Hydrologic Processes and Water Resource Management of Tropical Watersheds:

An Interdisciplinary Study in Costa Rica

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by
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Authorization to Submit Dissertation

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Abstract

Effective watershed management is essential to maintain water quality and quantity and to protect drinking water for communities. To effectively manage water resources, managers need to understand local hydrologic processes and the temporal changes that influence these processes. However, local hydrologic processes can be complex, as a combination of many factors influences the hydrology of each watershed. In the tropics, the rainy and dry seasons lead to different hydrologic responses. This study addresses the following research questions: 1) how is spring flow generated? 2) how do stable isotopes inform our understanding of the seasonality in the tropics? and 3) does framing water resource issues in terms of spatial and temporal scales allow for new insights to identify, analyze, and resolve natural resource problems in social ecological systems? Answers to these questions are based on a combination of methodology, including stable isotope analysis, hydrometry, modeling in a microwatershed, and community interviews, to investigate hydrologic processes and watershed management in the Cartago province of Costa Rica.

The microwatershed (<1 km^2) was a coffee agroforestry watershed in Aquiares, Cartago, Costa Rica. A dual stable isotope approach of oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) was used to characterize precipitation influences in the watershed and to characterize hydrologic components. The physically based distributed Soil Moisture Routing (SMR) model was used to simulate water balance partitioning and hydrologic processes at the study site. A distinct isotopic seasonality in isotopic response was noted in this region, despite a weak hydrologic seasonality. Subsurface flow contributions were assessed to determine that lateral flow plays an important role in storm flow. The results of the SMR model showed that spring flow is an important contributor to stream flow in the study watershed. Finally, the interdisciplinary approach resulted in a tool to identify issues of scale mis-fit and for analysis of water resource management of springs in Costa Rica.

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I thank the Aquiares Farm for providing access to the field site, in addition to sharing data and supporting the project. Federico Gómez-Delgado established the hydrological setup in the Mejías watershed, shared data, and provided insight and suggestions on the project. CIRAD and FluxNet provided infrastructure for much of the research project. Alvaro Barquero provided constant field assistance, support, and advice that made this research project possible. Alejandro Barquero and the rest of the Barquero family also assisted with field efforts. Alexis Pérez provided field assistance and data collection, in addition to Amilkar Moncada.

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Chapter 1: Introduction

Watershed management efforts are critically important to maintain water quality and quantity and to protect drinking water for communities (Bruijnzeel 2004; Dudley and Stolten 2003; Postel and Thompson 2005). In Costa Rica, both flooding and water quality are significant concerns. Flooding is one of the most common natural disasters, causing significant economic hardship for communities through property and infrastructure damage, and loss of life (Bower 2013; Waylen and Laporte 1999). In addition, during storm events, many small watersheds face the detrimental impacts of contaminant loading to streams through non-point source pollution (Agnew et al. 2006; Kundzewicz and Krysanova 2010; Sheridan et al. 1999; Tong and Chen 2002). The hydrologic response of a watershed is an important influence on both flooding and contaminant loading (Grayson et al. 1992).

Landscapes often face temporal changes that influence watershed hydrology, including seasonal changes, changes from year to year (e.g., due to El Niño Southern Oscillation (ENSO) phenomenon and La Niña (UNESCO 1994)), or more lasting changes from climate change. Due to climate change more extreme events, such as increased amounts of precipitation, are expected to occur (Haines et al. 2006; Huntington 2006; Kundzewicz and Krysanova 2010; Wohl et al. 2012), which could exacerbate flooding and water quality issues already seen. Temporal changes can influence many factors, including precipitation regimes, stream flow, and evapotranspiration amount (Bruijnzeel 2004; Cadol et al. 2012; Rozanski and Araguás 1995). Analyzing these changes is important for assessing the impacts of climate change, management, and land conversion, as well as measuring hydrological components, such as base flow and evapotranspiration losses (Bruijnzeel, 2004; Sánchez-Murillo et al., 2013; Tang et al., 2011).

Local hydrologic processes can be complex, as a combination of many factors influences the hydrology of each watershed (Beven and Kirkby 1979). One important watershed hydrologic component is spring flow. Springs commonly are found in volcanic regions, where they contribute significantly to streams (Whiting and Stamm 1995). Generally springs occur in steep slopes where either groundwater flow or subsurface lateral flow above the water table exits the land surface (Manga 1996; Smakhtin 2001). Despite their importance for watershed hydrology, the hydrologic processes governing spring flow generation have not been well studied. Few studies have analyzed spring flow generation or processes, complicating on-the-ground management of springs. The hydrologic processes driving spring flow and identification of the source of spring waters have important implications for watershed hydrology, and, in particular, drinking water. Since springs often serve as community drinking water sources in many parts of the world, then characterization of spring flow processes can potentially improve drinking water resources.

In Costa Rica, springs are one of the most important sources of drinking water for small rural communities. Costa Rica is located on the Central American Continental Divide and experiences a tropical humid climate, with a rainy season from approximately May through October and a transition period from November to January, followed by the dry season (Waylen and Caviedes 1996). The Costa Rican Institute for Water and Sewer (ICAA) oversees drinking water management and infrastructure in the country. However, in many rural communities, ICAA has delegated responsibility to local community-based drinking water organizations (CBDWOs, or ASADAs and CAARs in Spanish) for overseeing the management and provision of drinking water (Madrigal et al. 2011). CBDWOs are subject to laws and regulations of the country regarding how to administer their water services, and in return receive limited support from ICAA.

The two laws that most directly affect how CBDWOs manage their drinking water are the Water Law No. 276 (Costa Rica Government 1942) and the Forestry Law No. 7575 (Costa Rican Government 1995). These two laws require a forested buffer zone of 200 m and 100 m radii, respectively, around springs being used as drinking water sources. However, most community members are uncertain as to which radius to use, and enforcement of these protection areas is nominal. These radii are not based in scientific evidence and use a circular protection zone rather than basing protection areas off watersheds and topography. Therefore, much of the area contributing to the springs is not protected under the two laws.

