ABSTRACT

RICE, JOSHUA SAYRE. Land Use and Runoff Generation in the Southern Appalachian Mountains. (Under the direction of Dr. Ryan Emanuel).

The movement of water through the terrestrial portions of the hydrologic cycle is a vital process that supports human society and ecological systems, shapes the landscape, and plays a major role in the larger Earth System. Achieving a better understanding of how human activity influences runoff generation, a key phase of the terrestrial hydrologic cycle, is a crucial step in increasing humanity's ability to live with, and not just in, the world around us. It has been suggested that human land use is the most pervasive and persistent environmental impact of human activity. Here a case study approach has been applied to consider the influence of land use on runoff generation within the Little Tennessee River Basin (LTRB) of the southern Appalachian Mountains. The application of an interdisciplinary set of methods incorporating spatial data, physical hydrology, and stable isotope hydrology suggests that land use within the LTRB is capable of exerting a strong influence on runoff generating processes. However, this methodology has also shown that runoff generating processes remain highly complex. Despite this complexity, strong evidence exists showing that land use plays an important role in defining local water balances within the LTRB. As water plays an important role in many natural systems this finding indicates that land use, through its influence on the movement of water, may potentially have broad reaching environmental impacts within the LTRB.

Land Use and Runoff Generation in the Southern Appalachian Mountains

by
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BIOGRAPHY

Joshua Rice was born on March 12, 1983 in Burlington, VT. Following four years spent in the military as an infantry soldier, Joshua began undergraduate work at Appalachian State University in Boone, NC in January of 2008. In May of 2011 Joshua received a B.S. in Environmental Science from Appalachian State. August of 2011 marked the beginning of Joshua's time as a graduate student in the Department of Forestry and Environmental Resources at North Carolina State University.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

Overview

1a. Introduction

Throughout history a hallmark of human society has been increasing effort and ability to modify the environment, a pattern that will likely continue in the foreseeable future as population and rates of natural resource extraction and consumption remain unsustainable [*Palmer et al*., 2004]. Of the many activities undertaken by humans with environmental consequences, land use has perhaps the most pervasive impact to many of the Earth's systems, especially the hydrologic cycle [*Houghton*, 1994; *Vitousek et al.*, 1997; *Foley et al*., 2005]. Human land use has the potential to modify the hydrologic cycle through a variety of mechanisms including: alterations in the partitioning of precipitation into other components of the hydrologic cycle [*Foley et al*., 2005], shifts in surface runoff and discharge patterns [*Vitousek et al*., 1997], variations in the demands placed upon freshwater supplies [*Defries and Eshleman*, 2004], and changes in water quality [*Foley et al*., 2005]. The links between land use and the hydrologic cycle at large spatial scales have been focal points for research in recent years [e.g. *Vitousek et al*., 1997; *Vorosmarty et al*., 2000]; thus the impacts of specific land-use activities, such as irrigation and the building of dams and canals, are increasingly well-understood. How land use may impact the hydrologic cycle by altering runoff generation at the hillslope scale, particularly in mountain headwater watersheds where many major river systems begin, is still unclear. Examining how these hillslope scale processes evolve to watershed-scale observations is a crucial step in understanding hydrologic responses at the basin scale [*National Research Council*, 2012].

This project examines the potential influence of land use on runoff generation within mountain headwater catchments using an interdisciplinary approach. This methodology focused on a combination of three analytical components: hydrometric data analyses, water stable isotope analyses, and spatial data analyses. Using a case study approach, these analyses were applied to the three dominant forms of land use found in the southern Appalachian Mountains region of the southeastern United States. Logistic constraints and issues related to property access prevented the collection of hydrometric and isotope data at residential land use sites, but spatial analyses were applied to forest, pasture, and residential land use within the study area.

1b. Goals

The goal of this project was to identify hillslope scale differences in runoff generating processes between forms of land use common to the southern Appalachian Mountains. By leveraging hydrometeorological data (e.g. precipitation and potential evapotranspiration), observed patterns in runoff generating processes were considered in the context of the local water balance. This project pursued the additional goal of identifying fundamental differences in the spatial organization of land use that may be of consequence when considering hydrologic functioning at the river basin scale. Completion of these goals has generated knowledge that increases understanding of the role land use plays in the hydrologic cycle.

1c. Links to previous experience and future career goals

A substantial portion of my previous research experience has focused on the influence of urban land-use in mountain headwater catchments on surface water hydrology [*Rice et al*., 2011]. The project described in this document has built on my previous work both conceptually and technically. An expansion of my conceptual knowledge has been gained by investigating a larger range of land-uses as well as multiple pools of water. With a focus on links between various physical and biological systems, this project has had a substantial interdisciplinary component, reinforcing the importance of posing questions in the context of boundary crossing connections between systems that have been identified as a crucial path for future research [*Palmer et al*., 2004; *National Research Council*, 2012]. The use of specific tools, including stable isotopes, hydrometric data, and remote sensing products has expanded my technical skill set with tools that are robust and broadly applicable, greatly enhancing my effectiveness as a researcher. By building on the fundamental skill set and knowledge developed during my earlier experiences, this project has increased my conceptual and technical abilities while at the same time producing an important contribution to current understanding of the forces influencing runoff generation at the hillslope scale.

Scientific background and methodology

2a. Study area and land use

The Little Tennessee River Basin (LTRB) within the southern Appalachian Mountains region is an ideal setting for investigating potential links between land use and runoff generation in mountain headwater catchments. The LTRB is characterized by mountainous terrain, a large number of low-order headwater streams, and a wide range of land uses. An important feature of this area is its history of nearly continuous human modification of the landscape since at least the mid 1800's [*Gragson and Bolstad*, 2006]. Between the mid 1800's and early 1900's much of the region was subjected to extensive forest clearing for timber harvesting and conversion to agricultural land [*Ayres and Ashe*, 1905; *Williams*, 1989]. The unsuitability of many locations for agriculture resulted in abandonment followed by reforestation [*Turner et al*., 2003]. The extensive mixed hardwood deciduous forests that now dominate the region are the result of decades of reforestation [*Kloeppel et al*., 2003]. Recent patterns in land use in the LTRB have shifted away from agriculture and extractive land use toward rural residential, or exurban, development [*Wear and Bolstad*, 1998; Kloeppel *et al*., 2003]. Currently, the three main forms of land use in the LTRB, by area, are: mixed hardwood deciduous forest (forest), pasture agriculture (pasture), and residential (see Chapter 2 for areas). The LTRB is also home to the U. S. Forest Service's Coweeta Hydrologic Laboratory as well as the Coweeta Long-Term Ecological Research (LTER) program. A primary focal area of the Coweeta LTER program is investigating the response of watershed-scale hydrological processes to ecosystem disturbance and environmental gradients, such as land-use, in the southern Appalachian Mountain region. As a component of the Coweeta LTER program, this project complements the goals of the larger program by examining the potential influence of the three most common forms of land use in the region on runoff generation.

2b. Spatial analysis

Land use, in a very basic sense, is an imposition of human wants and needs on the natural landscape. This means that land use continuously involves interactions between natural and anthropogenic forces, and suggests patterns in the spatial distribution of land use may be influenced by the same forces. If the spatial distribution of different forms of land use is related to variables capable of impacting hydrologic function, then the same forms of land use may exhibit fundamentally different hydrology. Previous work in this region has demonstrated a relationship between several variables describing landscape position and the spatial distribution of land use [*Wear and Flamm*, 1993; *Turner et al*., 1996; *Wear and Bolstad*, 1998]. In chapter 2, we further consider the relationship between landscape position and the spatial distribution of land use with data representing 20 years (1986 – 2006) of steadily evolving land use in the LTRB. As these data are examined particular attention is paid to variables with potential hydrologic importance in an effort to identify a relationship with land use distribution that may impact the basic hydrologic function of discrete landscape units.

2c. Hydrometric analysis

The portion of this project focusing on physical and hydrometric data will investigate two aspects of runoff generation, water table response and hydrologic connectivity. During and after storm events, infiltrating rainfall leads to a measurable response in water table levels [*Sklash and Farvolden*, 1979; *Pearce et al*., 1986]. This response is capable of exerting a strong influence on subsurface discharge and thus runoff generation [*McGlynn et al*., 1999].

Observing how water table levels respond to inputs, both in terms of response time and magnitude, is an important step in understanding how runoff generation occurs at the hillslope scale [*McGlynn et al*., 2004]. Hydrologic connectivity has been defined previously as the concurrent presence of a persistent water table across a spatial continuum, such as the path linking hillslope, riparian, and stream zones [*Pringle*, 2003; *Jencso et al*., 2009]. The development of hydrologic connectivity plays an important role in runoff production in mountainous, headwater catchments [*James and Roulet*, 2007; *Jencso et al*., 2009; *Jencso et al*., 2010). Chapter 3 of this thesis details an examination of patterns in the behavior of water table response and shallow groundwater connectivity on forest and pasture hillslopes using observations of water table levels recorded between August 2011 and November 2012 .

2d. Stable isotope analysis

Of the many methods used to infer knowledge of hydrologic functioning at the catchment scale, isotopic tracers have proven to be quite useful [*Genereux and Hooper*, 1998; *Kendall and Caldwell*, 1998]. Oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopes, in particular, make ideal conservative tracers to investigate the movement of water within and out of catchments as the isotopes are the actual water molecule [*Kendall and Caldwell*, 1998]. As precipitation is the primary input of water to a catchment, knowledge of variations in the isotopic composition of this input, or signal, can be used to make inferences about how water is moving within a catchment [*Genereux and Hooper*, 1998; *Ingraham*, 1998]. One common application of this relationship is estimation of the age, or mean residence time (MRT), of water within or leaving individual hillslopes and catchments [e.g. *DeWalle et al*., 1997; *Soulsby et al*., 2000; *McGuire et al*., 2005]. MRT, as applied in the subsurface, refers to the average length of time water takes to reach a particular point within the system, relative to when it was deposited [*McGuire et al*., 2002]. The MRT of water within a system provides useful information when considering variation in flow pathways and storage [*McGuire et al*., 2005]. Understanding MRT can also provide insight into questions involving nutrient transport as many biogeochemical processes are strongly affected by time [*McGuire et al*., 2005]. Chapter 4 of this thesis discusses the use of oxygen stable isotopes ($\delta^{18}O$) as conservative tracers to estimate MRT as a means of comparing differences in the hydrology of forest and pasture hillslopes in the LTRB.

Research objectives and hypotheses

Each of the three methodologies outlined in the previous section provide a means to examine different aspects of the possible relationship between land use and runoff generation. By crafting separate objectives and hypotheses for each methodology, the results of this project make a more interdisciplinary and holistic contribution to existing knowledge. These objectives and hypotheses are outlined in the remainder of this section.

3a. Spatial analysis objective and question

Objective 1: Examine the spatial distribution of land use as a function of landscape position to answer the following question. (*1*) Do different forms of land use exhibit a tendency to occupy significantly dissimilar landscape positions that may result in altered hydrology when comparing land use types?

Hypothesis 1: The forms of land use in question occupy significantly different landscape positions with respect to hydrologically-relevant variables.

3b. Hydrometric analysis objective and questions

Objective 2: Investigate potential variation in runoff generation between agricultural and forested hillslopes in the context of the local water balance using physical, hydrometric and hydrometeorological data by answering the following questions. (*1*) Is there variation in the timing and persistence of shallow groundwater hydrologic connectivity between forest and pasture land use hillslopes? (*2*) Is there variation in the dynamics of water table behavior between forest and pasture land use hillslopes?

Hypothesis 2: Significant differences exist between patterns in the physical hydrology of forest and pasture land use hillslopes, based on hydrometric and hydro-meteorological data.

3c. Stable isotope analysis objective and question

Objective 3: Examine differences in runoff generation between pasture and forest hillslopes using water stable isotopes to answer the following question. (*1*) Does the MRT of subsurface water on forest hillslopes differ systematically from the MRT of subsurface water on pasture hillslopes?

Hypothesis 3: Subsurface water on pasture hillslopes has a substantially longer MRT than subsurface water on forest hillslopes.

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CHAPTER 2: SPATIAL ANALYSIS OF LAND USE DISTRIBUTION: A MANUSCRIPT PREPARED FOR SUBMISSION TO THE *JOURNAL OF GEOPHYSICAL RESEARCH – BIOGEOSCIENCES*

The Spatial Organization of Land Use in the Southern Appalachians: A Dynamic Relationship between Natural and Anthropogenic Influences.

Authors

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Abstract

Land use/land use change (LUC) directly alters ecological, biogeochemical, and hydrological processes by modifying the land surface. Additional links between LUC, ecosystem, and hydrologic processes can arise due to relationships between the spatial distribution of LUC and topographic variables, such as slope and elevation. Understanding these links requires an understanding of the variables that influence the spatial distribution of land use relative to landscape position. Here we examine the intersection of landscape structure and land use distribution by focusing on the relationship between select natural and anthropogenic variables describing landscape structure and dominant classes of land use in the Little Tennessee River basin (LTRB) of the southern Appalachian Mountains. We show that landscape position, as determined by the variables in consideration, influences the distribution of land use in the LTRB. Our results provide evidence that all of these variables (slope, elevation, and distance from road) play a prominent role in determining the distribution of land use. The same variables also influence the likelihood of land use change through time, with the majority of land use change being centered in low slope, low elevation areas with accessibility to major road networks. These results suggest that different classes of land use can be expected to behave differently in terms of hydrologic, ecosystem, and biogeochemical functioning not only because of direct alteration through land-use, but also because of the relation between landscape position and the spatial organization of LUC.

Keywords: land use distribution, land use change, southern Appalachians, ecohydrology

Introduction

As the demand for resources and technological prowess of human society increases, the impact of human activity on the Earth and its natural systems also grows. The ability of human activity to affect these systems has grown to the point where it has been recognized as one of the dominant forces on the Earth [*Vitousek et al*., 1997; *Palmer et al*., 2004]. Of the myriad human activities that influence the Earth, land use/land use change (LUC) has been recognized as having a particularly widespread effect [*Vitousek et al*., 1997]. Land use change has transformed approximately one-third to one-half of the Earth's land surface [*Vitousek et* al., 1997]. A broad range of environmental consequences is associated with human land use. These consequences include transformation of ecosystem structure and function, alteration of energy, water and biogeochemical balances, and interactions with other sources of environmental disturbance and change [*Vitousek et al*., 1997; *Foley et* al., 2005]. Other research has suggested that the consequences of LUC may even overshadow effects of climate change on a global scale [*Sala et al*., 2000; *Vorosmarty et al*., 2000]. In addition to the useful services they provide, some forms of LUC bring potentially unwanted or unexpected environmental impacts as well. However, many land use practices provide critical support to human society, necessitating at least some level of LUC despite the potentially unwanted or unexpected environmental impacts [*Foley et al*., 2005]. Human land use thus presents a quandary and creates the need for a thoughtful and sustainable approach to management that balances the needs of society and the health of the planet. To manage land resources in a manner that fulfills both of these objectives, a deeper understanding is needed of the factors influencing LUC. Investigating how interactions between humans and the natural world affect patterns in the distribution of LUC is thus an important endeavor [*Wear and Bolstad*, 1998; *Turner et al*., 2003].

If LUC is an imposition of human wants and needs on the natural world then the distribution of LUC is inherently an interaction between natural and anthropogenic forces. Thus patterns in the distribution of LUC are driven by interactions between human and natural processes. In light of this point, previous research focusing on the factors influencing the spatial distribution of LUC has examined both anthropogenic and natural variables. Previous work by *Turner et al*. [1996] and *Wear and Bolstad* [1998] used modeling approaches to demonstrate the need to consider anthropogenic and natural influences on the spatial patterns of LUC. Additional work focusing on patterns of LUC found evidence linking anthropogenic variables to land use distribution and change [*Laurance et al*., 2001; *Soares-Filho et al*., 2006]. For example, accessibility to transportation has been previously identified as an influence on LUC [e.g. *Wear and Bolstad*, 1998; *Laurance et al*., 2001; *Soares-Filho et al*., 2006]. However, focusing on anthropogenic and natural influences separately ignores the coupled effects of these types of influences on LUC.

To investigate the influence of anthropogenic and natural variables on land use distribution, we use a case-study approach focused on the Little Tennessee River Basin (LTRB) in the southern Appalachian Mountains region (USA). The LTRB is home to both the Coweeta Hydrologic Laboratory and Coweeta Long-Term Ecological Research (LTER) program. An important characteristic of this area is its history of nearly continuous human modification of the landscape since at least the mid 1800's [*Gragson and Bolstad*, 2006]. Between the mid 1800's and early 1900's much of the region was subjected to extensive forest clearing for timber harvesting and conversion to agricultural land [*Ayres and Ashe*, 1905; *Williams*, 1989]. The unsuitability of many locations for agriculture resulted in abandonment followed by reforestation [*Turner et al*., 2003]. The extensive mixed hardwood deciduous forests that now dominate the region are the result of this reforestation [*Kloeppel et al*., 2003]. Current trends in land use in the LTRB have shifted away from agriculture and extractive land use toward rural residential, or exurban, development [*Wear and Bolstad*, 1998; *Turner et al*., 2003]. Past studies in the region have demonstrated a relationship between landscape position, defined by topography and accessibility, and the distribution of separate land use classes and the occurrence of land use change [*Wear and Flamm*, 1993;

Turner et al., 1996; *Wear and Bolstad*, 1998]. Despite previously produced information, questions concerning the complex interactions that influence the spatial distribution of LUC still remain.

The primary goal of this paper is to gain insight into the interactions between natural and anthropogenic forces that influence the distribution of LUC. We consider the influence of natural forces on the distribution of LUC by examining landscape position in the context of topography using slope and elevation. We also take into account the influence of anthropogenic factors by considering the distance of a given point to major road networks in the study area. However, it is also important to consider the potential combined influence of natural and anthropogenic variables. This need is addressed by creating a Land Use Suitability Indicator (*LUSI*) representing two landscape characteristics, which we describe as ruggedness and remoteness. The *LUSI* variable combines topographic variability (ruggedness) and distance from road (remoteness) into a single metric. This metric is based on the argument that actively maintained forms of land use (i.e. those that require regular upkeep), such as agriculture and residential, are more suitable for areas with less ruggedness and remoteness. As we consider the factors that influence the distribution of LUC we focus on answering the following questions. If both natural and anthropogenic factors influence the distribution of LUC, which factors are most influential and does the relative influence vary among land use classes? Is there a coupling of natural and anthropogenic variables that exerts a stronger influence on the distribution of LUC than that of either category alone? Do patterns of land use change through time reflect the combined influence of natural and anthropogenic factors on the distribution of land use?

Methods

The LTRB is located primarily in Western North Carolina with a small portion extending into northern Georgia (Figure 2.1). Climate in the region is relatively mild and is classified as marine, humid temperate [*Swift et al*., 1988]. Mean annual precipitation in the area ranges from approximately 1800 mm at lower elevations to nearly 2400 mm along high ridgelines [*Kloeppel et al*., 2003]. The region is characterized by heterogeneous mountain topography with elevations in this 1125 km^2 river basin ranging from 537 m to 1650 m and slopes ranging from 0° to 72°. The main populated areas within the basin are Franklin, NC and Highlands, NC (Figure 2.1). Three forms of land use occupy over 80% of the LTRB area: deciduous forest (748 km^2, 66%), pastoral agriculture (87 km^2, 8%), and residential (86 km^2, 8%). In this study we focus on these three dominant types of land use within the LTRB.

Thirty meter resolution, Landsat ETM+ and TM derived land cover class datasets were obtained for the years 1986, 1991, 1996, 2001, and 2006 from the Coweeta LTER web-based GIS data catalog (http://coweeta.ecology.uga.edu/). These datasets were developed using the same methodology used to create the National Land Cover Dataset (NLCD). Land cover classifications are based on those outlined by *Anderson et al*. [1976] and are used as a proxy for actual land use. Processing of the land cover datasets was conducted using ArcGIS

10 (ESRI, Inc., Redlands, CA). The land use classes relevant to this study were identified and extracted from each of the five land use datasets. Shapefiles of each land cover class from the 2006 dataset were used to export the class-specific spatial extent of each potentially influential landscape variable (described below). Areas undergoing land use change were identified by intersecting the coverage of a land use class from one time period with the coverage from the previous time period, resulting in four intersecting coverages (e.g. 2006 and 2001, 2001 and 1996, 1996 and 1991, and 1991 and 1986). The intersecting coverage, or area that was consistent in land use between each time period, represents areas that did not experience land use change during the interval in question. These areas were then used to clip the land use coverages from each time period to identify areas not included in the intersection. Areas not included in the intersecting coverages represented either a change in land use from one class to the class in question or from the class in question to another class. For example, the intersection between the 2001 and 2006 forest land use coverages was used to clip the forest coverage from both of these time periods, thus identifying areas that transitioned from forest to another land use class or to forest from another land use class between 2001 and 2006. This process was repeated for each of the land use classes in consideration and was completed using ArcGIS 10.

Spatial datasets of landscape variables were analyzed and derived using tools found within ArcGIS 10. A one-third arc-second (~10 m) digital elevation model (DEM) was obtained from the U.S. Geological Survey's National Elevation Dataset [e.g. *Gesch et al.*, 2009]. A coverage of slope for the LTRB was also derived from the DEM. Together, these variables (elevation and slope) were used to assess terrain characteristics for landscape positions within the LTRB. The watershed boundary of the LTRB was also delineated using the 10 m DEM and an outlet upstream of Fontana Lake in Swain County, NC (USGS stream gage 03503000). A road network dataset from the TIGER 2010 Primary Roads dataset [*U. S. Census Bureau*, 2012] was used to assess ease of access to landscape positions by humans. Road data from 2010 were considered acceptable for use here because the roads in question are all major highways and not subject to extensive change over a span of several decades.

