INVESTIGATING THE DRIVING MECHANISM OF SUBSURFACE RUNOFF RESPONSE ON A VEGETATED HILLSLOPE IN THE GEORGIA PIEDMONT

by

ERNEST WILLIAM BEASLEY IV

(Under the Direction of John F. Dowd)

ABSTRACT

The near instantaneous runoff response of upland ephemeral channels to high intensity rainfall events has been shown to be minimally influenced by direct precipitation and Hortonian overland flow. Geochemical results have demonstrated that the majority of such runoff water is already present in the catchment before the onset of the storm. This work builds upon the work of McKinnon and Thomas at the USDA – ARS J. Phil Campbell research farm in Oconee County, GA. Their work suggested the significance of the kinematic, or pressure wave, phenomenon in generation of instantaneous subsurface runoff at the site. However their results were questioned as macropore flow may have been able to produce similar data. This work approaches the problem from two different angles, using physical and chemical evidence, to pinpoint the driving mechanism behind the observed runoff at the ARS study site established by McKinnon and Thomas. Our experiments suggest that the kinematic wave phenomenon drives the near instantaneous subsurface runoff observed at the site while demonstrating that the phenomenon is mutually exclusive with saturated conditions at the soil surface.

INDEX WORDS: kinematic, pressure wave, runoff, *new* water, *old* water, stormflow, subsurface runoff, tracers

INVESTIGATING THE DRIVING MECHANISM OF SUBURFACE RUNOFF RESPONSE ON A VEGETATED HILLSLOPE IN THE GEORGIA PIEDMONT

by

ERNEST WILLIAM BEASLEY IV

B.S., James Madison University, 2005

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2011

INVESTIGATING THE DRIVING MECHANISM OF SUBURFACE RUNOFF

RESPONSE ON A VEGETATED HILLSLOPE IN THE GEORGIA PIEDMONT

by

ERNEST WILLIAM BEASLEY IV

Major Professor: John F. Dowd

Committee: Dory Franklin
Dinku Endale

Electronic Version Approved:

Maureen Grasso
Dean of The Graduate School
The University of Georgia
May 2011

ACKNOWLEDGEMENTS

Many thanks to everyone who has made this project and my graduate school experience possible. You have each individually contributed greatly to my education and advancement in my field whether you realize it or not. I'd specifically like to thank John Dowd, Steve Fitzpatrick, Dory Franklin, Dinku Endale, Stephen Norris, Dwight Seamans, Steve Baedke and the JMU Geology Department (for letting me camp out in their lab for a month and a half to use their IC), Darcy and Rick with UGA Engineering (for their help with IC work), Paul Schroeder, Liz Cary, Richard Cary, Bill Miller and Jason Thomas for directly contributing to my completion of this project. I'd also like to thank all of my professors for such a great experience in school and for providing me with the tools I need to accomplish my goals. Thanks to Biz for sticking this out with me and thanks to my whole family for standing behind me through it all. Finally, I'd like to thank Steve Dancz and Dan Nettles (Tank and Bleed, too!) of the UGA jazz department, who welcomed a random geology grad student into their program with open arms. My experience with the UGA jazz program kept me balanced during grad school. Not only did I get exactly what I was looking for out of the UGA Geology Department, but while in graduate school I was exposed to broad musical wisdom that I will continue to develop and share with whoever wants to listen.

TABLE OF CONTENTS

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

The runoff response of small upland catchments to intense rainfall events has been a subject of hydrologic research since the early 20th century and the near instantaneous rise of the storm hydrograph in response to such events continues to intrigue hydrologists. Aware that direct precipitation and throughfall from the forest canopy onto the stream channel during storm events could not possibly account for the observed rapid rise in gage height at the stream, early hydrologists attributed the excess water to surface runoff. However in the mid- to late 20th century, upon the advancement of the field of isotope geochemistry and the recognition that much of the observed response consisted of pre-storm event water, the significance of subsurface processes became clear.

One of the most important and perhaps least understood of these processes that has surfaced in the recent literature is the kinematic or pressure wave phenomenon. It has been understood for some time that during storm events, macropore flow within the soil can contribute significantly to runoff and contaminant fate and transport. Until recently, any rapid response was attributed to macropore flow, and kinematic processes were ignored. It was assumed that rapid subsurface response could only be from macropore flow because Darcian flow was too slow. Kinematic response, however, is many times faster because the velocity is the celerity of the pressure wave, not the advective velocity of the water in the pores (Rasmussen *et al*. 2000).

This study uses a hillslope gutter system and artificial rainfall to assess the mechanism(s) behind the near instantaneous subsurface runoff response observed on a vegetated hillslope in the Piedmont of Georgia. Previous work has suggested that the kinematic wave phenomenon controls the runoff at the site, but previous results cannot unambiguously distinguish between macropore flow and kinematic processes. Past studies at the site have related measured volume of runoff to rainfall intensity and antecedent soil moisture conditions. Observations of concentrated points of runoff on cut soil faces at the site during past rainfall simulation experiments have suggested the presence of preferential flow pathways. No existing data suggests that these pathways classify as macropores. In reality, they are most likely zones of preferential flow within the soil horizon related to hydrologic heterogeneities. This work uses applied ionic tracers and rainfall simulations in attempt to pinpoint the locations of preferential flowpaths and to determine the driving force behind the subsurface runoff. This work also explores the mutually exclusive relationship between the relatively recently identified instantaneous runoff driving mechanism, the kinematic wave phenomenon, and saturated conditions at the soil surface.

CHAPTER 2

LITERATURE REVIEW

One of the principal problems in hydrology is that most of the flow with which we are concerned occurs underground; this fact makes most hydrological processes extremely difficult to measure, analyze and quantify (Beven 2000). Not surprisingly, one of the most accurate hydrological measurements made in relatively small watersheds is stream discharge. Water that occurs as streamflow represents the integration of all processes within the catchment with contributions coming from groundwater, direct precipitation, subsurface runoff, and overland flow. It has been the focus of many hydrologists since the early 20th century to decipher the stream hydrograph and quantify its components, relating them directly to the observed volume of water in the stream to predict runoff volumes and timing and to determine the fate of contaminants.

Research has shown that during large runoff events in small, humid, vegetated catchments, water is quickly transmitted to the stream (eg. Meyles *et al*. 2003, Grayson *et al*. 1997). The paradox encountered in such systems is that the vast majority of this runoff typically shows the isotopic signature of "old" water, or pre-storm event water (Kirchner 2003). How does a high intensity storm event cause an essentially instantaneous rise in gage height at the stream? Most likely no single process is the cause, as in reality every catchment is unique and the contribution of each process varies depending on the climate, watershed morphology and geology. Early hydrologists were aware that it would be impossible for direct precipitation to the stream channel of concern to account entirely for this rapid response as there is simply not enough volume (Beven 2000). Thus, they speculated that other processes must be contributing to the almost instantaneous response observed in stream discharge.

Runoff Mechanisms

Hortonian Overland Flow

The earliest conceptualization of runoff response relied solely upon overland flow, or surface runoff, to account for the excess volume observed in the storm hydrograph. The concept of overland flow was brought to public attention by Horton in the 1930s. Horton (1933) claimed that during large rainfall events flow across the ground surface often occurs as the infiltration capacity of the soil is exceeded by precipitation rate. The classic definition and popular conceptual understanding of Hortonian overland flow assumes sheet flow. Although his name is generally associated with overland sheet flow, Horton acknowledged the fact that this phenomenon commonly occurs in urban or developed areas and is in fact rarely seen in natural systems. Typically in nature, overland flow occurs as localized channel flow (Beven 2000).

Because of nature's inherent heterogeneities, soil infiltration capacities may vary quite significantly from one location to another on the same hillslope. So water can occur as surface runoff in one location where infiltration capacity is exceeded and travel downhill to a location where soil properties allow for infiltration to occur, or vice versa. Such complications become an issue when the geochemistry of the runoff water is considered, as will be discussed in a later section.

Saturation Excess Overland Flow

Overland flow can occur either as the infiltration capacity of a soil is exceeded (Hortonian case) or as a saturation excess mechanism (Hewlitt and Hibbert 1963, Dunne and Black 1970, Beven 2000). In areas where soil is saturated at the surface, rainfall is unable to infiltrate and thus becomes overland flow. Saturation excess overland flow typically dominates runoff in and around upland ephemeral channels, areas adjacent to streams, in slope concavities, or where the subsoil is relatively impermeable and perched saturated conditions exist (Williams *et al.* 2002). Return flow is a variation that occurs where upslope additions of subsurface water exceed the drainage capacity of the downslope soil, and as the water table rises to the soil surface, overland flow results (Dunne and Black 1970).

Variable Source Area Concept

Hewlitt and Hibbert conducted a series of experiments examining runoff processes at the Coweeta Hydrologic Laboratory in Otto, NC in the 1960s. They operated and maintained a number of small watershed models to simulate hillslope processes and conducted a series of rainfall-runoff experiments. Hewlitt and Hibbert's research culminated in what became known as the variable source area concept, which is widely accepted as a major process contributing runoff in near stream areas during large storms. The concept is based on the observation that the contributing area to runoff is somewhat proportional to rainfall volume.

Around the same time, Dunne and Black (1970) conducted a series of experiments in a Vermont watershed with similar results. They attributed the observed rise in the hydrograph to a saturated near-stream area that changes in size throughout a single storm event.

The variable source area concept relies upon saturation excess overland flow to occur in near stream areas, valley floors, and upland ephemeral channels. The area over which saturated conditions exist is dynamic and changes with seasonal water table fluctuations, rainfall intensity, soil moisture and antecedent moisture conditions:

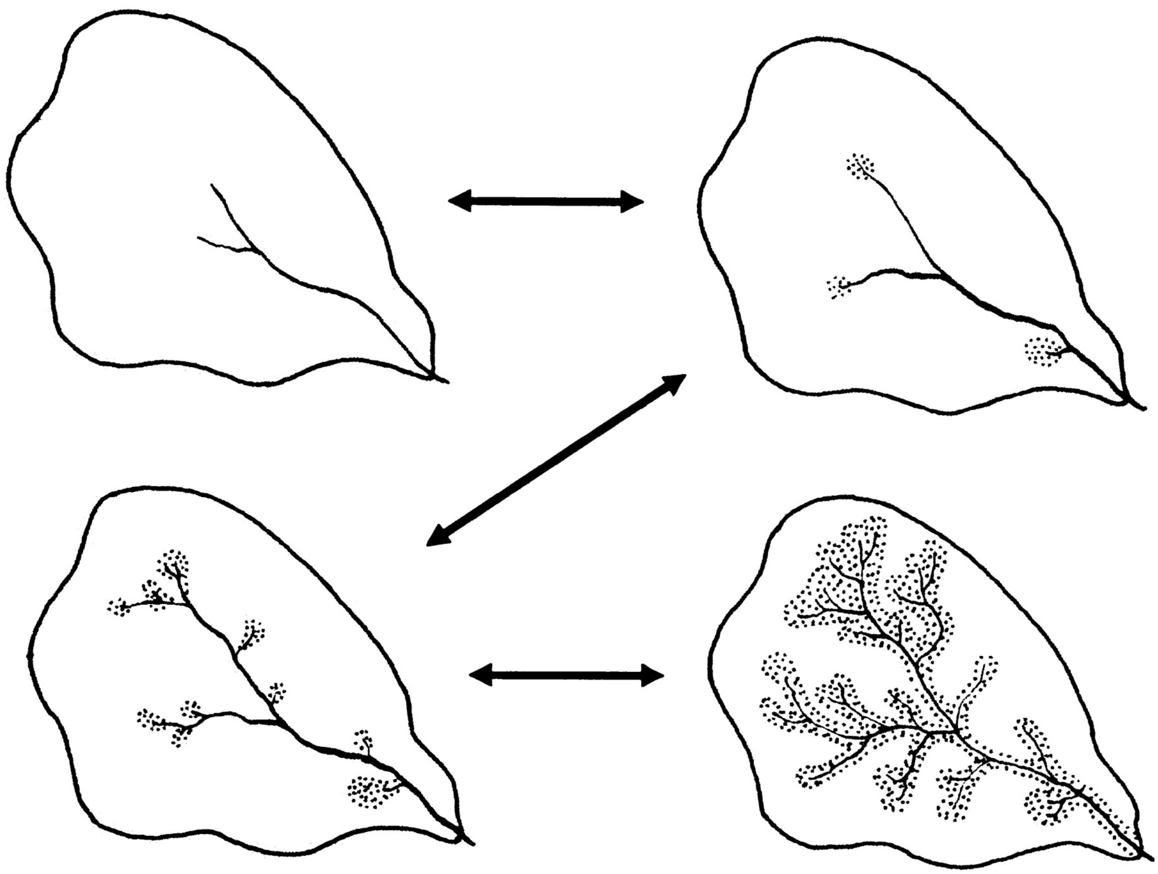


Figure 1: Variable Source Area as it changes temporally and spatially. (Dougherty et al. 2004)

Hewlitt and Hibbert's work shifted the understanding of rainfall-runoff processes away from overland flow, emphasizing the importance of saturation excess overland flow, the variable source area, and subsurface runoff (Hewlett and Hibbert 1963).

Precipitation falls on a hillslope and displaces pre-event water stored in the soil. This water moves laterally downslope and becomes what Hewlett and Hibbert refer to as translatory flow, ultimately emerging as return flow in near stream areas. Translatory flow is a subsurface process that produces runoff much faster than the flow of the actual water. This marks perhaps the first mention in the literature of the rapid propagation of a pressure wave in the shallow subsurface acting as the driving force behind exfiltration of subsurface water to the channel. The pressure wave phenomenon has become a common theme in rainfall-runoff literature and is now widely used to explain the near instantaneous response and unsaturated subsurface flow as will be described in a later section. Hursh (1944) suggested the concept of subsurface runoff as early as the 1940s, but until Hewlitt and Hibbert's publications in the 1960s, it was not integrated into the general conceptual approach to rainfall-runoff modeling by much of the hydrological community.

The variable source area concept explains a system's runoff response during small events, but fails to explain what happens under intense rainfall events. In Hewlitt and Hibbert's model the contributing area to runoff is limited to near-stream areas, but other research has shown that during large storms a rapid high-volume response occurs in which the contributing area can include up to two thirds of the entire catchment (Meyles *et al*., 2003).

Subsurface Runoff

Hydrologists have used a number of different terms to refer to subsurface runoff over the years including interflow (Hursh 1944), subsurface storm flow (Whipkey 1965), translatory flow (Hewlitt and Hibbert 1965), and throughflow (Kirkby and Chorley, 1967). While each definition differs slightly from the rest, hydrologists agree that subsurface runoff often occurs in the vadose zone during rainfall events and is capable of contributing significantly to runoff peaks in storm hydrographs. This unanimity is largely because surface processes could not explain the observed stream discharge. Research since the 1960s has shown that subsurface runoff has a much broader influence on runoff response and displays much more dynamic behavior than the piston-type flow mechanism behind translatory flow as described in the previous section.