Springs are initially selected for their convenience to communities and observations of high flow. However, many CBDWO members do not know the physical extent of the contributing areas to springs, here referred to as springsheds, and therefore do not know the appropriate land areas to manage. Physical tests to determine springshed areas are both costly and logistically difficult. Not only do CBDWO members not know where the water originates, but also they often do not have extensive knowledge of its quantity or quality. Monitoring of water quantity is very limited, if performed at all.

These limited protection zones are a concern due to management practices that occur within potential recharge zones for springs. These practices have a significant potential to adversely impact drinking water being used for community consumption, but CBDWOs often do not manage the watershed recharge zones, nor do they have any legal recourse to protect their water. In rural areas of Costa Rica, common land uses that exist within springsheds include pasture (associated with nitrogen, phosphorus, and fecal coliform) and agriculture (associated with nitrogen, phosphorus, and pesticides). CBDWOs are mandated to conduct water quality tests every six months. However, CBDWO members are not instructed how to interpret results, and many communities will test their water only sporadically (for example, once every two years). Therefore, in regions like Costa Rica, cost-effective tools for identifying the origins of spring water and the processes driving spring flow are critical.

This dissertation study uses several approaches for assessing water management and watershed hydrologic processes. To analyze watershed hydrology and spring flow processes, a focused study was conducted in the Mejías Creek in Aquiares, Cartago. These studies included stable isotope analysis, hydrometric measurements, and modeling to analyze watershed dynamics and spring flow processes. The study also investigated water resource management in rural communities in the region using an interdisciplinary study of drinking water management through interviews conducted with CBDWO representatives in rural communities in the Cartago province.

The Mejías Creek microwatershed is part of the Turrialba watershed and the larger Reventazón watershed, one of the major drainage basins in Costa Rica. The Mejías Creek microwatershed lies on the southern slope of the Turrialba Volcano in Aquiares, Cartago, which is located in the Central Caribbean region of the country. The study site is a single land use watershed situated within a coffee agroforestry system on the Aquiares Farm, one of the largest coffee farms in Costa Rica. The dominant land cover is Coffea arabica interspersed with Erythrina poeppigiana shade trees (Gómez-Delgado et al. 2011). The

Aquiares Farm is part of the CoffeeFlux project, developed by the French institute CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) and the Costa Rican institute CATIE (Centro Agronómico Tropical de Investigación y Enseñanza). The site is part of the global network of FLUXNET micrometeorological sites and SOERE F-ORE-T network of observatories (France). As such, long-term hydrologic data have been collected on site since 2009.

This dissertation addresses the following objectives: to determine 1) how spring flow is generated; 2) how stable isotopes inform our understanding of the seasonality in the tropics; and 3) whether framing water resource issues in terms of spatial and temporal scales allow for new insights to identify, analyze, and resolve natural resource problems in SES. The three chapters of this dissertation address different aspects of these objectives and are outlined in more detail below.

In Chapter 2, I used a combined stable isotope and hydrometric approach to characterize watershed hydrology components and to analyze how those components change during the duration of the study. A dual isotope approach of oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) can provide important information for assessing temporal changes in watershed hydrology. Stable isotope methodology has been used in a variety of hydrologic studies, including the identification of source locations (Burns et al. 2001; Kendall 1998; Rhodes et al. 2006), flow pathways (de Jesús-Crespo and Ramírez 2011; Genereux and Hooper 1998; Genereux et al. 2005; Goldsmith et al. 2012; Goller et al. 2005), and mean transit times within a watershed (McGuire et al. 2002; Sánchez-Murillo et al. 2015; Turner et al. 1987). Stable isotopes are also useful for characterizing and quantifying water balance components and source contributions (Goldsmith et al. 2012). Studying the seasonal fluctuations of stable isotope ratios in precipitation, groundwater, and stream water in tropical areas can inform watershed modeling and improve understanding about hydrologic processes in tropical landscapes.

Stable isotopes were used in this study to examine what factors influence precipitation and local hydrology and how local hydrology is influenced by seasonality. Stable isotopes also were used to investigate the source of water and to analyze base flow to quantify the relative contributions of precipitation and groundwater to stream flow. This chapter builds on past knowledge of the factors that influence local watershed hydrologic processes and stable isotope hydrology in the tropics and specifically in Costa Rica. The overall goal of this chapter was to assess how stable isotope ratios differed temporally in hydrologic components throughout a small watershed and whether isotopes are a good tracer of seasonal hydrologic dynamics.

In Chapter 3, I further analyze the hydrologic processes of the Mejías Creek watershed using a distributed model to simulate watershed components. The main goal of this study was to analyze hydrologic processes, particularly subsurface flow, in a tropical watershed through field observations coupled with physically based models. The hydrologic processes driving spring flow in the tropics are not well understood, and few models exist that simulate the complex spring flow generation processes. However, accurate watershed simulations can help inform scientists of the processes that influence spring flow generation. We used a physically-based model, the Soil-Moisture Routing (SMR) model, for its ability to synthesize, view, and manipulate spatially-explicit information across a watershed (Brooks et al., 2007). SMR is a physically based distributed model that utilizes GRASS (Geographic Resources Analysis Support System), a Geographic Information System (GIS), to simulate water balance processes at the watershed scale. For this study, SMR was modified to include a spring flow component and a semi-impervious runoff component. We used spatially explicit information, including the location of semi-impervious surfaces and spring locations, to analyze hydrologic processes in the watershed. In addition, we assessed the processes of subsurface flow and spring flow generation.

Finally, in Chapter 4, I worked with an interdisciplinary team of IGERT (Integrative Graduate Education and Research Traineeship) students to explore water resource management in Costa Rica and in the Palouse region of Washington and Idaho through a case-study approach. A scale mis-fit, or a discrepancy between the scale of management and the scale of biophysical processes, often occurs in natural resource systems, hindering appropriate management of resources. A six-step approach is presented for analyzing scale mis-fit in resource management by examining the scale of governance and biophysical processes. We used this approach to analyze drinking water management in Costa Rica, as well as the management of the Palouse Basin Aquifer. In the Costa Rican case study, we analyzed how the discrepancy between managing the springs at a 100 m buffer, rather than at the scale of the spring's watershed, is creating a scale mis-fit that hinders appropriate management of drinking water resources.