Creation of a *LUSI* variable that incorporates terrain characteristics and accessibility of individual landscape positions used the spatial datasets described above. Terrain characteristics were assessed for non-overlapping, one hectare (100 pixel) blocks in the LTRB by defining the "ruggedness" of each block as:

$$R_u = \sigma_e + \sigma_s \quad (1)$$

where R_u is equal to ruggedness, σ_e is the standard deviation of elevation within the one hectare block, and σ_s is the standard deviation of slope within the same one hectare block. The R_u value was assigned to each 10 m pixel in the block. Accessibility of individual landscape positions was assessed by defining the "remoteness" of each position as the Euclidean distance between each 10 m pixel and the nearest major road as:

$$R_e = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (2)$$

where R_e is remoteness, x_2 and y_2 are the coordinates of the 10 m pixel, and x_1 and y_1 are the closest coordinates along a major road. The *LUSI* was defined from the ruggedness and remoteness of each 10 m pixel as:

$$LUSI = R_u + R_e \qquad (3)$$

Each component of the *LUSI* variable had a similar range, allowing them to be combined arithmetically without weighting the range of values systematically toward either R_u or R_e. Prior to choosing the equal weighting combination of *LUSI* components multiple versions testing unequally weighted combinations of the components were tested. The equal weighting version was chosen as it was the best performer, in terms of statistically describing differences in land use distribution across the landscape using the two-sample Kolmogorov-Smirnov test. The final coverage of the *LUSI* ranged from a low of 0 to a high of 51 with low values representing less rugged and more accessible landscape positions and high values representing more rugged and less accessible landscape positions. Following the creation of each spatial dataset the distribution of slope, elevation, and *LUSI* within each land use class were determined by clipping the full basin coverage to the extent of each land use class and the areas identified as undergoing land use change.

A one-sample Kolmogorov-Smirnov (KS) test demonstrated at the 95% confidence level that the distribution of each landscape variable did not conform to a normal distribution, and so non-parametric statistical tests and measures were used. Median and interquartile range (IQR) were calculated to describe meaningful, physical differences in the distributions of landscape variables among land use classes. The two-sample KS test was used to compare difference in the distribution of each land use class as a function of landscape position. The two-sample KS test quantifies, through the KS statistic, the maximum distance (in frequency units) between the cumulative distribution frequency distributions of two variables and it has proven useful for determining the relative importance of different variables for explaining spatial patterns in the environment [e.g. *Kaiser et al*., 2012]. Statistical analyses were conducted using Matlab R2012a (Mathworks, Inc., Natick, MA).

Clustering analysis was used to examine the strength of each landscape variable's influence on the distribution of land use and land use change in the LTRB. An unsupervised clustering analysis, fuzzy c-means (FCM) clustering [e.g. *Bezdek et al*., 1984], was conducted in Matlab using the full LTRB extent of each variable as an input. The FCM method is particularly helpful as it can be used to examine the underlying organization of input data [*Bezdek et al*., 1984]. Rather than grouping data into clusters with strictly defined boundaries, FCM clustering determines the likelihood of a specific point belonging to each cluster. As land use distribution within the LTRB exhibits a high level of spatial heterogeneity (Figure 1), the probability based (i.e. fuzzy) output of FCM clustering was considered appropriate. Since three classes of land use were being considered, three clusters were specified in the FCM clustering analysis. Each landscape position was assigned membership to the cluster to which it exhibited the highest probability of membership based on values from the FCM output membership matrix. These clusters represent objective divisions in the distribution of the input data and are not an attempt to model or predict land use distribution. Rather, the clusters are used to assess the influence of landscape variables on the distribution of LUC. The FCM clusters were imported to ArcGIS 10 and the fraction of each land use class and the distribution of each landscape variable within each cluster were quantified. Fractions of land use and distributions of landscape variables within clusters were used to assess the relative influence of landscape variables on the distribution of LUC.

Results and Analysis

Statistics describing the distribution of each landscape position variable within specific land use classes suggest clear patterns in the spatial organization of land use within the LTRB (Table 2.1, Figure 2.2). Half of forest land use within the LTRB falls in areas over 887 m above mean sea level, on slopes at least 22.0°, and 2.4 km or more away from major roads. In comparison, half of the land within the entire LTRB occupies areas that are above 823 m above mean sea level, on slopes that are at least 19.2°, and 2.1 km or more away from major roads. In comparison, approximately 90 % of pasture land use and 70 % of residential land use occurs in areas where elevation is below 800 m above mean sea level and slope is 15° or less (Figure 2.2). Seventy percent of pasture land use and slightly less than 80 % of residential land use can be found within 2 km of a major road (Figure 2.2). A similar pattern exists when considering the distribution of *LUSI* values among each land use class and the entire basin. The upper 50 % of areas where forest land use can be found have *LUSI* values above 18.9. Over 80 % of both pasture and residential land use occurs in areas with a *LUSI* value less than the basin median, 17.4 (Table 2.1 and Figure 2.2). Examination of the interquartile range for each landscape position variable suggests that of the three land use classes, forests occupy the widest range of landscape positions while pastures are the most concentrated, with the exception of residential land use described as a function of distance from major roads (Table 2.1). These observations show that forest land use within the LTRB is located primarily in steep, high elevation, rugged, and relatively remote areas whereas pasture and residential land uses are mainly found in low elevation, low slope, and gentle terrain positions that tend to be relatively accessible.

Two-sample KS tests provide additional insight into how the spatial distributions of landscape variables vary among land use classes. The distribution of each landscape variable was significantly different ($p < 0.05$) among land use classes, based on 2006 data (Table 2.2). Comparing the elevations occupied by forest and pasture land uses resulted in the clearest difference between the distribution of these two land uses across the landscape (KS = 0.71). The *LUSI* variable resulted in the largest difference when comparing the distribution of forest and residential land uses (KS = 0.51). The largest difference between pasture and residential land uses, in terms of landscape position, resulted from comparison of the elevations occupied by the two land uses (KS = 0.26). Based on the magnitude of the KS statistic produced by the assessment of each land use class's frequency distribution, forest and pasture land uses differ most in terms of landscape position (Figure 2.2). Pasture and residential land uses occupy the most similar landscape positions, again based on differences between the frequency distributions for each land use class (Figure 2.2). Overall, *LUSI* had a marginally higher sum of KS statistic values (1.43) than elevation (1.42) and slope (1.37). Road distance had a relatively small sum of KS statistic values (0.80) compared to other landscape variables.

Pasture and residential land uses conformed to FCM clusters relatively well (Table 2.3). An individual elevation cluster ranging from 537 – 793 m contained 93% of pasture land use within the LTRB (Figure 2.3). Seventy eight percent of residential land use within the LTRB fell within a single cluster based on road distance that ranged from 0 – 1.8 km (Figure 2.3). Whereas individual elevation and road distance clusters contained the highest percentage of pasture and residential land uses clusters produced by other variables also contained a large percentage of these two land use types. One slope cluster, representing areas with slope between 13° and 25°, contained 86% of pasture land use and 66% of residential land use. Eighty five percent of pasture land use and 66% of residential land use fell within the *LUSI* cluster representing the least rugged and least remote areas within the LTRB with *LUSI* values between 0 and 12. Forest land use proved more difficult to contain in a single cluster. The highest percent of forest falling in a single cluster only reached 51% in the middle range *LUSI* cluster whose values were between 13 and 20 (Figure 2.3). No other individual cluster contained over 50% of the forest land use within the LTRB.

The distribution of individual land use classes is only one aspect of the relationship between landscape structure and LUC. It is also important to examine the forces influencing the distribution of land use change. For each land use class and variable being considered, there is a significant difference (two-sample KS test, $p < 0.05$) between the distribution of landscape positions undergoing land use change between 1986 and 2006 and the distribution of landscape positions within the entire LTRB (Figures 2.4 – 2.6). Changes in forest land use during this time period are focused in low elevation, low slope, near road landscape positions that can be described as having relatively gentle and accessible terrain (Figure 2.4). As with changes in forest land use, changes in pasture land use between 1986 and 2006 are concentrated in low elevation, low slope, near road areas with gentle, accessible terrain (Figure 2.5). The distribution of landscape positions where residential areas experienced changes in land use between 1986 and 2006 exhibits the same general trend as pasture and forest area undergoing land use change. Changes in residential land use occurring between 1986 and 2006 show a tendency to be concentrated in low elevation, low slope, near road areas defined by gentle, accessible terrain (Figure 2.6). Despite the clear variation in landscape positions between land use classes (e.g. Figure 2.2), over 50 % of the changes in land use within each class are focused in areas under 750 m in elevation, on slopes less than 16°, within 1.8 km of major roads, and with *LUSI* values under 16 (Figure 2.4 – 2.6).

Discussion

Variation in the influence of landscape position among different factors and land uses

Whereas land use within the LTRB is fairly heterogeneous, the three dominant land use classes in the area occupy significantly different landscape positions (Table 2.1 and Figure 2.2). Variation in the measures used to define landscape position (elevation, slope, road distance, and the combined-variable, *LUSI*) among land uses suggests that the level of influence of these measures changes depending on the land use class in question. However, based on KS statistic values (Table 2.1), the variable representing the combined influence of natural and anthropogenic forces (*LUSI*) exerts the strongest overall effect, closely followed by elevation. The landscape position variables being considered clearly divide forest land use from both pasture and residential land uses (Table 2.1 and Figure 2.2), but differences between the distribution of pasture and residential land use are less clear. As this is true for each variable being considered it is likely that they all are capable of influencing the distribution of land use, though the influence may vary depending on the land use class in question. This may in part be an effect of how these measures of landscape position affect land use feasibility, or the relative ease with which an area may be used for a given activity (e.g. residential development on steep slopes vs. residential development on low slopes). Pasture and residential land uses in the LTRB require active management, or regular upkeep and input of energy, to be kept in their current state; deciduous forest land use does not require active management to exist. In fact, the current widespread existence of deciduous forest in the LTRB is largely the result of areas formerly subject to active use being abandoned [*Kloeppel et al*., 2003; *Turner et al*., 2003; *Gragson and Bolstad*, 2006]. Certain landscape positions are more conducive to the active management necessary to maintain pasture and residential areas, thus the narrow range of positions occupied by pasture and residential land uses. In this sense, deciduous forest land use represents a more "opportunistic" class of land use than pasture or residential land uses as it has a tendency to occupy landscape positions that are relatively undesirable for other activities. Simply put, forests have a propensity to exist where other, more management intensive, forms of land use do not exist, rather than the opposite. This opportunism results in the distribution of forests being spread more evenly over the range of landscape positions found in the LTRB, while the two active land use classes, pasture and residential, occur primarily within a limited range of landscape positions (Figure 2.2). These results indicate that the distribution of land use requiring active management is more constrained by slope, elevation, and road distance than the distribution of forests. The high level of agreement between pasture and residential land use distribution and the results of FCM clustering further support this hypothesis.

Interaction between measures of landscape position and the influence on land use distribution

Our land use suitability indicator, or *LUSI*, was built to encompass each of the three measures of landscape position by creating a general measure of ruggedness and remoteness. The purpose of doing so was to learn if the combined influence of the landscape positions variables is stronger than separate influence of each variable. If the combined influence (*LUSI*) of anthropogenic and natural forces is greater than the individual variables, *LUSI* could be expected to produce larger overall KS statistics when comparing the distribution of each land use class and greater levels of agreement between FCM cluster and actual land use. Based on the data presented in tables one and two, we find that the combined influence (*LUSI*) of natural and anthropogenic variables on LUC distribution is greater than the influence of each landscape position variable when considered individually. When considering the value of KS statistics describing differences between the distributions of each land use class across the range of landscape positions, *LUSI* produces the largest combined KS statistic, though it is closely followed by elevation and slope. Considering the overall results of FCM clustering a similar trend is seen. While *LUSI* based FCM clusters only produced one cluster that provided the best match to a single land use (Forest), overall it outperformed each of the individual variables representing natural and anthropogenic influences. This suggests that though each measure of landscape position may exert an effect on land use distribution, the combined effect of these measures is greater than their individual effect.

Are certain landscape positions more likely than others to experience land use change?

The majority of land use change within the LTRB is concentrated in a fairly narrow range of landscape positions relative to the full range of landscape variability within the basin. Our results indicate that low elevation, low slope areas, near major roads with gentle and accessible terrain are subject to more land use change than other areas within the LTRB (Figures 2.4 – 2.7). These results support the hypothesis that landscape position, defined by natural and anthropogenic variables, is related to the distribution of land use change. These findings are in agreement with previous work examining similar issues [*Chomitz and Gray*, 1995; *Turner et al*., 1996; *Nelson and Hellerstein*, 1997; *Wear and Bolstad*, 1998] and suggest that landscape position may be useful in identifying areas that are particularly vulnerable to land use change. The tendency for land use change to be more common in a particular range of landscape positions also raises interesting implications when considering the distribution of individual land use classes across the LTRB landscape. Over 50 % of the observed land use change within each land use class occurs in areas under 750 m in elevation, on slopes less than 16°, within 1.8 km of major roads, and with LUSI values under 16 (Figure 2.4 – 2.6). The majority of forest land use occurs in landscape positions with values above these and the majority of pasture and residential land use is found in landscape positions with values below these (Figure 2.2). As pasture and residential land uses are highly focused in positions where land use change is common (e.g. LUSI cluster 3, Figure 2.7) it is reasonable to conclude that these forms of land use are more likely to experience land use change than forest land use within the LTRB. Based on the distribution of past land use change it is a reasonable to assume that the remaining forests in areas with a high potential for land use change will be more vulnerable to loss than forests in positions with a lower potential to experience land use change (e.g. LUSI cluster 1, Figure 2.7). Additionally, the relative lack of forest land use in the areas where land use change is most common suggests that future loss of forests from these areas will be proportionately more impactful than forest loss from the extreme headwaters. It should be noted that in addition to variables describing landscape position the influence of other factors such as land use history, private owner interests, changes in land value, zoning laws, and technological capabilities are all capable of influencing land use change [*Wear and Bolstad*, 1998; *Turner*, 2005; *Gragson and Bolstad*, 2006]. Land values, in particular, are likely to be an important factor, especially when discussing land use change, as changes in land use are likely to be accompanied by changes in ownership. Thus, land value may act as an important control on land use and land use change, though the argument can be made that the factors discussed here may themselves impact land values. This complexity makes forecasting future land use trends with a high level of specificity and accuracy rather difficult. However, based on the trends displayed by past land use change, it appears likely that landscape position will continue to influence broad trends in the distribution of land use change within the LTRB.

Implications for broader ecohydrological and biogeochemical processes

Our results support the hypothesis that both natural and anthropogenic variables exert a strong influence on the distribution of land use and patterns of land use change in the LTRB. The strong association of terrain characteristics (e.g. slope and elevation) with certain land use classes and land use change is especially important to consider in the context of hydrological, ecological and biogeochemical processes in headwater regions. Precipitation in this region is highly variable in response to elevation with higher precipitation more common at higher elevations [*Kloeppel et al*., 2003]. Slope plays an important role in determining the magnitude and direction of water fluxes, both on the surface and in the subsurface by establishing energy gradients across the landscape [*Zevenbergen and Thorne*, 1987] and by influencing the partitioning of precipitation into groundwater recharge and runoff [e.g. *Scanlon et al.*, 2005]. Though pasture and residential land uses can be found at relatively high elevations within the LTRB, the overwhelming majority of these land uses occur in lower elevation landscape positions (Table 2.1, Table 2.2, Figure 2.2). Similarly, residential land use and pasture are somewhat uncommon on steeper slopes (Table 2.1, Table 2.2), exhibiting a tendency to be focused in lower slope landscape positions (Figure 2.2). As a result of the relation between land use and landscape position, understanding the water balance for these land uses in the southern Appalachian Mountains requires simultaneous consideration of direct land use effects (e.g. modified infiltration, evapotranspiration, interception, etc.) and the influence of landscape position. Additionally, by impacting hydrologic processes the distribution of each land use class may in turn influence biogeochemical and ecologic functioning through variations in runoff generation, water availability, nutrient transport, and potentially other processes. Important ecological characteristics have also been shown to be related to landscape structure in the LTRB. In particular, patterns in the composition and structure of vegetation within this region have been correlated with topographic variables [*Day and Monk*, 1974; *Bolstad et al*., 1998]. Through the link between landscape position and land use distribution, different classes of land use can be expected to demonstrate different ecological characteristics regardless of the magnitude of land surface modification. As with hydrologic and ecologic considerations, biogeochemical functioning within the LTRB is also related to landscape structure. Variation in both nitrogen [*Knoepp and Swank*, 1998] and carbon [*Bolstad and Vose*, 2001; *Garten and Hanson*, 2006] biogeochemical processes have been previously correlated with variation in landscape structure in the study area. Future investigations of LUC and hydrological, ecological and biogeochemical processes in the LTRB and similar headwater regions should consider the influence of landscape position and structure on hillslope function in addition to the direct effects of land surface modification.

Conclusion

The goal of this paper was to answer three questions concerning the distribution of LUC. Which factors most influence the distribution of land use, and does the relative influence vary among land use classes? Is there a coupling of these natural and anthropogenic variables resulting in a stronger influence than either category alone exerts? Do patterns of land use change through time reflect the combined influence of natural and anthropogenic factors on the distribution of land use? To answer these questions a case study approach focusing on land use change between 1986 and 2006 in the LTRB of the southern Appalachian Mountains was applied. This study included assessments of both natural and anthropogenic variables that were considered likely to have an influence on the distribution of land use and land use change. Statistical comparisons and a fuzzy c-means clustering analysis were used to associate differences in the distribution of land use with natural and anthropogenic variables. Analysis of frequency distributions of each landscape position variable for the areas undergoing land use change identified a tendency for land use change to be highly focused in a narrow change of landscape positions.

The distribution of land use in the LTRB is influenced by both natural and anthropogenic variables (elevation, slope, and road distance). However, a land use suitability indicator (*LUSI*) combining all three variables proved to be the strongest metric for discerning differences in the distribution of each land use class. This observation indicates that the combined effect of natural and anthropogenic variables is greater than the effect of individual variables. The same variables also have had an impact on the distribution of land use change in the LTRB between 1986 and 2006, with the majority of changes in land use being concentrated in areas under 750 m in elevation, on slopes less than 16°, within 1.8 km of major roads, and with LUSI values under 16 (relatively gentle and accessible terrain). The relationship between landscape position and the distribution of LUC may result in different forms of land use exhibiting different behavior in terms of hydrological, ecological and biogeochemical processes.

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Chapter 2 Tables

Table 2.1. Land use class distribution statistics.

	Full basin median, IQR	Forest median, IQR	Pasture median, IQR	Residential median, IQR
Elevation (m)	823, 336	887, 318	652, 37	671, 229
Slope (°)	19.2, 15.8	22.0, 13.7	5.5, 6.8	9.7, 10.7
Road Dist. (km)	2.1, 2.7	2.4, 2.7	1.3, 1.8	0.8, 1.6
LUSI	17.4, 9.5	18.9, 7.6	7.8, 5.7	10.5, 7.7

Table 2.2. Land use distribution KS-test results.

	Forest/Pasture KS stat.	Forest/Res KS stat.	Pasture/Res. KS stat.	Sum of KS stat.
Elevation	0.71, $p<0.0001$	0.45, $p<0.0001$	0.26, $p<0.0001$	1.42
Slope	0.66, $p<0.0001$	0.47, $p<0.0001$	0.24, $p<0.0001$	1.37
Road Distance	0.27, $p<0.0001$	0.36, $p<0.0001$	0.17, $p<0.0001$	0.8
LUSI	0.69, $p<0.0001$	0.51, $p<0.0001$	0.23, $p<0.0001$	1.43

Table 2.3. Level of agreement between land use classes and clustering results.

	Level of Agreement			
Cluster	*Forest*	*Pasture*	*Residential*	Range
Elevation-1	15%	2%	11%	794 – 1038 m
Elevation-2	26%	3%	17%	1039 – 1650 m
Elevation-3	36%	93%	65%	537 – 793 m
Slope-1	46%	21%	27%	0 – 12 °
Slope-2	20%	86%	66%	13 – 25 °
Slope-3	35%	2%	7%	26 – 72 °
Road Distance-1	3%	6%	3%	4.2 – 9.3 km
Road Distance-2	41%	25%	19%	1.8 – 4.2 km
Road Distance-3	42%	69%	78%	0 – 1.7 km
LUSI-1	33%	2%	6%	21 – 51
LUSI-2	51%	13%	28%	13 – 20
LUSI-3	21%	85%	66%	0 – 12

Chapter 2 Figures

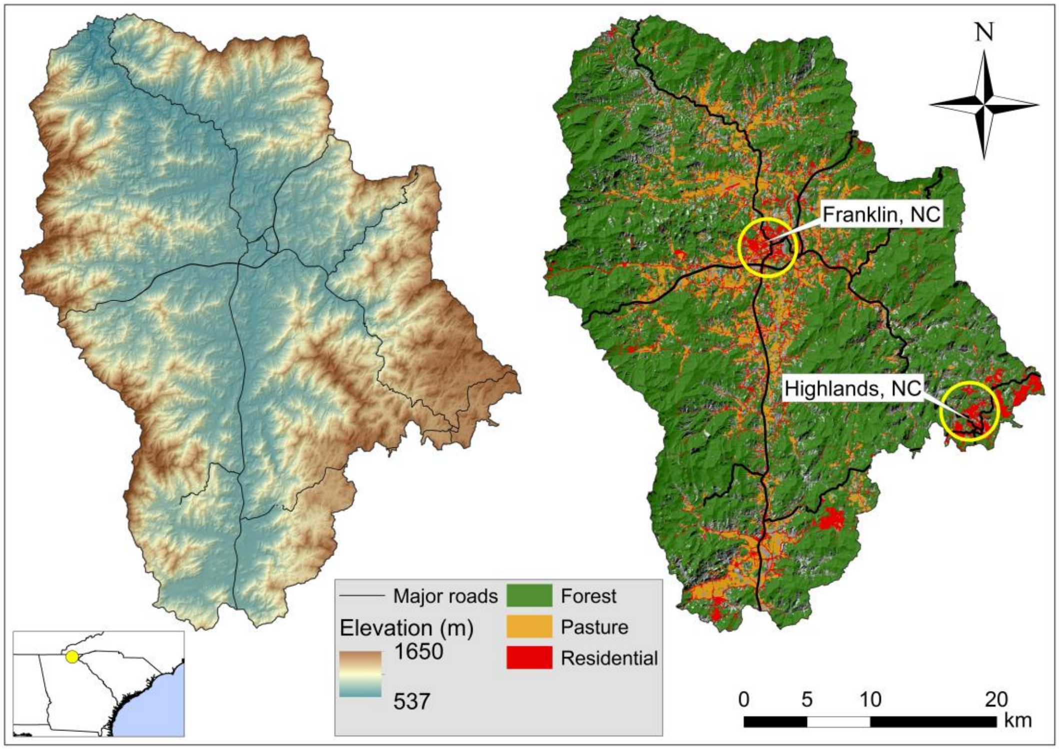

Figure 2.1. Elevation and the distribution of deciduous forest, pasture, and residential land uses within the LTRB. Major populated areas and primary roads within the basin are also shown for contextual purposes.

