore, since this location also appears to have a restrictive layer near the surface, a perched water table builds up at this location as well. However, because of the medium rainfall intensity during this event, the water table did not reach the soil surface.

For event 3, the time period from 0330 to 0350 hours was selected for discussion (Figure 2.4c). This period is the initial part of the long duration storm that lasted for 19 hours and 35 minutes. During this period, rainfall intensity was much lower than the saturated hydraulic conductivity at most of the locations within the field. During this event location 4 and 26 showed runoff for the initial 10-15 min, followed by no runoff (Table 2.5 a, d). This was attributed to the initial existence of hydrophobicity of the soil. Location 6 (Table 2.5b), which had a high soil hydraulic conductivity, did not show any runoff during this event. Also, with the exception of a short period, no runoff was observed at locations 4 and 26.

Overall, data from three rainfall events with different characteristics and four sampling locations, representing three different landscape locations and three different soil hydraulic conductivities showed that even though a low hydraulic conductivity layer (sandstone layer and fragic characteristics) is present in this region, the mechanism of runoff generation in this region is mostly IE. Because the IE runoff generation mechanism is the primary mechanism generating runoff, soil hydraulic conductivity is the most important parameters that control runoff generation. Furthermore, since hydraulic conductivity controls runoff generation, understanding variations in the rainfall intensities is important. This study also suggests that runoff is most likely not generated from an entire hillslope, and that during a rainfall event, runoff is generated during periods when the rainfall intensity is high. This study, therefore, supports the findings of Zollweg *et al.* (1995) and Walter *et al.* (2000) which suggested that HAAs contribute runoff disproportionately with respect to overall watershed response.

2.4.2 SUMMARY OF RUNOFF GENERATION FROM OTHER EVENTS

Because of the repetitive nature of the data, detailed data on other rainfall events have not been presented. However, overall summary of all the data collected for the rainfall events during the sampling period is presented in Table 2.6. The data clearly showed that IE runoff generation mechanism is the main mechanism in this region of Alabama (Table 2.6). Out of 26 rainfall events, eight events produced runoff at the edge of the hillslope. Of these, four events showed both IE and SE runoff generation mechanisms. Analysis of surface and subsurface sensors for each event which produced runoff showed that rainfall intensity played an important role in generating runoff. Other two factors which seemed to enhance runoff generation were antecedent moisture condition and rainfall duration.

Table 2.6 also shows the spatial variability of runoff generation areas for different rainfall events. Surface and subsurface sensor data showed that, out of 31 locations, as many as 26 locations produced runoff at some point during the rainfall events that generated runoff at the outlet of the hillslope. Surface runoff generation areas were spatially and temporally variable during a particular rainfall event and among rainfall events.

2.4.3 PRACTICAL IMPLICATIONS

As opposed to the SE runoff mechanism that usually occurs near streams, the IE runoff mechanism in the pastures of the Sand Mountain area can occur wherever the soil hydraulic conductivity is low. If the areas of high soil hydraulic conductivity are downslope from the areas of low hydraulic conductivity, the runoff generated at low conductivity areas might infiltrate and not reach a stream. The presence of IE runoff makes the identification of HAA areas challenging in this region and requires good estimates of soil hydraulic conductivity data at high spatial resolution and rainfall intensity data with high spatial and temporal resolution.

Even though such data are generally not available, accurate quantification of the amount of runoff generated and the location of HAAs is important for management of NPS in the pastures of this region. High spatial resolution soil hydraulic conductivity data can be obtained using the method presented in this paper. This procedure takes about 10-15 min to estimate soil hydraulic conductivity at each location. Since, the soil hydraulic conductivity estimates provided by this method is about two-third of saturated hydraulic conductivity, this method can be used to delineate areas of low hydraulic conductivity. Connected areas (connected to an outlet) of low hydraulic conductivity will most likely produce surface runoff. Further, once these areas are delineated, land application of poultry litter can be optimized to provide improved protection to surface water quality and optimal land application of litter.

It should be noted that saturated hydraulic conductivity is highly spatially variable. Further, in addition to saturated hydraulic conductivity, infiltration (and thus runoff) is affected by antecedent moisture conditions, which is difficult to quantify at a high spatial and temporal resolution. However, knowing the main mechanism of surface runoff generation has great practical significance for controlling NPS pollution. For example, just knowing that the main mechanism of runoff regeneration is infiltration excess, connected areas of low saturated hydraulic conductivities can be mapped and management can be tailored to avoid input of NPS pollutants to those areas.

Also, at this site, since a number of rainfall events did not produce runoff, this suggests that there is a potential for significant subsurface flow in this region. Researchers have found that significant subsurface flow can be the dominant P transport path as compared to the overland flow (Scanlon *et al.*, 2005; Heathwaite and Dils, 2000; Biggs *et al.*, 2006). Thus, results from this and other study suggest that understanding surface and subsurface hillslope hydrological pathways are important for reducing P transport.

2.4.4 SUMMARY

In this study, a hillslope pasture was intensively instrumented using surface and subsurface sensors. Three rainfall events were evaluated to identify the mechanism of runoff generation in the Appalachian Plateau (Sand Mountain) region of North Alabama. Event 1 was a high-intensity rainfall of short duration. Event 2 was characterized as a medium-intensity rainfall of medium duration, while Event 3 was a low-intensity rainfall of long duration. Results from all three events showed that the surface runoff generation mechanism is mostly IE. However, during events 1 and 2, a few locations, which have high soil hydraulic conductivity showed an increase in perched water table. This was attributed to the presence of a restrictive layer near the surface, on top of which a perched water table builds up during intense rainfall events. Analysis of surface and subsurface sensors data showed that variability in rainfall intensity and soil hydraulic conductivity have significant effects on surface runoff generation in this region. Events 1 and 2 clearly showed that whenever the rainfall intensity was greater than the soil hydraulic conductivity, IE runoff occurred. Similarly, results from event 3 showed that with the rainfall intensity lower than soil hydraulic conductivity, there were very few locations which generated runoff. During intense storms (e.g., event 1) surface runoff was observed from fairly large areas across the hillslope. Results suggested that even though the soils in the Sand Mountain area have fairly high soil hydraulic conductivity, there are locations within the field that have low soil hydraulic conductivity and these are the areas that most often generate runoff.

It can be concluded that rainfall intensity and soil hydraulic conductivity play an important role in surface runoff generation in this area. This makes the identification of hydrologically active areas (HAAs; and thus management of nonpoint source pollution) and estimation of runoff volume leaving a hillslope pasture difficult. To accurately identify HAAs and estimate runoff volume leaving a hillslope pasture, high spatial resolution soil hydraulic conductivity data and high spatial and temporal resolution rainfall data is needed. Information gathered during this field investigation suggested that by estimating soil hydraulic conductivity using a device similar to the one used in this study, spatial variability in soil hydraulic conductivity over a landscape can be adequately represented and HAAs can be identified. The HAAs connected to the outlet will have this highest potential to produce surface runoff and nonpoint source pollution. This information appears to be suitable for use as a self-assessment tool for the application of poultry litter or fertilizers by farmers.

Table 2.1. Soil description and properties at two landscape positions (one upslope and one downslope) at the study site.

Location	Horizon	Depth (cm)	Sand	Silt	Clay
			-----------------------	%	-----------------
Pit 1, Upslope	Ap1	0-11	55.43	35.41	9.16
	Ap2	11-25	55.31	34.33	10.36
	Bt	25-59	46.69	38.42	14.89
	Btx	59-96	50.12	28.86	21.01
	BC	96-125	60.67	11.07	28.26
	Cr	125+	74.23	10.76	15.01
Pit 2, Downslope	Ap1	0-19	58.81	32.96	8.23
	Ap2	19-33	55.12	35.14	9.74
	BE	33-76	55.98	32.80	11.22
	Btx	76-119	56.94	27.55	15.51
	BC	119-159	65.39	20.61	14.00
	Cr	159+	75.88	32.96	8.23

Table 2.2. Hydraulic conductivity values calculated from the cumulative infiltration for the Sand Mountain study site at 31 sampling points. The data from the highlighted (in bold) sampling points are discussed in the Results and Discussion section.

Sampling Point	Hydraulic conductivity, *k* (mm/hr)	Categorized Hydraulic Conductivity*
1	21.5	High
2	56.1	High
3	2.8	Low
4	**11.1**	**Medium**
5	20.1	High
6	**51.2**	**High**
7	24.2	High
8	10.4	Medium
9	29.1	High
10	11.1	Medium
11	1.4	Low
12	3.5	Low
13	1.4	Low
14	0.7	Low
15	53.3	High
16	**3.5**	**Low**
17	9.7	Medium
18	0.5	Low
19	4.8	Low
20	10.4	Medium
21	6.9	Medium
22	1.4	Low
23	13.2	Medium
24	0.7	Low
25	2.8	Low
26	**0.7**	**Low**
27	18.7	Medium
28	22.2	High
29	30.5	High
30	17.3	Medium
31	4.8	Low

* low = <5.0 mm/hr, medium = 5.0-20.0 mm/hr, and high = >20.0 mm/hr

Table 2.3. Interpretation of data collected during high intensity short duration rainfall (event 1) from surface and subsurface sensors at four different locations (4, 6, 16, and 26) on the hillslope.

(a) Location 4 (estimated soil hydraulic conductivity 11.1 mm/hr)

Time (hhmm)	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence† (yes/no)	Interpretation (IE means infiltration excess)
1510	2.54	30.5	42	Yes	IE runoff
1515	6.35	76.2	40	Yes	IE runoff
1520	5.33	64.0	40	Yes	IE runoff
1525	3.56	42.7	40	Yes	IE runoff
1530	1.52	18.3	40	Yes	IE runoff
1535	0.508	6.1	27	Yes	IE runoff
1540	0.508	6.1	27	Yes	IE runoff
1545	0.254	3.1	27	Yes	IE runoff
1550	0.00	0.0	40	Yes	IE runoff

(b) Location 6 (estimated soil hydraulic conductivity 51.2 mm/hr) ††

Time (hhmm)	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence† (yes/no)	Interpretation (IE means infiltration excess)
1510	2.54	30.5	42	Yes	IE runoff
1515	6.35	76.2	4	Yes	IE runoff
1520	5.33	64.0	4	Yes	IE runoff
1525	3.56	42.7	4	Yes	IE runoff
1530	1.52	18.3	4	Yes	IE runoff
1535	0.508	6.1	4	Yes	IE runoff
1540	0.508	6.1	4	Yes	IE runoff
1545	0.254	3.1	4	Yes	IE runoff
1550	0.00	0.0	4	Yes	IE runoff

†Runoff detected during 1530 and 1550 hours is most likely residual runoff from high intensity rainfall period that preceded this period.

†† This location has high soil hydraulic conductivity. In addition, presence of a restrictive layer is possible at this location because perched water table tends to build up at this location.

Table 2.3: ***contd..***

(c) Location 16 (estimated soil hydraulic conductivity 3.5 mm/hr)

Time	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
1510	2.54	30.5	42	Yes	IE runoff
1515	6.35	76.2	27	Yes	IE runoff
1520	5.33	64.0	4	Yes	IE runoff
1525	3.56	42.7	4	Yes	IE runoff
1530	1.52	18.3	4	Yes	IE runoff
1535	0.508	6.1	4	Yes	IE runoff
1540	0.508	6.1	4	Yes	IE runoff
1545	0.254	3.1	4	Yes	IE runoff
1550	0.00	0.0	4	Yes	IE runoff

(d) Location 26 (estimated soil hydraulic conductivity 0.7 mm/hr)

Time	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
1510	2.54	30.5	42	Yes	IE runoff
1515	6.35	76.2	40	Yes	IE runoff
1520	5.33	64.0	27	Yes	IE runoff
1525	3.56	42.7	27	Yes	IE runoff
1530	1.52	18.3	27	Yes	IE runoff
1535	0.508	6.1	40	Yes	IE runoff
1540	0.508	6.1	40	Yes	IE runoff
1545	0.254	3.1	40	Yes	IE runoff
1550	0.00	0.0	40	Yes	IE runoff

Table 2.4. Interpretation of data collected during medium intensity medium duration rainfall (event 2) from surface and subsurface sensors at four different locations (4, 6, 16, and 26) on the hillslope.

Time (hhmm)	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
(a) Location 4 (estimated soil hydraulic conductivity 11.1 mm/hr)					
1620	1.52	18.3	42	Yes	IE runoff
1625	1.52	18.3	42	Yes	IE runoff
1630	1.52	18.3	27	Yes	IE runoff
1635	1.27	15.2	27	Yes	IE runoff
1640	1.52	18.3	27	Yes	IE runoff
1645	1.52	18.3	27	Yes	IE runoff
1650	1.52	18.3	27	Yes	IE runoff
1655	1.52	18.3	27	Yes	IE runoff
1700	1.27	15.2	27	Yes	IE runoff
(b) Location 6 (estimated soil hydraulic conductivity 51.2 mm/hr)					
1620	1.52	18.3	42	No	No runoff
1625	1.52	18.3	19	No	No runoff
1630	1.52	18.3	4	No	No runoff
1635	1.27	15.2	4	No	No runoff
1640	1.52	18.3	4	No	No runoff
1645	1.52	18.3	4	No	No runoff
1650	1.52	18.3	4	No	No runoff
1655	1.52	18.3	4	No	No runoff
1700	1.27	15.2	4	No	No runoff

Table 2.4: ***contd..***

(c) Location 16 (estimated soil hydraulic conductivity 3.5 mm/hr)

Time	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
1620	1.52	18.3	42	No	No runoff
1625	1.52	18.3	40	No	No runoff
1630	1.52	18.3	27	No	No runoff
1635	1.27	15.2	9	Yes	IE runoff
1640	1.52	18.3	4	Yes	IE runoff
1645	1.52	18.3	4	Yes	IE runoff
1650	1.52	18.3	4	Yes	IE runoff
1655	1.52	18.3	4	Yes	IE runoff
1700	1.27	15.2	4	Yes	IE runoff

(d) Location 26 (estimated soil hydraulic conductivity 0.7 mm/hr)

Time	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
1620	1.52	18.3	42	Yes	IE runoff
1625	1.52	18.3	42	Yes	IE runoff
1630	1.52	18.3	42	Yes	IE runoff
1635	1.27	15.2	42	Yes	IE runoff
1640	1.52	18.3	42	Yes	IE runoff
1645	1.52	18.3	42	Yes	IE runoff
1650	1.52	18.3	42	Yes	IE runoff
1655	1.52	18.3	42	Yes	IE runoff
1700	1.27	15.2	42	Yes	IE runoff

Table 2.5. Interpretation of data collected during low intensity long duration rainfall (event 3) from surface and subsurface sensors at four different locations (4, 6, 16, and 26) on the hillslope.

Time (hhmm)	Incremental Rainfall (mm)	Rainfall Intensity (mm/hr)	Subsurface Sensor - Depth to water table (cm)	Surface Sensor - Runoff Occurrence (yes/no)	Interpretation
(a) Location 4 (estimated soil hydraulic conductivity 11.1 mm/hr)					
330	0.254	3.1	42	No	No runoff
335	0.254	3.1	42	Yes	IE runoff
340	0.254	3.1	42	Yes	IE runoff
345	0.00	0.0	42	Yes	IE runoff
350	0.254	3.1	42	No	No runoff
(b) Location 6 (estimated soil hydraulic conductivity 51.2 mm/hr)					
330	0.254	3.1	42	No	No runoff
335	0.254	3.1	42	No	No runoff
340	0.254	3.1	42	No	No runoff
345	0.00	0.0	42	No	No runoff
350	0.254	3.1	42	No	No runoff
(c) Location 16 (estimated soil hydraulic conductivity 3.5 mm/hr)					
330	0.254	3.1	42	No	No runoff
335	0.254	3.1	42	No	No runoff
340	0.254	3.1	42	No	No runoff
345	0.00	0.0	42	No	No runoff
350	0.254	3.1	42	No	No runoff
(d) Location 26 (estimated soil hydraulic conductivity 0.7 mm/hr)					
330	0.254	3.1	42	Yes	IE runoff
335	0.254	3.1	42	Yes	IE runoff
340	0.254	3.1	42	No	No runoff
345	0.00	0.0	42	No	No runoff
350	0.254	3.1	42	No	No runoff

Table 2.6. Summary for all the rainfall events collected during the study period (January 2006-January 2007). The runoff-producing rainfalls are highlighted in bold.

Rainfall Events	Rainfall Amount (mm)	Main Mechanism	Runoff at Outlet (Yes/No)	No. of surface sensors produced runoff	No. of surface sensors do not produced runoff
Feb 6 2006	11.2	IE	No	10	17
Feb 10-11, 2006	12.7	IE	No	9	18
Feb 22-23, 2006	26.6	IE	No	12	15
Feb 25, 2006	6.1	IE	No	8	19
Mar 9, 2006	7.8	IE+SE	No	23	4
Mar 20-21, 2006	**35.8**	**IE+SE**	**Yes**	**19**	**8**
May 5, 2006	**23.1**	**IE**	**Yes**	**22**	**5**
June 23, 2006	**21.3**	**IE**	**Yes**	**13**	**14**
July 9, 2006	13.7	IE	NA	-	-
Aug 21-22, 2006	**15.0**	**IE**	**Yes**	**20**	**7**
Sep 7, 2006	**34.3**	**IE+SE**	**Yes**	**26**	**5**
Sep 12-13, 2006	19.8	IE	No	11	16
Sep 18, 2006	12.7	IE	No	22	9
Sep 19, 2006	6.6	IE	No	14	18
Sep 22, 2006	**11.7**	**IE**	**Yes**	**21**	**6**
Sep 23-24, 2006	33.4	IE	No	21	6
Oct 1, 2006	16.0	IE	No	15	16
Oct 11, 2006	7.4	IE	No	14	17
Oct 16-17, 2006	74.2	IE	No	17	14
Oct 19-20, 2006	20.7	IE	No	14	17
Oct 22, 2006	4.8	IE	No	5	26
Oct 27, 2006	**33.0**	**IE**	**Yes**	**10**	**21**
Dec 12, 2006	3.3	IE	No	6	25
Dec 22, 2006	31.3	IE	No	9	22
Jan 5, 2007	12.2	IE	No	9	22
Jan7, 2007	**9.8**	**IE**	**Yes**	**22**	**9**

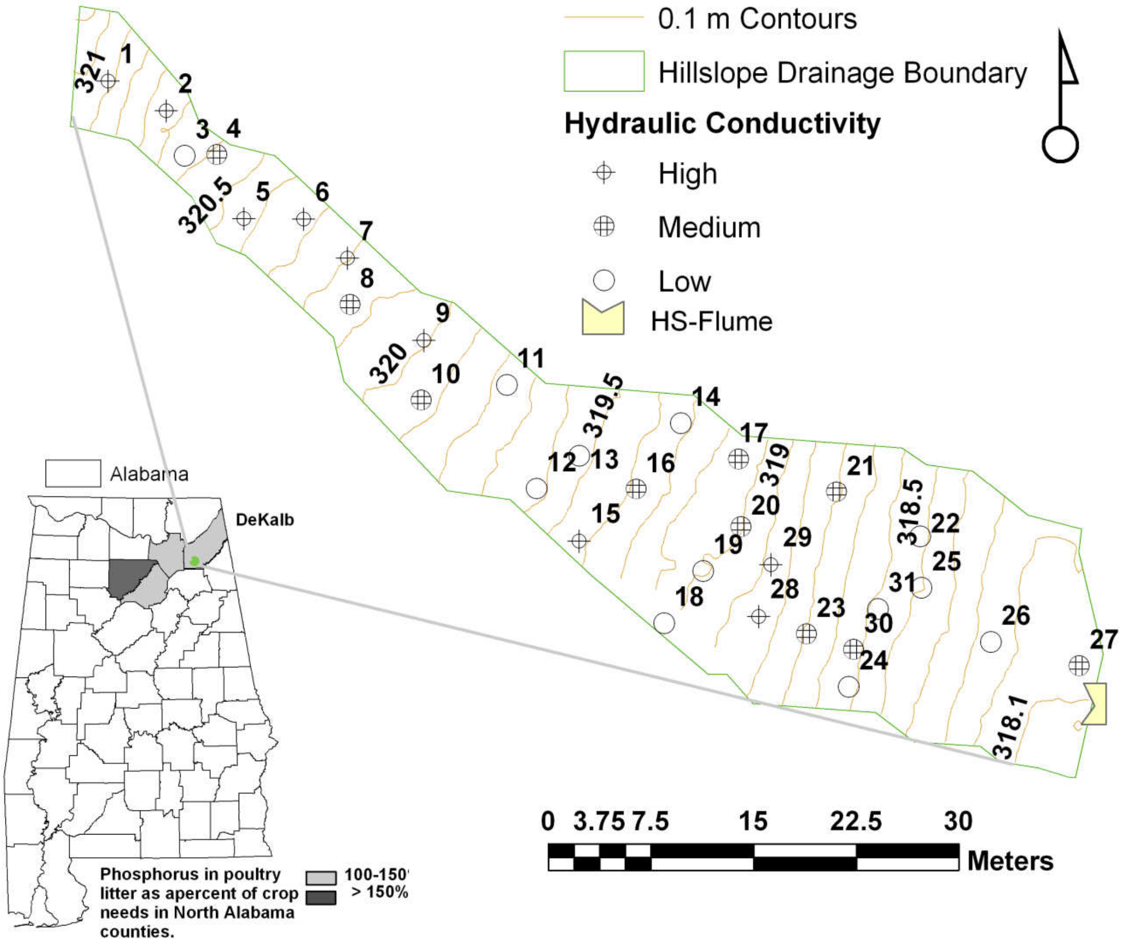


Figure 2.1. Major poultry production counties of North Alabama with phosphorus in poultry litter as a percent of crop needs. Location of the study site at the Sand Mountain Research and Experimental Station, DeKalb County, AL showing 31 sampling points (paired surface and subsurface runoff sensors) on a hillslope.