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Chapter 2: Seasonal isotope hydrology of a tropical coffee agroforestry watershed

Abstract

Seasonality in the tropics is characterized by relatively stable air temperature and variable precipitation regimes throughout the year. The rainy and dry seasons lead to different hydrologic responses and water quality conditions. While isotope hydrology has been well studied in temperate regions, information regarding key drivers controlling isotopic compositions in precipitation, groundwater, and surface water is still lacking in the tropics. Additionally, spring flow is an important contributor to watershed hydrology. This study examines the fluctuations of stable isotope compositions ($\delta^{18}O$ and $\delta^{2}H$) in water balance components in a coffee agroforestry microwatershed (<1 km^2) located in central Costa Rica on the Caribbean slope. Samples were collected in precipitation, groundwater, stream water, and spring water over two years across seasons to better characterize spatial and temporal isotopic variations and of the respective contribution of old and new water to stream flow in the watershed. Isotope ratios in precipitation ranged from −18.52‰ to −0.29‰ ($\delta^{18}O$) and −136.4‰ to 13.7‰ ($\delta^{2}H$). The Local Meteoric Water Line for the study site was $\delta^{2}H = 8.50 \cdot \delta^{18}O + 18.02$ ($r^2 = 0.97$). High deuterium excess compositions suggest that local moisture cycling contributes substantially to precipitation events. No correlation was seen with isotopes in precipitation and precipitation amount, otherwise known as the amount effect, which is the widely accepted source of variation in isotope compositions in precipitation in the tropics. Isotopes in precipitation were more enriched in the dry season, and the local meteoric water line shifted between seasons, with the greatest slope in the dry season. Stable isotopes in groundwater and stream water samples were more stable over time, although both components exhibited more enriched values in 2013. Stream water and base flow hydrograph separations identified an approximate 15 hour lag during storm events to the time that the precipitation signal reaches stream water. Stable isotope data indicate that spring flow is originating from a shallow groundwater system that is influenced by

precipitation inputs. These results indicate that isotope sampling improves the understanding of water balance components even in a tropical humid location, where substantial isotopic variations in rainfall challenge current modeling efforts.

1.0 Introduction

Temporal changes in watershed hydrology occur through varying precipitation regimes and evapotranspiration amount (Bruijnzeel 2004; Cadol et al. 2012; Rozanski and Araguás 1995). Studying these changes is important to assess the impacts of climate change, management, and land use change on hydrological components, such as overland flow and base flow (Bruijnzeel 2004; Tang et al. 2011; Sánchez-Murillo et al. 2013). Hydrological processes in the tropics have been studied less (Goldsmith et al. 2012) and differ greatly from those in temperate regions with relatively stable air surface temperatures year-round, precipitation regimes that vary greatly between seasons, and differences in vegetation, geology, and topography (Lachniet and Patterson 2002; Bruijnzeel 2004). More specifically, seasonal isotope variations of watershed components have not been well studied in general (Dewalle et al. 1997) and very little in the tropics.

One technique for assessing temporal changes in watershed hydrology is through a dual isotope approach of oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$). Stable isotopes have been used to identify source locations (Burns et al. 2001; Kendall 1998; Rhodes et al. 2006), flow pathways (de Jesús-Crespo and Ramírez 2011; Genereux and Hooper 1998; Genereux et al. 2005; Goldsmith et al. 2012; Goller et al. 2005), and mean transit times within a watershed (McGuire et al. 2002; Sánchez-Murillo et al. 2015; Turner et al. 1987). Mean transit times are important for understanding how fast water travels through the watershed, storage processes, and water origins (McGuire and McDonnell 2006). Stable isotope analysis also can be used to characterize and quantify different water balance components and source contributions (Goldsmith et al. 2012). Deuterium excess, or *d*-excess, is a measure of the deviation of local samples from the global meteoric water line (GMLW) (Craig 1961; Froehlich et al. 2002). *D*-excess is influenced by the physical conditions of the precipitation source, as well as the conditions along the route of the source air mass (Merlivat and Jouzel 1979; Froehlich et al. 2002).

By using the seasonal fluctuations of stable isotope ratios in precipitation, groundwater, and stream water in tropical areas, we can improve watershed modeling and quantify hydrologic processes in tropical landscapes. Several studies have examined the isotopic variations in precipitation between seasons and storm events in the tropical Americas (see Gat and Matsui 1991; Guswa et al. 2007; Rhodes et al. 2006; Salati et al. 1979; Sánchez-Murillo et al. 2013; Scholl et al. 2009; Vuille et al. 2003; Vuille and Werner 2005; Poveda et al. 2006). Stable isotope ratios of precipitation vary significantly throughout the year (Lachniet and Patterson 2002), and studying these variations is important for providing insight into regional and local isotope variations in other hydrologic components, such as base flow, soil water, and spring flow (Dewalle et al. 1997). Stable isotope variations in precipitation can aid in the identification of the air mass source of the water, as well as the hydrologic processes that occur in the system, such as evaporation and moisture cycling (Araguás-Araguás and Froehlich 1998; Dansgaard 1964; Froehlich et al. 2002). While many factors influence stable isotope ratios in precipitation, the correlation with precipitation amount, known as the "amount effect," has been widely used to explain isotope variations in the tropics (Araguás-Araguás et al. 2000; Dansgaard 1964; Risi et al. 2008; Rozanski et al. 1992; Rozanski et al. 1993; Sánchez-Murillo et al. 2013; Scholl et al. 2009). However, this correlation is primarily seen at a monthly time scale and is not as strong a correlation when examined on an event-basis (Risi et al. 2008; Vimeux et al. 2005; Wu et al. 2010; Wu et al. 2014).