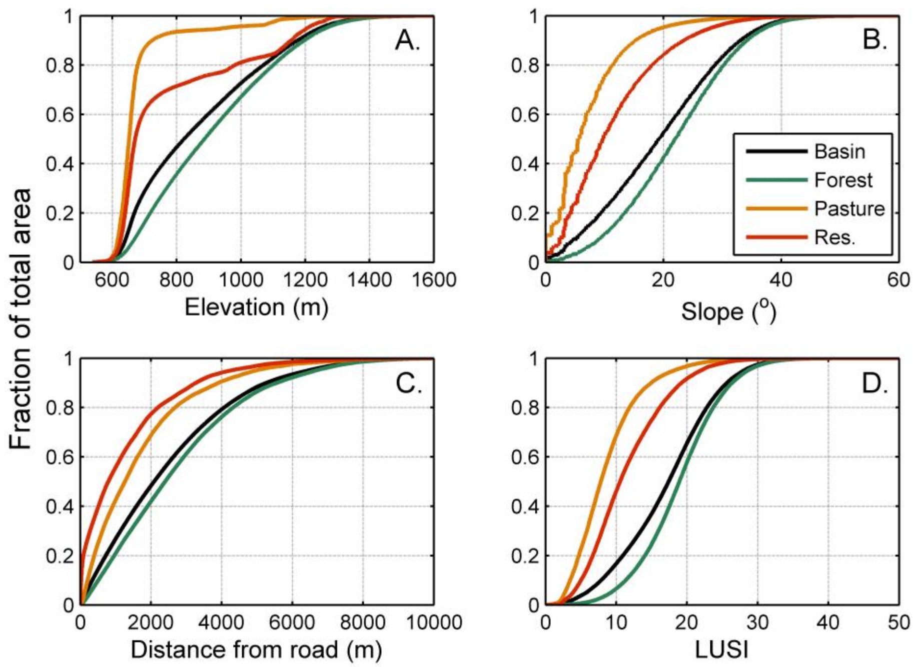

Figure 2.2. Frequency distributions of the landscape variables identified in Table 1 as significantly different among land uses. The distributions of elevation (A), slope (B), Road Distance (C) and *LUSI* (D) are shown for forest (green), pasture (yellow) and residential (red) land uses as well as for the entire basin (black).

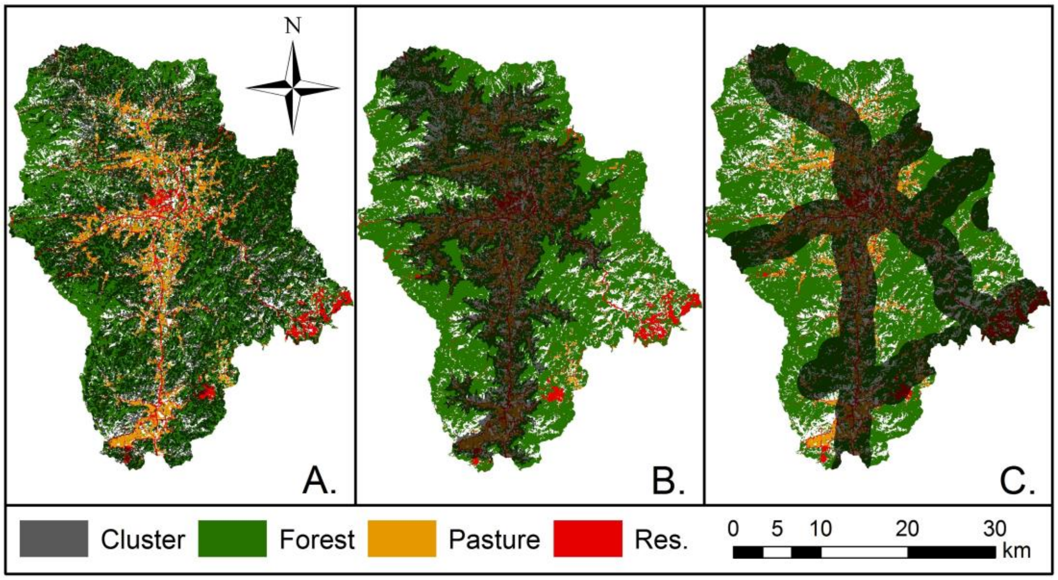

Figure 2.3. FCM clusters containing the highest fraction of each land use. Fifty-one percent of forest area is contained within cluster LUSI-2 (A). Ninety-three percent of pasture area is contained within cluster Elevation-3 (B). Seventy-eight percent of residential area is contained within cluster Road Distance-3 (C).

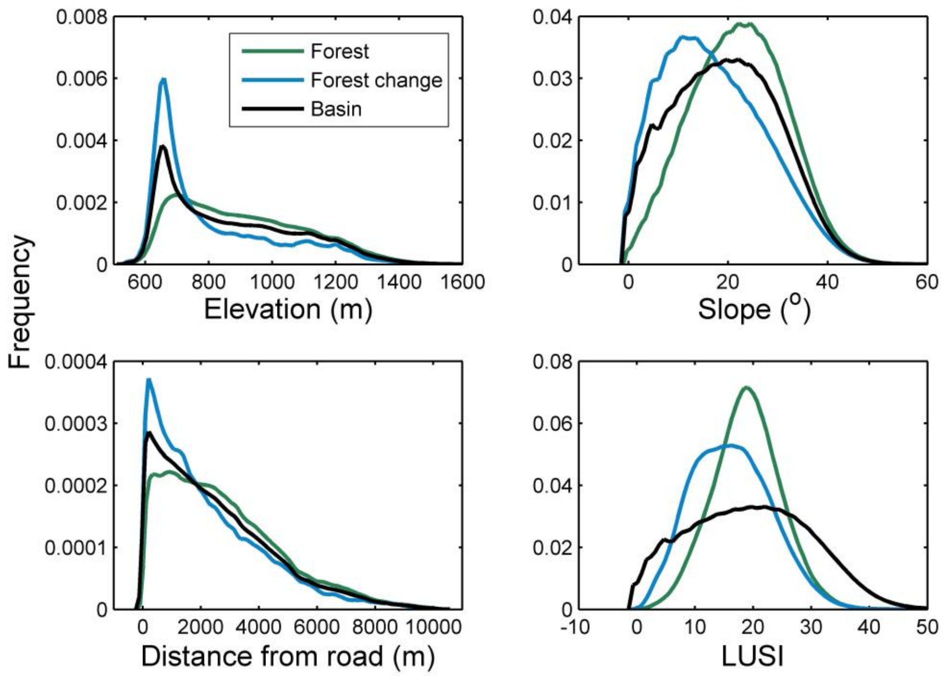

Figure 2.4. Frequency distributions of each landscape position variable within the total area occupied by forest land use in 2006 (solid green line), forest areas experiencing land use change between 1986 and 2006 (solid blue line), and the entire LTRB (solid black line).

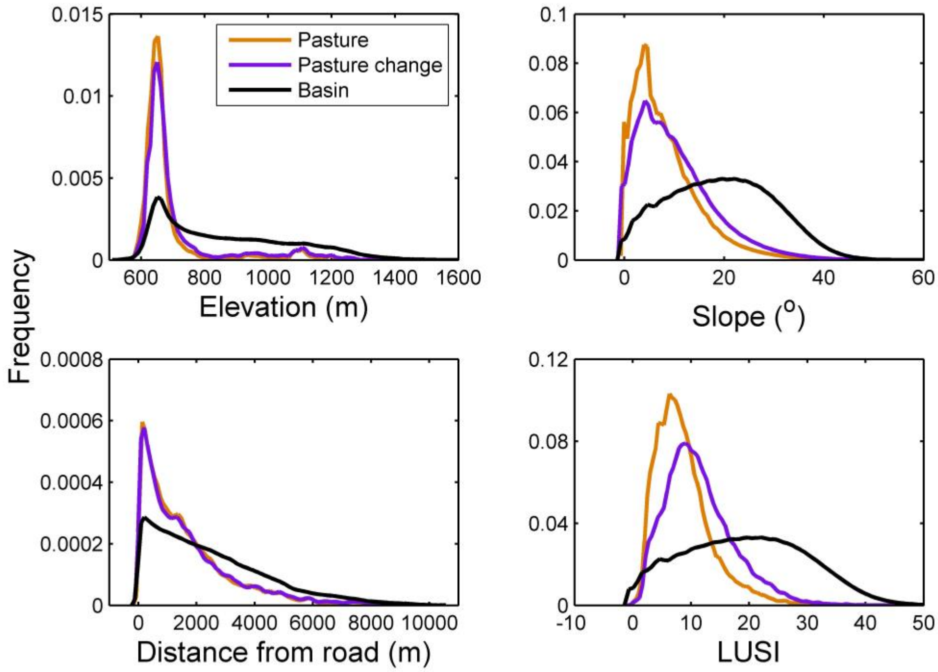

Figure 2.5. Frequency distributions of each landscape position variable within the total area occupied by pasture land use in 2006 (solid orange line), pasture areas experiencing land use change between 1986 and 2006 (solid purple line), and the entire LTRB (solid black line).

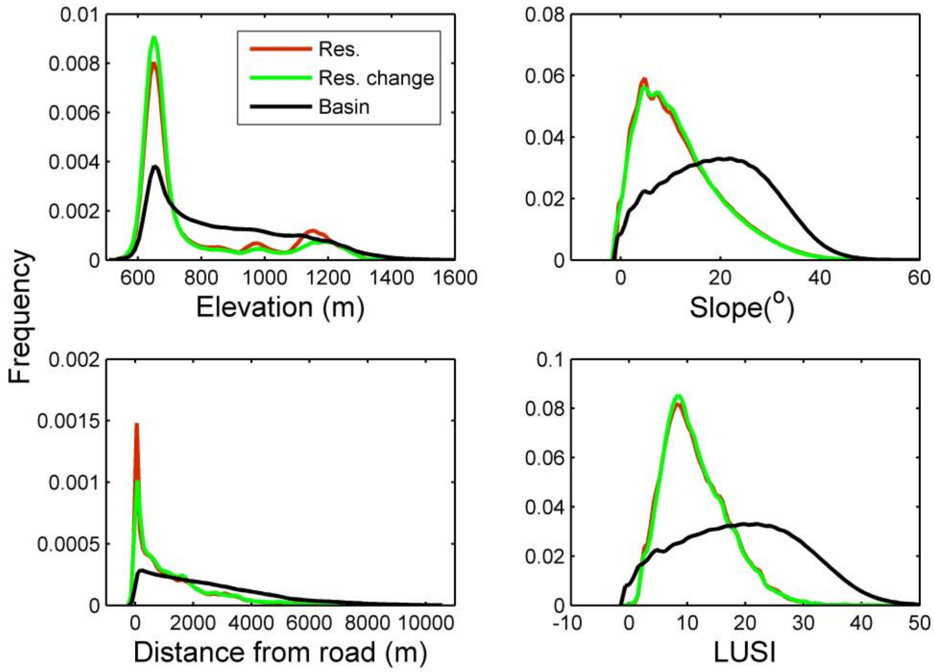

Figure 2.6. Frequency distributions of each landscape position variable within the total area occupied by residential land use in 2006 (solid red line), forest areas experiencing land use change between 1986 and 2006 (solid lime green line), and the entire LTRB (solid black line).

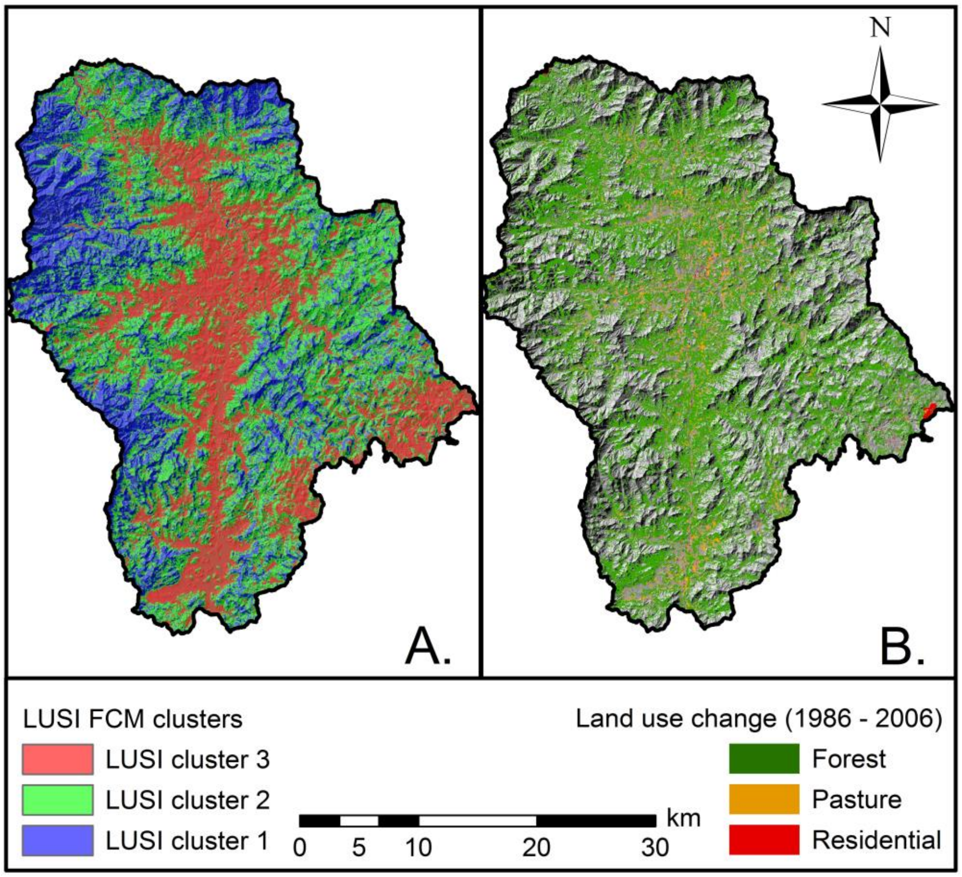

Figure 2.7. The output FCM membership matrix resulting from the entire LTRB coverage of the created *LUSI* variable is shown as a false color RGB image (panel A). Cluster three, gentle terrain and high accessibility, is assigned to the red band. Cluster two, moderate terrain ruggedness and accessibility, is assigned to the green band. Cluster one, highly rugged terrain and low accessibility, is assigned to the blue band. Panel B shows the spatial distribution of land use change occurring between 1986 and 2006 for each land use class.

CHAPTER 3: EXAMINATION OF PHYSICAL HYDROLOGY: A MANUSCRIPT PREPARED FOR SUBMISSION TO THE JOURNAL *WATER RESOURCES RESEARCH*

Altered runoff generation in southern Appalachian Mountain headwaters through land use related impacts on the water balance.

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Abstract

Runoff in mountain headwater catchments provides essential supportive flow for downstream channel networks and affects nutrient dynamics and biodiversity. As human land use expands into mountain headwater catchments, the influence of land use on runoff generation in these areas needs to be considered. We examine this potential influence using a case study approach focused on the two dominant land use types, deciduous forest (forest) and pasture agriculture (pasture), in the Little Tennessee River Basin (LTRB) within the southern Appalachian Mountains. Monitoring of shallow groundwater levels at sites dominated by each land use type was used to analyze patterns in hydrologic connectivity, water table elevation variability, and specific discharge. Forest hillslopes exhibited a strong tendency to remain in a disconnected state, whereas pasture hillslopes remained fully or partially connected for the entire period of the study (August 2011 – November 2012). During the same time period, monthly water table variability, as measured using a flashiness index, was an order of magnitude greater on pasture hillslopes than forest hillslopes. Pasture hillslopes also display increased variability in specific discharge than forest hillslopes. Consideration of these observations in the context of precipitation and evapotranspiration indicates a decoupling of the expected relationship between local climate and runoff generation. Our results suggest that land use may impact the water balance by altering the partitioning of infiltrating water into the various pools and fluxes present in the hillslope subsurface, raising important implications for runoff generation and nutrient dynamics both in headwater catchments and downstream reaches.

Keywords: headwaters, runoff, land use, water balance, connectivity, flashiness

Introduction

Mountainous regions occupy a crucial place in the water cycle, both by acting as the origin for many major river systems and by acting as "water towers" for adjacent lowlands in much of the world [*Messerli et al*., 2004; *Viviroli et al*., 2007]. Mountain headwater catchments are of particular importance due to their critical role as the origin of channel networks, as well as their involvement in nutrient cycling and the support they provide for biodiversity [*Gomi et al.*, 2002]. As human activity leads to a rapid decline in the areas of land that can be considered undisturbed it becomes increasingly important to undertake research that acknowledges the human influence on natural systems [*Palmer et al*., 2004].

Increased understanding of human activity's potential influence in headwater catchments is needed due to the tight coupling of hillslope scale processes, headwater stream reaches and increased variability in conditions, relative to higher order reaches [*Gomi et al.*, 2002].

Of the various activities undertaken by human society that impact the natural systems of our planet, land use is perhaps the most substantial [*Vitousek et al*., 1997; *Foley et al*., 2005]. It has even been suggested that the environmental consequences of land use may even outweigh those of climate change [*Sala et al*., 2000; *Vorosmarty et al*., 2000]. Through modifications of the land surface, land use directly alters ecosystem functioning and can cause changes in the water balance at large scales [*Vitousek et al*., 1997; *Foley et al*., 2005]. Understandably, the hydrologic influence of land use has been identified as an important area of interdisciplinary water-oriented research for the future [*DeFries and Eshleman*, 2004; *NRC*, 2012]. The potential effects of land use on the water cycle, particularly the partitioning of precipitation into other pools and fluxes, suggests that land use may impact the water balance at smaller scales, such as individual hillslopes.

Issues related to the scaling of knowledge concerning runoff generation from individual catchments up to larger areas have been, and remain, an unresolved problem in hydrology [*McGlynn et al*., 2004]. The relative lack of insight into the generalized factors that influence runoff generation at the hillslope scale contributes to difficulties in the scaling up of understanding from the hillslope to larger scales [*Bachmair et al*., 2012]. The high level of heterogeneity between individual hillslopes has proven to be a frustrating obstacle for efforts to gain this holistic, generalized knowledge [*Bachmair et al*., 2012]. As land use can be a major source of heterogeneity within watersheds, we argue that examining the role of land use is an important step in gaining broad, scalable, insight into hillslope scale runoff generation.

Consideration of the capability of land use to influence runoff begins with the water balance. For any given point in the subsurface of a hillslope the water balance (modified from *Scanlon et* al., 2005 and Emanuel *et* al., 2010) can be used to describe the relation between fluxes as:

$$\frac{dV}{dt} = I - R_z - R_l - ET \tag{1}$$

where *V* is the volume of water present, *I* is infiltration, R_z and R_l are the vertical and lateral components of subsurface runoff, and *ET* is evapotranspiration. The relationship in equation 1 begins with precipitation. During and after storm events, infiltrating rainfall leads to an increase in storage followed by a response in other fluxes from equation one [*Sklash and Farvolden*, 1979; *Seibert et al*., 2003]. As this response influences subsurface discharge it also influences the generation of runoff as water leaves a hillslope [*McGlynn et al*., 1999]. By observing how a portion of the system (e.g. groundwater) behaves over time inferences about the functioning of the hillslope can be made. Considering these observations in the context of the hydro-climatologic setting, or water supply (precipitation) and atmospheric demand (potential evapotranspiration), conclusions can be drawn about the potential influence of land use on runoff generation via disruptions of the water balance. It is important to note that while potential evapotranspiration (PET) is dependent on atmospheric demand and is not linked to land use; actual evapotranspiration (AET) will be affected by differences in vegetation [*Zhang et al*., 2001; *Emanuel et al.*, 2007; *Emanuel et al.*, 2010], and thus land use.