The influence of subsurface flow on channel discharge is highly variable (both temporally and spatially) and depends on a number of factors including site geology, soils, climate, rainfall intensity, and antecedent soil moisture. However, research has shown that in small, vegetated, humid, upland catchments, subsurface stormflow dominates the rising limb of the storm hydrograph (eg. Meyles et al. 2003, Brammer and McDonnell 1996, Beasley 1975,). Additionally, the work of many researchers suggests that the timing of this runoff is not related to how fast water moves through the catchment (eg. Anderson et al., 1997, Martinec 1975). High volume runoff response is often observed at the stream within minutes of the onset of a high intensity storm event, while the individual water molecules falling on the watershed as *new* water may take as much as months or years to migrate to the stream channel as they infiltrate and are stored in the soil matrix.

Rapid macropore flow of *new* water was originally postulated to account for the near instantaneous response of the hydrograph, but upon advancement of isotope geochemistry in the 1970s and the recognition that the bulk of runoff water is often pre-storm event water, this assumption was proven wrong (Beven, 2000). Macropore flow, or the flow of subsurface water through relatively large conduits, is however an important process in runoff response and will be discussed in detail in a later section.

Certain types of subsurface runoff are not major players in the near-instantaneous response of a catchment to high intensity rainfall events because the flow velocities under which they operate are simply too slow. Throughflow, for example, as defined by Kirkby and Chorley (1967) is a process by which subsurface water moves laterally downslope. It is not considered a significant factor in the instantaneous response of the storm hydrograph to intense rainfall events because it most often occurs as perched Darcian flow, which is much too slow to account for the rapid rise commonly observed in the hydrograph (Williams et al., 2002). Throughflow is often controlled by local geologic conditions, typically occurring on top of an impermeable soil later or at the interface of two horizons, the lower of which having much lower hydraulic conductivity. (Williams et al., 2002)

The following figure illustrates the major runoff pathways contributing to streamflow:

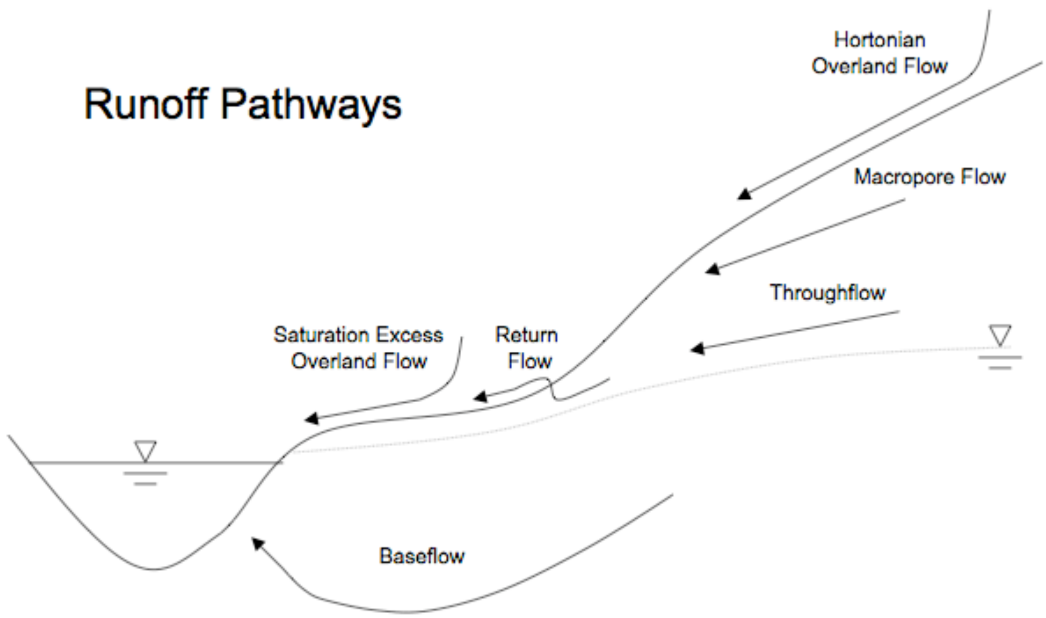


Figure 2: Examples of runoff pathways to the stream (modified from Mckinnon, 2005).

Hydrograph Separation – The Geochemical Approach

One of the most influential tools in the modern day field of hydrology is the use of geochemical data to provide additional insight into flow processes. In the context of rainfall-runoff studies, geochemical data allows for hydrograph separation based upon the individual components' relative concentrations of environmental or applied tracers.

A stream hydrograph shows the discharge of a river or stream at a single location as a function of time (Fetter, 2001). The storm hydrograph plots the total discharge of a stream in response to a rainfall event and alone gives no indication of the origin of the added volume of water. However the use of geochemical data has made it possible in many cases to separate the hydrograph into its basic components: baseflow, direct precipitation, overland flow, and subsurface runoff.

The following figure depicts a storm hydrograph for a watershed, shown first as total streamflow and then broken up into its individual components. This hydrograph is representative of a watershed in which overland flow is the major runoff component, likely an urban or developed area.

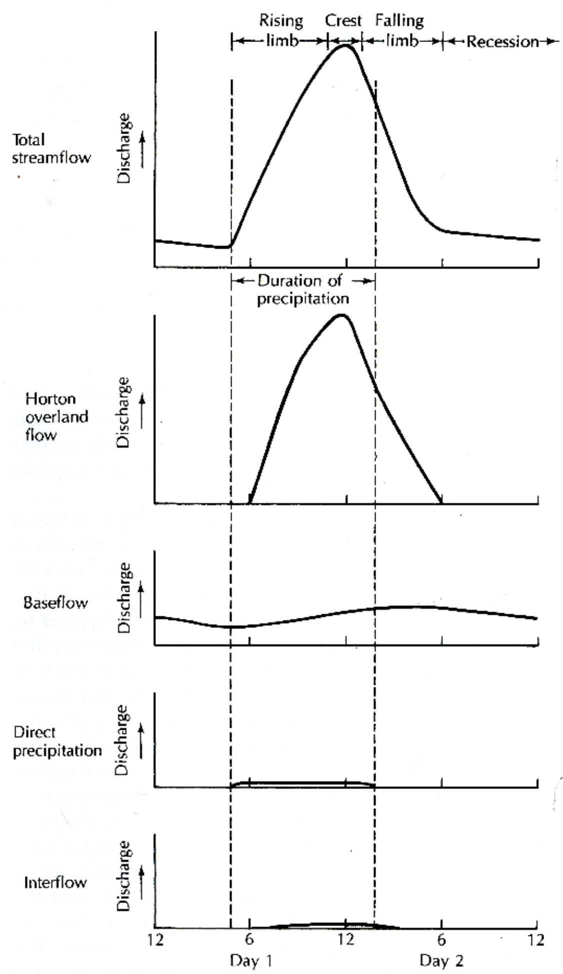


Figure 3: Storm hydrograph for an urban area shown as total stream flow in top plot, and broken down into its components (Fetter 2001).

The two-component mixing model is often used to facilitate hydrograph separation. In the earlier years separation by the technique was limited to baseflow and stormflow, or "old" water vs. "new" water. The limitation of this model is that no distinction beyond "old" water is made, lumping possibly many different flowpaths. Nevertheless, this approach has demonstrated in many catchments that old water dominates the rising limb of the hydrograph. (Sklash 1990)

During baseflow conditions in humid headwater catchments, all the water in a stream is "old" water, or recently discharged groundwater. The geochemical signature of stream water under baseflow conditions represents the integration of all "old" water discharged into the stream upgradient. The underlying assumption of the two-component mixing model is that the "old" and "new" water components are chemically or isotopically different and as "new" water is added to a stream during a large runoff event, the "old" water is diluted. The degree of dilution depends on the relative signatures and contributions of the individual components. If the geochemistry of the stream water during baseflow conditions and that of the "new" water is known, the following mass balance equations can be applied to determine the relative volumetric contributions of each component:

$Q_s = Q_o + Q_n$

$C_sQ_s = C_oQ_o + C_nQ_n$

Thus:

$Q_o = [(C_s - C_n)/(C_o - C_n)]\ Q_s$

$Q_n = Q_s - Q_o$

Where Q is discharge and C refers to tracer concentration of a component or the stream and the subscripts represent the stream and "new" and "old" water components, respectively. (Sklash 1990)

Stable isotopes, ^{18}O and ^{2}H (deuterium), and unstable ^{3}H (tritium) are commonly used to distinguish pre-event water, or "old" water – water that was already present in the watershed before the storm event – from "new" water that is introduced to the system during the storm event. (eg. Pearce 1986, Sklash 1979, Martinec 1975, Dincer *et al.* 1970)

Some of the first geochemical approaches to hydrograph separation on the scale of the watershed were based upon using ionic tracers, but chemical interactions with the environment raised doubt that accurate results could be obtained. These tracers are not conservative on the watershed scale so interactions with the environment would have to be accounted for, which would convolute the data analysis process, introducing compounding errors to the problem. The isotopes ^{18}O, deuterium, and tritium all form parts of natural water molecules and thus flow with the water as it follows its natural course through the watershed, truly reflecting hydrological processes. This allows for confident analysis on the watershed scale. (Sklash, 1990)

In addition to allowing for separation of "old" and "new" components, the use of environmental isotope tracers makes possible the differentiation of the individual components of "old" water in situations where vadose zone water and groundwater have unique chemical signatures.

The geochemical approach can become a bit ambiguous when dealing with mixed components because the interpreted data simply defines relative quantities of *old* and *new* water. For example, hydrologic conditions and soil properties on a hillslope may lead to water occurring as overland flow at one location and infiltrating at another location downslope. Alternatively, Kennedy (1977) suggests that rainwater may infiltrate, dissolve solutes, discharge at some point downslope due to hydrologic conditions, and then run off into the stream as overland flow. Dunne and Black (1970) referred to such runoff water as return flow, occurring where upslope additions of subsurface runoff exceed the drainage capacity of the downslope soil matrix. In this case, the runoff chemistry may approach that of soil pore water or groundwater, making differentiation of *old* and *new* components extremely difficult. This situation brings rise to the point that much of our conceptualization and approach to modeling these systems is reliant on our definitions of the individual components. Would the infiltrated water that is discharged midslope to enter the stream as overland flow be considered subsurface runoff or overland flow? The obvious dilemma is that it would not be considered either individually, but some combination of the two. Perhaps the more pertinent question would be, does the water show an isotopic signature closer to that of *old* or *new* water?

The application of geochemical approaches in the recent literature shows that in humid, vegetated, first-order catchments the rising limb of the hydrograph is typically dominated by pre-event water. This quick response of *old* water requires the displacement of soil moisture to occur rapidly despite the fact that subsurface flow velocities are understood to be much slower than surface flow velocities.

Macropore Flow and The Kinematic Wave Phenomenon

The classical conceptualization of vadose zone flow assumes the propagation of a uniform wetting front through the soil. Because of the occurrence of preferential flow pathways, this conceptualization has been shown to be insufficient, particularly in soils with significant macropores (Stephens 1996). These macropores serve as conduits for subsurface flow and can have serious implications for contaminant spread.

In many watersheds, flow through macropores becomes a large player in the near instantaneous response of the storm hydrograph to intense rainfall events. Macropore flow is controlled by a number of factors including soil properties, macropore properties, and antecedent soil moisture conditions (Meyles et al. 2003).

Flow through porous media can be broken down into two components: (1) micropore flow – or flow through the intergranular pore spaces, and (2) macropore flow – or flow which bypasses much of the intergranular pore space via larger conduits or preferential flow paths (Stephens 1996). More simply stated, micropore flow is defined as flow within a “lump” (or soil ped), and macropore flow is flow between “lumps” (Plaisance and Cailleux 1981).

Macropores can result from any number of processes and have been documented to be formed by soil fauna (eg. animal burrows, wormholes), plant roots, cracks and fissures in the soil matrix related to soil structure, and natural soil pipes (Beven and Germann 1982). The type of macropore, or more specifically how it is formed, greatly influences its morphology, extent, and hydrologic properties. For example, macropores formed by animal burrows and plant roots are typically tubular in shape, while those formed from soil cracks and fissures can vary greatly in morphology (Beven and

Germann 1982). Bouma and others (1982) noted a distinct difference in permeability of macropore walls between those formed by earthworms (lower permeability) and those formed by moles (much higher permeability).

Intuitively, the characteristics of flow are vastly different in micro- vs. macropores, the latter of which significantly speeds up runoff response because flow in macropores does not obey Darcy's law (Phillips *et al.* 1989). Consequently, a number of researchers have shown that solute concentrations in macro- and micropores are inherently different from one another (eg. Jardine et al. 1990).

In order for flow in macropores to occur, the fluid pressure must exceed water entry pressure (Stephens 1996). There are two mechanisms by which this condition can be met. The first is best described by Stephens (1996) in the following figure:

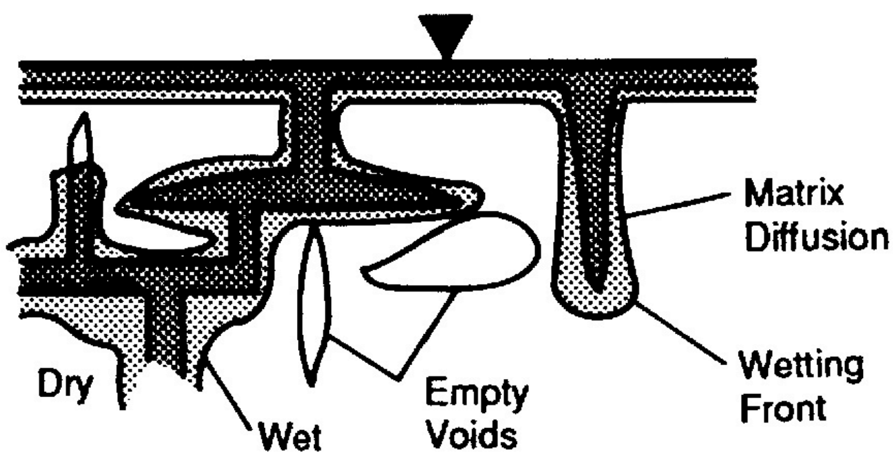


Figure 4: Macropore Network (Stephens 1996)

Here, ponded water at the ground surface is interconnected with water in the subsurface, controlling flow in the macropores. In this scenario, as soon as the ponded water drains, no more macropore flow will occur because it is the hydrostatic pressure of the ponded water that serves as the driving force for flow. It must also be noted that in this scenario all of the water that flows in the macropores is new water.

