Land use, hydrological processes and ecosystem services in the upper Reventazón watershed, Costa Rica.

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Abstract

Costa Rica experienced large scale deforestation between the 1940s and 1980s. Due to the rapid loss of forest, the Costa Rican government initiated the Pagos para Servicios Ambientales, or Environmental Service Payments (ESPs), program that linked ecosystem services such as biodiversity conservation and hydrological services to forested land cover by compensating private landowners for forest preservation, regeneration, or agroforestry activities. However, the effect of land use on hydrological services and processes remains an area of active research. Within the framework of the ESPs, this research investigated: 1) understanding the regional tropical hydrology, 2) determining whether regional land uses impact soil characteristics and hydrological processes, and 3) evaluating the significance and overlap of different ecosystem services within the context of conservation planning. In the first chapter, I measured soil properties and hydrological processes within common regional land uses (forest, coffee, sugar cane and pasture) at the point, the plot, and the field scales. Macropore networks facilitated much more percolation in the forest and coffee. Compaction in the sugar and pasture diverted precipitation horizontally as surface runoff and lateral flow. In Chapter 2, I investigated whether similar results could be observed at greater scales using one-cell and watershed model simulations based on the Soil Moisture Routing model. I combined land use parameterization to investigate the interplay of antecedent moisture content (AMC), infiltration, surface runoff and percolation using a one-cell model. At this scale, a 'fill and spill' runoff generation mechanism was observed when precipitation intensity exceeded the different land use soil storage amounts and conductivities. The greatest differences between land uses were observed at AMC less than

field capacity where subsurface connectivity was limited within the sugar and pasture. Seven nested watersheds were classified as either forested (>85% forested) or mixed-land use watersheds (<50% forested). At the watershed scale, greater amounts of percolation occurred during the transition from the dry season to the wet season in the forested watersheds than in the mixed-land use watersheds. Also, surface runoff occurred earlier in the mixed-land use watersheds than in the forested watersheds. The connectivity between the greater percolation and greater streamflow in the forested watersheds than the mixed-land use watersheds suggests the 'fill and spill' type mechanism may be enhanced through greater conductivities and macropore connectivity. In Chapter 3, I modeled multiple ecosystem services of different multi-strata coffee agroforestry systems (CAFS) within the Volcánica Central de Talamanca Biological Corridor. Interviews and a Strengths, Weaknesses, Opportunities and Threats analysis, and maps of the ecosystem services were used to prioritize ecosystem services and areas for conservation activities. Current CAFS management within the VCTBC provided the greatest opportunity for preservation of hydrological and integrated pest management services. While certain CAFS regions were prioritized because of specific ecosystem services, stakeholders included location, proximity to roads and resources, and organizational infrastructure as other themes for prioritization.

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List of Abbreviations

AMC- antecedent moisture condition

CAFS- coffee agroforestry systems

ET- evapotranspiration

F- forested

M- mixed-land use

P- percolation

VCTCB- Volcanicá Central de Talamanca Corredor Biologico

Introduction

Across the tropics, and the world, agricultural cropland and pasture have expanded into forest with little sign of retreat (Fisher and Helig 1997). In Costa Rica, a primary result of development over the past 70 years has been land use change. Costa Rica had an extremely high percentage of deforestation from the 1940s to the 1980s. In 1983, only 17% of the 1940 acreage remained intact. Between 1986-1991, Costa Rica experienced one of the highest deforestation rates in the world (Sader and Joyce 1988). While tropical hardwood extraction was one economic aspect of the deforestation, pasture and crop expansion drove the majority of the land use change (Sanchez-Azofeifa et al. 2001). During and after agricultural expansion, the Costa Rican landscape has been heavily influenced by cash crops, government subsidies, foreign aid, and the global economy. These influences promoted particular land uses (e.g., pasture, coffee, sugar cane, bananas, pineapples, etc.) throughout different periods of time (Hall 2000).

Due to the rapid loss of forest, and increasing concerns about the loss of its ecosystem services, the Costa Rican government passed Forest Law 7575 in 1996. The law was a product of over 30 years of debate, which linked ecosystem services such as biodiversity conservation, carbon sequestration, scenic beauty, and hydrological services to forested land cover (Reyes et al. 2000). This law introduced the Pagos para Servicos Ambientales (PSAs), or Environmental Service Payments. Within this program, individual landowners could be compensated for reforestation, sustainable management of forests, preservation, and regeneration of forests. The Costa Rican government funds this program through a separate fuel tax and unique international agreements (Chomitz 1999).

While carbon and biodiversity ecosystem services have drawn several prominent international agreements to fund the program, the provision of hydrological services has drawn a wide array of national and local stakeholders. In fact, negotiations with water users have developed more streamlined and novel applications of this governmental program than the other services. Agreements have been made with hydroelectric companies, water bottlers, agricultural cooperatives, municipal water supplies, and even hotels (Pagiola 2008).

The loss of hydrological services often has more direct consequences to local and national stakeholders than carbon sequestration and loss of biodiversity. Over the last several decades, hydroelectric power generation dramatically increased in Costa Rica (Quesado-Mateo 1990). In 2008, hydropower produced 78% of the country's electricity demand (Gomez-Delgado et al. 2011; UNESCO 2007). The watershed discussed in this dissertation, the Rio Reventazón, provides approximately 27% of Costa Rica's hydroelectricity (Locatelli et al. 2011). With no domestic oil supplies, Costa Rica relies heavily on its steep topography and plentiful rainfall to produce electricity. However, extreme peak flows and erosion cause loss of power generation due to the limited capacity of reservoirs in Costa Rica (Pagiola 2003). Flooding has also led to a significant loss of life, property and infrastructure throughout Costa Rica (Waylen and La Porte 1999). Sanchez-Azofeifa et al. (2002) observed likely trends between increased forest fragmentation and the amount of economic loss due to flooding in several of the major watersheds in Costa Rica.

Pagiola (2003) identified at least two major quantifiable hydrological services of importance to Central America. Some of these services include: 1) regulation and improvement of seasonal distribution of water flow, and 2) reduction of flooding and drought occurrence and magnitude. Increased infiltration, recharge of aquifers and reduced erosion have been suggested as other hydrological services of importance to Costa Rica (Gomez-Delgado et al. 2011, MEA 2005). One question that needs to be answered for a system of payment for hydrological services is what type of land use in a given location will provide the greatest level of hydrological services (Wunscher et al. 2008). Costa Rica, perhaps more than any other country, has made a significant investment to capitalize on ecosystem services provided by forests.

The influence of forests on hydrologic processes has been debated for several decades (Hamilton and King 1983; Bruijnzeel 1991, Tomich et al. 2004). This debate is especially interesting in Costa Rica when both increased base flows and a reduction of flooding are desired hydrological services. In forested catchments, hydrometric and isotope studies have suggested that groundwater and subsurface storm flow provide a significant amount of the stream discharge during a storm event (e.g. Kendall and McDonnell 1998). These studies suggest that efficient aquifer recharge is the dominant hydrological process controlling river discharge and baseflow. Others still question the extent land use change influences hydrological services, such as water supply, flood frequency and intensity. Forests are lauded for their natural services of increased infiltration and reduced erosion potential (Tomich et al. 2004). However, different conceptualizations of how soil characteristics influence hydrological response may well explain similar services (Dunne 1978; Elsenbeer 2001).

Forestry practices have been studied extensively in their hydrological responses (Bosch and Hewlett 1982; Harr 1986; Bruijnzeel 1991). Many of these studies have observed water yield increases due to less evapotranspiration(ET) of post-forest land cover types. Land use conversion changes vegetation type and structure, affecting the amount of ET, and its influence on storm runoff (Zhang et al. 2001). Deforestation leads to a greatly reduced leaf area, which in turn reduces or eliminates the interception capacity and transpiration of the forest. The loss of transpiration is of no small consequence; mature tropical forests in Costa Rica can transpire over 50% of the bulk precipitation (≈ 2 m) when unlimited in terms of soil moisture (Loescher et al. 2005). Decreased water demand, evapotranspiration, and extraction from deeper subsurface sources of water are other noted effects of forest conversion (Imbach et al. 1989; van Dijk and Bruijnzeel 2001). Changing ET demands influences the soil moisture conditions of a watershed and potentially its ground water reserves. Increased levels of antecedent soil moisture are often the precursor to surface runoff. Bruijnzeel (2004) found that if surface disturbance remains limited, the bulk of these increases occur during base flow (low flow) conditions. If infiltration characteristics of the forest are preserved, then most of this water should connect to the groundwater sources and increase base flow (Bosch and Hewlett 1982). Therefore, based solely on vegetation characteristics, conversion from forest to agriculture should increase water yields (Costa and Foley 1997; Calder 1998; Zhang et al. 2001; Costa 2003).

However, vegetation type also influences soil hydrological parameters related to soil structure such as infiltration capacity, hydraulic conductivity, macropore connectivity, antecedent moisture content and water retention (Himo et al. 1987; Williamson et al. 2004; Hanson et al. 2001; Hendricks and Flury 2001). Each of these impacts can potentially change flow paths from vertical to lateral throughout a watershed. Root zones potentially influence the vertical and horizontal hydraulic conductivity, and thus saturated overland flow (Beer et al. 1995; Elsenbeer 2001). Soil disturbance from agricultural land use, such as reduced infiltration and destruction of macropores, can affect flow paths leading to more flooding and less groundwater recharge. The saturated hydraulic conductivity (K_{sat}) plays an important role in the determination of flow paths within a soil (Elsenbeer 2001; Ziegler et al. 2004). Godsey and Elsenbeer (2002) measured K_{sat} values in forest, abandoned banana-cacao, and pasture. Differences between the land uses at shallow depths influenced the infiltration capacity and the associated runoff index.

Soil compaction is often the result of land use, such as heavy machinery use or animal traffic, impeding the connection to subsurface storm flow. Preferential flow paths, often destroyed or modified by compaction, play an important role in humid forested hillslope hydrology (Mosley 1979; McGlynn et al. 2002). The loss of macropore connectivity reduces infiltration rates and lateral flows (Bodhinayake and Cheng Si 2004; Wilson and Luxmoore 1988; Hanson et al. 2004). The investigation of macropore connectivity and land use change has only begun to be assessed at the plot scale (see Chapter 2; Hanson et al. 2004). Kamauzaman (1991) showed an increase in overland flow due to soil compaction. Lal (1996) and Gilmoure et al. (1987) showed that continued exposure of bare soil to intense rainfall and overgrazing are two other aspects of land use correlated with a switch from subsurface to surface flow. Costa et al. (2003) concluded that an increase in wet season flows was due to a significant portion of the watershed being compacted by pasture use. When compaction influences a watershed response, wet season flood frequency and intensity is increased, while dry season groundwater recharge is impeded (Costa et al. 2003; Bruijnzeel 2004). Within the first two chapters of this dissertation, I investigated how different land uses affected soil characteristics and hydrological processes at the point, plot, field and watershed scales.

Different land uses also influence the flow of organisms across the landscape (Gustafson and Gardener 1996). The final chapter models hydrological services (i.e., risk of soil erosion and groundwater contamination) in coffee agroforestry systems at the regional scale. This chapter evaluates the overlap of several different ecosystem services (hydrological services, biodiversity services, integrated pest management services), and investigates stakeholder preference for different ecosystem services within the Volcanica Central de Talamanca Biological Corridor. Research has shown that specific agricultural practices, especially agroforestry systems, can increase ecosystem services (i.e. “conditions and processes through which natural ecosystems sustain and fulfill human life”; Daily 1997) provided by those productive systems, while supporting productive activities (Harvey et al. 2005). Agroforestry systems are now included in payments for environmental services in Costa Rica (Wunscher et al. 2008).

Scientists have given much attention to coffee agroforestry systems (CAFS) as a potential sustainable land use. Coffee is prevalent throughout the tropics and one of the most heavily traded commodities in the global economy (Vegas and Rosenquist 2001). Within the upper Reventazón watershed, coffee agroforestry systems cover approximately 32% of the watershed area. CAFS can provide ecosystem services such as maintaining biodiversity, reduction of erosion, reduction of water contamination by agrichemicals, and reducing pest populations, depending on their structure and management (Perfecto et al. 1996; Somarriba et al. 2004; Pérez Nieto et al. 2005; Varón 2006). In many regions, CAFS often exist near critical regions for conservation (e.g., Southern Mexico; Moguel and Toledo 1999). Even though CAFS have potential as a sustainable economic activity within corridors, it is unknown how decision makers involved in corridor design and implementation value these systems and the services they provide.

Historically, conservation planning efforts have relied heavily on assessing systems from a biophysical perspective. Rarely did these efforts include the perceptions and values of local people from communities affected by the planning. The knowledge that local people can provide is often considered afterwards rather than as input during conservation planning (Brown et al. 2004). However, researchers and policy makers are beginning to understand the importance of recognizing landowner and stakeholder perspectives, and how local knowledge can inform project design (Russell and Harshbarger 2003). Understanding and incorporating local knowledge and perspectives into conservation planning can also help with the implementation of resulting actions. Scientists' understanding of the biological processes occurring in a particular region can be improved by drawing upon local knowledge (Brown et al. 2004). Incorporating decision makers can result in conservation plans that are scientifically sound but also publicly supported (Meo et al. 2002; Russell and Harshbarger 2003).

This dissertation details research conducted within the upper Reventazón basin near Turrialba, Costa Rica. Turrialba lies approximately in the middle of the Rio Reventazón basin, which is one of the major drainages running from the Cordillera Central in Central Costa Rica to the Atlantic Coast (Jansson 1996). Two volcanoes, Irazu and Turrialba, influence precipitation and soils in the study area. The International Model Forest at the Centro Agronómico Tropical de Investigación y Ensenanza (CATIE) and the Volcanica Central de Talamanca Biological Corridor both encompass significant portions of this watershed and focus on the integration of ecosystem services and socio-economic well being. The Rio Reventazón provides approximately 27% of Costa Rica's hydroelectricity. Locatelli et al. (2011) identified this watershed as one of the major priority watersheds for both conservation and restoration.

In this dissertation, I asked the following research questions: 1) How does land use influence soil characteristics and hydrological processes at the point, plot, and field scale?, 2) How does land use affect river discharge at the watershed scale in the upper Reventazón watershed?, 3) How do different ecosystem services overlap within the Volcanica Central de Talamanca Biological Corridor?, and 4) How do stakeholders incorporate ecosystem services for prioritization and restoration activities within the VCTBC?

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CHAPTER 1

Effects of land use on soil properties and hydrological processes at the point, plot, and field scale in volcanic soils in the Turrialba Region of Costa Rica.

Abstract

Deforestation and conversion to crop land and pasture in tropical regions has important effects on hydrological processes including increased flooding and reduced drought flows. Few studies have investigated the simultaneous effects of multiple land uses in tropical regions at different scales. Upscaling from point scale measurements remains a challenge due to soil heterogeneity. In this study, I measured soil properties and hydrological processes at four sites representing four common land uses in Costa Rica (forest, coffee, sugar cane and pasture) at the point scale, the plot scale (1 m^3), and the field scale (1-4 ha). At the point scale, I measured bulk density, organic matter, saturated hydraulic conductivity (K_{sat}), cumulative infiltration, and soil moisture at the soil surface and with depth. At the plot scale, I performed mass balance experiments in triplicate using artificial irrigation to determine infiltration, runoff, lateral flow, change in storage, and percolation, for each land use type. At the end of these experiments, I used Brilliant Blue dye to characterize differences in flow paths between the land uses. At the field scale, streamflow was measured from June 2004 to December 2006 using an H-flume that was installed below each land use type. While most of the soil characteristics between the field sites were similar, bulk density at the forest site (0.7 g/cm^3) was significantly lower than bulk density at the other field sites (1.0 g/cm^3). Soil moisture at the surface in the sugar cane and pasture sites was consistently greater than in soils of the forest and coffee sites.

Saturated hydraulic conductivity at the forest and coffee sites was at least twice K_{sat} at the sugar cane and pasture sites. At the plot scale, sugar cane and pasture plots had greater surface runoff and lateral flow coefficients (>30%) than the coffee and forest sites (<15%) during the mass balance experiments. Preferential pathways, along with deeper, thicker roots, facilitated the dye reaching greater depths at the forest and coffee plots. At the field scale, runoff was minimal at all of the field sites during the dry season. During the wet season, soil compaction and root characteristics played a strong role in shaping runoff characteristics. The sugar cane site had the greatest runoff coefficient (7%), event frequency, volume and intensity. Runoff coefficients at the other sites were less than 5%. The interplay of compaction at the surface, presence of different root distributions, and reduced bulk density with depth affected infiltration and storage dynamics in response to high intensity rainfall that provided primary controls for ‘fill and spill’ runoff generation during the wet season. In addition, flow convergence due to lateral flow from upland areas and restrictive layers augmented the 'fill and spill' mechanism. As measurement scale increased from the point to plot scale, infiltration rates increased due to the inclusion of more macropores. At the field scale, the effect of land use on runoff generation was somewhat diminished because the measurement scale included a greater number of macropores. These findings have implications for groundwater recharge and runoff predictions which are described in Chapter 2.

Introduction

In humid tropical countries, hydrological processes profoundly affect economic livelihoods, energy production, human health and the quality of the environment. In Costa Rica, storm runoff has led to loss of human lives, residences, crops, and public infrastructure (Waylen and La Porte 1999). Extreme peak flows and sediment transport reduce the capacities of the many small scale hydropower projects that produce a majority of the country's electricity demand (Jansson and Erlingsson 2000; Sanchez-Azofeifa et al. 2002). Percolation, surface runoff, and subsurface lateral flows direct chemical loading that negatively affects water quality as population increases (Reynolds-Vargas et al. 1994; Rawlins et al. 1998; Renderos-Duran et al. 2002). Increased understanding of the hydrological processes that drive flooding, erosion, and contamination will contribute to better water resource management in the humid topics.

Long-term water policies in Costa Rica and other countries in the humid tropics often lack the parameters needed to evaluate their efficacy (Sanchez-Azofeifa et al. 1994). In a 1996 Forestry Law, an innovative strategy was introduced to promote or conserve hydrological ecosystem services within the *Pagos para Servicios Ambientales (PSAs)*, or Environmental Service Payments program. While the definition of hydrological services is somewhat ambiguous, Pagiola (2003) identified two quantifiable hydrological services of importance to countries in Central America: 1) the regulation and improvement of seasonal distribution of water flow; and 2) a reduction in flooding and drought occurrences and magnitudes. Until now, 95% of these payments have gone to forest conservation (Pagiola, 2008). However, public and academic perceptions about the benefit of forest derived hydrological services continue to be debated (Hamilton and King 1983; Bruijnzeel 1991; Tomich et al. 2004). Since these payments are directed to specific types of land use, specific knowledge about the hydraulic conductivity, water retention characteristics and rooting patterns of different upland crops in tropical environments is needed both in Costa Rica and within the tropical hydrology community (Bonell 1993; Giambelluca et al. 1999; Bigelow 2001; Godsey and Elsenbeer 2002; Bruijnzeel 2004).

Land use affects soil hydrological characteristics such as preferential flow paths, saturated hydraulic conductivity (K_{sat}), macropore connectivity, root mass and water retention (Hendricks and Flury 2001; Himo et al. 1987; Hanson et al. 2004; Williamson et al. 2004). Preferential flow paths often determine flow directionality (e.g. lateral vs. vertical) in humid forested hillslopes (Mosely 1979; McGlynn et al. 2002; Tromp-van Meerveld and McDonnell 2006). The K_{sat} was shown to determine the dominant flow paths in tropical soils (Elsenbeer 2001; Ziegler et al. 2004). Godsey and Elsenbeer (2002) measured K_{sat} in forest, abandoned banana-cacao, and pasture in Brazil. Differences between the land uses were found at shallow depths suggesting compaction influenced K_{sat} and the resulting runoff indices. Other studies have suggested that compaction from cattle, tractors, plows and foot paths lowers infiltration rates, reduces percolation, destroys macropores, and increases surface runoff (Hanson et al. 2004; Verbist et al. 2007; Ziegler et al. 2006).

Frequently, effects of land use are documented at one particular scale (e.g., point, plot, field, or watershed). It is well known that it is a challenge to measure hydrological properties at the relevant scale (Brooks et al. 2004). Upscaling measurements from the point or plot scale can result in loss of actual *in situ* soil heterogeneity (Grayson et al. 1992).

At smaller scale measurements, quantity and quality of data collection and model resolution often prohibit a truly representative sample size, and one may not obtain the true parameter values. The investigation of macropore connectivity among different land uses has only begun to be assessed at the plot scale (Hanson et al. 2004; Lehmann et al. 2007)

In this field study, I characterized soils and hydrology of four land use types (forest, coffee, sugar cane, and pasture) at the point, plot and field scale. Specific objectives were to 1) determine differences in soil characteristics between the four land uses, 2) determine how land use impacts soil moisture, 3) determine how hydrological processes differ between the four land uses, 4) determine how land use affects the seasonal distribution of water flow, and/or hydrograph characteristics, and 5) determine how measurements at different scales provide different conceptual understanding of hydrologic processes.

Methods and Materials

Four field sites were selected to compare the forest, coffee, sugar cane and pasture land use based on field size (1-4 ha), proximity to each other (≈1 km), homogeneity of land use cover, slope, and presence of a channel. Precipitation was monitored at the Tropical Agricultural Research and Higher Education Center (CATIE) meteorological station and periodically at the field sites. At the point scale, soil surveys were completed at each field site for various soil physical characteristics. Soil moisture was measured from September 2006 to February 2007 at toe slope and mid slope locations in each field at the 0.1 m and 1 m depths. At the plot scale, three 1 m^3 runoff/lateral flow plots were established in each field to measure soil moisture, surface runoff, and lateral flow to 1 m depth. Dye tracers were used on the 1 m^3 plots to visualize flow paths within the plots. At the field scale, an H-flume was installed in the channel draining each field to measure runoff.

Study Site

Research was conducted on the CATIE farm near Turrialba, Cartago, Costa Rica at approximately 650 masl (Figure 1). The CATIE farm lies approximately in the middle of the Rio Reventazón basin, which is one of the major drainages running from the central mountain range to the Caribbean (Jansson 1996). The study area receives 2500-3000 mm of precipitation annually increasing with elevation (Chacón and Fernandez 1985; CATIE meteorological station). Two volcanoes, Irazu and Turrialba, influence precipitation and soils in the study area. During the dry season (January through April), monthly average rainfall ranges from 86.7-177.5 mm with an average of 15 days receiving more than 0.1 mm. During the wet season (May through December), average monthly precipitation ranges from 245 -310 mm, with an average of 23 days receiving 0.1 mm or more precipitation. Temperatures average between 20.6-22.7^{o}C throughout the year, with an absolute maximum temperature of 33^{o}C (December) and an absolute minimum temperature of 10^{o}C (January). Potential evapotranspiration ranges from 85 mm/month (July) to 115 (April) mm/month with a mean of 95 mm/month. Topography in the study area is characterized by steep slopes and numerous small drainages. The experimental field soils have been classified as Inceptisols. Soils at the study site are deep (≈ 5 m to bedrock), anisotropic clayey loams (up to 70% clay at 1 m depth), with andic properties in the upper 0.5 m of the soil.

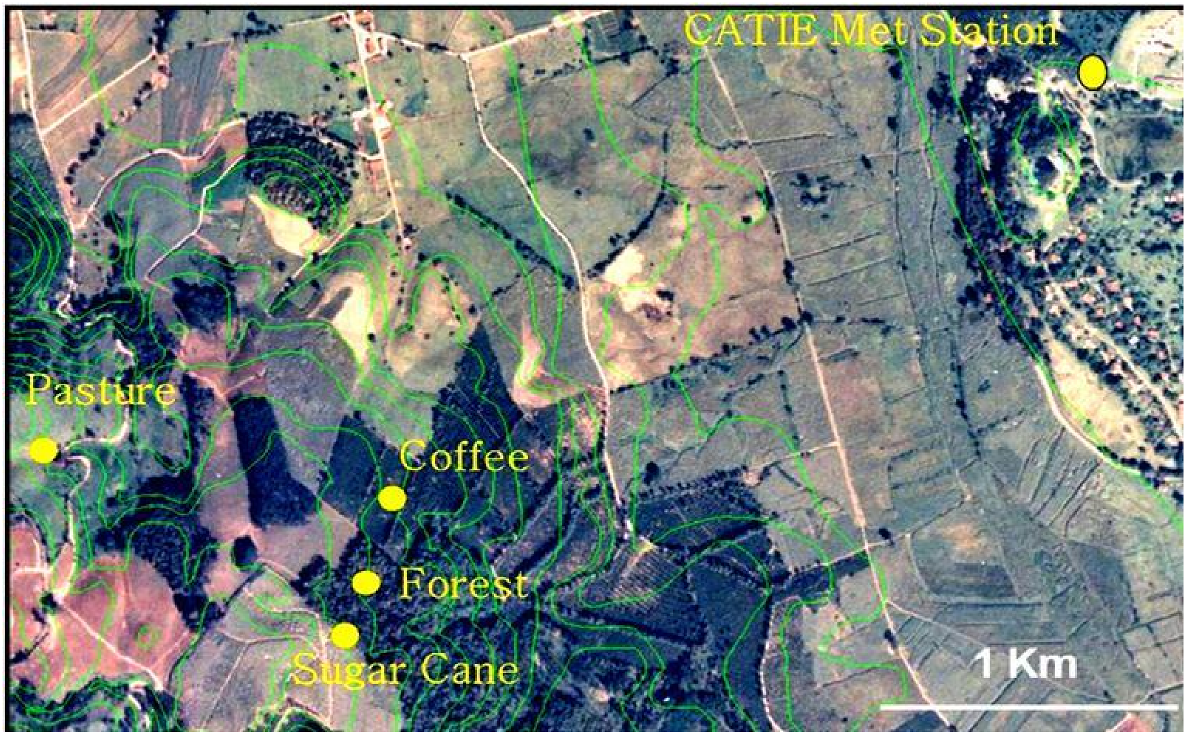

Figure 1. Location of forest, coffee, sugar cane and pasture land use field sites and the CATIE Meteorological station. Green lines are 10 m contours.

Precipitation

Continuous precipitation data were obtained from the meteorological station on the CATIE campus, located approximately 3 km from the field sites.

Land use characteristics and management

Experiments and monitoring were performed at four field sites (1-4 ha) with the following land use types: forest, pasture, sugar cane, and coffee. These land use types are representative for the upper Reventazón watershed (forest 40%, pasture 21%, coffee 14%, and sugar 12%). Each field site had distinct vegetation characteristics and management practices. The sugar cane site was harvested every year, which entailed one burning in April, clearing throughout April, a final burning, plowing, followed by seeding. Plowing and harvesting were aided by extensive use of a large tractor. Sugar cane grew to a height of 2 m in approximately 3 months. During this period, a very thin (10-20 mm) and heterogeneous organic layer of broken sugar cane leafs developed on top of otherwise bare soil. The forest site was immediately downstream of the sugar cane site. These sites were the only two sites to share a channel. The forest site contained a mixture of primary and secondary vegetation consisting of few large trees (>1 m in diameter at 1.5 m in height) and a sparse understory with an almost completely closed canopy. The organic layer in the forest was thin presumably due to the age of the forest (> 40 yrs). No management occurred at the forest site. In 2004, the pasture was active throughout the end of the year with approximately 10 cows/ha causing signs of compaction at the surface by hoof prints and cattle paths. After January 2005, when stocking cows in the pasture had been abandoned, razor grass with average height of 1 m quickly overtook the pasture field site. A dense, thick layer (0.1-0.15 m) of living organic matter and roots covered the soil surface in the pasture. The coffee site was managed as a standard *Inga spp.* shade system (≈50% shaded) with conventional chemical management. Coffee was harvested three times a year. Prior to harvest, the shade trees were pruned to a tall stump (1-1.5m) to allow ripening of the coffee beans. Therefore, this site received full sun for about three months of the year. *Impatiens walleriana* were a common ground cover at the coffee site and varied from completely covering the field site to being totally absent after herbicides were applied.

Point scale: soil properties

Soil sampling was conducted at each field site. Three transects were selected and followed perpendicular to the hillslope. Nine soil pits were dug in each field site to a 1 m depth, in toe slope, mid slope, and ridge positions along the transects. Soils were classified using the NRCS Handbook (Soil Survey Division Staff, 1993) based on observed soil horizons, color, structure, pore size and density, and rock content of the profile. Root size and depth was measured using calipers and a ruler. Root density was visually estimated along the profile. Soil sampling depths corresponded to soil horizons. Soil samples were taken from the upslope side wall from 0-0.1, 0.1-0.25, 0.25-0.5, and 0.5-1 m depths. These samples were analyzed at CATIE's Soil, Plant Tissue, and Water laboratory for bulk density, organic matter, aluminum and iron oxalate (AlO and FeO) composition (andic properties), and texture. Bulk density samples in duplicate were taken at 0-0.1, 0.40-0.50, and 0.90-1.0 m depths using brass rings with a radius of 31.5 mm and a length of 100 mm. Soil was excavated from the top down using a wide weeding machete to the desired depth. A brass ring was inserted vertically into the soil profile, excavated and capped for transport to the lab. Analysis of variance (ANOVA) statistics were performed to compare data between field sites and between different depths within field sites.

Point scale: saturated hydraulic conductivity (Ksat) and cumulative infiltration

Double ring infiltrometers (diameters of 0.20 m (inner) and 0.50 m (outer)) were used to measure K_{sat} using a steady infiltration rate at a constant head (Reynolds et al. 2002). Three transects were set up across each field site, at the toe slope, mid slope, and ridge. Thirty measurements at the surface and 20 measurements at the 0.5 m depth were taken in each field site. On flat surfaces (< 5% slope), vegetation was cut as close to the surface as possible. Leaf litter, twigs, etc., were removed from the sample location. On steeper surfaces and at the 0.5 m depth, careful excavation occurred at the sample location to allow the ring to be level. The steel rings were pushed into the soil to a depth of 50 mm with minimal soil disturbance. Surrounding soil was lightly tamped using the blunt edge of a pencil to avoid flow along the inside wall of the ring. Small rulers were inserted into the inner and outer rings. Both rings were filled to 40 mm height with water from a local spring. Once the level of the water within the rings lowered to 30 mm height, time was recorded, and the rings were refilled to the 40 mm height. This process was repeated until the same time was recorded at least three times in a row (2-6 hrs). At this point, it was assumed that steady-state flow was achieved. The K_{sat} was calculated based on the final time measurement. The water pressure head varied from 30 to 40 mm during the infiltration measurements. Therefore, 35 mm was used as the steady depth of ponded water (Bodhinayake and Si 2004).

Saturated hydraulic conductivity was calculated for a ponded ring infiltrometer with a constant head (Reynolds et al. 2002) as follow:

$$K_{fs} = \frac{\alpha G A Q}{(r(\alpha H + 1 + G\alpha\pi r^2)} \qquad (1)$$

where Q is the quasi-steady infiltration rate, A is the area of the inner ring, r is the radius of the ring, H is the height of the ponded water, α is the Gardner coefficient set at 12 1/m as a general value for agricultural soils (Reynolds et al. 2002), G is a dimensionless geometry factor calculated for H < 50 mm as in Reynolds and Elrick (1990):

$$G = 0.316\left(\frac{d}{r}\right) + 0.184 \tag{2}$$

where *d* equals the depth of the ring insertion (50 mm). Results were compared between each field site and each depth using ANOVA statistical tests. Finally, cumulative infiltration depths were calculated as the amount of water required to reach K_{sat}.

Point scale: soil moisture

A Davis Complete Soil Moisture/Temperature station (Davis Instruments Corp, CA) was installed in each of the field sites above the H-flumes. Each soil moisture station was comprised of four granular matrix sensors (Watermark Inc., CA). Two plot locations were selected in each field and placed on a similar slope, approximately 2 m from the stream channel and in the mid slope position approximately 25 m upstream from the H-flume. At each soil moisture site, two sensors were placed at depths of 0.1 m and 1 m. Soil moisture data were logged at 30-minute intervals. Soil water tension readings were converted to volumetric water content based on an existing soil water release curve for the field site soils. Data records for seasonal soil moisture cover several months. Data were recorded from 9/17/2006 to 12/15/2006 (forest and coffee), from 11/5/2006 to 1/15/2007 (forest and pasture), from 12/7/2006 to 2/9/2007 (coffee, sugar cane and pasture).

Plot scale: water balance

Three hillslope runoff plots (Figure 2) were established along a randomly selected transect at a toe-slope, mid-slope, and ridge location in each field site. Plots were installed in mid-January of 2007 (DOY 18-31). Plots (≈1 m^2) were isolated from the field sites by trenching to a 1 m depth on all four sides. A 0.1-0.15 m sod layer in the pasture field site was removed to expose the surface soil. Each soil plot was enclosed in heavy polyethylene plastic on three sides, leaving the down slope side and 0.15 m of the adjacent side walls open. Supports were put into place and trenches were backfilled and compacted on the opposite side of the plastic to the soil plot. Polyethylene extended 0.1 m above the soil surface to prevent loss of irrigation water. Experiments determined that water retention by the extended polyethylene was consistently less than 0.1% of the irrigation amount. On the open face of each soil plot, metal troughs were inserted at 0, 0.25, 0.5 and 1.0 m depths to collect lateral flow from the troughs through a system of funnels and collection containers.

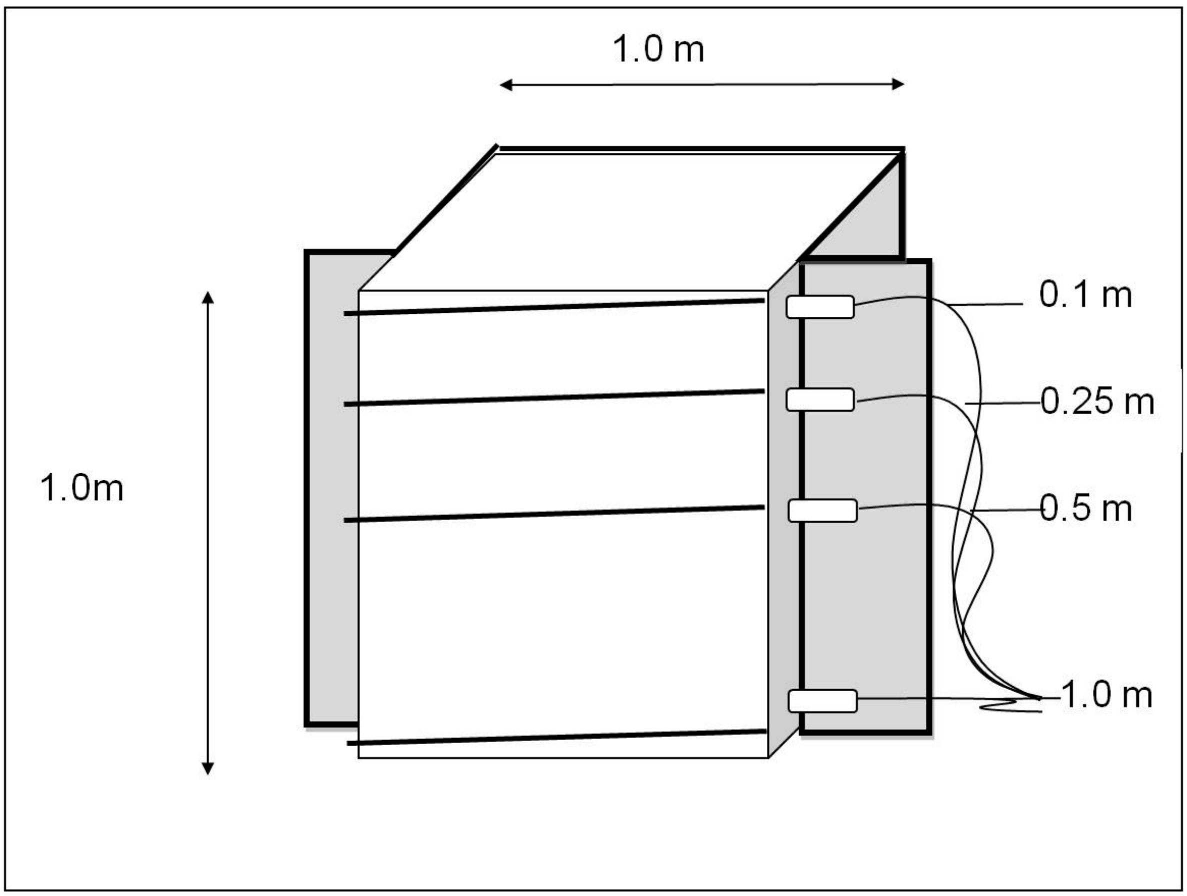

Figure 2. Diagram of runoff plots with lateral flow collector trays and water content reflectometers at 0.10, 0.25, 0.50 and 1.0 m depth.

Soil moisture content was measured with WCR probes (WCR_150, Campbell Scientific, Inc., Logan, UT) connected to a data logger (CR 10X, Campbell Scientific Inc., Logan, UT). The WCR probes were installed into one of the side walls of the runoff plot at 0.1, 0.25, 0.5, and 1 m depths (Figure 2). Soil moisture measurements were recorded every minute during the experiment. All WCR probes were individually calibrated during the field season using one runoff experiment at one of the plots in each field site by taking volumetric water content samples throughout the day as the plot approached saturation.

Runoff experiments were carried out on each plot at least three times. Tarps were placed over each plot during the experiment to minimize effects of natural rainfall and evapotranspiration (ET). In the forest, however, tarps could not cover two of the plots due to the presence of trees. The experiments on the forest plots were conducted on cloudy days with no precipitation during the time of the experiments. Prior to each runoff experiment, plots were irrigated during the afternoon of the previous day for at least 3 hours at 20 mm/hr intensity to reduce differences between plots due to ET. Water was added by two backpack sprayers constantly moving for 15 minutes. Sprayers were refilled within 2-4 minutes. Irrigation occurred in step-wise increasing intensities from 100 to 200 to 300 mm/hr. Irrigation occurred for at least one hour at each intensity.

Within the top 1 m of soil within each plot, a water balance was calculated using the applied irrigation water depth, lateral flow collected in the troughs, changes in soil moisture storage, and the assumption that ET losses were negligible. The water balance equation over the duration of the experiment was solved for percolation below the 1 m depth as follows:

$$D = P - \Delta S - R - L + e \tag{3}$$

where D is percolation (L) P irrigation water (L), ΔS soil moisture storage (L), R surface runoff, L lateral flow, and e is the measurement error. Errors in the water balance terms were estimated as 0.05 (L^3L^{-3}) for volumetric water content (Campbell Scientific 2004) and 5% for lateral flow (Redding and Devito 2008).

Infiltration rates were calculated at 0.1, 0.25, 0.5 and 1.0 m based on the final irrigation, soil moisture content, surface runoff, lateral flow, and percolation tallies in succession as follows:

$$I_{0.1} = P - R - L_{0.1} \tag{4}$$

$$I_{0.25} = D_{0.1} - L_{0.25} \tag{5}$$

$$I_{0.5} = D_{0.25} - L_{0.5} \tag{6}$$

$$I_{1.0} = D_{0.5} - L_{1.0} \tag{7}$$

where I is infiltration, and subscripts denote depth. At the final irrigation event, the plots were near saturation, so the change in soil moisture storage was negligible and therefore not included in calculations.

Plot scale: dye experiments

For the final runoff experiment at each plot in each field, 3.0 g of Brilliant Blue Dye was added to and mixed within the back sprayers every 15 minutes. At the end of the experiment, the plots were excavated from the top down every 0.1 m with a wide machete. Photos were taken, structural characteristics were noted, and depth of dye was recorded. Root diameters, depth from the surface, were also measured in three dimensions. Root density was visually estimated based on NRCS Soil Survey protocols.