The primary focus of this paper will be to examine the role land use plays in affecting the partitioning of incoming precipitation into the terms in equation one, particularly the vertical and lateral components of subsurface runoff. We hypothesize that land use exerts an influence on hillslope-scale runoff generation by affecting the partitioning of infiltrating water into vertical runoff (R_z), lateral runoff (R_l), and *ET*. To gain insight into the partitioning of water infiltrating the hillslopes used in this study, and how it is impacted by land use, we compare three characteristics of subsurface runoff generation: hydrologic connectivity, flashiness (i.e. temporal variability), and specific discharge. Hydrologic connectivity occurs when portions of the landscape (e.g. near stream and upper hillslope areas) are linked via the development of a persistent water table extending across these landscape units [*Jencso et al*., 2009]. Connectivity has been identified as an important factor in driving runoff generation and has been used as a metric to describe hydrologic behavior [*James and Roulet*, 2007; *Jencso et al*., 2009; *Michaelides and Chappell*, 2009; *Jencso et al*., 2010]. Not only does connectivity facilitate runoff at the hillslope scale, but it also has implications for nutrient export and water quality [*Stieglitz et al*., 2003; *Ocampo et al*., 2006; *Jackson and Pringle*, 2010].

Flashiness is a characteristic typically used to describe stream discharge, but here the term is adopted to describe temporal variability shallow subsurface flow. *Baker et al.* [2004] developed an index based on average daily flow to quantify and compare variability among different hydrographs. This index, or a modified version of it, has been used in past studies illustrating the influence of runoff variability on both ecological conditions and nutrient transport [*Royer et al*., 2006; *Vink et al*., 2007; DeGaspari *et al*., 2009; Sudduth *et al*., 2011; *Violin et al*., 2011]. Within the hillslope system it is possible to apply the same measure of flashiness to temporal fluctuations in shallow groundwater elevation. Similarly, specific discharge is used to examine variation in the actual rate of discharge from a section of a hillslope based on hydraulic conductivity and hydraulic gradient.

In this paper, we apply a case study approach to investigate the influence of land use on hillslope scale runoff generation within the Little Tennessee River Basin (LTRB) of the southern Appalachian Mountains. The LTRB is home to both the Coweeta Hydrologic Laboratory and Coweeta Long-Term Ecological Research (LTER) program. An important characteristic of this area is its history of nearly continuous human land use at least since the mid 1800's [*Gragson and Bolstad*, 2006]. Between the mid 1800's and early 1900's much of the region was subjected to extensive forest clearing for timber harvesting and conversion to agricultural land [*Ayres and Ashe*, 1905; *Williams*, 1989]. The unsuitability of many locations for agriculture resulted in abandonment followed by natural reforestation [*Turner et al*., 2003]. The extensive mixed hardwood deciduous forests that now dominate the region are the result of this reforestation [*Kloeppel et al*., 2003]. Based on the most recent land use data available (2006), the two dominant land use types (by area) in the LTRB are forests dominated by mixed, deciduous hardwoods (referred to hereafter as forest) and short-grass dominated pasture (referred to hereafter as pasture). The focus of this paper will be to increase understanding of the influence that these two forms of land use, forest and pasture, have on subsurface runoff generation at the hillslope scale in the LTRB. This process will involve addressing several questions. Does land use exert an observable difference in patterns of runoff generation at the hillslope scale? If so, how does this influence relate back to the water balance and what are the implications of this influence?

Methods

The LTRB is located primarily in Macon County, North Carolina with a small portion extending into northern Georgia (Figure 3.1). This basin has an area of 1125 km^2; climate in the region is relatively mild and is classified as marine, humid temperate [*Swift et al*., 1988]. Average annual precipitation in the area ranges from ~1800 mm at lower elevations to nearly 2400 mm along high ridgelines [*Kloeppel et al*., 2003]. The region is characterized by heterogeneous mountain topography, with elevations ranging from 537 m to 1650 m, and slope values ranging from 0° to 72°. The main populated areas within the basin are the towns of Franklin, NC and Highlands, NC.

Four hillslopes within headwater catchments of the LTRB, two forested (F1 and F2) and two pasture (A1 and A2), were selected as study sites with instrument installation beginning in the summer of 2011. The study hillslopes all occupy areas less than 1 hectare (10000 m^2) and have slopes of 30° or less (Table 3.1). Each hillslope was instrumented with three shallow groundwater wells, consisting of slotted, 2 inch PVC pipe installed to the depth of bedrock. Wells were installed in a transect perpendicular to the stream (Figure 3.2). Transects have one well each in the near stream, low, and upper hillslope positions. Well locations were referenced using a mapping grade GPS receiver (Model GeoXT, Trimble Navigation Ltd., Sunnyvale, CA, USA). Well elevations were determined using a laser surveying system (Model ALH, CST/Berger, Watseka, IL, USA) and an arbitrary datum set as the midpoint of the streambed at the base of each hillslope. Groundwater level in each well was recorded every 10 minutes between August 2011 and November 2012 using a pressure transducer (Model CS450, Campbell Scientific, Logan, UT, USA). Meteorological data for sites F2, A1, and A2 were recorded over the same time period using an evapotranspiration monitoring station installed at each hillslope (Model ET107, Campbell Scientific, Logan, UT, USA). Meteorological data for site F1 were obtained from a U.S. Forest Service climate station, roughly 400 m west of the hillslope, operated by the Coweeta Hydrologic Laboratory in Otto, NC. Saturated hydrologic conductivity (K) within the shallow water table was determined at each well during June and July of 2012 using the *Hvorslev* [1951] method of interpreting water level recovery after rapid withdrawal of water from the well. Only K values from the near stream positions were used in subsequent analyses as a persistent water table was only present in the near stream positions of the forested sites, preventing determination of K in other hillslope positions.

Because variation in the inputs of precipitation to the hillslopes could potentially lead to variations in runoff generation, patterns in rainfall received by each hillslope between August 2011 and November 2012 were examined. Using hourly observations of total precipitation at each site the following characteristics of precipitation were considered: number of storms, storm arrival times (time between one storms arrival and the arrival of the next storm), storm interval length (length from the end of one storm to the beginning of the next storm), storm duration, storm depth, storm intensity, and total monthly precipitation. Calculation and analysis of rainfall characteristics were completed using MATLAB.

To account for atmospheric influences on observed differences between hillslope responses to precipitation, estimated daily PET was calculated for each site following the *Hamon* [1963] method. The Hamon method is a temperature based approach to calculating PET and uses the following equations:

$$PET = 0.1651 * L_{day} * \rho_{sat} \tag{2}$$

$$\rho_{sat} = \frac{216.7 * e_s}{T + 273.3} \tag{3}$$

$$e_s = 6.108 * e\hat{}\left(\frac{17.26 * T}{T + 273.3}\right) \tag{4}$$

where PET = daily potential evapotranspiration (mm), T = daily mean air temperature (°C), L_{day} = daytime length, or time from sunrise to sunset in multiples of 12h, ρ_{sat} = saturated vapor density, and e_s = saturated vapor pressure at the given value of T. Equation (3) is derived from *Murray* [1967] and allows air temperatures to fall below 0°C, essential for accurate estimates in this region where winter air temperatures less than 0°C regularly occur. Previous work in the area [e. g. *Rao et al*., 2011] has suggested the Hamon method for calculating PET underestimates actual evapotranspiration (AET) in forested areas of this region. However, our goal was not to model AET, but to estimate atmospheric demand for water among sites; thus, this method was considered appropriate. A one sample KS test indicated that none of the PET datasets conformed to a normal distribution ($p<0.001$), and non-parametric methods were used to test for a statistically significant difference in estimated mean monthly PET among study sites. Calculation of PET and statistical analyses were completed using MATLAB.

Based on an adaptation of the methods used by *Jencso et al*. [2009], groundwater level data from each site were used to assess temporal patterns of hydrologic connectivity. Three potential states of connectivity in which a hillslope could exist were considered: disconnected, partially connected, and fully connected, and the length of time each hillslope spent in a given state was determined. The disconnected state was defined as occurring when a persistent water table existed only at the near stream well position and not at the low hillslope or upper hillslope positions. Partial connectivity required the presence of a persistent water table at the near stream and low hillslope positions, but not the upper hillslope position. Full connectivity occurred if a persistent water table was present at all three positions. The fraction of time each hillslope spent in a given state was calculated using MATLAB (R2012a, Mathworks, Inc., Natick, MA, USA).

Patterns in flashiness of groundwater at each hillslope site were investigated using a modified version of the index outlined in *Baker et al*. [2004] following the form:

$$F = \frac{\sum_{i=1}^{n} |\gamma_i - \gamma_{i-1}|}{\sum_{i=1}^{n} \gamma_i} \qquad (5)$$

where F is the calculated flashiness index value, γ is the mean daily groundwater level, based on 10 minute observations and *n* is the number of hours under consideration. Rather than derive a single value for flashiness for the entire data record, daily flashiness values were summed for each month where data were available, creating a monthly flashiness data set where a high flashiness value indicates highly variable behavior. Using monthly flashiness index values allows the data to reflect the seasonal variations in ambient conditions. A one-sample Kolmogorov-Smirnov (KS) test indicated that flashiness data do not conform to a normal distribution ($p<0.001$), so non-parametric statistical measures and tests were used to compare flashiness among sites. Variability was further examined using a record of specific discharge (*q*) calculated using Darcy's law:

$$q = -K\frac{dh}{dl} \tag{6}$$

where *K* is the saturated hydraulic conductivity in the shallow water table at the riparian position of each site and $\frac{dh}{dl}$ is the hydraulic gradient between the riparian well and the streambed. Hydraulic gradient was determined using the results of surveying to convert water table depth to water table elevation relative to the streambed (*dh*) and GPS data to calculate the horizontal distance of each near stream well from the arbitrary streambed datum (*dl*). The use of the streambed was considered an appropriate point of reference for calculating *dh* because the streams in question are shallow, with average depth never greater than approximately 10 cm. Calculation of flashiness index and specific discharge data and the subsequent graphical and statistical analyses were conducted using MATLAB.

Results and Analysis

Differences in rainfall patterns and PET between each site are of particular interest as these variables represent important portions of the water balance, and are thus linked to runoff generation. Between 10/1/11 and 9/30/12 monthly rainfall totals at the study sites vary significantly based on results of the Kruskal-Wallis test ($p = 0.0011$, Figure 3.3). During this time period, site F1 received over 2000 mm of total rainfall and experienced a mean storm intensity of 3.5 mm/hr (Table 3.2, Figure 3.3). With the exception of June and August 2011, site F1 displays substantially higher monthly rainfall totals than other study sites. During the same time period site A1 only received 850 mm of rainfall with a mean storm intensity of 1.0 mm/hr. Of all the study sites, site A1 consistently receives the lowest monthly rainfall totals during the time period in consideration. Sites F2 and A2 were assumed to be subject to the same precipitation events as they area approximately 400 m apart from each other. From 10/1/11 to 9/30/12, sites F2 and A2 received 1400 mm of total rainfall and the mean storm intensity at these sites was 1.5 mm/hr. Monthly estimates of PET from each site did not exhibit a significant difference based on results of the Kruskal-Wallis test ($p = 0.91$, Figure 3.3). Because these sites are all within 30 km of one another and lie within a fairly narrow range of elevations ($\pm$ 200 m), similar ambient air temperatures, and thus PET estimates are to be expected.

When considering fluctuations in the shallow water table on each hillslope, a difference between the behavior on pasture and forest hillslopes is clearly observable (Figure 3.4). The shallow water table on each pasture hillslope displays regularly occurring peaks followed by tails; similar to what might be expected from a traditional hydrograph (Figure 3.4). Despite receiving significantly more precipitation than the other study sites (Table 3.2, Figure 3.3), site F1 shows a heavily muted water table response. The site that received the least rainfall during the study period, site A1, exhibits the most responsive water table, with notably more frequent and larger peaks than the other study sites (Figure 3.4). Additionally, strong diurnal fluctuations can be seen in the water table of site A1 during the summer of 2012 that are not observed on the other study hillslopes (Figure 3.4). Comparison of the shallow water table time series from sites F2 and A2 also show a muted response on the forest hillslope, despite these two sites experiencing the same storm events and having the same rainfall characteristics (Table 3.2, Figure 3.3).

Patterns in hydrologic connectivity of shallow groundwater exhibit distinct variations when comparing pasture and forest land use sites (Figure 3.5). Analysis of connectivity showed site F1 existing in the disconnected state 94% of the total record, the partially connected state 4% of the record, and the fully connected state 2% of the record. Full connectivity at site F1 occurred over a single continuous period of 11 days during February 2012 (Table 3.3). Partial connectivity at site F1 was also observed over a single continuous period, occurring over a period of 21 days during January 2012 (Table 3.3). Site F2 existed in the disconnected state for 100% of the data record. Pasture site A1 remained in the fully connected state 100% of the record. Pasture site A2 was fully connected 57% of the record and partially connected 43% percent of the record. Partial connectivity at site A2 was observed over several periods, ranging from several days to slightly over one month, during the spring and summer of 2012 (Table 3.3). In general, forest sites have a tendency to exist almost exclusively in the disconnected state while pasture sites always have some level of connectivity, either partial or full. Deviations from the disconnected state on forested hillslopes only occurred during winter months and deviation from full connectivity on pasture hillslopes only occurred during the spring and summer months.

Considering observations of patterns in connectivity in relation to precipitation and PET places them into the context of the water balance. Monthly connectivity, defined as the state of connectivity a site spent the majority of each month in, is shown as a function of precipitation and PET in Figure 3.6. During each month of the study where data were available at each location, sites F1, F2, and A2 remain in a potentially water-rich (precipitation > PET) state. Site A1 is the only site that displays both potentially water-rich and water-limited (precipitation < PET) monthly states. With the exception of a brief period during early 2012 at site F1, each forest site remains disconnected despite the potential for a water surplus based on precipitation and PET (Figure 3.6). Site A2 exhibits less surprising behavior given the water-rich state it tends to exist in, remaining at least partially connected throughout the study (Figure 3.6). As the only site spending time in a potentially water-limited state, site A1 could be expected to fluctuate between states of connectivity. However, site A1 remains in the fully connected state regardless of whether conditions create a possible water surplus or deficit (Figure 3.6).

Application of a flashiness index (equation 5) to mean daily water table elevation allows shallow groundwater variability to be quantified and examined with a unitless index.

Analysis of shallow groundwater flashiness for each site shows a sizable difference between the two land use classes. Forested sites had monthly flashiness index medians of 0.0023 (F1) and 0.0033 (F2). The interquartile range (IQR) for forested site flashiness was 0.0017 (F1) and 0.0027 (F2). Pasture sites had monthly flashiness index medians of 0.0165 (A1) and 0.0134 (A2), and an IQR of 0.0130 (A1) and 0.0142 (A2). Overall pasture site flashiness medians and IQRs are both an order of magnitude greater than the forest site counterparts. Similar to connectivity, examining flashiness in relation to precipitation and PET provides context for the observed patterns in shallow groundwater behavior (Figure 3.7). At any given potential water availability condition, forest sites exhibit a tendency towards reduced flashiness as well as less variation in flashiness than pasture sites (Figure 3.7). Even during periods of potential water deficit, pasture site A1 displays a higher level of flashiness than the maximum of forest sites during water rich periods. Interestingly, observations of flashiness at site A1 do become substantially more consistent during water limited times than during periods of potential water surplus.

Median specific discharge values at the study sites vary somewhat, from a low of 0.069 cm/hr at site A2 to a high of 0.102 cm/hr at site F1. Site A1 and F2 have very similar median specific discharges falling roughly in the center of the range formed by the values from site A2 and F1. Median specific discharge for sites A1 and F2 were both 0.083 cm/hr. Although a distinct pattern in median specific discharges between land use classes is not clear, examination of the IQRs for specific discharge does show a clear difference between the land uses. The specific discharge IQRs for sites F1 and F2 were 0.0032 cm/hr and 0.0015 cm/hr, respectively. Each pasture site had a specific discharge IQR notably larger than the forested sites, with site A2 having an IQR more than 30% greater (0.0043) than the greatest forest site IQR (site F1) and site A1 having an IQR an order of magnitude greater than either of the forested sites (0.0143 cm/hr). As with connectivity and flashiness, considering the relationship between specific discharge, PET, and precipitation aids in placing physical observations in the context of the water balance (Figure 3.8). Though clear patterns in median specific discharge rates are not observed when comparing forest and pasture sites, the variability in specific discharge rates between land uses does vary in the context of precipitation and PET. Throughout the range of potential water-rich conditions observed, pasture sites display substantially higher variability in specific discharge rates than forest sites (Figure 3.8).

Discussion

Does land use exert an observable difference in patterns of runoff generation at the hillslope scale?

Individual hillslopes act as systems routing the movement of water by providing the pathways that water follows as it moves through the landscape as various components of the water balance. The primary goal of this paper was to consider whether or not there is evidence of land use influencing the subsurface runoff component of the water balance within these hillslope systems. Physical data does suggest that a link exists between land use and subsurface hillslope runoff. Shallow groundwater on forest and pasture land use hillslopes exhibits substantially different patterns in connectivity, overall variability, and fluctuations in specific discharge from near stream areas. When considered in the context of the water balance, data indicate that the routing, or partitioning, of rainfall as it moves into and through hillslopes follows distinctly different paths on forest and pasture hillslopes. The difference in the partitioning of infiltrating rainfall forces water to follow different pathways as it enters, moves through, and leaves forest and pasture hillslopes.

Physical interpretation of observations

Reduced connectivity on forest hillslopes relative to pasture hillslopes indicates a difference in the spatial extent of shallow groundwater on the same hillslopes. Relative to the disconnected state, the partially and fully connected states require that the shallow water table extend over a larger portion of a hillslope. This means that the partially and fully connected states require the presence of a larger active hillslope area [e.g. *Hewlett and Hibbert*, 1976] than the disconnected state. For this to occur, infiltrating precipitation must reach the water table and either maintain its current extent, if the hillslope is in the partially or fully connected state, or extend it, if moving from a state of lower to higher connectivity. Based on this reasoning, several possible causes could result in the observed differences in connectivity between forest and pasture hillslopes. If the routing, or partitioning, of infiltrating rainfall functions similarly between hillslopes than variability in water supply should drive connectivity; increases in potential water supply will translate to increased connectivity and vice versa. It is also possible that differences in how water entering the hillslope is partitioned among the various pools and fluxes present may produce a decoupling of patterns in connectivity from the hydro-climatic setting. Consideration of patterns in connectivity in the context of potential water supply (Figure 3.6) indicates that the second explanation, a decoupling of connectivity from the hydro-climatic setting, may be the more plausible explanation. Despite having the largest potential surplus of available water of all the study sites, and receiving significantly more rainfall than other sites (Table 3.2, Figure 3.3), forest site F1 remains disconnected throughout the study with the exception of a brief period during the winter of 2012 (Table 3.3, Figure 3.6). The opposite behavior is displayed by pasture site A1. Site A1 receives significantly less rainfall than any other study site (Table 3.2, Figure 3.3), yet remains fully connected throughout the study, even during potentially water limited periods (Figure 3.6). Forest site F2 and pasture site A2 are subject to the same storm events due to their close proximity, but show drastically different patterns in connectivity (Figure 3.5, Figure 3.6). Sites F2 and A2 remain in a state of possible water surplus during the entire study, yet site F2 remains disconnected for the entire period where observations are available while site A2 remains either fully or partially connected during the same period (Figure 3.5, Figure 3.6). These observations all suggest that water moving through forest hillslopes is partitioned differently than water moving through pasture hillslopes. Based on patterns in connectivity and the hydro-climatic setting, it is reasonable to conclude that a greater proportion of rainfall infiltrating pasture hillslopes is transferred downward to the water table than on forest hillslopes, leading to increased connectivity on pasture hillslopes relative to forest hillslopes.

Similar to patterns in states of connectivity, groundwater variability, or flashiness requires that infiltrating rainfall reach the water table. Increased flashiness indicates either more infiltrating rainfall being delivered to the water table, or faster delivery of infiltrating rainfall to the water table. If the partitioning of infiltrating rainfall on forest and pasture hillslopes followed similar patterns than the expectation of similar water table behavior, in terms of variability, would be reasonable. However, analysis of shallow groundwater flashiness provides additional evidence that partitioning of infiltrating rainfall into the various pools and fluxes present on a hillslope occurs differently on forest hillslopes than on pasture hillslopes. On the hillslopes used in this study, markedly different behavior of shallow groundwater, in terms of variability in elevation above the streambed, is observed when comparing pasture and forest sites (Figure 3.4, Figure 3.7). Pasture hillslopes display much more variable water table behavior, as measured using a flashiness index, than forest hillslopes. Throughout the study, Site F1, with the highest rainfall totals and constant potential water surplus, displays significantly reduced shallow groundwater flashiness than either pasture site (Figure 3.7). Site A1, the driest site (Table 3.2, Figure 3.3), counter intuitively is also the flashiest site and maintains a higher level of flashiness than either forest site even during potentially water limited periods (Figure 3.7). Despite receiving the same rainfall as site F2, site A2 exhibits significantly higher flashiness than the nearby forest hillslope (Figure 3.7). In general, at a given level of relative water supply (precipitation) and demand (PET) forest sites present reduced levels of flashiness in comparison to pasture hillslopes (Figure 3.7). These points all indicate that pasture and forest hillslopes partition new water into subsurface pools and fluxes differently. If pasture and forest hillslopes are not partitioning inputs differently, than based on rainfall patterns and atmospheric demand, observed trends in flashiness should be the opposite of what they are.

While the argument could be made that water in the subsurface of forest hillslopes simply moves faster due to differences in hydraulic gradient, specific discharge data suggest otherwise. The range of specific discharge values for all sites only varies by a few hundredths of a cm/hr (Figure 3.8). This indicates that the rate at which water is delivered from the hillslope to the stream does not differ greatly from site-to-site and is likely not the cause of observed differences in shallow groundwater behavior. Additionally, during periods of possible water surplus specific discharge on pasture hillslopes is substantially more variable than specific discharge on forest hillslopes (Figure 3.8). This observation again indicates a larger proportion of infiltrating rainfall is being transferred downward to the water table on pasture hillslopes than on forest hillslopes, providing further evidence that pasture and forest hillslopes partition water differently.