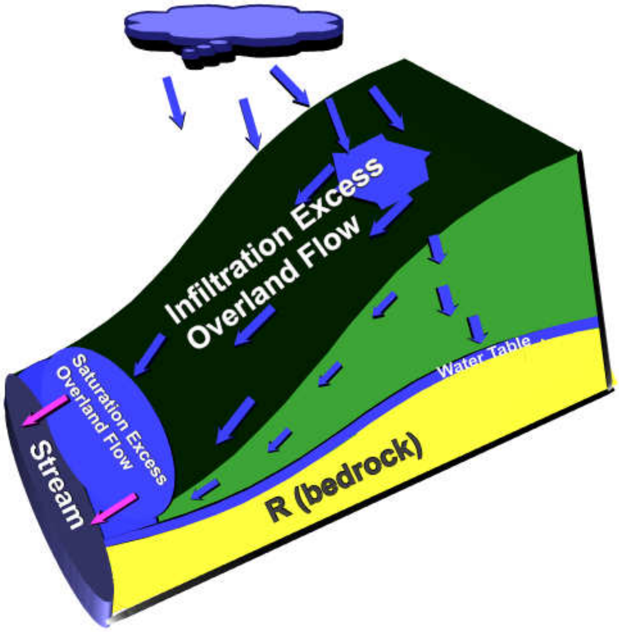


Figure 2.2. Conceptual model showing overland flow generation mechanisms at different landscape positions.

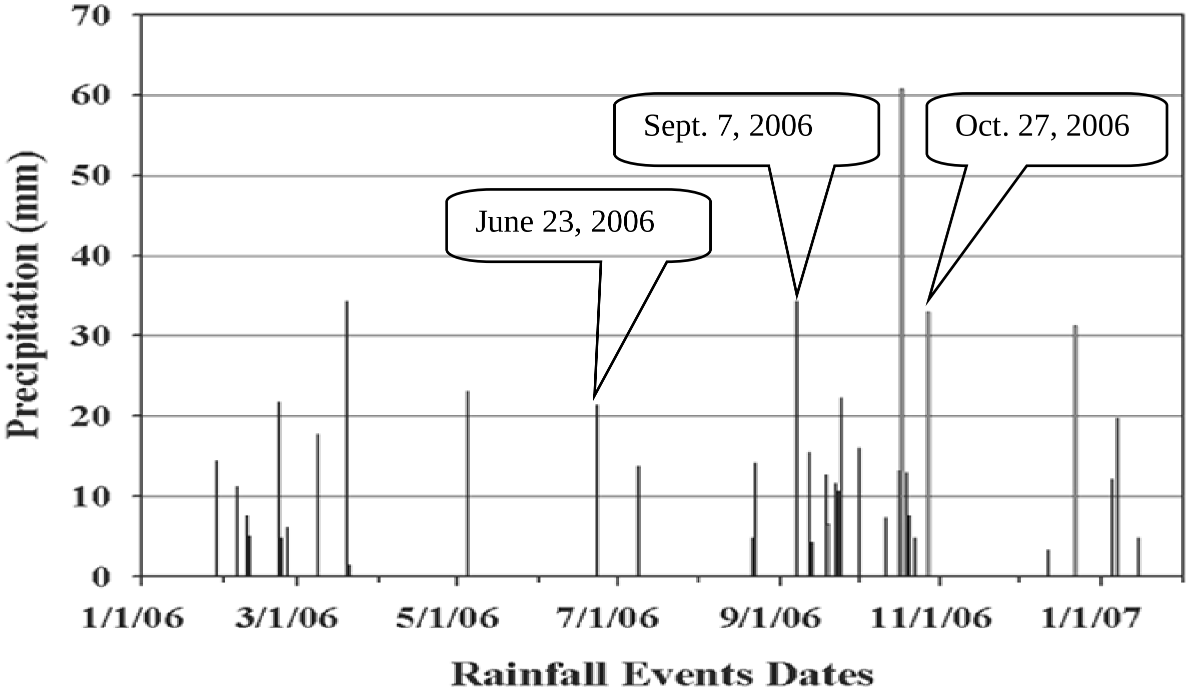


Figure 2.3. Rainfall events recorded from January, 2006, to January, 2007.

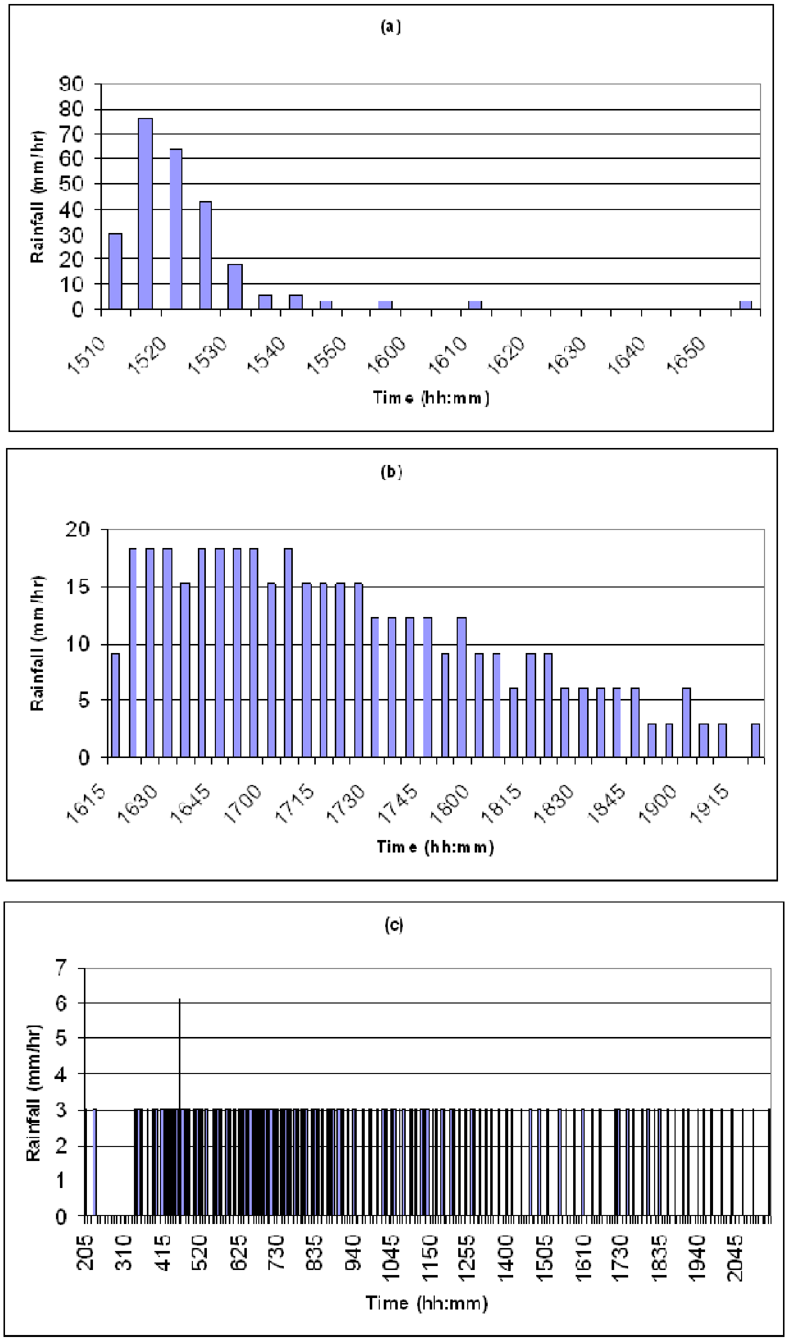


Figure 2.4. **(a) Rainfall hyetograph recorded on June 23, 2006 (event 1); (b) rainfall hyetograph recorded on September 7, 2006 (event 2); and (c) rainfall hyetograph recorded on October 27, 2006 (event 3).**

CHAPTER 3

SPATIAL-TEMPORAL VARIABILITY AND HYDROLOGIC CONNECTIVITY OF RUNOFF GENERATION AREAS IN A NORTH ALABAMA PASTURE

3.1 INTRODUCTION

Hydrologic characteristics play an important role in conversion of rainfall to runoff in a watershed. Several mechanisms of runoff generation, for example, infiltration-excess surface runoff, saturation-excess runoff, and subsurface flows, have been proposed (Horton, 1933; Hewlett and Hibbert, 1967; Freeze, 1974). The infiltration-excess mechanism occurs when rainfall intensity exceeds the infiltration rate (Horton, 1933). This mechanism tends to mainly occur where there are major changes in infiltration capacity and hydraulic conductivities (*k*) due to anthropogenic activities (e.g., see Ward, 1984; Goodrich *et al*., 1997). Surface runoff generated by infiltration-excess mechanism is very sensitive to rainfall intensity, infiltration capacity, and hydraulic conductivity (Walter *et al*., 2003; Ward, 1984). It has also been shown that the saturated hydraulic conductivity (*ks*) plays an important role, not only in infiltration-excess runoff generation but also in infiltration of runoff downslope (run-on) (Corradini *et al*., 1998; Descroix *et al*., 2002).

Saturation-excess runoff occurs when all precipitation infiltrates into the soil surface and a (sometimes perched) water table rises to the ground surface, saturating the whole soil profile (Dunne and Black, 1970); further precipitation on the saturated soil becomes surface runoff. This type of runoff mechanism tends to occur in the bottom of valleys and expands outwards from the stream channels. It also concurs with the theory of “partial contributing area” given by Betson (1964) and “variable source areas” (VSAs) given by Hewlett and Hibbert (1967). Hillsides with mild slopes, concave topography, low saturated hydraulic conductivity, and high shallow water table have high propensity for VSAs as compared to steep slope hillsides (Hernandez *et al.*, 2003). In addition, Hursh and Fletcher (1942) discovered that subsurface flows can also contribute to flood peaks. This was further validated by the work of Hewlett and Hibbert (1963) and Whipkey (1965).

One or more of these mechanisms of runoff generation might be simultaneously present in a particular watershed. For example, a number of researchers (e.g., Wetzel, 2003; Godsey *et al.*, 2004; Perrin *et al.*, 2001; Jordan, 1994; Pilgrim, 1978) report that the spatial heterogeneity of the landscape leads all of the above-mentioned mechanisms to be present in a particular watershed at the same time. However, depending on the hydrologic characteristics of a watershed, one or more of these mechanisms often dominate (Scherrer *et al.*, 2007).

Runoff generation is highly variable, spatially and temporally (e.g., Pilgrim *et al.*, 1978; Jordan, 1994; Hoover, 1990; Latron *et al.*, 2007). The interaction between the static characteristics, such as, topography and land cover, and dynamic characteristics, such as, time-varying rainfall characteristics, antecedent soil moisture conditions, infiltration rates, soil hydraulic properties, and depth to water table affect runoff generation within a watershed (e.g., Srinivasan *et al.*, 2001; Hernandez *et al.*, 2003; McGuire *et al.*, 2007). A number of studies (e.g., Gburek and Sharpley, 1998; Srinivasan *et al.*, 2001; Srinivasan *et al.*, 2002) have suggested that surface runoff often occurs across small, identifiable portions of a landscape. Surface runoff from these areas, termed as hydrologically active areas (HAAs; Sen *et al*. 2008), was found to contribute disproportionately to the overall watershed response (Zollweg *et al.*, 1995). Furthermore, scientists have reported that storm flow (stream) originates from small but consistent portions of upstream areas that constitute less than 10% (usually 1-3%) of the watershed area, and even in these areas, only 10-30% of the rainfall causes surface runoff (Freeze, 1974; Walter *et al*. 2000). Jordan (1994) suggested that delineation of saturated areas in a catchment is relatively easy and found that 10% of the catchment generated saturation excess runoff. However, Jordan (1994) suggested difficulties in delineating the infiltration-excess runoff or subsurface flow generation areas if areas remain small.

In addition to spatial and temporal variability of runoff generation areas, it is also important to understand the hydrologic connectivity of runoff contributing areas. Hydrologic connectivity refers to the water movement from one location to another on a landscape which can generate some surface runoff response (Bracken and Croke, 2007). Therefore, to understand the hydrologic response of a natural landscape, it is important to study hydrologic connectivity of surface runoff contributing areas. The complexity of the hydrological processes occurring in a watershed during a rainfall event is due to interaction between runoff generation mechanisms, hydrologic connectivity of runoff-generating areas, and infiltration of runoff further down slope (Reaney *et al.*, 2007). Reaney (2008) used a physically based, distributed dynamic hydrology model, the Connectivity of Runoff Model (CRUM), to study the spatial and temporal dynamics of runoff-generating areas, and transmission of runoff from catchment to outlet through channels during a high intensity, low frequency storm. Results showed that with the same amount of rainfall, two catchments responded differently due to difference in runoff-generating areas, and their connectivity. The study showed that there were areas in the catchment which were showing runoff generation; however, those areas were not hydrologically connected to the outlet, so there was no runoff response at the outlet. Results from this study also showed that reduction in the catchment discharge is related to reduction in the contributing areas. Mueller *et al.* (2007) studied the effect of connectivity of different hydrologic features on spatial variability of runoff generation patterns. Using binary system and conditional stochastic simulation approaches, they suggested that more connected hydrologic feature patterns can be used in hydrologic modeling, which results in better understanding of runoff generation mechanisms. Joel *et al.* (2002) found that large plots (10.0 m x 5.0 m) produced only 40% of the runoff measured from small plots (0.5 m x 0.5 m), suggesting that the amount of runoff decreases with increasing plot length. Similar results were found by Gomi *et al.* (2008) who suggested that hydrologic connectivity of runoff generation areas depends on rainfall intensity and soil conditions on a hillslope. A similar field investigation conducted by

Cammeraat (2002) showed that hydrologic connectivity is an important factor in runoff contributing and absorbing areas from the micro-plot to the catchment scales.

Even though a number of studies have suggested that runoff generation is spatially and temporally variable, and hydrologic connectivity of runoff generation areas is important for overall hillslope response, only a few recent studies have showed this through hillslope studies under natural rainfall conditions, especially on hillslopes where infiltration-excess runoff dominate. Specifically, this study is geographically important because the study site lies in one of the largest poultry producing counties of north Alabama. Many similar studies are needed to test the initial hypothesis of runoff generation mechanisms and its variability. Therefore, the objectives of this study were (a) to delineate spatial and temporal variability of runoff generation areas under natural rainfall conditions and (b) to demonstrate that hydrologic connectivity is important for generating hydrologic response from a hillslope on which infiltration-excess runoff mechanism dominates.

3.2 METHODOLOGY

3.2.1 HILLSLOPE STUDY AND INSTRUMENTATION

3.2.1.1 GENERAL DESCRIPTION OF THE HILLSLOPE STUDY

The study was conducted on a 0.12 ha hillslope pasture in the eastern part of the Sand Mountain area of the Cumberland Plateau section of the Appalachian Plateau physiographic province (Baker and Osborne, 1994) in Alabama (Figure 3.1). Elevation of the study area is 330 m above mean sea level. Climate in this area is humid and temperate with a mean annual precipitation of about 137 cm. Occurring mainly as rainfall, a significant portion of annual precipitation falls during the winter (average 37 cm) and early spring months (average 26 cm). Precipitation during the summer months is dominated by isolated thunderstorms. The study site was maintained by the Sand Mountain Research and Extension Center (SMREC) located in DeKalb County, Alabama (Figure 3.1). The SMREC is one of the field research and extension units of the Alabama Agricultural Experiment Station. The hillslope represents a typical pasture in this region. A cool season grass (Kentucky 31 Tall Fescue) has been growing on this site for more than 30 years. Soils on the hillslope are Hartsells (fine-loamy, siliceous, subactive, thermic Typic Hapludults) and Wynnville (fine-loamy, siliceous, subactive, thermic Glossic Fragiudults) (Soil Survey Staff, 2009). The Hartsells series consists of moderately deep (sandstone at 50–100 cm), well-drained, moderately permeable soils that are formed from acid sandstone. Permeability is in the moderately high ks class (0.36 – 3.6 cm h^{-1}) (Soil Survey Staff Division, 1993). These soils are found on nearly level to moderately steep ridges and upper slopes of hills and mountains. The Wynnville soils are moderately well-drained, slowly permeable soils also formed from sandstone. Permeability of these soils is in two *ks* classes, one which above fragipan is in moderately high ks class (0.36 – 3.6 cm h^{-1}) and second which is in fragipan is moderately low *ks* class (0.036 – 0.36 cm h^{-1}) (Soil Survey Staff Division, 1993). The Wynnville soils have fragipans in the subsoils which are slowly permeable. Because both the sandstone layer and the fragipans are slowly permeable, short durations of water perching occur above these restrictive layers during rainfall events. More detail on the soils is presented in Sen *et al*. (2008).

The study site was extensively surveyed using a Real-Time Kinematic GPS (Trimble Navigation Limited, Sunnyvale, CA) unit to generate detailed microtopography (Figure 3.1). Microtopography data from the GPS unit were used to develop a 0.5-m resolution digital elevation model (DEM) using ArcGIS 9.1 software (ESRI, Redland, CA). The hillslope has a slope range from 0.2 to 3.4% with a standard deviation of 0.76. Elevation differences in the middle are less as compared to upper and lower sections of the hillslope. The detailed microtopography data were used to install surface and subsurface sensors on the hillslope. Flow paths were generated using the Hydrologic Modeling extension (D8 flow routing technique) in ArcGIS 9.1.