Field scale: runoff

Four H-flumes were installed in incised channels on the CATIE farm to measure field-scale storm runoff for each land use type between July 2004 and December 2006. Pressure Transducers (Druck, ISCO) and CR10X data loggers (Campbell Scientific, Logan, UT) were installed in each flume tower to record water level in the flume at 15-minute intervals. Due to extreme weather events, vandalism, or instrument malfunction several gaps exist in the data set as follows: June 2004-April 2005 (sugar cane), 1/1/05 to 1/15/05 (all sites), 1/24/06 to 2/05/06 (coffee), 7/3/06 to 7/12/06 (pasture), 7/12/06 to 8/26/06 (sugar cane), 7/31/06 to 8/12/06 (forest), and sporadic readings from 7/3/06 to 8/14/06 (coffee). Therefore, runoff coefficients may be greater than reported.

Channels draining the field sites were intermittent. Hydrographs were analyzed to determine peak flow, event response times, event frequency, peak intensities, and event and annual runoff coefficients. Rainfall volumes were determined using 15-minute rainfall intensities. Peak discharge was determined using maximum 15-minute discharge values. Event response times were defined as the time between the initiation and cessation of runoff. Event based runoff coefficients were calculated using depth of event runoff divided by precipitation that occurred during the event. Event based runoff coefficients were also plotted as a function of 30-day antecedent precipitation to the end of the runoff event. Annual runoff coefficients were determined as the amount of runoff for the year divided by the amount of precipitation for that year (Dingman 1994).

Results

Precipitation

Storm volume, duration and intensities during the period 2004 through 2006 were characterized by many relatively small storms and a few large storms. Annual rainfall from 2004 – 2006 was 2,850, 3,159, and 2,760 mm respectively. The maximum rainfall intensity (based on 15-minute data) was 120 mm/hr for the period studied. Less than 1% of storms had a maximum rainfall intensity greater than 60 mm/hr. Over 85% of storms had a maximum intensity less than 20 mm/hr and over 90% of storms during this time period had a volume of less than 10 mm and a duration less than 10 hours (see Figure 3).

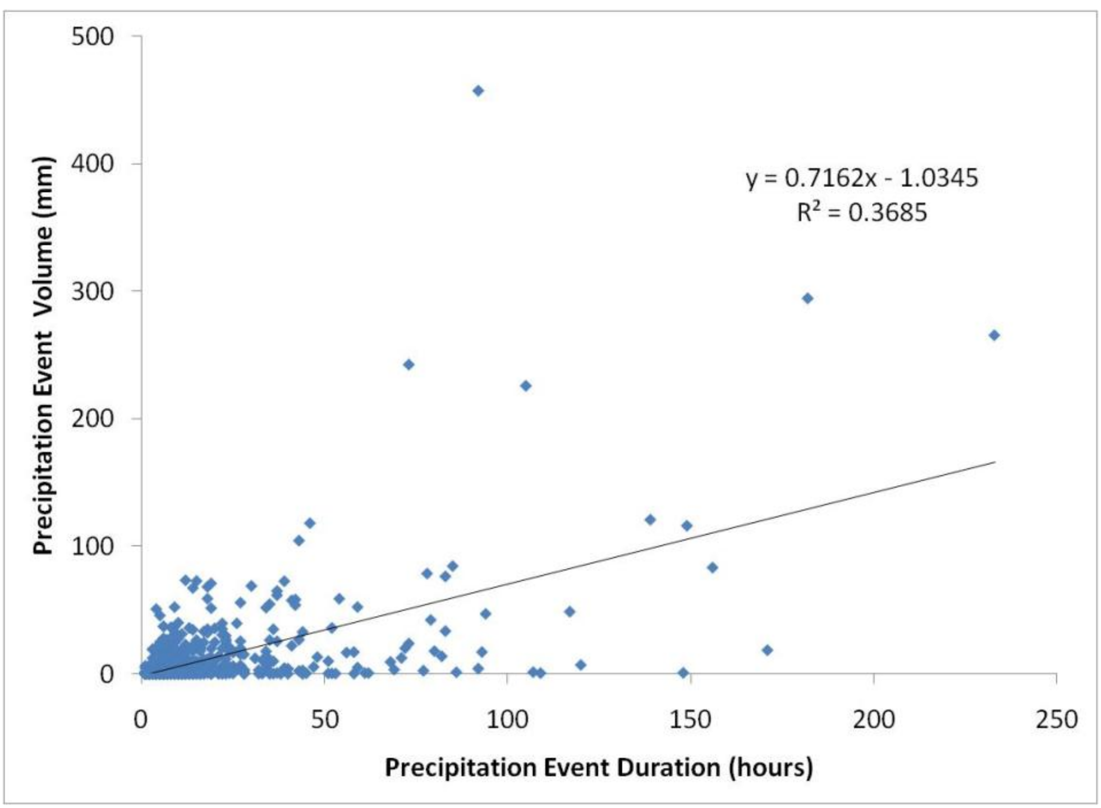

Figure 3. Precipitation event duration (hours) and volume (mm) for June1, 2004 to December 31, 2006 from the CATIE meteorological station

Point scale: soil properties

Soil sampling indicated each field site was located on an Inceptisol with three different horizons. A dark A-horizon extended to about 0.2 m. An AB-horizon was a transition layer from about 0.2 m to 0.6 m, followed by a reddish B-horizon. A drainage ditch excavated on the border of the coffee field site showed the B-horizon extending to at least 2.5 m. An existing embankment nearby the forest field site showed the B-horizon extending to at least 5 m. Bedrock was observed at about 5 m depth in an old railroad cut just east of the pasture site.

Clay content, organic matter and andic properties were similar at all field sites (Table 1). At the surface, clay content was less than 30% and significantly increased to over 40% with depth ($p<0.05$). Organic matter was greater than 5% at the surface at each field site and decreased with depth to approximately 2% at 1 m. At the surface, AlO and FeO in each of the field site soils was either just above or slightly below the threshold of 1.0% to be classified as having andic properties (NRCS 1993). Percentage of rocks was extremely low at all field sites (0-5%). At some of the pit excavations, small amounts of saprolitic rock (*roca muerte*) were found towards the bottom of the 1 m pits. Compared with soils described by Winoweicki et al. (2007), our soils lie just above a lahar flow in the toposequence for this area. Considering the high clay content, organic matter and the influence of andic properties, these soils have a tremendous storage capacity within the upper 0.5 m of the soil profile.

The bulk density of the forest field site at the surface (0.73 g/cm^3) was significantly lower ($p<0.05$) than surface bulk density at the other three field sites (Table 1). Also, surface bulk density at the pasture site was lower than surface bulk density at the sugar cane site. For both pasture and forest, bulk density was significantly greater at 1 m depth than at the surface. However, in the sugar cane and coffee profiles, bulk density did not significantly increase with depth. The matrix soil was very similar between all the field sites at the point scale of measurement with the exception of the differences in bulk density at the forest and pasture site.

Table 1. Soil characteristics at different depths within each field site.

Field Site	Depth (m)	Bulk Density (g/cm^3)	Porosity (%)	AlO + 1/2 FeO (%)	Soil Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)
Forest	0.05	0.73a	72	0.90a	6.5a	57	21	22a
Forest	0.5	0.81a	69	0.94a	4.3a	38	22	40a
Forest	1.0	0.95b	64	0.86a	2.5b	32	18	50b
Coffee	0.05	0.92b	65	0.89a	5.3a	48	22	30a
Coffee	0.5	0.86b	68	0.7b	3.4a	33	19	48b
Coffee	1.0	0.94b	65	0.62b	1.6b	30	17	53b
Sugar	0.05	0.99bd	63	1.2a	5.5a	51	24	24a
Sugar	0.5	0.91bd	66	1.0a	4.5a	42	23	35a
Sugar	1.0	0.99bd	63	0.89a	1.8b	38	18	44b
Pasture	0.05	0.87bc	67	1.0a	5.3a	47	28	25a
Pasture	0.5	0.87bc	67	0.70b	4.1a	34	30	36a
Pasture	1.0	1.00bd	62	0.60b	2.2b	27	24	48b

*Within each soil characteristic, different letters imply a statistically significant difference.

Point scale: soil moisture

During the period of soil moisture monitoring (9/2006-2/2007), soils in the pasture field site were consistently wetter than soils in the other land uses (Figure 4a and 4c). At the 0.1 m depths, the soil moisture recession curves were steeper in the forest and the coffee sites than in the pasture and sugar cane sites suggesting differences in drainage and/or ET rates (Figures 5b and 5c). When precipitation stopped, moisture contents were lowest at the forest and coffee sites. At all land use field sites, the 0.1 m soil moisture sensors responded to rainfall rapidly. At 1.0 m depth, much smaller variations in soil moisture content occurred at all field sites. Figure 4a, shows a delay of soil moisture increase in the forest when compared to the pasture.

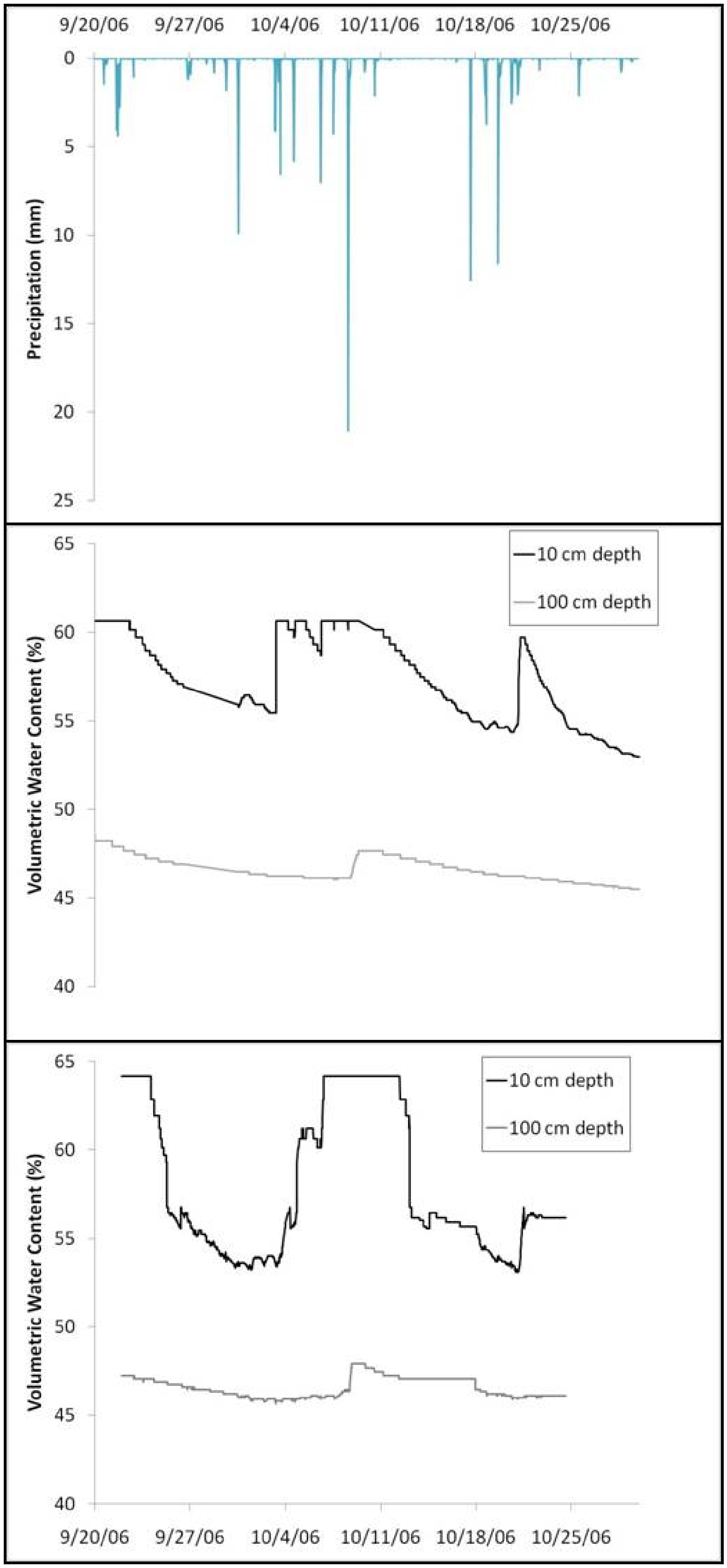

Figure 4a. Forest (top) and coffee (bottom) volumetric soil water content.

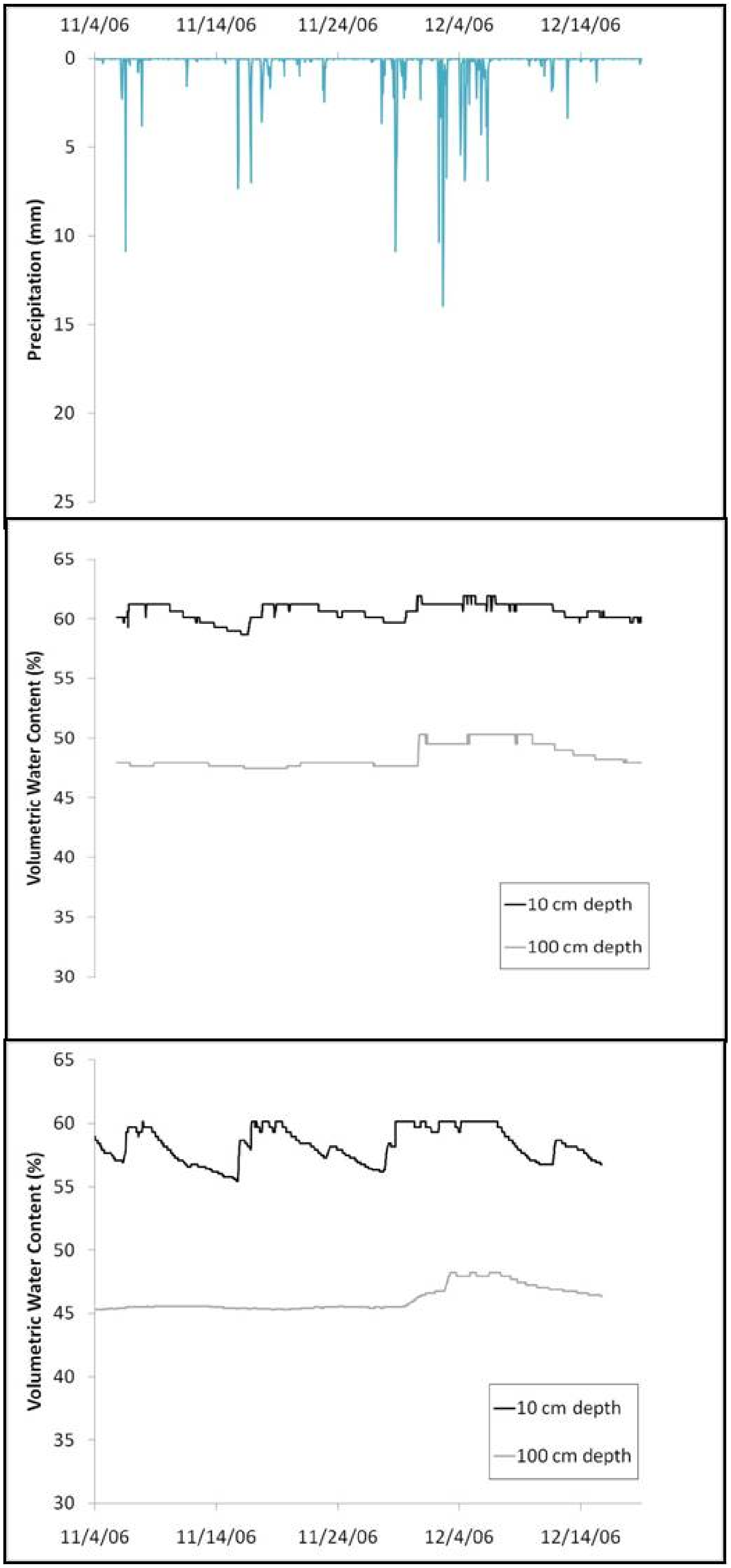

Figure 4b. Pasture (top) and forest (bottom) volumetric soil moisture.

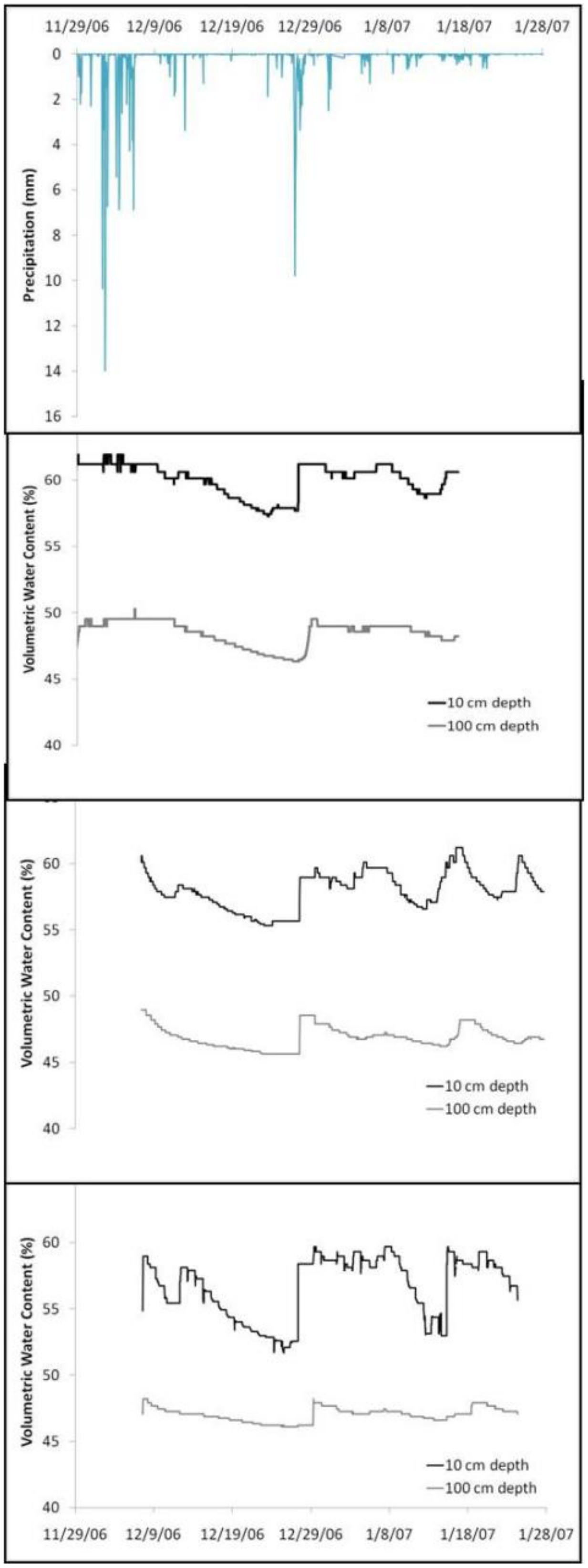

Figure 4c. Pasture (top), sugar (middle) and coffee (bottom) volumetric soil moisture content (VWC). Change these to degree of saturation.

Point scale: saturated hydraulic conductivity (Ksat) and cumulative infiltration

At the surface, the K_{sat} values in the forest and coffee field sites were almost three times greater than in the pasture and sugar cane sites. The forest and coffee field sites also exhibited the greatest amount of variance in K_{sat} at the surface with several outliers reaching above 7000 mm/d (Figure 4). At 0.5 m, K_{sat} mean and variance values in the forest and coffee field sites also were greater than in the pasture and sugar cane sites. The K_{sat} values measured at 0.5 m were less than K_{sat} values measured at the surface, except for the K_{sat} at 0.5 m in the pasture which were greater than K_{sat} at the surface (Table 2). Sugar cane had the lowest variance of K_{sat} at 0.5 m among all field sites.

When looking at cumulative infiltration to reach K_{sat}, the woody vegetation land uses were considerably drier than the herbaceous sugar cane and pasture sites (Table 3). However, despite lower K_{sat} in coffee, cumulative infiltration in coffee was somewhat greater than in forest. These greater values may be the result of increased soil evaporation at the coffee site similar to the observations provided by the soil moisture sensors. The coffee site receives much more direct sunlight than the forest site at the surface. The forest canopy effectively blocks most direct sunlight from reaching the forest soil surface. All of these results correlate well with soil moisture monitoring data at the point scale.

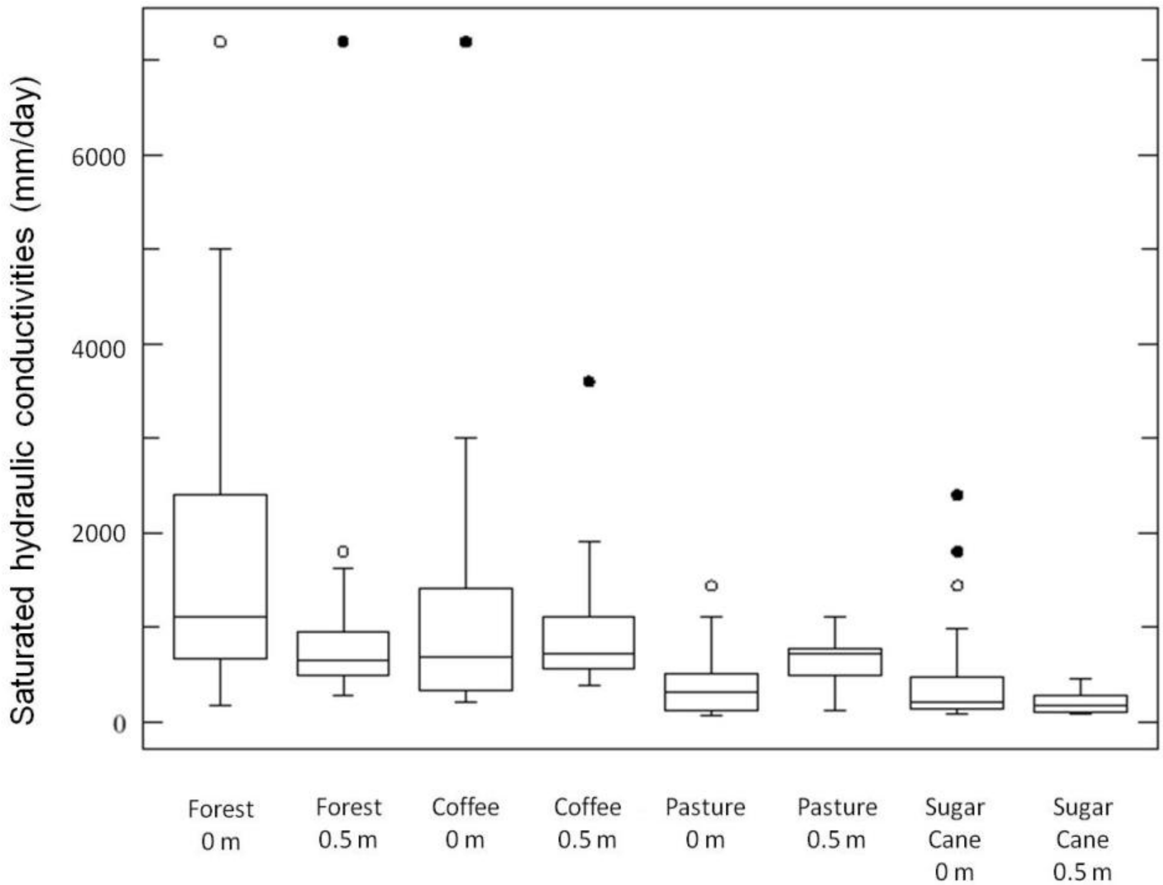

Figure 5. Box and whiskers plots of saturated hydraulic conductivity for each field site at the surface and 0.5 m depth (Open circles represent 1.25 quantile outliers and closed circles represent 1.75 quantile outliers).

Table 2. Geometric means of K_{sat} obtained using a double ring infiltrometer.

Forest 0 m (mm/hr)	Forest 0.5 m (mm/hr)	Coffee 0 m (mm/hr)	Coffee 0.5 m (mm/hr)	Sugar 0 m (mm/hr)	Sugar 0.5 m (mm/hr)	Pasture 0 m (mm/hr)	Pasture 0.5 m (mm/hr)
56	37	32	37	13	7	12	23

Table 3. Cumulative infiltration water depths using a double ring infiltrometer.

	Forest 0 m	Forest 0.5 m	Coffee 0 m	Coffee 0.5 m	Sugar 0 m	Sugar 0.5 m	Pasture 0 m	Pasture 0.5 m
Mean (mm)	67	61	79	63	38	25	48	72

Plot scale: water balances and macropore flow

Following incremental increases in irrigation intensity, soil moisture at 0.5 m and 1.0 m in the forest and coffee plots (Figures 6 and 7) increased later than in the sugar cane and pasture plots (Figures 8 and 9). Soil moisture at the 0.1 and 0.25 m depth in forest and coffee plots decreased rapidly after the end of irrigation likely due to fast drainage via macropores. Similar results were found with the soil moisture monitoring data at the point scale. Almost all lateral flow generation began when the wetting front reached the 0.5 m soil moisture sensor. Antecedent moisture conditions, field capacity, or by-pass flow mechanisms likely influenced this pattern.

While the coffee and forest plots experienced some surface runoff and lateral flow, these amounts were relatively small (<12% combined surface runoff and lateral flows) and only occurred after much precipitation (4-6 hours) (Figures 6 and 7). Lateral flow generation began before surface runoff in all coffee and forest plots suggesting a saturation excess runoff mechanism. Vertical percolation was the dominant hydrological process at the coffee and forest plots. Similar to the longer-term soil moisture monitoring, much of this percolation seems to have bypassed the sensors placed at 1 m in the soil matrix.

Plots in the sugar cane and pasture field sites had much greater surface runoff as a percentage of applied water than plots in forest and coffee field sites (Table 4). Sugar cane surface runoff, which mostly started within the first hour of irrigation, was greater than 25% of the applied irrigation with varying amounts of lateral flow from subsurface layers (Table 4). Surface runoff continued to increase proportionally as irrigation intensity increased (Figure 8). Most of this surface runoff was occurring on the compacted rows between the sugar cane, or approximately 50% of the plot. Frequently, lateral flow at 0.25 m constituted about 5% of the applied irrigation water in the sugar cane, but arrived later than the surface runoff (Figure 10). At each plot in the sugar cane field site, I observed a plow layer about 0.1-0.15 m wide starting at approximately 0.25-0.40 m in depth. Therefore, lateral flow also appears to limit percolation at the sugar cane site. Soil moisture at the 0.5 m and 1.0 m depth responded relatively quickly indicating that water was delivered to the deeper soil matrix, but macropore flow was not occurring to the extent observed in the forest and coffee plots.

In the pasture field site, lateral flows at 0.25 and 0.5 m preceded surface runoff. However, surface runoff eventually increased to be a greater proportion (14-35%) of the applied water suggesting a limited conductivity in the deeper soil horizons (Figure 9). In the pasture, lateral flows down to 0.5 m accounted for 14-32% of the applied water (Table 4). Therefore, during these experiments surface runoff appeared to result from a perched water table between 0.25-0.5 m in the pasture. At 0.5 m, soil moisture increased rapidly even during the lowest irrigation intensities. Lateral flow at this depth begins when soil moisture approaches saturation (Figure 9). As irrigation intensity increased, surface runoff, lateral flows at 0.25 and 0.5 m increased. The combination of the surface runoff, lateral flows, and change in storage during the experiments severely limited percolation in all three of the pasture plots (<15%) (Table 4). During wet periods with high intensity rainfall, percolation in the pasture field site may be limited by surface runoff and lateral flow.

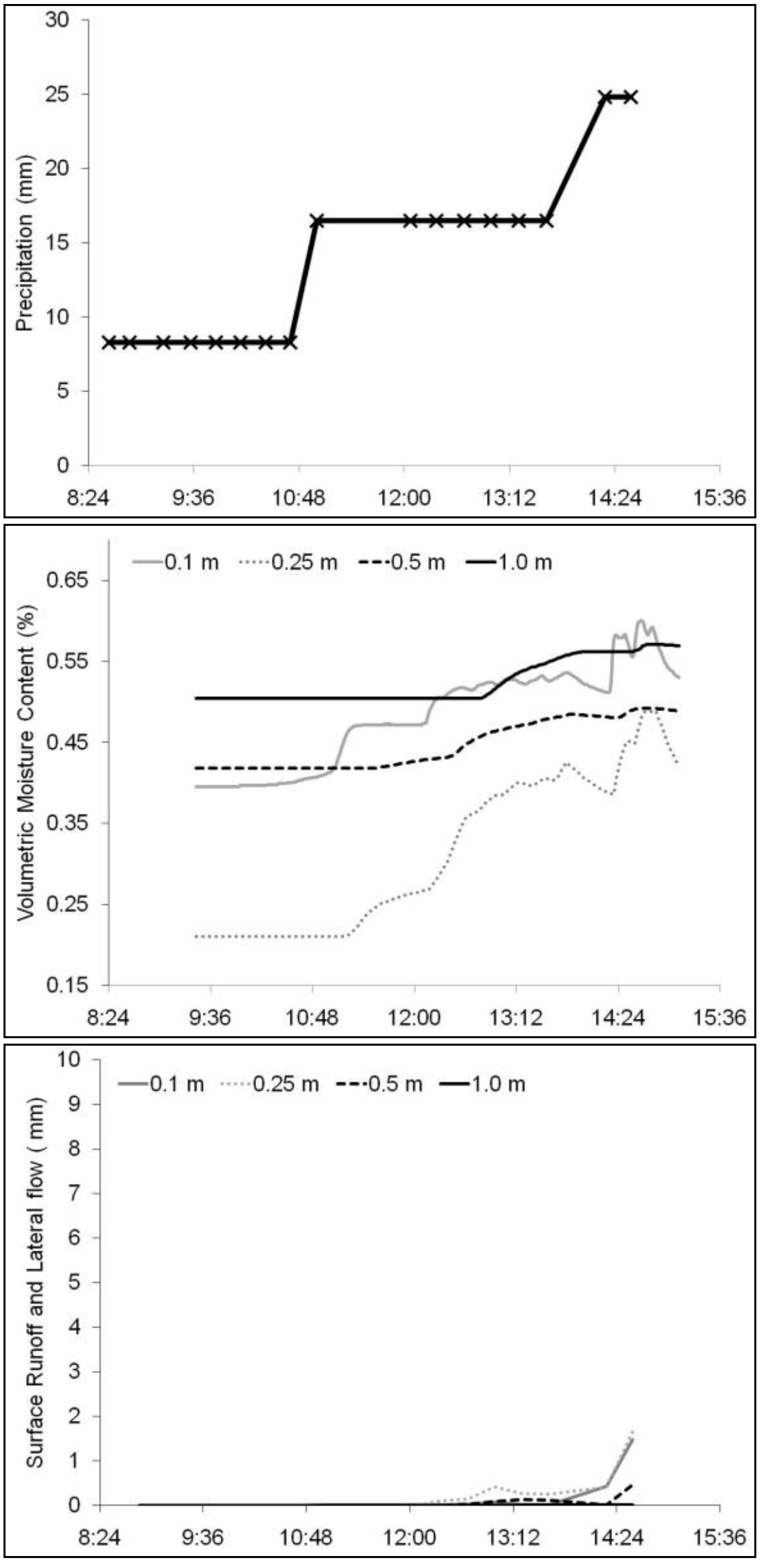

Figure 6. Forest runoff plot experiment: a) precipitation, b) volumetric moisture content at 0.1, 0.25, 0.5, and 1.0 m depths, and c) surface runoff and lateral flow at 0.1, 0.25, 0.5, and 1.0 m depths.

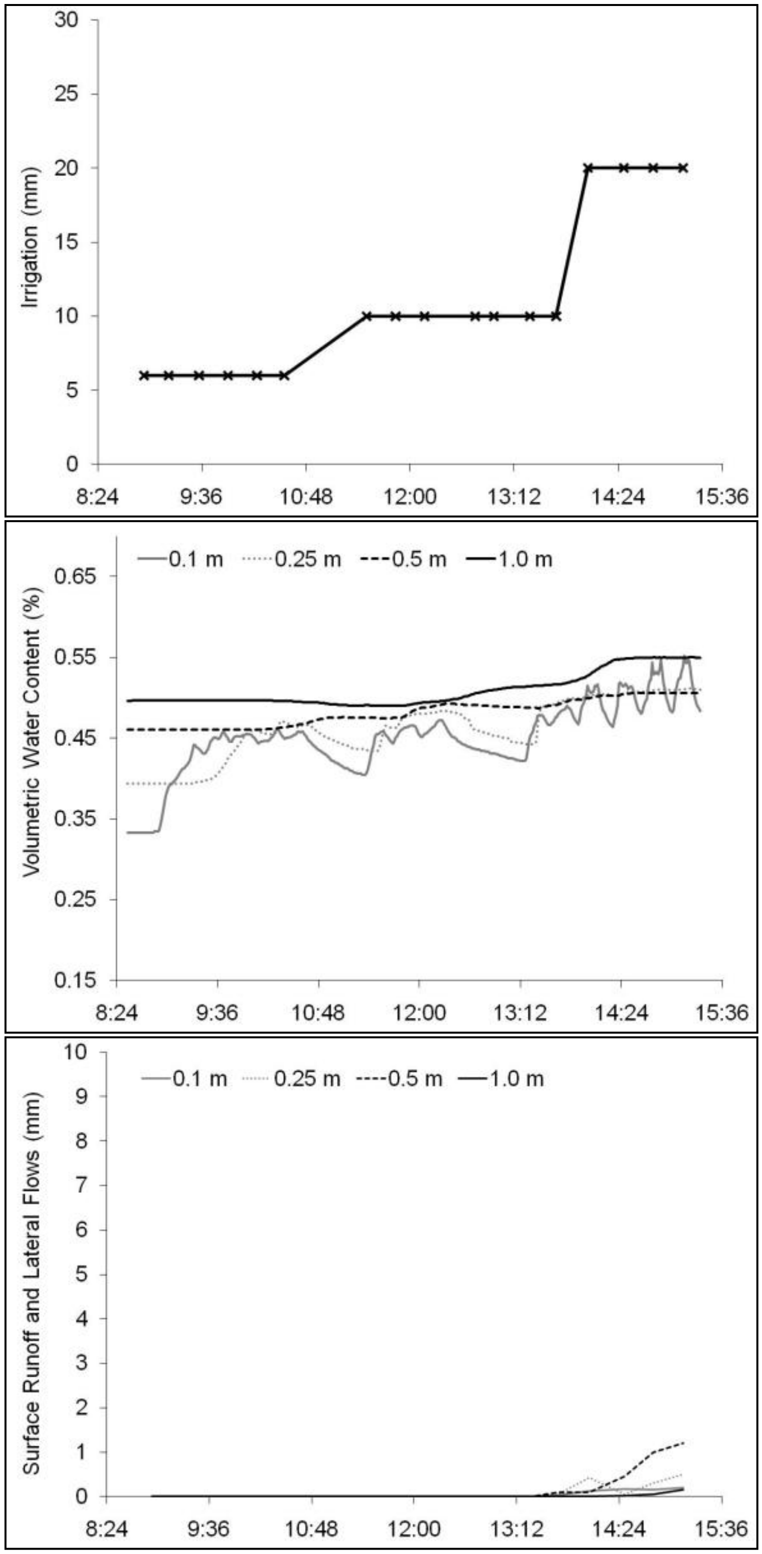

Figure 7. Coffee runoff plot experiment: a) precipitation, b) volumetric moisture content at 0.1, 0.25, 0.5, and 1.0 m depths, and c) surface runoff and lateral flow at 0.1, 0.25, 0.5, and 1.0 m depths.

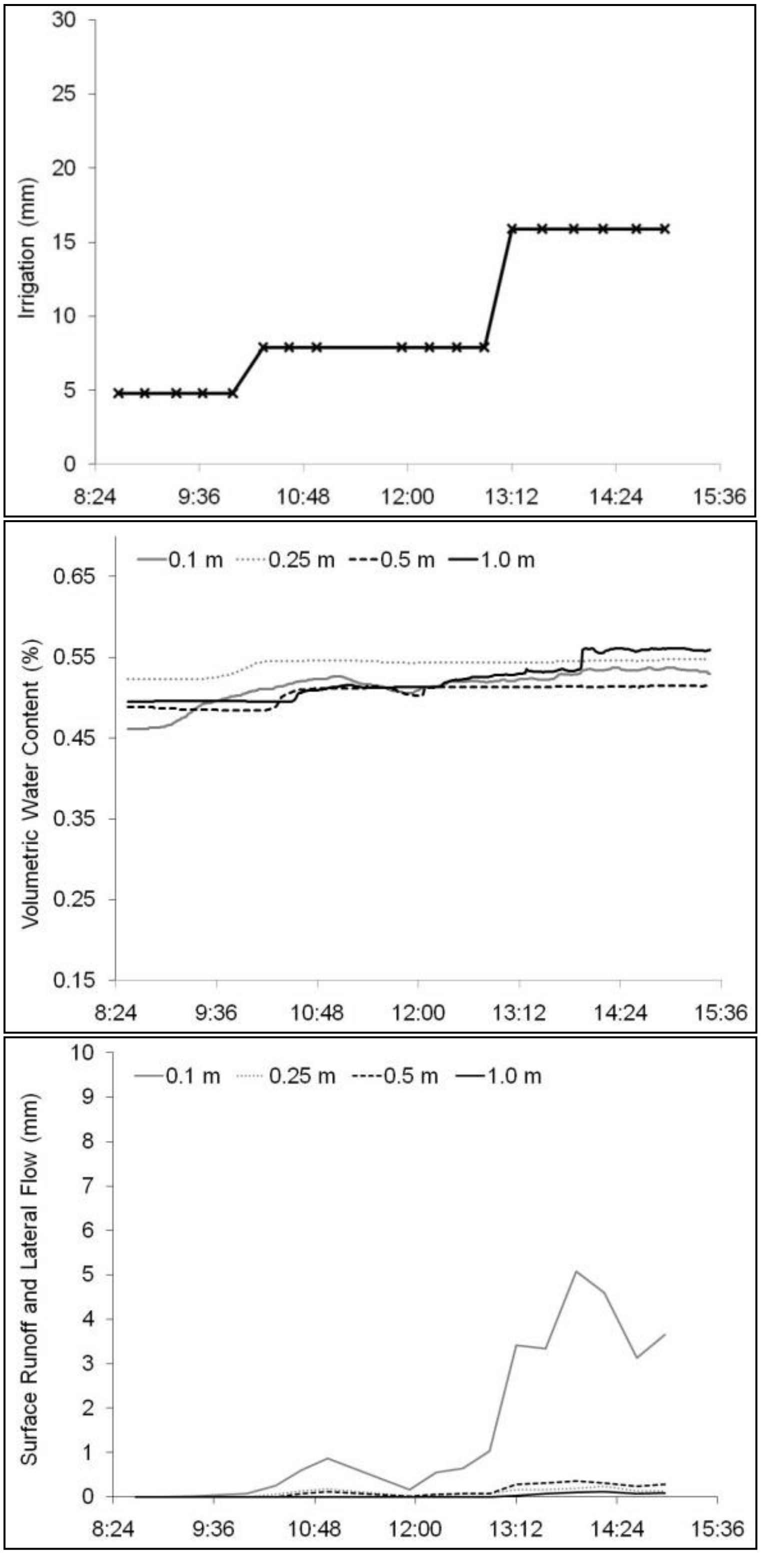

Figure 8. Sugar runoff plot experiment**:** a) precipitation, b) volumetric moisture content at 0.1, 0.25, 0.5, and 1.0 m depths, and c) surface runoff and lateral flow at 0.1, 0.25, 0.5, and 1.0 m depths.