The second mechanism is more important in addressing the double paradox as defined by Kirchner (2003) and involves the exfiltration of soil pore water into some available space (i.e. a macropore or an open channel). This mechanism requires a higher fluid pressure in the soil matrix than in the macropore, channel or, in the case of this experiment, subsurface runoff collection trench. The simplest case, explored in great detail by Phillips *et al.* (1989) in a series of laboratory experiments, requires the soil matrix to be completely saturated along the entire length of a macropore. Since the macropore flow we refer to here occurs in the vadose zone, a mechanism for water entry under unsaturated conditions must be discussed. It is widely known that under unsaturated conditions soil pore water is under negative pressure. Thus, a mechanism to quickly drive this pressure to values high enough to exceed macropore water entry pressure is needed to explain the type of instantaneous flow observed by so many hydrologists over the years (eg. McDonnell 1990).

This mechanism is often referred to as the kinematic wave phenomenon and involves the propagation of pressure waves through the vadose zone resulting from falling raindrops impacting the soil surface. The vertical propagation of the pressure waves causes an increase in intergranular pore water pressure at the edge of the macropore or channel, often resulting in exfiltration of *old* water stored in the micropores. It is not surprising that many researchers have linked the occurrence of the kinematic wave phenomenon and thus macropore flow to high antecedent soil moisture conditions.

The *old* water stored in the soil matrix is affected by the propagation of pressure waves resulting from falling raindrops on the soil surface, such that surface tension forces are overcome and the pore water pressure of the matrix exceeds the fluid pressure of the macropore or surface channel. For the same reason that water in the capillary fringe will not flow into an open borehole (it is held in the pore spaces by capillary forces), flow of *old* water within the macropores or small surface channels will not occur if this pressure gradient is not steep enough. It is the aforementioned pressure wave phenomenon which raises pore water pressure above some threshold, allowing the flow of *old* water to dominate the instantaneous subsurface runoff response. This threshold is different for every location and depends on a number of factors including antecedent moisture conditions, hydrologic properties of the geologic material involved, and rainfall intensity (Torres 2002).

The ultimate control of subsurface runoff for a specific soil is where it falls on the moisture release curve: a soil in a drier state will not be as susceptible to producing runoff as will the same soil in a wetter state. Meyles and others (2003) showed that for the soils at their Dartmoor study site, the threshold for significant runoff response was somewhere around 60% (v/v) soil moisture. Obviously this threshold varies depending on the specific soil of question, but nevertheless the work of Meyles and colleagues clearly illustrates the point that a certain wetness value must be attained in order for an instantaneous high-volume runoff response to occur. Figure 5 illustrates the average soil moisture *versus* runoff (with a fitted curve) for the Dartmoor site.

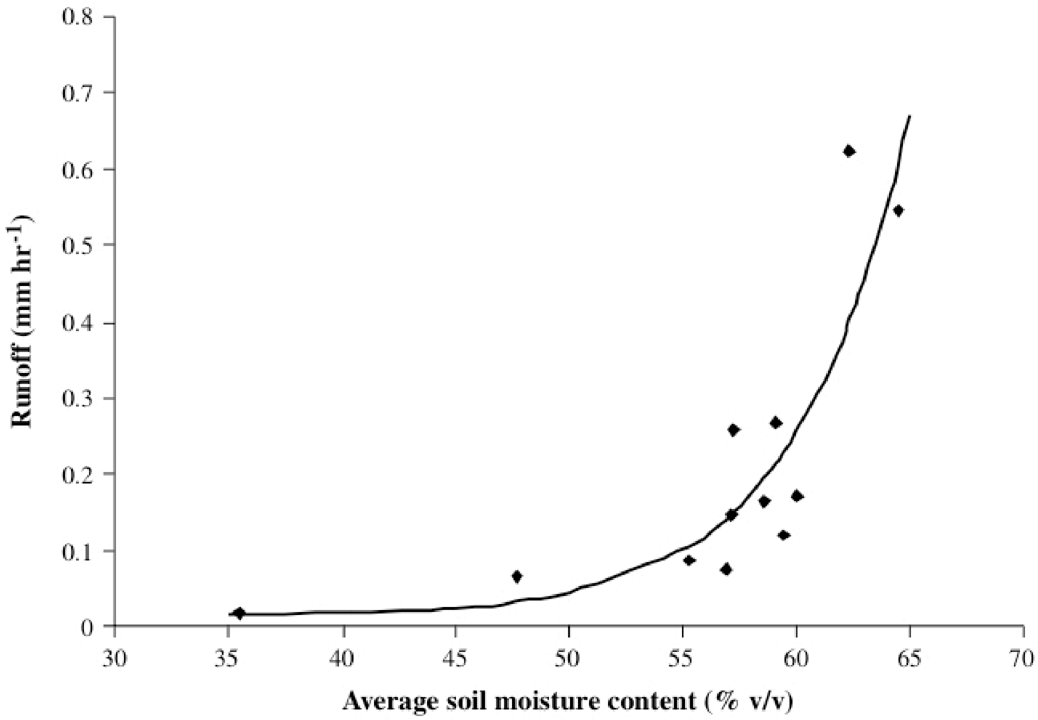


Figure 5: Runoff vs. Soil Moisture for Dartmoor catchment (Meyles et al. 2003). Very wet conditions are needed for rapid pressure wave generated runoff.

Numerous studies (eg. Rasmussen et al. 2000, Meyles et al. 2002, Williams *et al.* 2002) suggest that the rapid mobilization of old water to the stream is controlled by this kinematic process, driven by pressure wave propagation through the soil, which is much faster than the flowrate of the actual water molecules. Rasmussen et al. (2000) demonstrated the nature of the pressure wave phenomenon in a series of laboratory experiments with intact saprolite columns. The experiment involved the application of Cl^- tracer at the top end of the upright, unsaturated saprolite columns followed by closely monitored short-duration irrigation surges. Tensiometers were employed to measure pressure head and samples of the exfiltrated water from the bottom end of the column were collected to produce a Cl^- breakthrough curve. Rasmussen et al. (2000) reported that the irrigation-induced pressure wave velocities were approximately 1000 times faster than the tracer velocities. They also demonstrated that such a response is not unique to their particular experiment; they showed that pressure wave velocities are predicted to be faster than tracer velocities regardless of the type of unsaturated hydraulic conductivity model used.

Baldwin (1997) conducted a laboratory investigation in which tracers were applied to intact saprolite cores, followed by closely monitored irrigation experiments. Baldwin states that “as water is added the total head responds throughout the core almost instantaneously.” Baldwin’s tensiometer data indicates not only that the applied tracers moved much slower than the irrigation-induced pressure waves, but that the kinematic wave phenomenon does not operate when the soil surface is saturated. That is, the pressure wave phenomenon driving the exfiltration of soil pore water shuts off when the soil surface is saturated. The kinematic wave phenomenon is an unsaturated phenomenon and is therefore mutually exclusive with overland flow, which occurs when the infiltration capacity of a soil is exceeded.

The kinematic wave phenomenon is addressed in great detail by both McKinnon (2006) and Thomas (2009) in reference to the ARS gutter site, where the experiments discussed in this work took place. Both McKinnon and Thomas argue that the kinematic wave phenomenon (in the absence of macropore flow) is the dominant contributor to runoff to their gutters. This work supports their field evidence with chemical data and emphasizes the under-recognized importance of the phenomenon in small, humid, upland catchments.

Many researchers report that initiation of macropore flow is threshold-dependent, and is controlled not only by pre-storm soil moisture conditions but also by rainfall intensity (Uchida et al. 2005, Torres 2002). Of course, these threshold values are unique for each location and vary temporally and spatially and it is possible for the threshold at a single location to not be reached until part way through a big storm.

Not surprisingly, antecedent soil moisture plays a major role in macropore flow and in the kinematic response (Meyles et al. 2003, Grayson et al. 1997), and the response of a watershed to a large storm event is most often directly related to the soil moisture conditions before the event. Grayson and others (1997) distinguished between two preferred states for runoff response: wet and dry conditions. In the dry state a highly heterogeneous soil mosaic exists which is dependent on soil type and land use management (Meyles et al. 2003). Soil moisture content is low and lateral hydraulic conductivity is minimal. For large storms the dominant direction of flow in the dry state is vertical. Soil moisture of specific locations may be linked to surface runoff (Kirkby and Chorley 1967, Dunne and Black 1970) and although the antecedent moisture conditions of some areas will be such that subsurface runoff is generated, flux won't contribute to stream discharge unless connectivity with the channel or variable source area exists. Any subsurface flow from such areas will be reabsorbed at another location on the hillslope. (Meyles et al. 2003) In contrast, the soil moisture pattern in the wet state is highly organized and topography is the dominant control of runoff. The lateral hydraulic conductivity increases significantly and subsurface lateral flow dominates. (Grayson et al. 1997)

Some researchers have reported that antecedent soil moisture conditions play a much smaller role in macropore flow (eg. Beasley 1975, Flury *et al.* 1994). Flury and others (1994) claim that in some cases, soil moisture conditions have no effect at all upon runoff generation and preferential flow in the vadose zone. While this may be true for a select few study sites throughout the world (every individual site is unique in that it exists as the result of summation and compounding of an enormous number variables), the vast majority of the literature suggests that in most humid, vegetated, upland catchments throughout the world antecedent soil moisture conditions play a major role in runoff response and macropore flow.

Common Misconceptions

Most engineering models today still operate under the assumption that all runoff occurs as sheet flow, while this phenomenon is rarely actually observed in nature (Weiler and Naef, 2003). Subsurface runoff is lumped into what the modelers call "runoff" which is conceptualized as overland flow. From a quantitative standpoint, all water can be accounted for and their models often do match the observed hydrograph. However, when geochemical data is introduced and the actual source of the water becomes a question, the typical conceptualization of an engineering model is proven grossly inaccurate. Such models are not to be trusted when water quality is the issue of concern.

CHAPTER 3

SITE DESCRIPTION

The study area is located on a dedicated hillslope in research pasture 1E of the East Unit of the J. Phil Campbell, Senior, Natural Resource Conservation Center, a United States Department of Agriculture – Agricultural Research Service (ARS) farm located in Oconee County, Georgia. The site vicinity is described by Endale and others (2002) as a humid vegetated watershed in the Southern Piedmont Physiographic Province (Figure 6). On average, Oconee County receives between 48 and 50 inches of rainfall annually (National Weather Service, 2010). The study plot slopes approximately 32 degrees to the southeast (Thomas, 2010) and is vegetated with well-established fescue grasses.

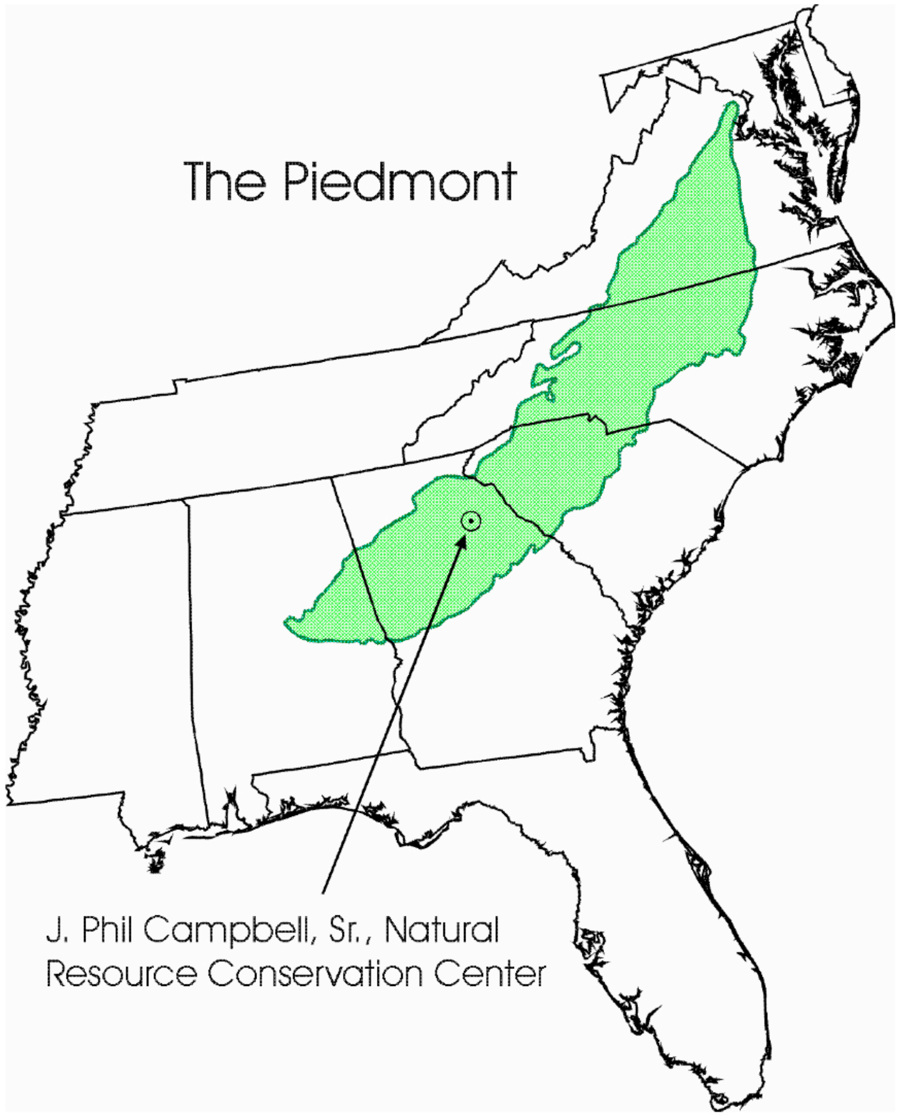


Figure 6: Location of site within Piedmont physiographic province

Site Soil, Mineralogy and Geochemistry

The site soil is a sandy loam of the Cecil soil series (typic kanhapludult). Cecil soils are common throughout the piedmont and typically occur on ridgetops and hillslopes ranging from 0-25 percent grade, most commonly on 2-15 percent slopes (USDA Web Soil Survey). The mineralogy of the geochemically active portion (or clay fraction) of the soil includes kaolinite, goethite, gibbsite, hydroxy interlayered vermiculite, and a mixed-layer clay (either hydrobiotite, which contains a vermiculite component, or interlayered muscovite and vermiculite). These data were collected using a Bruker X-Ray Diffractometer and can be found in Appendix A. Because of the occurrence of numerous clay minerals in the site soil (most importantly vermiculite, with a relatively high cation exchange capacity), no cationic tracers were used in this study. Lithium, for example, is a common ionic tracer used in hydrologic studies (Botter *et al*. 2009, Holmbeck-Pelham 1998) but was not used in these experiments because its plus two valence would likely lead to retardation effects due to the relatively high clay content in the site soils. Some researchers have reported sorption of anions being an issue in soils with vermiculite, gibbsite and goethite components (Hingston, Posner, and Quirk, 1972). However the sorption capacity of these minerals is far below the concentrations we used in the field tracer experiments.