3.2.1.2 INSTRUMENTATION

The hillslope was intensively instrumented with surface runoff and subsurface sensors, a tipping bucket rain gauge, and a 0.3-m HS-flume. In particular, pairs of surface runoff and subsurface sensors were installed at 31 points. The surface runoff sensors were miniature v-notch weirs made of 2-mm thick galvanized sheet metal with a sensor pin and a ground pin set 2 cm apart and 3 cm away from the v-notch and located on the upslope side of the sensor. The subsurface sensors, installed as deep as 42 cm depth, recorded water table fluctuations near the soil surface. Details of the surface runoff and subsurface sensors can be found in Srinivasan *et al.* (2001). All sensors were connected to a series of multiplexers and dataloggers (model CR10X, Campbell Scientific, Inc. Logan, UT). A tipping bucket rain gauge measured the rainfall at 5-min intervals. The site was instrumented such that the hillslope drained to a point where an HS-flume recorded the overland flow from the entire instrumented hillslope. All 31 surface runoff and subsurface sensors were installed in pairs to study the interaction between water table and surface runoff for the characterization of HAAs and runoff generation mechanisms.

Detailed runoff contributing area analysis on each of 11 selected sampling locations (locations 5, 6, 9, 10, 12, 18, 19, 20, 22, 24, and 27) was conducted across the hillslope using ArcGIS 9.1 software (Figure 3.1). Out of the 31 sensor locations, these 11 sensor locations were selected because they were located on hydrologic flow paths. The total contributing areas and the percentage of contributing areas of each selected location within the medium and low conductivity areas were also calculated in ArcGIS (Table 3.1).

3.3 DATA COLLECTION

At the initiation of a rainfall event, the rain gauge activated the datalogger to collect data from the surface runoff and subsurface sensors and the pressure transducers in the HS-flume until six hours after a rainfall event had ceased. Rainfall, water table levels (at subsurface sensor locations), and occurrence of runoff at surface and subsurface sensor locations were collected at 5 min intervals. The data collection began in January 2006. However, for addressing the objective of this paper, six rainfall events were considered for detailed analysis. Out of these six, three selected events occurred during the summer of 2007, representing summer thunderstorms (dry period) and three events were selected during the winter of 2007, representing the wet period of the year (Figure 3.2).

3.3.1 IN-SITU SOIL HYDRAULIC CONDUCTIVITY MEASUREMENTS

Several studies have been conducted to explore the role of spatial heterogeneity in saturated hydraulic conductivity (*ks*) on the hydrologic response of a hillslope. Results of these field and modeling investigations concluded that *ks* strongly influences the hydrologic response of a hillslope (Corradini *et al.*, 1998, 1998; Govindaraju *et al.*, 2006). Thus, in this study, in situ hydraulic conductivity (*k*) values were measured using a disc infiltrometer (Decagon Devices, Inc., Pullman WA) which measures about two-thirds of the true *ks* (Koorevaar *et al.*, 1983). Data collection was performed at 94 locations in 5-m grid across the whole hillslope. To calculate the hydraulic conductivity, van Genuchten parameters (van Genuchten, 1980) for a sandy loam soil were used (α = 0.075 cm-1; n = 1.89). The other parameters used were the radius of the disc ($r_o \approx 2.25$ cm) and the nondimensional coefficient (A = 3.89). Hydraulic conductivity was calculated using the Zhang (1997) method, which is given by:

$$I = (C_1 t + C_2 \sqrt{t}) \qquad (1)$$

where, I is the cumulative infiltration (cm), t is the time (s), and C_1 (cm.s^{-1}) and C_2 (cm.s$^{-1/2}$) are the parameters related to sorptivity and hydraulic conductivity. The hydraulic conductivity of the soil was then computed using

$$k = \frac{C_1}{A} \qquad (2)$$

where A was computed from

$$A = \frac{11.65(n^{0.1} - 1)e^{[2.92(n-1.9)\alpha h_o]}}{(\alpha r_o)^{0.91}} \qquad \text{where, } n \geq 1.9 \qquad (3)$$

where, h_o is the suction at the disk surface.

Soil hydraulic conductivity data was interpolated across the hillslope using Geostatistical Analyst extension in ArcGIS 9.1 software. Different methods of interpolation such as inverse distance weighted (IDW), kriging, etc., were compared for the actual representation of k-values across the hillslope. Initially, ordinary kriging interpolation method was used with semivariogram models such as spherical, Gaussian, exponential, etc. Though the interpolated k-map was reasonably similar to the actual k-values, there was very weak spatial structure shown by semivariogram. Similarly, IDW method was used with different power functions for k interpolation across the hillslope. After comparing different interpolated maps with actual k-values, IDW with power 1 was found to provide the best representation of k-values across the hillslope (Figure 3.3).

3.3.2 RAINFALL MEASUREMENTS

Figure 3.2 shows the amounts of 67 rainfall events recorded from January 2007 to December 2007. Rainfall amounts recorded during this period ranged from 0.08 to 4.14 cm, totaling approximately 63 cm for the whole year (which is well below the 137 cm for an average year). A few rainfall events, which occurred in late March until mid April were missed because of power failure at the study site. However, the total rainfall amount recorded by a nearby National Climate Data Center (COOP ID: 017207) in 2007 was 90 cm with an average rainfall amount of 7.5 cm and standard deviation of 1.26. Events were spread out throughout the year (Figure 3.2). As presented in Sen *et al.* (2008), very few rainfall events generated surface runoff at this study site.

3.4 RESULTS AND DISCUSSION

3.4.1 SELECTED RAINFALL EVENTS

Rainfall events (Figure 3.2; Table 3.2) were selected on the basis of rainfall characteristics (amount, duration, and intensity), and data availability (when all the sensors were working). Available data was thoroughly checked before using for analysis. To specifically focus on the objectives of this study, selected six events were categorized into low- and medium-intensity, medium duration events and high-intensity, short- and medium duration events.

Under low- and medium-intensity, medium duration events category, the first event occurred on 23 July 2007 (event 1) for 6 h 50 min and was categorized as a medium-intensity, medium duration event (Figure 3.4e). During event 1, 1.50 cm of rainfall occurred with a maximum intensity of 36.6 mm h^{-1} (between 1645 and 1650 h). The second event hereafter referred as event 2 occurred on 22 October at 2225 h and ceased at 0515 h on 23 October 2007 (Figure 3.5e). During this event (event 2), a total of 1.63 cm of rainfall occurred in 6 h 50 min, with a maximum intensity of 33.5 mm h^{-1} (at 0020 h) and was characterized as a medium-intensity, medium duration event. The third event under this category occurred on 23 October 2007 and was a low-intensity, medium duration event (Figure 3.6e). This event started approximately 5 hours after event 2 had ceased. During this event (event 3), 1.37 cm of rainfall occurred in 7 h 5 min, with a maximum intensity of 15.2 mm h^{-1} (at 1235 h).

Similarly, three events were selected under high-intensity, short- and medium duration events category. The first event occurred on 20 July 2007 (event 4) for 1 h 50 min and was categorized as a high-intensity, short duration event (Figure 3.7e). During event 4, a total of 1.80 cm of rainfall occurred with a maximum intensity of 51.8 mm h^{-1} (between 1045 and 1055 h). The second event occurred on 25 August 2007 (event 5) and was characterized as a high-intensity, short duration event (Figure 3.8e). The total amount of rainfall occurred during event 5 was 1.90 cm, with a maximum intensity of 61.0 mm h^{-1} (at 2000 h). The third event under this category occurred on 14 November 2007, hereafter referred as event 6, and was a high-intensity medium duration event (Figure 3.9e). During event 6, 3.23 cm of rainfall occurred in 8 h 5 min, with a maximum intensity of 42.7 mm h^{-1} (between 2215 and 2220 h). About 2.95 cm out of 3.23 cm of rainfall occurred between 2145 and 2325 h.

3.4.2 SPATIAL AND TEMPORAL VARIABILITY AND HYDROLOGIC CONNECTIVITY OF HYDROLOGICALLY ACTIVE AREAS (HAAS)

Surface runoff sensor data at the selected 11 locations (Figure 3.1) were analyzed to quantify the spatial and temporal variability of HAAs during and after rainfall events (Figure 3.4-3.9). The spatial and temporal variability of HAAs were demonstrated under low- and medium-intensity, medium duration events and high-intensity, short- and medium duration events.

Low- and Medium-Intensity, Medium Duration Events

Analysis of low- and medium-intensity, medium duration events (event 1, 2 and 3) showed that these events started with an average rainfall intensity of 3.1 mm h^{-1} which was either higher or close to k values at locations 12, 18, 19, 22, and 24 (Figure 3.4e, 3.5e and 3.6e). At this initial rainfall intensity, about 42 to 57% of the total area showed runoff generation, however, no or little runoff was recorded at the outlet (Figure 3.4f, 3.5f and 3.6f). Except for event 3, at this intensity, none of the locations showed runoff generation. This might be due to the presence of high antecedent moisture conditions for event 3 because event 2 occurred just before this event (Figures 3.5a and 3.6a). As the events proceed and reached up to the maximum intensity, the runoff-generating areas were expanded over the hillslope (66% to 80% of the total area). For example, events 1 and 2, at 1645 h and at 0020 h, respectively, reached the maximum intensity between 30-40 mm h^{-1},and at the same time 66% and 69% of the total area, respectively, showed runoff generation (Figure 3.4b and 3.5b). A different trend was demonstrated by event 3 (low-intensity, medium duration), during which at 1235 h, rainfall intensity was 15.2 mm h^{-1} (maximum) (Figure 3.6e), but only 57% of the total area showed runoff generation from the similar areas at 1110 h as shown in Figure 3.6a. However, after 60 min (at 1340 h), about 80% of the total area showed runoff generation, at this time around 11 mm of total amount of rainfall had occurred, which was 81% of the total rainfall amount of the event (Figure 3.6b). The possible reason for the delay in expansion of runoff-generating areas might be the amount of rainfall occurred up to this time and wet initial conditions. As rainfall intensity of the events started decreasing, the runoff-generating areas were contracted, with a range from 27 to 64% of the total area of the hillslope (Figure 3.4c, 3.5c and 3.6c).

All three event analysis showed the similar trend in the percentage of rainfall converted to runoff at the hillslope outlet, which was less than 1% (Table 3.2). During events 1, 2 and 3 with the onset of rainfall same locations 12, 18, 19, 22, and 24 showed runoff generation, and as the rainfall continued runoff-generating areas were expanded and contracted based on rainfall intensities. Figures (3.4b-c and 3.6b-c) clearly showed that the time period when the low soil hydraulic conductivity areas in the middle section of the hillslope were hydrologically connected with runoff-generating areas on the lower section of the hillslope (Figure 3.3), and the runoff was recorded (although low) at the outlet at the same time period. During event 2, no runoff was recorded at the outlet. Surface sensor data analysis also confirmed that there was no hydrologic connectivity between the middle and lower section of hillslope (Figure 3.5b-d). Data showed that two important hydrologic properties which seem to play an important role in hydrologic connectivity of the runoff-generating areas and the percentage of rainfall converted to runoff at the outlet. These properties are the time of maximum rainfall intensity and the amount of rainfall that had been occurred before the maximum rainfall intensity has reached during an event. For example, during event 1 and 3, the maximum rainfall intensity occurred after a significant portion of the total rainfall had occurred (Figure 3.4e and 3.6e), and just after the maximum rainfall intensity was reached, runoff was recorded at the outlet of the hillslope (Figure 3.4f and 3.6f). However, during event 2, the maximum rainfall intensity occurred at the beginning of the event, and afterwards the lower rainfall intensity was not enough to develop hydrologic connectivity in between the runoff-generating areas (Figure 3.5b-d) to record runoff at the outlet. Figures 3.4a and d, 3.5b-d and 3.6a and d) also pointed out an important hydrologic process during the events, the “run-on process”, which is runoff occurring from lower conductivity areas (such as locations 10, and 22 in event 1; locations 18, 19, 22, and 24 in event 2; and locations 19, and 22 in event 3) might be infiltrating at the higher conductivity areas (location 27).

High- Intensity, Short- and Medium Duration Events

Figures (3.7e, 3.8e and 3.9g) showed that high-intensity, short- and medium duration events started with the rainfall intensities equal to or more than 9.1 mm h^{-1}, and the maximum intensities were reached within few minutes. The maximum rainfall intensities, ranging from 43 and 61 mm h^{-1}, were much higher than the soil hydraulic conductivity values of soil over the hillslope. Data analysis showed that at the onset of the high-intensity events, percentage of runoff-generating areas were higher as compared to the low-intensity events, for example, events 4, 5, and 6 showed 33 to 78% of total area was generating runoff at the onset of event (Figure 3.7a, 3.8a and 3.9a). During the high-intensity portions of the events, 100% of the hillslope area showed runoff generation at or just passed the maximum intensity time period. Also, also at the same time the runoff was recorded at the outlet of the hillslope. Figures (3.7 and 3.8) also showed the effect of rainfall intensities on the expansion and contraction of runoff generation areas. For example, during event 4 and 5, with the total rainfall amount was 15.0 mm and 19.0 mm, respectively, the spatial variability of runoff-generating areas strictly followed the temporal variation in rainfall intensities during the events. During event 6, with the total rainfall amount of 32.2 mm, although the runoff-generating areas also expanded with an increase in rainfall intensities, similar to events 4 and 5, the areas contracted slowly after the event ceased, most likely due to the high total rainfall amount (Figure 3.9d-f).During these events, the percentage of rainfall converted to runoff at the hillslope outlet ranged from 4 to 8% (Table 3.2). Similar trends of hydrologic connectivity of runoff-generating areas were observed during these events as compared to low- and medium-intensity, medium duration events. The hydrologic connectivity of the runoff-generating areas are shown in Figures (3.7b, 3.8b-c and 3.9d-e). Initially, the lower soil hydraulic conductivity areas in the middle section of hillslope started generating runoff and as the rainfall intensities increased, those areas were hydrologically connected to the runoff-generating areas at the lower section of hillslope and eventually with the outlet of the hillslope. The runoff recorded at the outlet of the hillslope during events 4 ad 5 showed similar trends with the highest peak occurring just after the maximum rainfall intensities (51.8 and 61.0 mm h^{-1}, respectively). However, during event 6 with lower maximum rainfall intensity (42.7 mm h^{-1}) as compared to events 4 and 5, the highest runoff peak was recorded after the rainfall ceased. This suggests that there was a slow flow condition across the hillslope and a lag time between rainfall and the runoff process.

Results of all six events demonstrated spatial and temporal variability in HAAs. As suggested by others (e.g., Morbidelli *et al*., 2006; Joel *et al*., 2002), spatial and temporal variability of runoff generation across a hillslope depends mainly upon the heterogeneity of soil hydraulic conductivity and rainfall characteristics (amount, intensity, and duration). Figures (3.4a, 3.5a, 3.6a, 3.7a, 3.8a, 3.9a) clearly suggest that at the onset of any rainfall event, a relatively small percentage of the total hillslope area generated surface runoff, and mainly in lower hydraulic conductivity areas. However, as a rainfall event proceeds and reaches a maximum intensity, runoff generating areas expand across the hillslope (see, for example, Figures 3.4b, 3.5b, 3.6b, 3.7b, 3.8b, and

3.9b). The range of percentages of runoff contributing areas found in this study concurs with the results found by Vigiak *et al*. (2006). Overall spatial and temporal analysis of runoff generation areas suggest that, depending on the rainfall intensity, when the intensity increases, areas generating runoff expand across the whole hillslope and contribute towards the total runoff at the hillslope outlet (Table 3.2). On the other hand, when the intensity decreases areas generating runoff contract and runoff flowing over the higher soil hydraulic conductivity areas infiltrates into the soil. Similar results have been reported by different studies explaining that spatial variability depends on the geomorphic components and temporal variability depends on antecedent soil moisture conditions (Sidle *et al*., 2000; Morbidelli *et al*., 2006; Joel *et al*., 2002).

Many field investigations (Woolhiser *et al*., 1996; Binley *et al*., 1989) have reported similar findings and have suggested that understanding the spatial variability of soil hydraulic conductivity is crucial in explaining runoff/runon production. An interpolation technique utilized in this study was found to be representative of the actual values of soil hydraulic conductivities. Figure 3.4 shows the variability of soil hydraulic conductivity values across the hillslope. Medium soil hydraulic conductivity values were observed at upslope and downslope areas while lower values were measured in the middle section of the hillslope. Analysis of runoff generation at 11 locations suggests that during all six rainfall events runoff at the outlet of the hillslope was recorded mainly when runoff-generating areas in the middle and downslope sections of the hillslope showed runoff generation (Figures 3.4-3.9). This suggests that hydrologic connectivity of these runoff-generating areas plays an important role in the overall runoff generation from the hillslope during a rainfall event (Bracken and Croke, 2007).

3.5 IMPLICATIONS FOR NON-POINT SOURCE POLLUTION CONTROL

Many studies all over the world have shown that surface runoff is the primary mechanism of transport of particulate-bound pollutants (e.g., phosphorus (P), nitrogen (N), and pathogens) from agricultural fields to nearby water bodies (Wetzel, 1983; Fleming and Cox, 1998). Scientists (Pionke *et al.*, 1996; Gburek and Sharpley, 1998; Gburek *et al.*, 2002) have recognized that to control nonpoint source (NPS) pollution, it is important to identify the hydrologically active areas (HAAs; areas generating surface runoff). Thus, in the last few decades, a plethora of models have been developed to simulate NPS pollutants transport at different scales, such as point, field, and watershed. Many of the widely used watershed-scale models such as AnnAGNPS (Bingner and Theurer, 2003), ANSWERS (Bouraoui and Dillaha, 1996, 2000), HSPF (Bicknell *et al.*, 2001), and SWAT (Neitsch *et al.*, 2002) also treat entire fields as runoff-contributing areas. Further, often these models are applied at a resolution at which it is often impossible to determine (a) areas within a field that generate runoff and (b) whether these areas are connected to the outlet of the field. Field-scale models such as APEX (Williams and Izaurralde, 2005), CREAMS (Knisel 1980), and EPIC (Williams *et al.*, 1984)], although often capable of identifying runoff-generating areas (resulting from infiltration-excess mechanisms) within a field, do not consider hydrologic connectivity of these areas for estimating runoff and pollutant loads leaving the field. As a result, watershed-scale and field-scale models are often not very accurate when used in uncalibrated modes.

To truly identify areas that contribute runoff (and pollutants) to the outlet and to accurately estimate amount of runoff (and pollutant loads) leaving the field, it is critical that we delineate spatially- and temporally- variable runoff generation areas and their connectivity to the outlet. This is also important for effective control of particulate-bound NPS pollutants through management practices. Connected runoff generation areas that receive high levels of pollutant inputs would most likely be the first candidates for application of BMPs. Advancement of our understanding of spatial and temporal distribution of runoff generation areas and their connectivity will lead to development of effective management practices. Below, a few examples of how the results of this study can be used to control runoff of phosphorus (P), a particulate-bound pollutant, are presented.