Implications

The fact that these results support the hypothesis that land use is capable of influencing runoff generation at the hillslope scale has interesting broader implications. The development of hydrologic connectivity is an important step in the process of transporting nutrients and solutes from upper portions of the hillslope through the riparian zone and into the stream [*Creed et al*., 1996; *Buttle et al*., 2001; *Stieglitz et al*., 2003]. The difference in connectivity between the forest and pasture hillslopes implies that nutrient and solute transport processes may vary among hillslopes dominated by different forms of land use. By influencing hydrologic connectivity, and thus runoff generation, land use in mountain headwater catchments may be capable of impacting ecological conditions and biogeochemical processes further downstream. The difference in water table variability, or flashiness, among land use types may also be important in the context of nutrient transport and downstream conditions. Variability in water table behavior translates into variability in hydraulic gradients, and thus the movement of water and the various solutes it transports from the hillslope to the stream. The relatively consistent water table behavior seen on forest hillslopes, relative to pasture hillslopes, provides an additional mechanism by which land use in mountain headwater catchments can impact downstream conditions.

Conclusion

If the water balance can be thought of as describing the potential pathways water may take as it moves through a hillslope than careful interpretation of observations made in the context of the water balance can provide insight into the functioning of the hillslope system. Differences in hydrologic connectivity as well as patterns in the behavior of groundwater flashiness and specific discharge are readily observable when comparing data from forested and pasture hillslopes. Forested hillslopes exhibit a tendency to exist almost exclusively in a disconnected state whereas pasture hillslopes exist entirely in the partially and fully connected states. Analysis of water table behavior shows that the shallow water table found on forested hillslopes is relatively constant whereas pasture site shallow water tables are much more dynamic, displaying highly variable behavior. A similar pattern can also be observed when examining specific discharge. These results indicate that the physical differences between forest and pasture hillslopes lead to differences in hydrologic functioning and thus differences in the delivery in water from the hillslope to adjacent streams. As the movement of water from hillslopes to streams is an important component of nutrient and solute transport, the observed differences in runoff generation between forest and pasture land uses may have a substantial impact on nutrient and solute transport. These findings indicate that as land use modifies the landscape of mountain headwater catchments it may have broad consequences on local hydrology, ecological conditions, and biogeochemistry that are capable of extending far downstream.

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Chapter 3 Tables

Table 3.1. Study hillslope basic characteristics.

Site	Land use	Area	Mean Slope	Mean elevation
F1	Forest	3400 m^2	26°	874 m
F2	Forest	1800 m^2	30°	811 m
A1	Pasture	9400 m^2	12°	674 m
A2	Pasture	2800 m^2	4°	750 m

Table 3.2. Rainfall statistics from 10/1/11 – 9/30/12.

Site	Total storms	Mean storm arrival time (hr.)	Mean storm interval (hr.)	Mean storm duration (hr.)	Mean storm depth (mm)	Mean storm intensity (mm/hr)	Total rainfall (mm)
F1	218	39.0	37.0	2.0	9.5	3.5	2040
F2	262	32.5	29.5	2.5	5.5	1.5	1400
A1	268	31.5	29.0	2.5	3.0	1.0	850
A2	262	32.5	29.5	2.5	5.5	1.5	1400

Table 3.3. Timing of changes in connectivity at sites F1 and A2.

Site	Dominant state	Timing of deviations
F1	Disconnected	2/1/12 – 2/12/12 (fully connected) 1/8/12 – 1/29/12 (partially connected)
A2	Fully connected	3/7/12 – 4/21/12 (partially connected) 4/30/12 – 5/3/12 (partially connected) 7/8/12 – 7/11/12 (partially connected)

Chapter 3 Figures

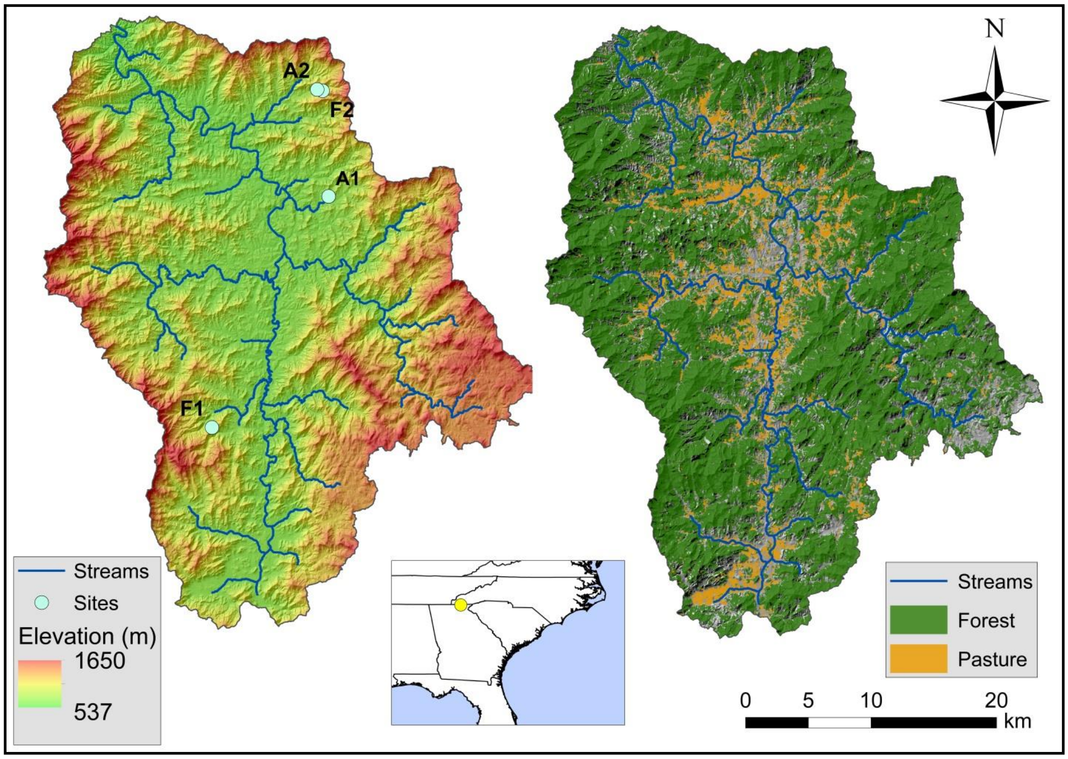

Figure 3.1. The distribution of forest and pasture land uses within the LTRB are shown along with forest study sites (F1 and F2) and pasture study sites (A1 and A2). Major streams within the basin (5^{th} order and higher) are depicted for hydrological context. Location of the LTRB within the southeastern U. S. is depicted for reference purposes.

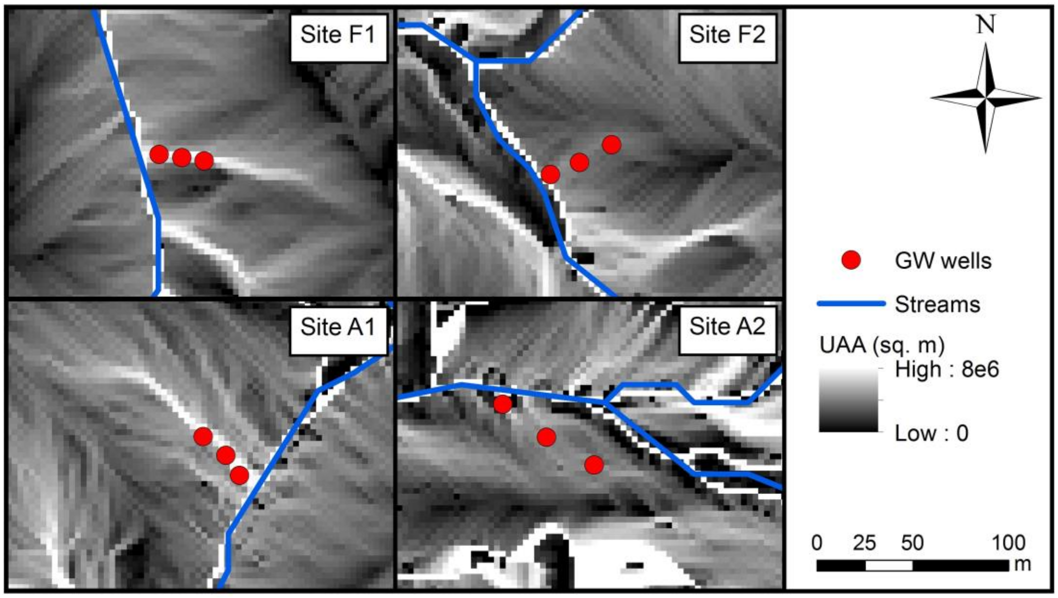

Figure 3.2. Site layout diagram, the positioning of shallow groundwater wells are shown along with the stream flowing at the base of each study hillslope. Upslope accumulated area (UAA), as calculated based on surface elevation, is shown as a background for context. Lighter shades indicate areas of high UAA (streams and subsurface flowpaths), darker shades indicate areas of low UAA. A log-scale color table is used to represent UAA.

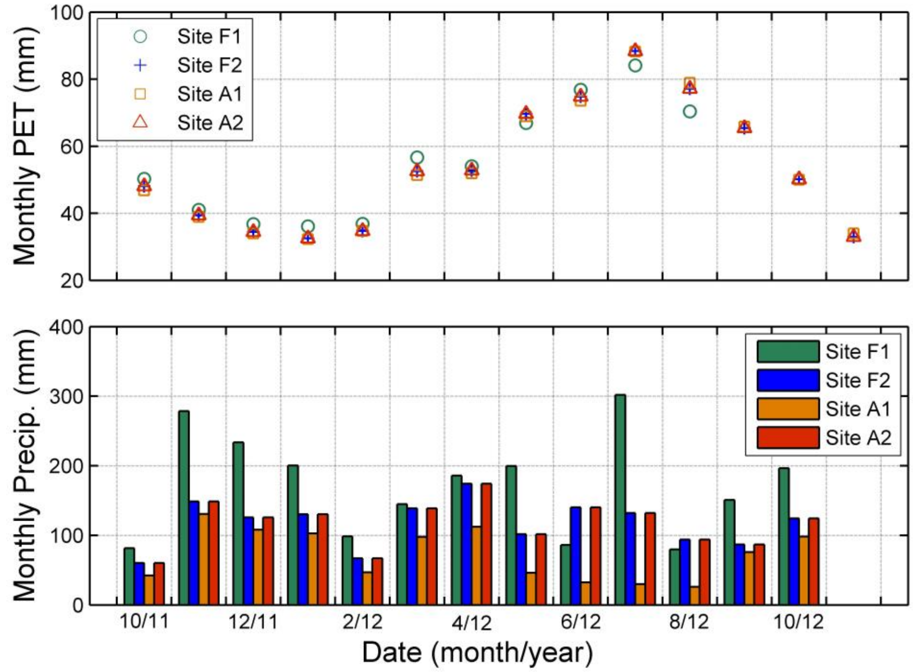

Figure 3.3. Monthly estimates of PET are based on hourly observations of air temperature (℃) and were calculated using equations 4 – 5. Total monthly rainfall data are also based on hourly observations. Observations are only shown where the full month of data was available to avoid under-representing PET and rainfall.

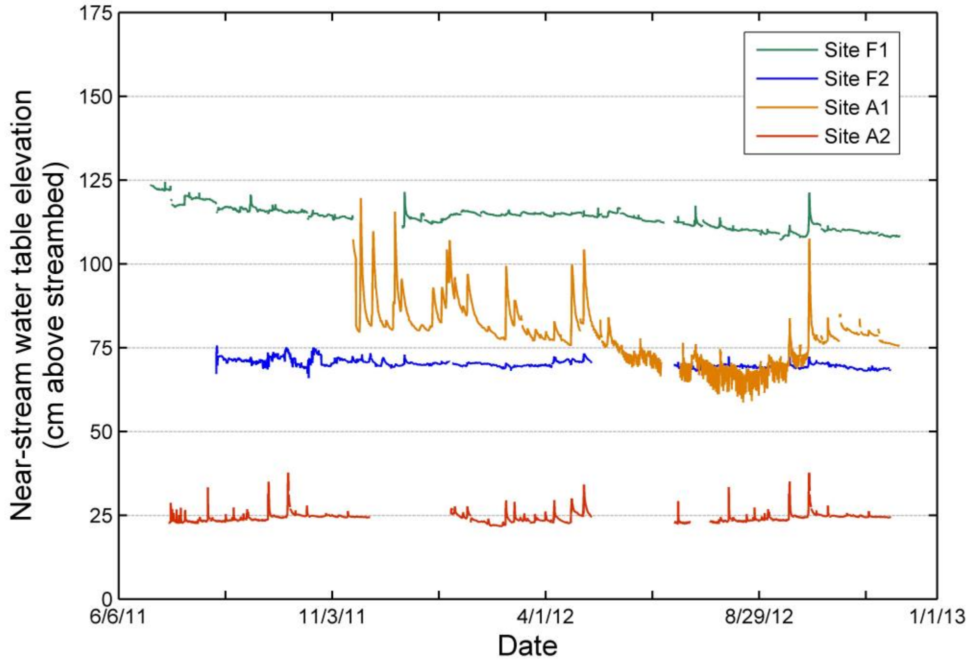

Figure 3.4. A time series of water table elevation for each study site is shown for context. These data are the raw 10-minute observations used for analyzing patterns in connectivity, flashiness, and specific discharge. As forest sites had water tables extending past the near-stream area only briefly (site F1), or not at all (site F2), and to avoid excess clutter, only near-stream well data are shown. Gaps in each time series are present due to data logger power supply issues, these time periods were not included in further analysis.

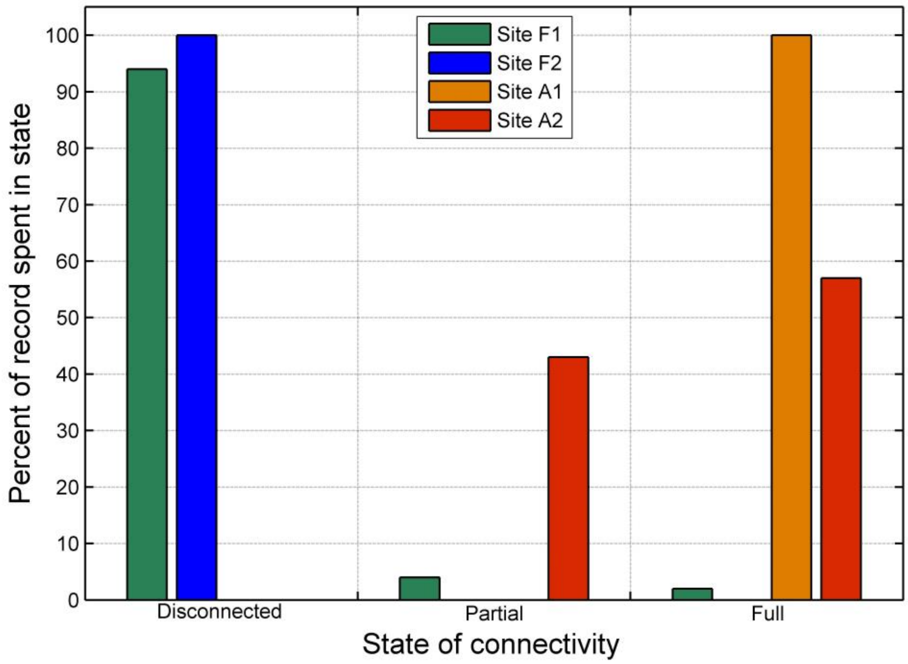

Figure 3.5. The percent of the total data record spent in the no connectivity, partial connectivity, or full connectivity state by each study hillslope. Hydrologic connectivity was determined using continuous monitoring of groundwater level from August, 2011 through November, 2012.

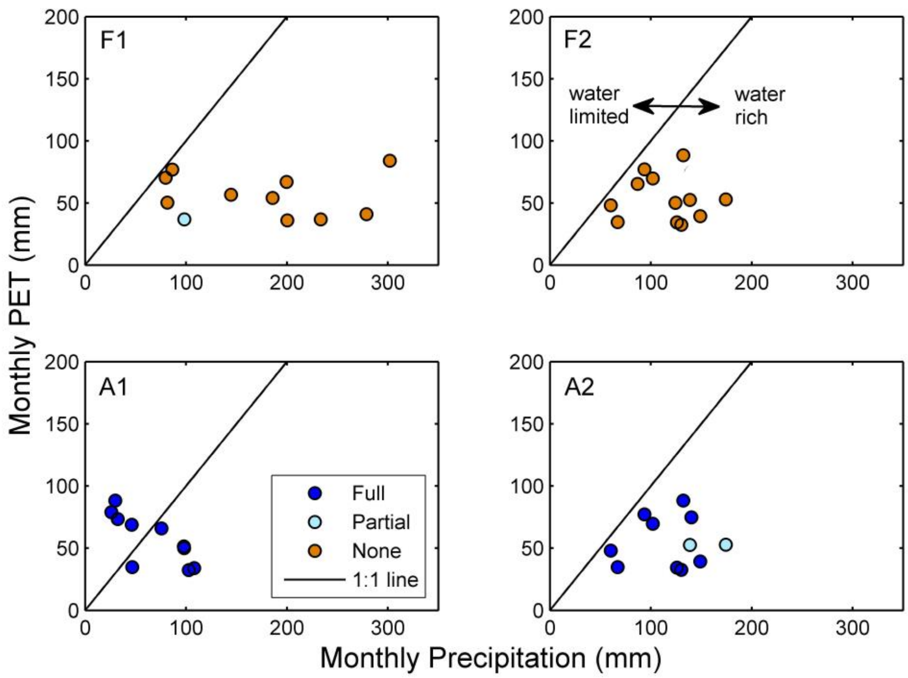

Figure 3.6. The dominant state of connectivity for each month plotted as a function of total monthly precipitation (mm) and monthly PET (mm). The hypothetical one-to-one line where precipitation and PET are equal represents the hypothetical boundary between water-limited (PET > precipitation) and water-rice (PET < precipitation) conditions. State of connectivity is indicated by marker color. The partially connected month at site F1 is January, 2012 and the partially connected months at site A2 are March and April, 2012.

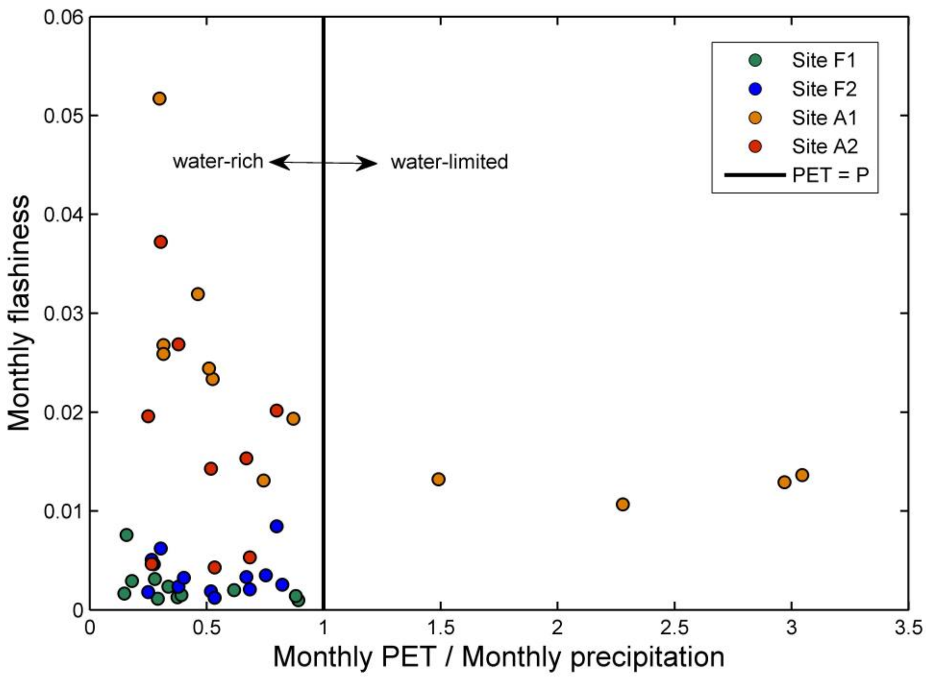

Figure 3.7. Monthly flashiness index values calculated using equation five and modified from *Baker et al.*, 2004, as a function of potential water availability. Periods of possible water surplus, or when precipitation > PET, occur when x-axis values are less than one. Periods of potential water deficit, or when precipitation < PET, occur when x-axis values are greater than one. The one-to-one line representing the transition point between water-rich and water-limited conditions is shown as a black vertical line at x = 1.