The tracers used in this study were selected based on their relatively conservative behavior as shown by many years worth of past research (Holmbeck-Pelham, 1998). With that said, the goal of this study is not quantitative from the standpoint of the water chemistry. For this experiment, the question was first whether or not the tracers even showed up in the subsurface runoff samples, and if so, where they came from. Once threshold wetness had been attained, different anionic tracers were applied to the soil at predetermined locations on the study grid (chosen at points where suspected preferential flowpaths existed based upon GPR data and direct observation of exfiltration of runoff water on the cut soil face) and rainfall simulations were continued. Quantitative values for tracer concentrations are not required in this work as it is simply the presence of a tracer in the sampled runoff water that provides the information necessary to interpret the active processes contributing to the observed rapid runoff response. The presence of Bromide, for example, in the runoff water would indicate that the gutter had received runoff from the area on the study grid where Bromide had been applied. Bromide concentration is unimportant as the question here is, "where is the water coming from?"

CHAPTER 4

MATERIALS AND METHODS

Field studies were conducted from June 7, 2010 though June 16, 2010 during a series of simulated rainfall-runoff experiments at the site. Rainfall simulations were accomplished using a Tlaloc 3000 single spray nozzle rainfall simulator (by Joern's Inc., West Lafayette, NC), shown in Figure 7. The artificial rainfall was piped from a spigot located in a nearby pasture and the water was supplied by the local municipal water provider. The rainfall simulator nozzle was located approximately 3.5 meters above the 2 x 3 meter study grid. A rain gauge was placed on the study plot to monitor rainfall rate, which remained at a steady three inches per hour throughout the duration of the experiments.

Figure 7: Rainfall Simulator set up over study plot. Note rain gauge to quantify rainfall rate.

A collection trench and accompanying gutter collection system, previously constructed by Jason B. Thomas as part of his master's thesis work, were upgraded and employed during the field experiments. The setup was located in a zone of shallow topographic convergence where macropore flow may have occurred during previous rainfall simulation experiments. The trench was oriented perpendicular to the slope of the hill so as to intercept all subsurface runoff within its footprint along a topographic contour. Steel drip plates were pounded into the upslope vertical soil face at approximately 10 cm depth so as to direct subsurface runoff into the underlying collection gutter.

The rainfall simulator was set up so that direct precipitation fell on the trench in order to make certain that the portion of the study plot just up slope of the trench (the most likely part to contribute runoff) achieved adequate wetness along with the rest of the grid. A section of plywood was placed over the trench to prevent direct precipitation from falling on the gutter. When viewing of the soil face was necessary for observation of exfiltration of runoff (and for checking the gutter system for leaks) the plywood was simply lifted up from the downhill end, leaving the uphill end flush with the ground to block direct precipitation from falling on the gutter. In addition, sections of metal flashing were installed on the uphill edge of the trench to prevent overland flow from running into the collection system and influencing the results. Figures 8 and 9 depict a front-view and a side-view of the gutter setup:

Figure 8: Gutter setup. Note metal flashing to prevent overland flow into gutter and steel drip plates pounded into cut soil face at approximately 10 cm to promote flow into the gutter.

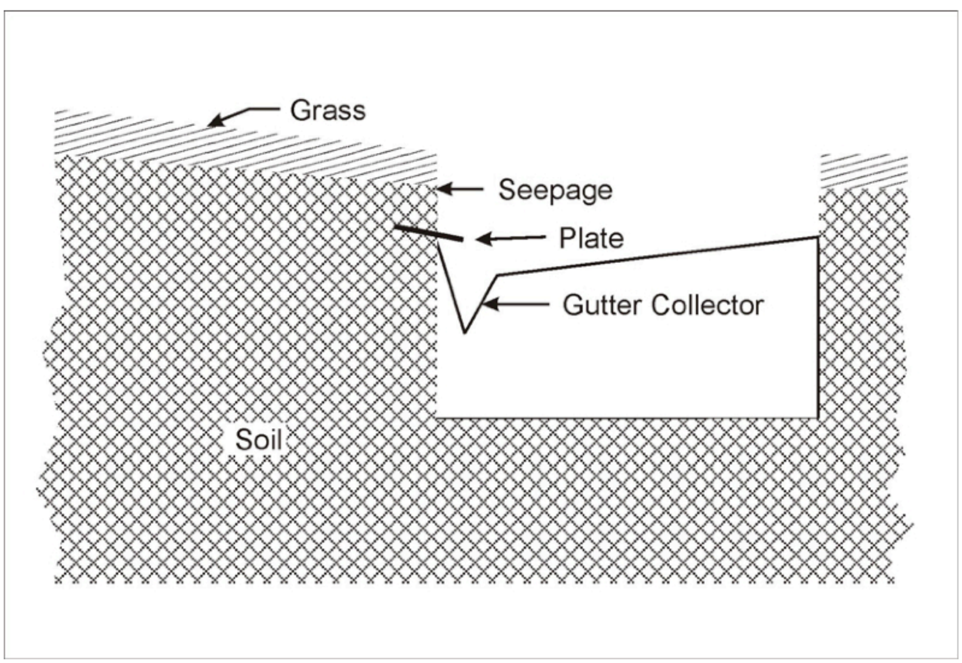


Figure 9: Side-view of gutter setup. Flashing to prevent overland flow not shown. (McKinnon 2005)

As shown in Figure 8, the gutter was slightly raised on one end to promote flow to a drainage tube, which ran downhill to an ONSET tipping bucket rain gauge (Figure 10), equipped with a HOBO datalogger. The tipping bucket was wired to a Campbell Scientific datalogger (CR-23X) for quantification of runoff (Figure 11). Three thermisters were also wired to the datalogger to measure temperature. One thermister (T1) was emplaced directly into the study plot (oriented vertically) a few centimeters uphill of the trench. Another (T2) was installed in the cut soil face (located to monitor wetting of the face), and the other (T3) was set in the collection gutter to measure runoff temperature.

Figure 10: ONSET tipping bucket rain gauge located downhill of trench.

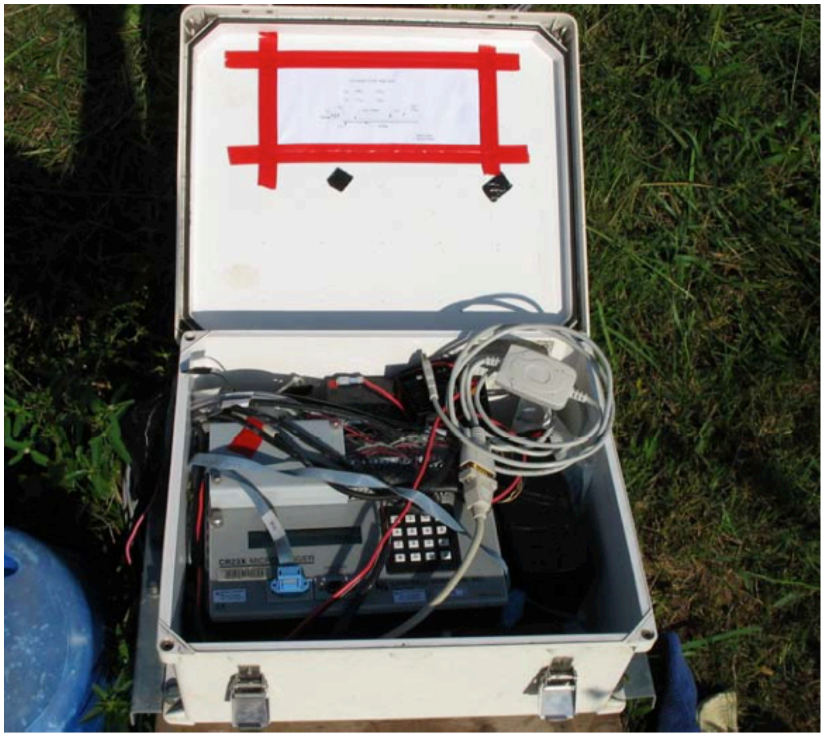


Figure 11: Campbell Scientific CR23X datalogger wired to thermisters.

Note that by constructing such a gutter system on the hillslope, we are in effect changing the localized flow characteristics. The gutter setup is inducing the flow conditions observed at the soil face by introducing impermeable surfaces (steel drip plates) and by changing the boundary conditions of the domain (the cut soil face now exists where continuous soil medium used to be). Because of the emplacement of the trench and drip plate setup, a near saturated wedge is formed at the soil face, generating exfiltration of runoff water at the soil face (McKinnon, 2005). Locating the drip plates 10 cm below the ground surface was chosen arbitrarily but is a logical depth for a number of reasons, the most obvious being that the maximum effects of the kinematic pressure waves generated during rainfall events can be observed in the shallower subsurface. Roger Baldwin (1997) documented the attenuation of pressure waves at increased depth in his laboratory irrigation experiment. Previous rainfall-runoff studies at our site were conducted with steel drip plates installed at 10 cm depth and significant gutter flow occurred. We ran our experiments with drip plates located 10 cm below the soil surface so as to be confident that we would observe substantial flow for our experiments.

GPR Experiments

Ground penetrating radar (GPR) experiments were conducted as a series of tests, with each iteration taking place at a different soil wetness. A *SIR 2000* GPR unit with a 1500 MHz antenna was used for collection of GPR data, and the *GPR Slice* program was used for computer analysis of the data.

GPR data was collected on a pre-measured grid located just upslope of the collection trench. The 2.0 m x 3.0 m grid was laid out with twine held to the ground surface by three inch nails and was divided into 10.0 cm x 10.0 cm sections. Initial GPR data was collected before any rainfall simulations had been carried out to observe the study plot under dry conditions. Following the initial run, the rainfall simulator was moved over the grid and turned on for one hour to begin wetting the soil. After one hour of simulated rainfall, the simulator was moved to a staging area and more GPR data was collected. This process of wetting the plot followed by collecting GPR data was repeated until a runoff response was observed in the gutter system, then a final series of GPR runs was conducted. Figure 12 illustrates GPR data collection:

Figure 12: GPR run between rainfall simulations.

(See Stephan Fitzpatrick's M.S. thesis, "Ground-Penetrating Radar Investigation of Preferential Flowpaths on a Hillslope" (2011), for a more detailed account of the GPR experiments.)

Achieving Threshold Wetness

Rainfall simulations were run during daytime hours for four days until threshold conditions were reached and a subsurface runoff response was observed. A timeline of the field experiments is shown in Appendix F. Once threshold wetness was attained, the subsurface runoff could be shut off and back on instantaneously by simply turning the rainfall simulator off and on. Direct observation of the near-instantaneous nature of the kinematic wave-driven subsurface runoff in conjunction with runoff chemistry data and chemical results from a soil coring investigation led to the conclusions reached in this paper.

On multiple occasions during the field experiments, the kinematic response turned on instantaneously as the threshold was breached and turned off once the plot surface had become completely saturated. This occurred because the moisture conditions under which the kinematic response is active at the ARS site, like many other studied sites around the world, exist relatively close to saturation (see Figure 5). Figure 13, from Fitzpatrick 2011, shows Brooks and Cory and Van Genuchten moisture release curves for the study plot soils. This figure illustrates the threshold condition which must be met in order for rapid, pressure wave-driven subsurface runoff to occur. Moisture is held in the soil pores under negative pressure. Under drier conditions (to the right on the curve) a small change in pressure results in almost no change in moisture content. In contrast, where the curve steepens, a small increase in pressure is enough to breach the threshold and exfiltrate *old* water from the soil pores. Research has shown that the pressure waves generated by falling raindrops impacting the ground surface produce enough disturbance in tension at the pore scale to breach this threshold (Rasmussen 2000). These conditions (and required rainfall rate, for that matter) are different for different soils and can vary temporally during a single rainfall event.

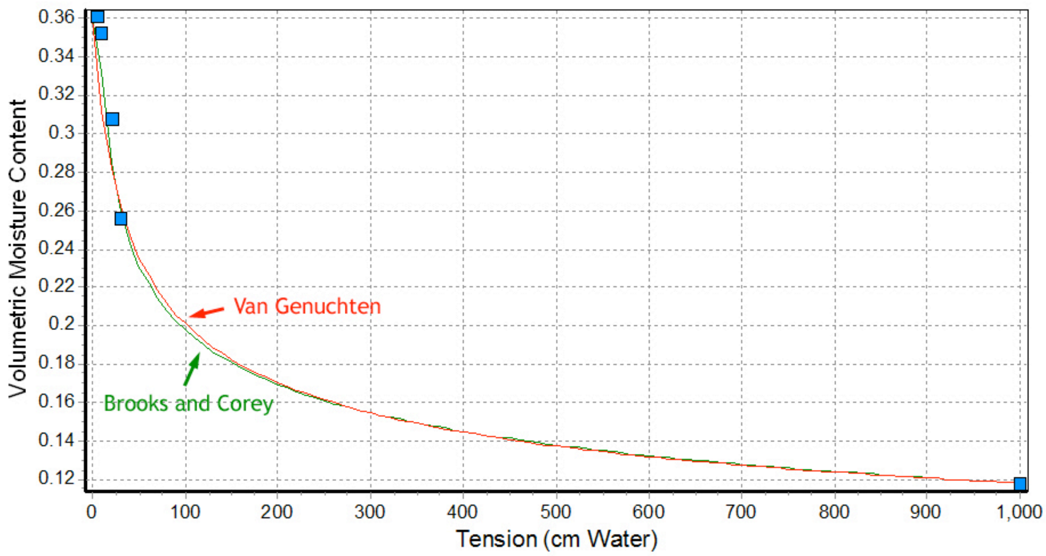


Figure 13: Moisture release curve for study plot soil at 0-6cm depth. (Y-axis units [volumetric moisture content] are cm^3/cm^3). Brooks and Corey and Van Genuchten solutions shown. Threshold conditions exist close to saturation. (Fitzpatrick 2011)

A response similar to that mentioned by Torres (2002) was also observed during the field experiments. Torres concluded that perturbations to rainfall rate, including decreased rate, can trigger the kinematic response. At one point during the experiments, I turned off the rainfall simulator to allow for infiltration and redistribution of soil moisture because the simulator had been on for hours. It must be noted that raindrops continued to fall from the grasses and grid strings, acting as a decreased rainfall rate even though the simulator had been shut off. After about a minute of this much lower rainfall rate, the system displayed a rapid response. I turned the simulator back on and the kinematic response continued for another twenty or so minutes until I shut the rainfall off again to apply the tracers.