3.5.1 PHOSPHORUS INDEX (P-INDEX)

A P-index (e.g., Alabama P-index (USDA-NRCS, 2001; 1994) is an assessment tool that uses, among other factors, agronomic soil P threshold, runoff classes, soil erodibility, proximity of surface water, fertilizer and manure application rates, and method of application to determine vulnerability of a field to transport of P to a water body. The vulnerability rating is then used to vary manure application rates (one rate for an entire field). If spatial and temporal variability of runoff generation areas and their hydrologic connectivity is not considered, the areas contributing runoff at the outlet will receive as much manure as the areas that do not contribute any runoff at the outlet. This will lead to inadequate runoff P control and might not lead to improvements in water quality. Application of results of this and similar studies will help improve the reliability of the P-Index as a management tool. The finding of this and similar studies will also lead to models that operate at sub-field scales and consider the spatial and temporal variability of runoff generation areas and their hydrologic connectivity.

3.5.2 VARIABLE RATE MANURE APPLICATION

Recent developments in variable rate technology (VRT) allow farmers to focus on site-specific nutrient management. Studies have shown that traditional uniform-rate application tends to over- and under-apply, while VRT can result in more efficient application of manure on agricultural fields (Fulton *et al.*, 2005) if vulnerable areas can be identified. Combining the results of this study with variable-rate manure application will result in a sustainable, effective management of manure application.

3.5.3 PHYTOREMEDIATION

Using the results of this study, areas with high propensity of runoff generation can be delineated within a watershed. Also, using the soil test P, high soil P areas can be delineated. Combining the hydrologically-connected areas of high propensity of surface runoff generation with high soil P will lead to delineation of critical source areas. Thus, at these critical source areas, crops or forage which can consume higher rates of P can be planted, which will eventually reduce surface transport of P.

3.6 CONCLUSIONS

An intensive monitoring of surface runoff generation areas at multiple locations across a pasture hillslope, during natural rainfall events, was performed to delineate the spatial and temporal variability of runoff generation areas and their hydrologic connectivity. Six rainfall events having different characteristics, three of which occurred in the summer months and three in the winter months, were evaluated. Rainfall events were characterized as high-intensity, short duration (events 1 & 3), medium-intensity, medium duration (event 2 & 4), low-intensity, medium duration (event 5), and high-intensity, medium duration (event 6). Analysis of all six events showed similar results, which clearly suggested the existence of a spatial and temporal pattern in the surface runoff generation areas across the study area. It can be concluded that rainfall intensity and soil hydraulic conductivity play an important role in the expansion and contraction of runoff generation areas and their hydrologic connectivity. On average, events with rainfall intensities higher than 40 mm h^{-1} converted 4 to 8% of the total rainfall into runoff at the outlet, which signifies that in this region high-intensity, short duration and high-intensity, medium duration events are likely to generate runoff.

The results also confirmed the importance of hydrologic connectivity of runoff-generating areas in hillslope response. Higher hydraulic conductivity values were found on the upslope and downslope as compared to the middle section of the hillslope. Results from all six events illustrate the occurrence of runoff mainly from the middle section of the hillslope. Runoff at the outlet was mainly observed when runoff-contributing areas at the downslope section of the hillslope showed runoff generation and were connected to areas in the middle section of the hillslope.

The study showed that, on hillslopes dominated by infiltration-excess runoff, in situ soil hydraulic conductivity and rainfall intensities can be used to identify runoff generation areas and their hydrologic connectivity. Detailed data on rainfall intensity and soil hydraulic conductivity can also be used to estimate runoff amounts during a rainfall event. This information can be used to develop management practices that are effective and the models that accurately depict the processes occurring on the hillslope/field.

Table 3.1. Total contributing areas of each sampling locations and their respective area percentages in medium and low soil hydraulic conductivity areas.

Sampling Locations	Contributing Areas (m^2)	Percentage of Area Calculated using GIS	
		Within Medium* Soil Hydraulic Conductivity	Within Low* Soil Hydraulic Conductivity
5	23	100	0
6	52.5	100	0
9	6.75	100	0
10	27.25	100	0
12	47	100	0
18	94.5	86	14
19	55.5	34	66
20	147	77	23
22	396	75	25
24	162	81	19
27	311	100	0

* low = <5.0 mm h^{-1}, and medium = 5.0-20.0 mm h^{-1}

Table 3.2. Summary for the rainfall events selected for detailed analysis.

Storm Event	Total Rainfall (mm)	Max. Rainfall Intensity (mm/h) $^{\text{Time (hhmm)}}$	Percentage of Rainfall Converted to Runoff at the Outlet (%)	Max. Contributing Area (%) $^{\text{Time(hhmm)}}$
23rd July 2007	15.0	36.6 $^{1645-1650}$	<1	67 ^{1650}
22nd-23rd October 2007	16.3	33.5 ^{0020}	0	0
23rd October 2007	13.7	15.2 ^{1235}	<1	87 $^{1310-1340}$
20th July 2007	18.0	51.8 $^{1045-1050}$	8	100 $^{1045-1055}$
25th August 2007	19.0	61.0 ^{2000}	4	100 $^{1955-2020}$
14th November 2007	32.3	42.7 $^{2215-2220}$	8	96 $^{2210-2225}$

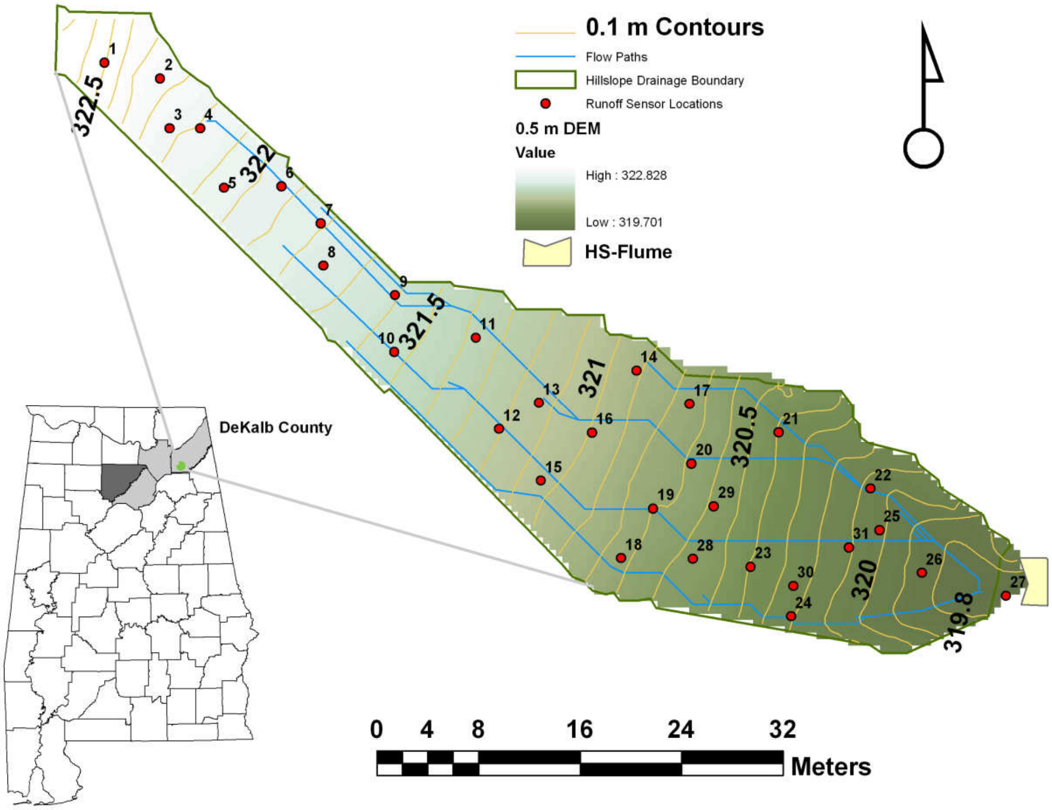


Figure 3.1. Location of the study site at the Sand Mountain Research and Experimental Station, DeKalb County, AL, USA, showing 31 sampling points (paired surface and subsurface runoff sensors) on a hillslope. The counties in gray are major poultry producing counties. Resulting poultry litter is mostly surface applied.

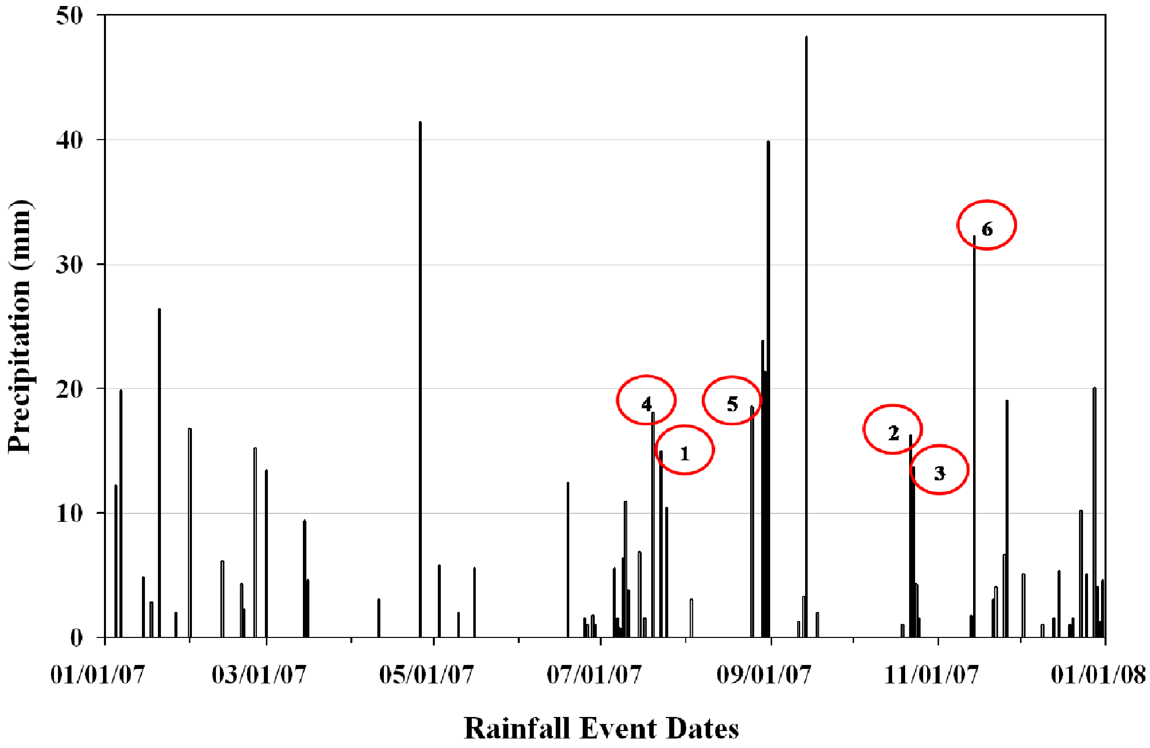


Figure 3.2. Rainfall events recorded from January, 2007 to December, 2007. The rainfall events selected for detailed analysis are also highlighted: (1) July 23, 2007; (2) October 22-23, 2007; (3) October 23, 2007; (4) July 20, 2007; (5) August 25, 2007; and (6) November 14, 2007.

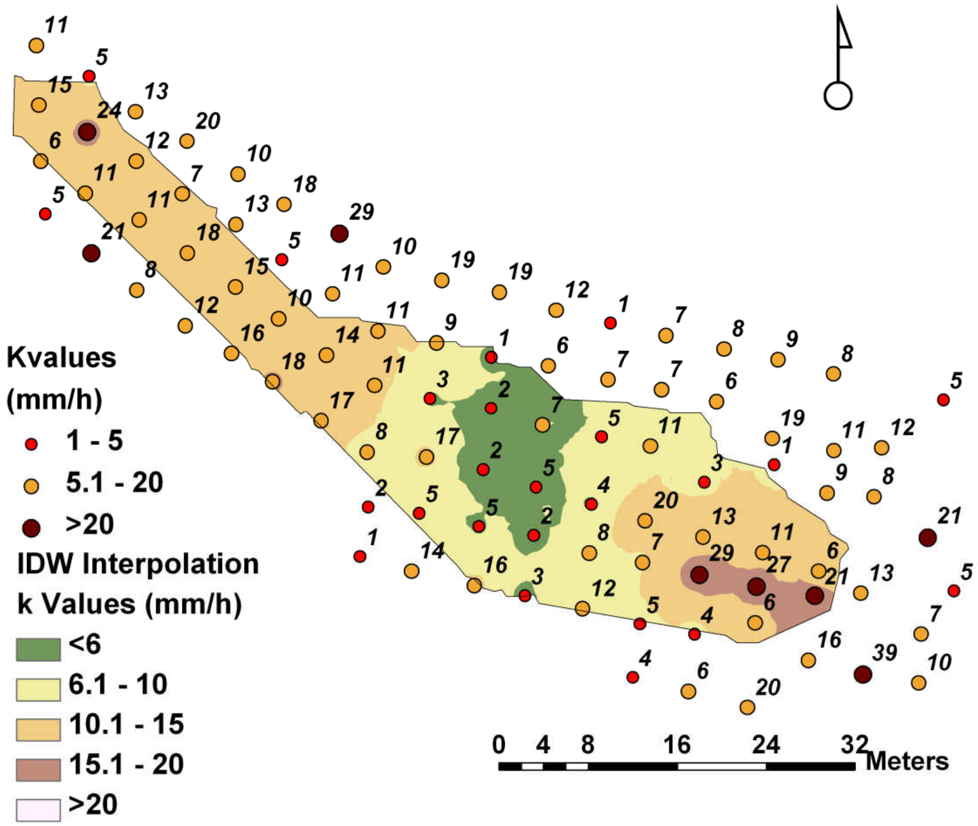


Figure 3.3. Spatial variability of soil hydraulic conductivity (interpolated and measured values) across the entire hillslope.

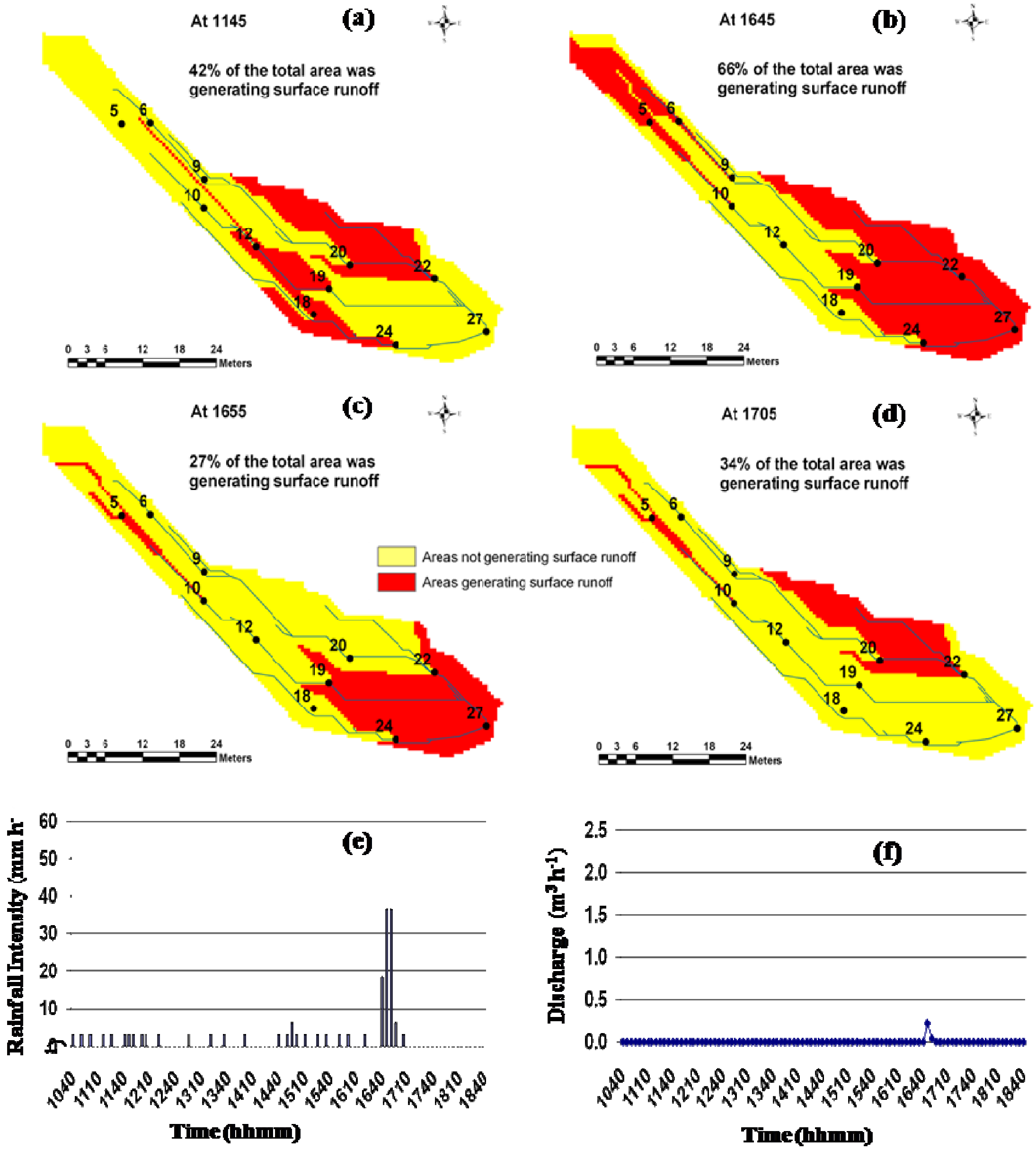


Figure 3.4. (a-d) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on July 23, 2007 (event 1); (e) rainfall hyetograph; (f) discharge hydrograph.

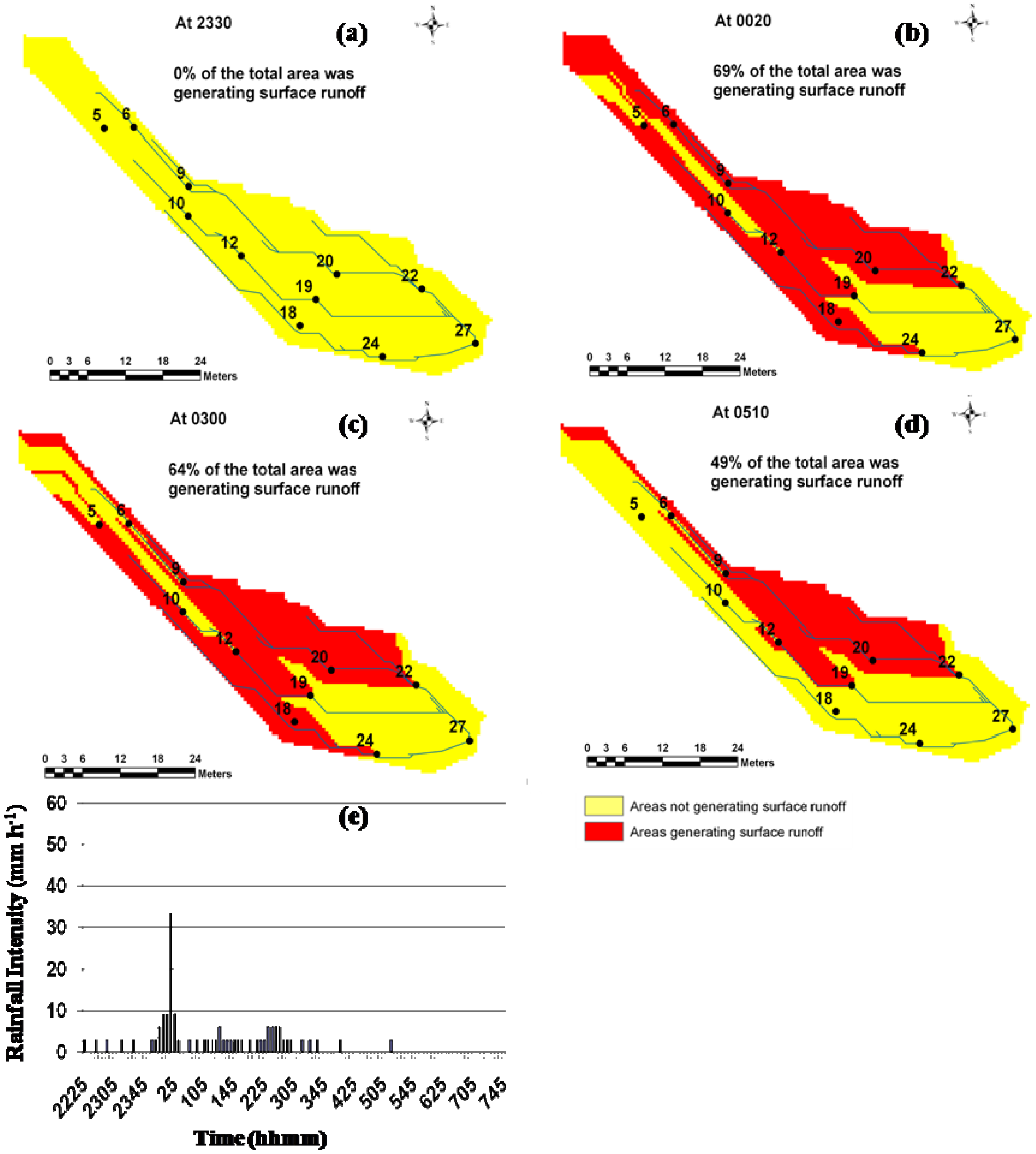


Figure 3.5. (a-d) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on October 22-23, 2007 (event 2) and no runoff was detected at the outlet; (e) rainfall hyetograph.