Stable isotope studies related to precipitation within Costa Rica recently were initiated by Sánchez-Murillo et al. (2013), who determined the Local Meteoric Water Line (LMWL) for the Central Caribbean region as $\delta^2H = 8.17 \cdot \delta^{18}O + 12.27$. Watersheds on the Caribbean slopes of Costa Rica are influenced predominantly by the transport of moisture from the Caribbean Sea to the Caribbean lowlands. Within this region of Costa Rica, the absence of significant orographic barriers and abundant vegetation results in isotopically enriched precipitation in comparison with precipitation over the Pacific slope (Sánchez-Murillo et al. *in review*). Rather than the previously defined amount effect for monthly composite samples, Sánchez-Murillo et al. (*in review*) determined that lifting condensation level and surface relative humidity play a greater role in influencing isotopic ratios of precipitation in Costa Rica.

Stable isotope analysis also has been useful in determining transport of water within a watershed (Genereux and Hooper 1998; Goller et al. 2005; Goldsmith et al. 2012; Hildenbrand et al. 2005; Kendall and McDonnell 1998; Rodgers et al. 2005; Sklash and Farvolden 1979). While stable isotopes have commonly been used as isotopic tracers to describe various watershed components, such as processes that influence precipitation, groundwater recharge, and evapotranspiration, they have less frequently been used to classify seasonal hydrology of these components (Dewalle et al. 1997; Goller et al. 2005). Studying variations in different watershed components could explain how sources change throughout the year and what factors influence these components. In one study in a temperate location, Dewalle et al. (1997) found a seasonal relationship in Appalachian watersheds in soil water and base flow that lagged precipitation, indicating how long soil water travels to streams, as well as the length of time for groundwater storage and mixing.

Often one significant component of water transport in watersheds is spring flow. Springs in watershed hydrology occur in many places throughout the world, but their origin and behavior is not always clearly understood. In particular, despite the prevalence of temporary springs around the world, few isotope studies exist that examine the influence of springs in watershed hydrology (Buttle et al. 2012). In one isotope study on spring flow in French Polynesia, springs were sampled and found to correspond to elevational differences in precipitation, suggesting localized recharge (Hildenbrand et al. 2005). In general, little information about the physical processes of spring flow generation exists, and the processes appear difficult to characterize. We hypothesize that deep and shallow groundwater systems in watersheds have different behaviors that influence watershed hydrology. Deeper groundwater systems contribute to base flow and often are more stable, while shallow groundwater systems contribute to spring flow and fluctuate more based on precipitation inputs.

This study provides understanding of the role of subsurface flow in a watershed in the tropics, in Costa Rica, with specific focus on seasonal and event-based aspects of local hydrology. To our knowledge, no isotope studies on the transport of subsurface water through watersheds have been conducted in the tropics. One other study in the tropical Americas may be representative, where Goller et al. (2005) examined flow pathways in three tropical catchments and found that precipitation generally infiltrated vertically during normal conditions, but during storm events shallow lateral subsurface flow became a predominant pathway. Within our study watershed, intermittent springs contribute to stream flow during the rainy season and periods of significant precipitation. The importance of spring flow in the watershed is not clear.

The overall goals of this study were to examine temporal variations of stable isotope ratios in a small tropical watershed and to use stable isotopes to characterize subsurface flow processes. This study was motivated by the following research questions: 1) how does seasonality influences isotopic ratios of precipitation? 2) are isotope ratios of hydrological components consistent with seasonal patterns seen in precipitation? and 3) how can isotopes improve understanding of subsurface flow in watershed hydrology? To address these questions, we analyzed temporal variations in isotopic and hydrometric information for precipitation, stream water, groundwater, and springs in a microwatershed (<1 km^2) in Costa Rica between September 2011 and December 2013.

2.0 Methodology

2.1 Study Site

The study was conducted in the Mejías Creek microwatershed, which is part of the Turrialba watershed and the larger Reventazón watershed (Figure 1) in Costa Rica. The Mejías Creek microwatershed is located close to the town of Aquiares, Cartago province, and lies on the southern slope of the Turrialba Volcano in the Central Caribbean region of the country. The study site is a single land use watershed situated within a coffee agroforestry system on the Aquiares Farm, one of the largest coffee farms in Costa Rica. The dominant land cover is *Coffea arabica* at a density of 6,300 trees/hectare interspersed with *Erythrina poeppigiana* shade trees (Gómez-Delgado et al. 2010). Coffee leaf area index varied seasonally between 2.4 and 4.4 m^2 m^{-2} and around 0.67 m^2 m^{-2} for the shade trees (Taugourdeau et al. 2014). The Aquiares farm is managed quite intensively with fertilizer application (average 214 kg N ha^{-1} yr^{-1} from 2000-2012), and complies with Rainforest Alliance™ guidelines for pest and weed management.

Our study is part of the CoffeeFlux observatory, developed by CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) and CATIE

(Centro Agronómico Tropical de Investigación y Enseñanza). The observatory contributes to the global network of FLUXNET micrometeorological sites and SOERE F-ORE-T network of observatories (France). Long-term hydrologic data have been collected on site since 2009.

Elevation at the site ranges from approximately 1,018 to 1,280 m.a.s.l., and slopes average 20% with steeper slopes of 80% in the upper portions of the watershed. Soils within the study region have been classified as Andisols, using the United States Department of Agriculture (USDA) soil taxonomy. Andisols are soils that originate from volcanic ejecta and are mainly subjected to weathering and mineral transformations (USDA 1999). This soil order is characterized as having at least 60% andic soil properties in the upper 60 cm of the soil profile (USDA 1999). Andisols tend to have high available water capacity (USDA 1999) and retain a high amount of phosphorus and carbon. Soil organic carbon on the site varies between 48 and 172 g kg^{-1} in the surface soil of our site (Kinoshita et al., *in review*). Andisols in the study region tend to have very high infiltration capacity, therefore resulting in almost no overland runoff (Benegas et al. 2013; Gómez-Delgado et al. 2011; Toohey 2012). In addition, macropores in the soil create conditions of rapid water movement through subsurface soils (Benegas et al. 2013; Spaans et al. 1989).