Tracer Experiments

The GPR data was used to determine where to apply the ionic tracers for the second phase of this project. The objective was to determine where suspected preferential flow paths would likely be based on the geophysical data, and to apply ionic tracers in those locations on the grid during a simulated rainfall event. It was assumed that the wetter areas according to the geophysical data marked the locations of preferential flow. If the tracers showed up in the subsurface runoff collected from the downhill trench within a reasonable amount of time, we would conclude a) that macropore flow, or some related type of rapid preferential flow, dominated the runoff response and b) that the GPR tests did in fact indicate where these preferential flow paths are located.

Five different anionic tracers were used: sulfate, nitrate, chloride, iodide, and bromide. Figure 14 represents an image of the GPR data after runoff response was achieved and includes the locations of where each tracer was applied. Nitrate was applied about 10cm uphill of the gutter in a zone that was suspected to exhibit macropore flow based on observations at the soil face prior to analysis of the geophysical data. Bromide was applied about a half meter uphill from the gutter in a zone that, according to the GPR data, appeared to be interconnected with the same preferential flow path as that which received the nitrate. Our reasoning was that if both bromide and nitrate appear in the runoff at about the same time, macropore flow does occur in that specific zone of our study plot.

Sulfate and chloride were also applied to different suspected macropore locations, the latter of which was applied higher upslope to investigate the aerial extent of the study plot contributing to runoff. Sulfate was applied to a location on the plot adjacent to the gutter, where flow had been directly observed on the cut soil face during subsurface runoff response. Iodide was applied to an area of the plot that was predicted not to contribute to the observed runoff response, based on the GPR data.

Figure 14 is a reproduction of a GPR data set (~0-5 cm depth), which spatially represents the study plot. Shown are the locations of tracer application. The runoff collection gutter was located along the x axis of this figure (values on axes represent decimeter units):

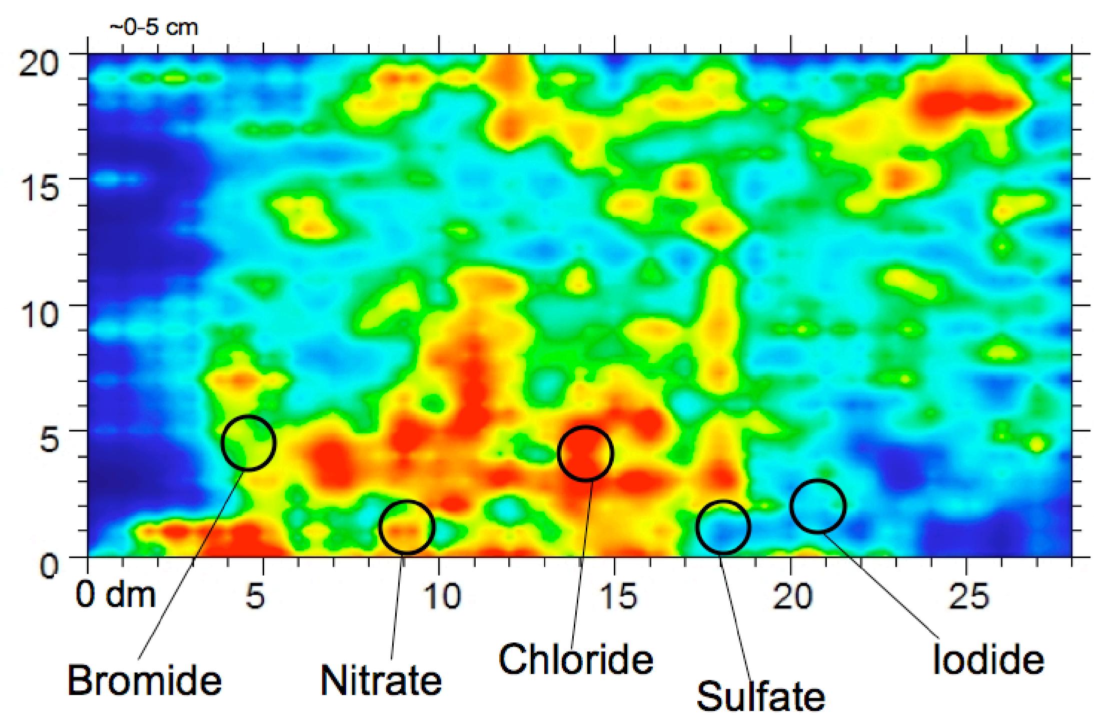


Figure 14: GPR image with tracer locations shown; gutter is located along x-axis of figure, uphill end of study plot is located at the top of the figure.

Tracers were introduced to the study plot in two different applications, the first of which included the application of about 1 liter of each 250 mg/L tracer solution to its designated location. The second included the application of a smaller volume (about 300 mL) of each solution to the same respective locations. A series of runoff samples was collected from the gutter collection system approximately 10 hours after the first application and another was collected approximately 11 hours after the second application (see Appendix F). Tracers were applied using cut sections of 3” PVC pipe held flush against the ground surface to ensure complete infiltration of the tracer solutions to minimize their loss to overland flow and to ensure that they only infiltrated within the intended areas of application.

Runoff samples were collected from the trench at two-minute intervals during active subsurface runoff, which lasted just under an hour for both sampling runs. Samples were immediately chilled upon collection and were analyzed in the laboratory using a Dionex Ion Chromatograph.

Soil-Coring Investigation

Following the rainfall simulation experiments, a soil-coring investigation of the study plot was carried out to characterize the final spatial distribution of the applied tracers. Some time passed between tracer application and borehole sampling and a number of natural rainfall events soaked the plot in the mean time. Optimum results would have been obtained had the soil-coring investigation occurred immediately following the tracer experiment, but it wasn’t until the runoff samples had been analyzed in the lab that we decided to implement the soil-coring investigation. With that said, the soil-coring investigation did produce interpretable results and most definitely shed an interesting light on this study.

On July 13, 2010 sixty-three cores were taken from the plot grid and samples were collected at depths of 0-5 cm, 5-10 cm, and 10-20 cm to investigate the extent of tracer dispersion from the locations where they were applied. The cores were taken roughly 2 decimeters apart on most of the grid. In areas on and around where the tracers had been applied, the cores were collected 1 decimeter apart for better resolution. Boreholes were numbered sequentially so that, once the data was processed, they could be graphed with borehole number on the x-axis and concentration on the y-axis. This layout facilitated quick and easy visual interpretation of the data as a peak in concentration on the graph represents an area of the study plot where a given tracer was detected. See Appendix B for a representation of borehole numbering scheme.

Soil samples were sealed in plastic bags upon collection and immediately transported to the lab. Select samples (chosen for even spatial representation) were weighed and placed in a drying oven for 24 hours at 105°C. Samples were weighed after drying and volumetric moisture contents were calculated assuming a bulk density of 1.38 g/cc (as reported by Stephan Fitzpatrick 2011). See Appendix C for moisture content calculation table.

There is no standard method for soil extraction so I closely followed the recommendations of Dr. Bill Miller of the UGA Crop and Soil Sciences Department during the next phase of my lab work. All samples were air-dried in paper bags and resealed after drying was complete. Each sample was ground and homogenized with a mortar and pestle before 10 gram subsamples were weighed out and placed in different vials. 40 mL of deionized water was then added to each subsample and the vials underwent an afternoon of vigorous agitation in attempt to dissolve any ions adsorbed to the soil particles. The vials were set upright overnight and the solution was decanted off of the settled sediment the following day. Once the soil samples had been converted to water samples, they were individually vacuum filtered with .45 micron filter papers and analyzed with a Dionex Ion Chromatograph.

CHAPTER 5

RESULTS AND DISCUSSION

Once threshold wetness had been attained, the instantaneous nature of the driving force behind subsurface runoff at the site was directly observed. Figure 15 illustrates the instantaneous nature of the phenomenon. The black line represents total quantified subsurface runoff (expressed in number of "tips" of the tipping bucket rain gauge – shown on the right y-axis) and the blue, yellow and red lines represent thermisters 1, 2 and 3, respectively. The pink line indicates times when the rainfall simulator was turned off (up position) and when it was turned on (down position). The left y-axis represents degrees Celsius and the x-axis functions as a timeline for the field experiment, spanning several days:

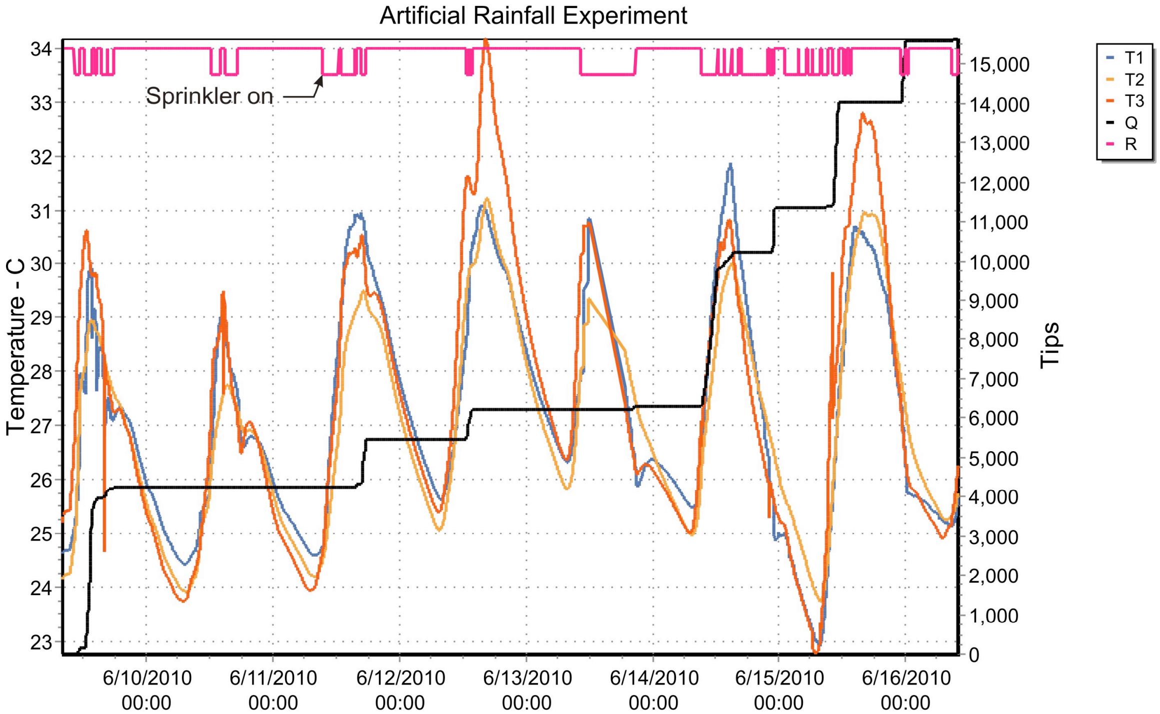


Figure 15: Q = cumulative gutter flow ("tips" of rain gauge), T1 = thermister 1, T2 = thermister 2, T3 = thermister 3. Pink line indicates when rainfall simulator was on/off. First actual runoff response occurred on 6/12 at about 3:30 PM – first apparent response on plot is the result of overland flow leaking into gutter.

Generally, declines in temperature of the thermisters unrelated to diurnal temperature fluctuations mark periods of artificial rainfall. A step up of the black line represents a rapid runoff response, shown also by a concurrent drop in temperature of T3 (most visible between 6/11 and 6/12, 6/12 and 6/13, and 6/15 and 6/16). Upon the study of these relationships in Figure 15 the instantaneous nature of the subsurface runoff response becomes very clear.

Calculations were performed to determine whether or not the runoff volumes recorded in Figure 15 are sufficient for artificial rainfall to have replaced all existing pore water and become *old* water (Appendix D). A conservative approach was taken as the system was assumed to have been previously saturated and porosity was estimated at

50%. Previous work at our site has indicated that the contributing area of the study plot to gutter flow is actually very small, with <10 cm of the plot uphill of the gutter contributing to collected subsurface runoff. Calculations were done for contributing areas of 10 and 20 cm uphill of the gutter and values were converted to "tips" of the tipping bucket rain gauge (because volume is expressed in "tips" in Figure 15). We determined that, during our field experiments, sufficient gutter flow was measured for all pore water to have been replaced with artificial rainfall before tracer application. While a small few water molecules most likely remained in the tiniest of pores and in those with poor connectivity, the chemical signature of the runoff water would have been expected to become very similar, if not nearly identical, to that of the artificial rainfall long before the GPR runs for Steve Fitzpatrick's work were complete. For a contributing area of 2,300 cm^3 (10 cm uphill of trench) a required cumulative gutter flow volume of 2,482 tips would be required assuming previously saturated conditions. This value was almost reached during only the second runoff response recorded on June 12, 2010. For a contributing area of 4.600 cm^3 (20 cm uphill of trench) a required volume of 4,964 tips was calculated: a number that was reached in the response recorded just before tracer application. These values are very conservative estimates and our reasoning tell us that the natural soil moisture present in the study plot before our experiments was flushed out during our earliest rainfall events. These calculations indicate that artificial rainfall most likely displaced the water that already existed in the study plot soils and that it effectively became *old* water.

Runoff Sampling Data

Ion chromatography analysis of the runoff samples confirmed that no tracers showed up in the sampled subsurface gutter flow (see Figure 16 for chemical data from select representative samples). The chemical signature of each runoff sample looked identical to that of the applied rainfall (Figure 16 – abbreviated results, Appendix E - comprehensive results). At this point in the experiment, two possibilities were identified: 1) the tracers may have been washed away by the applied rainfall as surface runoff or 2) the chemicals (and thus the water that held them in solution) remained in the subsurface and hydrologic processes did not expel them at the downslope collection trench as was hypothesized.