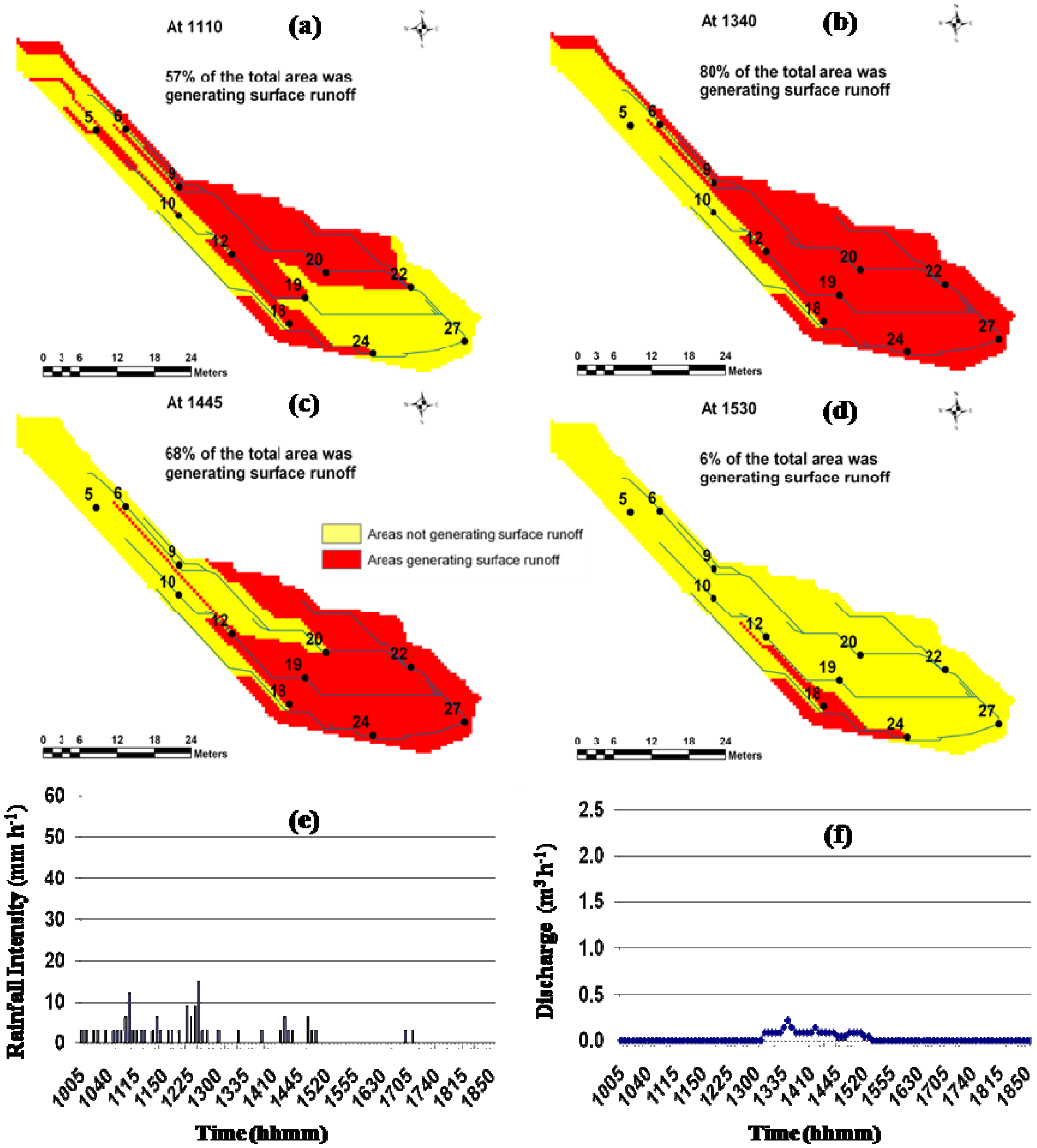


Figure 3.6. (a-d) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on October 23, 2007 (event 3); (e) rainfall hyetograph; (f) discharge hydrograph.

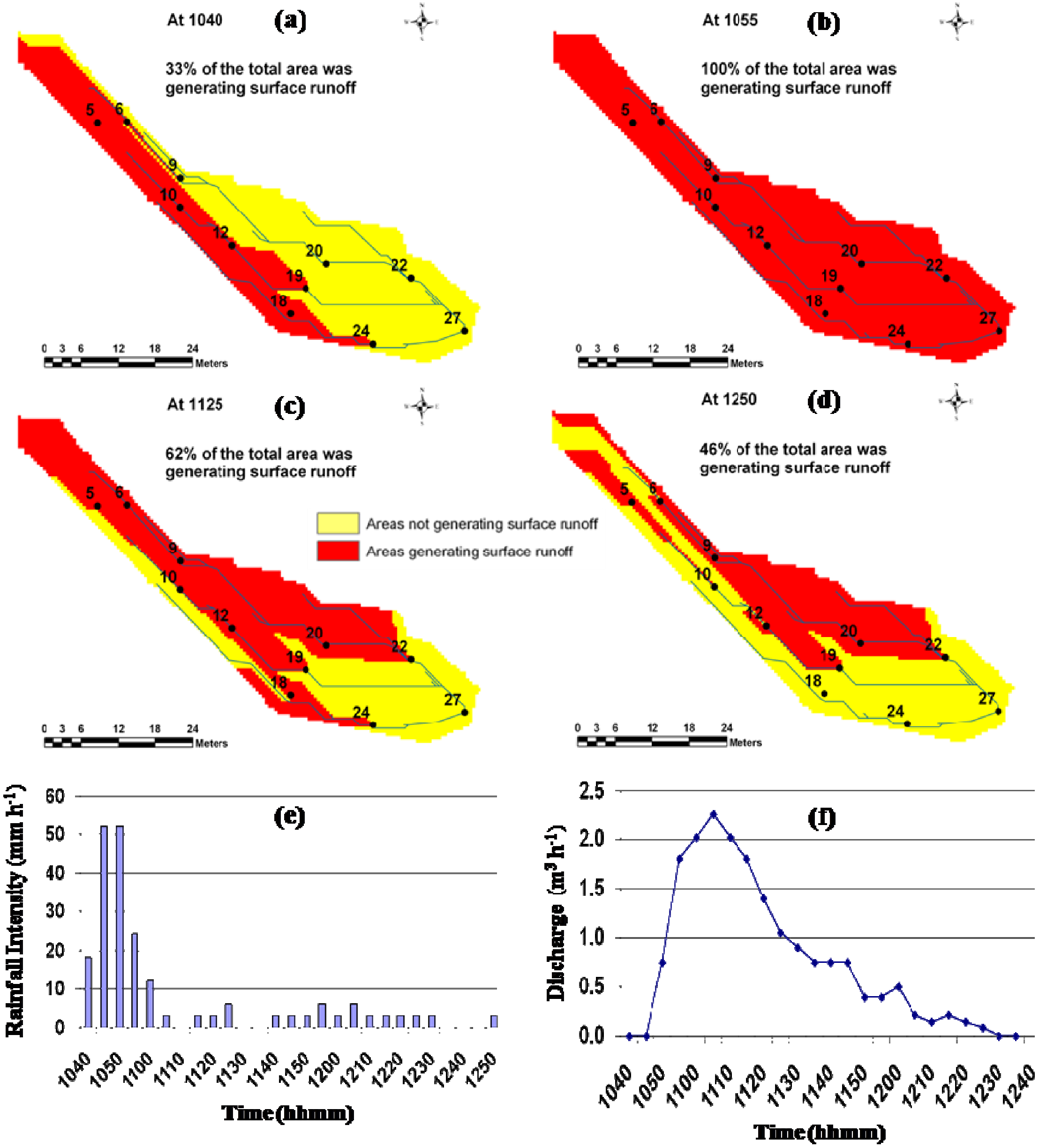


Figure 3.7. (a-d) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on July 20, 2007 (event 4); (e) rainfall hyetograph; (f) discharge hydrograph.

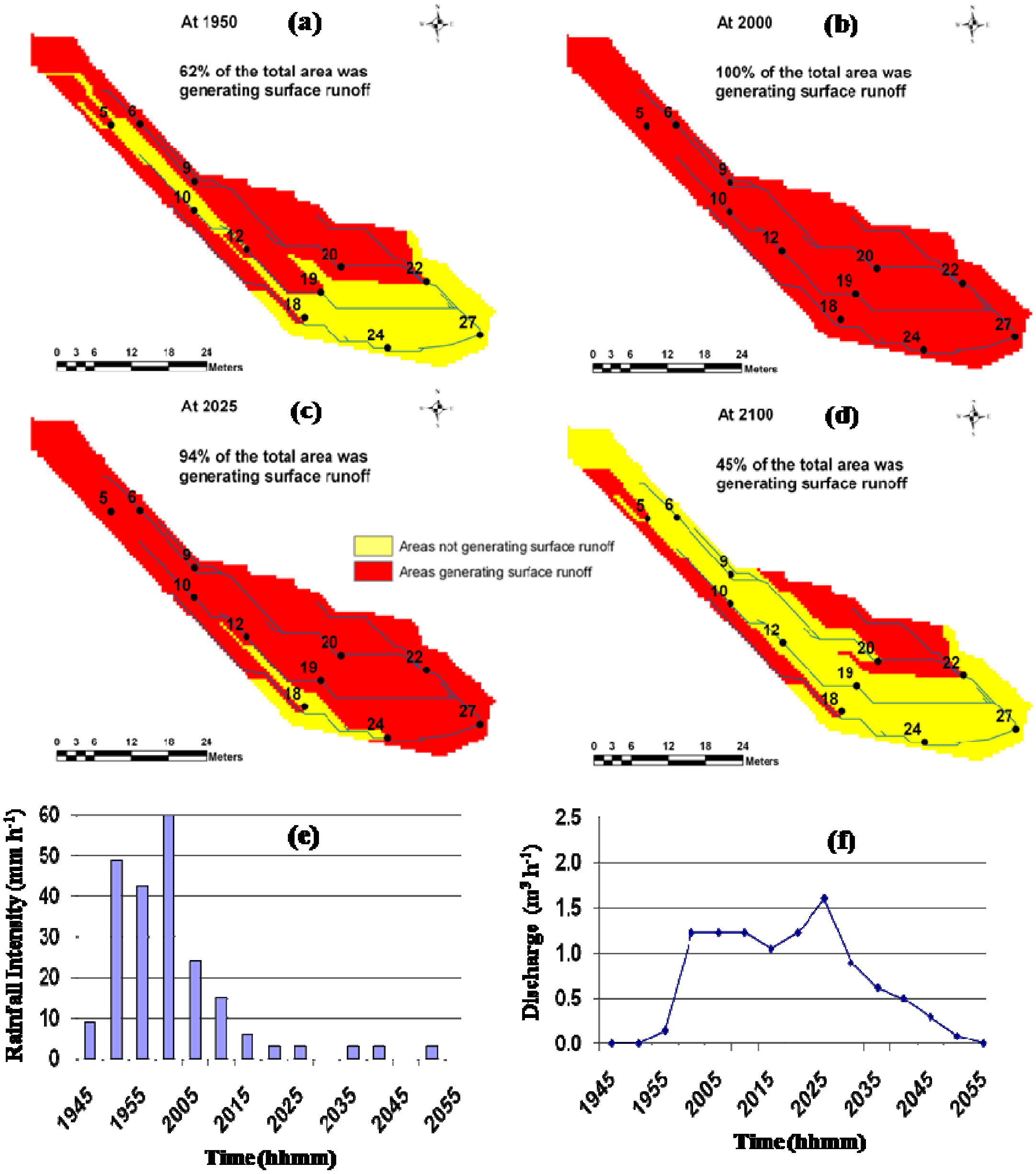


Figure 3.8. (a-d) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on August 25, 2007 (event 5); (e) rainfall hyetograph; (f) discharge hydrograph.

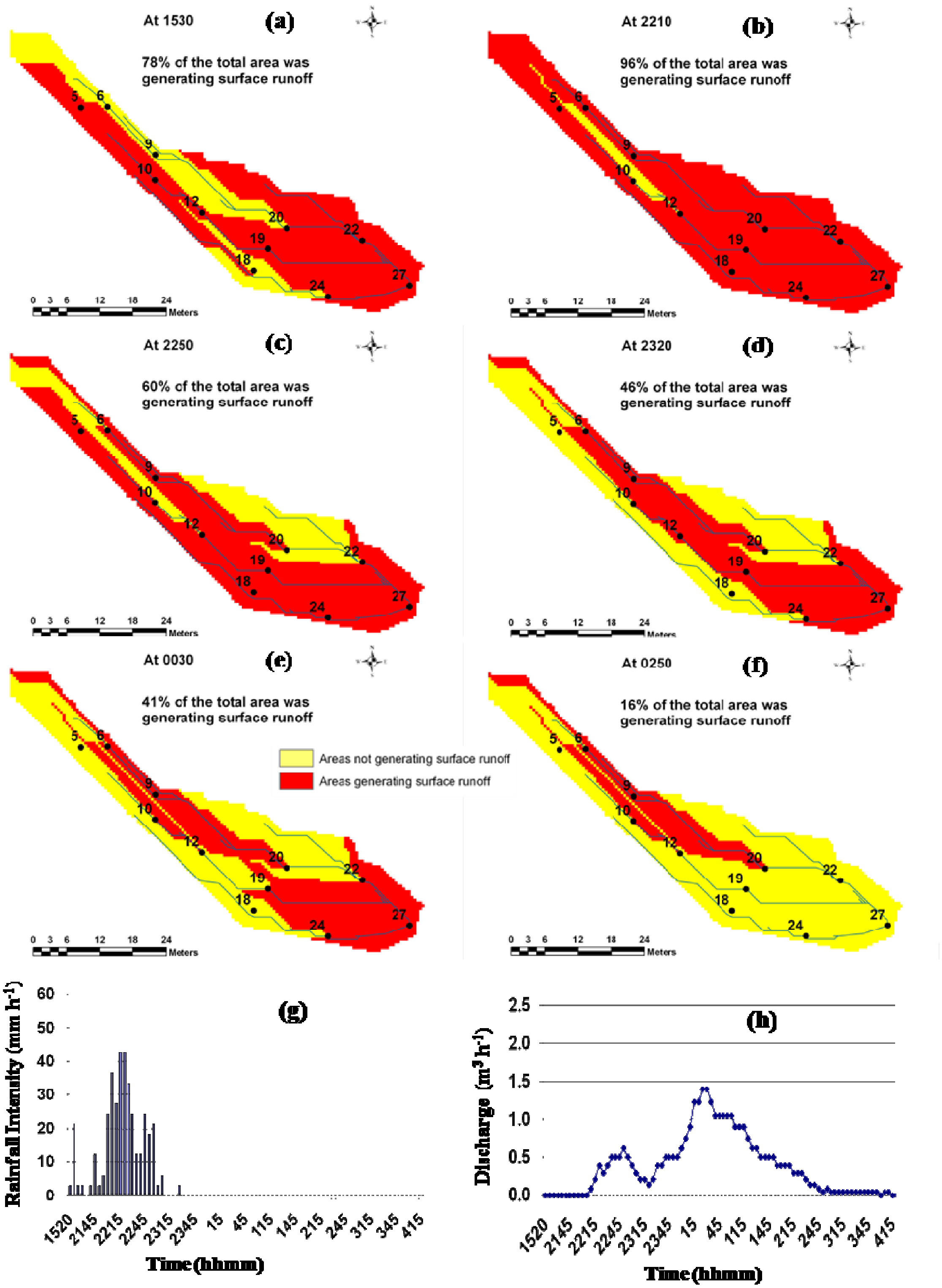


Figure 3.9. (a-f) Spatial and Temporal variability of HAAs at different times (hhmm) across the hillslope on November 14, 2007 (event 6); (g) rainfall hyetograph, (h) discharge hydrograph.

CHAPTER 4

APPLICATION OF HIRO$_2$ HYDROLOGIC MODEL FOR SIMULATING HORTONIAN OVERLAND FLOW ON A PASTURE HILLSLOPE IN NORTH ALABAMA

4.1 INTRODUCTION AND LITERATURE REVIEW

Hillslope hydrologic modeling is an essential element of watershed modeling to understand different hydrological processes occurring during and after a rainfall event. Kirkby (1988) suggested that more than 95% of stream water passes through hillslope soil or over a hillside before reaching a channel network. Over the years, researchers have recognized the importance of hillslope hydrology not just in watershed-scale hydrological studies, but also because of its applicability in environmental, water quality, hydroecology and hydrogeomorphology studies (e.g., Hewlett and Hibbert, 1963; Whipkey, 1965; Kirkby, 1978, 1988; and O'Loughlin, 1990; Bronstert and Plate, 1997; Loague *et al.*, 2006). Hopmans and Pasternack (2006) suggested that there is a great need of hydrologic studies using the innovative approaches. A number of hydrologic studies at experimental hillslopes have been conducted under different climatologic, hydrologic and pedologic conditions and have been used for development and testing of hillslope hydrological models (Horton, 1933; Dunne and Black, 1970;

Srinivasan *et al.,* 2001, 2002; Leh *et al.,* 2008; and Sen *et al.,* 2008; Freeze, 1978; Bronstert and Plate, 1997; Bronstert, 1999; Beven 2000, 2002; Singh and Woolhiser, 2002; Tromp-van Meerveld and Weiler, 2008). Bronsterst and Plate (1997) tested a physically-based hydrological model, HILLFLOW, to demonstrate the effects of macropores on infiltration, soil moisture movement on a natural hillslope, water dynamics of a slope of a landfill cover, and 3D simulation of a storm event on a micro-catchment. Tromp-van Meerveld and Weiler (2008) studied the complexity of a hydrological model required to simulate hillslope hydrological processes. The results showed the importance of parameters or processes such as spatial variability of bedrock conductivity (bedrock leakage), preferential flow and variation in soil depth on subsurface flow. They suggested that these parameters should be incorporated in hydrological models where subsurface is the dominant hydrological flow path. They also emphasized the need for a new methodology for collecting experimental data for these parameters. Bronstert (1999) examined the model HILLFLOW and suggested that it performs reasonably well in representing Hortonian runoff generation and other hydrologic processes over a hillslope, if input parameters such as initial soil moisture content and hydraulic conductivity are well known. Meng *et al.* (2008) reviewed various models and classified them with distributed infiltration models and runoff as fully three-dimensional (3D) models and flow-path based models. Examples of these models include InHM, CAS2D, GSSHA, and KINEROS. These distributed models were determined to be computationally intensive. However, other models that use hydrologic response units (HRU) (e.g., SWAT, PRMS, SWIM) do not take into account the spatial and temporal variability of hydrologic processes and hence as computationally more efficient.