The study site is a tropical humid location with precipitation events throughout the year in both the rainy and dry seasons. Mean annual precipitation for the site was 2,706 mm during the three years when this study was conducted (3,139 mm in 2011, 2,974 mm in 2012, and 2,006 mm in 2013). Precipitation varies throughout the year with the highest amount falling during the rainy season from May through October. In the study region, the “dry” season is more of a “drier” season, as rainfall does occur during this time (precipitation amounts in the dry season for 2012 were 633 mm and for 2013 were 420 mm). Within the study watershed 28 spring locations were recorded, all directly contributing to stream flow, particularly during high flow and long duration events in the rainy season.

2.2 Climatology and isotope seasonality of precipitation in Costa Rica

The mean annual precipitation of Costa Rica ranges from less than 1,500 mm to 8,500 mm depending on the region of the country (Sánchez-Murillo et al. 2013). Located across the Central American Continental Divide, the region experiences a rainy season (May through October) dominated by continental winds originating from the Pacific Ocean

(Sánchez-Murillo et al. 2013). The Intertropical Convergence Zone (ITCZ) shifts throughout the year and significantly impacts the dual seasonality in this region (Lachniet and Patterson 2002; Poveda et al. 2006). A transitional period occurs from November – January, followed by the dry season (February – April) dominated by the trade winds from the Caribbean Sea (Waylen and Caviedes 1996). Isotopically depleted events generally occur after the ITCZ arrives in mid-May while isotopically enriched events are frequent during the dry season (Sánchez-Murillo et al. 2013). This shift in climate patterns over the course of the year produces a variable pattern of stable isotope compositions in precipitation, which can be used to study local variations of isotopic ratios in groundwater and surface waters.

2.3 Hydrometric measurements

Rainfall was recorded every 10 minutes using four ARG100 tipping buckets (R.M. Young Company, USA) distributed throughout the watershed. An eddy-flux tower at the site recorded climate and meteorological variables every 30 minutes. Tower instrumentation included a net radiation sensor (NR-Lite, Kipp and Zonen, The Netherlands), a temperature and relative humidity probe (HMR45C, Campbell-Scientific, USA), and a 03001 R.M Young Wind Sentry Set (USA) to measure wind speed and direction. Actual evapotranspiration data were collected at the eddy-flux tower at a reference height of 26 meters, *i.e.* above the shade trees (Gómez-Delgado et al. 2011).

Stream flow was measured with a 3.9 meter long steel flume located near the watershed outlet. Water levels were measured every ten minutes with a pressure transducer (PDCR-1830, Campbell-Scientific, USA) placed in a stilling well connected to the flume. Four groundwater wells were placed throughout the watershed to measure groundwater levels with pressure transducers (Micro-Divers, Schlumberger Water Services, USA), and data were collected every half hour. Wells were installed to 4 m depth. More details are available in Gómez-Delgado (2010) and Gómez-Delgado et al. (2011).

2.4 Field sampling

Field sampling for stable isotopes in the study watershed is outlined in Table 1. Precipitation water was sampled for stable isotopes on an event-basis at three locations at elevation 1040, 1128, and 1210 m.a.s.l. The lowest collector was in operation between

September 2011 and December 2013, and two additional collectors were added in November 2011 and December 2011, respectively. The passive collectors were comprised of a 10 cm diameter plastic funnel equipped with a fine metal mesh atop the funnel to prevent external contamination from debris. The funnel drained via plastic tubing to a 0.5 or 1 L high-density polyethylene (HDPE) container. A 2 cm layer of mineral oil was placed inside the container to prevent evaporation and fractionation according to standard sampling protocols (IAEA 2012). The collection container was placed inside a plastic shield to protect the samples from sunlight and extreme temperature variations. Precipitation samples were collected from the field following a storm event and transported to the laboratory, where the mineral oil was separated from the sample water with a 500 mL separatory funnel.

Groundwater samples were collected at four well locations in the watershed (Figure 1) proximate to the rain gauges. Samples were collected according to a standard protocol of purging the well prior to sampling. Groundwater samples were collected weekly between December 2011 and December 2013. Stream water was sampled at four locations throughout the watershed (Figure 1), from the lowest elevation to the highest: ASA (flume), ASC (lower), ASB (middle), and ASD (upper), and were located in relative proximity to the groundwater wells. Stream water samples were collected manually on a weekly basis between November 2011 and December 2013. Additionally, three fine-resolution sampling campaigns were conducted at the flume (see Table 1). Samples were collected on an hourly basis at the outlet of the watershed in the flume on three separate occasions during the rainy season: on 1 November 2012, 26 November – 3 December 2012, and 9 – 13 December 2013. Following the results of the one-day sampling event on 1 November 2012, we conducted two additional weeklong sampling campaigns at the outlet of the watershed to capture variability in precipitation regimes and meteorological conditions. This sampling campaign was conducted between 26 November and 3 December 2012. Samples were collected hourly during the day, hourly the first night, and every two hours for remaining nights (8 pm – 6 am). During the sample campaign from 9 – 13 December 2012, samples were collected hourly during the day (4 am to 8 pm) with one additional sample at midnight.

Overland flow grab samples were collected during one rain event (9 November 2012) throughout the watershed at random locations where overland flow occurred along roads and footpaths. A full sample campaign of all 28 springs occurred when all springs were flowing on 29 March 2013, and three additional samples were collected at six of the main springs during the rainy season between September and November 2013. All samples were collected in 30 mL HDPE bottles, covered with parafilm to prevent evaporation, and stored upside down. Samples were refrigerated until laboratory analysis. The collection consisted of 275 precipitation samples representing 149 storm events, 327 groundwater samples, and 380 weekly stream water samples.