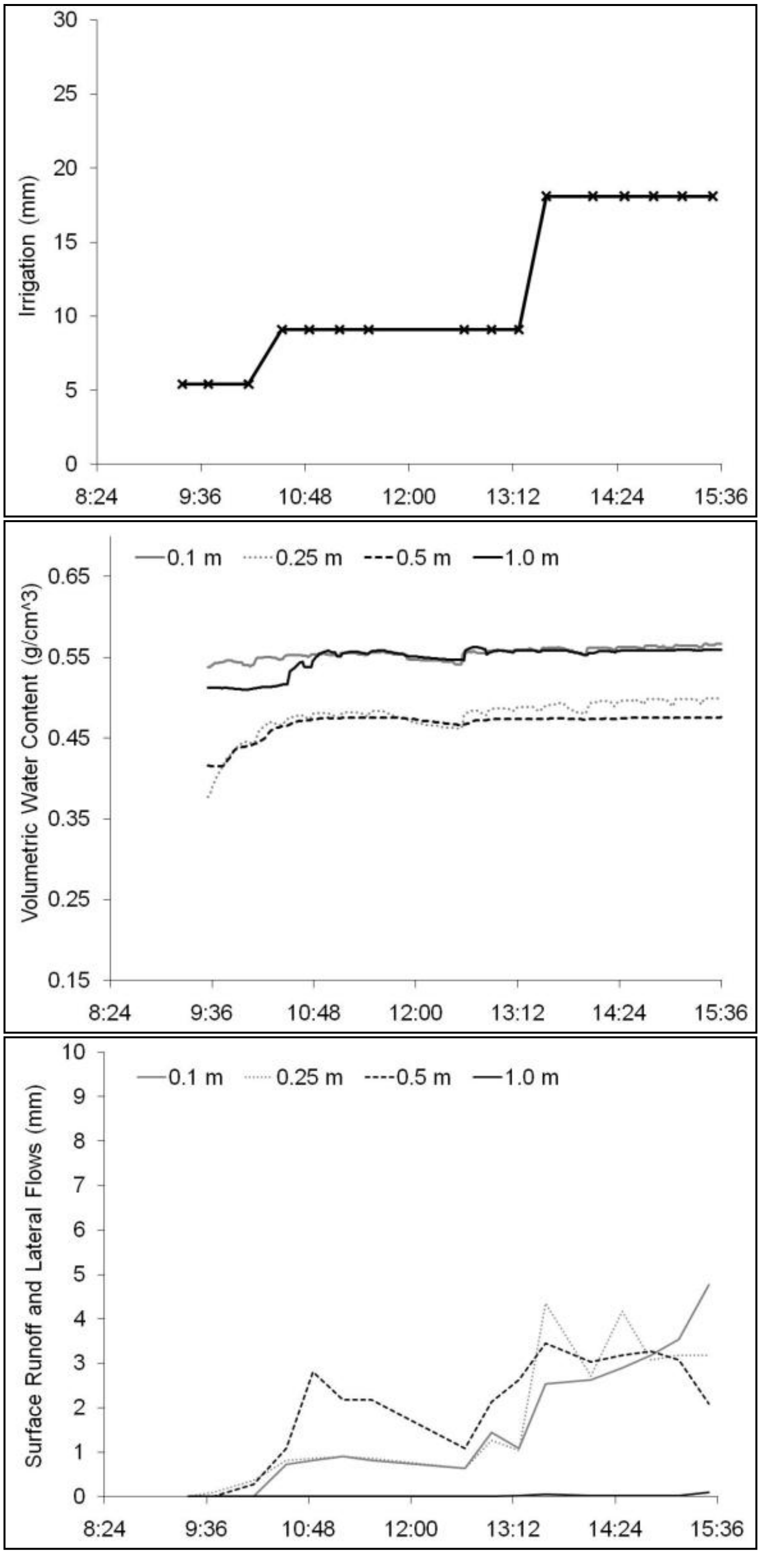

Figure 9. Pasture runoff plot experiment**:** a) precipitation, b) volumetric moisture content at 0.1, 0.25, 0.5, and 1.0 m depths, and c) surface runoff and lateral flow at 0.1, 0.25, 0.5, and 1.0 m depths.

Table 4. Irrigation experiment water balances based on a 1 m depth.

Land Use	Irrigation (mm)	Event duration (min)	Maximum Event Intensity (mm/hr)	Surface Runoff (mm)		Lateral Flow (mm)		Delta Storage (mm)		Percolation Below 1m (mm)	
Forest	280	362	60	3	**1%**	5	**2%**	150	**54%**	122	**44%**
Forest	230	255	60	2	**1%**	4	**2%**	123	**53%**	103	**44%**
Forest	530	148	220	23	**4%**	36	**6%**	112	**21%**	421	**69%**
Coffee	190	247	60	1	**0.4%**	4	**2%**	78	**42%**	102	**55%**
Coffee	320	143	100	2	**0.3%**	48	**15%**	110	**34%**	164	**51%**
Coffee	430	132	200	1	**0.3%**	52	**11%**	114	**24%**	309	**65%**
Sugar	170	260	60	43	**25%**	17	**10%**	66	**38%**	47	**27%**
Sugar	180	221	60	55	**31%**	13	**7%**	22	**12%**	86	**48%**
Sugar	340	241	60	100	**29%**	12	**3%**	69	**20%**	160	**47%**
Pasture	190	233	60	26	**14%**	60	**32%**	74	**39%**	29	**15%**
Pasture	210	210	60	63	**31%**	32	**15%**	101	**49%**	10	**4%**
Pasture	280	283	60	97	**35%**	40	**14%**	87	**31%**	31	**11%**

In general, final infiltration rates were two to four times greater than the K_{sat} values obtained with the ring infiltrometers (Table 5). Coffee and forest plots had the greatest final infiltration rates compared to sugar cane and pasture. Final infiltration rates decreased with depth at each site.

Table 5. Arithmetic means of final infiltration rates (I) obtained at the end of plot irrigation experiments (see Equations 4 and 5).

Depth (m)	**Forest** (mm/hr)	**Coffee** (mm/hr)	**Sugar** (mm/hr)	**Pasture** (mm/hr)
0.1	95	100	55	55
0.25	86	78	50	40
0.50	84	72	50	32
1.0	84	65	45	32

Plot scale: dye experiments

Dye stained roots in the forest and coffee plots carried water to greater depths than in the sugar cane and pasture plots (Figures 10-13). In forest and coffee plots, dye stained the large, thick roots and their surrounding soils concentrated in the upper 0.5 m and several roots preferentially down to depths of 1.0 m, the bottom of the excavated sections (Figure 10). Dye stains in the sugar cane and pasture plots showed a more uniform pattern of small roots up to approximately 0.5 m, with very little dye moving past this depth (Figures 11 and 12). Dye experiments showed roots and other preferential pathways as evidence of both lateral and vertical water transport at the coffee and forest field sites (Figure 10). These roots and macropore networks in the woody vegetation land use sites represent a major difference from the herbaceous land use sites. As shown above, when the upper layer of soil was saturated, water flow appeared to activate these macropores in the coffee and forest sites to deeper soil depths, bypassing the soil matrix.

Point scale: plant roots

Root size, density, and vertical distribution differed among the four land uses. At the coffee and forest field sites, roots were much larger (up to 50 mm in diameter) than in the pasture and sugar cane sites. At the pasture and sugar field sites, many small roots were present in the upper 0.1 m of the soil. The pasture field site had the smallest roots (1 mm diameter) followed by sugar cane roots (5 mm diameter). A 0.1-0.15 m thick vegetative mass in the pasture field site extended above the soil surface. Root density decreased with depth at all four sites. Most commonly, only a few fine roots (1 mm) were found at a depth of 0.5 m and greater in the sugar cane and pasture site. However, at the coffee and forest sites, large roots (5-50 mm) were found throughout the 1 m profile. The forest had the largest roots and the greatest root density. Root size and distribution were distinctly different between the herbaceous and woody vegetation land uses.

Figure 10. Coffee plot dye experiment (each line on ruler equals 0.1 m).

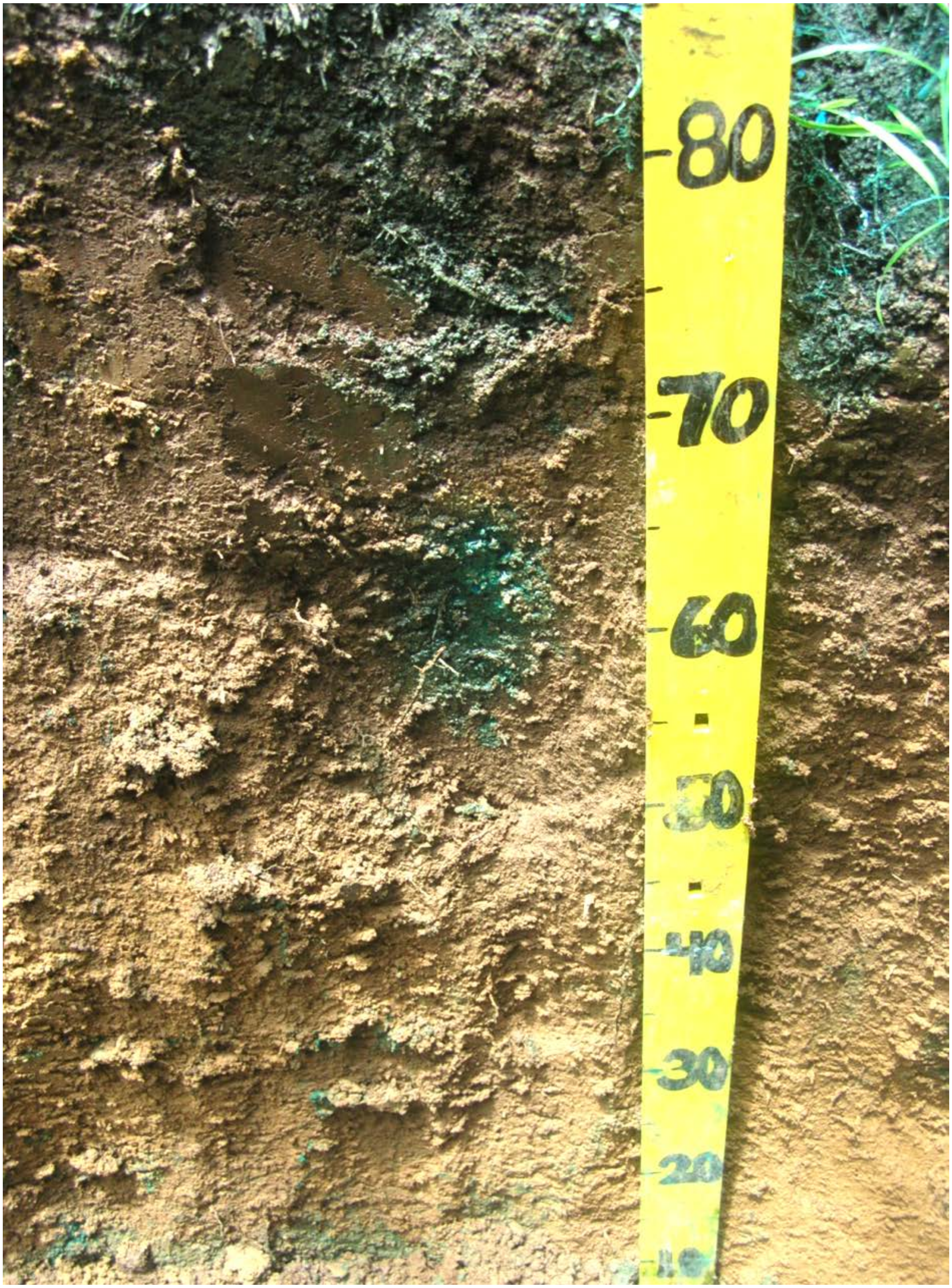

Figure 11. Sugar cane plot after the dye experiment.

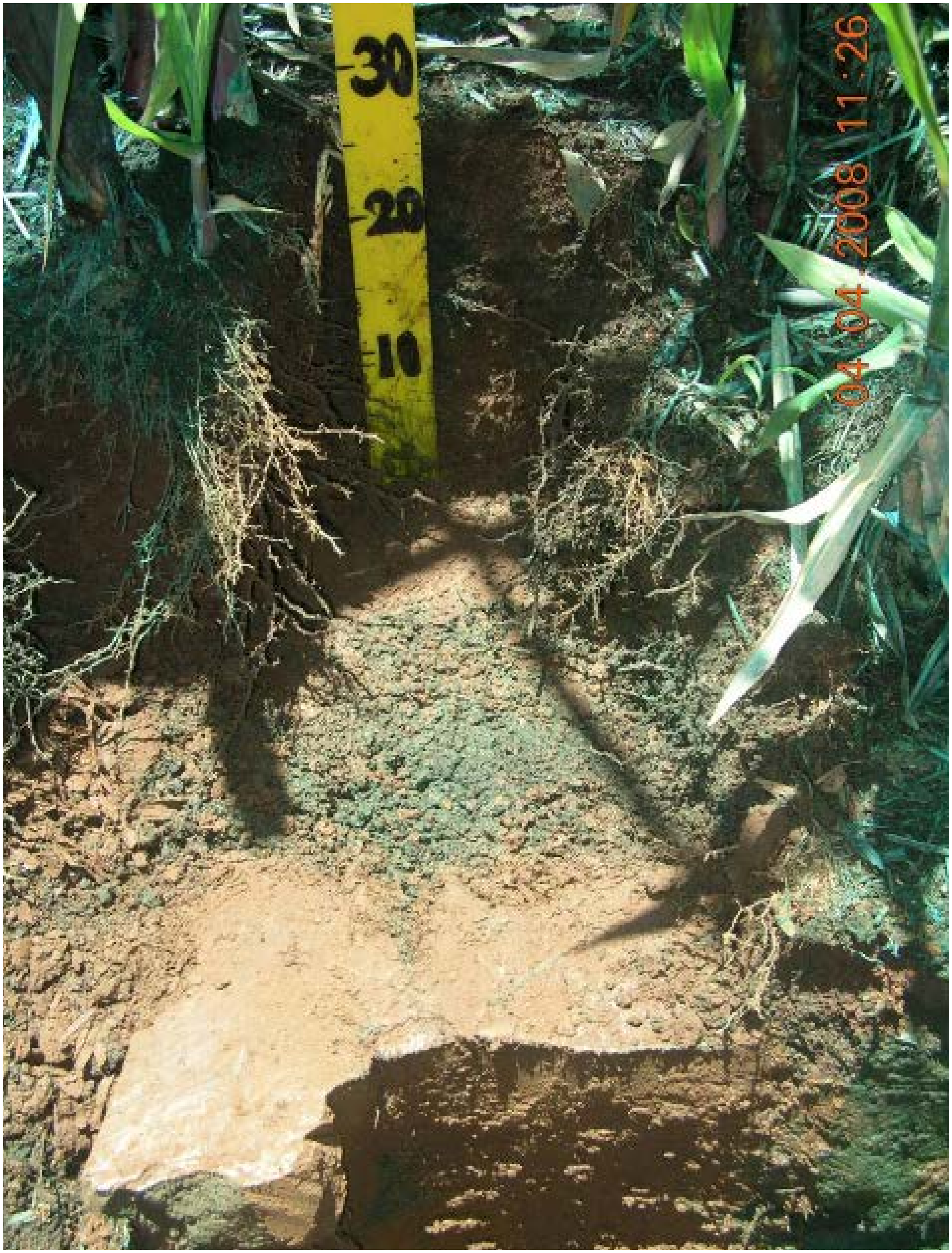

Figure 12. Sugar Cane plot after a dye experiment with plough layer at 0.3 m depth.

Figure 13. Pasture plot after the dye experiment (lines on the ruler equals 0.1 m).

Field Scale: runoff

Runoff at the field scale differed between land uses with respect to frequency, intensity, volume, and duration (Figure 14). One of the most obvious differences between the land uses can be seen when observing coffee runoff (Figure 14). Runoff event intensity at the coffee field site is much less than at the other field sites. However, runoff duration at the coffee field was much longer than all of the other field sites (Table 6). Often, forest, and to a lesser extent sugar cane, have similar long duration events. However, due to the intensity of all sugar cane and forest events, these durations are less observable at this scale. Due to the forest site being downstream of the sugar site, their runoff data became more difficult to separate.

Figure 14d represents the sugar cane site runoff response. The sugar cane responds rapidly to high precipitation intensities and/or volumes. Overall, the sugar cane field site had the greatest frequency of runoff events, peak runoff rate, and maximum runoff event volume (Table 6). When 10 mm of precipitation occurred within 1-2 hours, sugar cane runoff often responded and then quickly subsided after precipitation intensity decreased. This 10 mm threshold correlates well with the observed K_{sat} at this site (Table 2). However, as can be seen in Table 6, sugar had the second greatest duration of runoff events. Several times over the years that these data were collected, a variable source area was observed within the sugar cane field site. Therefore, while an infiltration-excess mechanism appears to have occurred within the sugar cane site, the draining of this variable source area contributed greatly to the duration of several large events. As I reported from our various infiltration data, the infiltration capacity of the forest site was great. This infiltration capacity is confirmed with the results from the field scale data. After subtracting sugar cane runoff from forest runoff, the forest field site had the second lowest runoff depth. As the runoff left the sugar cane field site, approximately 70% of the sugar cane storm flow re-infiltrated in the forest. Several large rainfall events occurred, however, where runoff measured below the forest site was greater than below the sugar cane site. Accordingly, duration of the forest runoff events was generally greater than at the sugar cane runoff events except for when the variable source area had developed in the sugar cane. It is hypothesized that as the variable source area drained, runoff velocity and amount decreased enabling re-infiltration into the forest field site. Two other patterns emerge when looking at Figure 14. First, when both the sugar cane and the forest sites experienced runoff, the forest site actually started runoff sometimes before the sugar cane. Second, sometimes the forest field site experienced runoff when the sugar cane did not. These types of forest runoff events occurred during very wet periods of the year, but during storms with relatively lower precipitation intensity.

Finally, in Figure 14e, the pasture site rapidly responded to high precipitation intensity and/or volumes during wet periods of the year. Pasture runoff response had classic infiltration excess runoff curves with great intensities and very short durations. Similar to the sugar cane, when precipitation intensity decreased pasture runoff quickly subsided. However, compared to the other land uses, runoff rarely occurred at the pasture site.

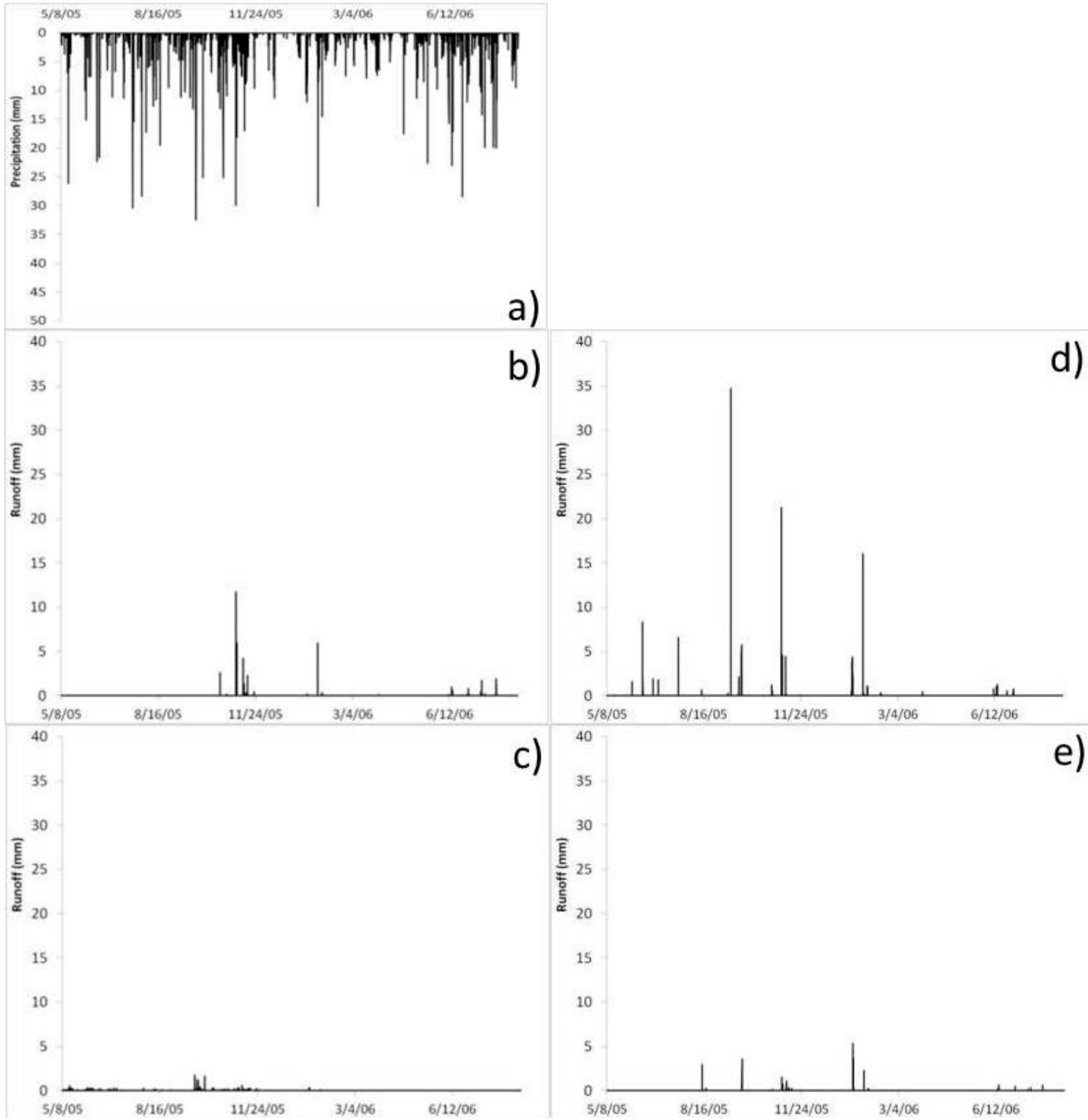

Figure 14. Precipitation (mm/hr) (a) and runoff at the field scale for in forest (b), coffee (c), sugar cane (d), pasture (e).

Table 6. Runoff characteristics at each of the field sites for 4/2005-7/2006 and 10/2006-12/2006.

Runoff Characteristics	Forest	Coffee	Sugar	Pasture
Rainfall (mm)	3826	3826	3826	3826
Total Runoff Volume (mm)	79	114	262	49
Number of Events	100	134	195	37
Total Runoff Time (hrs)	381	1990	1221	230
Maximum Runoff Event Intensity (mm/hr)	11.1	1.7	34.7	11.7
Max Storm Volume (mm/event)	37.4	6.5	51.8	12.2
Runoff coefficients	2%	3%	7%	1%

Discussion

The lower bulk density in the forest was the only difference between soil matrix properties. Spaans et al. (1989) found similar results in Costa Rican soils north of our field sites when comparing bulk densities before and after forest clearing. The soils at each field site represented a typical profile for an older, tropical, deep soil (≈5 m) with little rock content. Clay content increased with depth to approximately 50% at 1 m depth. Also, organic matter contents, which were high at the surface, decreased with depth. At the surface, organic matter content was greatest in the forest (6.5%), but it was not significantly different than at the other field sites where organic matter content was also high (>5%). In similar studies, forested sites often have much greater organic matter content than pasture that generally leads to lower bulk densities and greater infiltration capacities (Solomon et al. 2000; Richter and Markewitz 2001). This may be one of the reasons why bulk density was lowest at our forest site. Also, andic properties decreased with depth. Andic properties greatly increase the surface area of soils due to the size and structure of volcanic ash and glass. These substances combine with organic material in soils to form structurally stable volcanic ash aggregates (Shoji et al. 1993). Andic properties explain why porosity, field capacity, plant available water, and infiltration capacities are substantially greater than in other soils (Dalhgren et al. 2004; Jimenez et al. 2006). During the runoff experiments, subsurface lateral flow was initiated between 0.25-0.5 m at each land use. The decrease of andic properties along with the increase of clay content, most likely formed a semi-restrictive layer as noted by increased soil moisture content at this depth. The similarities of the soil matrix properties at the different field sites provided the opportunity to determine what impact the individual land uses have on hydrological processes within deep tropical soils that have the unique ability to absorb large amounts of water at a high rate because of their andic properties.

Effects of Land Use on Root Distribution and Compaction

Hydrological processes such as infiltration, soil water re-distribution, percolation, and runoff generation differed greatly between the land uses at the point and plot scales. Our observations suggest that these differences were due to root and macropore size and distribution.

The Effects on Root Distribution

The forest and the coffee had the greatest K_{sat}, the greatest infiltration rate, and the least amount of surface runoff and lateral flows at the point and plot scales. Upon excavation of the forest and coffee plots after dye application, the dye reached greater depths than in the sugar cane or pasture plots by using thicker roots and/or preferential pathways down to at least a 1 m soil depth. The forest and coffee plots had much larger roots at greater depths than the sugar cane and pasture. Tree roots can promote wider and deeper preferential flow paths than cultivated cropland or pasture (Yunusa et al. 2002; Martinez-Mesa and Whitford 1996). Roots create preferential pathways through the combination of localized compaction by root growth and the addition of root exudates to the adjacent soils (Johnson and Lehman 2006). Root death and decay is another plausible cause of preferential flow paths. In each land use, root density and preferential flow paths decreased with depth from the surface. Different root zones can increase K_{sat} relative to the soil below the root zone. This gradient of conductivities often determines flow path direction in terms of percolation, lateral flow, or saturation-excess overland flow (Beer et al. 1995; Elsenbeer 2001). The decrease of organic matter and andic properties with depth may further drive this gradient by limiting aggregate formation and thus storage capacity and preferential pathway formation into deeper soil horizons. At the coffee and forest sites, much greater amounts of water percolated downward than at the sugar cane and pasture sites during the runoff experiments. Gomez-Delgado et al. (2011) modeled similar percolation amounts in a nearby coffee basin. The lack of these preferential pathways in the sugar cane and pasture likely contributed to the generation of surface runoff and lateral flow during the runoff experiments.

At the plot scale, infiltration rates were at least twice as great as the point scale K_{sat} measurements even though soil moisture contents appear to have reached saturation complete with lateral flow generation. The woody vegetation land uses reached a value of approximately 100 mm/hr. Most likely, the increase of volume of the sample size enabled the measurement to capture more of the preferential pathways within these systems (Brooks et al. 2004). Several of the K_{sat} values for the forest and coffee field sites were greater than 7000 mm/day (Figure 4). While these values were treated as outliers in our analysis, these outlier values likely were caused by preferential pathways located under the ring infiltrometers. Several K_{sat} outlier values were also observed in the sugar cane site (Figure 4). These coincided with measurements taken over the actual sugar cane plants (not on the rows between) suggesting a bypass flow mechanism in the sugar cane. Variance of surface K_{sat} values in the forest and coffee was the greatest representing macroporosity among these woody vegetation land uses. Finally, at each of the field sites, variance in K_{sat} values decreased with depth. This suggests that the relative effect of land use on K_{sat} below the root zone was smaller than at the surface due to limited root access and less macropore presence.

The Effects on Soil Compaction

At the point scale of measurement, surface bulk density at the forest field site was statistically significantly lower than at the other field sites. This lower bulk density in the forest suggests evidence of compaction in the sugar cane, coffee, and pasture field sites. Each of these sites received foot, cattle, and/or machinery traffic. Many studies have shown that forest soils have lower bulk density than soils in other land uses in similar areas due to less human and cattle induced compaction (Price et al. 2010; Lee and Foster 1991; Ziegler et al. 2006). The andic nature of these soils also suggests they may be particularly susceptible to compaction when physical aggregate degradation occurs. The low bulk density of pasture soils is most likely due to the abandoned nature of the pasture and the dense, fine root network of the pasture near (and above) the surface of the profile that developed when razor grass overtook pasture grasses. This mat had very high porosity and the ability to retain water. The mat likely moderated runoff response in the pasture field site. As discussed above, due to andic properties and organic matter content, all bulk densities were low (<1.0 g/cm^3) even though clay contents were high, likely contributing to the great ability of these soils to infiltrate high intensity rainfall.

While lack of roots in the sugar cane definitely influenced infiltration capacities and the soil-water redistribution process, the sugar cane field site also seemed to be influenced by burning, tillage, and compaction. In terms of infiltration, the sugar cane had the lowest K_{sat} at the surface and at 0.5 m depth. During the plot experiments, the sugar cane produced the most surface runoff (≈30%). Surface runoff generally occurred within the first hour of irrigation at intensities greater than or equal to 20 mm/hr that roughly correlated with our data from the ring infiltrometers suggesting occurrences of infiltration-excess runoff. Although lateral flow occurred at the sugar cane plots, it occurred later than surface runoff and the volume was much less (<10%). Interestingly, lateral flow most often was generated at the 0.25 m depth before deeper horizons. From the dye application, a plow layer was observed at this depth which likely explains the lateral flow generation. Jimenez et al. (2006) determined that anthropogenic disturbance (e.g., burning, tillage and air drying) significantly lowered the naturally high infiltration capacities of andic soils and increased surface runoff. The tillage discs, used at the sugar cane site, might cause subsurface compaction and the formation of a plow layer at the 0.25 m depth. The destruction of andic aggregates and macropore structure through crop management practices of sugar cane could very well contribute to the lower K_{sat} and greater surface runoff in the sugar cane. Therefore, the sugar cane plots appeared to exhibit a very shallow saturation-excess runoff mechanism combined with infiltration-excess at higher precipitation intensities.

At the pasture site, infiltration, surface runoff, and lateral flow generation seem to be influenced by soil compaction, lack of large roots and macropores and the absence of andic properties with increasing depth. The K_{sat} at 0.5 m depth was two-fold greater than at the surface in the pasture site. However, at the plot scale, the pasture site clearly indicated a saturation-excess runoff generation, or a type of "fill and spill" mechanism (Tromp-van Meerveld and McDonnell 2006, Spence and Woo 2003), as lateral flow initiated at 0.5 m. The original 'fill and spill' mechanisms describe bedrock topography being a primary control on subsurface connectivity and lateral flow generation in shallow soils. The mechanism observed here differed in two important ways. First, irrigation intensity needed to exceed soil storage amount and conductivities to generate runoff in the pasture and sugar. Once this threshold was reached, subsurface connectivity was limited due to lateral diversion of irrigation. Second, in the forest and coffee, as soil storage became saturated, vertical macropore networks were activated that promoted a 'fill and drain' or percolation that increased subsurface connectivity. Although runoff and lateral flow occurred in very small amounts, a similar mechanism was observed in coffee and forest.

Field scale runoff

The apparent differences between the field sites at the point and plot scales due to compaction and root distribution diminished at the field scale where differences in the annual runoff coefficients were very small (1-7%). These runoff coefficients include the dry season which also explains their magnitude. Similar runoff coefficients were found for coffee near our study sites (Gomez-Delgado et al. 2011). Even in tropical humid climates, studies show that annual runoff coefficients are frequently less than 10% of precipitation in small catchments (Jansson 2002; Cattan et al. 2006). At this scale, impact of land use starts to lose influence on runoff generation because the measurement scale is more representative of the effects of macropores (Figure 3). However, these small runoff coefficients still translate to 50-260 mm of annual surface runoff. In general, most of the literature reports that deforestation and conversion to agricultural land uses increases river discharge and groundwater levels due to the loss of the evapotranspiration of the forest. Similar to Hanson et al. (2004), percolation at the pasture field site was limited by lateral flow generation when this site reached saturation. During the same saturation period, the forest and coffee field sites were able to percolate much more water suggesting that under large storm events, these woody-based land uses may indeed have the ability to recharge ground water supplies.

Conceptual Model of 'Fill and Spill' in Deep Tropical Soils

While the original 'fill and spill' hypothesis for a hillslope depended on bedrock depressions to act as the restrictive layer (Tromp-van Meerveld and McDonnell, 2006), I observed a 'fill and spill' mechanism controlled by a combination of reduced bulk density with depth, root distribution and macropore connectivity, a decrease of andic properties, a restrictive layer, and lateral flow accumulation from upslope areas. For most rainfall events of low intensity or short duration, water readily infiltrated and percolated through the profile without filling the available storage space and causing lateral flow (i.e. spilling). For high intensity rainfall and/or long duration, the profile would fill and spill, typically for short durations, when exceeding the storage capacity and vertical K_{sat}. This conceptual model was greatly impacted by land use through several mechanisms.

In forest and coffee sites, the mechanism of 'fill and spill' is very similar. The major difference at these sites is the size and density of roots and macropores. The forest site had a slightly greater density of larger roots and macropores at greater depths that inhibit the restrictive layer due to large amounts of percolation. The coffee site behaved similarly, but with slightly less volume of roots and macropores.

In the sugar cane site, compaction at the surface enhanced the 'fill and spill' mechanism when rainfall intensity was greater than surface K_{sat}. However, when precipitation intensity was less than surface K_{sat}, subsurface compaction from the plow layer provided a shallower restrictive layer than the more natural conditions seen in forest and coffee. Also, compaction only happened on about half of the sugar cane field. The rows of sugar cane acted as a bypass flow mechanism to increase soil moisture content even when infiltration-excess runoff was occurring between the rows.

Finally, in the pasture, the lack of large roots and the destruction of macropores through compaction greatly reduced K_{sat} and facilitated transfer of lateral flow from upslope contributing areas. It would seem to follow that runoff events would then occur frequently at the pasture site. However, due to the large storage capacity of these soils and the dense vegetative mat that overtook our abandoned pasture site, runoff occurred less frequently. When runoff occurred, it exhibited high intensity and short duration.

Conclusions

Lower bulk density at the surface of the forest was the only observed soil matrix difference due to land use in this study. However, all land uses had relatively low bulk densities due to high organic matter (>5%) and the presence of andic properties in this soil. Therefore in the top 0.5 m of these soils, water absorption capacity was very high. Below 0.5 m, clay content significantly increased while organic matter and andic properties decreased. The difference between these two layers provided for a semi-restrictive layer at approximately 0.5 m.

The grass based land uses (i.e., pasture and sugar cane) remained wetter longer than the woody land uses (i.e., forest and coffee). Pasture had the least influence on soil moisture followed closely by sugar cane. The coffee and forest decreased the amount of soil moisture by at least twice the amount of pasture and sugar cane. The often exposed soil surface (e.g., after herbicide application) of the coffee field site was the driest land use with the steepest soil moisture recession curves. However, all of the land uses' moisture contents rose quickly and close to saturation in response to rainfall. The impact of land use on soil moisture at 1.0 m was much less than at the surface.

Point and plot scale measurements showed that infiltration, percolation, and runoff were influenced by land use. Compaction and/or burning and tillage limited infiltration at the sugar cane site to the point of causing infiltration-excess runoff at greater rainfall intensities. At lower precipitation intensities, subsurface compaction at the plow layer contributed to runoff generation through lateral flow generation. The woody based land uses had much larger preferential pathways and roots when compared to the herbaceous land uses. These preferential pathways appeared to greatly increase infiltration and percolation at the point and plot scales.

At the field scale, land use affected runoff during the wet season. During the dry season, runoff events were extremely limited. The decreased intensity and volume of rainfall during the dry season was not sufficient to cause runoff based on the soil storage capacity and K_{sat} at each field site. Therefore, at these field sites, no differences were observed between land uses and dry season flow. During the wet season, sugar cane had the greatest runoff event depth, frequencies and intensities observed. The majority of this response was due to infiltration-excess runoff. Pasture events were rare because of the large storage capacity of the soils, and the dense vegetation that overtook the pasture site when it was abandoned. When pasture runoff events did occur, they generally occurred in response to high intensity and short duration rainfall as the result of a 'fill and spill' saturation excess mechanism moderated by the abandoned vegetative mat. Based on our plot experiments, percolation was limited during extreme rainfall events with most water being diverted laterally as subsurface flow and runoff. Limited percolation during these events may limit groundwater recharge. During the wettest periods, coffee and forest both appeared to deliver runoff when precipitation volume was high with low precipitation intensity. The K_{sat} and the dye patterns suggest that lateral conductivities may result in subsurface discharge to the channel or some type of return flow mechanisms. The majority of coffee and forest runoff events had lower intensities than the sugar cane or pasture. During extreme irrigation events in these woody land uses, most water was directed vertically as percolation deeper than 1 m. Therefore, runoff generation may be a mixture of 'fill and spill' type mechanisms, the macroporosity and associated percolation of the woody land uses may be a substantial source of groundwater recharge during wet periods. Due to the setup of our field sites, I observed that forest had an immense ability to re-infiltrate sugar cane runoff. Therefore, woody-based land uses may contribute to some mitigation of flooding and recharge of aquifers. Finally, lateral flow or return flow, via lateral conductivity due to roots and macropores, may be a subtle but important runoff mechanism for woody based land uses during very wet periods. More replication and detailed study at the landscape scale due to the heterogeneity of these systems should be conducted to properly assess this potential.

As measurement scale increased, the influence and importance of macropores became evident. At the point scale, variance in K_{sat} measurements points to the need to make measurements at a larger scale to increase the likelihood of incorporating the effects of preferential pathways. More studies that seek to quantify K_{sat} variance with depth will result in useful information for modelers. Even though increases in scale increased infiltration rates, the effect of land use on infiltration rate was still obvious at the larger scale. While runoff coefficients were small at the field scale, water yield between the land uses was significantly different in intensity and amount. Especially during wet periods, pasture and sugar cane may limit percolation due to limited root distribution and compaction, and lateral flow generation. The impacts of land use and land use change should continue to be studied at larger scales with varying climatic conditions.

In this study, I observed differences in K_{sat} at the point scale due to land use. At the plot scale, I observed a mechanism similar to the 'fill and spill' concept. However, in this mechanism, lateral flow was generated as the result of precipitation intensity exceeding soil storage and conductivity. Also, at this scale, it was apparent that land use modified the conceptual model to generate different amounts of surface runoff and subsurface lateral flow. Finally, at the field scale, different runoff characteristics were unique to each land use.