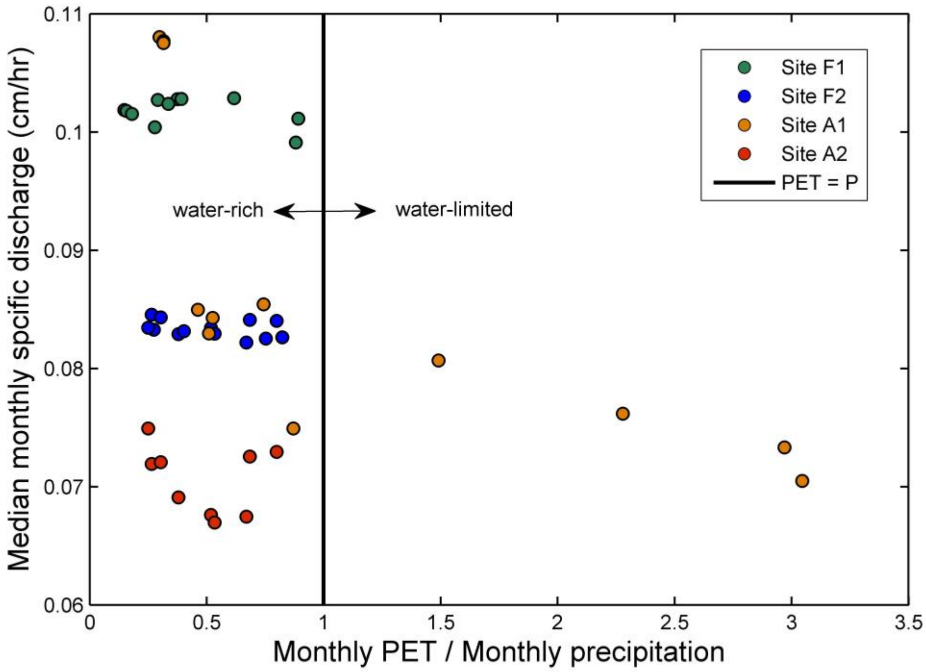

Figure 3.8. Specific discharge (*q*), calculated using equation three (Darcy's law), as a function of potential water availability. Periods of possible water surplus, or when precipitation > PET, occur when x-axis values are less than one. Periods of potential water deficit, or when precipitation < PET, occur when x-axis values are greater than one. The one-to-one line representing the transition point between water-rich and water-limited conditions is shown as a black vertical line at x = 1.

CHAPTER 4: STABLE ISOTOPE HYDROLOGY: A MANUSCRIPT PREPARED FOR SUBMISSION TO THE JOURNAL *HYDROLOGICAL PROCESSES*

Exploring the influence of land use on runoff generation in southern Appalachian headwater catchments with water stable isotopes.

Authors

Joshua S. Rice

Ryan E. Emanuel

Abstract

Mountain headwater catchments hold a unique and critical place in the water cycle. As human activities such as land use encroach on these sensitive areas it becomes increasingly important to examine the potential impacts of such disturbances on runoff generation. We use water stable isotopes as conservative tracers of water sources to assess the impact of land use on hillslope scale runoff generation. Specifically, we focus on the Little Tennessee River Basin (LTRB) of the southern Appalachian Mountains and two of the prominent forms of land use, deciduous forest (forest) and pasture agriculture (pasture), in the region. Samples of precipitation, mobile A-horizon soilwater, mobile B-horizon soil water, and shallow groundwater at study sites were sampled bi-weekly between Aug. 2011 and Nov. 2012. Using measured oxygen stable isotope ($\delta^{18}O$) values from these samples, mean residence time (MRT) was estimated for the subsurface pools sampled on each study hillslope. In

general, MRT increased along with depth, with shallow groundwater having the longest MRT at each study hillslope. Systematic variation in MRT between the two target land uses was not observed. However, differences in characteristics of rainfall patterns, such as storm frequency and intensity, between study sites may mask the influence of land use on MRT. In light of this, we are unable to conclude that land use does or does not impact runoff generation by influencing the MRT of water in the subsurface of individual hillslopes in the area of this study.

Keywords: hydrology, land use, stable isotopes, residence time, runoff generation, headwaters

Introduction

The world's mountains occupy a crucial position in the water cycle, by providing the beginnings for many major river systems and by serving as an important source of runoff generation for nearby lowlands [*Messerli et al*., 2004; *Viviroli et al*., 2007]. Headwater catchments in mountain regions play an essential part due to their critical role as the origin of channel networks, areas of high biodiversity levels, and their role in biogeochemical processes [*Gomi et al.*, 2002]. Human activity is leading to a decline in the areas of land that can be considered undisturbed [*Vitousek et al*., 1997; *Palmer et al*., 2004]. As environmental disturbance cause by human activity spreads it is important to acknowledge, and understand, the influence this disturbance may have on natural systems [*Palmer et* al., 2004]. This point is particularly true for mountain areas due to their important role in the water cycle. More specifically, the potential influence of human activity in headwater catchments is in need of attention due to the tight coupling of hillslope processes and headwater stream reaches and increased level of variability in conditions, relative to larger stream reaches [*Gomi et al.*, 2002].

Of the various human activities that have associated environmental impacts, land use is perhaps the most pervasive [*Vitousek et al*., 1997; *Foley et al*., 2005]. Land use related environmental consequences are extensive enough that it has been suggested their impact may be more substantial than those of climate change [*Sala et al*., 2000; *Vorosmarty et al*., 2000]. By modifying the land surface, land use directly alters ecosystem functioning and can cause changes in the water balance [*Vitousek et al*., 1997; *Foley et al*., 2005]. The influence of land use on the water cycle has been acknowledged as an essential area for interdisciplinary hydrologic research in the future [*DeFries and Eshleman*, 2004; *National Research Council of the National Academies*, 2012]. Previously identified effects of land use on the water cycle involve both vegetation related and non-vegetation related processes. Examples of vegetation related effects include such processes as: canopy and leaf litter interception of rainfall [*Durocher,* 1990], initiation of preferential surface flowpaths [*Ludwig et al*., 2005], and modified soil infiltration rates [*Dunne et al*., 1991; *Thompson et al*., 2010]. Examples of non-vegetation related effects include processes such as: changes in the physical properties of soil [*Booth and Jackson*, 1997; *Zimmermann et al*., 2006] and a wide variety of effects linked to the introduction of impervious surfaces [*Leopold*, 1968; *Nelson and Palmer*, 2007]. As land use interacts with incoming precipitation prior to its being partitioned into subsurface pools and fluxes, runoff generation, in particular, is a logical focal point for considering the influence of land use on the water cycle at the hillslope scale.

The watershed water balance provides an excellent context for considering the hydrologic functioning of watersheds as a simple system. For any given point in the subsurface of a hillslope the water balance (modified from *Scanlon et* al., 2005 and *Emanuel et* al., 2010) can be used to describe the relation between fluxes as:

$$\frac{dV}{dt} = I - R_z - R_l - ET \qquad (1)$$

where V is the volume of water present, I is infiltration, R_z and R_l are the vertical and lateral components of subsurface runoff, and ET is evapotranspiration. The relationship in equation one begins with precipitation. During and after storm events, infiltrating rainfall leads to an increase in storage followed by a response in other fluxes from equation one [*Sklash and Farvolden*, 1979; *Seibert et al*., 2003]. As this response influences subsurface discharge it also influences the generation of runoff as water leaves a hillslope [*McGlynn et al*., 1999]. As the various processes at work on a hillslope are linked, examining how one aspect of the hillslope system, such as subsurface flow, functions allows inferences about the overall hillslope to be made. Considering these observations in conjunction with potential hydro-meteorological influences (e.g. atmospheric demand (potential evapotranspiration) and precipitation) allows for these external influences to be accounted for. It is important to note that while potential evapotranspiration (PET) is dependent on atmospheric demand and is not linked to land use; actual evapotranspiration (AET) will be affected by differences in vegetation [*Zhang et al*., 2001; *Emanuel et al.*, 2007; *Emanuel et al.*, 2010], and thus land use.

The main focus of this study is the influence of time related impacts on the runoff components (R_z and R_l) of Equation (1). Rather than examining stream discharge directly, we consider water in the hillslope subsurface prior to reaching the stream. With the exception of overland flow, water must move through and interact with the subsurface portion of a hillslope prior to reaching a stream and continuing through the water cycle as surface runoff. This point is particularly true within the area examined by this study as infiltration rates are generally high and overland flow tends to be minimal [*Hewlett*, 1961; *Hewlett and Hibbert*, 1967]. This makes examining the factors that influence the movement of water in the subsurface of hillslopes an essential step in understanding the process of runoff generation and how it influences stream discharge and downstream water supplies. To gain insight into how these processes are impacted by land use, we the stable isotopes of water (oxygen and hydrogen) as conservative tracers of water sources to study the movement of water through the subsurface pools found on individual hillslopes representing different types of land use.

Of the many methods used to infer process based hydrologic knowledge at the catchment scale, isotopic tracers have proven to be quite useful [*Genereux and Hooper, 1998; Kendall and Caldwell*, 1998]. Oxygen (^{18}O) and hydrogen (^{2}H) isotopes, in particular, make ideal tracers to investigate the movement of water within and out of catchments because the isotopes make up the water molecule itself [*Kendal and Caldwell*, 1998].

Knowledge of variations in the isotopic composition of precipitation (i.e. the input signal) can be used to infer how water is moving within a catchment [*Genereux and Hooper*, 1998; *Ingraham*, 1998]. A common application of this relationship is the estimation of the characteristic age, or mean residence time (MRT), of water within or leaving individual hillslopes and catchments [e.g. *Dewalle et al*., 1997; *Soulsby et al*., 2000; *McGuire et al*., 2005; *Rodgers et al*., 2005; *Kabeya et al*., 2007]. In the subsurface, MRT refers to the average length of time water takes to reach a particular point within the system relative to when it was deposited [*McGuire et al*., 2002]. The MRT of water within a system provides useful information when considering variation in flow pathways and storage [*McGuire et al*., 2005]. Understanding MRT can also provide insight into questions involving nutrient transport as many biogeochemical processes are strongly affected by time [*McGuire et al*., 2005]. Most approaches to estimating MRT are based on the work of *Maloszewski and Zuber* [1982], and make use of seasonal variations in the stable isotope composition of precipitation and the response of water within the system to this seasonal input [*McGuire et al*., 2002].

Here we apply a case study approach employing a stable isotope of oxygen (^{18}O) as a tracer to estimate MRT and investigate the influence of land use on hillslope scale runoff generation within the Little Tennessee River Basin (LTRB) of the southern Appalachian Mountains. The LTRB is home to both the Coweeta Hydrologic Laboratory and Coweeta Long-Term Ecological Research (LTER) program. An important characteristic of this area is its history of nearly continuous human land use at least since the mid 1800's [*Gragson and Bolstad*, 2006]. Between the mid 1800's and early 1900's much of the region was subjected to extensive forest clearing for timber harvesting and conversion to agricultural land [*Ayres and Ashe*, 1905; *Williams*, 1989]. The unsuitability of many locations for agriculture resulted in abandonment followed by reforestation [*Turner et al*., 2003]. The extensive mixed hardwood deciduous forests that now dominate the region are the result of this reforestation [*Kloeppel et al*., 2003]. Based on the most recent land use data available (2006), forests dominated by mixed hardwood, deciduous vegetation (referred to as forest hereafter) and short-grass dominated pasture agriculture (referred to as pasture hereafter) are the two dominant forms of land use, by area, in the LTRB. Our focus will be on the influence of these two forms of land use, forest and pasture, on subsurface runoff generation at the hillslope scale in the LTRB. As we explore this issue we consider several questions. Do estimates of MRT using the ^{18}O composition of various pools indicate a systematic difference in the movement of water through hillslopes dominated by different forms of land use? If so, what implications may these observations have for processes linked to the movement of water through the hillslope system?

Methods

The LTRB is located primarily in Macon County, North Carolina with a small portion extending into northern Georgia (Figure 4.1). Climate in the region is relatively mild and is classified as marine, humid temperate [*Swift et al*., 1988]. Average annual precipitation in the area ranges from approximately 1800 mm at lower elevations to nearly 2400 mm along high ridgelines [*Kloeppel et al*., 2003]. The region is characterized by heterogeneous mountain topography, with elevations in this 1125 km^2 river basin ranging from 537 m to 1650 m, and slope values ranging from 0° to 72°. The main populated areas within the basin are Franklin, NC and Highlands, NC.

Four hillslopes within the LTRB, two dominated by forest (F1 and F2) and two dominated by pasture (A1 and A2), were selected to be used as a case study examining the influence of land use of runoff generation (Figure 4.1). The study hillslopes range in area from 1800 m2 (F2) to 9400 m2 (A1) and on average, slope from 4° (A2) to 30° (F2). Site characteristics are further described in Table 4.1. Each hillslope contained four instrument clusters arranged in a roughly linear transect moving upslope, away from the stream at the base of the hillslope (Figure 4.2). Instrument clusters were installed in the near-stream, lower-hillslope, mid-hillslope, and upper-hillslope areas. Near-stream and low-hillslope areas were equipped with shallow groundwater wells and porous cup suction lysimeters (Series 1900, Soilmoisture Equipment, Inc., Santa Barbara, CA, USA). Mid-hillslope areas were equipped with wells only, while upper-hillslope areas are equipped with lysimeters only. Lysimeters were installed in pairs, one targeting the A-soil and one targeting the B-soil horizon. Shallow groundwater wells consisted of two inch diameter slotted PVC pipe installed to the depth of bedrock (0.6 m – 8.3 m). Each groundwater well contained dedicated flexible PVC tubing to avoid cross-contamination of samples. Prior to sampling of shallow groundwater, each well was purged using a peristaltic pump with silicone tubing and allowed to recharge. In addition, each hillslope was equipped with a rain gauge collecting total bulk precipitation falling during each sampling interval. Rain gauges were filled with approximately 0.25” depth of mineral oil to prevent evaporation and possible isotopic fractionation of collected rainfall [e.g. *Donovan and Ehleringer*, 1994; *Hsieh et al*., 1998]. Samples of water from each hillslope pool (incident precipitation, mobile A-horizon soil water, mobile B-horizon soil water, and shallow groundwater) were collected every two weeks between August, 2011 and November, 2012. At the time of sampling, all water samples were placed in 20 mL vials with polycone caps to eliminate headspace and prevent isotopic fractionation during storage [e.g. *Brooks et al*., 2010; *Goldsmith et al*., 2011]. Prior to analysis of isotopic composition these vials were kept in a refrigerated environment as an additional measure to prevent fractionation during storage.

Water samples were analyzed for δ^2H and δ^{18}O using a cavity ring-down spectrometer (model L2120-I, Picarro, Inc., Santa Clara, CA, USA) equipped with an HTC PAL autosampler (LEAP Technologies, Inc., Carrboro, NC, USA). All δ^2H and δ^{18}O values are expressed relative to Vienna Standard Mean Ocean Water (VSMOW)/ Standard Light Antarctic Precipitation (SLAP) scale in units of permil (‰)

$$\delta^2\text{H or } \delta^{18}\text{O} = \left(\frac{R_{sample}}{R_{standard}} - 1\right)*1000 \qquad (2)$$

where R is the ratio of deuterium to hydrogen atoms or ^{18}O to ^{16}O atoms of the sample and the reference standard. Raw instrument data were corrected according to guidelines published by the International Atomic Energy Agency (IAEA) Isotope Hydrology Laboratory [*Tanweer et al*., 2009]. Uncertainty in the analytic instrument was determined using results from three calibration runs conducted on separate days during March 2012. Each calibration run used the primary reference materials VSMOW and SLAP as standards and the primary reference material Greenland Ice Sheet Precipitation (GISP) as a blind unknown run in duplicate. Total instrument δ^2H and δ^{18}O uncertainty was quantified as the average δ^2H and δ^{18}O standard deviation of GISP (precision) across runs plus the average δ^2H or δ^{18}O absolute difference (accuracy) between the measured and published values of GISP. Instrument δ^2H accuracy was found to be 0.95 (‰) and δ^2H precision was found to be 0.21 (‰), giving a total instrument δ^2H uncertainty of 1.17 (‰). Instrument δ^{18}O accuracy was determined to be 0.05 (‰) and δ^{18}O precision was determined to 0.05 (‰), resulting in total instrument δ^{18}O uncertainty of 0.10 (‰). As δ^{18}O provided the lowest uncertainty, these data were selected for estimating MRT rather than δ^2H.

Within every sample run a variety of quality control measures were followed. During analysis standards were analyzed prior to, and following, every batch of nine samples to ensure consistent calibration and reduce the potential effects of drift in the resulting data. Each batch of nine samples contained a standard, calibrated with VSMOW/SLAP, treated as a blind unknown. Total accuracy for each sample run was quantified as the mean absolute difference between the measured and calibrated values of the duplicated blind unknown standards. Total precision for each sample run was quantified as the mean standard deviation in the measured values of the duplicated blind unknown standards. Based on all sample runs conducted during the study (n=22), mean within run δ^{18}O accuracy was calculated to be 0.17 (‰) and mean within run δ^{18}O precision was calculated to 0.19 (‰), resulting in a mean within run total uncertainty of 0.36 (‰) for δ^{18}O. Data from the same sample runs produced a mean within run δ^2H accuracy of 1.89 (‰) and a mean with run δ^2H precision of 0.29 (‰), resulting in a mean within run total uncertainty of 2.18 (‰).

In this paper we make use of measured $\delta^{18}O$ values in water samples and the sine-wave method of MRT estimation [e.g. *DeWalle et al*., 1997; *Soulsby et al*., 2000; *Rodgers et al*., 2005; *Kabeya et al*., 2007] to consider the potential influence of land use on runoff generation. This method makes use of seasonal variation in the isotopic composition of precipitation inputs to individual hillslopes and the damping of this signal as it propagates through the hillslope subsurface. Seasonal variations in precipitation, mobile A-horizon soil water, mobile B-horizon soil water, and groundwater were used to estimate MRT of each pool during the study period (Aug., 2011 – Nov., 2012), based on the method presented by *DeWalle et al*., [1997]. A seasonal sine wave function was used to model the annual fluctuation in sample $\delta^{18}O$ variations as:

$$\delta^{18}O = \bar{X} + A[cos(ct-\theta)] \tag{3}$$

where $\delta^{18}O$ is the expected value at a given time, $\bar{X}$ is the mean annual $\delta^{18}O$ value, A is the annual amplitude of $\delta^{18}O$ fluctuations within the respective pool, c is the radial frequency of annual fluctuations (0.017214 rad d^{-1}), t is the time in days after the start of the study period, and θ is the phase lag of the annual peak of $\delta^{18}O$ values in radians. The fit of modeled $\delta^{18}O$ fluctuations was quantified by calculating RMSE for each modeled function and pool. From Equation (3), MRT of water leaving each subsurface pool being investigated is estimated as:

$$MRT = c^{-1}[(Az2/Az1)^{-2} - 1]^{0.5} \tag{4}$$

where *Az1* is the observed amplitude of precipitation and *Az2* is the observed amplitude of the subsurface pool in question. The method used for estimating MRT uses a simple steady-state, well-mixed model where the input of precipitation is assumed to mix rapidly with pre-existing water on the hillslope. It should be noted that this method provides a first approximation of MRT only, though the frequent application of this method supports its usefulness in assessing the behavior of various hydrologic systems. Estimation of MRT using Equations (4) was conducted using MATLAB R2012a (Mathworks, Inc., Natick, MA, USA).

In order to account for variations in atmospheric demand for water as a potential driver of any observed variations in MRT among the study hillslopes daily PET was calculated for each site using the *Hamon* [1963] method. The Hamon method is a temperature based approach that uses the following equations:

$$PET = 0.1651*L_{day}*\rho_{sat} \qquad (5)$$

$$\rho_{sat} = (216.7*e_s)/(T+273.3) \qquad (6)$$

$$e_s = 6.108*e\text{^}((17.26*T)/(T+273.3)) \qquad (7)$$

where PET = daily potential evapotranspiration (mm), T = daily mean air temperature (°C), L_{day} = daytime length, or time from sunrise to sunset in multiples of 12h, ρ_{sat} = saturated vapor density, and e*s* = saturated vapor pressure at the given value of T. Equation five is derived from *Murray* [1967] and allows air temperatures to fall below 0°C, essential for accurate estimates in this region where winter air temperatures less than 0°C regularly occur. Previous work [e. g. *Rao et al*., 2011] has suggested the Hamon method for calculating PET underestimates actual evapotranspiration (AET) in forested areas of this region. However, as the interest was not modeling AET, but rather determining if the atmospheric demand for water was consistent among sites, the Hamon method was considered appropriate given the available data. A one sample KS test indicated that none of the PET datasets conformed to a normal distribution ($p<0.001$). In light of this, the Kruskal-Wallis test was used to test for a statistically significant difference in estimated mean monthly PET at each study site. Calculation of PET and statistical were completed using MATLAB R2012a (Mathworks, Inc., Natick, MA, USA).

As any variation in the inputs of precipitation to the study hillslopes could potentially lead to variations in MRT, patterns in rainfall received by each hillslope between August 2011 and November 2012 were examined. Using hourly observations of total precipitation at each site the following descriptors of precipitation patterns were considered: number of storms, storm arrival times (time between one storms arrival and the arrival of the next storm), storm interval length (length from the end of one storm to the beginning of the next storm), storm duration, storm depth, storm intensity, and total monthly precipitation. Variation in the number of storms occurring at each site was compared using the percent difference in storm number. Comparisons for every other calculated rainfall variable were made between each site, again using the Kruskal-Wallis test. Calculation and analysis of rainfall descriptors was completed using MATLAB R2012a (Mathworks, Inc., Natick, MA, USA).

Results and Analysis

The δ^{18}O values of precipitation at each site fluctuate throughout the year in a relatively seasonal pattern (Figure 4.3). Low δ^{18}O values for precipitation occur during the cold winter months when, due to temperature effects, precipitation can be expected to be relatively depleted in ^{18}O [*Dansgaard*, 1964; Gat, 1996]. High values in annual the δ^{18}O of precipitation samples are observed in the warm summer months when, again due to temperature effects, precipitation can be expected to be less depleted in ^{18}O [*Dansgaard*, 1964; *Gat*, 1996]. While precipitation inputs do vary from month-to-month, precipitation is distributed relatively uniformly throughout the year with no distinct wet or dry season to skew the overall isotope signal present in the subsurface (Figure 4.3). Though precipitation trends may influence isotope content within individual storms, the method of sampling bulk precipitation used here integrates these variations, resulting in a sample representative of the sum of precipitation received during a given time period.