2.5 Isotope analyses

Stable isotope analyses of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) were conducted in the Idaho Stable Isotopes Laboratory at the University of Idaho in Moscow, Idaho (for samples collected in 2011) using a Cavity Ring-Down Spectroscopy (CRDS) water isotope analyzer L1120-i (Picarro, USA); and at the Stable Isotope Laboratory at the National University (UNA) in Heredia, Costa Rica (for samples collected in 2012 and 2013) using a CRDS water isotope analyzer L2120-i (Picarro, USA). Stable isotope values are presented in delta notation (‰, per mil), relating the ratios (R) of $^{18}O/^{16}O$ and $^{2}H/^{1}H$, relative to Vienna Standard Mean Ocean Water (V-SMOW), according to the standard definition of

$$\delta = \left[\frac{R_{sample} - 1}{R_{standard}}\right] \times 1000$$

where R_{sample} and $R_{standard}$ are the isotope ratios (either $^{18}O/^{16}O$ or $^{2}H/H$) in the sample and standard, respectively. Deuterium excess, or *d*-excess, was also calculated for all samples. *D*-excess is a comparison of the proportions of δ^2H to $\delta^{18}O$ in water samples, and is defined as *d*-excess = $\delta^2H - 8 \cdot \delta^{18}O$ (Dansgaard 1964; Froehlich et al. 2002).

Using stable isotope values of groundwater and stream water, we calculated the mean transit time, or the approximate time for a water molecule to travel through the watershed to a certain point, for various hydrologic components. The mean transit time (τ) is defined as:

$$\tau = c^{-1} * \sqrt{[(D)^{-2} - 1]}$$

where *c* is the radial frequency constant ($2\pi/365$) in rad per degree and *D* is equal to the standard deviation of all sample point values divided by the standard deviation of all precipitation sample values (McGuire 2004; Sánchez-Murillo et al. 2015).

Base flow hydrograph separation was conducted to gain further insight into the processes driving stream flow and subsurface water contributions. We followed methodology outlined by Sklash and Farvolden (1979) and relied on previously identified assumptions that the isotope ratios of pre-event and event water differ significantly, the isotope composition of both pre-event and event water remains relatively constant, soil water input is not significant, and surface storage inputs to stream flow are not significant (Buttle 1994; Klaus and McDonnell 2013; Moore 1989).

Historic data of monthly composite samples were analyzed from the Global Network of Isotopes in Precipitation (GNIP) database, maintained by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO). Data were recorded for Turrialba, Costa Rica (n=28), approximately 10 km from the project site, from February 2002 through January 2004.

2.6 Statistical analysis

We applied a simple linear regression between $\delta^{18}O$ and $\delta^{2}H$ ratios in precipitation to calculate the LMWL for the study site. Additionally, a Pearson product-moment correlation was applied to assess potential relationships between observed isotope ratios in the measured hydrologic components and surface meteorological data collected on site. We assessed the correlations between $\delta^{18}O$, $\delta^{2}H$, and *d*-excess in precipitation, stream water, and groundwater; month of year; and meteorological parameters measured at the site. Results, including correlations and their associated p-values, are reported as bivariate plot correlational matrices. All statistical analyses were conducted with the statistical package R, version 3.1.0.

3.0 Results and Discussion

3.1 Seasonal variation of isotopes in precipitation

Overall, there was less precipitation in 2013 (2,006 mm) than in 2012 (2,974 mm), and less rain fell during all seasons in 2013. Table 2 provides seasonal and annual precipitation totals, as well as stable isotope information. The average event size for the rainy season in 2013 was 11 mm, which was the smallest of all seasons during the study period. December 2013 yielded only 102 mm of precipitation, significantly less than during December 2012 when 301 mm were recorded. Sánchez-Murillo et al. (*in review*) previously found climate anomalies in 2013 throughout Costa Rica with less precipitation volume for 2013 than in previous years.

In addition to precipitation amount, a change in isotope composition was noted between years. From 2012 to 2013, a depletion of $\delta^{18}O$ and $\delta^{2}H$ ratios occurred, as well as a decrease in the average *d*-excess value. Based on the 198 precipitation samples collected at three locations within the watershed, the local meteoric water line (LMWL) of the Aquiares study site was $\delta^{2}H = 8.50 \cdot \delta^{18}O + 18.02$ (r^2= 0.97) (Figure 2). For reference, the LMWL of Turrialba derived from GNIP data was $\delta^{2}H = 8.62 \cdot \delta^{18}O + 16.53$ (r^2= 0.99). The LMWL in 2011 was $\delta^{2}H = 8.65 \cdot \delta^{18}O + 17.96$ ($r^2 = 0.99$); LMWL in 2012 was $\delta^{2}H = 8.48 \cdot \delta^{18}O + 19.94$ ($r^2 = 0.98$); and the LMWL in 2013 was $\delta^{2}H = 8.43 \cdot \delta^{18}O + 16.98$ ($r^2 = 0.97$). The slopes are similar for both years, but the decrease in the LMWL intercept and average *d*-excess values for 2013 could be attributed to the drier year. An increase in *d*-excess is likely indicative of increased continental moisture recycling (Froehlich et al. 2002; Gat et al. 1994), which is to be expected with less precipitation. The overall high slopes (>8) observed at the study site are due to the sample ratios during the dry season with high *d*-excess compositions. Others have explained high intercepts and slopes as due to enhanced moisture recycling processes, such as localized strong convective events fed by evapotranspiration fluxes, whereby *d*-excess increases as a result of increased evaporate content (Gat and Matsui 1991; Froehlich et al. 2002).

The average $\delta^{18}O$ ratio in precipitation during the study period was −6.05 (σ^2 = 3.61), with a range of −18.52‰ to −0.29‰. The average $\delta^{2}H$ ratio in precipitation was −33.4‰ (σ^2 = 31.08), with a range of −136.4‰ to 13.7‰. The average *d*-excess ratio during the study period was 15.0‰ (σ^2 = 5.29), which indicates that moisture recycling is an important component of the local hydrology in this region (Rhodes et al. 2006). There was no relation between elevation of the precipitation sample and $\delta^{18}O$ composition.