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CHAPTER 2

Historical land use cover and change and its effects on hydrological processes in the upper Reventazón River, Costa Rica

Abstract

Across the tropics, and the world, land use change has been a primary result of the development with major impacts on hydrological processes. In this study, I combined land use parameterization (e.g., forest, coffee, sugar and pasture) derived from field observations to investigate the interplay of antecedent moisture content (AMC), infiltration, surface runoff and percolation using a one-cell model. To look for similar patterns at the watershed scale, I performed a supervised land use classification of two satellite images (1986 and 1996) of the upper Reventazón watershed in Costa Rica. While minimal land use change occurred from 1986 to 1996, seven nested watersheds were classified as either forested (>85% forested) or mixed-use watersheds (<50% forested). In the one-cell modeling, at AMC of field capacity or greater, sugar and pasture initiated percolation quicker and with less cumulative rainfall than the forest and coffee at lower precipitation intensities (<3.5 cm/hr). At the wetter moisture contents in the forest and coffee, increased lateral flow (matrix and macropore) delayed the initiation of percolation. Also at the greater AMC, sugar and pasture initiated surface runoff more quickly and with less cumulative precipitation due to their lower conductivities (0.7 and 1.3 cm/hr respectively). With high precipitation intensity (10 cm/hr), surface runoff was greater in the sugar and pasture than in the forest and coffee. At the same intensity, no percolation occurred within

the sugar and pasture. At the drier AMC, much more distinct differences were observed between the forest, coffee, sugar and pasture. At the drier AMC, hydrological connectivity throughout the entire soil profile was disrupted in the sugar and pasture. While the sugar and pasture initiated surface runoff quickly and with less cumulative precipitation than in the forest and pasture, percolation was delayed in the sugar and pasture due to the lower conductivities resulting in a smaller vertical flow to the deeper, soil horizons. In the forest and coffee, greater conductivities allowed for the rapid transfer of water throughout the soil profile. In general, the one-cell modeling showed that differences in surface runoff and percolation between land uses diminished with increasing moisture content and precipitation intensity. Basic hydrological analyses (Flow Duration Curves) and runoff coefficients) showed that the forested watersheds had much greater water yields with less variability than mixed-land use watersheds. However, on average, the forested watersheds also received more precipitation due to elevation and regional microclimates. Due to a good regional cover of data, but a poor temporal resolution, model results were compared to monthly discharge values within the seven watersheds. The majority of the simulations predicted discharge better than using the mean of the data. Similar results to the one-cell modeling were observed at the watershed scale with greater amounts of percolation occurring at the transition from the dry season to the wet season. Also, during the transition to the wet season, surface runoff occurred much earlier in the mixed-land use watersheds. Finally, greater percolation within the forested watersheds led to greater baseflow contribution to river discharge. Therefore, while bedrock topography may provide a quantitative depth threshold for subsurface connectivity and ultimately lateral flow, in these deep tropical soil systems, the soil and its conductivity may control the rate at which this depth is exceeded. This connection may be particularly important during the transition from dry to wet season.

Introduction

Across the tropics, and the world, agricultural cropland and pasture have expanded into forest with little sign of retreat (Fisher and Helig 1997). Land use change has been a primary result of the development in Costa Rica over the past 70 years. Costa Rica had an extremely high percentage of deforestation from the 1940s to the 1980s. In 1983, only 17% of the 1940 forest acreage remained intact (Sader and Joyce 1988). While tropical hardwood extraction was one economic aspect of the deforestation, pasture and crop expansion drove the majority of the land use change (Sanchez-Azofeifa et al. 2001). Over roughly the same time period, hydroelectric power generation dramatically increased (Quesado-Mateo 1990). In 1995, hydropower produced 90% of the country’s electricity demand (Sanchez-Azofeifa et al. 2002). Currently, the Rio Reventazón produces about 27% of Costa Rica's hydroelectricity (Locatelli et al. 2011). However, extreme peak flows and erosion cause loss of power generation due to the limited capacity of reservoirs in Costa Rica (Pagiola 2003). Sanchez-Azofeifa et al. (2002) observed likely trends between increased forest fragmentation and the amount of economic loss due to flooding in several of the major watersheds in Costa Rica. During and after agricultural expansion, the Costa Rican landscape has been heavily influenced by cash crops, government subsidies, foreign aid, and the global economy. These influences promoted particular land uses (e.g., pasture, coffee, sugar cane, bananas, pineapples) throughout different periods of time (Hall 2000).

Due to the rapid loss of forest, and increasing concerns about the loss of its ecosystem services, the Costa Rican government passed Forest Law 7575 in 1996. The law was a product of over 30 years of debate, which linked ecosystem services such as biodiversity conservation, carbon sequestration, scenic beauty, and hydrological services to forested land cover (Reyes et al. 2000). This law introduced the Pagos para Servicos Ambientales (PSAs), or Environmental Service Payments. Pagiola (2003) identified several quantifiable hydrological services of importance to Central America. Some of these services include: 1) regulation and improvement of seasonal distribution of water flow, and 2) reduction of flooding and drought occurrence and magnitude. One question that needs to be answered for a system of payment for hydrological services is what type of land use in a given location will provide the greatest level of hydrological services. Through payments, land-owners can be compensated for ecosystem services through reforestation efforts and some agroforestry operations. Costa Rica, perhaps more than any other country, has made a significant investment to capitalize on ecosystem services provided by forests.

The influence of land use on hydrology has been debated for several decades (Hamilton and King 1983; Bruijnzeel 1991). In forested catchments, hydrometric and isotope studies have suggested that groundwater and subsurface storm flow provide a significant amount of the stream discharge during a storm event (e.g. Kendall and McDonnell 1998). However, many still question the extent to which land use change influences hydrological services, such as water supply, and flood frequency and intensity.

Forests are lauded for their natural services of increased infiltration and reduced erosion potential (Tomich et al. 2004), even while different conceptualizations of how soil characteristics influence hydrological response are being developed (Dunne 1978; Elsenbeer 2001). Lack of high quality long term monitoring data (e.g, precipitation, potential evapotranspiration, discharge), imagery resources, and data intensive hydrologic models usually prevent or hinder successful hydrological analysis in the tropics (Bruijnzeel 2004).

Hydrological responses to forestry practices have been studied extensively around the world (Bosch and Hewlett 1982; Harr 1986; Bruijnzeel 1991). Many of these studies have focused on water yield increases due to less evapotranspiration (ET) of post-forest land cover types. Land use conversion changes vegetation type and structure, affecting the amount of ET, and its influence on storm runoff (Zhang et al. 2001). Once a forest has been removed, leaf area is greatly reduced, which in turn reduces or eliminates the interception capacity and transpiration of the forest. The loss of transpiration is of no small consequence; mature tropical forests in Costa Rica can transpire over 50% of the bulk precipitation (≈ 2 m) when unlimited in terms of soil moisture (Loescher et al. 2005). Decreased water demand, interception, evaporation, and extraction from deeper subsurface sources of water are other noted effects of forest conversion (Imbach et al. 1989; Van Dijk and Bruijnzeel 2001). Changing ET demands influence the soil moisture conditions of a watershed and potentially its groundwater reserves. Bruijnzeel (2004) found that if surface disturbance remains limited, the bulk of these increases occur during base flow (low flow) conditions. If infiltration characteristics of the forest are preserved, then most of this water should connect to groundwater sources and increase base flow (Bosch and Hewlett 1982). Therefore, based solely on vegetation characteristics, conversion from forest to agriculture should increase water yields (Costa and Foley 1997; Calder 1998; Zhang et al. 2001; Costa 2003).

Vegetation type influences soil hydrological parameters related to soil structure such as infiltration capacity, hydraulic conductivity, macropore connectivity, and water retention (Himo et al. 1987; Williamson et al. 2004; Hanson et al. 2001; Hendricks and Flury 2001). Root zones potentially influence the vertical and horizontal hydraulic conductivity, and thus saturated overland flow (Beer et al. 1995; Elsenbeer 2001). Soil disturbance from agricultural land use, such as reduced infiltration and destruction of macropores, can affect flow paths leading to more flooding and less groundwater recharge. The saturated hydraulic conductivity (K_{sat}) plays an important role in the determination of flow paths within a soil (Elsenbeer 2001; Ziegler et al. 2004). Godsey and Elsenbeer (2002) measured saturated K_{sat} values in forest, abandoned banana-cacao, and pasture. Differences between the land uses at shallow depths influenced the infiltration capacity and the associated runoff index.

Preferential pathways and soil compaction determine the direction (i.e. vertical vs horizontal) of hydrological flow paths. Preferential flow paths play an important role in humid forested hillslope hydrology (Mosley 1979; McGlynn et al. 2002). Soil compaction is often the result of land use, such as heavy machinery use or animal traffic, impeding the connection to subsurface storm flow. The loss of macropore connectivity reduces infiltration rates and lateral flows (Bodhinayake and Cheng Si 2004; Wilson and Luxmoore 1988; Hanson et al. 2004). The investigation of macropore connectivity and land use change has only begun to be assessed at the plot scale (see Chapter 2; Hanson et al. 2004). Kamauzaman (1991) showed an increase in overland flow due to this type of soil compaction. Lal (1996) and Gilmoure et al. (1987) showed that continued exposure of bare soil to intense rainfall and overgrazing are two other aspects of land use correlated with a switch from subsurface to surface flow. Costa et al. (2003) concluded that an increase in wet season flows was due to a significant portion of the watershed being compacted by pasture use. When compaction influences a watershed response, the potential for flood frequency and intensity is increased, while dry season groundwater recharge is impeded (Costa et al. 2003; Bruijnzeel 2004).

Many studies have investigated trends in discharge at the river basin scale (Karl and Knight 1998, Xu 2003, Lettenmaier et al. 2004, and Small et al. 2006). However, natural climate variability can make it difficult to detect hydrological trends due to land use change. Trend detection is limited by the short history of detailed hydrological and meteorological databases (Defries and Eshleman 2004). While many different land uses have been evaluated for hydrological responses and characteristics, actual land use *change* over time has received little attention (Lambin et al. 2002). Climate variability, land use change, and anthropogenic withdrawals all modify the discharge of a river. However, climate variability and changes in land use are two of the most frequently mentioned factors influencing long-term discharge (Costa 2003).

Hydrological models allow investigation of the impacts of land use change and climate variability. With the advent of distributed hydrological models, the effect of land use on ET, infiltration, lateral flows, storage and percolation needs to be verified for accurate simulations. The Soil Moisture Routing (SMR) model (Boll et al. 1998; Frankenberger et al. 1999; Brooks et al. 2007) was developed as a distributed hydrological model for shallow soil systems. Deeper tropical soil systems may have sufficient anisotropy to warrant use of the SMR model (Brooks, personal communication; Elsenbeer 2001). SMR combines a digital elevation model with soils maps, evapotranspiration calculations, land use, and a variety of other parameters to produce simulated soil moisture and overland flow. SMR can be run on small time steps with a layered soil system. One of the benefits of using SMR in Costa Rica is that is has limited data requirements (digital elevation model, soils map, meteorological data). Simulated hydrological data, based on measured precipitation, and assessed against measured discharge data, provides the opportunity to investigate the hydrological processes such as recharge and overland flow. Finally, the deep tropical soils have high infiltration capacities which may also lead to saturation overland flow rather than infiltration excess overland flow.

Chapter 1 described field observations of soil and hydrological properties of four of the most common land uses (i.e., forest, coffee, sugar cane and pasture) in the upper Reventazón watershed on the Atlantic slope of Costa Rica. Hydrological parameters (i.e. K_{sat}), roots, and macropore distribution were very different among these land uses. Also, land use accounted for small differences in soil moisture dynamics. Runoff coefficients at the field scale (between 1-7%) were much smaller than those reported for major watersheds in Costa Rica (between 45-80%, UNESCO (2007)). Costa Rica's detailed databases present a rare opportunity to assess land use change in the tropics at a regional scale spanning two decades. Our overall objective, therefore, is to better quantify the regional hydrology and determine if hydrological processes are affected by land cover at the watershed scale in the Reventazón river basin in Costa Rica. We start with translation of the conceptual understanding of hydrological processes at the plot and field scale based on field observations in Chapter 1 to a quantitative response model for the four common land uses. With the quantitative response model I determine how antecedent moisture content and precipitation intensity affect the amount and timing of surface runoff and percolation by land use type. This quantitative understanding of the underlying hydrological responses for individual land use types was incorporated into the SMR model to determine how discharge characteristics differ between seven nested watersheds in the Reventazón river basin ranging in size from 65-1300 km^2. I analyzed observed and modeled hydrological and meteorological data at these seven nested mixed land use watersheds to determine how runoff coefficients and water balance components in these watersheds changed between 1986 and 1996.

Methods

Site description

The watersheds used in this study are located within the upper Rio Reventazón basin, Costa Rica with varying geospatial characteristics (Table 1). The Rio Reventazón basin is a major drainage running from the Cordillera Central in Central Costa Rica to the Atlantic Coast (Jansson 1996). The area is topographically diverse, with elevations ranging from 500 m in river valleys to over 2500 m. Two volcanoes, Irazu and Turrialba, and the Cordillera Central influence precipitation and soils in the study area. Depending on elevation, annual precipitation ranges from 2000 mm up to 8000 mm. The soils within the watershed include andisols, inceptisols, and ultisols. Andisol presence depends on proximity to the Volcanoes. Predominant land uses in the area are forest, coffee, pasture, annual crops (e.g. sugar cane and vegetables) and urban areas. The Reventazón is a major hydroelectric generating river within Costa Rica (Locatelli et al. 2011). Seven gauging stations at the outlets of different watersheds were used in our analysis (Figure 1). Watersheds will be referred to as their alpha-numeric codes throughout the rest of the document (see Table 1) where F is forested, M is mixed land use. I defined the upper Reventazón watershed as upstream of the Angostura (M3) gauging station. Each of the additional watersheds is nested within the M3 watershed. The El Humo (F1) is located within the Oriente (F2) watershed. The Montecristo (F3) watershed is located within the Palomo (F4) watershed. The remaining watersheds, La Troya (M1) and Turrialba (M2), drain separate parts of the M3 watershed. M1 and M2 also have the largest urban areas (i.e. Cartago and Turrialba, respectively) within their watersheds.

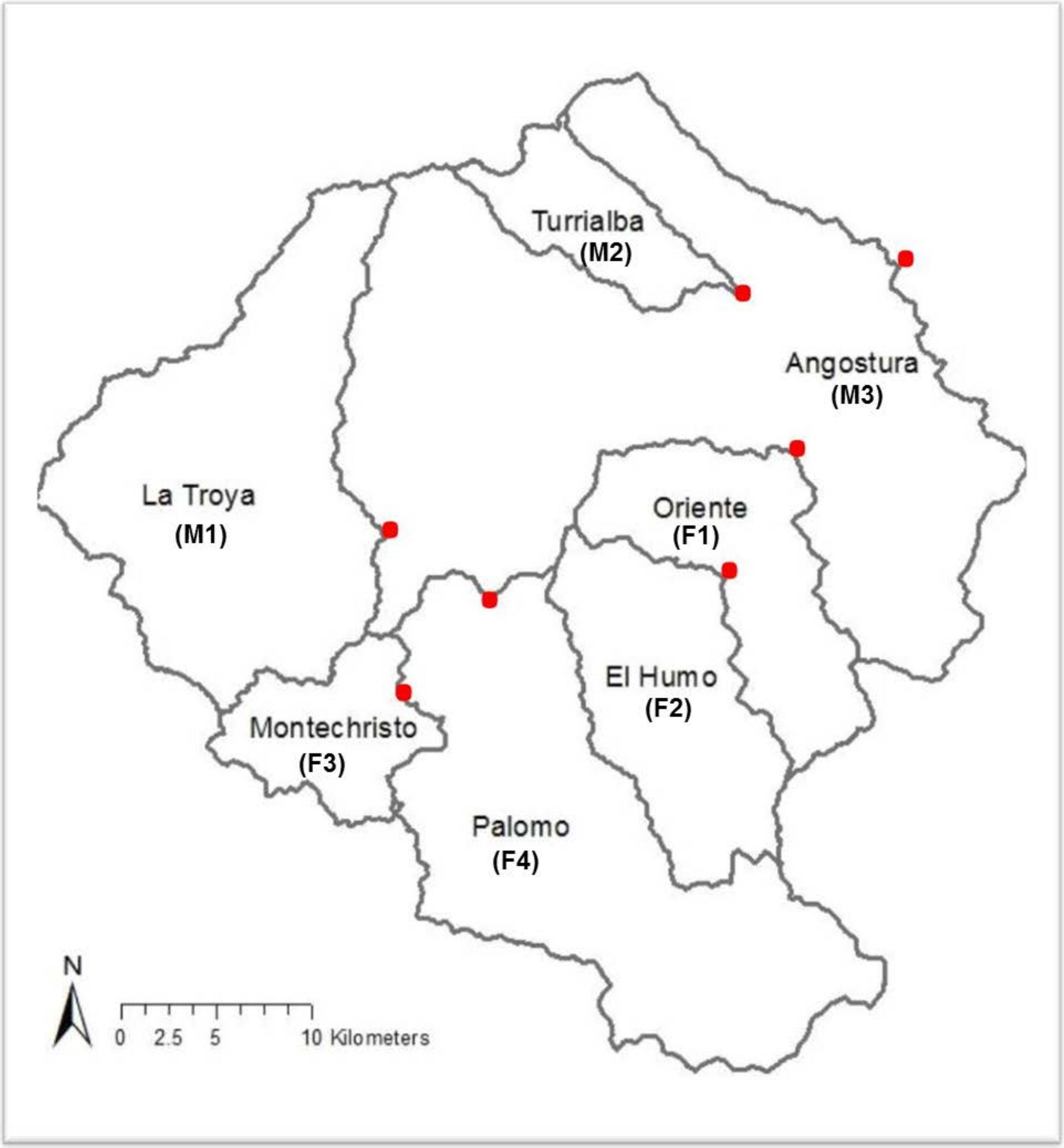

Figure 1. Location of the study watersheds within the Angostura (M3) watershed or upper Rio Reventazón basin. The red dots indicate the location of the discharge gauging stations used in this study.

Table 1. Watershed characteristics and data descriptions (F1-F4 are forested watersheds; M1-M3 are mixed land use watersheds).

Watershed	Area (km^2)	Latitude	Longitude	Elevation	Data Type	Data Record
F1 (El Humo)	137	09°47’36”	83°43’08”	692	Daily	1974-2004
F2 (Oriente)	227	09°49’38”	83°41’31”	619	Daily	1974-2004
F3 (Montecristo)	65	09°44’55”	83°52’00”	1659	Daily	1974-1995
F4 (Palomo)	371	09°46’57”	83°50’23”	1077	Monthly	1974-1995
M1 (La Troya)	275	09°48’43”	83°51’59”	1029	Monthly	1981-1997
M2 (Turrialba)	77	09°54’22”	83°40’17’	570	Monthly	1981-1997
M3 (Angostura)	1337	09°52’58”	83°39’00”	538	Monthly	1974-1995

One-cell Model

Conceptual modeling of the different land uses occurred using SMR algorithms (see below) for a 10 m^2 cell in Excel. Soil physical parameter values were obtained from the field experiments and surveys (see Table 2). Synthetic precipitation volume and intensity were varied to determine threshold values for percolation and runoff consisting of the amount of precipitation or time to initiate percolation or runoff. Differences in land use changed the vertical K_{sat} (Ksub in Table 2), soil depth, soil storage amount (e.g., differences in land use modified soil horizons), matrix and macropore K_{sat}. Each field site had the same soil type, so porosity and field capacity were the same for each land use. Evapotranspiration was set to zero to focus solely on water movement through the soil. The one-cell model was run at a 1 minute time step.

Table 2. Parameters used for the one-cell model for the different land uses.

Parameter	Forest	Coffee	Sugar	Pasture
Ksub A (cm/hr)	5.5	3.5	1.3	1.3
Soil Depth A (cm)	40	40	10	10
K_{sat} matrix A (cm/hr)	5.5	3.5	1.3	5
K_{sat} macropore A (cm/hr)	10	10	3	10
Ksub B (cm/hr)	3.5	3.5	0.7	1.3
Soil depth B (cm)	40	40	25	40
K_{sat} matrix B (cm/hr)	3.5	3.5	0.7	1.3
K_{sat} macropore B (cm/hr)	10	10	2	3
Ksub C (cm/hr)	3	3	0.7	2.4
Soil depth C (cm)	20	20	65	50
K_{sat} matrix (cm/hr)	3	3	1	2.4
K_{sat} macropore C (cm/hr)	5	5	1	3
Slope (%)	5	5	5	5

A number of parameters (field capacity, wilting point, and residual water contents, porosity, volumetric rock content, soil depth, and the K_{sat} for the matrix, macropores and the subsurface layer) are required to calculate change in soil moisture, percolation, runoff and lateral flow. The one-cell model, similar to the SMR model, computes basic water balances by assuming step by step quasi-steady state (Brooks et al. 2007), as follows

$$D_i \frac{d\theta_i}{dt} = P(t)_i - ET(t)_i + \frac{\sum Q_{in,i} - \sum Q_{out,i}}{A} - L_i - R_i \quad (1)$$

where i is the cell address, D_i equals the restricting layer depth (m), θ_i is the volumetric moisture content of the cell (m^3/m^3), P is the precipitation (m), ET is the actual ET (m), $\Sigma Q_{in,i}$ is the lateral inflow from surrounding upslope cells (m^3), $\Sigma Q_{out,i}$ is the lateral outflow to surrounding downslope cells (m^3), L_i is the vertical leakage or percolation out of the surface soil layer (m), R_i is the surface runoff (m), A is the area of the grid cell (m^2), and t is time (minute) (Figure 2).

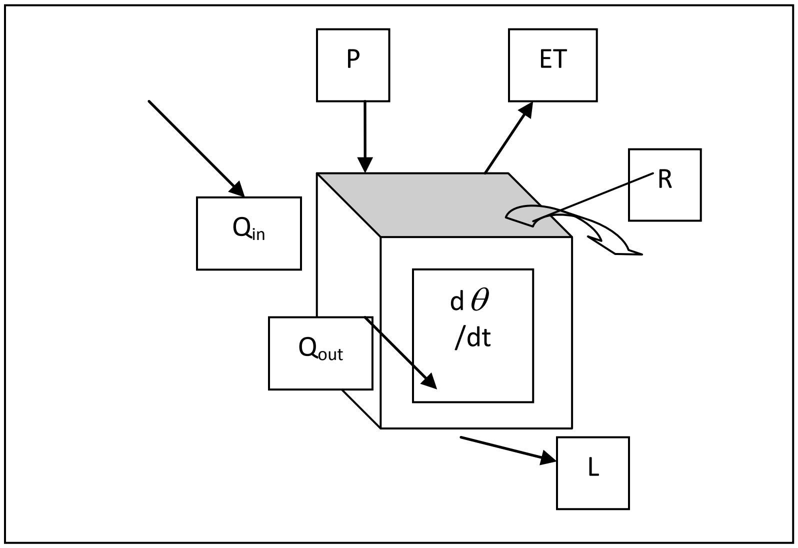

Figure 2. Depiction of the one-cell and SMR Model water balance.

Land Use Change

Landsat satellite images from February 1986 (TM) and November 1996 (TM)were obtained from Earth Resources Observation and Science (EROS) Center (USGS, 2011). Images were classified using ArcGIS 10 and computer processing techniques (supervised classification) and visual interpretation (manual interpretation) with aid of aerial photos (from the different time periods), the ICAFE database, other land use maps, and ground point observations (Petchprayoon et al. 2010). Images were classified into 12 land use categories including: forest, coffee, sugar cane, pasture, urban, bare soil, mixed agriculture, saran (ornamental production), greenhouses, water, clouds and shadows. The supervised classification used the maximum likelihood method due to its robustness (ArcGIS 10). The assumption of normally distributed data was checked using the histogram and summary statistics within ArcGIS 10 (Petchprayoon et al. 2010). Clouds and shadows were removed based on the integration of additional images from these time periods with different patterns of cloud cover. The Raster Calculation technique in the Spatial Analyst extension in ArcGIS was used to integrate these additional images and identify areas of land use change between the different time periods.

Hydrometric data

Hydrometric data (precipitation and discharge) were obtained from the Instituto Costariccense de Electricidad (ICE). Length and temporal period of data record differed between most gauging stations based on ICE resources, priority and access to the station. Precipitation data were obtained as daily or monthly totals of precipitation depth. Discharge data were obtained as either daily or monthly average values. These data were converted to depth using number of days within the month for monthly data, and watershed area.

Flow duration curves and runoff coefficients

Flow duration curves (FDCs) were used to summarize the flow regime at a particular site (Smakhtin 1999; Vogel and Fennessey 1994). The FDC is a cumulative density function that displays the relationship between runoff (cm) and the percentage of time mean discharge is exceeded. In this capacity, FDCs were used to depict mean discharge and variability of high discharge and low discharge. FDCs were calculated using monthly time steps.

Annual runoff coefficients were calculated for each watershed by dividing the annual discharge by the annual precipitation. Distributed precipitation was generated using the SMR model, local meteorological stations, and 30 arc second (1-km^2) WorldClim monthly precipitation raster maps (Hijmans et al. 2005) clipped to the Reventazón basin. Each 1 km^2 pixel within the monthly WorldClim raster map contains a precipitation value that is the historical average precipitation for that month at that location. For each month, precipitation ratio raster maps were calculated based on the observed precipitation of a particular meteorological station. For example, at the Tuccurique meteorological station in March where the observed value was 100 mm, the entire raster map was divided by 100 mm to determine the precipitation ratio. At the Tuccurique meteorological station the precipitation ratio would be 1. If the average monthly precipitation for March in a different location was 80 mm, then this location would receive a 0.8 precipitation ratio. Due to the spatial heterogeneity of the WorldClim grids the precipitation ratios accounted for lapse rates and regional specific microclimates. Daily precipitation was then input into the SMR model to distribute the daily precipitation over the entire watershed multiplied by the precipitation ratio.

Daily precipitation data from the F1 precipitation gauge was used to model all of the watersheds. Precipitation ratio raster maps were made for each month of the year using the WorldCLIM monthly precipitation maps. Evapotranspiration was modeled in a similar manner to precipitation. However, ET data were obtained from the CATIE weather station. Evapotranspiration data were only available in monthly totals. Therefore, the monthly value of ET was converted to daily data by dividing the monthly value by the number of days in the month.

Input Maps

SMR uses three primary input maps: elevation, soils and land use. A 30 m digital elevation model was obtained from the CATIE GIS department. The soils map was a merged product from a more detailed 1:24,000 map (Winoweicki et al. 2007) and the Costa Rican Atlas (2005) at 1:200,0000. Soil depth, porosity, field capacity, wilting point, rock content, and matrix K_{sat} were obtained for each soil type from the two combined soil maps to make the primary soils map. The 1986 land use map was used as the land cover for the daily simulations. The conceptual models were integrated into a secondary soils map as modifications of the macropore K_{sat}.

Performance criteria

The model efficiency, modified model efficiency (E_1), mean absolute error, root mean square error, the index of agreement and modified index of agreement (d_1) for discharge were used to compare measured and simulated data (Nash and Sutcliff 1970; Legates and McCabe 1999). The modified statistics were used because of their more conservative nature (e.g., absolute values rather than squared) when compared to their previously mentioned counterparts. While E' and d' provide a relative, yet dimensionless, assessment of model performance, mean absolute error (MAE) was calculated to describe the difference between observed and modeled data in units of discharge (L). These statistics were calculated using the following formulas:

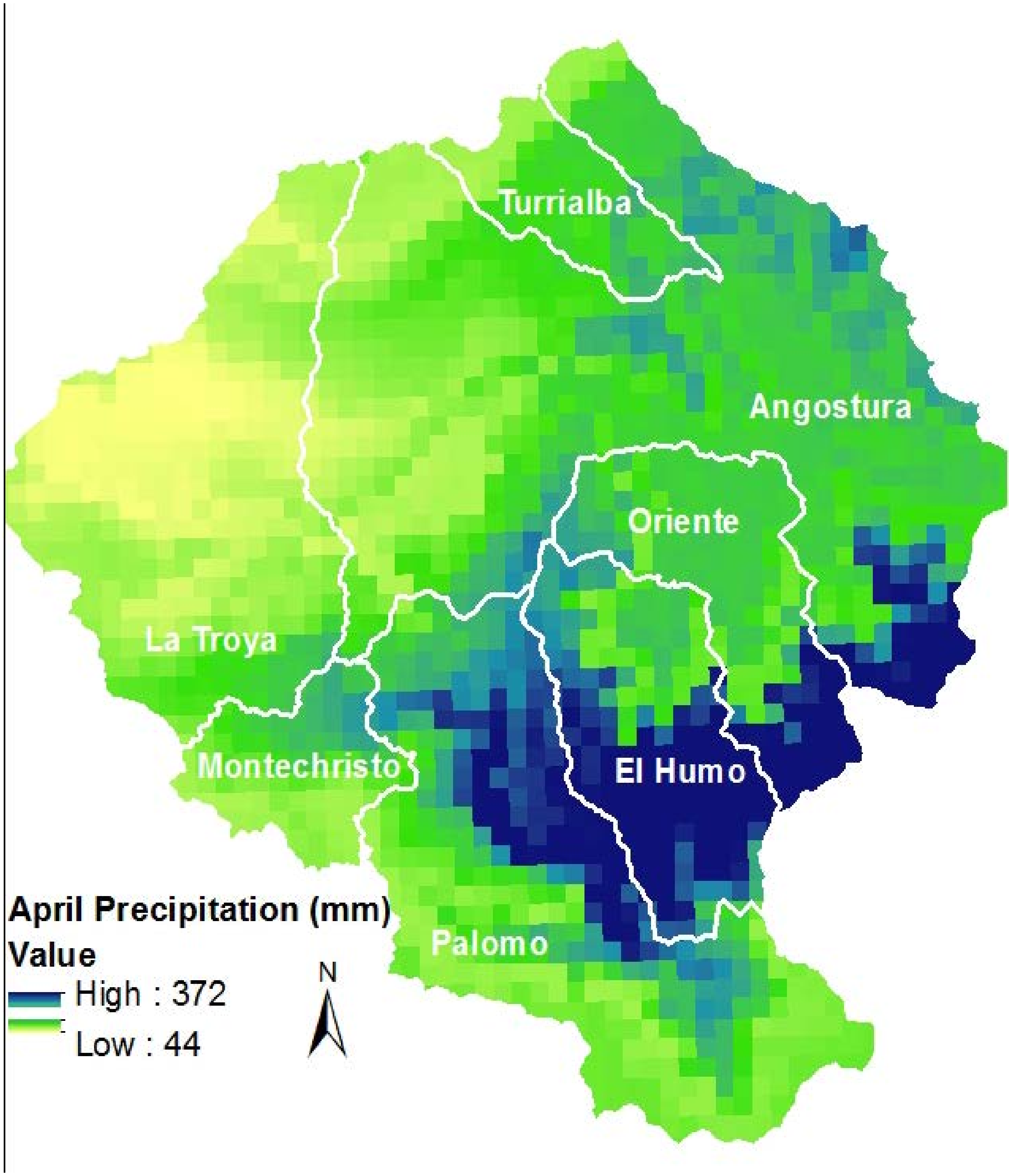

Figure 3. Example of a monthly precipitation map from World CLIM (April).

$$E_1 \equiv 1.0 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} |O_i - \bar{O}|} \quad (2)$$

$$d_1 \equiv 1.0 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} \left(|P_i - \bar{O}| + |O_i - \bar{O}| \right)} \quad (3$$

$$MAE \equiv N^{-1} \sum_{i=1}^{N} |O_i - P_i| \quad (4)$$

where O_i is the observed discharge, P_i is the predicted discharge, and $\bar{O}_i$ is the average value of O_i for the period being simulated. When $E_1 > 0$, the model is a better predictor than the observed mean (Wilcox et al. 1990). The d_1 value ranges from 0.0 to 1.0. The E_1 and d_1 should approach 1 for valid simulations (Legates and McCabe 1999).

Results

One cell model

Precipitation volume and intensity drive the interplay between soil storage, rate of infiltration and conductivity to determine the initiation of percolation and/or runoff. Results from the one-cell model for the different land use types depict this interplay for three antecedent moisture conditions (Figures 4-7). The first series of plots depicts *cumulative* precipitation (cm) to initiate percolation as a function of precipitation intensity (Figure 4). Figure 5 depicts cumulative time to initiate percolation as a function of precipitation intensity. Figures 6 and 7 depict the same response variables for surface runoff. As precipitation intensity increased in each land use, cumulative precipitation required to initiate percolation was relatively constant at the lower precipitation intensities then reached a threshold followed by a linear increase (see Figure 4). The threshold occurs when the minimum vertical K_{sat} within the soil profile is exceeded by precipitation intensity and the rate of deep infiltration has reached its maximum and fills storage rapidly to saturation. The linear increase with increasing precipitation intensity occurs because more precipitation is diverted to surface runoff as precipitation intensity increases. Cumulative precipitation needed to generate surface runoff decreased with precipitation intensity until a threshold was reached when it became constant. This cumulative precipitation threshold occurs when soil storage is exceeded so rapidly that the rate of percolation and lateral flow become less effective. At dry antecedent moisture conditions (AMC), the depth of water to reach saturation is greater for forest and coffee (8 cm) than for pasture and sugar (2.05 cm) based on differences in soil depth.

Cumulative time to percolation decreased with increasing precipitation intensity, rapidly at first, then more gradual in exponential fashion. Cumulative time to runoff decreased piece-wise linearly with increasing precipitation intensity. Differences in AMC (dry, field capacity, and wet) and land use type (forest, coffee, sugar cane, and pasture) are described next.

Antecedent moisture content greater than or equal to field capacity

At field capacity and the wet AMC, both cumulative precipitation and time to initiate percolation were lowest (respectively) in the sugar and pasture (Figures 4-7). In the sugar cane, percolation occurs with minimal precipitation at both field capacity (1.8 cm) and wet AMC (0.01 cm). At the wet AMC, infiltration transfers water rapidly (at the rate of K_{sat}) throughout the profile with percolation quickly occurring after the initiation of precipitation. At low precipitation intensity with AMC at field capacity in the sugar, it can take up to 5 hours to initiate percolation but percolation occurs within 1 hr at greater precipitation intensities (2 cm/hr). The pasture requires slightly greater cumulative precipitation to initiate percolation at field capacity AMC (2.6 cm) and wet AMC (0.05 cm). Similar to the sugar cane, percolation can take up to 5 hours to start but percolation begins rapidly as precipitation intensity increases in the pasture. Due to greater active soil depth, the amount of water required to initiate percolation in forest and coffee required 4.3 cm (field capacity) and 1.8 cm (wet AMC). Time to percolation for both forest and coffee required approximately 5 hrs at the lower precipitation intensities but rapidly approached instantaneous as precipitation intensity increased. At field capacity, forest required slightly greater precipitation intensities and more time to initiate percolation than coffee. Differences in vertical K_{sat} (Table 2) and thus connectivity control the drainage at each time step within the top two soil layers explaining the major differences in the amount of percolation between the forest (3.5 cm/hr), coffee (3.5 cm/hr), sugar (1.3 cm/hr), and pasture (1.3 cm/hr). At the surface, differences in lateral K_{sat}, and thus lateral flow, account for the more finer detail differences between the forest (5.5 cm/hr) and coffee (3.5 cm/hr) and the sugar (1.3 cm/hr) and pasture (5 cm/hr) at field capacity AMC.

Cumulative precipitation and time to runoff were much lower in the sugar cane and pasture compared to forest and coffee. At wet AMC in the sugar, runoff occurred almost immediately with little additional precipitation required. At less than 2 cm/hr at field capacity in the sugar, cumulative precipitation (1.8 cm) and time (2.2 hrs) to generate runoff rapidly decreased then leveled out as precipitation intensity increased. Slight increases of both cumulative precipitation and time at greater precipitation intensities for field capacity AMC and wet AMC in the sugar cane are due to relatively much lower K_{sat} and the time-step resolution of the model. Even at a 1 minute time step, the model cannot properly account for the distribution of water. In the pasture, both at field capacity and wet AMC, cumulative precipitation to initiate surface runoff was observed at 2.1 cm and 0.55 cm regardless of precipitation intensity (Figure 6). The pasture had no increase or decrease of cumulative precipitation or time regardless of intensity. In the forest, cumulative precipitation to generate runoff remained level at field capacity (4.8 cm) and the wet AMC (1.8 cm) until precipitation intensity exceeded storage. At this point, cumulative precipitation to initiate runoff decreased linearly with increasing precipitation intensity. Cumulative time decreased from 1.25 hrs to zero as precipitation intensity increased. At a precipitation intensity of 5 cm/hr, both cumulative precipitation and time reached a threshold that approached zero as precipitation intensity increased.

Dry antecedent moisture conditions

While the cumulative precipitation to initiate percolation was similar in each land use at ≈20 cm, this amount was only observed for precipitation intensities less than 1 cm/hr in the sugar and pasture (Figure 4). Cumulative precipitation to initiate percolation in forest and coffee did not increase until precipitation intensities reached 5.5 cm/hr (forest) and 3.5 cm/hr (coffee). As previously mentioned, the increase of cumulative precipitation to initiate percolation corresponds to the amount of precipitation diverted to surface runoff that is controlled by the amount of available storage due to the lowest vertical K_{sat} within the soil profile. The stability of cumulative precipitation required to initiate percolation lies to the left of the vertical K_{sat} while the increase lies to the right.

One of the greatest differences between land uses was observed for time to percolation (Figure 5). In the sugar and pasture, time to percolation decreased rapidly as precipitation intensity increased above about 2 cm/hr. In the sugar, the lowest observed time to percolation was 18 hrs. In the pasture, the least time to percolation observed was slightly lower at 13 hrs. At the dry AMC, the hydrological connectivity between the upper and the deeper soil horizons is limited by the K_{sat} of the upper layer. Even when the upper soil layer is saturated, water can only infiltrate at the rate of the lowest K_{sat} to the deeper soil layers. As water infiltrates deeper into the lower soil horizons, the moisture content must reach field capacity before water can further infiltrate. In the forest and coffee, a similar decrease for time to percolation was observed. However, in the forest and coffee, the upper end of precipitation intensity was 4 cm/hr. Both the forest and the coffee time to percolation was much lower at 4.8 hrs. The lower times in the forest and coffee were due to the high vertical K_{sat} including the macropore $\mathrm{K_{sat}}$ that allows for nearly unlimited transfer of water throughout the soil profile. In the sugar and pasture, infiltration of water to deeper soil layers is limited by their reduced K_{sat} and thus lower connectivity with the upper horizons.

Sugar and pasture required the least amount of cumulative precipitation (2.1 cm) to initiate surface runoff. As precipitation intensity increased in the sugar, precipitation required to initiate surface runoff decreased rapidly in a linear manner until a precipitation of 1.7 cm/hr where precipitation intensity could not lower cumulative precipitation any further. In the pasture, cumulative precipitation required to initiate surface runoff was constant, however, runoff did not occur until a precipitation intensity of 1.7 cm/hr. In the coffee, as precipitation intensity increased to 5 cm/hr, cumulative precipitation decreased linearly to 8 cm. Precipitation intensity had no further effect on cumulative precipitation beyond this intensity. The forest was the only land use to have a continuous linear decrease in cumulative precipitation as precipitation intensity increased.

Cumulative time required to initiate runoff in sugar followed a sharp linear decrease of time until precipitation intensity reached 1.7 cm/hr. At greater intensities the amount of time (2 hrs) required to initiate runoff is constant. As precipitation intensity increased within the forest, coffee, and pasture, time to initiate surface runoff generally decreased. Pasture required the least amount of time to initiate surface runoff regardless of precipitation intensity. However, at the greater precipitation intensities, forest and coffee may approach similar response times to sugar and pasture.

Finally, at the wet AMC in each land use, slightly less cumulative precipitation and time were required to initiate percolation than surface runoff. Also, as AMC and precipitation intensity increase the differentiation between land uses becomes smaller. At the dry AMC, this pattern held true for forest and coffee. At the dry AMC, percolation occurred at lower precipitation intensities than surface runoff. However, with greater precipitation intensities at the dry AMC, surface runoff initiated with less cumulative precipitation and time than percolation in the sugar and pasture due to the formation of a perched water layer at the lowest conductivity. Since the deeper soils remained at the dry AMC while this perched water layer formed, these land uses had relatively less connectivity between the surface layers and the deeper soil horizon where percolation occurs. In the sugar, the perched water layer occurred within the middle soil horizon (0.7 cm). Infiltration into the deepest soil horizon was controlled by the vertical K_{sat} with percolation not occurring until its moisture content exceeded field capacity. In the pasture, this perched water layer also formed in the middle soil horizon. Finally, the pasture was the only land use where conductivities did not decrease with depth. In Figure 6, the pasture does not have the exponential decrease in cumulative precipitation required to initiate surface runoff. This is because the K_{sat} does not decrease with depth throughout the soil profile.