Although there has been significant progress in understanding the processes governing the rainfall-runoff processes (Stomph *et al.*, 2002), researchers have continuously mentioned the need for experimental data from hillslope studies for testing hydrologic models (Loague and VanderKwaak, 2004). Due to the high spatial and temporal variability in many hydrological parameters in nature, some physical laws which are scale dependent cannot express these variabilities. Morbidelli *et al.* (2006) illustrated the importance of spatial variability of soil hydraulic conductivity for the infiltration-excess runoff generation mechanism through numerical simulation. Vivoni *et al.* (2007) studied the transition and scale-dependency of runoff generation mechanisms over a catchment-scale using a distributed model, tRIBS. They found that transitions of runoff nonlinearity are mainly due to shifts in the dominance of runoff generation mechanisms. Their results showed that spatial and temporal variability of runoff generation was a function of storm properties and antecedent moisture conditions. They also suggested that there is a need for using numerical models which can properly capture the spatial and temporal distribution of runoff generation over the watersheds. However, the majority of the hydrological models developed until now that represent these processes are still site specific and scale dependent. Beven *et al.* (1988) found that as the scale increases, different interactions occur between different hydrologic processes, which cause difficulty in calibration of hydrological parameters. An extensive re-calibration and field data are required for models to be used in other climatic zones with different hydrologic conditions (Bonnel and Balek, 1993). Thus, there is a need to develop a robust physically-based hydrological model which can be applied at different climatic zones and most importantly can be applied at different scales, such as the hillslope and watershed scale (Kirkby, 1988; Loague and VanderKwaak, 2004). Hydrological models should not only present the total runoff from a hillslope but also the spatial and temporal variability of hydrologic processes during a rainfall event.

To address the above mentioned characteristics in a hydrological model that can account for spatial variability of rainfall and infiltration properties at the watershed-scale, Meng *et al.* (2008) developed a physically-based, distributed rainfall-runoff model, called HIRO$_2$ (Hortonian Infiltration and Runoff/On). The model is based on advanced flow-path algorithm, simulate infiltration and ponding time and routes infiltration excess runoff and channel flow at the pixel level. Though HIRO$_2$ has tested at a watershed scale, a detailed numerical simulation of dynamic hydrologic processes has not been carried out at the hillslope scale to test the applicability of the model.

The objective of this paper is to test HIRO$_2$ model using a hillslope dataset collected in the northern Alabama region. The model simulations were used to understand the dominant runoff generation mechanism and spatial-temporal variability in the Sand Mountain pastures of northern Alabama. During the field study, a large amount data including the soil hydraulic conductivity across the hillslope, spatial and temporal location of runoff generation areas, and discharge data at the outlet of the hillslope (Sen *et al.*, 2008, 2009), were collected for multiple rainfall events. In this study, HIRO$_2$ was used to simulate the observed spatially and temporally variable runoff generation areas and to generate the measured surface runoff at the hillslope outlet.

4.2 MODEL DESCRIPTION

The Hortonian Infiltration and Runoff/On ($HIRO_2$) model is a physically-based, distributed hydrological model and has been developed for event-based hydrological studies at the watershed-scale (Meng *et al.*, 2008). The $HIRO_2$ model consists of the following basic elements: flow path scheme, ponding time computation, infiltration computation, overland flow routing, and channel flow routing. The $D\infty$ procedure is used to represent flow direction (between 0 and 2π), which is based on the steepest downward slopes and apportions flow from a pixel to one or two downslope pixels based on the flow direction (Tarboton, 1997). The watershed area contributing runoff to each pixel can be calculated based on flow directions of its upslope pixels. During the simulation, a threshold contributing area is defined so that pixels with contributing areas larger than the threshold value will be taken as channel pixels. Flow path and routing sequence is determined at the pixel level. The model uses a one-dimensional routing scheme and an implicit finite difference method for solving channel flow routing. In the routing process, computation proceeds down a hierarchy of pixels at each time step. The first set of pixels where infiltration and excess runoff are simulated is the ones that can not have inflow from their neighboring pixels. The next set of pixels only receives inflows from the first set of pixels. This routing procedure lasts until all the pixels are processed for each time step and then until the end of the time period of interest. Since $HIRO_2$ uses variable rainfall both in space and in time, a formula developed by Smith and Parlange (1978) and

Broadbridge and White (1987) is incorporated to handle variable rainfall in the computation of ponding time. The Green-Ampt model is adopted to determine the infiltration capacity. The kinematic wave model is used for the computation of overland flow routing and channel flow routing where the channel is assumed to have a trapezoidal shape. $HIRO_2$ requires the following input data: DEM, soil hydraulic conductivity, initial soil moisture content, porosity, wetting front suction, Manning's roughness coefficient, and rainfall rate. This model can simulate surface infiltration rate, cumulative infiltration, and runoff at any pixel and at any time and the output can be obtained in ASCII format. More details on the model are given in Meng *et al.* (2004) and Meng *et al.* (2008).

4.3 STUDY SITE

4.3.1 GENERAL DESCRIPTION OF THE HILLSLOPE

The hillslope used to test the applicability of the $HIRO_2$ model is located in the eastern part of the Sand Mountain region of northern Alabama (Figure 4.1). The hillslope has an area of 0.12 ha and is situated at an elevation of 330 m above the mean sea level. Climate in this area is humid with a mean the annual precipitation of about 137 cm. A significant portion of annual precipitation falls during the winter and early spring months. Precipitation during the summer months is dominated by isolated thunder storms. A cool season grass (Kentucky 31 Tall Fescue) has been growing on this site for many years. Soils on the hillslope are Hartsells and Wynnville soil series. The Hartsells series consists of moderately deep (sandstone at 50–100 cm), well-drained, moderately permeable soils that are formed from acid sandstone. These soils are found on nearly level to moderately steep ridges and upper slopes of hills and mountains. The Wynnville soils are moderately drained, slowly permeable soils, which were formed from sandstone. The Wynnville soils have fragipans in the subsoils which are slowly permeable. More detail on the soil properties is presented in Sen *et al.* (2008). The study site was surveyed extensively using a Real-Time Kinematic GPS (Trimble Navigation Limited, Sunnyvale, CA) unit to generate detailed microtopography (Figure 4.1). Microtopography data from the GPS unit was used to develop a 0.5-m resolution DEM using ArcGIS 9.1 software (ESRI, Redland, CA). The hillslope has an average slope of 3.3%. Elevation differences in the middle are less as compared to upper and lower sections of the hillslope. The detailed microtopography data was used to install surface and subsurface sensors on the hillslope.

4.3.2 INSTRUMENTATION

The hillslope was intensively instrumented with surface runoff and subsurface sensors, a tipping bucket rain gauge, and a 0.3-m HS-flume. In particular, pairs of surface runoff and subsurface sensors were installed at 31 points. The surface runoff sensors were miniature v-notch weirs made of 2-mm thick galvanized sheet metal with a sensor pin and a ground pin set 2 cm apart and 3 cm away from the v-notch and located on the upslope side of the sensor. The subsurface sensors, installed up to 42 cm depth, recorded perched water table fluctuations near the surface. Details of the surface runoff and subsurface sensors can be found in Srinivasan *et al.* (2001). The surface runoff and subsurface sensors were powered using 12-volt DC batteries. All sensors were connected to a series of multiplexers and dataloggers (model CR10X, Campbell Scientific, Inc.

Logan, UT). The tipping bucket rain gauge measured the rainfall at 5-min intervals. The site was instrumented such that the hillslope drained to a point where an HS-flume recorded the overland flow from the entire instrumented hillslope. All 31 surface runoff and subsurface sensors were installed in pairs to study the interaction between water table and surface runoff for the characterization of HAAs and runoff generation mechanisms.

Previous studies at this test site have shown that infiltration-excess is the main runoff generation mechanism. These studies also revealed no perched water table fluctuations as recorded by subsurface sensors (Sen *et al.*, 2008, 2009). Therefore, the 31 observation locations were reduced to 11 to capture spatially and temporally variable runoff generation areas that produce surface runoff at the outlet of the hillslope (Figure 4.2). Each of these sensor locations represents a certain contributing area and the combination of these contributing areas covers the entire hillslope area.

4.4 DATA COLLECTION

At the initiation of a rainfall event, the rain gauge activated the datalogger to collect data from the surface runoff and the pressure transducers in the HS-flume until six hours after a rainfall event had seized. Rainfall and runoff occurrence at surface sensor locations were collected at 5 min intervals. The data collection began in January 2006, but very few rainfall events have generated runoff at the outlet of the hillslope. For addressing the objective of this paper, two rainfall events (Figure 4.3) were considered for detailed analysis. Both events occurred in the summer of 2007. Infiltration-excess runoff or Hortonian runoff was determined to be the dominant runoff generation mechanism in the study area where overland flow occurs when rainfall intensity exceeds infiltration rate (see Sen *et al.,* 2008). The spatial and temporal variability of runoff generation areas were also extensively studied for these rainfall events (Sen *et al.*, 2009 in review).

4.4.1 IN-SITU SOIL HYDRAULIC CONDUCTIVITY MEASUREMENTS

The effect of spatial heterogeneity in saturated hydraulic conductivity (k_s) on the runoff generation mechanism has been studied at the test site (Sen *et al.*, 2008). Several other field and modeling investigations concluded that k_s strongly influences the hydrologic response of a hillslope (Corradini *et al.*, 1998, Govindaraju *et al.*, 2006). Sen *et al.* (2008) obtained a detailed data set of in-situ hydraulic conductivity (k) values using a disc infiltrometer (Decagon Devices, Inc., Pullman WA), which measures about two-third of the true k_s values (Koorevaar *et al.*, 1983). Data collection was performed at 94 locations with a 5-m grid spacing. The hydraulic conductivity was calculated by using the van Genuchten parameters (van Genuchten, 1980) for a sandy loam soil ($\alpha = 0.075$ cm^{-1}; $n = 1.89$) and the Zhang (1997) method (see Sen *et al.*, 2008; 2009). Interpolation analysis was conducted using the Geostatistical Analyst extension in the ArcGIS 9.1 software (ESRI, CA). Different methods of interpolation such as inverse distance weighted (IDW), kriging, etc. were compared for the actual representation of k-values across the hillslope. Initially, ordinary kriging interpolation method was used with semivariogram models such as spherical, Gaussian, exponential, etc. Though the interpolated k-map was reasonably similar to the actual k-values, there was very weak spatial structure shown by semivariogram. Similarly, IDW method was used with different power functions for k interpolation across the hillslope. After comparing different interpolated maps with actual *k*-values, IDW with power 1 was found to be the best representative of *k*-values across the hillslope (Figure 4.4). The interpolated *k*-values were used as the input in HIRO$_2$ model.

4.4.2 RAINFALL MEASUREMENTS AND OTHER HYDROLOGICAL PARAMETERS

Figure 4.5 shows the hyetographs of the two rainfall events which were used for this study. Rainfall amounts recorded during both events ranged between 1.80 and 1.90 cm. The first event occurred on 20 July 2007 (event 1) for 1 h 50 min and was categorized as a high-intensity, short duration event. During event 1, 1.80 cm of rainfall occurred with a maximum intensity of 51.8 mm h^{-1}. The second event occurred on 25 August 2007 (event 2) and was also characterized as a high-intensity, short duration event. The total amount of rainfall occurred during event 2 was 1.90 cm, with a maximum intensity of 61.0 mm h^{-1}. As presented in Sen *et al.* (2008), very few rainfall events generated surface runoff at this study site. Other hydrological parameters which were used in computation of infiltration and runoff were wetting front suction, porosity, Manning's roughness coefficient, and initial soil moisture content. Some of the input values were taken from Koorevaar *et al.* (1983), Rawls and Brakensiek (1985) and Chow *et al.* (1988).

4.4.3 RAINFALL-RUNOFF SIMULATIONS AND STATISTICAL ANALYSIS

Due to limited number of rainfall events, event 1 was used for calibration and event 2 was used for validation of HIRO$_2$ model. During calibration process, interpolated *k*-values were kept constant. However, the other hydrological parameters such as Manning's roughness coefficient, porosity, initial moisture content and wetting front suction were adjusted within their physical value range as found in literature, until a good fit was found between the simulated and the observed hydrograph at the outlet of the hillslope. For validation process, interpolated *k*-values, Manning's roughness coefficient and porosity values were kept constant, except initial water content and wetting front suction were used based on hydrologic conditions across the hillslope prior to the event. Each simulation was run for 10-15 min after the rainfall event ceased so that all the rain water had exited the hillslope.

This paper focuses mainly on the applicability of the HIRO$_2$ model at the hillslope scale and its potential to represent the spatial and temporal distribution of hydrologic responses (especially, runoff generation areas). Thus, the primary evaluation measure was a comparison between the model predicted and the observed hydrograph at the outlet for each event. This evaluation was conducted based on the coefficient of efficiency, E (Nash and Sutcliffe, 1970).

$$\mathbf{E = 1} - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2}\right] \qquad (1)$$

where O_i is the observed runoff value at time i, P_i is the predicted value at time i, n is the total number of observations, and $\bar{O}$ is the mean of observed values.

Similarly, the Root Mean Squared Error (RMSE) was estimated between the observed and the simulated hydrographs for runoff volume (V), peak runoff (Q_p) and time to peak (T_p). The RMSE is one of the commonly used error index statistics (Chu and Shirmohammadi, 2004).

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - P_i)^2} \qquad (2)$$

where O_i and P_i are the observed and the simulated values for parameter of interest.

The secondary evaluation measure compared simulated runoff and infiltration maps, generated at each pixel across the hillslope at different time intervals, and runoff maps generated using the actual field data.

4.5 RESULTS AND DISCUSSION

4.5.1 HYDROGRAPH CALIBRATION, SENSITIVITY ANALYSIS AND VALIDATION

As mentioned above, event 1 was used to calibrate the model. During calibration process, interpolated *k*-values were kept constant, and other hydrological parameters were adjusted until a good fit was found between the simulated and the observed hydrograph at the outlet of the hillslope. Table 4.1 shows the calibrated hydrological parameters. The calibrated value for Manning's roughness coefficient of 0.17 was used for overland pixels and 0.09 for channel pixels. Since the hillslope used in this study has dense grass cover, 0.17 value was in the range given by Engman (1986). Also, $HIRO_2$ model do not incorporate the macropore flow, which was found to be a significant contributor to subsurface flow at the study site in a separate study conducted (data not shown). Therefore, to adjust the macropore effect, higher wetting front suction value was used during calibration, which also lies in the range given by Koorevaar *et al.* (1983) for sandy loam soils. The Nash-Sutcliffe coefficient for V was 0.83 (Figure 4.5a) and the Root Mean Square Error (RMSE) values for V, Q_p, and T_p was 0.21 m^3, 0.56 m^3 h^{-1}, and 5 min, respectively (Table 4.2). Figure 4.5 also shows the simulated and the observed hydrograph for event 1. The statistics derived from the model results for event 1 were very good considering all the uncertainties involved in the field data.

A sensitivity analysis was also performed to identify the most important hydrological parameters which affect the hydrological response of the hillslope. During sensitivity analysis, the parameters such as porosity, initial water content, wetting front suction and Manning's roughness coefficient were increased and decreased by 20% of the calibrated values for event 1. For soil hydraulic conductivity values, ±20% perturbation was conducted on the log *k*-values. Table 4.3 shows the RMSE values between the calibrated values and the model results for three runoff variables (V, Q_p and T_p).

Results of sensitivity analysis which demonstrates that porosity and *k* play a dominant role in $HIRO_2$ model for simulating V and Q_p. Meng *et al.* (2008) found similar results at a watershed scale. Two other parameters i.e., wetting front suction and initial water content have some effect on V and Q_p, however, no parameter showed any sensitivity effect on T_p. It was expected that Manning's roughness coefficient would be the most sensitive parameter for T_p (Meng *et al.*, 2008).

The validation of $HIRO_2$ model was performed for event 2 using calibrated parameter values, except initial water content was used 0.12 m^3 m^{-3} lower than calibrated value of 0.18 m^3 m^{-3}. Figure 4.3 shows that the antecedent moisture condition of soil was higher during event 1 as compared to event 2. Using these parameter values, the E value between the simulated and the observed hydrograph was -7.10, indicating that simulation results were worse than using the average measured runoff volume. The poor simulation results for this event could be caused by the absence of macropore flow process in $HIRO_2$

model. Since macropore flow might be higher when the soil has lower initial water content due to higher suction and vice versa. However, the calibrated wetting front suction value used for event 2 was obtained from higher initial water content scenario (event 1). Therefore, another simulation for event 2 was run with wetting front suction of 6.5 m, using other parameters unchanged. The time-varying overland flow at the outlet of the hillslope was found to be in good agreement with the observed flow, with E value of 0.67 (Figure 4.5b). The RMSE values for V, Q_p and T_p were 0.03 m^3, 0.83 m^3 h^{-1} and 10 min, respectively (Table 4.2).

Overall, hydrograph analysis for both events clearly shows that the model was simulating the runoff processes reasonably well. For example, time to peak and the total amount of rainfall converted as runoff at the outlet were in good agreement with the observed data. Some discrepancies in the rising and recession limb of hydrograph, however, were observed for both the events. This was mainly attributed to the low runoff volumes generated (and observed) by these events. As mentioned in Sen *et al.* (2008, 2009), the pastures in the Sand Mountain regions of Alabama usually do not generate large overland flows. However, large runoff volumes can be generated from these pastures during hurricane events and large tropical storms. Although rainfall events studied in this study were smaller as compared to Meng *et al.* (2008), still the model performance was reasonably well. However, the incorporation of macropore flow and subsurface flow processes will enhance the model performance and much better representation of hydrologic processes is anticipated for larger events.

4.5.2 SPATIAL AND TEMPORAL DISTRIBUTION OF HYDROLOGICAL PROCESSES

Illustrating (and delineating) the spatial and temporal distribution of hydrological processes occurring during and after rainfall event across a landscape, at a watershed-scale or at a hillslope-scale, is a significant feature of the $HIRO_2$ model. This feature has tremendous applications for reducing nonpoint source (NPS) pollutants from hillslopes and as a result from watersheds. For example, for land application of farm animal wastes, using the $HIRO_2$ model, areas that generate overland flows and are connected to the outlet can be delineated. Management practices can then be developed to treat these areas differently from the areas that either do not generate overland flow or are not connected to the outlet. This would help significantly reduce NPS pollutants reaching surface water bodies. Model results can also help in studying the interaction of hydrologic characteristics such as topography, soil parameters, and rainfall characteristics and their interactions with surface runoff generation mechanism. The following analysis of both the rainfall events (event 1 & 2) illustrates the use of $HIRO_2$ in representing the distribution of hydrologically active areas (areas that generate runoff over the hillslope) as compared to observed field data (Figure 4.6 & 4.7).