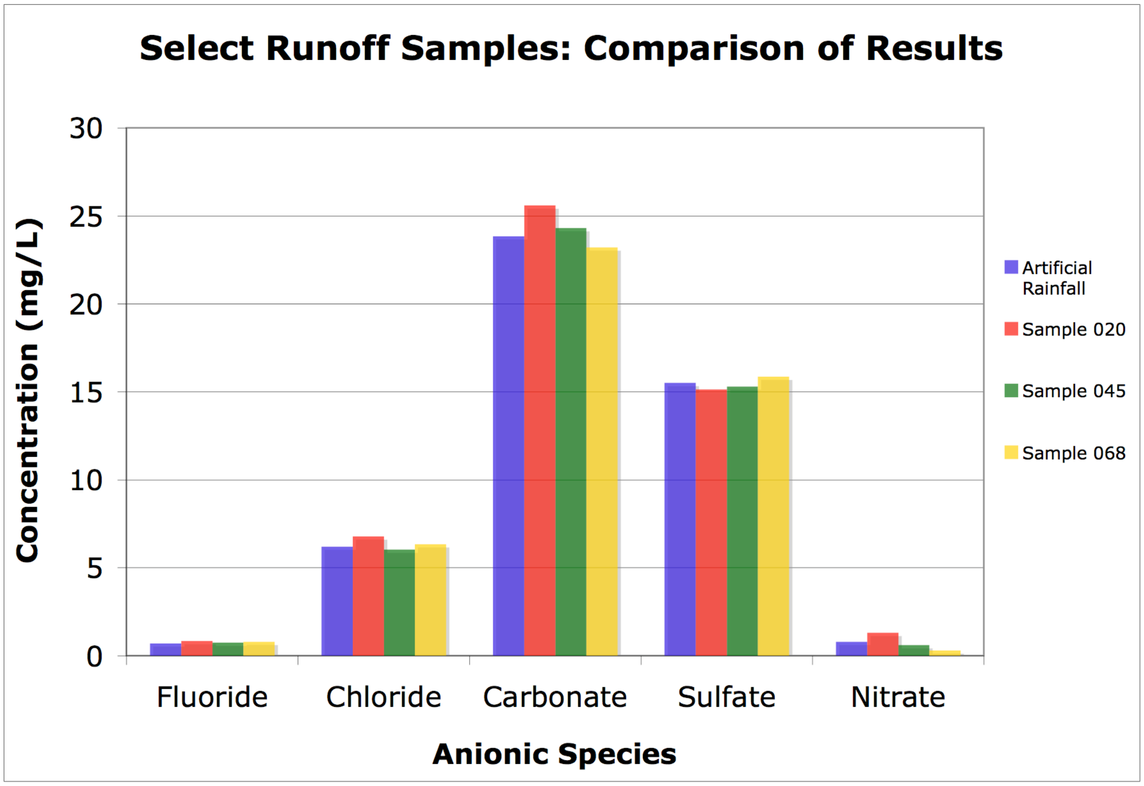


Figure 16: Chemistries of representative subsurface runoff samples in comparison with artificial rainfall chemistry. Runoff samples show no signs of tracers and chemistries match up almost perfectly with that of the artificial rainfall, which by this point in the experiments had become *old* water.

If the tracers had not been washed away, the fact that none showed up in the subsurface runoff samples suggested a number of points. First, the runoff water generated during the hillslope's kinematic response is clearly *old* water. The rainfall system had been running for days prior to the tracer experiments so that essentially all of the soil pore water at the time of the experiments came from this applied rainfall. Although it had been recently applied (i.e. within the previous few days), this soil pore water is considered to be *old* water because it had had time to redistribute into the micropores of the soil matrix and therefore occurred as antecedent soil moisture during the tracer experiments. Second, the lack of tracers in the runoff water would imply that macropore flow did not occur on our study plot during the experiments. The soil coring investigation was carried out to determine if the tracers did in fact remain in the site soil.

Soil-Coring Data

The IC data from the soil-coring phase of this experiment suggest that the tracers did remain in the sediments of the study plot during the experiment and that none traveled any significant distance from the point of infiltration. However, some difficulty did arise in the interpretation of the soil core data and not every tracer produced interpretable results.

The difficulty in interpreting the IC data is directly related to the inherent multi-phase dilution that occurred during this experiment: I started out with tracer solutions of about 250ppm. Those solutions were immediately diluted upon application to the study plot as the soil matrix was near saturation. More dilution occurred as *new* water was added during the subsequent rainfall simulations, and even more dilution occurred as a natural rainfall event wetted the plot between the rainfall simulations and the soil-coring phase. Also, a significant volume of deionized water was added to the dry soil during the extraction, which diluted the samples further. Because of this repeated dilution, the tracers occurred in the extracted samples in very low concentrations, often at or below detection limits.

Nitrate shows the easiest results to interpret as spikes in nitrate concentration at the point of application can clearly be seen as the values jump from background to 10 to 15 ppm at the location of tracer application. Figure 17 is a graph of the nitrate tracer data, with borehole number on the x-axis and nitrate concentration on the y-axis. Refer to Figure 18 for borehole locations within study plot. The peak in concentration occurs at the location of nitrate tracer application, in the vicinity of boreholes numbered 22-29. The high values encountered in the lower numbered boreholes are interpreted as anomalies that could have been caused by a number of factors including cross-contamination or the presence of animal droppings.

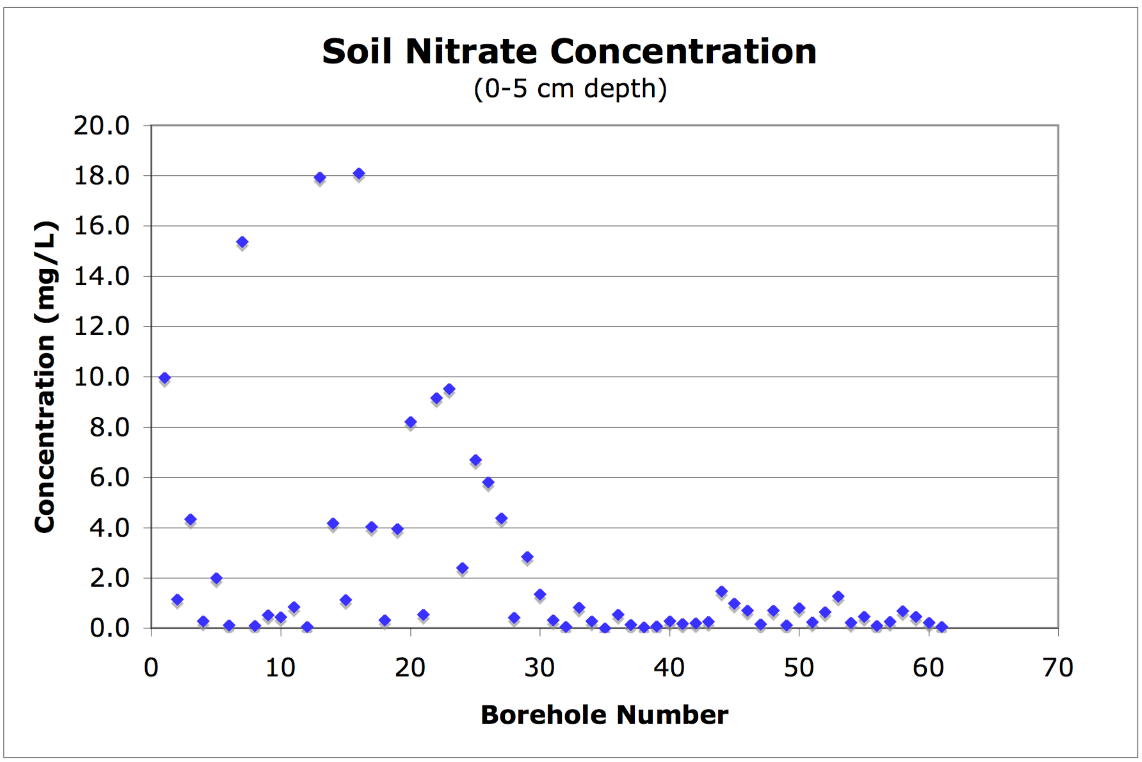


Figure 17: Nitrate IC results after extraction of soil samples. Peak located at boreholes numbered in the 20s is interpreted as nitrate tracer that remained in the study plot soils.

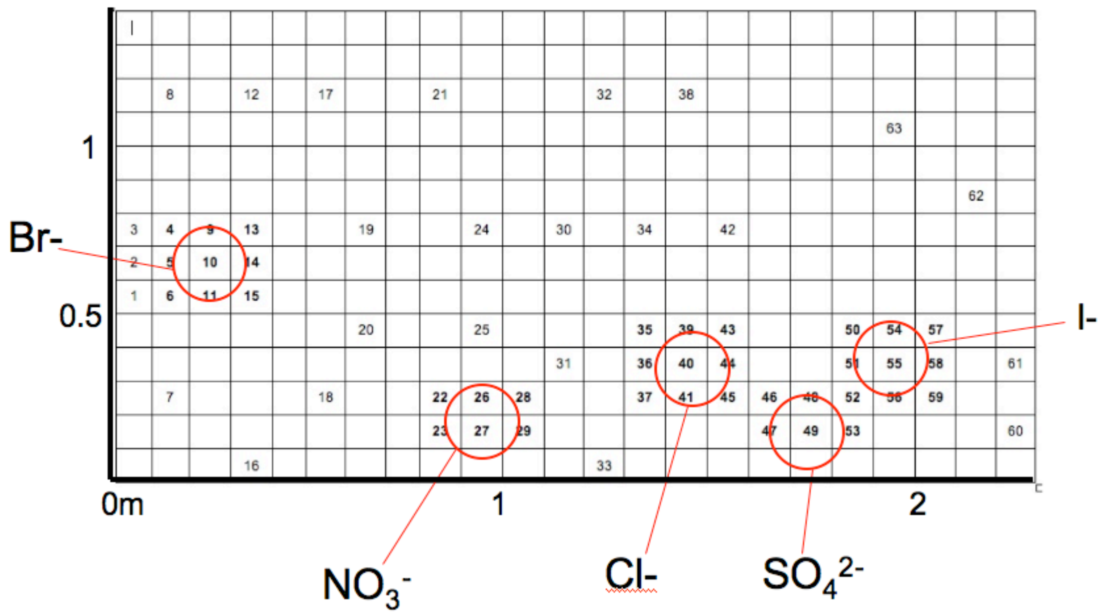


Figure 18: Borehole numbering scheme with locations of tracer application shown. Gutter is located along x-axis. Samples from boreholes 17, 21, 32, 38, 62, and 63 were collected to investigate background levels of the constituents of concern.

Most of the IC data is not as straightforward as the nitrate data. Bromide, for example, is an anion that does not occur naturally at my study site, so any Br^- occurrence can be interpreted as applied tracer. Bromide did not show up in a concentration significantly above detection limits, but traces were detected only at the location of bromide application (See Appendix E). These traces are interpreted as bromide "hits" and suggest that the bromide tracer infiltrated the study plot and probably remained trapped in fine pores in the soil that contained relatively immobile water throughout the duration of the experiment.

Both chloride and sulfate are unfit for use as tracers in this study because their background occurrence is too high for the amount of dilution that was imposed on the samples during the experiment. Boreholes 17, 21, 32, 38, 62, and 63 were emplaced significantly uphill of where the tracers were applied and are considered to exhibit background levels of all ionic species of interest in this experiment.

Iodide would have been a useful tracer, most likely occurring at levels at or near detection limit and being interpreted similarly to the data of the bromide tracers, had our analytical methods allowed for iodide detection. Iodide takes longer to pass through the IC column than any of the ions in the standard solution used in this study and the run time for each sample was arbitrarily set at 15 minutes (just long enough to let all the ions in the standard through.) It wasn't until after the laboratory work was completed that we learned that the chromatographic response was longer than our measurement time. Iodide did not show up on the chromatogram when two spiked samples of known iodide concentration were run through the IC because the run time was not set for long enough.

The two tracers that produced interpretable data for this experiment were Nitrate and Bromide. Neither was detected at any significant distance from the location of application and both showed up only in the shallowest depth sampled. It does not appear that any movement, horizontal or vertical, of the tracers occurred during the experiments. It is possible, however less likely, that the tracers picked up in the soil-coring phase of this experiment represent the residual left behind in the small pores, after that which ended up in larger pores was drained. This study does not explore contributing pore size and further work would be required to clarify this issue.

The information provided by the soil-coring investigation strongly supports a kinematic wave explanation for the observed runoff response. Because the tracers remained in the soil only in the immediate vicinity of where they were applied and none showed up in the runoff water, we conclude that macropore flow is not a significant contributor to the observed instantaneous subsurface runoff.

Implications on the Watershed Scale

We observed pressure wave-driven runoff on our study plot under monitored conditions on the hillslope scale, but how does such flow occur on the catchment scale? The flow occurred as exfiltrated soil pore water into the open gutter trench at our study site. In natural watersheds some open channel or macropore (analogous to our gutter) is needed to receive the exfiltrated soil pore water and transmit it to the stream. Studies have demonstrated that the kinematic contributing area to a single "channel" is very small, shown by McKinnon and Thomas to consist of no more than a 10 cm wide strip adjacent to the gutter on our study plot. Meyles *et al.* (2003) provided evidence that during high intensity rainfall events at a Dartmoor catchment, the contributing area of *old* water to rapid runoff response can exceed two-thirds of the entire watershed area. Thus, a kinematic explanation for runoff generation on the watershed scale requires a fine network of ephemeral channels and interconnected macropores to receive exfiltrated *old* water throughout the catchment and quickly transmit it to the stream. The ephemeral network can be conceptualized in the context of the variable source area discussed earlier in this paper. The contributing network is dynamic and changes with soil moisture conditions, rainfall intensity, etc., and is largely controlled by heterogeneities related to soil type, soil moisture variations and varying precipitation rates. The variable source area explains a watershed's response during small events, but the concept must be extended to include the kinematically-fed contributing ephemeral network when large storms are considered. (Meyles *et al*. 2003, Williams *et al*. 2002)

Future Work

The findings of this work lead to two approaches that must occur in order to further advance rainfall-runoff research: extensive laboratory work followed by watershed-scale field studies. First, comprehensive laboratory experiments, similar to those conducted by Baldwin (1997) and analyzed by Rasmussen (2000), must be carried out for a wide range of soil types. Thorough laboratory data collection (soil moistures, tracer breakthrough times, pressure wave velocities, volumes of *old/new* water, etc.) will influence the design of watershed scale studies. To date, experiments conducted on the catchment scale, while producing convincing results, have been carried out with limited instrumentation. Large-scale studies with detailed instrumentation throughout the watershed to identify and monitor soil moisture conditions and differences in response due to heterogeneities would shed light on the driving mechanism for rapid subsurface stormflow. Watershed-scale investigations of pressure wave-driven runoff and the variable contributing ephemeral network would aid in predicting flood runoff volumes and timing for large intensity events. Soil data should be collected to outline heterogeneities and moisture conditions should be continuously monitored throughout an entire upland catchment before the installation of gutter systems similar to those employed in this study. For thorough analysis on the catchment-scale, multiple gutters should be set up in each unique soil type and in locations with different moisture conditions in order to be truly representative of the inherently heterogeneous natural watershed.

CHAPTER 6

CONCLUSIONS

This experiment has brought together both physical and chemical evidence to demonstrate that the kinematic wave phenomenon is the dominant mechanism behind runoff generation into the gutters, and that other contributors such as overland flow and macropore flow are minimal. The physical evidence alone has been previously documented at our site, but the interpretations of past researchers have been questioned. McKinnon and Thomas both interpreted the hillslope's physical response to high intensity rainfall events at our site as being kinematic in nature. However, their results were ambiguous, as a similar response could be obtained if macropore flow was the primary mechanism. This experiment supports the interpretations of both McKinnon and Thomas. The near instantaneous nature of the kinematic wave response was observed, and this interpretation was supported by the tracer results. If macropore flow were a major contributor to flow to the gutter, the tracers would have appeared in the collected runoff water during the rainfall simulations. Another common counter-argument to the kinematic wave interpretation has been that overland flow must be contributing to the observed subsurface runoff. Had overland flow been responsible for a significant portion of the collected runoff, the tracers would have appeared in the runoff samples.