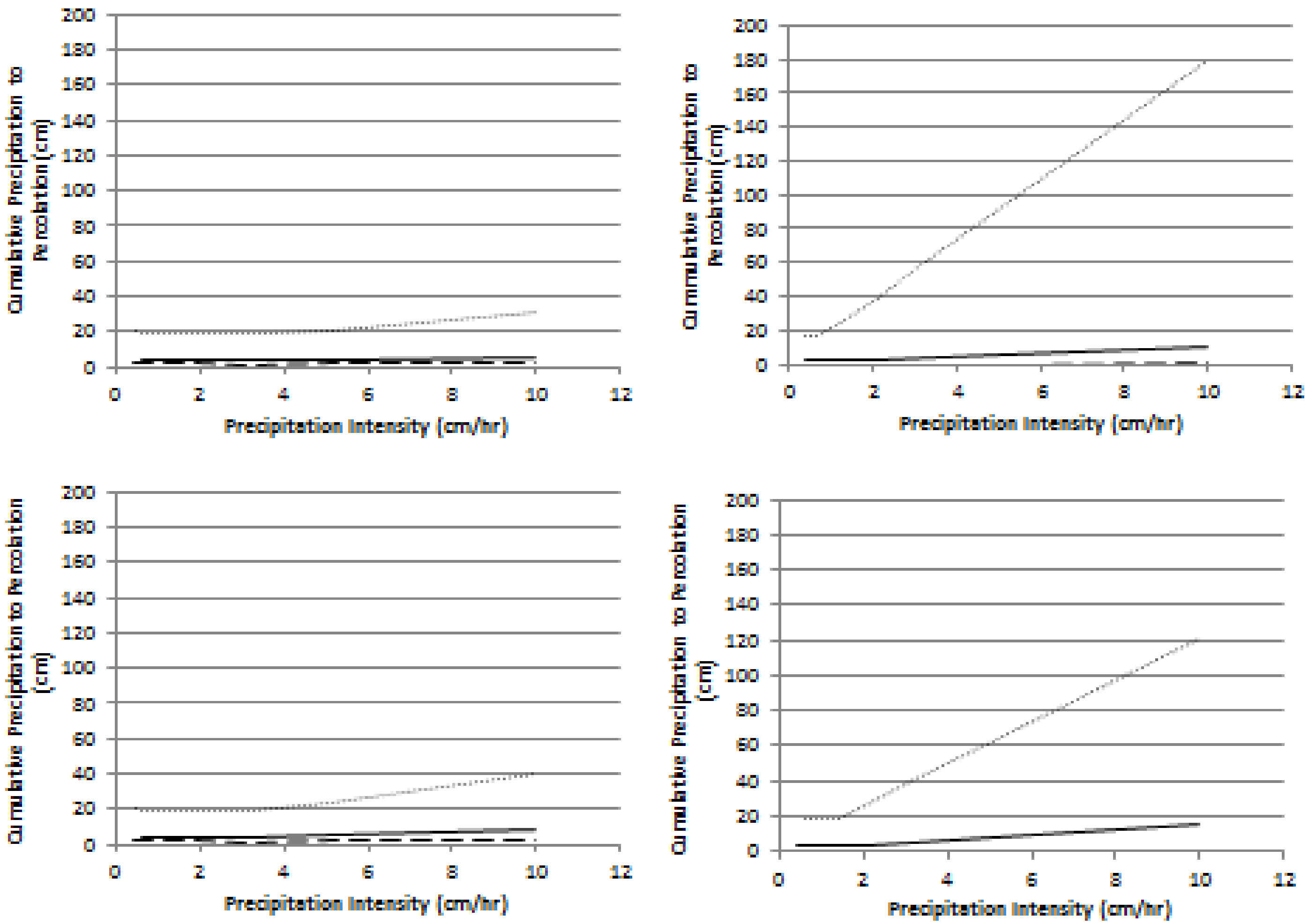

Figure 4. One cell simulation of cumulative precipitation needed to initiate surface runoff based on three antecedent moisture contents (DRY = 40 % moisture content (short dash), Field Capacity =55% mc (solid), and WET = 57.5% mc (long dash) for forest (upper left), coffee (lower left), sugar (upper right), and pasture (lower right).

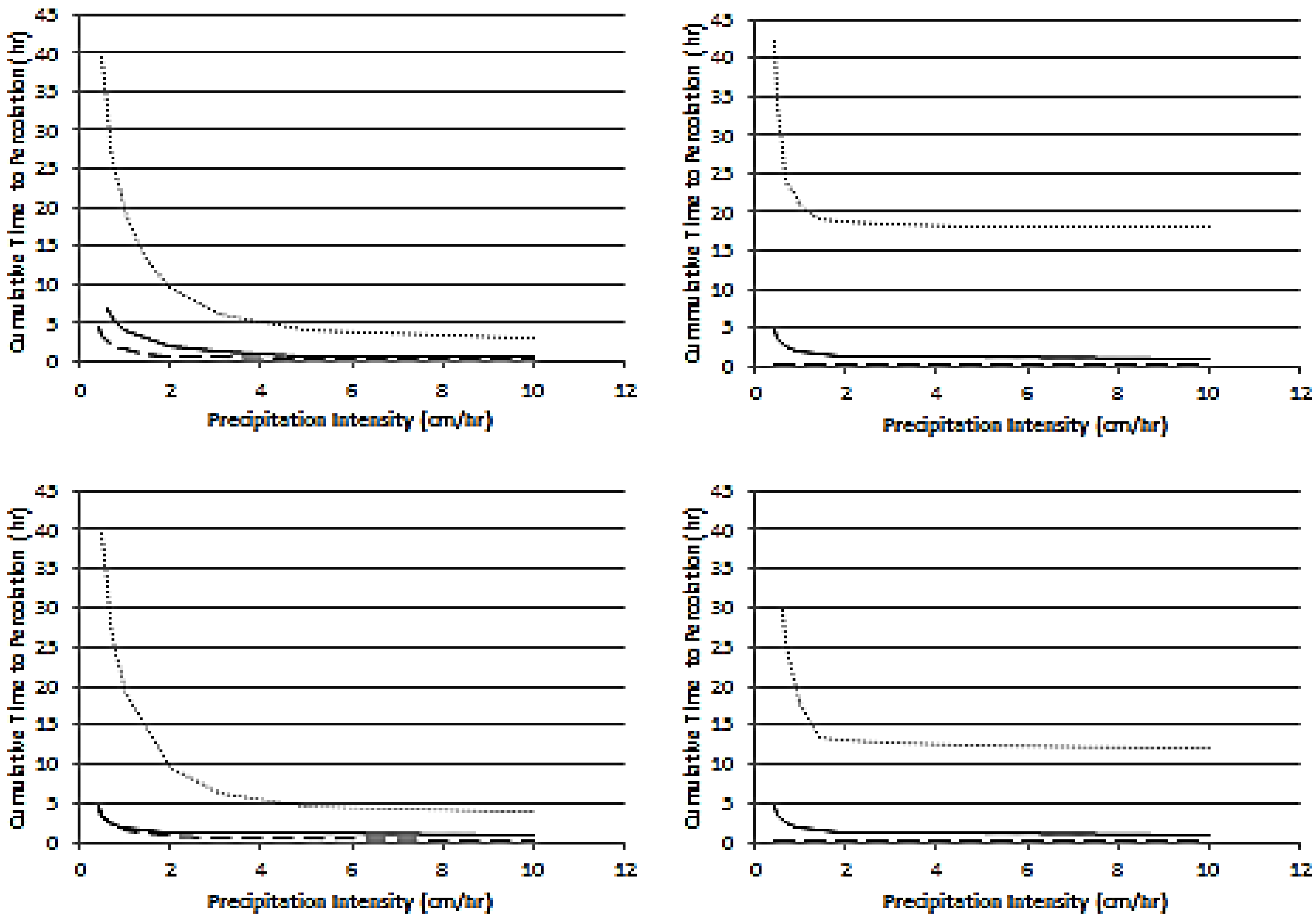

Figure 5. One cell simulation of cumulative time needed to initiate percolation based on three antecedent moisture contents (DRY = 40 % moisture content (short dash), Field Capacity =55% mc (solid), and WET = 57.5% mc (long dash) for forest (upper left), coffee (lower left), sugar (upper right), and pasture (lower right).

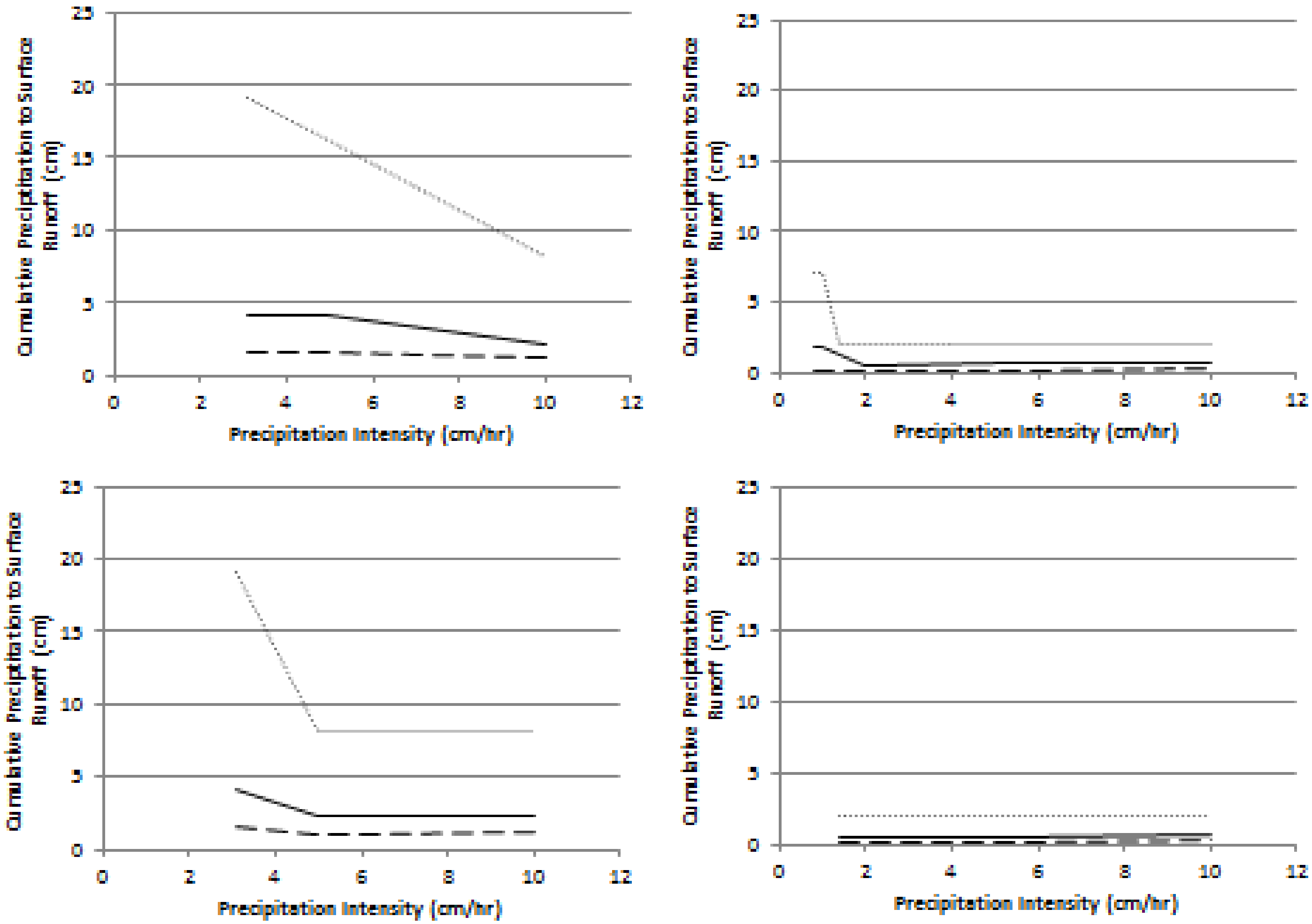

Figure 6. One cell simulation of cumulative time to initiate surface runoff based on three antecedent moisture contents (DRY = 40 % moisture content (short dash), Field Capacity =55% mc (solid), and WET = 57.5% mc (long dash) for forest (upper left), coffee (lower left), sugar (upper right), and pasture (lower right).

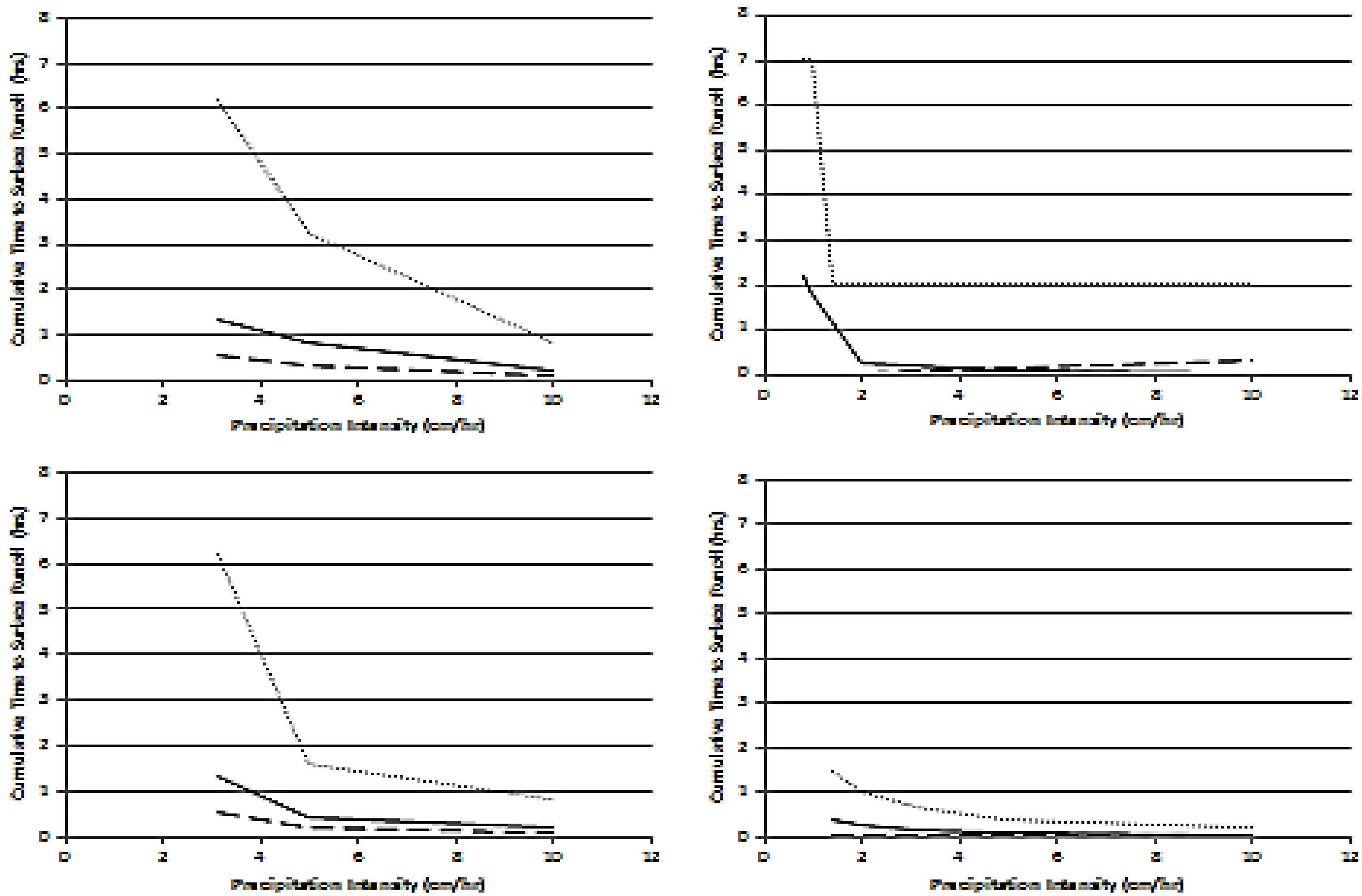

Figure 7. One cell simulation of cumulative time needed to initiate surface runoff based on three antecedent moisture contents (DRY = 40 % moisture content (short dash), Field Capacity =55% mc (solid), and WET = 57.5% mc (long dash) for forest (upper left), coffee (lower left), sugar (upper right), and pasture (lower right).

Water balance at field capacity AMC: the one-cell model

Long duration, low intensity precipitation events trigger mostly changes in storage, while long duration, high intensity precipitation events generate mostly runoff. At medium intensities, long duration storms generate mostly percolation. The effect of precipitation intensity (0.1 cm/hr, 1 cm/hr, and 10 cm/hr) for a 10 cm storm is shown for each land use in Figures 8-10. For example, following the changes for increasing rainfall intensity for forest shows that 52% of the water at the 0.1 cm/hr intensity is percolation, 59% of the water at the 1 cm/hr intensity is percolation, and 51% of the water at the 10 cm/hr intensity is runoff. Lateral flow initially is important, and less so as precipitation intensity increases. This sequence shows that during medium intensity storms, after storage approaches saturation, the rate of infiltration and hydraulic conductivity avoids soil saturation generating mostly percolation. After soil saturation occurs, and the rate of infiltration and K_{sat} are exceeded, runoff is initiated.

At low precipitation intensities much of the water infiltrates to increase soil moisture to saturation in each of the land uses (17-40%) (Figures 8-10). Along with lateral flow that occurs in the forest and coffee (8%) these account for the differences in percolation at this intensity. At intermediate precipitation intensities, percolation is similar among all land uses (54-59%) indicating similar duration of saturation of the bottom soil layers. Lateral flow differences still exist, but at a much smaller percentage of precipitation. Lateral flow also contributes to drainage and increased soil storage in the forest and coffee. Therefore, greater soil depth is available to infiltrate water and enhance connectivity throughout these profiles. Surface runoff accounts for 23-35% of the water balance in sugar and pasture. The medium precipitation intensity exceeds the minimum conductivity within the sugar. Once this conductivity is exceeded, the perched water layer develops in the top two soil horizons with saturation-excess runoff occurring shortly thereafter. At high precipitation intensities, surface runoff becomes the dominant hydrological process with sugar and pasture generating approximately 1.5 times the amount than forest and coffee, where percolation remains the second most dominant hydrological process. At high precipitation intensities, percolation ceases in the sugar and pasture due to a lateral diversion of infiltration through surface runoff.

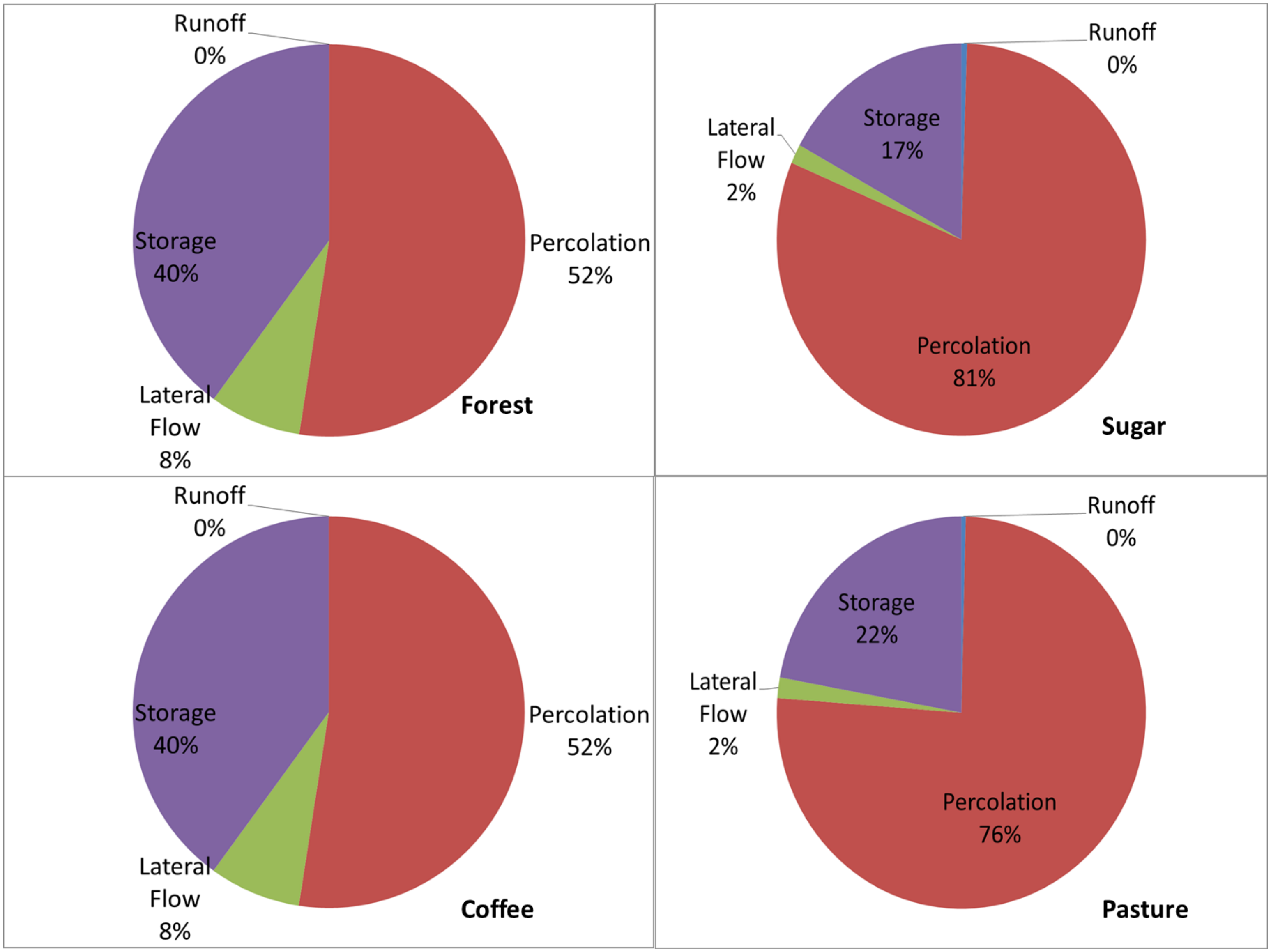

Figure 8. Water balance for low intensity precipitation (0.1 cm/hr) for a 10 cm event in each of the land uses.

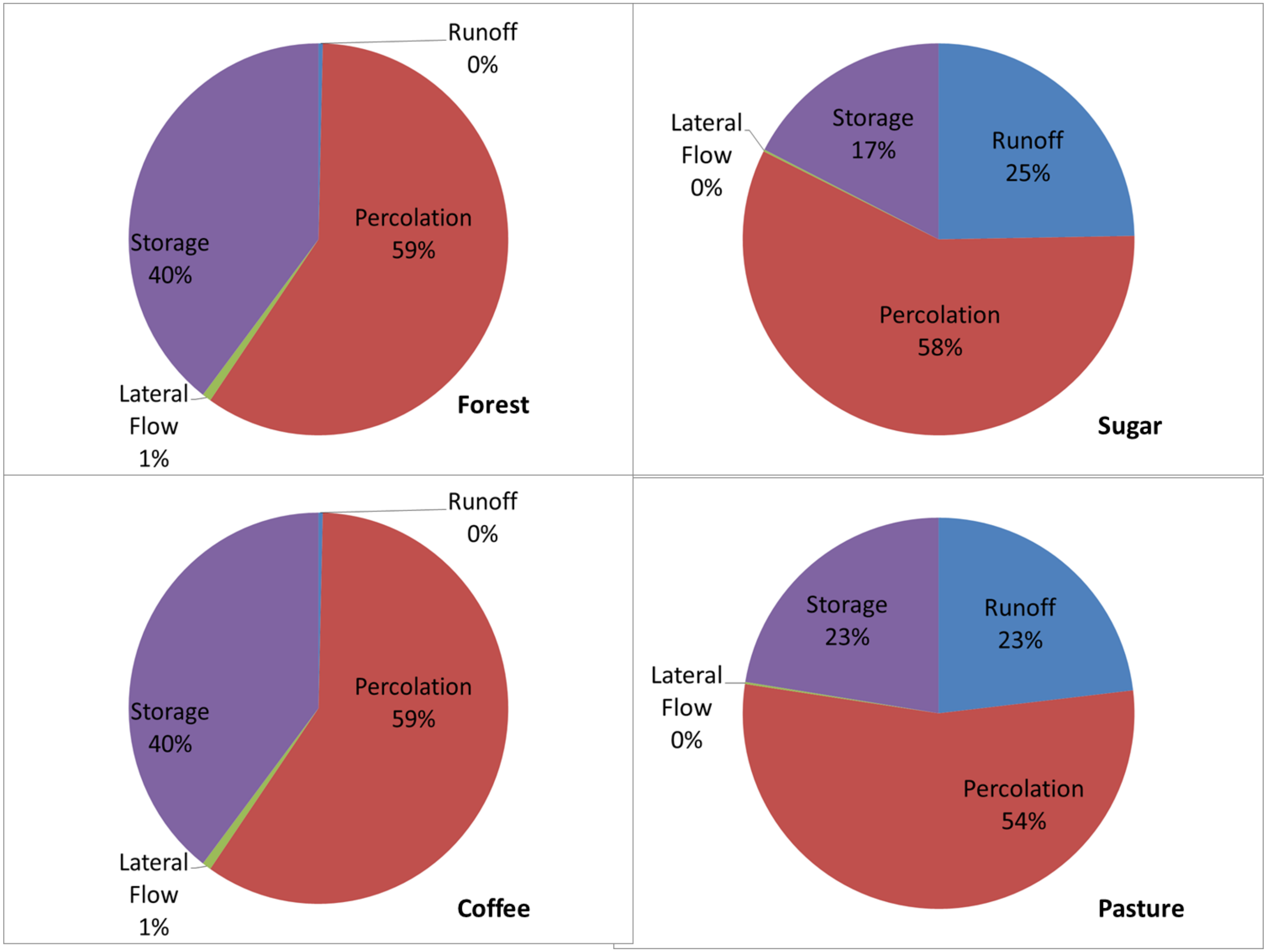

Figure 9. Water balances for a medium intensity precipitation (1 cm/hr) for 10 cm event in each of the land uses.

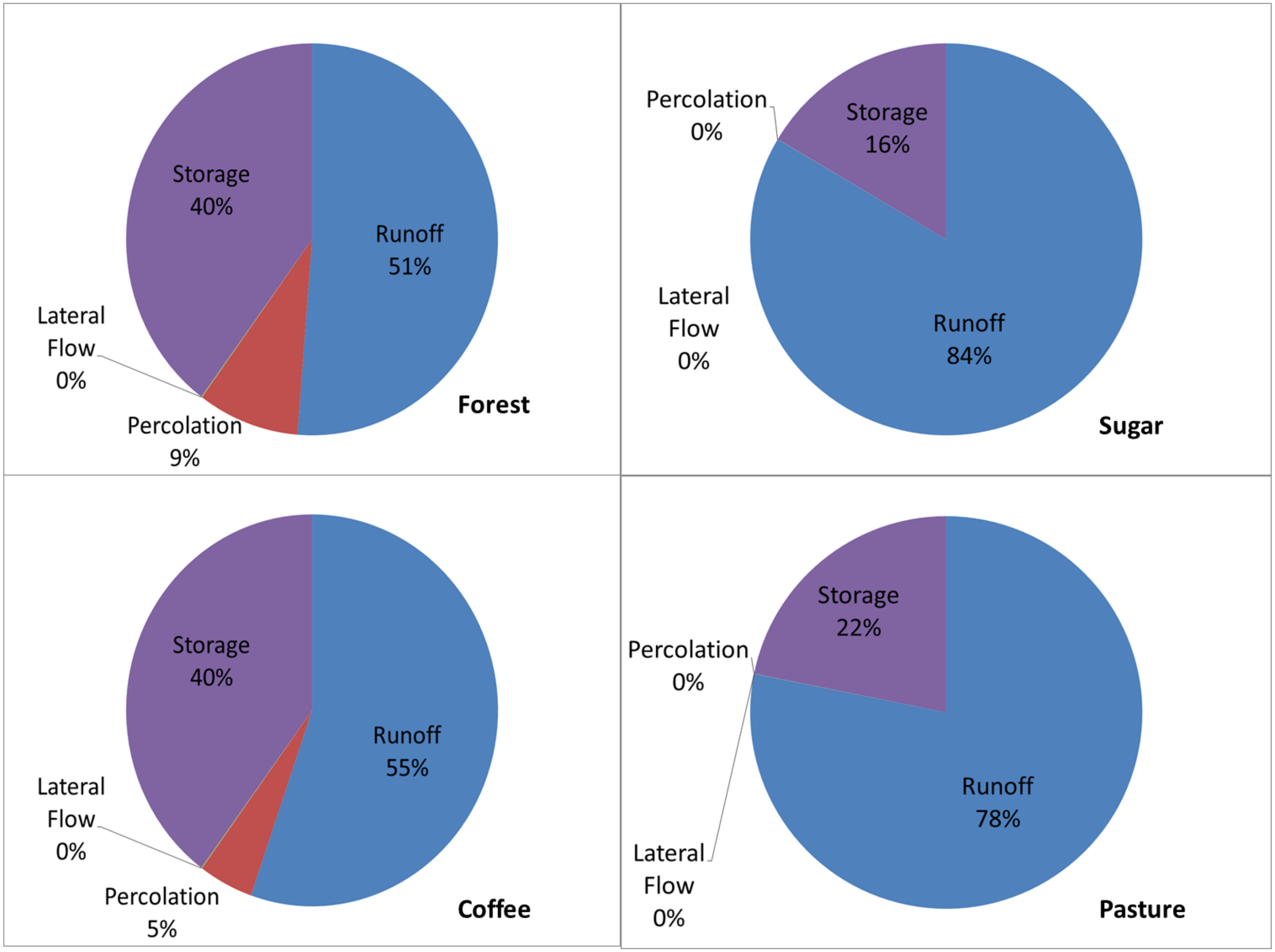

Figure 10. Water balances for a high intensity precipitation (10 cm/hr) for 10 cm event in each of the land uses.

Land use change

Two types of watersheds were characterized within the upper Reventazón watershed based on land use distributions within each watershed. The first type includes the 'forested' watersheds: F1, F2, F3, and F4. Within these watersheds, 70-90% of the land area was covered by some type of forest and 5-20% by coffee (Table 3). In each of these watersheds 90% of the area consisted of forest and coffee. Pasture, sugar cane, and water (within the F4 watershed) covered from 0-8% of the land area. The second type of land use distribution is 'mixed-land use' watersheds: M1 and M2. For the mixed-land use watersheds, depending on the year, coffee or pasture was the predominant land use (25-50%). Within these watersheds, forest cover ranged between 15-25% of the area. M1 watershed had the greatest amount of urban area (approximately 10%). Sugar Cane, agriculture and bare soil (most likely sugar cane or annual crops) covered approximately 5-10% of the watershed area. In the M3 watershed, forest cover was just under 50%. Coffee and pasture were the next predominant land use classes, respectively. Sugar cane covered between 4-8% of the watershed. Besides M1 watershed, the remaining watersheds had less than 5% urban area throughout this period of time.

The greatest amount of land use change occurred within the mixed-land use watersheds with pasture being replaced by coffee and to a lesser extent sugar cane.. Within both types of watersheds, forest cover was fairly stable between 1986 and 1996 (Figures 11-19). Minor decreases of forest cover occurred in F3, F4, M1 and the M2 watersheds (>5%). Within F1 and F2, coffee land cover remained fairly stable with a small decrease in the amount of pasture (<3%). In the F3and F4 watersheds, coffee slightly increased (<6%) from 1986 to 1996. In M1 watershed, urban areas increased from about 8 to 12% in 1996. Over the same time period, coffee cover increased from 25 to 45%, while pasture cover decreased from 37% to less than 5%. Sugar cane and bare soil increased by about 5% in 1996. While urban areas in M2 and M3 only slightly (<3%) increased, similar trends of increase in coffee and sugar cane and loss of pasture occurred from 1986 to 1996 in these watersheds.

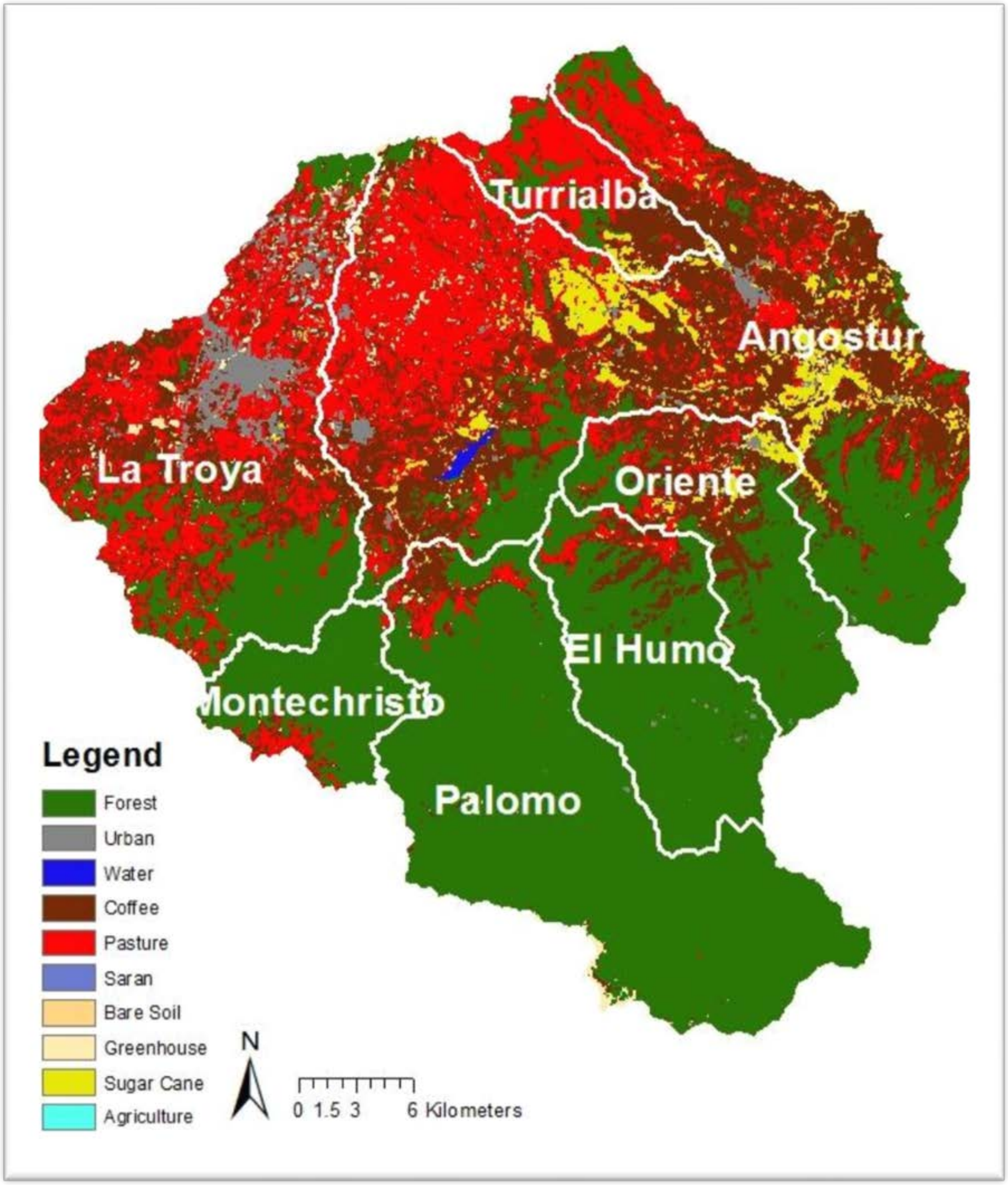

Figure 11. Land use in the upper Reventazón Watershed for 1986.

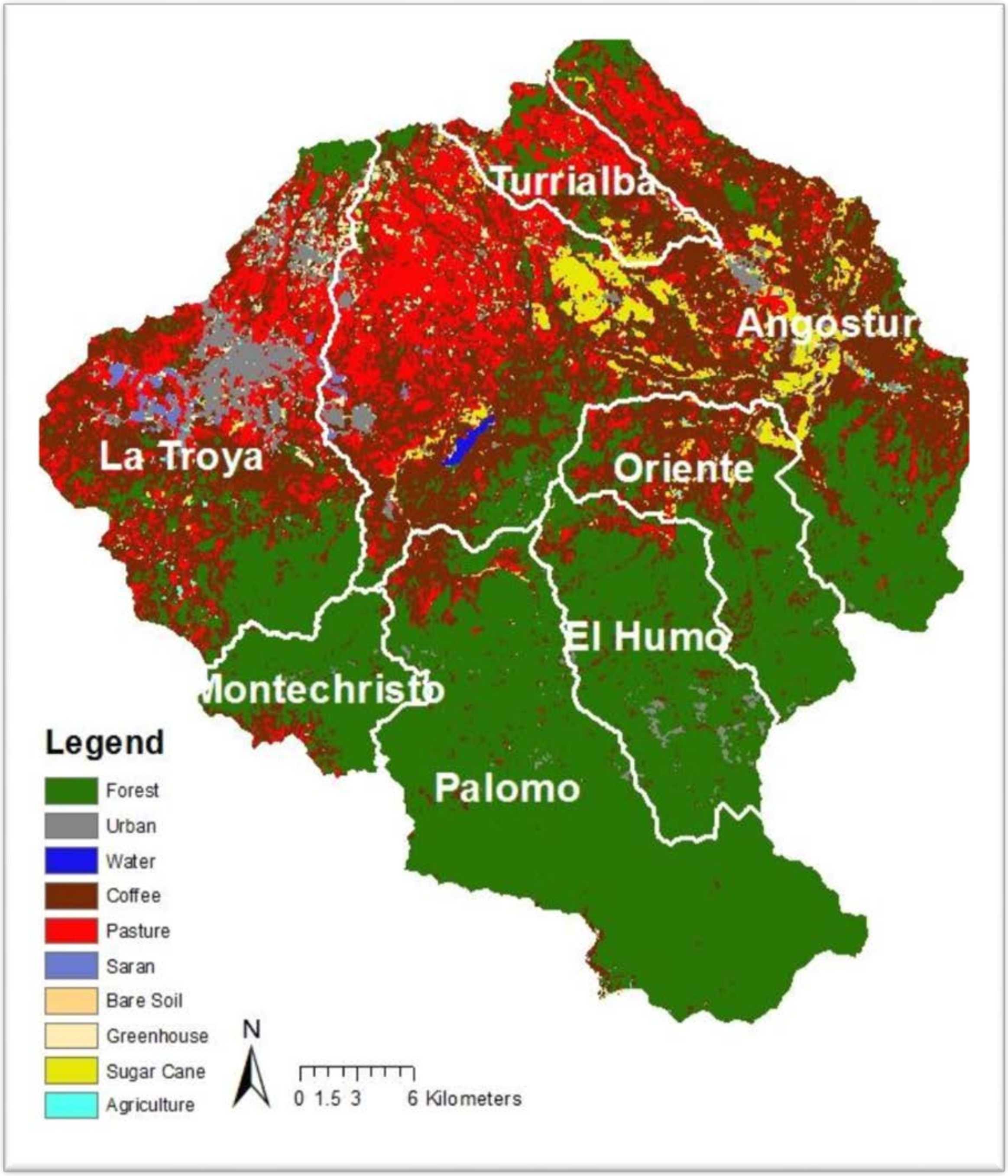

Figure 12. Land use distribution in the upper Reventazón watershed during 1996.

Table 3. Land use distribution and change within the forested watersheds (F) between 1986 and 1996.