Seasonality influenced $\delta^{18}O$ ratios in precipitation when examining the distribution of ratios in precipitation by month (Figure 2). The enrichment during the rainy season relative to the dry season is evident. Monthly-averaged data for $\delta^{18}O$ from samples from the

GNIP database exhibit a sinusoidal wave pattern corresponding to the time of the year (Figure 3). Figure 3 shows the monthly composite samples of precipitation together with precipitation amount from the GNIP database for Turrialba, Costa Rica for February 2002 through January 2004. As evidenced from these figures, isotopes ratios in rainfall events occurring during the dry season (December – April) are mostly related to small, enriched events. By mid-May, when the ITCZ travels over Costa Rica, a typical sharp depletion in isotope ratios is observed. This depletion has been often related to the drastic increase of precipitation amounts (Sánchez-Murillo et al. 2013; Sánchez-Murillo et al. *in review*). Shifting of the ITCZ and the prevalence of mid-summer drought conditions (Magaña et al., 1999) across Central America result in greater isotopic variability throughout the wet season.

Table 2 presents the isotopic composition of precipitation grouped by the regularly accepted seasons in Costa Rica (Solano and Villalobos 2000). The slope and intercept of the LMWL for each season show the shifting dynamics of isotopes in precipitation between seasons. The slope is lowest in the rainy season, increases in the transitional season, and is greatest during the dry season, while the intercept significantly decreases in the rainy season. Goldsmith et al. (2012) explained similar seasonal differences for their project site in Mexico due to similar physical processes we experienced at our site; higher *d*-excess compositions in the dry season could be due to isotopically enriched precipitation events originating from the northwest that experience moisture recycling. Westerly sourced events that occurred during the rainy season yielded more depleted precipitation compared to the dry season. Goldsmith et al. (2012) attributed the more depleted events in the dry season to the amount effect, although we did not see any amount effect when data were analyzed on an event-basis.

Pearson product-moment correlations conducted on $\delta^{18}O$, $\delta^{2}H$, *d*-excess, and surface meteorological parameters are shown in Figure 4. Both $\delta^{18}O$ and $\delta^{2}H$ ratios in precipitation were correlated with the month ($p<0.001$), which was expected given the seasonal variations mentioned previously. Of note from Figure 4 is that isotope ratios were also significantly correlated ($p<0.05$) with several meteorological variables measured at the study site: photosynthetic active radiation, wind speed, wind direction, and air temperature ($p<0.0001$).

Additionally, the $\delta^{18}O$ and $\delta^{2}H$ ratios in precipitation were correlated with wind speed and wind direction, which are influenced by the source of the air mass. The air mass source often shifts according to the season (and therefore the month), as air masses generally originate from the Pacific side in the rainy season and the Caribbean side in the dry season. These different air masses influence both wind speed and direction. The $\delta^{2}H$ ratio in precipitation was significantly correlated with photosynthetic active radiation total and potential evapotranspiration; however, the $\delta^{18}O$ ratios were not (although the significance level was close at $p=0.067$ and 0.061, respectively). As evapotranspiration contributes to moisture cycling, which is significant for this region, we would expect a correlation between isotope ratios and evapotranspiration amount.

No correlation was observed between precipitation amount and $\delta^{18}O$ ratios when observed on a monthly or event-basis. Although the amount effect has been widely cited as the main influencing factor in the tropics (Araguás-Araguás et al. 2000; Dansgaard 1964; Risi et al. 2008; Rozanski et al. 1992; Rozanski et al. 1993; Sánchez-Murillo et al. 2013; Scholl et al. 2009), this effect has primarily been examined with monthly-averaged data, such as those in the GNIP database. However, the amount effect relationship as reported by Sánchez-Murillo et al. (*in review*) on daily precipitation of Costa Rica did not exhibit a strong correlation when isotope ratios are examined at the event or daily scale, suggesting that other variables such as relative humidity or the lifted condensation level may control the isotopic variations observed for Costa Rica. Additionally, the seasonal variation could be explained by the source of the air mass (i.e., the Caribbean Sea to the east or the Pacific Ocean to the west), which changes by season with the shifting ITCZ and the influence of the trade winds. Our results confirm these previous findings, and correlations with wind speed, wind direction, and air temperature suggest that the source of the air mass has more influence than the amount of precipitation.

3.2 Seasonal variations of isotopes in groundwater

Isotope ratios in groundwater ranged from –7.82‰ to –3.62‰ ($\delta^{18}O$) and –48.5‰ to –24.3‰ and plotted on the LMWL (see Figure 2). With the exception of WTL-4, ratios became slightly depleted moving up in elevation in the watershed (–0.0033 ‰/m for $\delta^{18}O$

and –0.023 ‰/m for δ^2H; for elevations, see Table 3). The groundwater well located in the upper portions of the watershed, WTL-5, exhibited more depleted compositions (see Table 3) compared with the lower elevation wells (WTL-1 and WTL-2). Evaporation may influence water in different flow paths, as it travels downslope and resides in the subsurface for a longer time, causing the depleted compositions we observed. Most enriched ratios were observed at WTL-4, which is a mid-elevation well in the watershed. These results are shown in Figure 5, which illustrates the $\delta^{18}O$ ratios obtained from weekly samples at the study site.

Groundwater isotope compositions are more noticeably enriched during the 2013 rainy season, which could be because 2013 was a drier year, with approximately 1,000 mm less rain falling in 2013 than in 2012. However, data in Table 2 show that averaged isotope ratios in precipitation were more depleted between seasons, beginning with comparing the transitional season in 2012-2013 with that in 2011-2012, which does not mirror averaged groundwater results. Unlike precipitation, where samples were more enriched in the dry season, groundwater samples tested throughout the year were relatively more stable (see Table 4). Wells WTL-1 and WTL-4 were more enriched than WTL-2 and WTL-5 during the course of the year, particularly during the rainy season. Wells WTL-1 and WTL-4 also have experienced more fluctuating groundwater levels and a faster response to precipitation events than the other wells (Gómez-Delgado et al. 2011). The approximate mean transit time (τ) of groundwater was calculated for each well using stable isotope data collected during the study period (see Table 3). The resulting values times indicate that groundwater τ averaged approximately one year, with the exception of the mid-elevation well, WTL-4, which averaged 279 days. Well WTL-4 has exhibited a slightly different behavior from the other wells, including a fast-response to precipitation (see Gómez-Delgado et al. 2011). This behavior could be due to well placement, such as sitting atop fractured bedrock. The mismatch of the isotope composition in precipitation and groundwater well data may be due to a seasonal lag time that is shorter than τ although none has been apparent in the data.