The soil coring experiment showed that some of the chemical tracers (and thus the water that held them in solution) did in fact remain in the study plot soils for the duration of the experiment, and were not washed away by either overland flow or macropore flow. Our volumetric calculations and chemical data suggest that the runoff water collected from the subsurface trench is *old* water likely expelled by kinematic forces.

The most universal and perhaps most significant result of this work is the demonstration that overland flow and the kinematic wave phenomenon are mutually exclusive. Rasmussen *et al*. (2000) demonstrated that the type of response observed in our experiments is strictly an unsaturated phenomenon. They showed that the kinematic celerity of the pressure wave is equal to $dk/d\Theta$ (where k is equal to hydraulic conductivity and Θ is equal to moisture content). Overland flow requires exceedance of the soil's infiltration capacity, which implies saturation at the surface. In agreement with Rasmussen's results, my field experiments have shown that the kinematic wave phenomenon does not operate when the soil surface is saturated. It must be emphasized that hillslope soils are highly heterogeneous and that while saturated conditions at the surface may exist in one location, unsaturated conditions at the surface may (and often do) exist very close by. The overland flow that was observed during these experiments while the kinematic response was active is attributed to nature's inherent heterogeneities and is interpreted as having occurred as localized zones of overland flow. See the moisture contents calculated for randomly selected study plot boreholes included in Appendix C for an illustration of the unquestionable heterogeneity of the site soil within the study plot.

Baldwin (1997) demonstrated this mutual exclusivity in his experiments with intact saprolite cores, but did not explicitly state the fact. He monitored the runoff response of upright intact saprolite cores in the laboratory as they were intermittently sprayed at the top. Up to a certain point, Baldwin observed the kinematic wave phenomenon in action, but his tensiometers seemed to "stop working" and the runoff response was shut off when the soil surface became saturated. Upon infiltration and redistribution of the soil pore water, the instantaneous runoff response was observed again and the tensiometers "appeared to be working again." Baldwin's work is an exact laboratory account of what was illustrated in my field experiments: the mutual exclusivity of the kinematic wave phenomenon and saturated conditions at the soil surface.

LITERATURE CITED

Baldwin Jr., R.H. Water and Tracer Behavior in Undisturbed Saprolite Soil Cores. Geology. Athens, GA, University of Georgia. **Master of Science.**

Beasley, R. S. (1976). "Contribution of Subsurface Flow from Upper Slopes of Forested Watersheds to Channel Flow." Soil Science Society of America Journal **40**(6): 955-957.

Beven, K. and P. Germann (1982). "Macropores and Water Flow in Soils." Water Resources Research **18**(5): 1311-1325.

Beven, K. J. (2000). Rainfall-runoff modelling : the primer. Chichester ; New York, Wiley.

Botter, G., E. Milan, et al. (2009). "Inferences from Catchment-Scale Tracer Circulation Experiments." Journal of Hydrology **369**: 368-380.

Bouma, J., C. F. Belmann, et al. (1982). "Water Infiltration and Redistribution in a Silt Loam Subsoil with Vertical Worm Channels." Soil Science Society of America Journal **46**: 917-921.

Brammer, D. and J. McDonnell (1996). An Evolving Perceptual Model of Hillslope Flow at the Maimai Catchment. Advances in Hillslope Processes. M. G. A. a. S. M. Brooks, John Wiley and Sons Ltd. **1**.

Cailleux, A. Plaisance G. (1981). Dictionary of Soils. New Delhi and Springfield, Va. Amerind Pub. Co

Dincer, T., B. Payne, et al. (1970). "Snowmelt Runoff from Measurements of Tritium and Oxygen-18." Water Resources Research **6**(1): 110-124.

Dougherty, W., N. Fleming, et al. (2004). "Phosphorous Transfer in Surface Runoff from Intesive Pasture Systems at Various Scales: A Review." Journal of Environmental Quality **33**: 1973-1988.

Dunne, T. and R. Black (1970). "Partial Area Contribution to Storm Runoff in a Small New England Watershed." Water Resources Research **6**(3): 1296-1311.

Endale, D., M. Cabrera, J. Steiner, D. Radcliffe, W. Vencill, H. Schomberg, L. Lohr (2002). "Impact of conservation tillage and nutrient management on soil water and yield of cotton fertilized with poultry litter and or ammonium nitrate in the Georgia Piedmont." Soil and Tillage Research **66**: 55-68.

Fetter, C. W. (2001). Applied Hydrogeology. Prentice-Hall, Inc: Upper Saddle River, New Jersey.

Fitzpatrick, S. (2011). Ground-Penetrating Radar Investigation of Preferential Flowpaths on a Hillslope. Geology. Athens, GA, University of Georgia. **Master of Science.**

Flury, M., H. Fluhler, et al. (1994). "Susceptibility of soils to preferential flow of water: Afield study." Water Resources Research **30**(7): 1945-1954.

Grayson, R., A. Western, et al. (1997). "Preferred states in spatial soil moisture patterns: Local and nonlocal controls." Water Resources Research **33**(12): 2897-2908.

Hewlett, J. and A. Hibbert (1963). "Moisture and Energy Conditions within a Sloping Soil Mass during Drainage." Journal of Geophysical Research **68**(4): 1081-1087.

Hingston, F., A. Posner, et al. (1972). "Anion adsorption by goethite and gibbsite. I. The role of the proton in determinting adsorption envelopes." Journal of Soil Science **23**: 177-192.

Holmbeck-Pelham, S.A .(1998) Regulatory and technical suitability of groundwater tracers for the Savannah River Site, South Carolina. Forestry. Athens, GA, University of Georgia. **Master of Science**.

Jardine, R., G. Wilson, et al. (1990). "Unsaturated solute transport through a forest soil during rain storm events." Geoderma **46**: 103-118.

Kennedy, V. (1977). "Hypothesis to Explain the Rapid Release of Solutes from Soil During Storm Runoff." EOS (Trans. Am. Geophys. Union) **58**: 386 (abstract).

Kirchner, J.W., 2003, "A double paradox in catchment hydrology and geochemistry." Hydrological Processes **17**: 871-874.

Kirkby, M. and R. Chorley (1967). "Throughflow, Overland Flow and Erosion." Bulletin of the International Association of Scientific Hydrology **12**: 5-21.

Martinec, J. (1975). "Subsurface Flow From Snowmelt Traced by Tritium." Water Resources Research **11**(3): 496-498.

McDonnell, J. (1990). "A rationale for old water discharge through macropores in a steep, humid catchment." Water REsources Research **26**(11): 2821-2832.

McKinnon, R. J. (2006). A Mechanism for Storm Runoff Generation During Large Rainfall Events. Geology. Athens, GA, University of Georgia. **Master of Science:** 111.

Meyles, E., A. Williams, et al. (2003). "Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England." Hydrological Processes **17**(2): 251-264.

National Weather Service (2010) Average Annual Precipitation of Georgia Map, http://www.srh.noaa.gov/images/ffc/gapcpn.gif.

Pearce, A. J., M. K. Stewart, et al. (1986). "Storm Runoff Generation in Humid Headwater Catchments .1. Where Does the Water Come From." Water Resources Research **22**(8): 1263-1272.

Phillips, R., V. Quisenberry, et al. (1989). "Mechanism of Water Entry into Simulated Macropores." Soil Science Society of America Journal **53**: 1629-1635.

Rasmussen, T., R. Baldwin Jr, et al. (2000). "Tracer vs. Pressure Wave Velocities through Unsaturated Saprolite." Soil Science Society of America Journal **64**: 75-85.

Reinsch, T. and R. Grossman (1995). "A method to predict bulk density of tilled Ap horizons." Soil & Tillage Research **34**: 95-104.

Sklash (1990). Environmental isotope studies of storm and snowmelt runoff generation. Process Studies in Hillslope Hydrology. T. P. B. M G Anderson, John Wiley and Sons Ltd**:** 401-435.

Sklash, M. (1979). "The Role of Groundwater in Storm Runoff." Journal of Hydrology **43**: 45-65.

Stephens, D.B. (1996). Vadose Zone Hydrology. CRC Press: Boca Raton, FL.

Thomas, J. (2009). Pressure Wave Generation of Runoff in a Convergent Zone. Geology. Athens, GA, University of Georgia. **Master of Science:** 93.

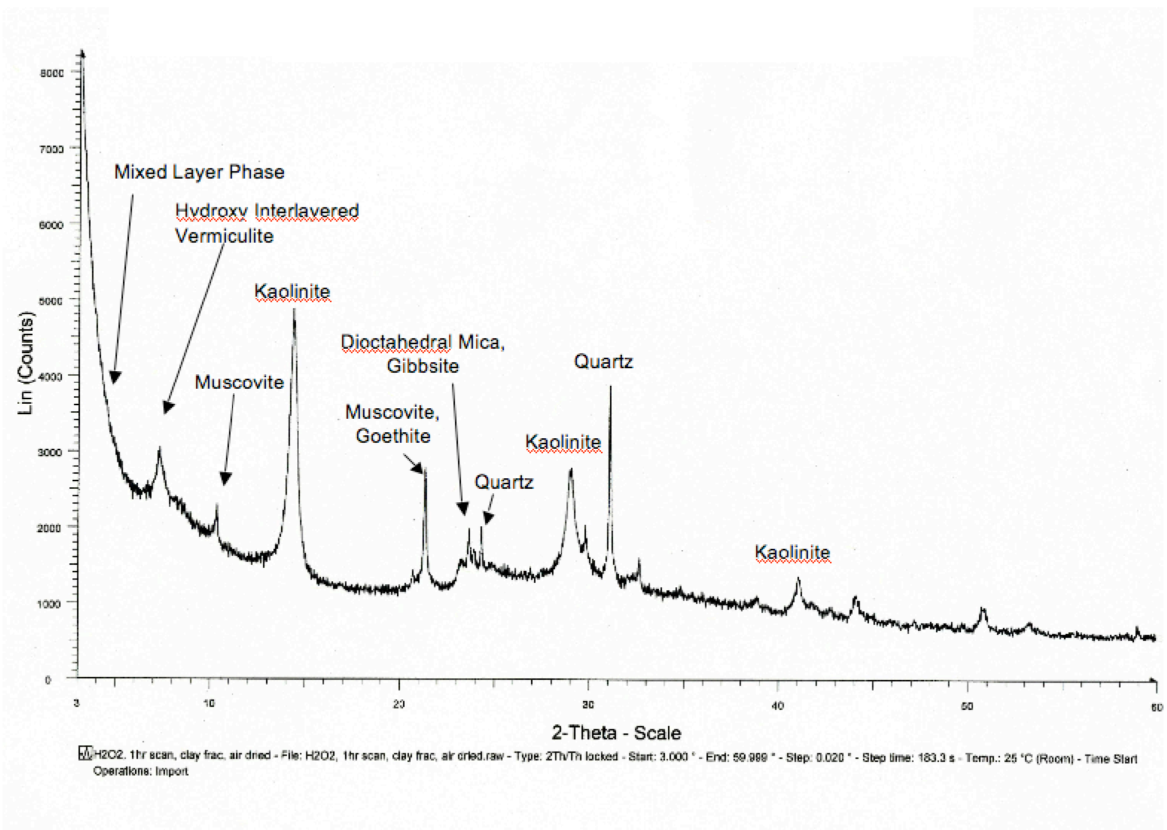
Weiler, M. and F. Naef (2003). "An experimental tracer study of the role of macropores in infiltration in grassland soils." Hydrological Processes **17**: 477-493.

Whipkey, R. (1965). "Subsurface stormflow from forested slopes." Bulletin of the International Association of Scientific Hydrologists **10**(2): 74-85.

Williams, A.G., Dowd, J.F., Meyles, E.W. (2002). “A new interpretation of kinematic stormflow generation.” Hydrological Processes **16**: 2791-2803.

APPENDIX A

XRD DIFFRACTOGRAM OF SITE SOIL SAMPLE

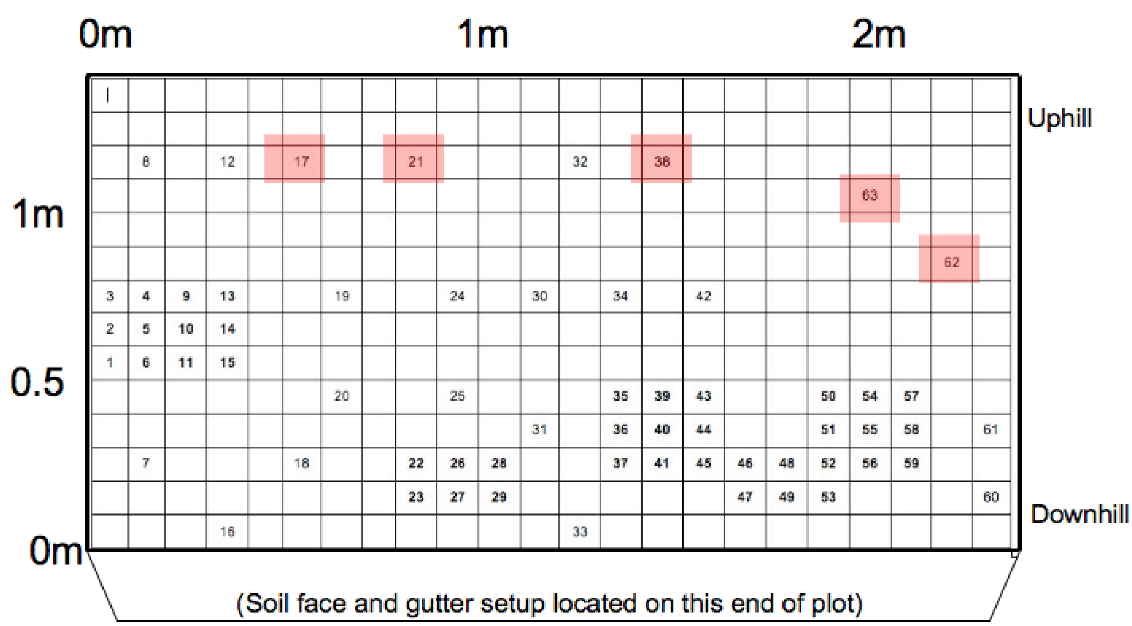


X-ray diffractogram of site soil sample with peak interpretations labeled. Sedimented mount, air dried, 1 hour scan. Sample treated with hydrogen peroxide prior to analysis to remove organics and clear up diffractogram.