F1	**Km2**	**% cover**	**km2**	**% cover**	**% change**
Forest	120.1	87.6	117.1	85.5	2.1
Urban	0.5	0.4	3.8	2.8	-2.4
Coffee	11.9	8.7	13.9	10.1	-1.5
Pasture	4.3	3.1	1.9	1.4	1.7
Saran	0.0	0.0	0.0	0.0	0.0
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare Soil	0.0	0.0	0.0	0.0	0.0
Sugar	0.3	0.2	0.2	0.2	0.0
Agriculture	0.0	0.0	0.1	0.1	-0.1
F2					
Forest	165.9	73.1	163.7	72.1	1.0
Urban	1.5	0.7	4.0	1.7	-1.1
Coffee	41.9	18.5	48.6	21.4	-2.9
Pasture	12.4	5.5	6.9	3.0	2.4
Saran	0.0	0.0	0.0	0.0	0.0
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare Soil	0.2	0.1	0.1	0.1	0.0
Sugar Cane	5.0	2.2	3.5	1.5	0.7
Agriculture	0.0	0.0	0.2	0.1	-0.1
F3					
Forest	57.0	87.6	54.9	84.4	3.2
Urban	0.0	0.1	0.4	0.6	-0.6
Coffee	2.8	4.3	7.8	12.0	-7.7
Pasture	5.0	7.7	1.9	2.9	4.9
Saran	0.0	0.0	0.0	0.0	0.0
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare Soil	0.2	0.3	0.0	0.0	0.2
Sugar	0.0	0.1	0.0	0.0	0.0
Agriculture	0.0	0.0	0.0	0.0	0.0
F4					
Forest	342.6	92.3	335.3	90.4	2.0
Urban	0.2	0.1	2.1	0.6	-0.5
Water	12.2	3.3	0.0	0.0	3.3
Coffee	11.9	3.2	27.5	7.4	-4.2
Pasture	0.0	0.0	4.8	1.3	-1.3
Saran	0.0	0.0	0.1	0.0	0.0
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare Soil	3.7	1.0	0.6	0.2	0.8
Sugar	0.3	0.1	0.4	0.1	0.0
Agriculture	0.1	0.0	0.2	0.0	0.0

Table 3 (continued).

M1	Km2	% cover	km2	% cover	% change
Forest	18.8	24.4	16.9	21.9	2.4
Urban	6.8	8.9	8.0	10.4	-1.5
Coffee	20.2	26.2	30.7	39.8	-13.6
Pasture	28.2	36.6	16.8	21.9	14.7
Saran	0.0	0.0	1.2	1.5	-1.5
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare Soil	2.2	2.8	2.0	2.6	0.3
Sugar Cane	0.6	0.8	0.6	0.7	0.1
Agriculture	0.3	0.3	0.9	1.1	-0.8
M2					
Forest	12.6	16.4	11.8	15.3	1.0
Urban	0.3	0.3	1.2	1.6	-1.3
Coffee	20.9	27.2	30.6	39.8	-12.6
Pasture	39.3	51.1	27.2	35.3	15.8
Saran	0.0	0.0	0.0	0.0	0.0
Bare soil	0.2	0.3	0.8	1.0	-0.7
Sugar	3.5	4.5	4.9	6.3	-1.8
Agriculture	0.2	0.2	0.4	0.6	-0.3
M3					
Forest	632.9	47.3	619.9	46.4	1.0
Urban	32.6	2.4	45.2	3.4	-0.9
Water	1.7	0.1	1.7	0.1	0.0
Coffee	312.7	23.4	417.0	31.2	-7.8
Pasture	286.9	21.5	183.4	13.7	7.7
Saran	0.0	0.0	5.0	0.4	-0.4
Greenhouse	0.0	0.0	0.0	0.0	0.0
Bare soil	17.2	1.3	14.2	1.1	0.2
Sugar	51.4	3.8	44.8	3.4	0.5
Agriculture	1.6	0.1	5.8	0.4	-0.3

Flow duration curves

Flow duration curves (FDC) allow for direct comparisons of water yield (cm) between watersheds. Flow duration curves are useful to look at water yield characteristics which represent a combination of watershed size, slope, precipitation, geology and potentially land use. While mean water yield can be compared among watersheds at the 50% marker, valuable information describing maximum flows (i.e. flooding events) and minimum flows (i.e., baseflow) can also be discerned from the FDCs. The slope also describes the consistency of flow. For example, the flatter the slope of the FDC the more consistent the flow, suggesting a groundwater contribution. Forested watersheds had greater mean water yield per unit area (cm) than mixed-land use watersheds (Figures 13 and 14). Angostura's FDC is much closer to the forested watersheds in terms of slope, maximum, minimum and mean monthly runoff than the other mixed-use watersheds. The watersheds with the greatest forest cover (F1 and F4) had slightly greater mean and minimum monthly runoff than downstream (F2) and upstream (Montechristo) watersheds. M2 and M1 FDC means and minimum flows were much lower than the forested watersheds. While no pattern was observed for the high-flow end of the curves, the low flow end of M1 and M2 curves were slightly greater than the forested. These greater slopes suggest that minimum flows are less consistent in the mixed-use than the forested watersheds.

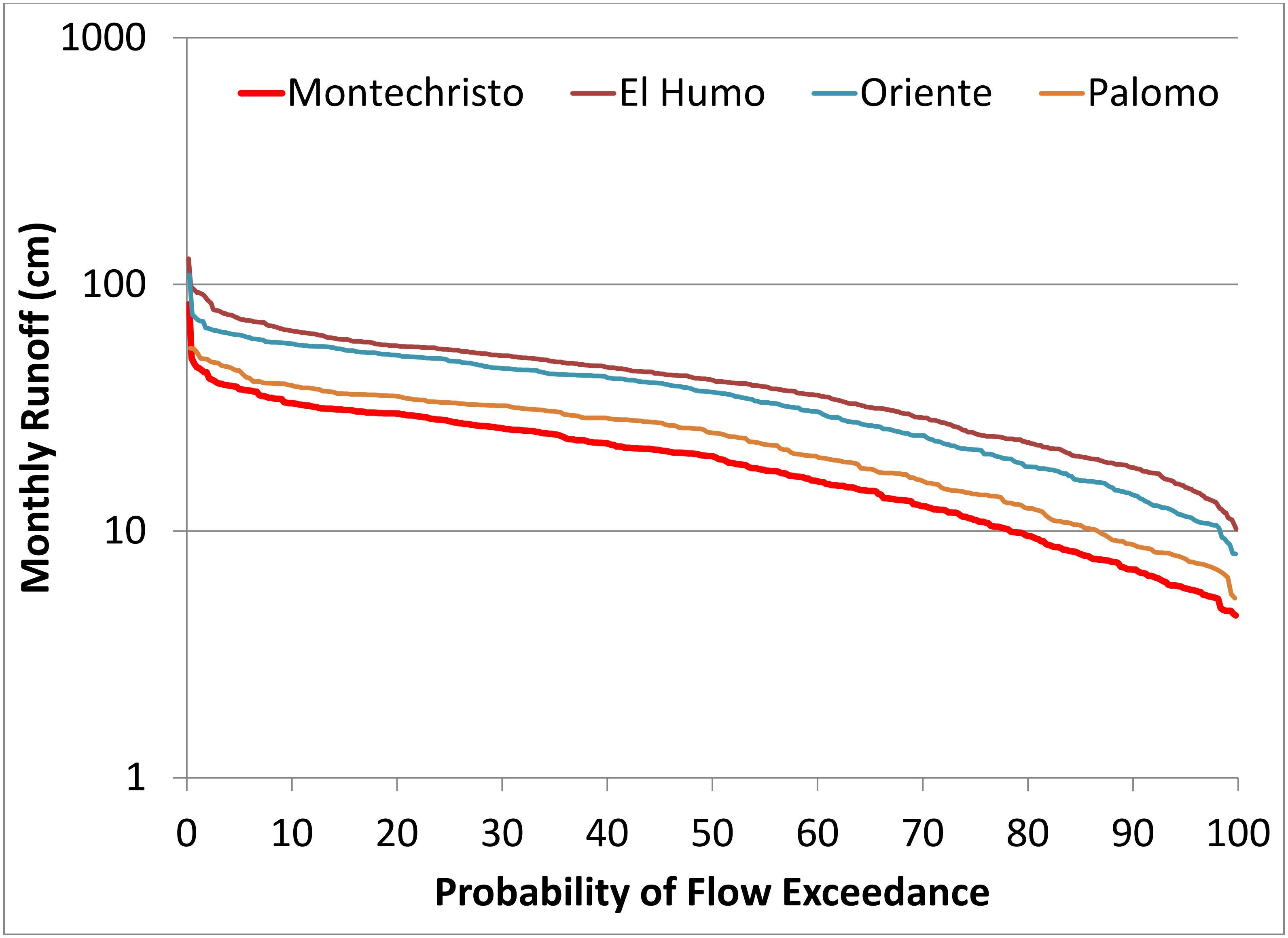

Figure 13. Forested watersheds flow duration curves.

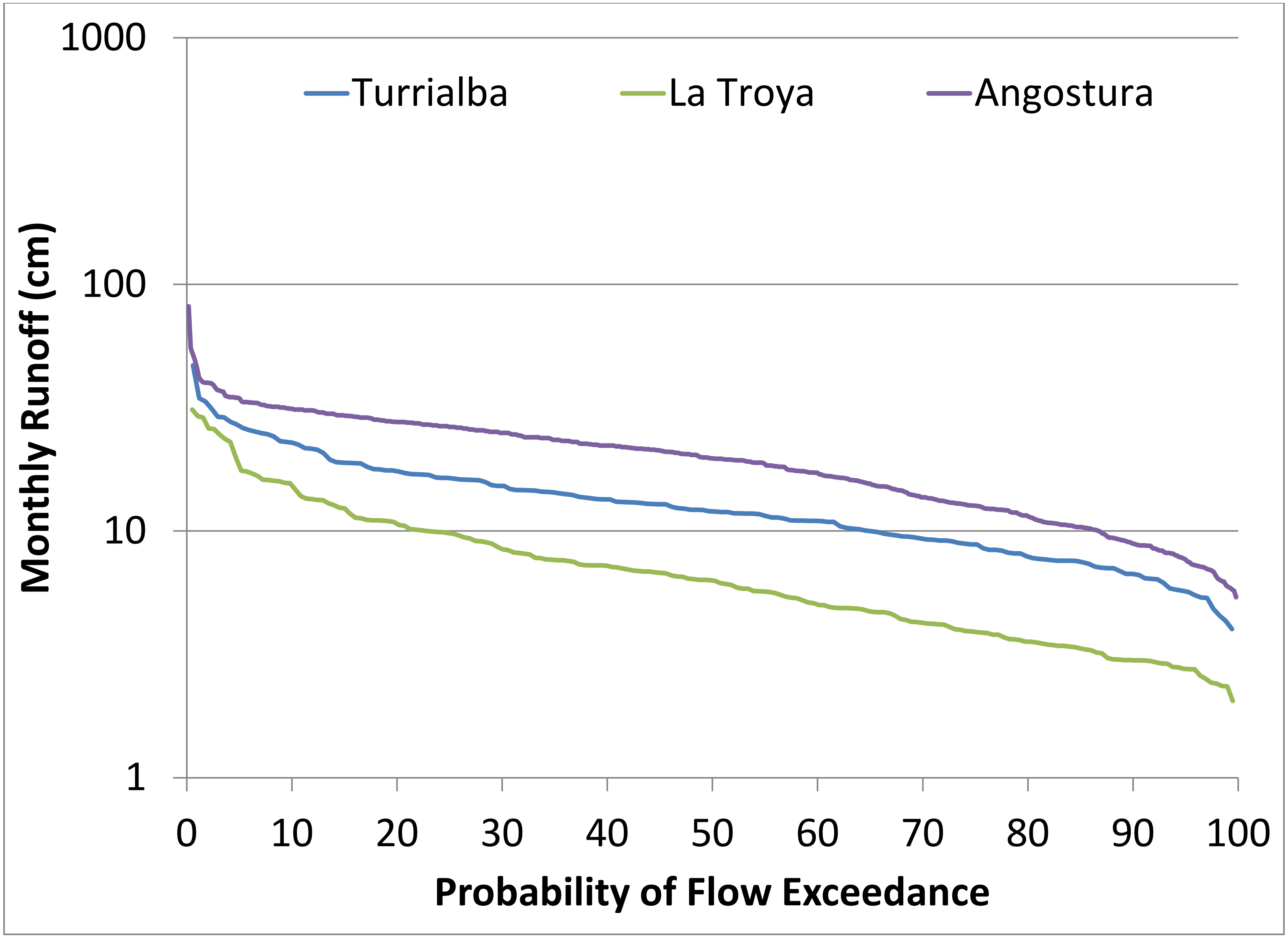

Figure 14. Mixed land use flow duration curves.

Runoff coefficients

Similar to the FDC and seasonal water yield analysis, runoff coefficients for the forested watersheds were greater than for the mixed land use watersheds (Figures 15-17). At this scale, 'runoff' generally consists of 4 sources: overland flow, baseflow, lateral flow, and direct channel precipitation. Therefore, runoff at this scale is greater than runoff coefficients observed for the one-cell simulations and based on plot and field studies. Runoff in M1 and M2 was less consistent than in the forested watersheds with more oscillation between high and low discharge years.

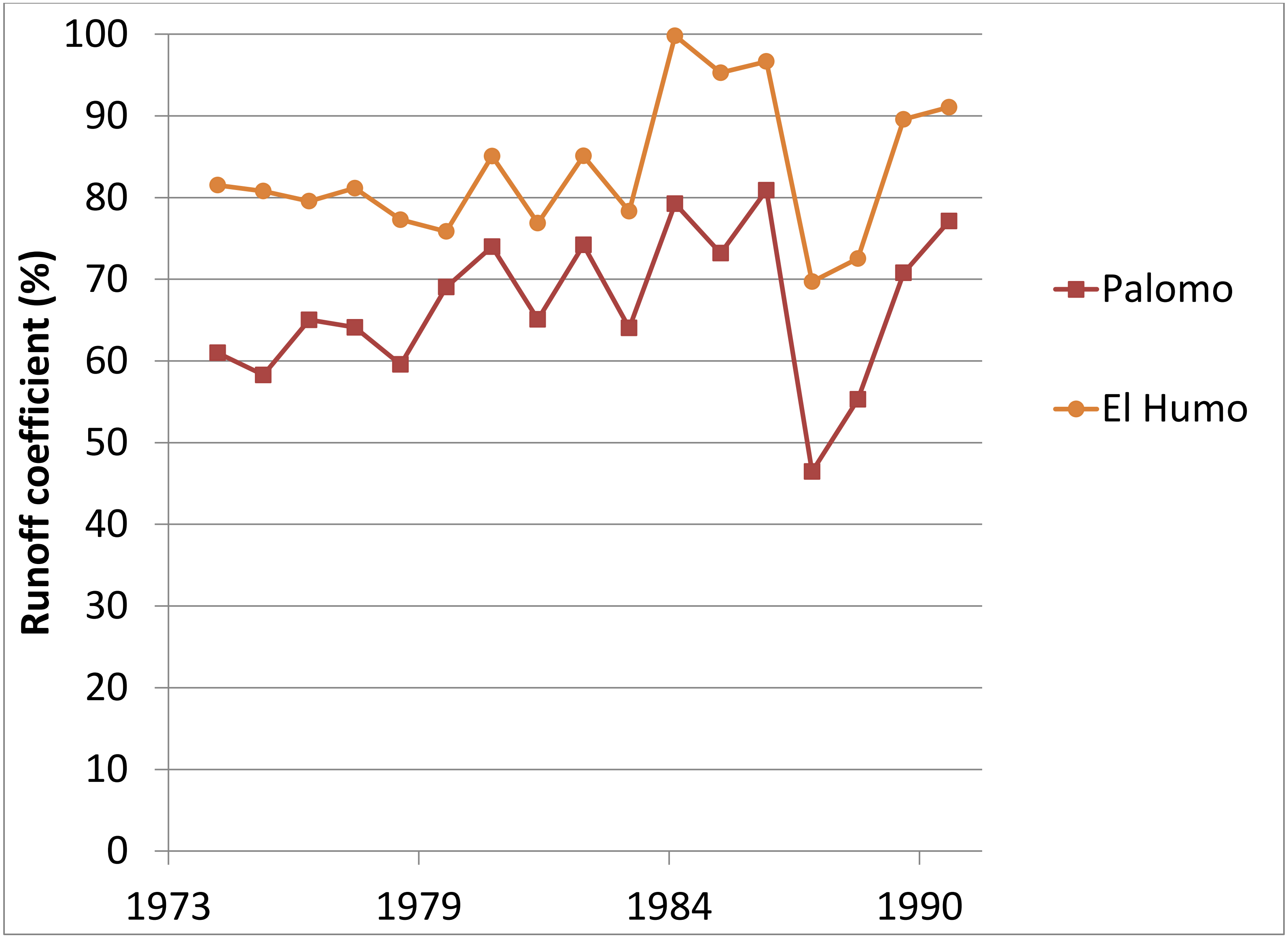

Figure 15. Annual runoff coefficients for the Palomo and El Humo watersheds.

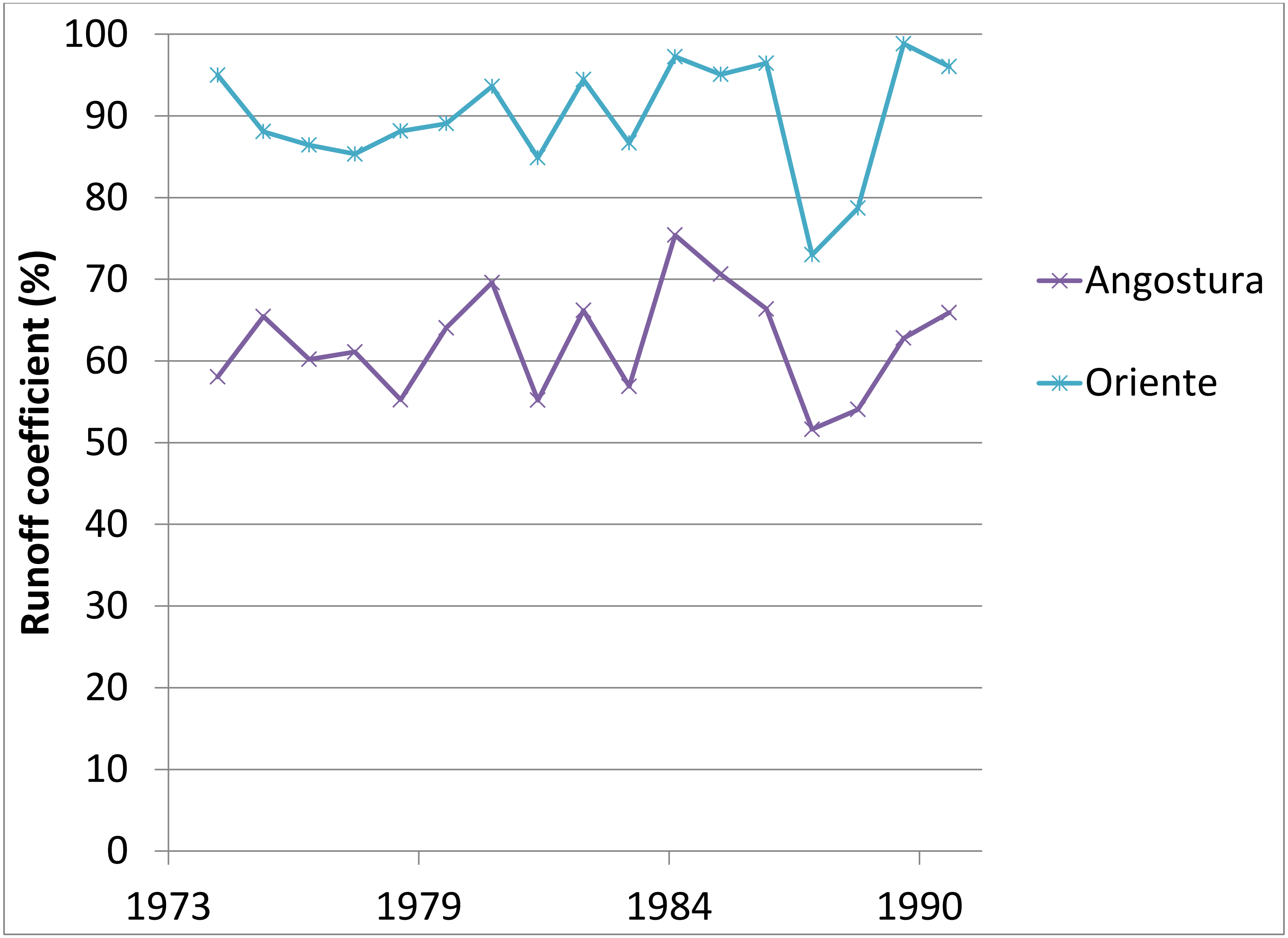

Figure 16. Annual runoff coefficients for Angostura and Oriente watersheds.

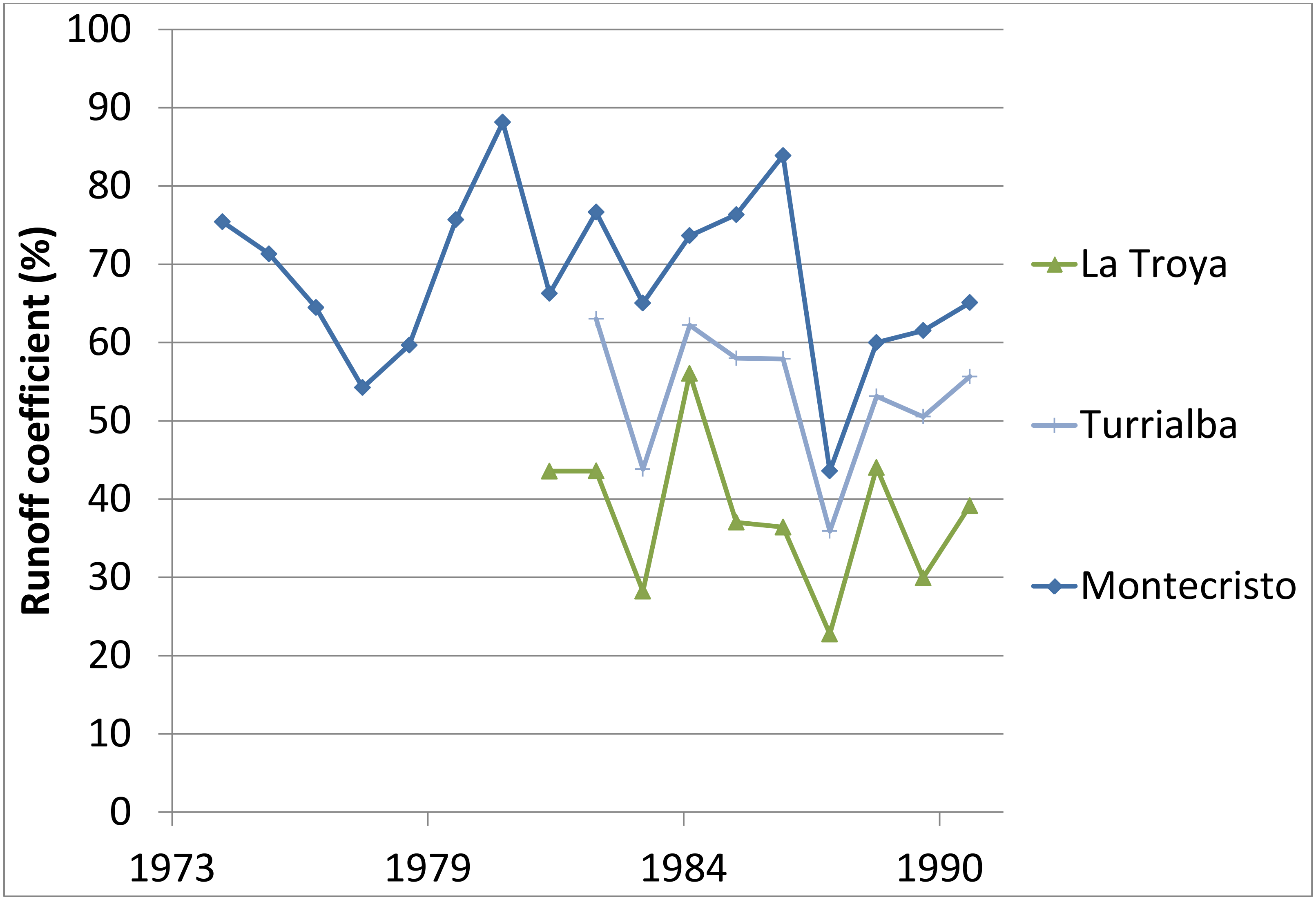

Figure 17. Annual runoff coefficients for La Troya, Turrialba, and Montecristo watersheds.

Watershed Scale Modeling

Modeling at the watershed scale was successful in capturing the general seasonality and some of the wet season peaks displayed in the observed data from each watershed (Figures 18-26). These results were achieved using the parameterization from field observations as described in the one-cell simulations without model calibration. Daily precipitation and ET were used to simulate daily streamflow. Daily streamflow was aggregated to monthly output for comparison with the observed data. Overall, simulated results with the SMR model were better than using the mean of the observed data E' (Table 4). In the F4 (Figure 19), wet season peak flows were generally over predicted. Wet season simulations could be improved with more sustained peak flows.

Water balance results reflect different precipitation amounts and depict the percentages of hydrological processes for each watershed. F1, F2, and F4 (all forested watersheds) had the greatest amount of precipitation due to their increased elevations (Table 2). Respectively, M1 (43.3%) and F3 (35.5%) had the greatest amount of ET most likely due to their position in the watershed within a rain shadow because of orographic lifting (Figure 3). F1 had the lowest amount of ET (24.3%) because of its historically greater precipitation and elevation. Percolation was the greatest in M2 (44.4) and M3 (34.8%) watersheds. Runoff was greatest in the F1 (52.2%) and F4 watersheds (50.4%). Results from these simulations include only overland flow as runoff. Therefore, with the greater conductivities because of forest in the F4, F1 and F2 watersheds, runoff is most likely due to the relatively greater precipitation within these watersheds.

The most direct comparison of different land use watersheds based on similar precipitation would be F3 (2115 cm) and M2 (2191 cm). F3 has the greatest ET (35.5%), while M2 has the greatest percolation (44.4%), and F3 has the greatest amount of runoff (38.6 %). Both watersheds are similar in size, but differ in elevation and land use cover. F3 has much more forest than M2.

Another comparison of three different watersheds (M1, F3, and F4) at the same elevation was observed in Figures 18-26. Evapotranspiration was very similar throughout the duration of the simulation for these three watersheds (Figure 19) even though M1 had much less forest cover than F3 and F4. At the shorter time scale (Figure 18), M1 ET is generally lower than F3 and F4 ET throughout the wet season. However, shortly after the dry season begins, F3 and F4 ET declines rapidly. M1 ET decreases much more slowly. In the F3 and F4 watersheds, ET becomes limited quicker because decreased soil moisture content starts to decrease available water for ET. While ET is a much lower percentage of the water balance in M1, F3 and F4 have greater absolute values of ET (Table 5).

In the Figures 30 and 31, percolation is greater in the F3 and F4 watersheds than in the M1 watershed. Over time, the differences in percolation between the three watersheds becomes substantial (≈200 cm). Part of the greater percolation in these watersheds must be attributed to the greater precipitation received in the F3 and F4 watersheds. Increased percolation may also be due to the increased vertical K_{sat} in these watersheds. However, focusing on the several weeks of transition from dry to wet season (April), it can be observed that percolation starts sooner and is greater in the F3 and F4 watersheds.

In the final set of graphs comparing the M1, F3 and F4 watersheds (Figures 25-26), F3 had the greatest amount of streamflow (baseflow plus runoff). Again, this is most likely due to the greater precipitation amounts received in these watersheds. When looking at the detailed simulated flow record, the M1 watershed experienced runoff earlier in the transition session than the F3 watershed. Also, there appears to be elevated dry season flow for at least part of the dry season in F3.

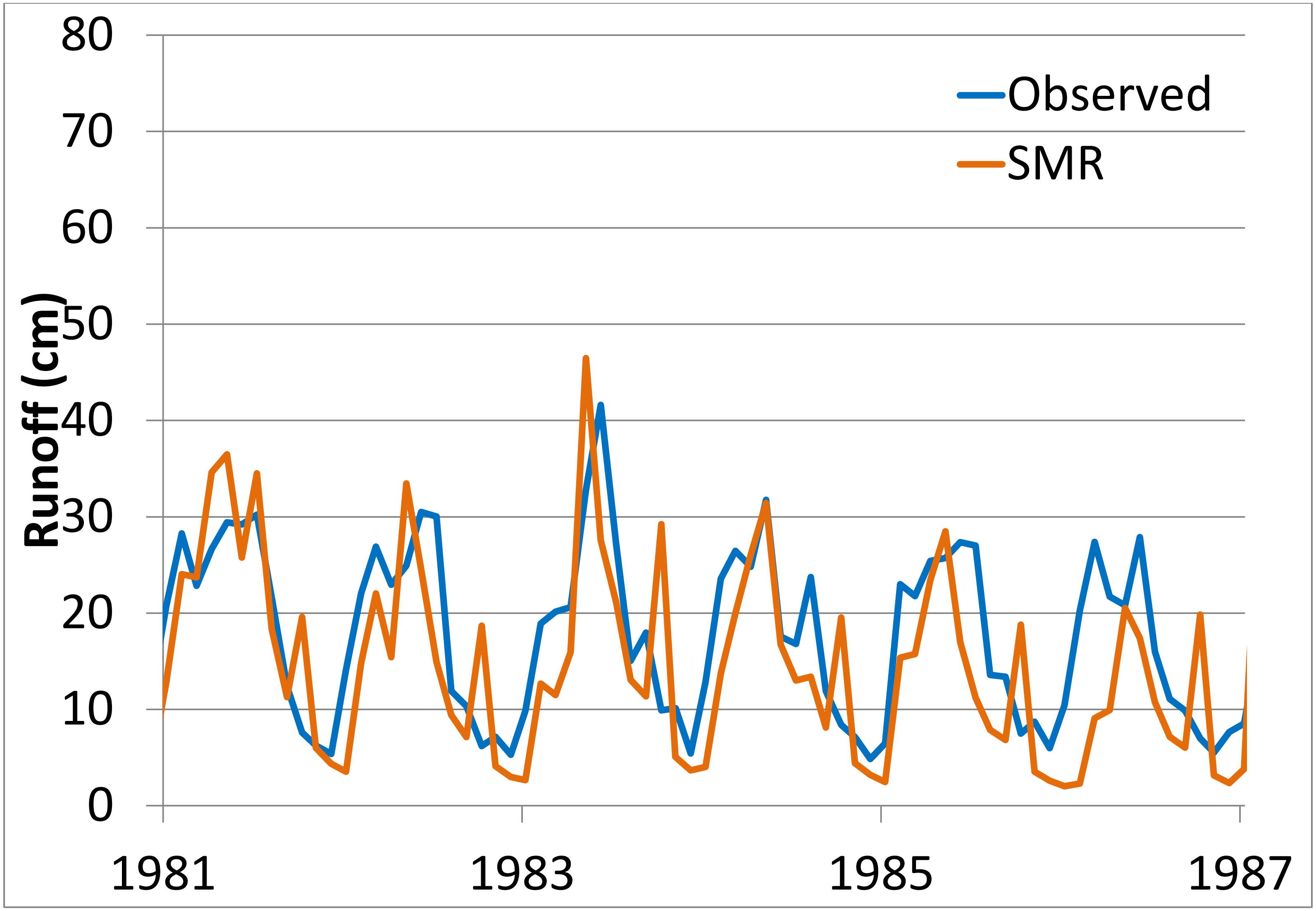

Figure 18. Historical watershed modeling for the F3 watershed.

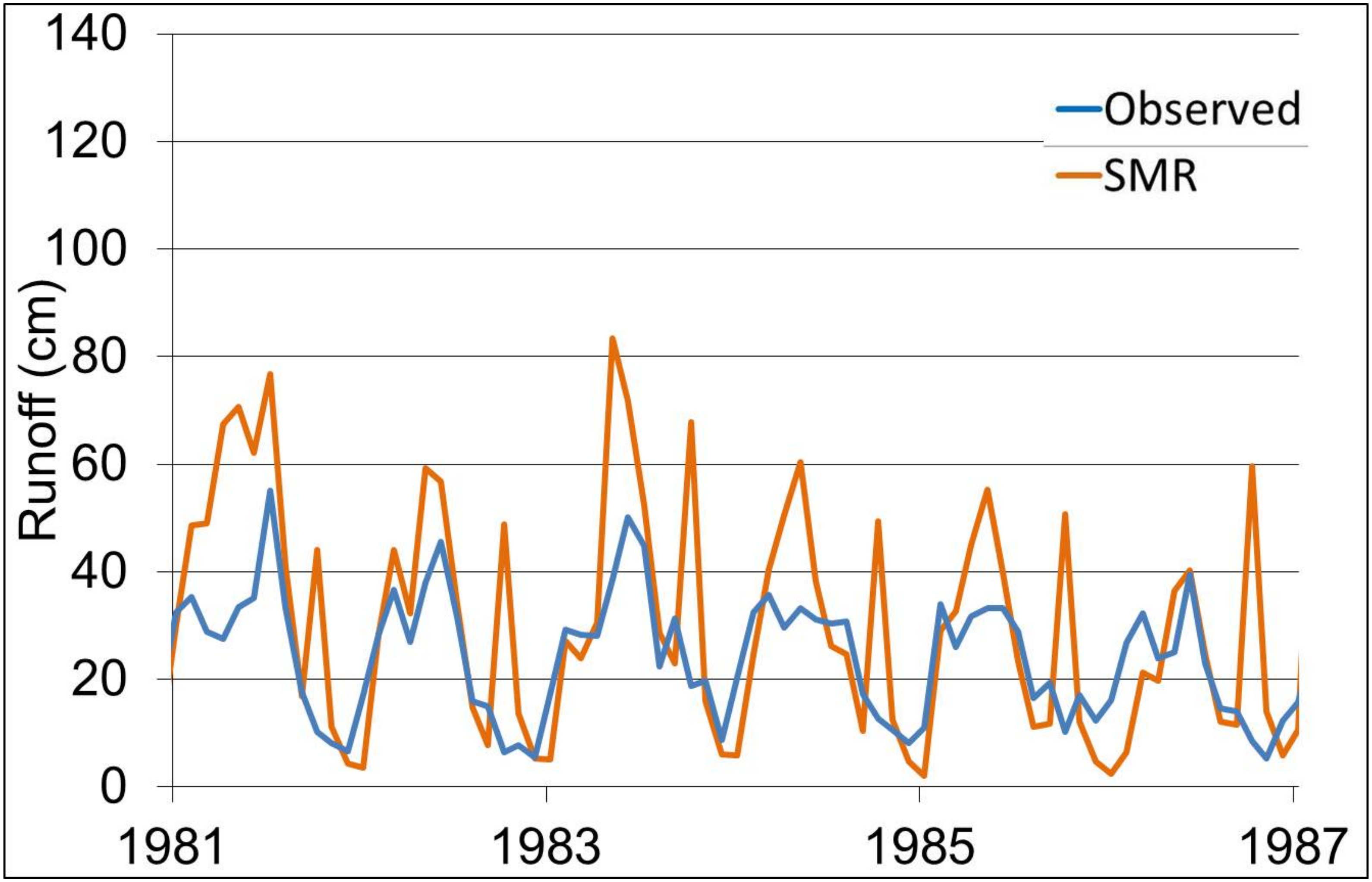

Figure 19. Historical watershed modeling for the F4 watershed.

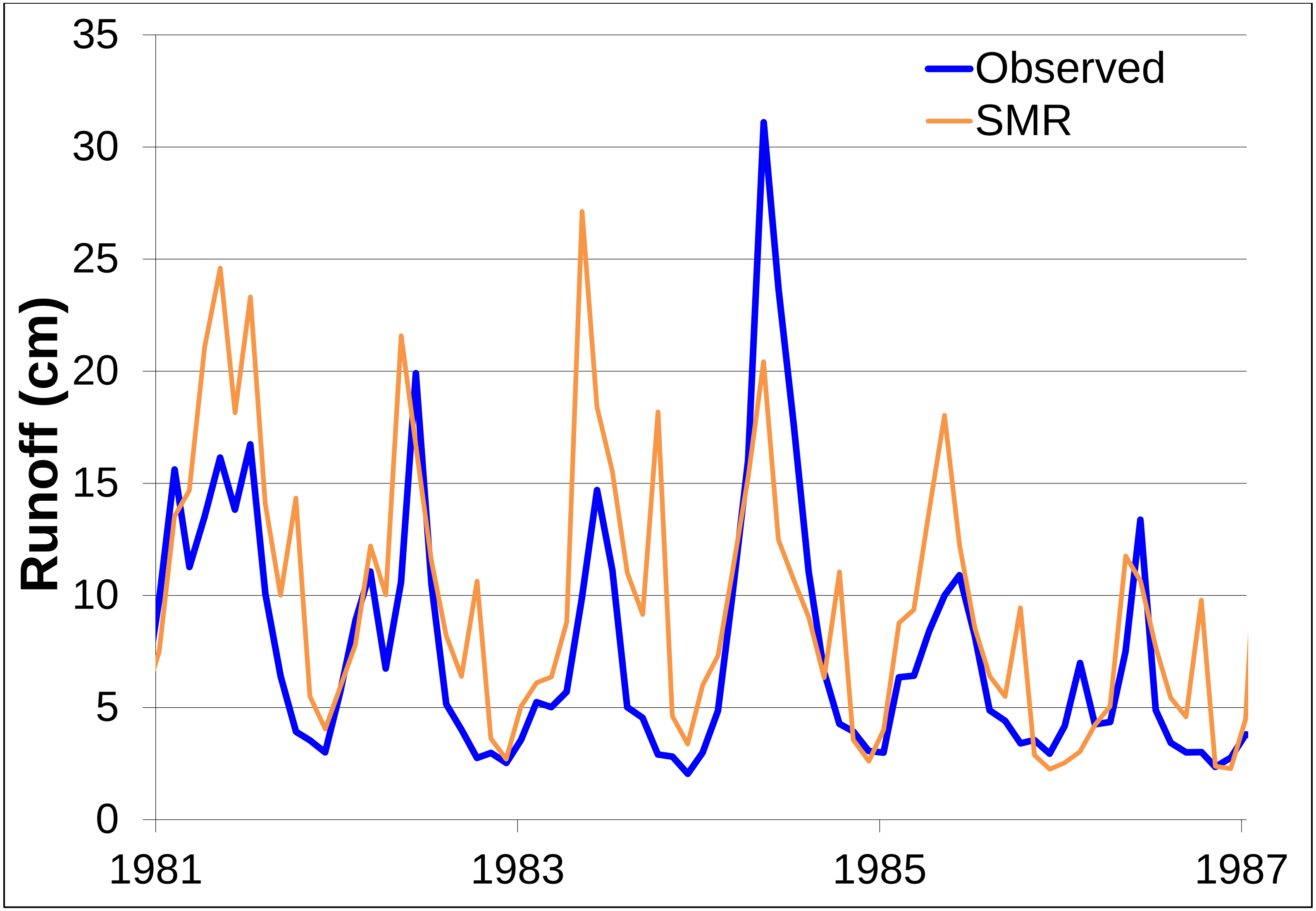

Figure 20. Historical watershed modeling for the M1 watershed.