The δ^{2}H values were used in conjunction with δ^{18}O values to plot individual samples in stable isotope phase space (Figure 4.4). This figure allows unexpected deviations from the precipitation inputs and the local meteoric water line (LMWL) to be identified. Taking this step prior to estimating MRT allows for evaporative fractionation that may disrupt the propagation of the seasonal isotope signal of precipitation to be identified. The observed movement along the LMWL, rather than deviation away from the LMWL, indicates that the relation between the δ^{2}H and δ^{18}O values of inputs is being maintained as the signal moves through the hillslope. This movement along the LMWL, rather than away from it, is indicative of the fluctuating seasonal input signal propagating through the subsurface. As no sampling pool exhibits notable deviation away from the LMWL with respect to the behavior of the other pools, it can be assumed that the isotope signal of precipitation is moving through the subsurface as expected.

The various subsurface pools sampled at each site display seasonal fluctuations that have experienced both phase shifts and dampening. The observed phase shifts represent the lag between the input of a new signal and its propagation into a subsequent pool. The annual fluctuations in $\delta^{18}O$ of subsurface pools at all sites were dampened relative to the fluctuations in $\delta^{18}O$ of input precipitation. In general, the degree of damping relative to precipitation increased moving downward through the subsurface with mobile A-horizon soil water displaying a tendency be the least dampened and shallow groundwater being the most heavily dampened (Table 4.2). Fitting of sine-wave models to a time-series of the annual $\delta^{18}O$ oscillations in each sampling pool using equation 3 clearly illustrates these points. Measured $\delta^{18}O$ data from site F1 samples, along with fitted sine-wave models and 95% confidence bounds for the modeled function, are shown in Figure 4.5 as an example.

Of the various pools of water being considered, precipitation, in general, has the most variable signal through time. Increased variability in the $\delta^{18}O$ value of precipitation samples is expected as precipitation can be rather variable from storm to storm and within storms, despite exhibiting a general seasonal trend when considered annually. This variability in the precipitation isotope signal translates into the lowest goodness-of-fit between actual observations and fitted sine-wave models (Table 4.1), though these values are not unexpected based on previously reported goodness-of-fit values using the same method to model precipitation [e.g. *Kabeya et al*., 2007]. Likewise, the decreased variability in isotopic composition of the subsurface pools being sampled results in substantial improvement in model fits with RMSE values of subsurface pool models ranging from a high of 0.83 to a low of 0.12 (Table 4.2). Using equation 4, MRT of each subsurface pool was estimated for each site. The MRT's vary widely among sites, ranging from less than one year to over two years (Table 4.2). At each study site estimated MRT displays a tendency to increase moving downward through the subsurface pools. In general, shallow groundwater at each site typically has a longer MRT than mobile A-horizon soil water, and mobile B-horizon soil water generally has a longer MRT than mobile A-horizon soil water. This general trend of increasing depth equating to increased MRT in the hillslope subsurface persists across both land use types. Despite the notable differences in MRT from each site, systematic variation in MRT between forest and pasture land use is not observable in the data produced here.

Monthly estimates of PET did not exhibit a significant difference among sites based on results of the Kruskal-Wallis test ($p = 0.70$, Figure 4.6). These sites are all within 30 km of one another, lie within a narrow range of elevations (± 200 m) relative to the entire LTRB, and have very similar ambient air temperatures; therefore, similar PET is to be expected. As PET does not differ significantly among study sites, differences in atmospheric demand for water are not responsible for the variations in estimated MRT among sites. Analysis of rainfall does show variation in precipitation inputs among several of the sites (Table 4.3). Site F1, in particular, has noticeably different trends in precipitation with fewer total storms, but shorter, more intense storms than other sites. However, variation in rainfall cannot be identified as the sole cause of variations in estimated MRT due to the results from sites F2 and A2. The close proximity (<500 m) of sites F2 and A2 makes it likely that these two sites are subject to the same storms, and thus precipitation inputs. Despite the close proximity of these sites, estimates of MRT for each pool at sites F2 and A2 still vary greatly, indicating that with the data available we cannot identify differences in rainfall as the sole cause of varying MRT's.

Discussion

Overall, our estimates of MRT do not indicate a systematic difference in the MRT of subsurface hillslope water of forest and pasture hillslopes when considering all sites. However, our results do not conclusively show that land use is not capable of influencing the MRT of subsurface hillslope water either. In addition to being dominated by different forms of land use, several of the sites from this study are subject to varying patterns in precipitation. Differences in the delivery of precipitation to the study hillslopes, particularly average storm depth and intensity, may potentially exert a masking effect on the influence of land use on MRT. The two study sites that do receive similar precipitation inputs, sites F2 and A2, do exhibit systematic differences in MRT estimates. Each subsurface pool from site A2 has a longer estimated MRT than the corresponding pool at site F2. Without further data from hillslopes receiving similar precipitation inputs it is difficult to form a definite conclusion concerning the influence of land use on MRT of subsurface hillslope water in the LTRB.

Either the use of paired hillslopes of different land use classes or a much larger dataset (e.g. many hillslopes) would be needed to deconvolve the influence of land use on MRT from external factors such as rainfall patterns. In order to gain additional insight into the influence land use may have on MRT of subsurface hillslope more research is necessary.

It is important to mention that while the isotope based analyses discussed in this study are not indicative of land use exerting a clear influence on hillslope scale runoff generation, analyses based on physical data from the same sites do indicate such an influence. Physical hydrological data from the study sites suggest that land use strongly influences the partitioning of precipitation inputs into the various pools of water present on each hillslope. At first glance these two findings appear to be counterintuitive, but with additional consideration a simple reconciliation presents itself. The MRT is an estimate of how long water resides in a given pool. On the other hand, physical data suggest a difference in the partitioning of water between land uses and do not address the time water resides in various pools. The results based on physical data only address how water is being partitioned between the pools present on the study hillslopes. Simply put, the isotope data based analyses and physical data based analyses conducted on these hillslopes are examining different aspects of runoff generation. Though these aspects of runoff generation (partitioning and residence time) undoubtedly interact as they are part of the same larger process, they do not necessarily drive one another. Thus it is possible for land use to influences some aspects of runoff generation while potentially having minimal impact on others.

Conclusion

Mean residence time is an important aspect of runoff generation at the hillslope scale as many processes related to runoff (e.g. nutrient transport, biogeochemical cycling, etc.) are strongly influenced by time [*McGuire et al*., 2005]. The influence of land use on MRT was examined here by estimating MRT of various subsurface pools using water stable isotopes (^{18}O). Based on the measured data it cannot be concluded that there is a systematic difference in the MRT of shallow groundwater, or A- and B- horizon soilwater on the forest and pasture hillslopes used in this study. However, due to variation in characteristics of precipitation among hillslopes it also cannot be concluded that land use does not exert an influence on subsurface MRT. Differences in total rainfall, storm frequency, and mean rainfall intensity among sites during the study period may be introducing substantial variability in MRT that masks the impact of land use. While the results presented here do not identify a clear effect of land use on MRT they do raise opportunities for current and future studies by identifying areas where experimental designs can be refined to better address similar issues. Paired-hillslope approaches, in particular, have the potential to more effectively untangle any influence of land use from external effects by minimizing difference in the hydro-climatic setting. Study designs examining variation in MRT on a single hillslope before and after changes in the type of land use, such as forest to pasture, also have considerable potential to better untangle land use and hydro-climatic effects.

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Chapter 4 Tables

Table 4.1. Study hillslope basic characteristics.

Site	Land use	Area	Mean Slope	Mean elevation
F1	Forest	3400 m^2	26°	874 m
F2	Forest	1800 m^2	30°	811 m
A1	Pasture	9400 m^2	12°	674 m
A2	Pasture	2800 m^2	4°	750 m

Table 4.2. Data used in modeling $\delta^{18}O$ fluctuations and calculating MRT.

Site	Pool	*n* samples	Mean annual $\delta^{18}O$ (‰)	Annual $\delta^{18}O$ amplitude (‰)	Model RMSE	MRT (days)
F1	Precip.	25	-4.5	2.5	2.11	N/A
	A-SW	31	-4.8	1.7	0.91	70
	B-SW	44	-4.8	1.0	0.39	130
	GW	22	-6.6	1.0	0.51	130
F2	Precip.	23	-4.8	4.5	3.08	N/A
	A-SW	44	-4.5	1.2	0.59	210
	B-SW	55	-4.6	0.8	0.40	340
	GW	20	-6.4	0.4	0.28	690
A1	Precip.	15	-4.2	3.4	2.06	N/A
	A-SW	19	-3.9	1.0	0.23	190
	B-SW	27	-4.7	1.0	0.68	190
	GW	45	-6.7	0.5	0.22	420
A2	Precip.	19	-4.5	4.5	3.56	N/A
	A-SW	37	-4.9	0.7	0.60	400
	B-SW	46	-5.6	0.5	0.34	550
	GW	20	-6.5	0.3	0.12	960

Table 4.3. Rainfall statistics from 10/1/11 – 9/30/12.

Site	Total storms	Mean storm arrival time (hr.)	Mean storm interval (hr.)	Mean storm duration (hr.)	Mean storm depth (mm)	Mean storm intensity (mm/hr)	Total rainfall (mm)
F1	218	39.0	37.0	2.0	9.5	3.5	2040
F2	262	32.5	29.5	2.5	5.5	1.5	1400
A1	268	31.5	29.0	2.5	3.0	1.0	850
A2	262	32.5	29.5	2.5	5.5	1.5	1400

Chapter 4 Figures

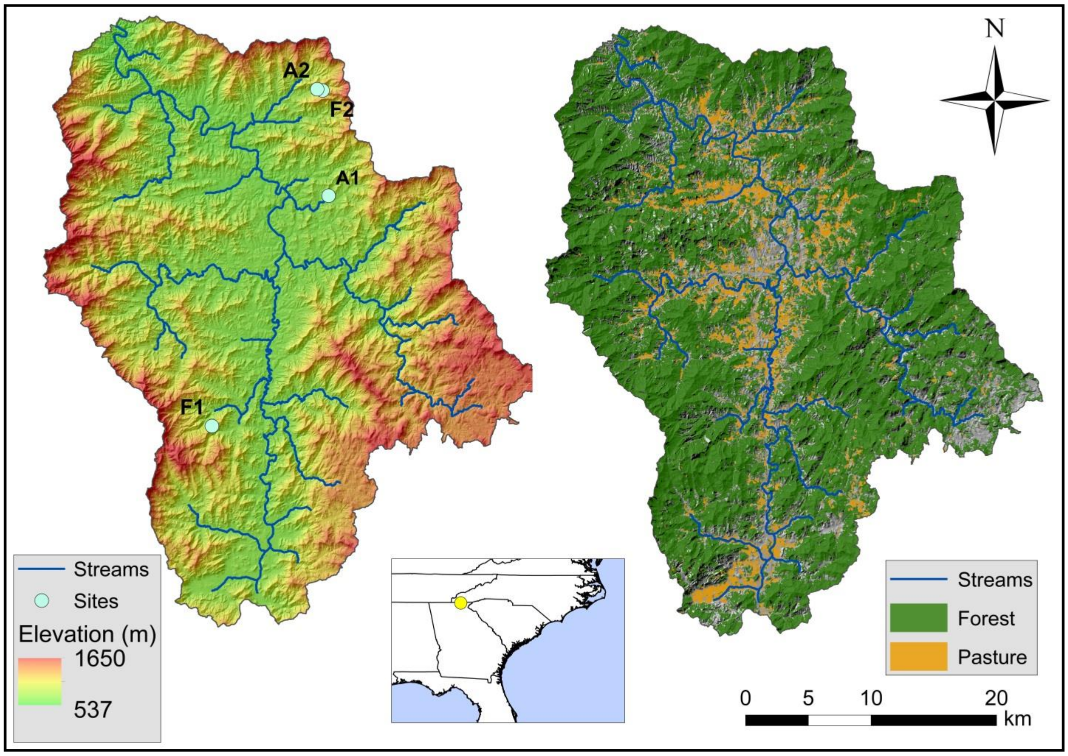

Figure 4.1. The distribution of forest and pasture land uses within the LTRB are shown along with forest study sites (F1 and F2) and pasture study sites (A1 and A2). Major streams within the basin (5th order and higher) are depicted for hydrological context. Location of the LTRB within the southeastern U. S. is depicted for reference purposes.

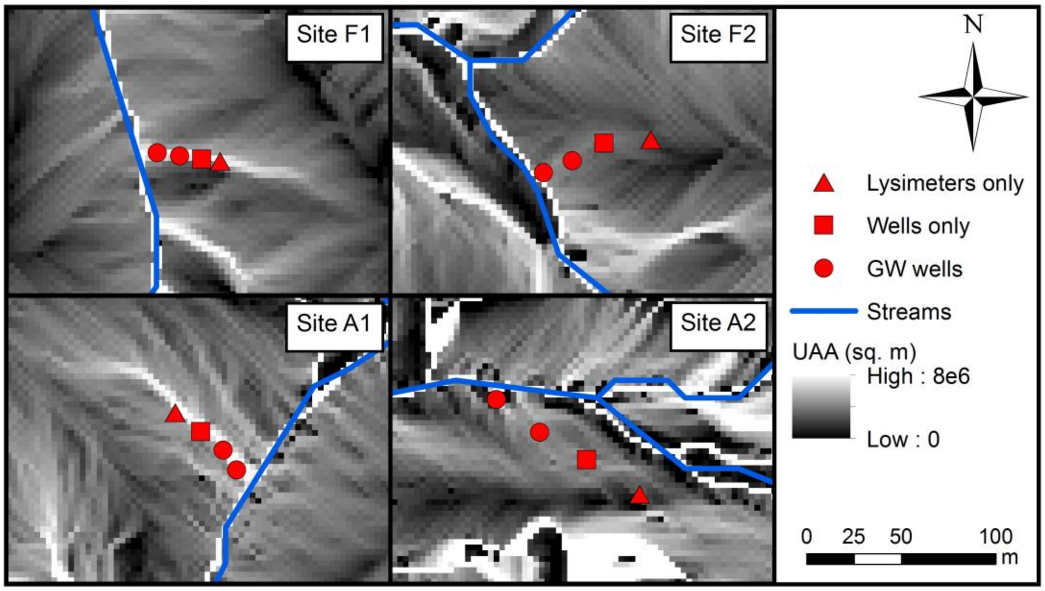

Figure 4.2. Site instrument layout and terrain derived upslope accumulation area (UAA). Riparian and low hillslope positions are equipped with shallow groundwater wells and lysimeters. The mid hillslope position is equipped with a shallow groundwater well only and the upper hillslope position has lysimeters only. The background for each figure panel shows UAA for reference purposes with lighter colors indicating a larger UAA. Light gray and white colors represent potential subsurface flow paths and streams.

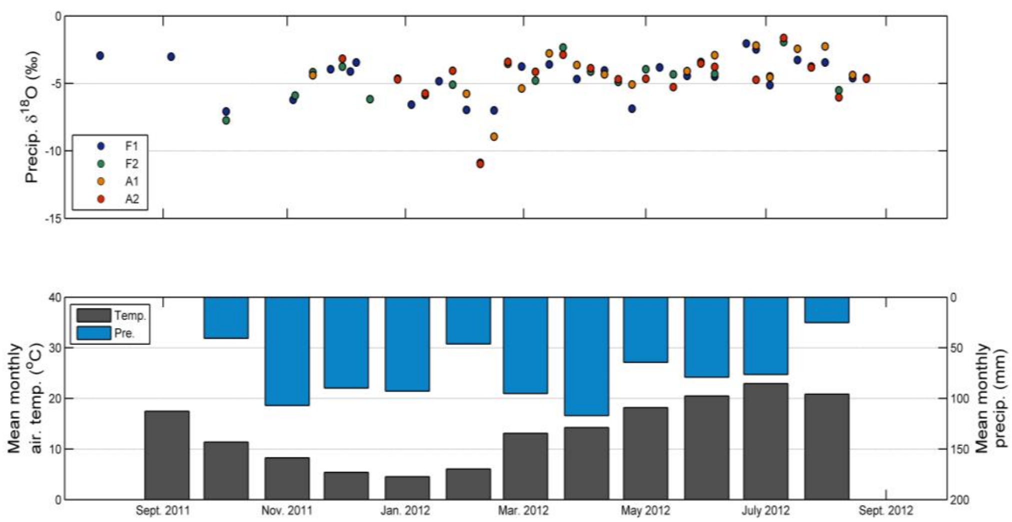

Figure 4.3. $\delta^{18}O$ values of precipitation samples, mean monthly air temperature, and mean monthly precipitation for all study sites. Mean monthly air temperature and precipitation data are based on observations from each study site. Mean monthly air temperature and precipitation are only shown where the full month of data was available.

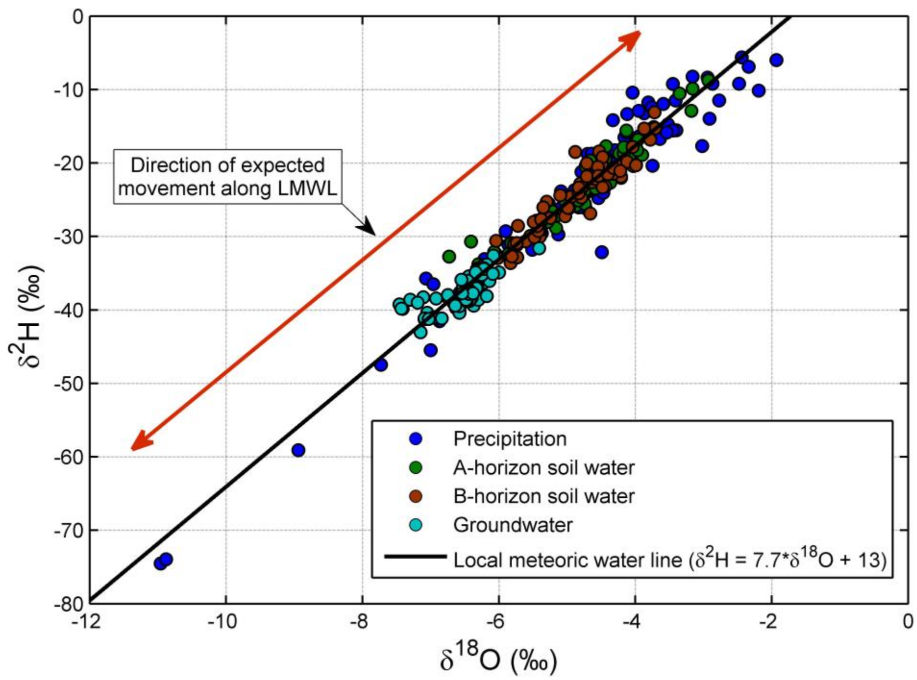

Figure 4.4. Phase diagram of sampled pools and the local meteoric water line (LMWL). LMWL was calculated based on the measured isotope composition of precipitation samples from all study sites. The direction of expected movement along the LMWL is shown by the solid red line. All study samples are shown here with samples from each study site grouped into the appropriate pool (e.g. precipitation, A-horizon soil water, etc.).

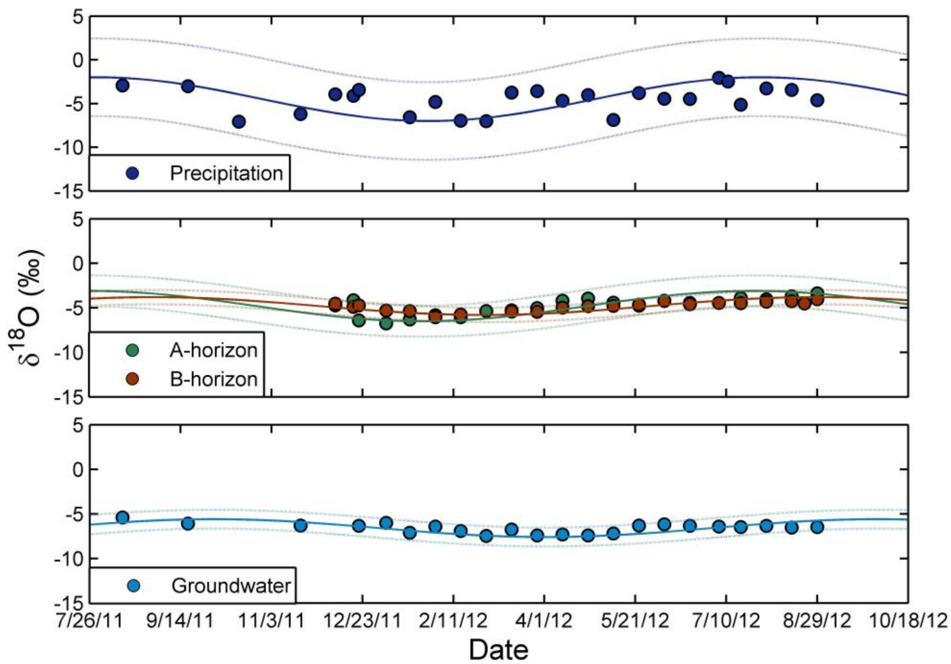

Figure 4.5. An example of the sine-wave models produced using equation four (Site F1). A time-series of the measured $\delta^{18}O$ value of samples is shown along with fitted sine-wave models (solid lines) and the 95% confidence bounds for each model (dashed lines).