Event 1 (Figure 4.5a) started at 1040 h with an intensity of 18.3 mm h^{-1}, which was higher than *k* of locations 10, 12, 18, 20, and 24. Around 33% of the total area showed surface runoff generation (Figure 4.6c) which might be due to the microtopography (ponding) of area. However, no runoff was recorded at the outlet of the hillslope. At the same time the model simulated no surface runoff (Figure 4.6a) anywhere on the hillslope, which might be due to model's assumption of higher infiltration capacity at the early stages of infiltration when the soils were relatively dry (Figure 4.6b). Figure 4.6b clearly shows that at this time infiltration rates were as high as 20 cm h^{-1} indicating no surface runoff. As the event continued, at 1055 h, a maximum rainfall intensity of 51.8 mm h^{-1} was reached. Field data showed that 100% of the total area was generating runoff and 1.8 m^3 h^{-1} of runoff was recorded at the outlet (Figure 4.5a). Similar results were shown by model simulation, channels over the hillslope showed maximum runoff of 5.00 m^3 h^{-1}, suggesting the whole hillslope was generating runoff (Figure 4.6a). However, model simulated discharge of 2.29 m^3 h^{-1} at the outlet was higher than the observed discharge. At 1125 h, rainfall intensity started decreasing (6.1 mm h^{-1}), and approximately 62% of the total area showed runoff generation (Figure 4.6c). Discharge of 1.05 m^3 h^{-1} was recorded at the outlet at the same time. Figure 4.5c shows that more runoff was generated on the middle section of the hillslope than on the upper and lower section, which clearly explains the effect of areas with low k values. The model simulation showed a similar trend with a discharge of 0.85 m^3 h^{-1} at the outlet (Figure 4.5a). At 1250 h, when the event almost ceased, field data show that approximately 46% of the total area was generating runoff; however, no runoff was recorded at the outlet (Figure 4.6c). A likely reason for observed runoff generation areas is ponding due to microtopography; however, model simulation did not show any runoff generation at this time (Figure 4.6a). Our overall analysis shows that the model simulated the distribution of runoff generation areas fairly well compared to the field data. Observed and simulated hydrographs started at the same time (at 1050 h). However, the simulated discharge stopped at 1155 h, which coincided with the end of the rainfall event, but the observed discharge stopped at around 1225 h (Figure 4.5a). This shows that the model may not be adequately simulating the lag time for runoff generation mechanisms. The other possible reason for discrepancy in the recession limb of observed and simulated hydrograph might be due to the absence of subsurface flow processes in the model.

Rainfall event 2 started at 1945 h with an intensity of 9.1 mm h^{-1} (Figure 4.5b). At 1950 h, the intensity increased to 48.8 mm h^{-1} (Figure 4.5b), and approximately 62% of the total area was contributing to surface runoff (Figure 4.7c). There was, however, no discharge recorded at the outlet (Figure 4.5b). At the same time, although the rainfall intensity was higher than the *k* values of a majority of hillslope area, the model did not show any runoff generation areas, which was attributed to the high infiltration capacity at the early stages of infiltration, when the soils are relatively dry (Figure 4.7a). The maximum rainfall intensity of 61 mm h^{-1} was recorded at 2000 h (Figure 4.5b). Field data show that 100% of the total area was contributing to surface runoff (Figure 4.7c) and a discharge of 1.22 m^3 h^{-1} was recorded at the outlet (Figure 4.5b). Model results show the same trend as the field data, with approximately the whole hillslope generating runoff (Figure 4.7a). However, the model simulated a discharge of only 0.66 m^3 h^{-1}, which was smaller than the observed discharge value (Figure 4.5b) of 1.22 m^3 h^{-1}. At 2025 h, the major portion of rainfall event 2 had occurred (1.78 cm), the intensity was 3.1 mm h^{-1} and was decreasing. At this time, the field data show that approximately 94% of the total area was generating surface runoff and a peak discharge of 1.60 m^3 h^{-1} was recorded at the outlet (Figure 4.7a and 4.5b). Figure 4.7a shows the model results at this time, which clearly illustrate some reduction in surface runoff generation areas as the rainfall intensity had decreased. The model estimated a 0.97 m^3 h^{-1} discharge at the outlet at this time. At 2050 h rainfall ceased. However, until 2100 h about 45% of the total area showed runoff generation, mainly in the low soil hydraulic conductivity areas, similar to event 1. The model also simulated similar surface runoff generation areas at this time as compared to observed data and no discharge was recorded at the outlet.

Results from this study demonstrate good agreement between simulated and measured spatial-temporal variability of runoff generation areas across a pasture hillslope. Analysis of two rainfall events of different intensity and duration emphasize the importance of soil hydraulic conductivity and rainfall characteristics in hydrologic modeling. Figures 4.6-4.7 show that runoff generation areas expanded across the whole hillslope (100%) as the rainfall intensity increases (events 1 and 2). The percentage of rainfall converted to runoff at the outlet of the hillslope followed the same trend as the runoff generation areas (Table 4.4). Events 1 and 2, with higher rainfall intensity, generated 8% and 4% of the total rainfall as runoff (Sen *et al.*, 2009, (in review)). A major contribution of this study was to evaluate the applicability of the $HIRO_2$ model at the hillslope-scale rather than at the watershed-scale. Using the field measurements in hydrologic modeling and by comparing the observed and simulated hydrographs and runoff generations areas maps, it was clearly illustrated that the $HIRO_2$ model can be a useful tool in hydrologic and water quality studies in this region.

4.6 CONCLUSIONS AND FUTURE WORK

The specific results of this study suggest that although the $HIRO_2$ model was developed and verified for the watershed scale, it is also applicable at smaller hillslope scales. Compared to the observed field data, the model simulated the spatial and temporal distribution of surface runoff generation areas and the overall hydrologic responses of a pasture hillslope under variable natural rainfall events reasonably well. Most importantly, the model captured the local run-on effects across the hillslope, which was mainly attributed to the spatial variability of k. The spatial variability of k was recognized to have a dominant role in the Hortonian overland flow generation for high intensity, short duration rainfall events (Sen *et al.*, 2008; Corradini *et al.*, 1998). Overall, $HIRO_2$ seems to be a very robust model applicable to different landscape scales and incorporates and simulates all the important hydrologic processes occurring during a rainfall event.

Results of this hydrologic modeling study helped in verification of the $HIRO_2$ model's applicability at the hillslope-scale and showed the capability of the model to simulate the hydrologic processes across the hillslope. Meng *et al.* (2008) have also calibrated and validated the model at the watershed-scale. The model simulated the runoff generation areas during rainfall events with different characteristics at a pixel level across a hillslope. Outputs of the model such as runoff, infiltration, etc., at the pixel level might be very useful in water quality studies, specially studies dealing with phosphorus transport from a hillslope and at the watershed scale.

As discussed earlier in the review section, there are currently many hydrologic models which are being used in water quality studies such as SWAT, PRMS, SWIM etc. These models do not take into the spatial and temporal variability of hydrologic processes occurring over/within a hillslope or watershed. However, if the outputs of the $HIRO_2$ model are incorporated with the phosphorus transport model of Vadas *et al.* (2007), which is a P transport model, it will mean a significant advance in hydrological studies. For example, if a water quality manager wants to know which area in a watershed or hillslope will generate surface runoff and how much P will be transported from that area, the $HIRO_2$ model will provide the amount of runoff generation and most importantly will generate the spatial and temporal runoff generation areas. Also, the outputs of the $HIRO_2$ model, such as runoff amounts from those areas, can be used in a P transport model, which will then estimate the amount of P transport to nearby water bodies. Thus, a water quality manager can develop the best management practices for those areas which will have high propensity of runoff generation and P transport.

Although the model simulates the hydrologic responses of a pasture hillslope very well, there are areas where the model can be improved. For example, currently, the model is an event-based hydrologic model. By extending it to a continuous model it would be a very useful tool for watershed modeling studies. If spatial and temporal outputs of infiltration and surface runoff at any time and at any pixel are incorporated with water quality models, the model will be very useful for water quality studies such as for evaluating the effect of spatially- and temporally-distributed management practices.

Table 4.1. Calibrated model parameter values for 20 July, 2007 event at the study site.

Model Parameters	Calibrated Values
Porosity, Φ (m^3 m^{-3})	0.45
Initial water content, θ_i (m^3 m^{-3})	0.18
Manning's, *n*	0.17 (overland) 0.09 (channels)
Wetting front suction, ψ (m)	4

Table 4.2. The root mean squared error between the observed and simulated runoff volume (V), peak runoff (Q_p) and time to peak (T_p) for 20 July (calibration event; event 1) and 25 August 2007 (Validation event; event 2).

Event	Runoff Variable	Observed	Calibrated	RMSE
20 July 2007	Runoff volume, V (m^3)	1.53	1.31	0.21
	Peak runoff, (Q_p) (m^3 h^{-1})	2.25	2.81	0.56
	Time to peak, T_p (min)	30	25	5
25 Aug. 2007	Runoff volume, V (m^3)	0.84	0.86	0.03
	Peak runoff, (Q_p) (m^3 h^{-1})	1.22	2.05	0.83
	Time to peak, T_p (min)	20	30	10

Table 4.3. Results of sensitivity analysis

Model parameters	% change in value	RMSE of V (m^3)	RMSE of Q_p (m^3/s)	RMSE of T_p (min)
Porosity, Φ (m^3 m^{-3})	+20	0.65	1.29	0.00
	-20	2.38	2.31	0.00
Initial water content, θ_i (m^3 m^{-3})	+20	0.55	0.81	0.00
	-20	0.37	0.65	0.00
Wetting front suction, ψ (m)	+20	0.52	0.95	0.00
	-20	0.94	1.26	0.00
Manning's *n (overland pixels)*	+20	0.00	0.00	0.00
	-20	0.00	0.00	0.00
Manning's, *n*	+20	0.24	0.55	0.00
	-20	0.40	0.84	0.00
Log *k*	+20	1.08	2.18	5.00
	-20	3.86	3.18	0.00

Base values of V, Q_p and T_p for calibrated event 1 are 1.31 m^3, 2.81 m^3 h^{-1} and 25 min, respectively.

Table 4.4. Discharge coefficient of efficiency and total rainfall amount converted as runoff

Event #	E of discharge	Total rainfall converted as runoff (%)	
		Observed	Simulated
1	0.83	8.3	7.1
2	0.67	4.4	4.5

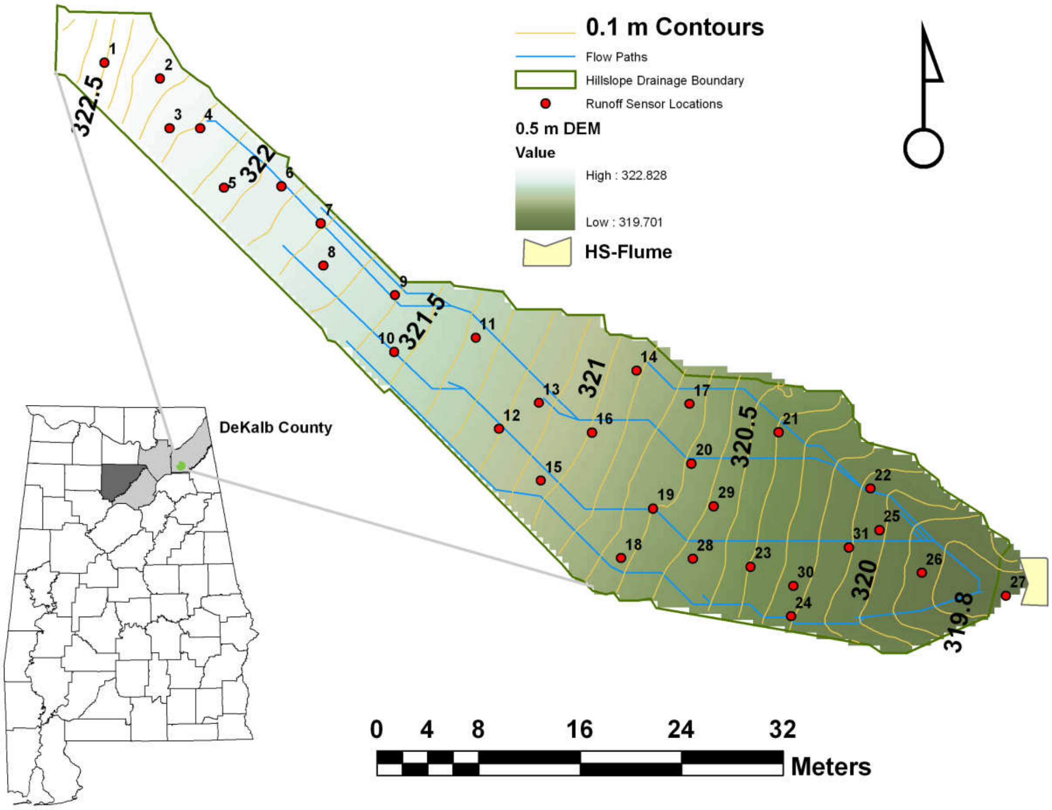


Figure 4.1. Location of the study site at the Sand Mountain Research and Experimental Station, DeKalb County, AL, USA, showing 31 sampling points (paired surface and subsurface runoff sensors) on a hillslope. The counties in gray are major poultry producing counties. The poultry litter is mostly surface applied.

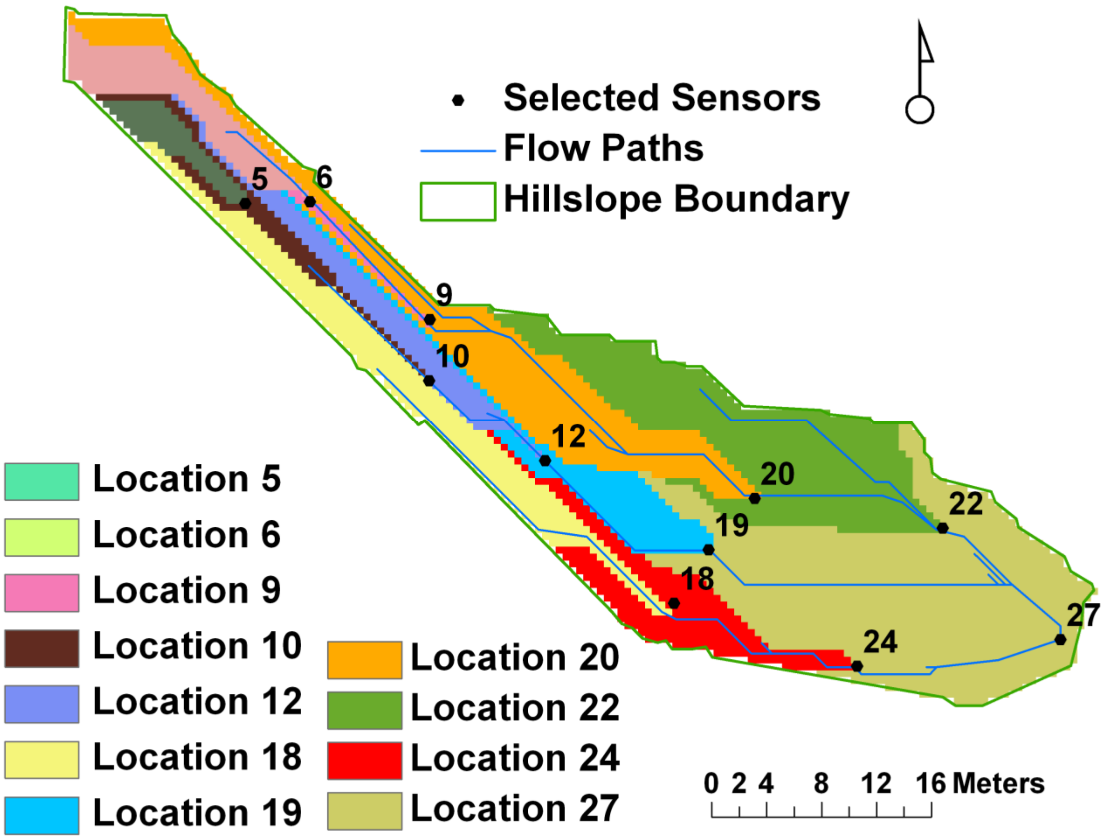


Figure 4.2. Contributing areas of selected 11 sampling locations over the entire hillslope area.

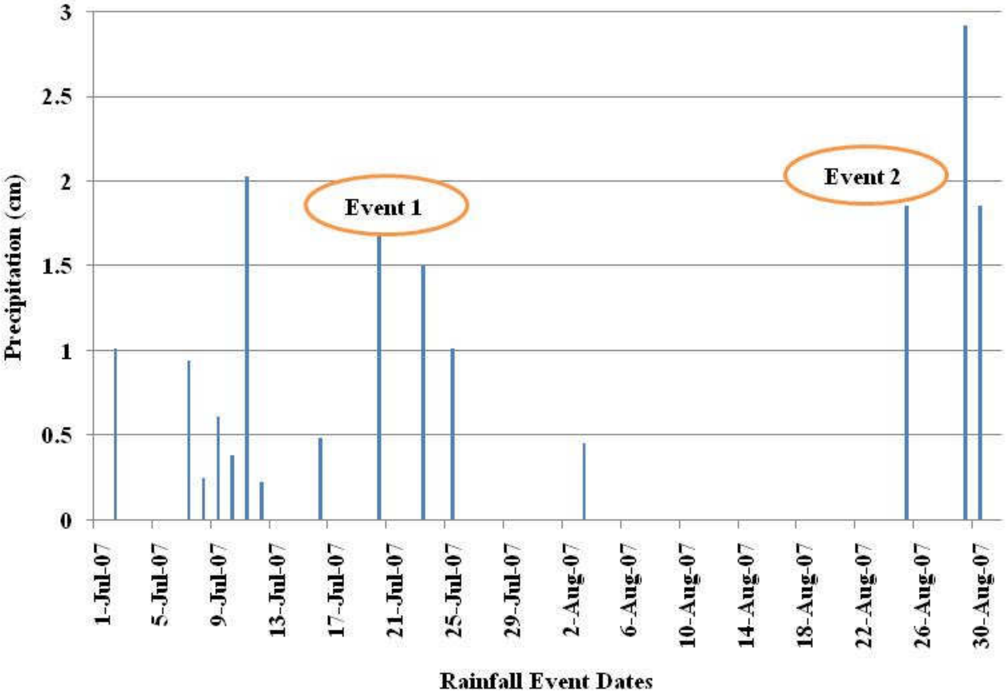


Figure 4.3. Rainfall events occurred in the months of July and August of 2007 and highlighted event 1 and event 2 occurred on 20 July and 25 August, 2007.