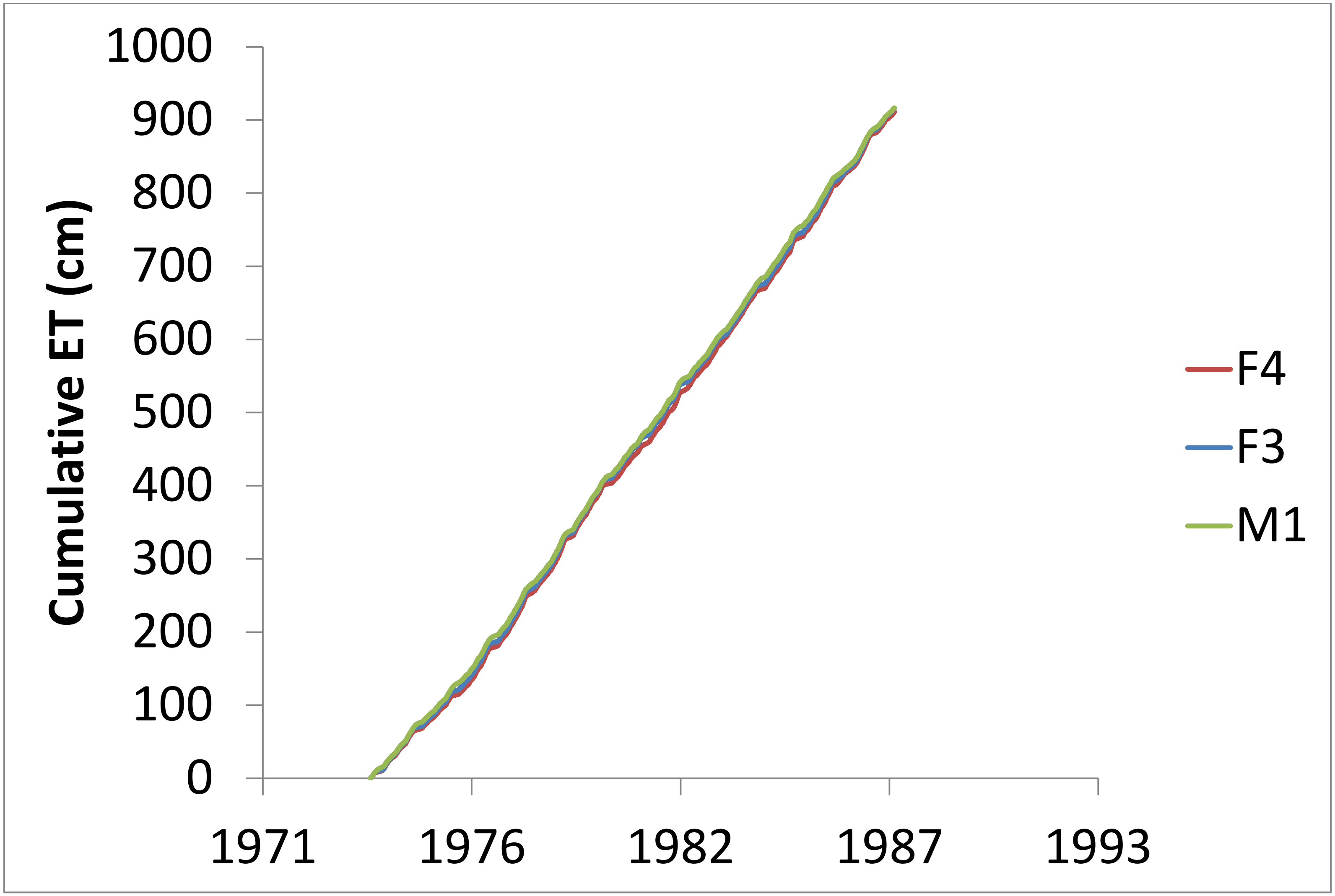

Figure 21. Simulated cumulative evapotranspiration for the M1, F3 and F4 watersheds.

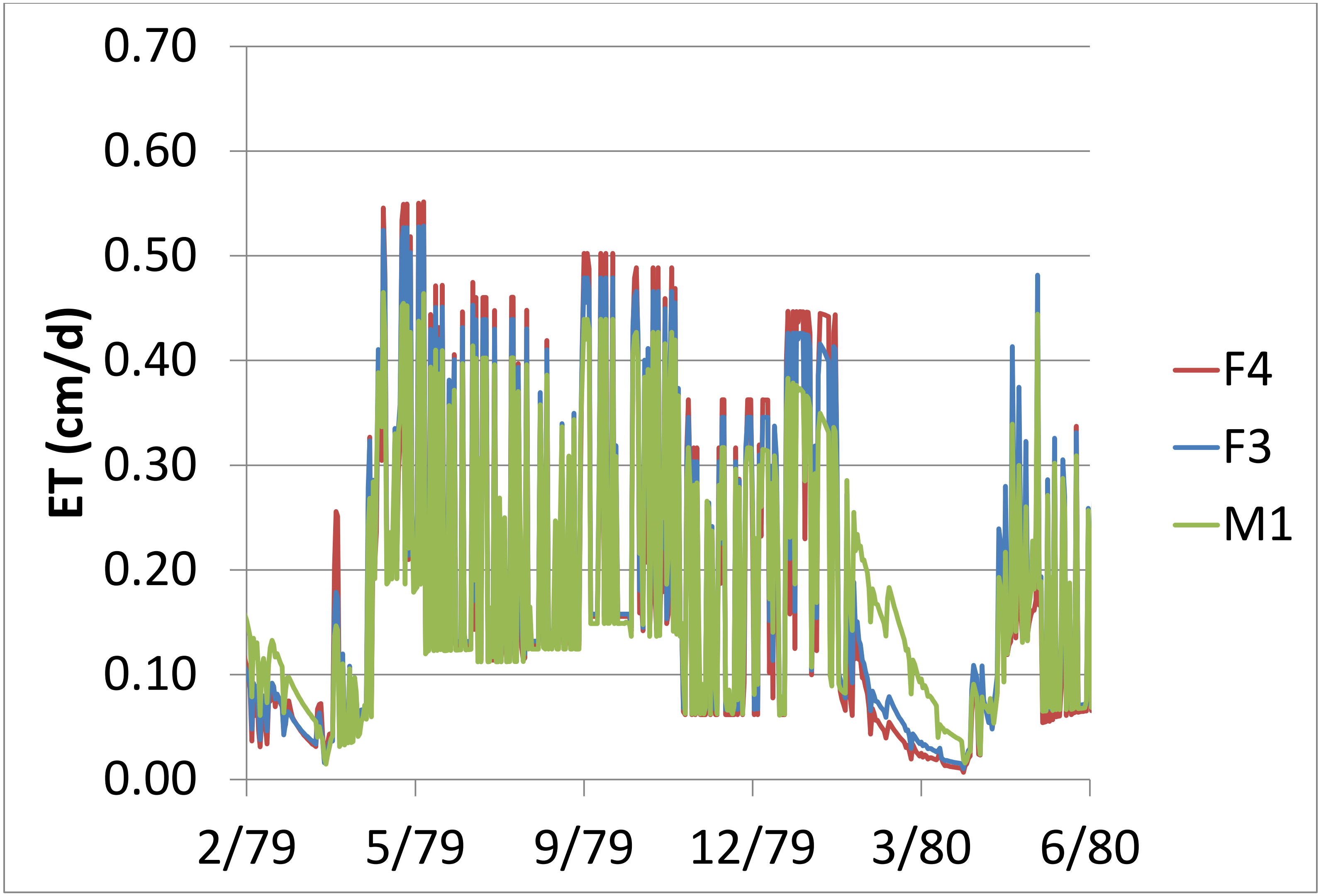

Figure 22. Simulated daily evapotranspiration for the F3, F4, and M1 watersheds.

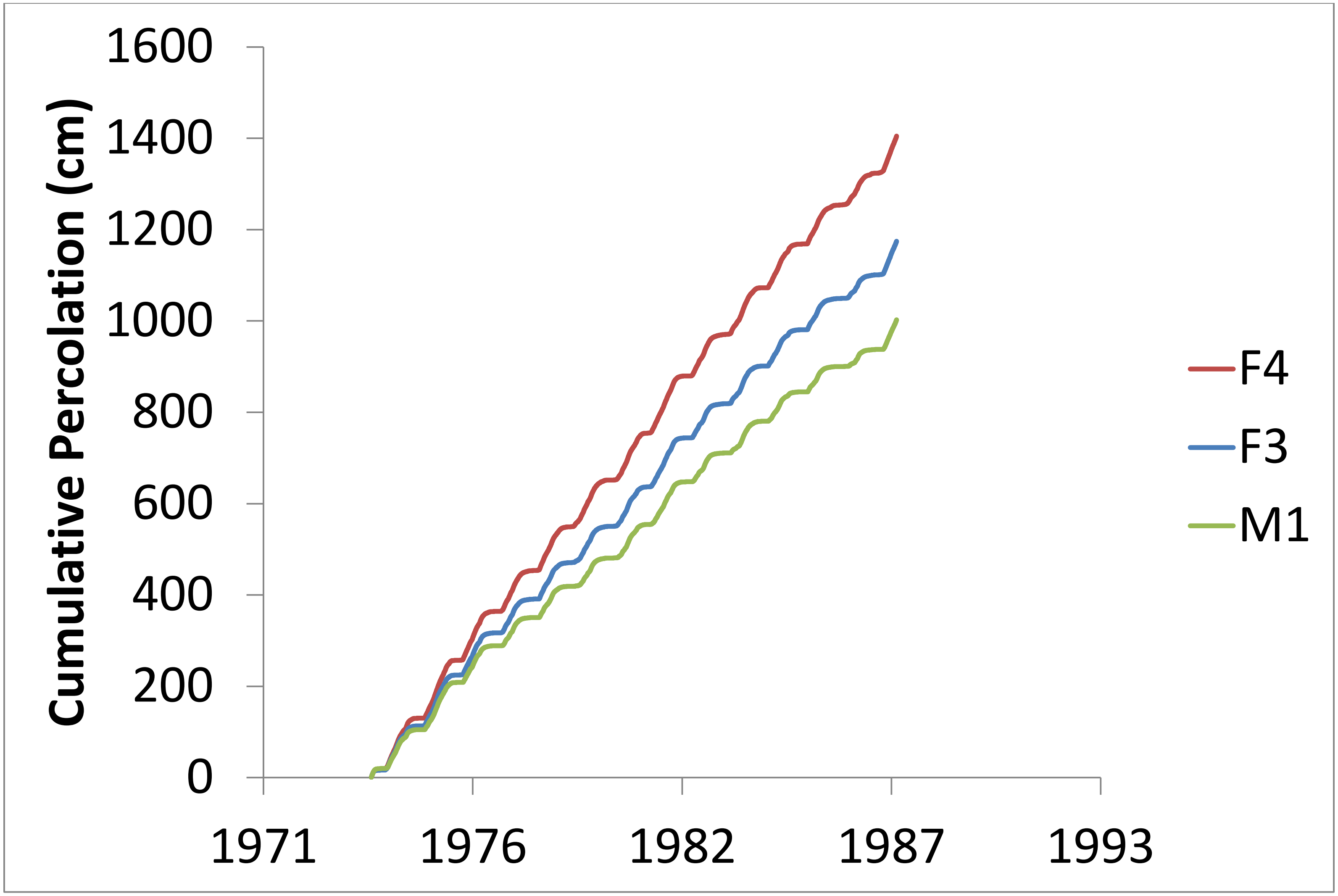

Figure 23. Simulated cumulative daily percolation for the M1, F3, and F4 watersheds.

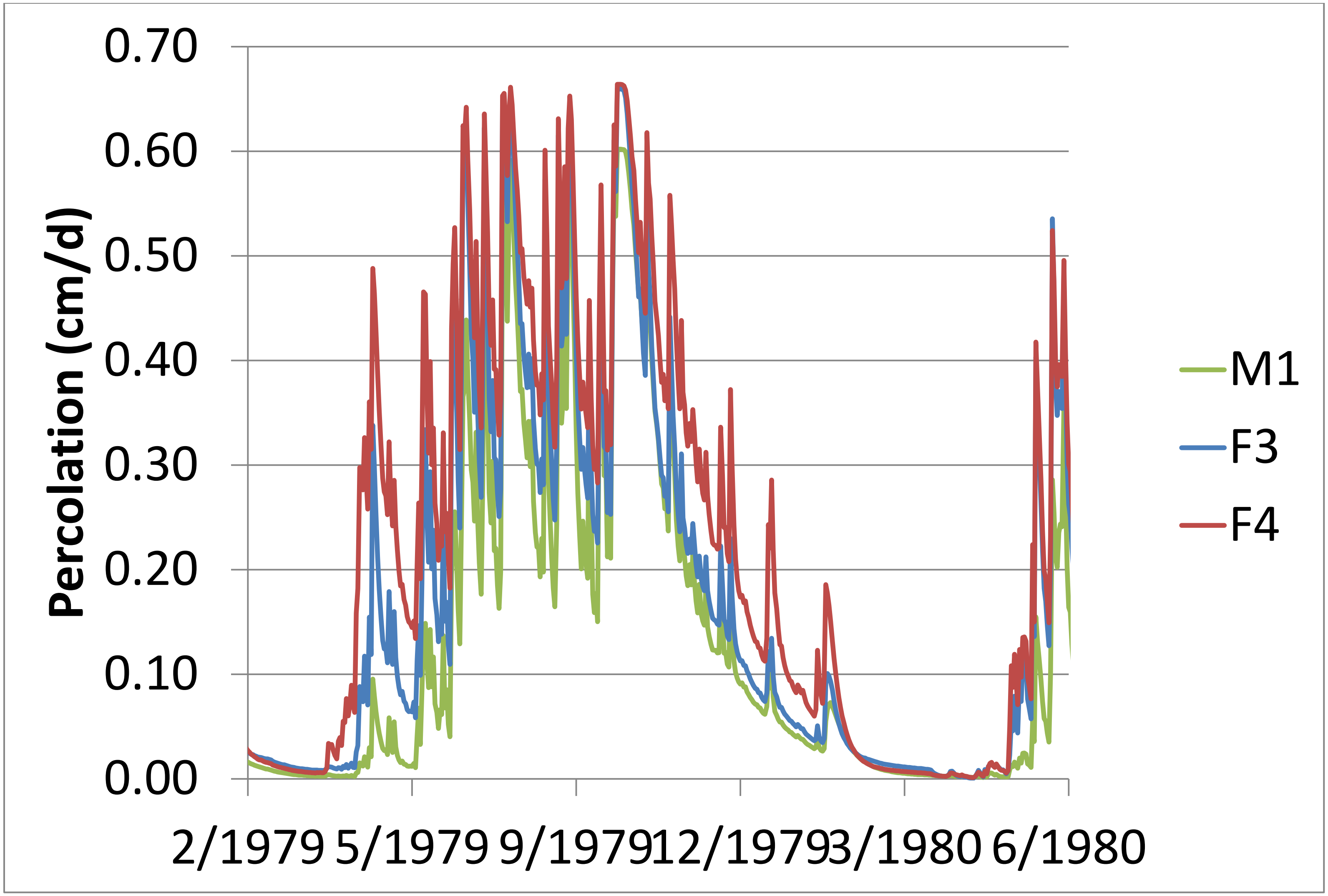

Figure 24. Simulated daily percolation of the M1, F3 and F4 watersheds.

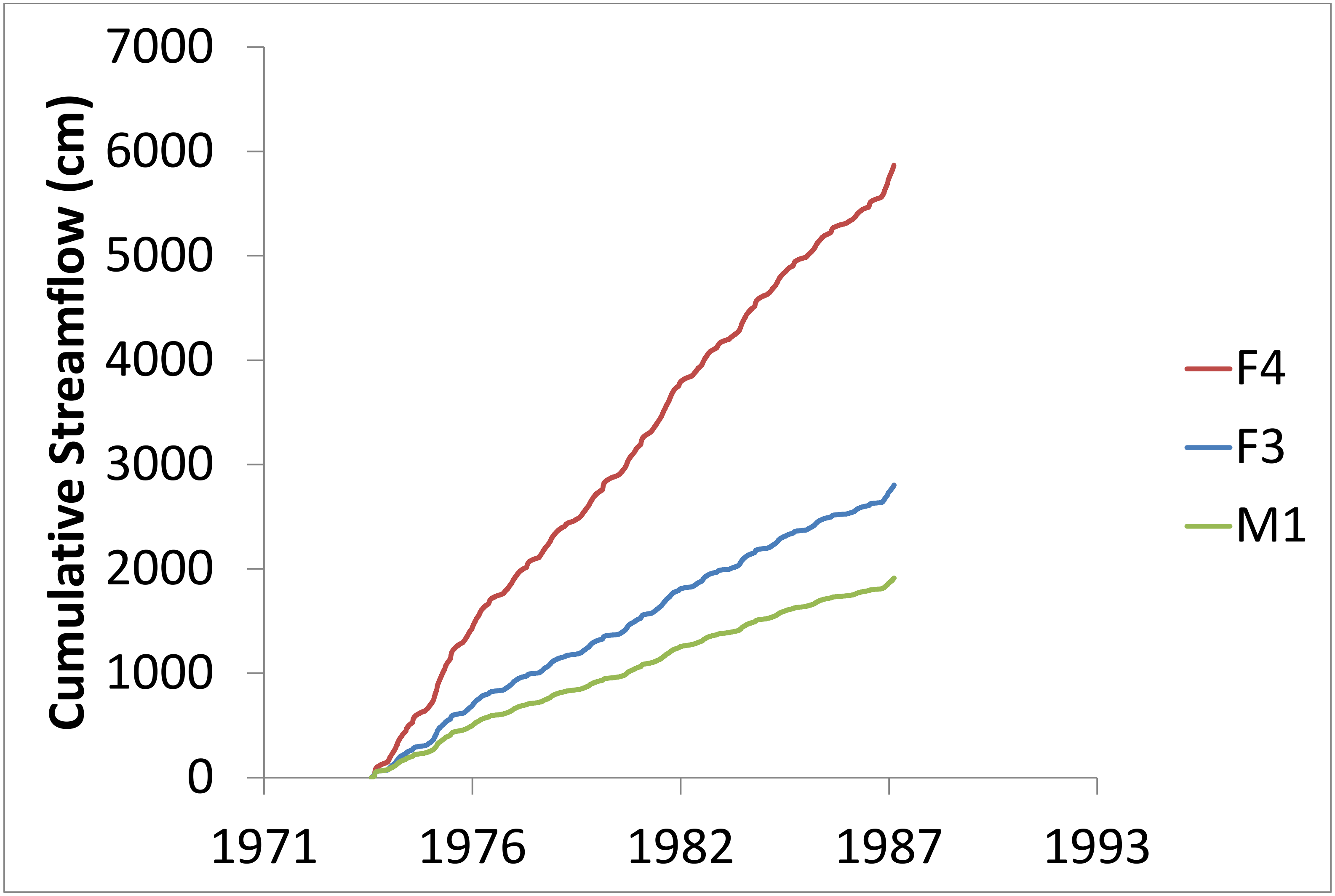

Figure 25. Simulated cumulative daily streamflow for the M1, F3, and F4 watersheds.

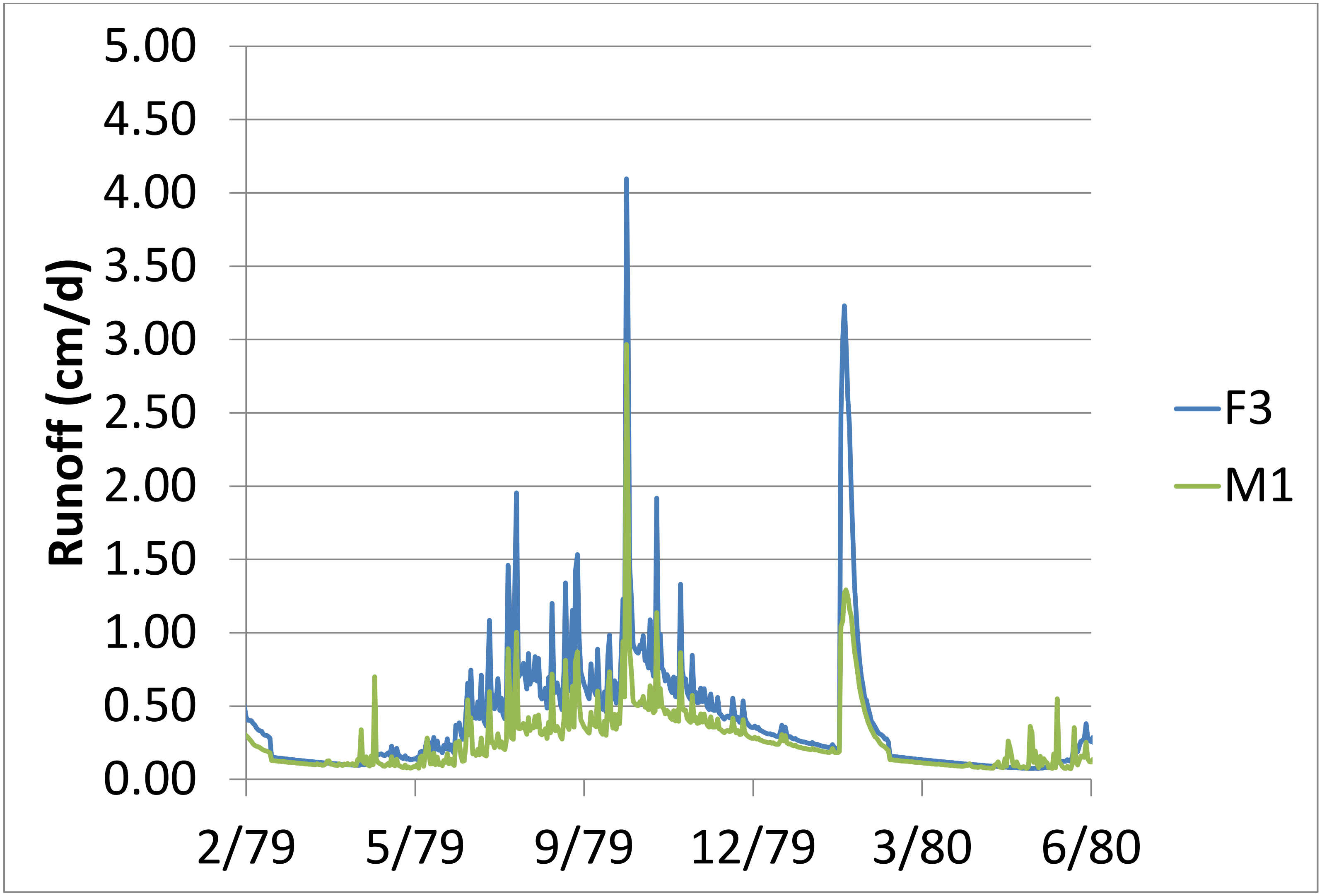

Figure 26. Simulated runoff (cm/d) for M1 and F3 watersheds.

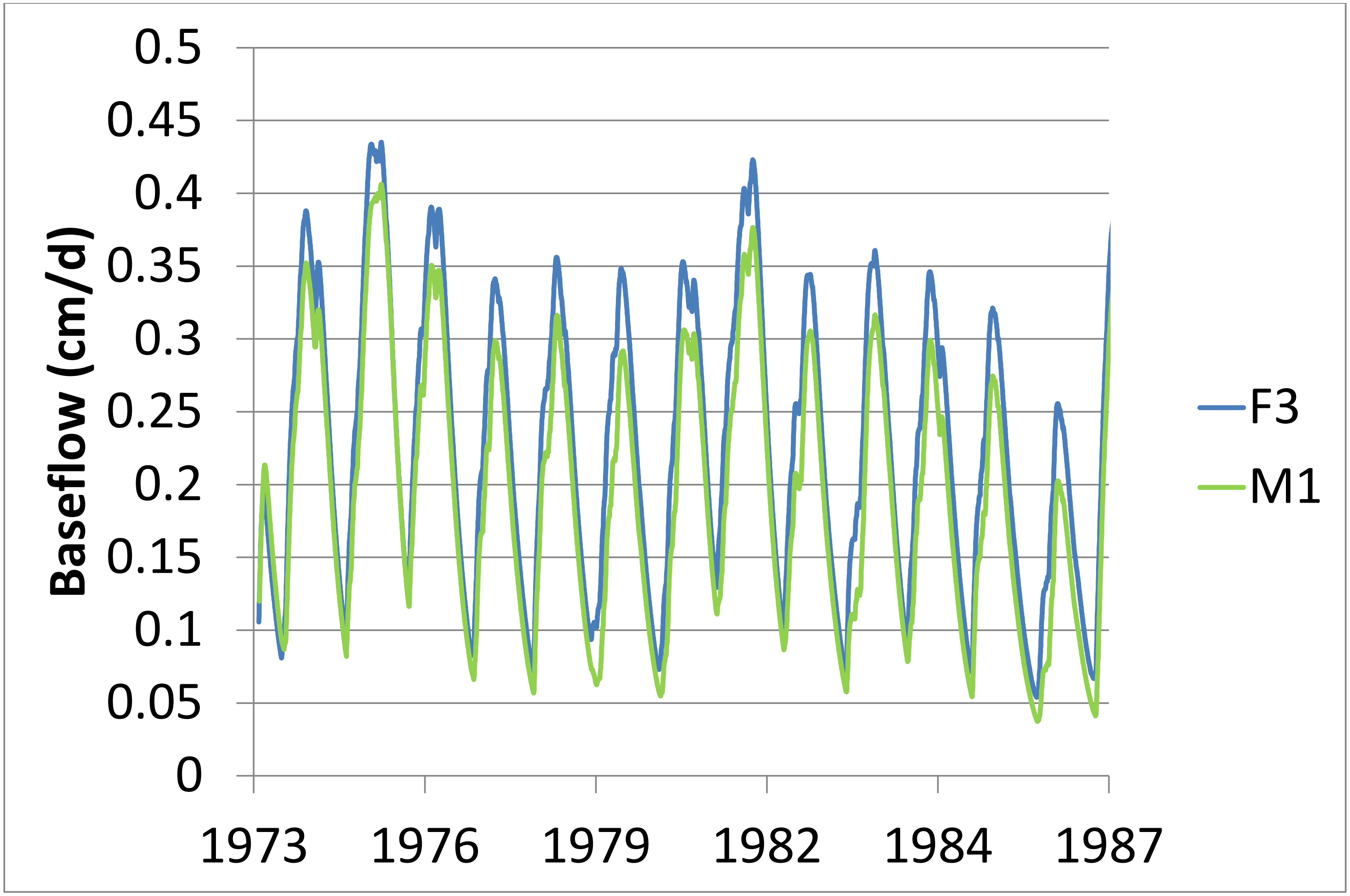

Figure 27. Simulated daily baseflow for the M1 and F3 watersheds.

Table 4. Modeling statistics for the large scale forested (F) and mixed-land use (M)watersheds.

Test Statistic	F1	F2	F3	F4	M1	M2	M3
E (N-S)	-0.12	0.15	0.26	-1.79	0.03	-1.25	-0.12
d	0.76	0.79	0.82	0.64	0.76	0.62	0.73
MSE	4.31	3.02	1.22	2.23	0.42	0.98	1.26
E'	0.01	0.16	0.19	-0.31	0.13	-0.10	0.13
d'	0.56	0.58	0.61	0.52	0.59	0.57	0.58
MAE (cm)	0.20	0.16	0.10	0.08	0.05	0.07	0.09
R2	0.38	0.45	0.46	0.34	0.40	0.20	0.25

Table 5a. Water balances for watershed scale modeling

Water Balance Term	F1		F2		F3		F4	
	%	(cm)	*%*	(cm)	%	(cm)	*%*	(cm)
Precipitation	*100%*	3381	*100%*	2841	100%	2115	*100%*	2887
Evapotranspiration	*24.3%*	820	*28.0%*	795	35.5%	752	*27.5%*	794
Percolation	*24.2%*	819	*29.2%*	831	26.6%	562	*22.8%*	658
Runoff	*52.2%*	1766	*44.0%*	1251	38.6%	816	*50.4%*	1456
Storage	*-0.7%*	-25	*-1.3%*	-36	-0.7%	-14	*-0.7%*	-21

Table 5b. Water balances for watershed scale modeling.

Water Balance Term	**M1**		**M2**		**M3**	
	%	(cm)	*%*	(cm)	*%*	(cm)
Precipitation	*100%*	1628	*100%*	2191	*100%*	2319
Evapotranspiration	*43.3%*	705	*26.4%*	579	*30.9%*	716
Percolation	*29.7%*	483	*44.4%*	973	*34.8%*	808
Runoff	*29.2%*	476	*30.7%*	673	*35.8%*	830
Storage	*-2.2%*	-36	*-1.6%*	-34	*-1.5%*	-35

Discussion

Based on the one-cell model, as AMC and precipitation intensity increased, differences between the initiation of surface runoff and percolation between land uses diminished. However, at AMC below field capacity, vertical connectivity in the sugar and pasture was reduced causing quicker initiation of surface runoff and reduced percolation. In simulations with the highest intensity, surface runoff dominated the water balances of sugar and pasture at over 90%, whereas forest and coffee percolated approximately 30% of the incoming precipitation. During the wet season, when compaction reduces infiltration after forest conversion, surface runoff can limit percolation ultimately affecting dry season base flows (Bruijnzeel 2004). Collectively, the one-cell simulations suggest that when looking solely at soil characteristics (thus ignoring the effect of ET), differences in K_{sat} and active soil depth as the result of different land uses control the rate of filling and storage capacity of the soil profile causing different proportions and timing of surface runoff and percolation as a form of spilling. Thus, a fill-and-spill mechanism not due to subsurface topography as in Tromp van Meerveld and McDonald (2006), but due to differences in connectivity and soil depth. While our system is very different than the Panola watershed (deep soils, tropical environment, minimal seasonal variation), determination of soil restrictive layer thresholds will also assist modelers in studying hillslope scale processes. An added effect is the influence of compaction at the soil surface in row crops such as observed in sugar cane.

Deep percolation and baseflow are a fundamental link between the field scale and watershed scale. During the transition from dry to wet season, percolation was greatest in the forested watersheds and streamflow was greatest in the mixed-land use watershed. These results mirrored the processes that were observed for the one-cell scale. These effects due to land use have important applications to water yield and potentially erosion. Soils in forested watersheds with good hydrological connectivity due to greater conductivities and larger macropore networks will fill deeper horizons quickly resulting in percolation (vertical spilling). In mixed land use watersheds, reduced connectivity, compaction, and less active soil depth causes a slower filling of deep horizons, quick filling of shallow soil systems resulting in overland flow (lateral spilling). At the watershed scale, the connectivity between deep percolation and baseflow is more like the 'fill and spill' hypothesis described by others (Tromp Van-Meerweld and McDonnell 2006, Spence and Woo 2003). However, due to the depth of these soils, the deep percolation is an additional control on top of the unknown bedrock topography in this region.

Water yield, normalized by precipitation (i.e. runoff coefficients), was much greater in the forested watersheds compared to the mixed land use watersheds (Figures 22-24). This is in contrast to many studies in temperate regions that assessed permanent land use change. Zhang and Schilling (2006) found that land use change in the Mississippi watershed from perennial to annual crops correlated well with increased base flow and stream flow due to decreased evapotranspiration. In this study, differences in ET between forested and mixed land use watersheds were not as great because new vegetation grows back quickly. ET quickly decreased soil moisture in the forested watersheds to the point where available soil moisture started to limit ET. The overall decreased ET in the mixed land use watershed allowed ET to progress much more consistently through the dry season within the mixed use watershed. Over the time period of the simulations, this greatly reduced differences in ET between forested and mixed-use watersheds. In the tropics, studies have reported considerable permanent increases in streamflow and wetter soils after the clearing of forest due to reduced ET, interception, and more shallow root systems that inhibit access to deeper soil water (Lal 1983, Fritsch 1993, Calder 1998, and van Dijk and Bruijnzeel 2001). However, every watershed has a certain capacity for soil water storage. Fritsch (1993) clearly demonstrated that soil depth can be a more explanatory variable for differences in streamflow than any change in land use. Bruijnzeel (2004) found that differences in precipitation and elevation can commonly account for differences in stream flow response attributed to different land uses. Different precipitations and elevations were observed throughout the seven watersheds with a direct correlation between increased precipitation, elevation and water yield.

At the watershed scale, I observed similar effects on these hydrological processes occurring both during the wet season and dry season. During the wet season, percolation and streamflow were greater in the forested watersheds due to their increased conductivity. Increased conductivity promoted connectivity between soil horizons to facilitate deep percolation. Deep percolation then drove the baseflow component of the system (Figure 33).

Conclusions

During one-cell model simulations, I observed that reduced conductivities in the sugar and pasture generated surface runoff more rapidly than in the forest and coffee by determining the amount of storage available for infiltration and percolation. The effect was the most pronounced at AMC less than field capacity. While some of the differences between the forested and mixed-land use watersheds can be explained by differences in location, elevation, and precipitation, our results show that land uses with reduced conductivities play a role in determining the amount of surface runoff and percolation generation at the watershed scale. Percolation, and its connection to baseflow, was a substantial component of streamflow at the watershed scale. Therefore, two types of 'fill and spill' mechanism were observed within the simulations. First, in the pasture and sugar, reduced conductivities and macropore networks led to a rapid shallow filling that resulted in surface runoff (lateral). In the forest and coffee, the 'fill and spill' mechanism was more vertical resulting when soil storage became greater than field capacity promoting percolation and ultimately baseflow at the watershed scale. Smaller scale studies need to identify how to capture and quantitatively represent these mechanisms between percolation and baseflow to better understand upscaling of field results at smaller scales.

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CHAPTER 3

Integrating decision-maker preferences and ecosystem services of coffee agroforestry systems within the Volcánica Central-Talamanca Biological Corridor, Costa Rica

Abstract

While forests often provide the most benefit for biodiversity conservation at a landscape scale, agroforestry systems can provide supplementary habitat for some species, reduce deforestation, and create a more permeable matrix when compared to other land uses. The objective of this study was to understand how decision makers involved in biological corridor management perceived and valued ecosystem services provided by coffee agroforestry systems (CAFS). In this project, I studied multiple ecosystem services (e.g., avian and insect biodiversity, insect pest regulation, and watershed services) of two common multi-strata coffee agroforestry systems (coffee plus *Erythrina poeppigiana,* and coffee plus *Erythrina poeppigiana* and *Cordia alliodora*) within the Volcánica Central de Talamanca Biological Corridor (VCTBC) in Costa Rica. I integrated the information from these studies with a digital elevation model, a land use cover map, a coffee database, a soils map, and a hydrological database to model a select suite of ecosystem services provided by CAFS at the landscape scale (720 km^2). Following data integration, I interviewed the thirteen members of the local biological corridor committee to determine their preference of the selected CAFS ecosystem service indicators (e.g., structural connectivity, avian diversity, Cicadellidae (leafhopper) diversity, leaf-cutting ant risk, risk of crespera coffee disease causal-agent vectors, and erosion and water contamination risks). Committee members made pair-wise comparisons of preference for the different ecosystem services. After selecting 10 regions of the VCTBC (based on CAFS density and corridor connectivity), I conducted a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis with the decision makers of the corridor committee to prioritize local perspectives of the top three regions of interest for resource allocation. CAFS regions were seen as Strengths or Threats depending on known management styles and locations. While certain CAFS regions were prioritized because of specific environmental services, the corridor committee included location, proximity to roads and resources, and organizational infrastructure as other common themes for prioritization.

Keywords. Coffee, ecosystem services, biodiversity, erosion, natural pest control, prioritization, connectivity, preferences

Introduction

Biological corridors are important regions for conservation (Chetkiewicz et al. 2006). The purpose of corridors is to connect similar patches (structural connectivity), or to increase the flow of organisms in a landscape (functional connectivity; Turner et al. 2001). While linear forested corridors might be easier to establish in a landscape (by government or non-governmental organizations), the efficacy of this type of corridor has been questioned because of the inconsistencies with many organisms movements (Rosenberg et al. 1997). Landscape heterogeneity can play an important role in the flow of organisms (Gustafson and Gardener 1996). Additionally, in the developing world, corridors are increasingly viewed not only as biophysically defined regions, but as socioeconomic and political tools (Zimmerer et al. 2004) within landscape decision-making. The Mesoamerican Biological Corridor (MBC) initiative aims to achieve biodiversity conservation and sustainable economic development, recognizing the sustainability of corridors will be strongly dependent on the well-being of its inhabitants. To integrate economic development with biodiversity conservation, the MBC initiative recognizes four land categories (Core Zones, Buffer Zones, Corridor Zones and Multiple-Use Zones), two in which sustainable economic activities are explicitly promoted (Miller et al. 2001).

Agriculture is the most common economic activity within national corridors participating in the MBC initiative (Godoy Herrera 2003). Research has shown that specific agricultural practices, especially agroforestry systems, can increase ecosystem services (i.e. "conditions and processes through which natural ecosystems sustain and fulfill human life"; Daily 1997) provided by those productive systems, while supporting productive activities (Harvey et al. 2005). Agroforestry systems are included in payments for environmental services in Costa Rica (Wunscher et al. 2008). Scientists have given much attention to coffee agroforestry systems (CAFS) as a potential sustainable land use. CAFS can provide ecosystem services such as maintaining biodiversity, reduction of erosion, reduction of water contamination by agrichemicals, and reducing pest populations, depending on their structure and management (Perfecto et al. 1996; Somarriba et al. 2004; Pérez Nieto et al. 2005; Varón 2006). In addition, in many regions, CAFS often exist near critical regions for conservation (e.g., Southern Mexico; Moguel and Toledo 1999). Even though CAFS have potential as a sustainable economic activity within corridors, it is unknown how decision makers involved in corridor design and implementation value these systems and the ecosystem services they provide.

Historically, conservation planning efforts have relied heavily on assessing systems from a biophysical perspective. Rarely did these efforts include the perceptions and values of local people from communities affected by the planning. The knowledge that local people can provide is often considered afterwards rather than as input during conservation planning (Brown et al. 2004). However, researchers and policy makers are beginning to understand the importance of recognizing landowner and stakeholder perspectives, and how local knowledge can inform project design (Russell and Harshbarger 2003). Understanding and incorporating local knowledge and perspectives into conservation planning can also help with the implementation of resulting actions. Scientists' understanding of the biological processes occurring in a particular region can be improved by drawing upon local knowledge (Brown et al. 2004). Incorporating decision makers can result in conservation plans that are scientifically sound but also publicly supported (Meo et al. 2002; Russell and Harshbarger 2003).

The objectives of this study included: 1) understanding how decision makers involved in the implementation of a biological corridor perceived ecosystem services provided by coffee agroforestry systems; and 2) determining if they considered ecosystem services for the prioritization of regions within the corridor for resource allocation. Due to the availability of existing information on ecosystem services provided by CAFS in the Volcánica Central de Talamanca Biological Corridor (VCTBC) in Costa Rica, this corridor was selected as a case study.

Methods

Case study area

Our study focuses on how perceptions influence the VCTBC administration committee decisions to prioritize regions for conservation or restoration within the corridor.

The recently formed committee represents a dramatic shift from top-down conservation to a more representative process that incorporates non-conservation stakeholder perspectives (hydroelectric companies, coffee producer groups, etc.). The VCTBC is part of the MCB Project, which attempts to connect protected areas through management of the agricultural matrix, restoration and reforestation (Miller et al. 2001). The VCTBC is located on the Atlantic slope of Costa Rica covering approximately 72,000 hectares. It has an average annual rainfall of 2,479 mm, an average temperature of 21.7°C, and an average relative humidity of 87%. The VCTBC landscape is dominated by agricultural production (28% pasture, 14% coffee, 6% sugarcane and 3% other crops), with 40% of its area under a highly fragmented forest cover. The VCTBC seeks to augment the connectivity between the Volcánica-Central and Talamanca mountain ranges, and eight protected natural areas.