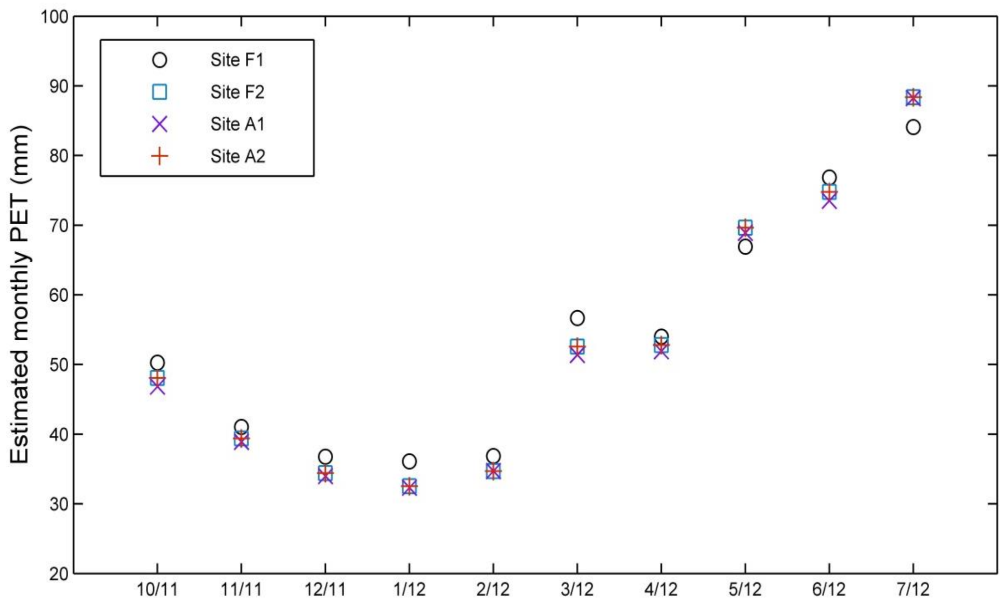

Figure 4.6. Monthly PET at each study site estimated using the *Hamon* [1963] method (equation 5). As expected, this air temperature based method yields annual lows in PET during the cool winter months and annual highs in PET during the warm summer months. Monthly PET across study sites did not differ significantly (Kruskal-Wallis test, $p = 0.70$).

CHAPTER 5: CONCLUSION

Summary

The overall goal of this project was to identify differences in hillslope-scale runoff generation between the land-use types being considered and explain these variations in the context of the local water balance. Additionally, this project examined differences in the spatial organization of land use at the basin scale that may be of consequence when considering hydrologic functioning. Three primary hypotheses were to be tested using an interdisciplinary set of methods to address the project goals:

Hypothesis 1: The forms of land use in question occupy significantly different landscape positions with respect to hydrologically-relevant variables.

Hypothesis 2: Significant differences exist between patterns in the physical hydrology of forest and pasture land use hillslopes, based on hydrometric and hydro-meteorological data.

Hypothesis 3: Subsurface water on pasture hillslopes has a substantially longer MRT than subsurface water on forest hillslopes.

Three forms of land use occupy over 80% of the LTRB area: deciduous forest (748 km^2, 66%), pastoral agriculture (87 km^2, 8%), and residential (86 km^2, 8%). Analysis of the distribution of these land uses across the LTRB shows that each land use type occupies a significantly different range of landscape positions. Two of the variables used to describe landscape position, slope and elevation, play an important role when considering the local

water balance. In general, forests exhibit a tendency to occupy high slope and high elevation positions, residential land use occupies more moderate slope and elevation positions, and pasture land use tends to be found in the lowest slope and elevation positions. Precipitation within the LTRB increases with elevation; this suggests that across the entire basin forested hillslopes will receive the most precipitation while pasture hillslopes will receive the least. Slope is an important control on hydraulic gradients; steeper slopes will translate to an increased lateral component in the subsurface movement of water. As each land use type occupies significantly different positions, in terms of slope, each land use type may exhibit substantially different hydrologic functioning due to variations in subsurface flow. The results of spatial analyses support hypothesis one; significant differences exist between the landscape positions occupied by forest, residential, and pasture land use that may result in altered hydrology.

Analysis of field observations of hydrometric and hydro-meteorological data was conducted to examine differences in subsurface runoff among forest and pasture hillslopes used for this study. Three metrics were used to quantify shallow groundwater behavior from these hillslopes: connectivity, flashiness, and specific discharge. Significant differences were found to exist in all three metrics when comparing data from forest and pasture hillslopes. Forest hillslopes exhibit a tendency to remain predominantly in a disconnected state whereas pasture hillslopes remained either partially or fully connected throughout the study, even during potentially water limited periods of time. Flashiness, or variability, of shallow groundwater is greater on pasture hillslopes than forest hillslopes. During periods of possible water surplus, where precipitation was greater than potential evapotranspiration, flashiness of pasture hillslopes was as much as a full order of magnitude greater than flashiness of forest hillslopes. Even when one of the pasture hillslopes experienced climatological water deficit (i.e. potential evapotranspiration > rainfall), its flashiness remained higher than that of any forest hillslope at any time. Examination of specific discharge observations again indicates a clear difference between pasture and forest hillslopes. While forest hillslope specific discharge shows fairly consistent behavior throughout the study, pasture hillslope specific discharge is notably more variable. Specific discharge for pasture hillslopes is, at a minimum, 30% more variable than forest hillslopes, and at a maximum, a full order of magnitude more variable than forest hillslopes. The results of analyzing hydrometric and hydro-meteorological data support hypothesis two; pasture and forest hillslopes display significant differences in terms of their physical hydrology.

Mean residence time (MRT) refers to the length of time water spends in a given reservoir. The use of $\delta^{18}O$ as a conservative tracer in precipitation, A- and B-horizon soil water, and shallow groundwater allowed for the estimation of the mean residence time (MRT) of these same subsurface pools of water. The widely used method employed here provides a first approximation of MRT based on seasonal fluctuations in the input isotopic signal (precipitation) to the system and the damping of that signal as it propagates through the subsurface. Testing of hypothesis three serves to examine differences in MRT between forest and pasture hillslopes. While the estimates of MRT obtained here do vary notably among hillslopes, MRT is not clearly linked to land use. These results do not provide sufficient evidence to support hypothesis three, there is not an indication of a systematic variation between the MRT of subsurface pools on forest and pasture hillslopes. However, there is a possibility that precipitation characteristics (i.e. total rainfall, storm frequency, and storm intensity) strongly influence MRT and variation in these factors among sites exert a masking effect, preventing observation of a land use related influence.

Conclusion

Runoff generation is a complex process even in relatively homogeneous, undisturbed landscapes. In more diverse landscapes the problem increases in complexity. These points highlight the continued need for efforts within the field of watershed hydrology to better understand how landscape heterogeneity impacts runoff generation. Here we have provided empirical evidence suggesting a link between land use and variation in processes related to runoff generation at the hillslope scale within the Little Tennessee River Basin of the southern Appalachian Mountains. Additionally, the tendency for land use to occupy significantly different landscape positions, as described by hydrologically important variables, suggests that at the river basin scale, runoff generation from areas of different types of land use can be expected to vary substantially. However, the relationship between land use and runoff generation remains complex. Additional research is needed in order to better understand variation in the hydrology of areas subject to different forms of land use. In particular, work focused on disparities between land use types in specific hydrologic mechanisms and processes such as, shallow throughflow and actual evapotranspiration, that minimizes variability in confounding (e.g. hydro-climatic) factors may make substantial contributions to current knowledge. Alternatively, long-term before and after experimental approaches examining changes in runoff generation following changes from one type of land use to another, such as forest to pasture, could prove to be extremely useful in better understanding the relation between land use and runoff generating processes.

Despite the continued complexity and challenges facing the need to develop a detailed understanding of the interaction between land use and the water cycle, this project has produced clear evidence of a relation between runoff generating processes and land use within the region in question. These results have contributed to current knowledge within the field of watershed hydrology by isolating a general area of processes by which hillslope scale land use can lead to altered hydrologic function. Additionally, the probable links between hydrological function and land use distribution identified by this project present possible basin scale impacts of land use on hydrologic function. As the movement of water has important implications for both life and the transport of matter via physical and chemical processes the findings of this project have the potential to contribute to understanding in a broad range of areas.

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APPENDICES

APPENDIX A: SITE WELL AND LYSIMETER INFORMATION

Table A.1. Hillslope well and lysimeter depths and locations

Site	Position	Well depth (cm)	Horizontal distance, streambed to well (cm)	A-horizon lysimeter depth (cm)	B-horizon lysimeter depth (cm)
F1	A (near-stream)	358	270	23	38
	B (low-hillslope)	203	N/A	26	40
	C (mid-hillslope)	260	N/A	N/A	N/A
	D (upper-hillslope)	N/A	N/A	25	39
F2	A (near-stream)	151	270	23	58
	B (low-hillslope)	179	N/A	22	42
	C (mid-hillslope)	425	N/A	N/A	N/A
	D (upper-hillslope)	N/A	N/A	24	43
A1	A (near-stream)	413	340	21	49
	B (low-hillslope)	668	N/A	24	99
	C (mid-hillslope)	737	N/A	N/A	N/A
	D (upper-hillslope)	N/A	N/A	25	37
A2	A (near-stream)	124	310	25	25
	B (low-hillslope)	112	N/A	23	71
	C (mid-hillslope)	104	N/A	N/A	N/A
	D (upper-hillslope)	N/A	N/A	24	94

APPENDIX B: PHYSICAL DATA SUMMARY

Table B.1. Site F1 physical data summary, near-stream

Month	Median water table elevation above streambed (cm)	Monthly flashiness index value	Median monthly specific discharge (cm/hr)
Aug. 2011	116.9	0.0025	0.105
Sept. 2011	115.9	0.0027	0.104
Oct. 2011	115.0	0.0020	0.103
Nov. 2011	113.7	0.0017	0.102
Dec. 2011	113.6	0.0076	0.102
Jan. 2012	113.3	0.0029	0.102
Feb. 2012	114.9	0.0013	0.103
Mar. 2012	114.9	0.0015	0.103
Apr. 2012	114.8	0.0011	0.103
May 2012	114.4	0.0023	0.103
June 2012	112.7	0.0010	0.101
July 2012	111.8	0.0031	0.100
Aug. 2012	110.1	0.0014	0.099
Sept. 2012	108.9	0.0032	0.098
Oct. 2012	110.3	0.0048	0.100
Nov. 2012	109.1	0.0013	0.098
Overall mean	*113.1*	*0.0025*	*0.107*

Table B.2. Site F2 physical data summary, near-stream

Month	Median water table elevation above streambed (cm)	Monthly flashiness index value	Median monthly specific discharge (cm/hr)
Aug. 2011	71.5	0.0047	0.085
Sept. 2011	71.3	0.0082	0.085
Oct. 2011	70.6	0.0085	0.085
Nov. 2011	71.1	0.0051	0.085
Dec. 2011	70.0	0.0046	0.084
Jan. 2012	70.1	0.0018	0.084
Feb. 2012	70.1	0.0019	0.083
Mar. 2012	69.6	0.0023	0.083
Apr. 2012	70.9	0.0062	0.084
May 2012	70.7	0.0021	0.084
June 2012	69.7	0.0012	0.083
July 2012	69.0	0.0033	0.082
Aug. 2012	69.4	0.0026	0.083
Sept. 2012	69.3	0.0035	0.083
Oct. 2012	69.8	0.0033	0.083
Nov. 2012	68.6	0.0030	0.082
Overall mean	*70.1*	*0.0039*	*0.084*

Table B.3. Site A1 physical data summary, near-stream

Month	Median water table elevation above streambed (cm)	Monthly flashiness index value	Median monthly specific discharge (cm/hr)
Aug. 2011	N/A	N/A	N/A
Sept. 2011	N/A	N/A	N/A
Oct. 2011	N/A	N/A	N/A
Nov. 2011	86.3	0.0517	0.111
Dec. 2011	83.8	0.0268	0.110
Jan. 2012	86.8	0.0259	0.108
Feb. 2012	81.0	0.0131	0.087
Mar. 2012	79.8	0.0234	0.086
Apr. 2012	80.5	0.0320	0.087
May 2012	76.2	0.0132	0.081
June 2012	71.8	0.0107	0.076
July 2012	69.0	0.0129	0.073
Aug. 2012	66.2	0.0136	0.071
Sept. 2012	70.6	0.0193	0.075
Oct. 2012	78.5	0.0244	0.084
Nov. 2012	78.8	0.0046	0.083
Overall mean	*77.6*	*0.0209*	*0.087*

Table B.4. Site A2 physical data summary, near-stream

Month	Median water table elevation above streambed (cm)	Monthly flashiness index value	Median monthly specific discharge (cm/hr)
Aug. 2011	23.5	0.0155	0.069
Sept. 2011	24.2	0.0327	0.071
Oct. 2011	24.9	0.0283	0.073
Nov. 2011	24.5	0.0066	0.072
Dec. 2011	N/A	N/A	N/A
Jan. 2012	25.5	0.0275	0.075
Feb. 2012	23.0	0.0208	0.068
Mar. 2012	23.5	0.0389	0.069
Apr. 2012	24.6	0.0527	0.072
May 2012	24.7	0.0075	0.073
June 2012	22.8	0.0063	0.067
July 2012	23.0	0.0165	0.068
Aug. 2012	23.5	0.0155	0.069
Sept. 2012	24.2	0.0327	0.071
Oct. 2012	24.9	0.0283	0.073
Nov. 2012	24.5	0.0066	0.072
Overall mean	*24.1*	*0.0224*	*0.071*

APPENDIX C: STABLE ISOTOPE DATA SUMMARY

Table C.1. Site F1 oxygen stable isotope data

Date	Precipitation $\delta^{18}O$ (‰)	A-horizon $\delta^{18}O$ (‰)	B-horizon $\delta^{18}O$ (‰)	Groundwater $\delta^{18}O$ (‰)
8/13/2011	-2.94	N/A	N/A	-5.41
9/18/2011	-3.02	N/A	N/A	-6.08
10/16/2011	-7.07	N/A	N/A	-6.32
11/19/2011	-6.21	N/A	N/A	-6.33
12/8/2011	-3.95	-4.73	-4.53	-6.00
12/18/2011	-4.12	-4.13	-4.88	-7.11
12/21/2011	-3.45	-6.41	-4.71	-6.42
1/18/2012	-6.57	-6.73	-5.30	-6.92
2/1/2012	-4.83	-6.30	-5.35	-7.46
2/15/2012	-6.96	-5.82	-6.04	-6.75
2/29/2012	-7.00	-6.05	-5.74	-7.41
3/14/2012	-3.75	-5.35	-5.42	-7.30
3/28/2012	-3.59	-5.29	-5.44	-7.43
4/11/2012	-4.68	-5.04	-4.97	-7.19
4/25/2012	-4.04	-4.21	-4.81	-6.32
5/9/2012	-6.87	-3.96	-4.78	-6.18
5/23/2012	-3.81	-4.43	-4.63	-6.33
6/6/2012	-4.44	-4.74	-4.21	-5.41
6/20/2012	-4.49	-4.22	-4.59	-6.08
7/11/2012	-2.48	N/A	-4.44	-6.43
7/18/2012	-5.13	-3.90	-4.48	-6.47
8/1/2012	-3.26	-4.04	-4.31	-6.35
8/15/2012	-3.45	-3.71	-4.24	-6.54
8/29/2012	-4.61	-3.38	-4.04	-6.48
9/12/2012	-4.31	-3.77	-3.92	-6.27
9/26/2012	-5.35	-4.23	-3.73	-6.62
10/11/2012	-5.45	-5.02	-4.50	-6.36
11/7/1012	N/A	-4.73	-4.58	-6.34
11/20/2012	-3.7	-4.83	-4.59	-6.42
Overall mean	*-4.63*	*-4.79*	*-4.73*	*-6.51*

Table C.2. Site F2 oxygen stable isotope data

Date	Precipitation $\delta^{18}O$ (‰)	A-horizon $\delta^{18}O$ (‰)	B-horizon $\delta^{18}O$ (‰)	Groundwater $\delta^{18}O$ (‰)
8/13/2011	N/A	N/A	N/A	N/A
9/18/2011	N/A	N/A	N/A	N/A
10/16/2011	-7.73	N/A	N/A	-6.14
11/20/2011	-5.9	N/A	N/A	-6.27
11/29/2011	-4.16	-4.24	-5.25	-6.22
12/14/2011	-3.76	-4.66	-4.83	N/A
12/28/2011	-6.17	-4.66	-4.48	-6.25
1/11/2012	-4.64	-6.07	-4.55	-6.22
1/25/2012	-5.86	-5.45	-4.71	N/A
2/8/2012	-5.09	-5.31	-5.10	-6.42
2/22/2012	-10.88	-5.22	-5.49	-6.84
3/7/2012	-3.54	-4.92	-5.38	-6.44
3/21/2012	-4.79	-4.83	-4.99	-6.48
4/4/2012	-2.34	-4.09	-4.83	-6.09
4/18/2012	-4.13	-3.74	-4.54	-6.34
5/2/2012	-4.89	-3.73	-4.33	-6.44
5/16/2012	-3.95	-4.17	-4.03	-6.46
5/30/2012	-4.33	-4.17	-4.12	N/A
6/13/2012	-3.41	-3.97	-3.99	-6.64
6/20/2012	-4.3	N/A	N/A	-6.38
7/18/2012	-4.47	N/A	-4.32	-6.55
7/25/2012	-1.93	-4.11	-4.22	-6.54
8/8/2012	-3.75	-3.69	-4.15	-6.14
8/22/2012	-5.51	N/A	-4.03	-6.50
9/5/2012	-4.6	-4.42	-4.34	-6.63
9/21/2012	-5.7	-4.59	-3.82	N/A
10/3/2012	-5.6	-4.96	-4.26	-6.14
10/24/2012	N/A	-5.05	-4.41	N/A
11/2/2012	-10.01	N/A	N/A	-6.48
11/14/2012	-7.49	-4.64	-4.53	-6.40
Overall mean	*-5.15*	*-4.58*	*-4.53*	*-6.39*

Table C.3. Site A1 oxygen stable isotope data

Date	Precipitation $\delta^{18}O$ (‰)	A-horizon $\delta^{18}O$ (‰)	B-horizon $\delta^{18}O$ (‰)	Groundwater $\delta^{18}O$ (‰)
8/13/2011	N/A	N/A	N/A	N/A
9/18/2011	N/A	N/A	N/A	N/A
10/16/2011	N/A	N/A	N/A	N/A
11/19/2011	N/A	N/A	N/A	-7.15
12/8/2011	N/A	N/A	N/A	N/A
12/18/2011	N/A	N/A	N/A	N/A
12/21/2011	N/A	N/A	N/A	N/A
1/18/2012	-5.76	N/A	N/A	N/A
2/1/2012	-8.94	N/A	N/A	N/A
2/15/2012	-5.37	-4.88	-5.72	-6.91
2/29/2012	-2.77	-4.62	-4.66	-7.09
3/14/2012	-3.64	-4.37	-5.39	-7.05
3/28/2012	-4.33	-4.50	-5.03	-6.96
4/11/2012	-5.08	-4.15	-5.40	-7.09
4/25/2012	N/A	-3.35	-4.94	-7.03
5/9/2012	-4.08	N/A	-4.21	-6.63
5/23/2012	-2.91	-3.16	-3.71	-6.28
6/6/2012	-2.19	-2.93	-3.78	-6.22
6/20/2012	-4.54	N/A	-4.79	-6.41
7/11/2012	-2.44	N/A	N/A	N/A
7/18/2012	-2.26	-3.18	-4.44	-6.58
8/1/2012	-4.37	N/A	-5.01	-6.38
8/15/2012	-4.8	N/A	N/A	-6.47
8/29/2012	-6.06	N/A	N/A	-6.44
9/12/2012	-5.29	N/A	N/A	-6.45
9/26/2012	-10.66	N/A	-4.86	-6.41
10/11/2012	-4.53	-4.36	-4.90	-6.51
11/7/1012	N/A	N/A	-4.75	-6.54
11/20/2012	N/A	N/A	-4.61	-6.39
Overall mean	*-4.78*	*-3.95*	*-4.76*	*-6.65*

Table C.4. Site A2 oxygen stable isotope data

Date	Precipitation $\delta^{18}O$ (‰)	A-horizon $\delta^{18}O$ (‰)	B-horizon $\delta^{18}O$ (‰)	Groundwater $\delta^{18}O$ (‰)
8/13/2011	N/A	N/A	N/A	N/A
9/18/2011	N/A	N/A	N/A	N/A
10/16/2011	N/A	N/A	N/A	N/A
11/20/2011	N/A	N/A	N/A	N/A
11/29/2011	N/A	N/A	N/A	-6.58
12/14/2011	-3.16	N/A	N/A	-6.74
12/28/2011	N/A	N/A	N/A	-6.66
1/11/2012	-4.7	N/A	N/A	-6.53
1/25/2012	-5.74	N/A	N/A	-6.37
2/8/2012	-4.06	-5.15	-6.20	N/A
2/22/2012	-10.96	-5.24	-6.02	-6.19
3/7/2012	-3.4	-4.85	-5.83	-6.42
3/21/2012	-4.14	-4.64	-5.78	-6.30
4/4/2012	-2.87	-4.71	-5.46	N/A
4/18/2012	-3.87	-4.87	-5.73	-6.32
5/2/2012	-4.69	-4.73	-5.54	-6.18
5/16/2012	-4.66	-4.74	-5.61	-6.40
5/30/2012	-5.27	-5.16	-5.81	-6.43
6/13/2012	-3.52	-4.58	-5.48	-6.58
6/20/2012	-3.77	-4.76	-5.38	-6.40
7/18/2012	-4.73	-5.86	-5.40	-6.47
7/25/2012	-1.63	-4.53	-5.22	-6.46
8/8/2012	-3.81	-4.66	-5.35	-6.45
8/22/2012	-6.03	-4.66	-6.18	-6.64
9/5/2012	-4.65	-4.61	-5.39	-6.58
9/21/2012	-6.43	-4.36	-5.38	N/A
10/3/2012	-5.93	-4.81	-5.80	-6.40
10/24/2012	-5.59	-5.05	-5.84	-6.25
11/2/2012	-9.71	-5.10	-5.62	-6.50
11/14/2012	-8.25	-5.11	-5.66	-6.36
Overall mean	*-5.07*	*-4.89*	*-5.65*	*-6.44*