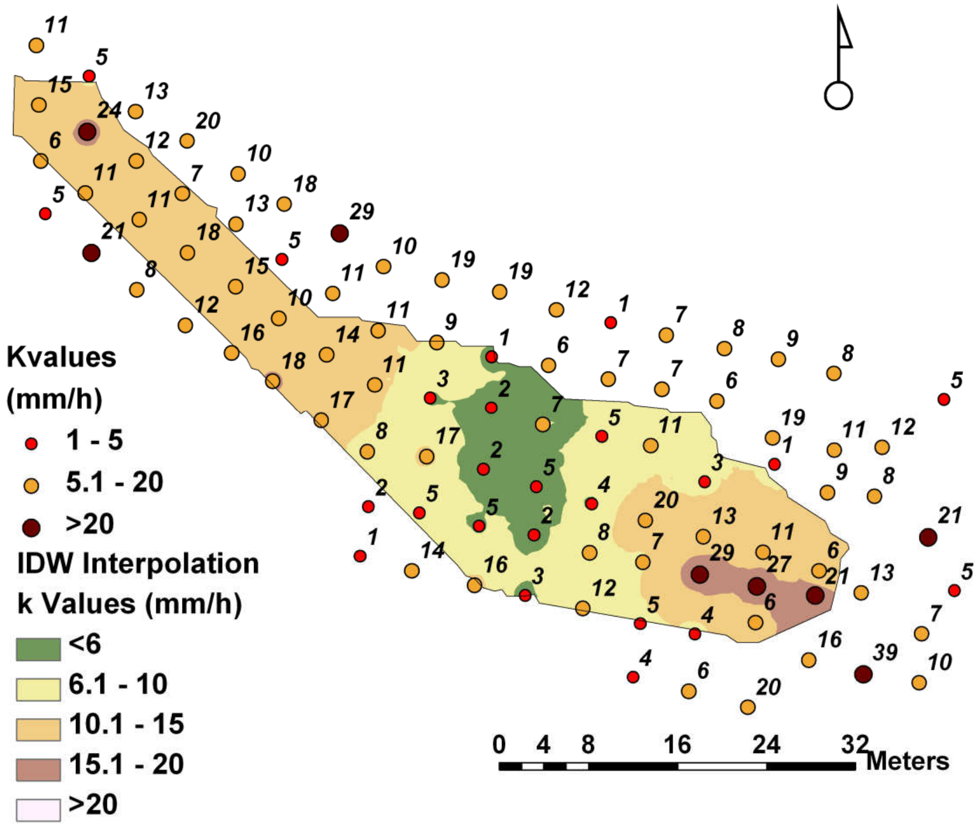


Figure 4.4. Spatial variability of soil hydraulic conductivity (interpolated and measured values) across the entire hillslope.

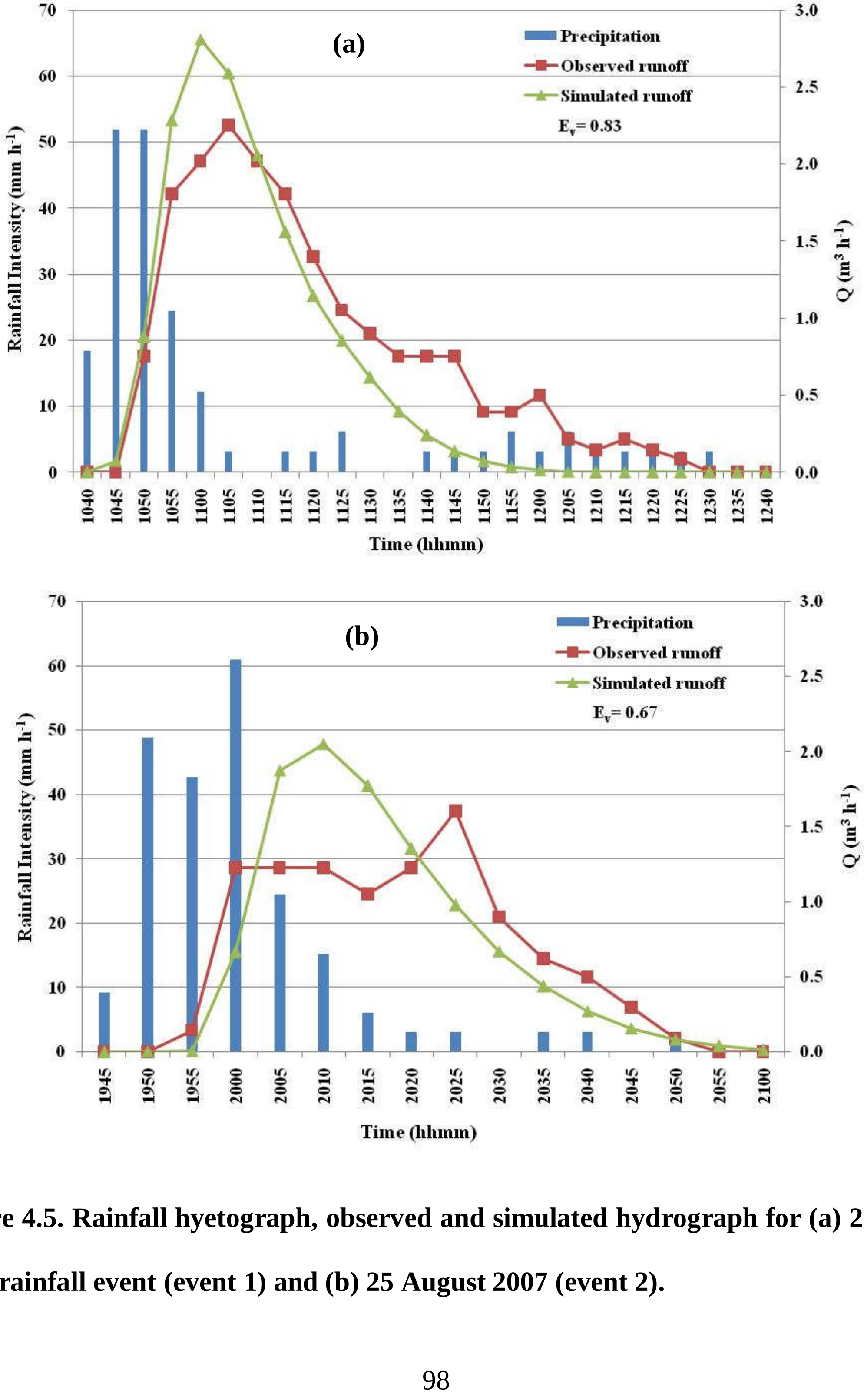
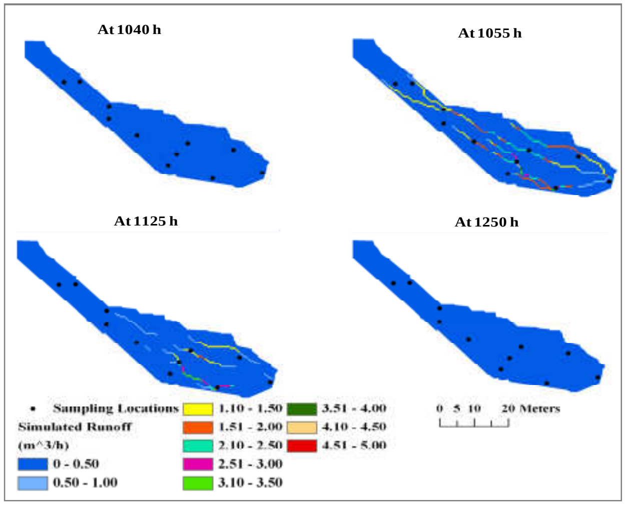
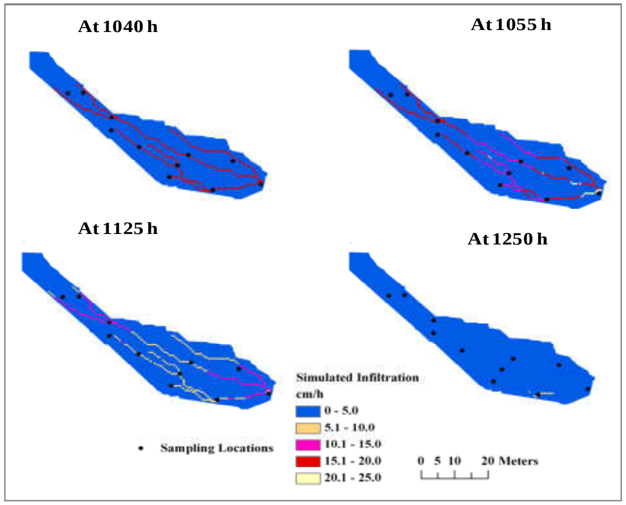


Figure 4.5. Rainfall hyetograph, observed and simulated hydrograph for (a) 20 July 2007 rainfall event (event 1) and (b) 25 August 2007 (event 2).





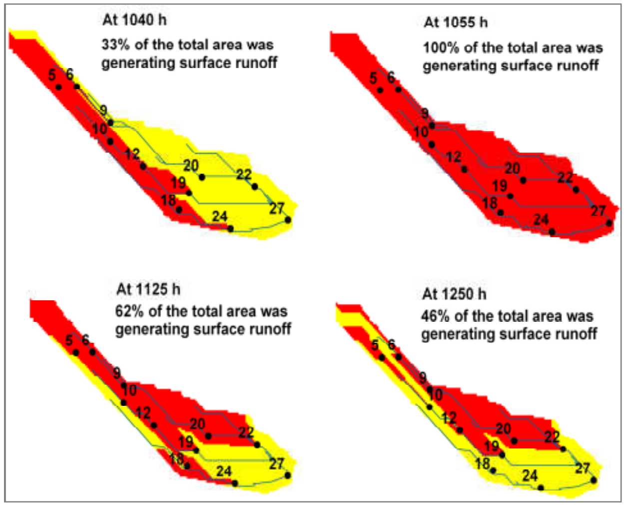
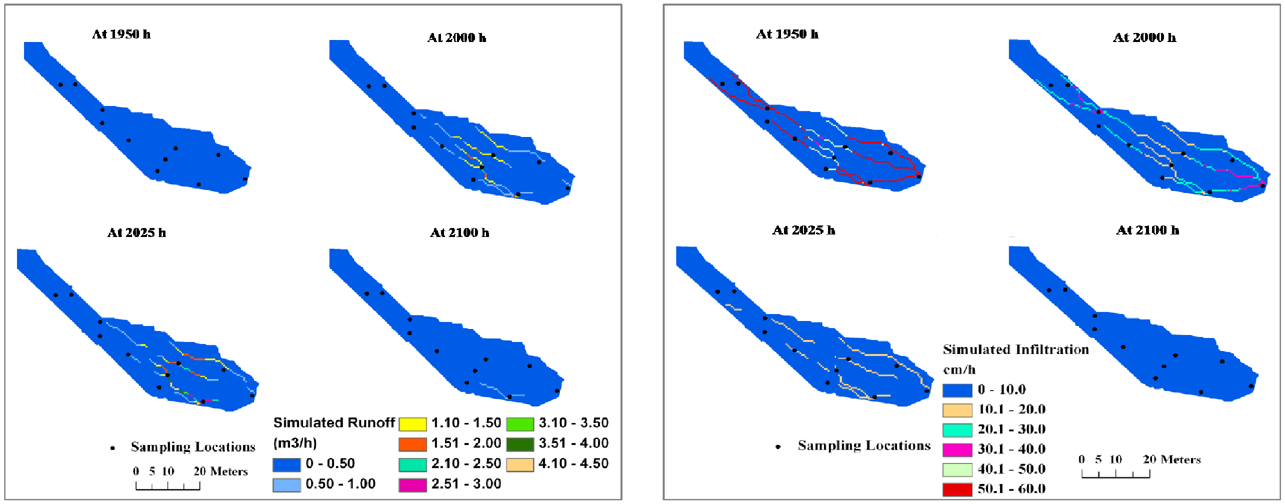


Figure 4.6. Images from rainfall-runoff event on 20 July 2007 of (a) model simulated surface runoff generation, (b) model simulated infiltration rate, and (c) observed surface runoff generation over the hillslope.



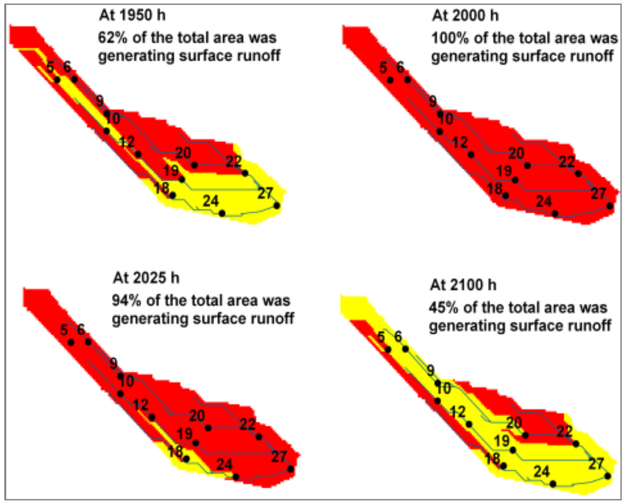


Figure 4.7. Images from rainfall-runoff event on 25 August 2007 of (a) model simulated surface runoff generation, (b) model simulated infiltration rate, and (c) observed surface runoff generation over the hillslope.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

The overall goal of this study was to identify the characteristics of surface runoff generation mechanisms which can be controlled using watershed management practices to improve water quality. This study was instrumental in understanding the importance of linkage between the spatio-temporal hydrologic variables and surface runoff generation mechanisms.

A pasture hillslope in the Sand Mountain region of north Alabama was intensively instrumented using surface runoff and subsurface sensors, rain-gage, HS-flume, and shallow wells. The hillslope drained to a point where a HS-flume recorded the surface runoff from the entire instrumented hillslope. The surface and subsurface sensors together provided insights into the surface runoff generation dynamics during and after a rainfall event. During the study period, which was from January 2006 to December 2007, more than 60 rainfall events occurred. Out of these events only a few generated runoff at the outlet of the hillslope. The dynamics of surface runoff generation mechanisms were analyzed for three rainfall events of different characteristics: high-intensity and short duration events, medium-intensity and medium duration events, and low-intensity and long duration events. Based on the data collected for different rainfall events during the study period, the following conclusions were made:

OBJECTIVE 1

Our first objective was to identify the dominant runoff generation mechanism using the distributed sensors data which was collected during and after rainfall events. Three rainfall events of differing characteristics with sensors installed in four locations having different soil hydraulic properties were analyzed.

Results showed that the main surface runoff generation mechanism in this region is infiltration excess. Also, the results of this study concurred with the findings from other hydrologic studies that suggest that rainfall-intensity and soil hydraulic conductivity play a dominant role in controlling infiltration excess mechanisms. Furthermore, only the short period rainfall events, during which the rainfall intensity was high, produced surface runoff. This suggested that a large portion of most of the rainfall events infiltrated, pointing out the importance of subsurface flow.

OBJECTIVE 2

The second objective was to delineate the spatially-and temporally-variable runoff generation areas and demonstrate that hydrologic connectivity is important for generating hillslope flows when infiltration-excess runoff mechanism is dominant. Six rainfall events were analyzed. Three of these rainfall events occurred during summer months, while the other three occurred during winter months. In addition to runoff data, *in-situ* soil hydraulic conductivity data was collected using a 5-m grid over the entire hillslope.

Analysis of data from surface runoff sensors, rain gage, and HS-flume help to characterize the spatial and temporal distribution of runoff generation areas. The results clearly showed how the runoff generation areas expanded and contracted depending on the intensity of rainfall event. The maximum runoff generation area, which contributed to give medium value runoff at the outlet of the hillslope, varied between 67 to 100%. Approximately, 4% and 8% of the total rainfall was converted as runoff at the outlet of the hillslope during high-intensity, medium and short duration rainfall events, respectively. It was also found that rainfall events with medium- to low-intensity and medium duration generated very little runoff at the outlet. Field observation also showed that areas with lower soil hydraulic conductivity generated runoff first, and then, depending on rainfall intensity of the event, runoff at the outlet was generated by hydrologically connected areas. It was concluded that within the infiltration-excess runoff dominated areas, rainfall intensity and soil hydraulic conductivity can be used to explain the observed hydrologic response.

OBJECTIVE 3

The third objective was to test the applicability of physically-based, distributed hydrological model, $HIRO_2$ at the study site to simulate the infiltration-excess runoff generation mechanism and the observed spatial-temporal variability of runoff generation areas. The numerical model used was developed by Meng *et al.* (2008) was previously tested at watershed scale. However, it had not been tested at a hillslope scale. Two rainfall events of varying intensity and duration were simulated and compared with observed field data to study the applicability of this model for describing the dynamics of hydrologic processes.

The model simulated patterns of spatial and temporal distribution of runoff generation areas compared well with observed data. In addition, the predicted hydrographs for the three events matched reasonably close to the hydrographs observed at the outlet of the hillslope. The Nash and Sutcliffe Coefficient of Efficiency (E) ranged between 0.83 and 0.67. The model was able to simulate the effects of hydrologic characteristics such as topography, soil parameters and rainfall variations on surface runoff generation mechanisms.

5.2 LIMITATIONS

Though our study showed some significant conclusions which can be used for better understanding the hydrology of the study site, there are still some limitations. The incorporation of these limitations might improve the quality of data collection for future works. Some of these limitations are as follows:

1) Though the study site was representative pasture, which are found in the Sand Mountain region of North Alabama, still other pastures might have different management practices. Therefore, replication of the study over other pastures will be useful in generalizing the results.

2) During the study period there were very few events which produced runoff at the outlet of the hillslope, thus our conclusions are based on few rainfall events. This limitation has also an effect on our modeling part. There were very few events to calibrate and validate the application of $HIRO_2$ model at the hillslope scale.

3) The other reason of having fewer rainfall events to be analyzed was functioning of all the sensors during a rainfall event. This might be eliminated in future by using the wireless network system.

4) The subsurface sensors were installed in ground using polyvinyl chloride (PVC) pipe. During some rainfall events with very small amount of rainfall, at some locations subsurface sensor have shown sudden rise and fall in perched water table, which occurred due to soil clogging PVC pipes.

5) The observed data suggested that approximately 90% of the rainfall amount infiltrates in the soil and moves as a subsurface flow. Therefore, there is a significant need of incorporating the subsurface flow component in the $HIRO_2$ model to estimate more accurate water budget at the study site. This incorporation might be helpful in understanding the transport and estimation of Phosphorus in subsurface flow.

5.3 SUGGESTIONS FOR FUTURE WORK

Results of this study suggest that rainfall characteristics and soil hydraulic conductivity are the two important hydrologic properties that control surface runoff generation areas in the pastures of the Sand Mountain region of North Alabama. The two-year field experiment showed that the majority of rainfall is infiltrating into the soil profile and may be adding water to nearby water bodies via subsurface flow. Following research efforts can be pursued to better understand this site:

1) The existing hydrological models, such as $HIRO_2$, can be improved by incorporating hydrological connectivity and runoff generation factors. This suggestion may be implemented by following the topographic index (TI) concept. The soil hydraulic

conductivity variable can be incorporated in TI to develop a new index which can be based on variation in topography, slope, soil hydraulic conductivity, and hydrological connectivity. This index might be a helpful tool for mapping the runoff generation areas and also for describing their connectivity to surface runoff flow paths.

2) Though the study was conducted successfully using 31 distributed surface and subsurface runoff sensors, installed on the pasture hillslope for almost two years, the instrumentation used can be improved by using new equipments such as CS616-L Water Content Reflectometer (Campbell Scientific, Inc.), more sensitive pressure transducers for flume, and redesigning the surface runoff sensors to have the exact runoff volume at each sampling location. The experiment can be conducted for a longer period of time to collect a better datasets.

3) As mentioned above, the subsurface flows, which can transport phosphorus and other pollutants to a nearby water body, might be significant in this region. A trench can be built at the outlet of the hillslope to quantify subsurface flows occurring in this region.

4) Tracer studies can be conducted at the hillslope and the data could be used to develop a solute transport model.

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