GIS layer development of ecosystem services

Several different GIS layers (watershed services, biodiversity, and natural pest control) were developed using common spatial resources for the VCTBC. These resources included a 90 m Digital Elevation Model, a land use cover map for 2005, and a database from the Instituto de Cafe that covered 5000 coffee farms. Each layer was normalized to a 100-scale for provision of ecosystem service (i.e., 100 was the highest provision of ecosystem service, 0 the lowest). In the end, layers were bundled to determine the overlap between ecosystem services at particular locations.

Watershed services

The watershed services map was developed using the Soil Moisture Routing model (Brooks et al. 2007). Runoff depth and slope were combined to identify erosion-risk areas. Days of saturation and number of fertilizer applications were used to identify critical source areas for nutrient contamination (Walters et al. 2000). These layers were then summed and normalized to a 1-100-scale.

Biodiversity

The biodiversity map was developed by combining in Arc GIS 9.1 two habitat suitability raster layers that were available for coffee agroforestry systems within the VCTBC (Florian et al. unpublished). The first map was an avian diversity layer that considered the species richness of birds in relationship to both CAFS vegetation structure and proximity to forest. The second map was a forest leafhopper habitat suitability layer that considered the abundance of forest leafhopper species in relationship to CAFS vegetation structure, CAFS organic management and proximity to forest. The layers were summed using the Raster Calculator, and the resulting layer was normalized to a 100-scale.

Natural pest control

The natural pest control map was developed by combining in Arc GIS 9.1 two insect pest habitat suitability raster layers that were available for coffee agroforestry systems within the VCTBC (Ramos et al. unpublished). The first map was a leaf-cutting ant (*Atta cephalotes*) habitat suitability layer that considered the abundance of *A. cephalotes* nests in relationship to CAFS vegetation structure, CAFS organic management and proximity to forest. *A. cephalotes* is an important pest of coffee in the region (Varón et al. 2007). The second map was a *Xylella* *fastidiosa* potential vector layer that considered the abundance of potential *X. fastidiosa* leafhopper vectors in relationship to CAFS vegetation structure, CAFS organic management and proximity to pasture. *Xylella fastidiosa* is the bacterial causal agent of crespera coffee disease in Costa Rica (Rodríguez et al. 2001). First, both layers were transformed to reflect the ecosystem service of natural pest control (i.e. invert values proportionally so higher values in the old layers reflect high values in the new ecosystem service layer). Then, the layers were summed using the Raster Calculator, and the resulting layer was normalized to a 100-scale.

Ecosystem services bundling

After the three ecosystem services layers were identified, the services were combined to summarize the information for decision makers. The methodology proposed by Wendland et al. (unpublished) was used to “bundle” ecosystem service layers. The z-normalization procedure (Wunscher et al. 2008) was not used, since all layers were already normalized to a 100-scale. Using the raster calculator, all areas with the three ecosystem service levels higher than 10% were identified. This was done for ecosystem service levels higher than 20%, 30%, 40%, 50%, 60%, 70%, 80 % and 90%. Additionally, areas in overlap of pairs of ecosystem services (i.e. water-biodiversity, water-pest control and biodiversity-pest control) were calculated following the same methodology. All ecosystem services received equal weights.

Connectivity emerged as a theme of concern among stakeholders in the region. Since areas with coffee agroforestry systems had to be grouped into a certain number of regions that could be evaluated by the committee, this factor was used for grouping. Ten regions were selected based on distance from the existing connectivity network (<1 km; Murrieta 2006) and coffee farm density (e.g., farm size in hectares). The area in overlapping ecosystem services of each region was calculated using the methodology described above.

Interviews and ranking of ecosystem services by TVCBC committee members

Semi-structured interviews were administered to the VCTBC administration committee (13 interviewees) in November 2006. These interviews aimed to gain institutional knowledge from decision makers, and to determine the prioritization of their institution's interests regarding CAFS in the context of the VCTBC. The various committee members represent government agencies, non-profit organizations, an educational institution, and local communities. The first part of the interview was designed to elicit institutional goals, interests within the corridor, existing projects within the corridor, and the preferred type of prioritization (restoration vs. conservation). The committee includes members of international institutions (International Model Forest), Ministry of the Environment (MINAE), Tropical Agriculture and Resarch Higher Education Center CATIE faculty, Institute of Coffee (ICAFE), an organic farmers' association (APOT), Instituto Costariccense de Electricidad (ICE) and representatives of several local communities. The final part of the interview involved determining preferences of ecosystem services provided by CAFS. To prioritize ecosystem services provided by CAFS, the committee members made pair-wise comparisons of the selected ecosystem services. Committee members compared ecosystem service surrogates (Moffett and Sarkar 2006). including: avian and leafhopper (Cicadellidae) diversity (biodiversity surrogates), leaf-cutting ants (*Atta* spp.) and crespera coffee disease causal-agent vectors (natural pest control surrogates), and risk of erosion and critical source areas (watershed services surrogate).

Committee members also evaluated a connectivity surrogate in the form of a previously established structural connectivity network (Murrieta 2006). The pair-wise comparisons of the ecosystem services were analyzed using the Analytical Hierarchy Process (AHP) and Inconsistency Index (Mendoza et al. 1999). The AHP is a multi-criteria analysis (MCA) characterized by its mathematical ability to analyze complex decision problems with multiple criteria (Saaty 1977; 1980).

SWOT Analysis

A workshop was conducted with 17 decision makers after the orignal interviews, which included four new members, from the VCTBC committee. The workshop objectives were to identify and prioritize regions of CAFS within the corridor. Maps provided some detail of the area, including forest fragments present and the level of overlapping ecosystem services provided by CAFS (Figure 5.1).

The strengths, weaknesses, opportunities and threats (SWOT) for each of the 10 regions were assessed (Team Action Management 2007). Strengths and weaknesses assess the internal elements affecting the region. Strengths were defined as the primary attributes and unique resources of a region and weaknesses were considered things about that region that are lacking or could be improved. Opportunities and threats were considered external factors impacting the regions. Opportunities were considered elements that were especially interesting or advantageous to workshop participants while threats were potential challenges participants may face working in regions (Mindtools 2007). Workshop participants worked collaboratively on the SWOT for approximately one hour. After completing the SWOT exercise, participants reviewed the generated information for each of the 10 regions. Participants were then given three labels and asked to place them on their top three priority regions for resource allocation.

Results

Ecosystem services bundling

Biodiversity conservation, natural pest control and watershed ecosystem services provided by CAFS overlapped in a maximum of 3,500 ha of coffee within the VCTBC. Higher spatial overlap of the three ecosystem services studied was found for lower levels of ecosystem services (Table 1). For ecosystem service levels of 50% or higher for each service, spatial overlap of the three services was largely reduced. No part of the VCTBC coffee area showed overlapping of ecosystem service levels of 70% or higher. A greater proportion of the area exhibited overlapping of watershed and natural pest control services at lower ecosystem service levels than the two combinations with biodiversity conservation service at lower levels.

Table 1. Land in overlapping (bundling) ecosystem services (ES) at different levels of ecosystem services.

Ecosystem Services	Land (ha) and Percentage of Total VCTBC Coffee Area in Ecosystem Services Bundling								
Level of ES	>10%	>20%	>30%	>40%	>50%	>60%	>70%	>80%	>90%
Water-Biodiversity	3499.2	3276.4	1808.5	1510.7	143.1	97.4	58.3	26.9	0
	83%	78%	43%	36%	3%	2%	1%	1%	0%
Water-Pest Control	3685.5	3321.2	1981.9	1704.4	1226.3	1114.3	916.0	116.6	99.1
	88%	79%	47%	41%	29%	27%	22%	3%	2%
Biodiversity-Pest Control	3931.2	3783.7	1975.1	1975.0	150.0	77.8	77.8	1.3	0
	90.1%	86.7%	45.2%	45.2%	3.4%	1.8%	1.8%	0.0%	0.0%
Water-Biodiversity-Pest Control	3499.2	3155.0	1676.9	1446.7	87.9	41.6	28.1	0.7	0
	83%	75%	40%	34%	2%	1%	1%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

The resulting ten regions selected for the SWOT analysis comprised 68% of the total VCTBC coffee area and had different proportions of land in coffee (Table 2). Regions 2, 3 and 4 had the greatest proportion of land in coffee. As observed in the whole VCTBC, for ecosystem service levels of 50% or higher for each service, spatial overlap of the three services was largely reduced in all regions (Table 2). Regions 3, 4 and 10 had the highest amount of land with overlapping of the three services at levels of 50% or higher. At levels of 50% or higher, regions 3 and 4 also exhibited the highest amount of land with overlapping pairs of ecosystem services (Tables 3, 4 and 5). Regions 3 and 4 showed a greater proportion of land with overlapping of watershed and natural pest control services than the other ecosystem service combinations.

Table 2. Land in overlapping (bundling) ecosystem services (ES) (water, biodiversity and pest control) at different levels of ecosystem services in each region selected for the SWOT analysis. For each region, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each region's land in ecosystem bundling.

VCTBC Region Name	Land (ha) in Overlap of Ecosystem Services								
Percentage of ES	>10%	>20%	>30%	>40%	>50%	>60%	>70%	>80%	>90%
1. Guayabo (65.3 ha)	53.2	51.0	15.0	15.0	0.8	0.0	0.0	0.0	0.0
	81%	78%	23%	23%	1%	0%	0%	0%	0%
2. Aquiares (792.0 ha)	672.0	592.5	538.2	340.1	0.5	0.5	0.5	0.0	0.0
	85%	75%	68%	43%	0%	0%	0%	0%	0%
3. Tres Equis (459.1	396.2	381.2	288.5	280.6	19.3	1.8	1.5	0.7	0.0
	86%	83%	63%	61%	4%	0%	0%	0%	0%
4. Pavones (518.4 ha)	442.2	377.1	125.8	125.8	14.9	9.2	9.1	0.0	0.0
	85%	73%	24%	24%	3%	2%	2%	0%	0%
5. Florencia (276.5 ha)	219.9	219.8	16.8	16.5	0.1	0.0	0.0	0.0	0.0
	80%	79%	6%	6%	0%	0%	0%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	19.7	19.7	2.6	2.6	2.6	0.0	0.0
	81%	78%	15%	15%	2%	2%	2%	0%	0%
7. Tuis (328.7 ha)	263.7	210.5	106.9	106.3	1.6	0.2	0.2	0.0	0.0
	80%	64%	33%	32%	0%	0%	0%	0%	0%
8. Tucurrique (104.0	82.2	68.3	4.5	4.1	0.0	0.0	0.0	0.0	0.0
	79%	66%	4%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	0.5	0.5	0.0	0.0	0.0	0.0	0.0
	86%	57%	0%	0%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	10.8	10.8	4.6	2.9	2.0	0.0	0.0
	78%	71%	14%	14%	6%	4%	3%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 3. Land in overlapping (bundling) ecosystem services (ES) (water and biodiversity) at different levels of ecosystem services in each region selected for the SWOT analysis. For each region, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each region's land in ecosystem bundling.

VCTBC Region Name	Land (ha) in Overlap of Ecosystem Services								
Percentage of ES	>10%	>20%	>30%	>40%	>50%	>60%	>70%	>80%	>90%
1. Guayabo (65.3 ha)	53.2	53.2	19.4	16.1	1.9	1.1	0.6	0.5	0.0
	81%	81%	30%	25%	3%	2%	1%	1%	0%
2. Aquiares (792.0 ha)	672.0	594.5	540.3	340.1	0.5	0.5	0.5	0.5	0.0
	85%	75%	68%	43%	0%	0%	0%	0%	0%
3. Tres Equis (459.1	396.18	385.4	294.84	284.4	22.68	5.22	3.6	3.06	0
	86%	84%	64%	62%	5%	1%	1%	1%	0%
4. Pavones (518.4 ha)	442.2	397.9	138.1	132.5	21.2	15.1	10.6	6.3	0.0
	85%	77%	27%	26%	4%	3%	2%	1%	0%
5. Florencia (276.5 ha)	219.87	219.9	24.66	22.5	6.1	6.12	3.69	0	0
	80%	80%	9%	8%	2%	2%	1%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	21.6	21.6	4.5	4.5	4.5	2.6	0.0
	81%	78%	17%	17%	4%	4%	4%	2%	0%
7. Tuis (328.7 ha)	263.7	239.9	130.9	111.4	6.9	5.5	3.1	0.2	0.0
	80%	73%	40%	34%	2%	2%	1%	0%	0%
8. Tucurrique (104.0	82.2	72.5	7.0	4.1	0.1	0.1	0.1	0.0	0.0
	79%	70%	7%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	11.5	7.4	0.0	0.0	0.0	0.0	0.0
	86%	57%	10%	6%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	60.7	11.5	10.8	4.6	2.9	2.0	2.0	0.0
	78%	78%	15%	14%	6%	4%	3%	3%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 4. Land in overlapping (bundling) ecosystem services (ES) (water and pest control) at different levels of ecosystem services in each region selected for the SWOT analysis. For each region, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each region's land in ecosystem bundling.

VCTBC Region Name	Land (ha) in Overlap of Ecosystem Services								
Percentage of ES	>10%	>20%	>30%	>40%	>50%	>60%	>70%	>80%	>90%
1. Guayabo (65.3 ha)	53.2	51.0	15.3	15.2	15.2	11.1	6.0	0.2	0.0
	81%	78%	23%	23%	23%	17%	9%	0%	0%
2. Aquiares (792.0 ha)	672.0	592.5	544.1	345.9	149.9	149.7	137.8	29.8	29.8
	85%	75%	69%	44%	19%	19%	17%	4%	4%
3. Tres Equis (459.1	396.2	381.2	290.0	282.1	263.0	236.3	193.0	18.3	18.3
	86%	83%	63%	61%	57%	51%	42%	4%	4%
4. Pavones (518.4 ha)	442.2	377.1	139.1	138.9	126.7	116.8	102.6	9.4	4.2
	85%	73%	27%	27%	24%	23%	20%	2%	1%
5. Florencia (276.5 ha)	219.9	219.8	31.1	30.7	24.9	10.6	10.6	0.0	0.0
	80%	79%	11%	11%	9%	4%	4%	0%	0%
6. Cruzada (127.9 ha)	104.0	100.0	81.5	54.0	19.7	19.7	18.0	0.0	0.0
	81%	78%	64%	42%	15%	15%	14%	0%	0%
7. Tuis (328.7 ha)	263.7	210.5	119.0	118.4	106.6	105.7	74.8	2.3	2.3
	80%	64%	36%	36%	32%	32%	23%	1%	1%
8. Tucurrique (104.0	82.2	68.3	10.1	6.7	4.1	3.9	3.8	0.0	0.0
	79%	66%	10%	6%	4%	4%	4%	0%	0%
9. Cachí (119.9 ha)	103.7	68.8	4.5	4.5	0.0	0.0	0.0	0.0	0.0
	86%	57%	4%	4%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	14.2	14.2	10.8	10.8	7.9	0.0	0.0
	78%	71%	18%	18%	14%	14%	10%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Table 5. Land in overlapping (bundling) ecosystem services (ES) (biodiversity and pest control) at different levels of ecosystem services in each region selected for the SWOT analysis. For each region, the first row indicates the amount of hectares in ecosystem service bundling and the second row, the percentage of each region's land in ecosystem bundling.

VCTBC Region Name	Land (ha) in Overlap of Ecosystem Services								
Percentage of ES	>10%	>20%	>30%	>40%	>50%	>60%	>70%	>80%	>90%
1. Guayabo (65.3 ha)	53.2	51.0	15.0	15.0	0.8	0.0	0.0	0.0	0.0
	81%	78%	23%	23%	1%	0%	0%	0%	0%
2. Aquiares (792.0 ha)	672.0	670.1	612.1	612.1	15.8	15.8	15.8	0.3	0.0
	85%	85%	77%	77%	2%	2%	2%	0%	0%
3. Tres Equis (459.1	396.2	392.0	298.6	298.6	29.3	10.3	10.3	0.7	0.0
	86%	85%	65%	65%	6%	2%	2%	0%	0%
4. Pavones (518.4 ha)	442.2	420.0	126.4	126.4	16.0	9.8	9.8	0.0	0.0
	85%	81%	24%	24%	3%	2%	2%	0%	0%
5. Florencia (276.5 ha)	219.9	219.8	16.9	16.9	0.1	0.0	0.0	0.0	0.0
	80%	79%	6%	6%	0%	0%	0%	0%	0%
6. Cruzada (127.9 ha)	104.0	104.0	19.7	19.7	2.6	2.6	2.6	0.0	0.0
	81%	81%	15%	15%	2%	2%	2%	0%	0%
7. Tuis (328.7 ha)	263.7	233.8	106.9	106.9	1.6	0.2	0.2	0.0	0.0
	80%	71%	33%	33%	0%	0%	0%	0%	0%
8. Tucurrique (104.0	82.2	77.7	4.5	4.5	0.0	0.0	0.0	0.0	0.0
	79%	75%	4%	4%	0%	0%	0%	0%	0%
9. Cachí (119.9 ha)	103.7	103.7	0.5	0.5	0.0	0.0	0.0	0.0	0.0
	86%	86%	0%	0%	0%	0%	0%	0%	0%
10. Tayutic (77.4 ha)	60.7	54.8	10.8	10.8	4.6	2.9	2.9	0.0	0.0
	78%	71%	14%	14%	6%	4%	4%	0%	0%

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Decision-maker interest

Analytical hierarchy process analysis of decision maker preference for ecosystem service surrogates showed small differences in preference for all surrogates analyzed (Table 6). However, connectivity received the highest rating (25%), while leafhopper diversity received the lowest (11%). The pest management surrogates were selected as second in terms of preference, while erosion and water pollution risk came in third.

Analysis using SWOT showed that higher levels of ecosystem services were considered as strengths, although lower values of ecosystem services were not considered as weaknesses (Table 7). Other topics related to the ecosystem services studied were mentioned by participants. Strengths identified included proximity to forest (which affects the services of biodiversity conservation and natural pest control) and coffee certifications (Rainforest Alliance and Organic; which may also affect the services of biodiversity conservation and natural pest control). Erosion and pollution (which affect watershed services) were mentioned as threats. In addition to these topics, employment, level of organization and tourism were considered important aspects for the prioritization of regions within the VCTBC (Table 7).

Table 6. Decision maker weights of ecosystem service surrogates.

Ecosystem service	Ecosystem service surrogate evaluated	Weight (%)
Watershed services	Erosion and water pollution	16
Biodiversity	Connectivity	25
	Leafhopper diversity	12
	Avian diversity	13
Natural pest control	Leaf-cutting ants	17
	X. fastidiosa potential vectors	17

Table 7. Topics commonly mentioned for VCTBC regions in the SWOT analysis.

Topic	SWOT	Regions	Total number
Level of overlapping ecosystem services	Strength (high)	2, 3, 4, 7	4
	Weakness (low)	8	1
Related to ecosystem services studied			
Pollution	Weakness	2, 3, 5, 9	4
	Threat	4, 8, 9, 10	4
Proximity/presence of forest	Strength	2, 3, 4, 7, 5, 9	6
	Weakness (low)	6, 8,10	3
Land use change	Threat	2, 4, 6, 7, 8	5
Intensive/ monoculture agriculture	Weakness	2, 5, 8	3
	Threat	3, 4, 7	3
Erosion	Weakness	9	1
	Threat	1, 3, 4	3
ES payments/ coffee certifications	Strength (existing)	5, 2, 4	3
	Opportunity (potential for)	6, 7, 3	3
Social aspects			
Community organizations/ participation	Strength	1, 2, 3, 4, 8, 10	6
	Opportunity	4, 5	2
	Weakness (lack of)	6, 7	2
Institutional presence/support	Strength	5, 8, 9	3
Employment	Opportunity	2, 3, 4	3
	Weakness (low)	1, 5, 6, 7	4
Tourism	Strength	1, 6, 8, 9	4
	Opportunity	1, 3, 4, 5, 8, 9	6

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

SWOT = Strengths, weaknesses, opportunities and threats; ES = Ecosystem service

Participants prioritized regions 2, 4, 3 and 9 for resource allocation (Table 8). The first three regions are also the ones with more land area. Regions 3 and 4 had the highest amount of land with overlapping of the three services at levels of 50% or higher. However, region 9 had almost no overlap of the three services at levels of 30% or higher. The discussion after the prioritization process reflected that participants selected regions based on their location on the VCTBC (region 2), the amount of small-scale CAFS present (regions 3 and 4), and the amount of forest (region 9) (data not shown). Ecosystem services provided by CAFS were not mentioned directly.

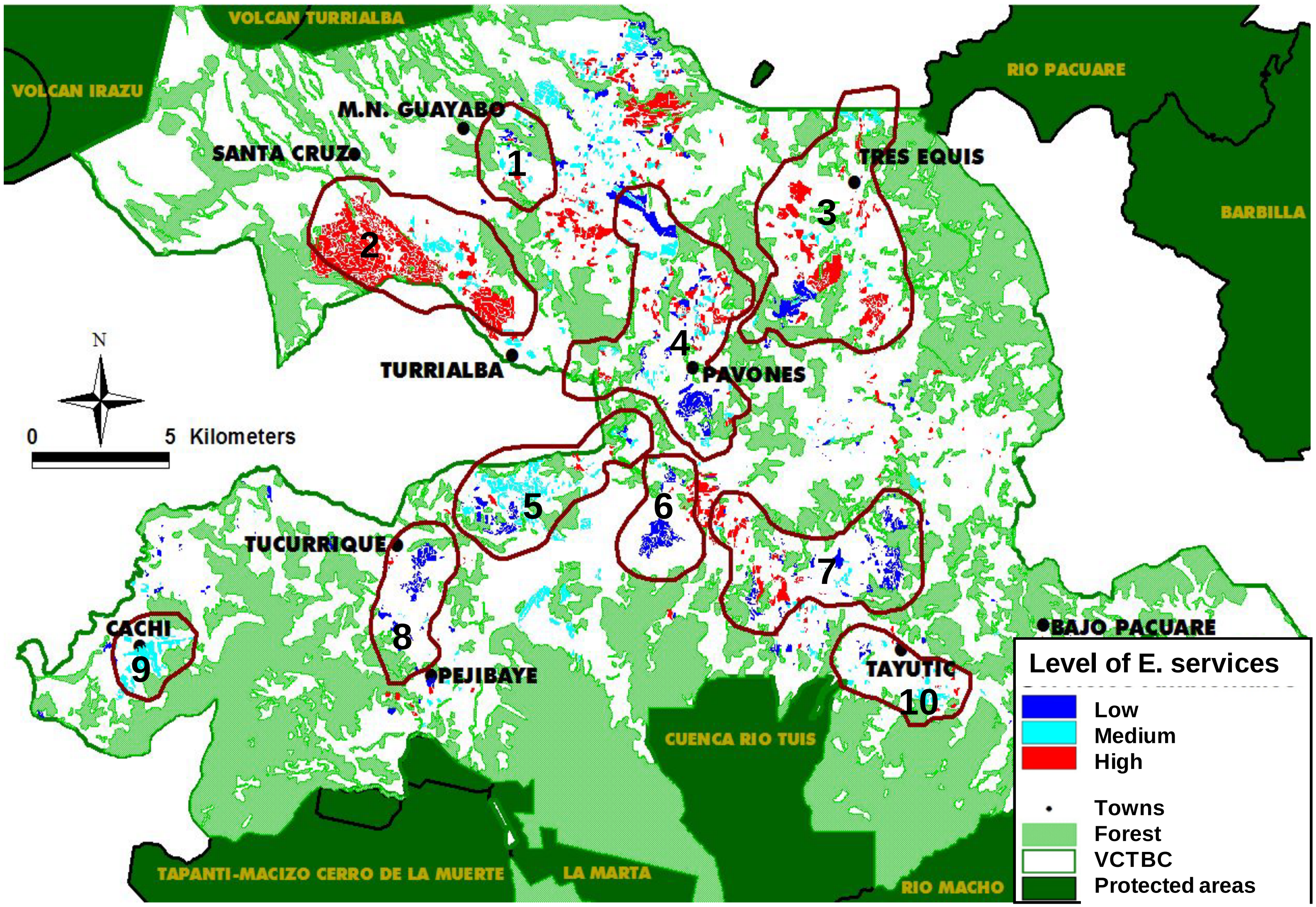

Figure 1. VCTBC coffee agroforestry regions evaluated in decision-maker workshop.

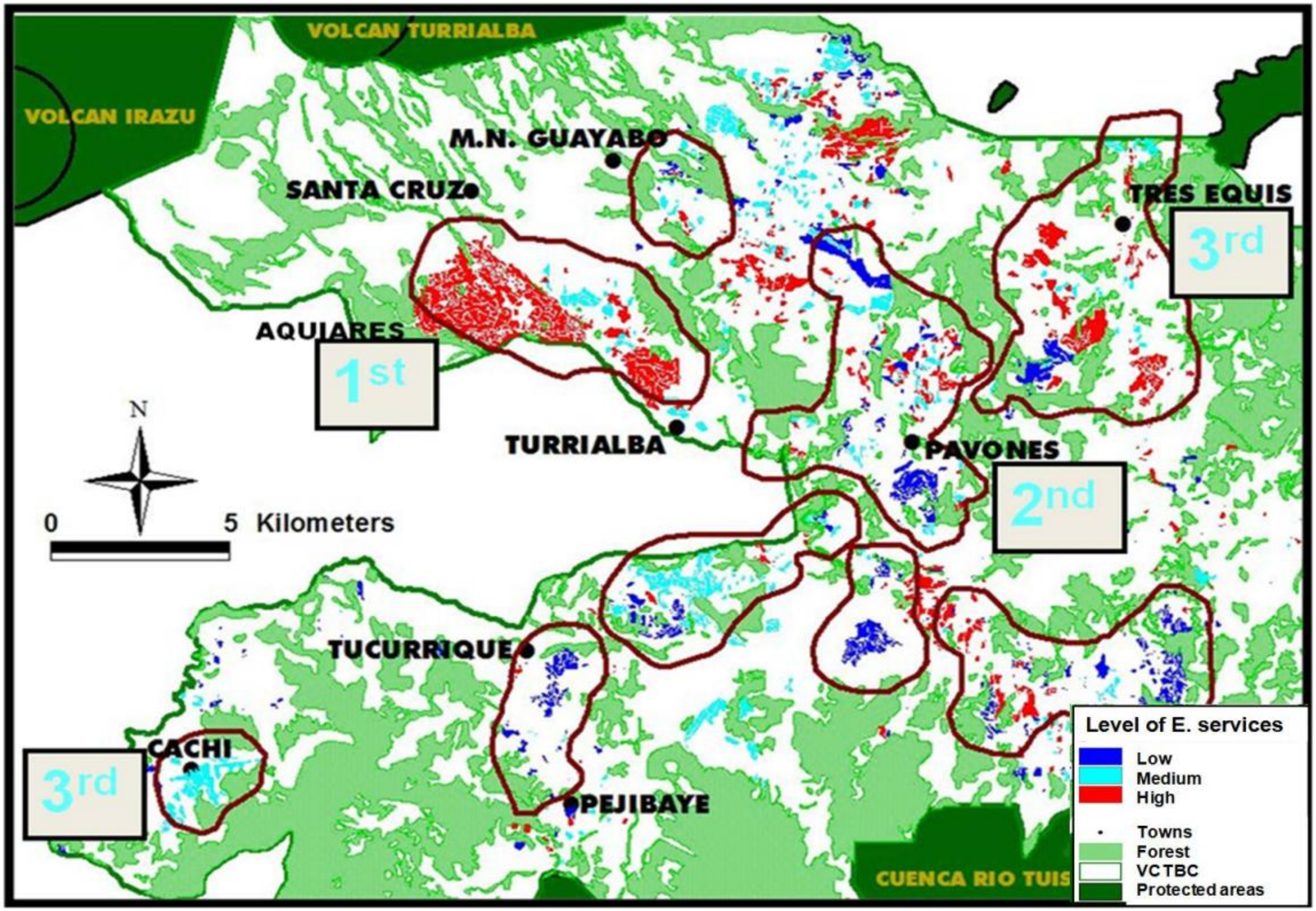

Figure 2. VCTBC committee votes for the prioritization of regions with high density of CAFS within the corridor.

Table 8. Ranking of regions by VCTBC committee members.

VCTBC Region	Number of votes	Prioritization ranking
1. Guayabo (65.3 ha)	1	
2. Aquiares (792.0 ha)	12	1^{st}
3. Tres Equis (459.1 ha)	8	3^{rd}
4. Pavones (518.4 ha)	11	2^{nd}
5. Florencia (276.5 ha)	2	
6. Cruzada (127.9 ha)	1	
7. Tuis (328.7 ha)	4	
8. Tucurrique (104.0 ha)	1	
9. Cachí (119.9 ha)	8	3^{rd}
10. Tayutic (77.4 ha)	3	

VCTBC = Volcánica Central de Talamanca Biological Corridor, Costa Rica

Discussion

Decision makers use a variety of strategies, knowledge and experiences when prioritizing CAFS regions for resource allocation. The evaluation of local knowledge and its application to scientific definition of concepts continues to be refined (Ericksen and Ardon 2003; Brown et al. 2004). In this study, while ecosystem services were differentiated by the AHP, the span of this differentiation was not large. One explanation for the small differentiation between the services may be due to inconsistencies by individual decision makers. Application of the Inconsistency Index (Mendoza *et al.* 1999) did not greatly change these results (Table 1). Although special attention was given to defining ecosystem services to committee members, the ecosystem services selected might have created some confusion. For example, structural connectivity was the most preferred ecosystem service, while other biodiversity surrogates (avian and leafhopper diversity) were rated lowest in terms of preference. This may be due to unfamiliarity with connectivity as a scientific concept by the decision makers. As a result, the overlap of services was not disproportionately reflected in one particular ecosystem service. The apparent lack of a strong preference may be an indication of the diversity of the committee, which includes representatives of local communities, CATIE, a hydroelectric company, and others.

During the SWOT analysis, ecosystem services appeared to be important to decision makers. For three of the top four regions, levels of ecosystem services from medium to high were explicitly mentioned as strengths. In addition, the internal strengths of a region that seemed particularly influential included a region's location, its proximity to roads and other resources, and the level of organizational infrastructure found in the region (e.g., current activities, possible synergistic activities). The threat of land use change may also deter resource allocation, which may imply decision makers are looking for stability and some insurance that their resources will have a lasting effect in decisions related to ecosystem services.

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Dissertation Conclusions

Within the first two chapters of this dissertation, both field and modeling evidence suggested that different land uses impacted soil characteristics and hydrological processes within the upper Reventazón watershed in Costa Rica. In the third chapter, I found that different areas and farm management styles provided different types of ecosystem services. Also, within this chapter, I found that while stakeholders preferred different ecosystem services and thought of them as important things to consider, infrastructure and current activities were prioritized for conservation planning activities within the VCTBC. Distributed hydrological modeling provides an excellent tool to simulate the impact of land use management techniques on hydrological processes. With the current resolution of spatial data resources, distributed hydrological modeling provides a powerful tool to investigate the effects of land use planning on hydrological processes and for conservation planning.

Soils at the study sites at CATIE within Chapter 1 were deep, clayey, tropical soils with high organic matter content and a small amount of andic properties within the surficial soil horizons. The forest site had slightly lower bulk densities and higher organic matter content. However,bulk densities were low and organic matter was high at each field sites. The combination of andic properties and high organic matter lead to the development stable volcanic ash aggregates (Shoji et al. 1993) and explains the high porosities and infiltration capacities (Dalhgren et al. 2004). These low bulk densities, presence of andic properties and high organic matter content allow for an enormous amount of soil storage within these systems. Similar bulk densities and andic properties were found north of our field sites by Spaans et al. (1989).As andic properties and organic matter decrease with depth, clay content increases. These matrix conditions contribute to greater amounts of soil storage and soil conductivity within the upper 0.5 m of the soil profile. Both of these conditions contribute to subsurface lateral flow and surface runoff generation within these field sites.

Field evidence showed that infiltration and percolation was much greater in the forest and coffee at the point and plot scales. During the dye experiments, the larger and deeper roots and macropores within the forest and coffee appeared to be the reason for the greater amounts of vertical water transfer within and beyond a 1 m depth in the soil profile. . Tree roots can promote wider and deeper preferential flow paths than cultivated cropland or pasture (Yunusa et al. 2002; Martinez-Mesa and Whitford 1996). Roots create preferential pathways through the combination of localized compaction by root growth and the addition of root exudates to the adjacent soils (Johnson and Lehman 2006). Root death and decay is another plausible cause of preferential flow paths. In addition to the lack of macropores and larger root networks, compaction and/or burning and tillage limited infiltration at the sugar cane site to the point of causing infiltration-excess runoff at greater rainfall intensities. At lower precipitation intensities, subsurface compaction at the plow layer contributed to runoff generation through lateral flow generation. Compaction also influenced infiltration and K_{sat} rates but not bulk densities. Part of this contradiction may be due to the abandoned nature of the pasture, however, this may also point to the influence of compaction on the destruction of macropores and ultimately K_{sat}.

While much of the debate on how land use influences hydrology investigates differences in soil characteristics, differences in evapotranspiration between land uses are also heavily investigated. In this research, the grass based land uses (i.e., pasture and sugar cane) remained wetter longer than the woody land uses (i.e., forest and coffee). The forest and coffee field sites had much steeper soil moisture recession curves once precipitation had stopped. These results correlate well with other studies performed in Costa Rica that suggest forest transpiration is up to 50% of the water balance (Loescher et al. 2005) and coffee agroforestry systems can transpire up to 40% of the water balance (Cannavo et al. 2011). However, other studies suggest that stomatal closure is much more important in this area which would reduce these percentages within the overall water balance (Gomez-Delgado et al. 2011). All of the land uses' moisture contents rose quickly and close to saturation in response to rainfall. The impact of land use on soil moisture at 1.0 m was much less than at the surface.

Therefore, at the point and plot scale, land use did impact soil characteristics and hydrological processes. As measurement scale increased, the influence and importance of macropores became evident. Most likely, the increase of volume of the sample size enabled the measurement to capture more of the preferential pathways within these systems (Brooks et al. 2004). At the point scale, variance in K_{sat} measurements points to the need to make measurements at a larger scale to increase the likelihood of incorporating the effects of preferential pathways. More studies that seek to quantify K_{sat} variance with depth will result in useful information for modelers. Even though increases in scale increased infiltration rates, the effect of land use on infiltration rate was still obvious at the larger scale. However, land use impact was much greater within the top 0.5 m of soil for both differences in preferential pathways and soil moisture regimes. As soil depth increases, variance of the different parameters also appears to decrease. Therefore, while heterogeneity of soil systems and preferential pathways continue to provide challenges for hydrological modelers, more detailed investigations should focus on this relationship and its quantification.

At the field scale, due to the setup of our field sites, I observed that forest had an immense ability to re-infiltrate sugar cane runoff. Woody-based land uses may contribute to some mitigation of flooding and recharge of aquifers. Finally, lateral flow or return flow, via lateral conductivity due to roots and macropores, may be a subtle but important runoff mechanism for woody based land uses during very wet periods. More replication and detailed study at the landscape scale should be conducted to properly assess this potential. While small differences were observed at the field scale with respect to runoff during the wet season, all runoff coefficients were less than 10% of precipitation. Similar runoff coefficients were found for coffee near our study sites (Gomez-Delgado et al. 2011) and in other andic-influenced soils (Poulenard et al., 2001; Cattan et al., 2006). Even in tropical humid climates, studies show that annual runoff coefficients are frequently less than 10% of precipitation in small catchments (Jansson 2002; Cattan et al. 2006). At this scale, impact of land use starts to lose influence on runoff generation because the measurement scale is more representative of the effects of macropores. In general, most of the literature reports that deforestation and conversion to agricultural land uses increases river discharge and groundwater levels due to the loss of the evapotranspiration of the forest. Similar to Hanson et al. (2004), percolation at the pasture field site was limited by lateral flow generation when this site reached saturation. During the same saturation period, the forest and coffee field sites were able to percolate much more water suggesting that under large storm events, these woody-based land uses may indeed have the ability to recharge ground water supplies.

While the original 'fill and spill' hypothesis for a hillslope depended on bedrock depressions to act as the restrictive layer (Tromp-van Meerveld and McDonnell, 2006), I observed the "fill and spill' mechanism controlled by a combination of precipitation intensity, volume, soil storage amount, conductivity and lateral flow accumulation from upslope areas. The mechanism observed here differed in two important ways. First, irrigation intensity needed to exceed soil storage amount and conductivities to generate runoff in the pasture and sugar. Once this threshold was reached, subsurface connectivity was limited due to lateral diversion of water. Second, in the forest and coffee, as soil storage became saturated, vertical macropore networks were activated that promoted a 'fill and drain' or percolation that increased subsurface connectivity. At the watershed scale, the connectivity between deep percolation and baseflow is more like the 'fill and spill' hypothesis described by others (Tromp Van-Meerveld and McDonnell 2006, Spence and Woo 2003). However, due to the depth of these soils, the deep percolation is an additional control on top of the unknown bedrock topography in this region.

At the watershed scale, runoff coefficients were much greater (40-80%) that at the field scale. Both in the field and the one-cell modeling, percolation was observed to be a dominant hydrological process. Percolation was also observed to be greater in most of the forested watersheds through the modeling activities which in turn fed the baseflow. . During the wet season, when compaction reduces infiltration after forest conversion, surface runoff can limit percolation ultimately affecting dry season base flows (Bruijnzeel 2004). This percolation, or potentially even subsurface lateral flow through a similar macropore network, is delivering large volumes of water throughout the year in the forested watersheds. Gomez-Delgado et al. (2011) observed a similar mechanism in their coffee dominated basin with very efficient soil and aquifer recharge mechanisms. In their study basin, percolation accounted for 69% of the incident rainfall. The lack of a well-defined dry season combined with the soil and infiltration characteristics suggests that this is a major mechanism for river discharge in the area. This effect was not as pronounced in the mixed-land use watersheds. More detailed analyses of the water chemistry and/or isotopic composition may better explain discharge generation at these larger scales. Much more detailed field and modeling investigations should focus on this part of the hydrological cycle within tropical systems. While surface hydrology is undoubtedly important in tropical systems, investigations focused at understanding the subsurface hydrology may illicit new information important for land use managers and hydrologic modelers.

Much of the research conducted within this dissertation suggests that different land uses affect hydrological processes that control the provision of hydrological services. While we did not observe much consistency between CAFS with high biodiversity and hydrologic service potential, there were many areas where changes in farm management could be targeted to achieve both of these goals. Also, conversation planners may want to consider focusing on ecosystem services besides biodiversity to increase interest and support for the plans. Decision makers use a variety of strategies, knowledge and experiences when prioritizing CAFS regions for resource allocation. The evaluation of local knowledge and its application to scientific definition of concepts continues to be refined (Ericksen and Ardon 2003; Brown et al. 2004). Often researchers correlate local knowledge to certain aspects of scientific knowledge with varying degrees of success. Existing organizational infrastructure, activities, and personnel play a key role in targeting conservation or restoration activities.

Woody land uses show potential for providing several desirable hydrological services within the upper Reventazón watershed. However, further investigations to the effects of land use at the watershed scale are needed to make definitive conclusions regarding historical impacts and future predictions. While areas that provided high levels of ecosystems services in all categories were relatively few in this watershed, this may be a truly regional result that could be highly variable throughout the world. Also, targeted restoration activities may well increase this overlap of ecosystem services within this biological corridor.

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