APPENDIX B

BOREHOLE NUMBERING SCHEME

The following figure depicts a spatial representation of the study plot. Approximate borehole locations are marked with respective identification numbers and each square measures approximately 10cm x 10cm:



Vertically cut soil face and gutter setup located along bottom of figure. Highlighted boreholes indicate locations of boreholes installed for the collection of "background" samples.

APPENDIX C

VOLUMETRIC MOISTURE CONTENT CALCULATIONS

Sample*	Initial Weight (g)	Dry Weight (g)	Water weight (g)	Gravimetric Water Content (%)	Bulk Density (g/cc)	Volumetric Moisture Content (%)
7A	6.06	4.61	1.45	23.90	1.38	32.99
7B	7.11	5.85	1.26	17.75	1.38	24.50
7C	7.70	6.31	1.38	17.97	1.38	24.80
13A	4.80	3.86	0.94	19.55	1.38	26.98
13B	6.70	5.70	1.00	14.85	1.38	20.50
13C	9.52	8.26	1.26	13.24	1.38	18.28
24A	6.42	5.45	0.97	15.10	1.38	20.84
24B	7.23	6.21	1.02	14.05	1.38	19.38
24C	9.40	8.21	1.19	12.63	1.38	17.44
25A	4.99	4.05	0.94	18.87	1.38	26.04
25B	10.06	8.35	1.71	16.96	1.38	23.41
25C	8.26	7.14	1.12	13.51	1.38	18.65
27A	7.28	5.74	1.54	21.09	1.38	29.11
27B	7.23	5.90	1.32	18.33	1.38	25.29
27C	5.77	4.91	0.86	14.90	1.38	20.56
38A	6.38	4.85	1.53	24.04	1.38	33.17
38B	6.08	5.24	0.84	13.82	1.38	19.08
38C	6.72	5.78	0.94	14.04	1.38	19.38
50A	4.94	3.54	1.40	28.29	1.38	39.04
50B	6.97	6.04	0.93	13.34	1.38	18.40
50C	5.68	4.85	0.83	14.54	1.38	20.07
53A	6.98	5.61	1.38	19.73	1.38	27.23
53B	8.88	7.23	1.65	18.60	1.38	25.67
53C	7.94	6.60	1.35	16.93	1.38	23.36
60A	7.29	5.79	1.51	20.63	1.38	28.47
60B	7.46	6.26	1.20	16.09	1.38	22.21
60C	10.88	9.40	1.48	13.63	1.38	18.80
63A	10.87	9.54	1.33	12.23	1.38	16.88
63B	7.49	6.61	0.88	11.74	1.38	16.20
63C	8.31	7.29	1.03	12.36	1.38	17.06

*Sample number corresponds with borehole number, sample letter indicates depth (A = 0-5cm, B = 5-10cm, C = 10-20cm). Bulk density was measured on study plot soils by Stephan Fitzpatrick, 2011.

APPENDIX D

Volumetric runoff calculations. Subsurface runoff volume required to flush all water out of soil pores and replace with applied rainfall water. 50% porosity and saturated conditions assumed. Calculated for 2,300 cm^2 (10 cm strip adjacent to gutter) and 4,600 cm^2 (20 cm strip along gutter) contributing areas; both are conservative estimates.

Volume of Grid Cell (cm^3)	Porosity	Volume of Unit Cell Pore Space (cm^3)	# Cells Across Soil Face	Volume of Pore Space, first 10 cm uphill of gutter (cm^3)	Volume of Pore Space, first 20 cm uphill of gutter (cm3)
1000	0.5	500	23	11500	23000

Volume of 1 “tip” = 4.633 cm^3

$$\text{\# tips required to replace all pore water under saturated conditions} = \frac{\text{Vol of Pore Space}}{\text{Vol of tip}}$$

The number of tips required to replace all pore water under saturated conditions if contributing area is 10” strip adjacent to and along the length of gutter is 2,482.

4,964 tips are required to replace all pore water under saturated conditions if contributing area is 20” strip adjacent to and along the length of gutter.

APPENDIX E

1. ION CHROMATOGRAPHY DATA

Subsurface Runoff Data:						
Sample ID	**Date/Time**	**NO_3 (mg/L)**	**SO_4 (mg/L)**	**Cl (mg/L)**	**Br (mg/L)**	**I (mg/L)**
Artificial Rainfall Sample	6/15/10 4:14		15.51	6.20	0	
[015] - first round runoff	6/15/10 10:16	1.34	15.43	6.94	0	
[020] - first round runoff	6/15/10 10:26	1.31	15.15	6.79	0	
[025] - first round runoff	6/15/10 10:37	1.30	15.11	6.36	0	
[030] - first round runoff	6/15/10 10:47	1.31	15.15	6.33	0	
[035] - first round runoff	6/15/10 10:58	0.23	3.84	2.10	0	
[040] - first round runoff	6/15/10 11:08	0.23	3.83	2.10	0	
[043] - first round runoff	6/15/10 11:14	0.24	3.83	2.12	0	
[045] - second round runoff	6/15/10 23:14		15.30	6.04	0	
[048] - second round runoff	6/15/10 23:20		15.60	6.37	0	
[051] - second round runoff	6/15/10 23:26		15.43	6.16	0	
Natural Rainfall Sample	6/15/10 23:41		1.57	0.87	0	
[064] - second round runoff	6/15/10 23:50		15.82	6.56	0	

APPENDIX E

2. ION CHROMATOGRAPHY DATA

Soil Coring Data:						
Sample ID (borehole #, depth)	**Date/Time**	**NO_3 (mg/L)**	**SO_4 (mg/L)**	**Cl (mg/L)**	**Br (mg/L)**	**I (mg/L)**
1 0-5	**9/7/10 16:50**	9.97	4.80	2.63		
2 0-5	**9/4/10 17:41**	1.15	6.80	5.93		
3 0-5	**9/7/10 22:46**	4.34	3.95	2.80	trace	
4 0-5	**9/5/10 10:34**	0.29	4.88	3.66	trace	
5 0-5	**9/7/10 23:23**	1.99	6.68	3.43		
6 0-5	**9/8/10 2:31**	0.12	8.68	4.32		
7 0-5	**9/4/10 21:07**	15.37	9.75	6.46		
8 0-5	**9/3/10 21:38**	0.10	6.39	3.32		
9 0-5	**9/8/10 1:34**	0.52	10.04	9.67		
10 0-5	**9/8/10 4:47**	0.44	5.83	3.68	trace	0.00
11 0-5	**9/7/10 22:08**	0.84	8.24	3.28		
12 0-5	**9/5/10 11:11**	0.06	5.09	3.53		
13 0-5	**9/5/10 4:00**	17.94	3.81	2.05		
14 0-5	**9/3/10 21:19**	4.18	4.71	1.73	trace	
15 0-5	**9/3/10 13:49**	1.13	4.53	2.64	0.00	0.00
16 0-5	**9/7/10 20:16**	18.09	4.40	1.83	trace	
17 0-5	**9/7/10 16:31**	4.03	3.76	2.63		
18 0-5	**9/8/10 16:54**	0.31	4.12	0.88		
19 0-5	**9/3/10 17:34**	3.95	3.84	1.43	0.00	0.00
20 0-5	**9/3/10 23:30**	8.22	4.33	1.60		
21 0-5	**9/7/10 18:05**	0.54	2.74	2.27		
22 0-5	**9/4/10 22:03**	9.17	4.07	2.02		
23 0-5	**9/3/10 13:11**	9.52	3.92	1.90	0.00	0.00
24 0-5	**9/4/10 2:38**	2.39	4.58	2.09		
25 0-5	**9/3/10 22:15**	6.70	4.78	2.04		
26 0-5	**9/3/10 11:57**	5.80	2.46	1.43	0.00	0.00
27 0-5	**9/4/10 18:18**	4.38	5.26	3.51		
28 0-5	**9/5/10 2:45**	0.43	4.26	2.22		
29 0-5	**9/3/10 16:19**	2.84	5.99	2.11	0.00	0.00

Sample ID (borehole #, depth)	Date/Time	NO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	Br (mg/L)	I (mg/L)
31 0-5	**9/8/10 21:55**	1.36	5.53	1.45		
32 0-5	**9/7/10 14:20**	0.31	3.37	1.55		
33 0-5	**9/3/10 22:53**	0.05	2.77	1.34		
35 0-5	**9/3/10 19:45**	0.82	4.75	3.03	0.00	0.00
36 0-5	**9/5/10 2:07**	0.29	3.22	1.83		
37 0-5	**9/7/10 14:57**	0.54	2.66	1.07		
38 5-10	**9/4/10 18:56**	0.13	2.35	2.84	0.00	0.00
39 5-10	**9/4/10 19:52**	0.04	2.82	1.20		
40 5-10	**9/8/10 15:21**	0.07	3.76	0.88		
41 5-10	**9/7/10 17:27**	0.29	2.80	1.27		
42 5-10	**9/8/10 19:24**	0.18	3.58	1.23		
43 5-10	**9/5/10 8:41**	0.20	2.45	2.19		
44 5-10	**9/3/10 16:38**	0.27	2.49	0.97	0.00	0.00
45 5-10	**9/7/10 15:35**	1.47	1.91	1.06		
46 5-10	**9/3/10 21:56**	0.98	2.61	1.15		
47 5-10	**9/3/10 11:38**	0.70	2.95	1.90	0.00	0.00
48 5-10	**9/3/10 20:04**	0.15	2.80	1.04		
49 5-10	**9/3/10 14:08**	0.71	2.53	2.49	0.00	0.00
50 5-10	**9/8/10 23:47**	0.11	4.18	1.29		
51 5-10	**9/4/10 19:33**	0.80	2.37	1.11	0.00	0.00
52 5-10	**9/3/10 17:53**	0.24	2.24	1.11	0.00	0.00
53 5-10	**9/5/10 1:11**	0.65	2.25	2.78		
54 5-10	**9/7/10 19:01**	1.27	2.01	1.52		
56 0-5	**9/8/10 0:38**	0.23	3.51	2.19		
56 5-10	**9/4/10 22:22**	0.46	1.83	1.68		
57 5-10	**9/8/10 15:58**	0.09	7.16	0.53		
58 5-10	**9/7/10 19:19**	0.27	1.87	1.79		
59 5-10	**9/7/10 21:31**	0.68	2.34	0.96		
60 5-10	**9/4/10 20:30**	0.47	3.98	1.70		
61 5-10	**9/4/10 0:08**	0.22	2.29	1.06		
62 5-10	**9/7/10 15:53**	0.07	3.08	1.15		
63 5-10	**9/7/10 13:05**	0.09	2.42	0.96		

APPENDIX F

TIMELINE OF FIELD ACTIVITIES

Timeline of Field Activities

Date	**Time**	**Notes**
6/7/10	13:38	GPR survey
	15:38	Sprinkler ON
	16:20	Sprinkler OFF
	16:25	Sprinkler ON
	18:24	Sprinkler OFF
	18:25	GPR survey
6/8/10	15:05	GPR survey
	16:00	Sprinkler ON
	17:00	Sprinkler OFF
	17:29	GPR survey
6/9/10	9:10	GPR survey
	10:15	Sprinkler ON
	11:15	Sprinkler OFF
	11:20	GPR survey
	12:16	Sprinkler ON
	13:44	Sprinkler OFF (for maintenance)
	14:06	Sprinkler ON

Timeline of Field Activities (cont'd)

Date	**Time**	**Notes**
6/9/10	14:38	Sprinkler OFF
	14:47	GPR survey
	15:16	Sprinkler ON
	16:26	Sprinkler OFF (for maintenance)
	16:31	Sprinkler ON
	17:31	Sprinkler OFF
6/10/10		overnight precip = 1/8"
	10:20	GPR survey
	12:05	Sprinkler ON
	14:05	Sprinkler OFF
	14:09	GPR survey
	14:44	Sprinkler ON
6/11/10	9:00	GPR survey
	9:25	Sprinkler ON
	12:25	Sprinkler OFF
	12:26	GPR survey
	12:57	Sprinkler ON

Timeline of Field Activities		
Date	**Time**	**Notes**
6/10/10	15:24	RUNOFF RESPONSE
6/11/10	15:28	Sprinkler OFF
	15:30	Sprinkler ON
	15:51	Sprinkler OFF
	15:57	GPR survey
	16:39	Sprinkler ON
	17:39	Sprinkler OFF
	17:45	GPR survey
6/12/10	12:33	Sprinkler ON
	12:43	RUNOFF RESPONSE
	13:04	Sprinkler OFF (for maintenance)
	13:07	Sprinkler ON
	13:43	Sprinkler OFF
	13:48	GPR survey
6/13/10	10:18	Sprinkler ON
	11:27	Sprinkler OFF (for maintenance)
	11:30	Sprinkler ON
	17:43	Sprinkler OFF
	17:45	Sprinkler ON
	20:44	Sprinkler OFF
	21:02	GPR survey
6/14/10	9:05	Sprinkler ON
	12:17	Sprinkler OFF (for maintenance)

Timeline of Field Activities (cont'd)		
Date	**Time**	**Notes**
6/13/10	12:22	Sprinkler ON
	13:40	Sprinkler OFF (for maintenance)
6/14/10	13:42	Sprinkler ON
	14:55	Sprinkler OFF (for maintenance)
	15:05	Sprinkler ON
	16:15	Sprinkler OFF
	16:45	Sprinkler ON
	21:43	Sprinkler OFF
	22:11	Sprinkler ON
	22:43	Sprinkler OFF
	22:45	Sprinkler ON
	22:46	RUNOFF RESPONSE
	23:01	Sprinkler OFF
		APPLIED FIRST ROUND OF TRACERS
6/15/10	1:06	Sprinkler ON
	3:36	Sprinkler OFF
	3:41	Sprinkler ON
	5:17	Sprinkler OFF
	5:19	Sprinkler ON
	6:11	Sprinkler OFF
	6:20	Sprinkler ON
	7:50	Sprinkler OFF

Timeline of Field Activities		
Date	**Time**	**Notes**
6/15/10	8:00	Sprinkler ON
	9:08	Sprinkler OFF
	10:08	Sprinkler ON
	10:13	RUNOFF RESPONSE
		COLLECTED RUNOFF SAMPLES
	11:14	Sprinkler OFF
		APPLIED SECOND ROUND OF TRACERS
	12:05	Sprinkler ON
	12:44	Sprinkler OFF

Timeline of Field Activities (cont'd)		
Date	**Time**	**Notes**
6/15/10	13:14	Sprinkler ON
	13:43	Sprinkler OFF
	22:56	Sprinkler ON
	23:11	RESPONSE
		COLLECTED RUNOFF SAMPLES
	23:58	Sprinkler OFF
6/16/10	0:10	Sprinkler ON
	0:30	Sprinkler OFF
	8:46	Sprinkler ON
	9:46	Sprinkler OFF