Pearson product-moment correlations indicate a correlation between both $\delta^{18}O$ and δ^2H ratios in groundwater and the month of the year, indicating a connection with precipitation (Figure 6). No correlation was noted between $\delta^{18}O$ ratios and any meteorological parameters measured on site. However, a positive correlation was noted between δ^2H and net radiation and vapor pressure deficit, while a negative correlation was observed between δ^2H and relative humidity. This relationship could be due to the high connectivity of all watershed components, as precipitation recharges the groundwater. However, from the mean transit time of approximately one year, we would not expect such a significant correlation between groundwater and meteorological parameters. The correlation could also indicate that precipitation infiltrates rapidly since the relationship is seen within monthly data. This information strengthens the findings of Benegas et al. (2013) that rapid infiltration occurs at the site.

3.3 Seasonal variations of isotopes in stream water

All stream water samples had isotope ratios that ranged from –8.44‰ to –4.47‰ ($\delta^{18}O$) and –45.9‰ to –21.2‰ (δ^2H). Samples also plotted along the LMWL (Figure 2). Stream samples show that location had an influence on isotopic ratios of the water (for elevations, see Table 5). Consistent with the groundwater data, the highest elevation sampling at ASD yielded the most depleted ratios on average, and samples tended to become progressively enriched moving downstream (see Table 5). Isotope ratios in precipitation that differ by elevation or evaporation on hydrologic components, including stream water, residing in the watershed longer moving downstream may have influenced these ratios. The τ value for all stream water samples was calculated to be 378 days, which is similar to τ values for groundwater. Stable isotope ratios collected from weekly stream water samples over the course of the study are shown in Figure 5. Consistent with groundwater, there are more enriched ratios in 2013 than in 2012. Pearson product-moment correlations conducted on $\delta^{18}O$ and δ^2H ratios in stream water and groundwater show a strong correlation ($p<0.001$) between stream locations and proximate groundwater locations, indicating the large influence of groundwater on contributions to the stream via subsurface flow.

Correlations conducted on $\delta^{18}O$, δ^2H, and *d*-excess in surface waters and meteorological parameters are shown in Figure 7. Pearson correlations between stream water ratios and other parameters reveal a significant correlation between isotope ratios and the month of the year, as was also noted in precipitation and groundwater. δ^2H was negatively correlated with net radiation, photosynthetically active radiation total, and evapotranspiration amount. Isotope ratios in stream water were also significantly correlated to the precipitation amount (not shown in Figure 7). Of note is that isotope ratios in precipitation are not significantly correlated to precipitation amount, but isotope ratios in stream water are positively correlated to precipitation amount. So with more precipitation the stream composition changes more as new event water pushes old water to recharge the groundwater system, which in turn flows into the stream. This results in greater amounts of old water to reach the streams, causing the isotopic ratios of stream water to be more enriched.

3.4 High-resolution isotope sampling in stream water

High-resolution samples in stream water show strong connectivity with precipitation values. Results of the first sampling event over the course of one day (1 November) are shown in Figure 8. Precipitation amount was relatively low in the days prior to sampling, with only 2 mm of rain falling the previous day and no rain falling on the sampling date. On the sampling date, $\delta^{18}O$ descended in a scalloped pattern, while $\delta^{2}H$ gradually increased over the course of the day. These results do not contribute as much to our understanding of subsurface water movement to stream water; however, one explanation of this behavior can be found in the fractionation behavior of ^{2}H versus ^{18}O. Since the relative mass difference of ^{2}H to ^{1}H is more significant than the relative mass difference between ^{18}O to ^{16}O, then $\delta^{2}H$ tends to fractionate more. We see a relative enrichment over the course of the day for $\delta^{2}H$.

Longer sampling periods of high-resolution data reveal the linkages between stream water and precipitation and meteorological conditions. Both $\delta^{18}O$ and $\delta^{2}H$ in stream water were significantly correlated ($p<0.0001$) with precipitation amount during the week. Results from the second weeklong sampling campaign (9 – 13 December 2013) were inconclusive due to insufficient variability in precipitation during the campaign (data not shown). Results from the week of 26 November to 3 December 2012 are presented in Figure 9, which compares $\delta^{18}O$ to stream water levels measured at the flume location. $\delta^{18}O$ ratios closely mirrored the water levels, with a delay of approximately 15 hrs (as noted on Figure 9), which is representative of the time for new water to reach the streams. A 15 hr lag is not compatible with overland flow, which would be nearly immediate, nor with the deep groundwater feeding the stream, which has a τ on the order of a year. The remaining possible flow path causing this time lag is shallow subsurface lateral flow reaching the stream directly or via springs contributing mostly to water level and isotope peaks.

Using the same data, we performed a base flow separation using $\delta^{18}O$ compositions over the course of one storm event. We conducted this analysis on the largest hydrograph peak for $\delta^{18}O$ on 29 November. There was one large peak in precipitation at 21:00 on 28 November 2012 preceding the stream flow peak. The $\delta^{18}O$ ratio for pre-event water was taken at 16:00 28 November, when the $\delta^{18}O$ ratio was relatively stable prior to the storm event and representative of the pre-storm conditions. Results are shown in Figure 10, which show that the majority of water entering the stream is pre-event water. At the peak of the hydrograph, pre-event water contributed 72% of the total water, which likely entered as base flow and subsurface lateral flow that entered the stream channel through piston flow. The maximum percent of event water was 28% of total water at 16:00 on November 29. Gómez-Delgado et al. (2011) and Welsh (dissertation, Ch 3) partitioned the water balance at this site and found that the majority of storm flow constitutes some form of base flow. A majority of studies in temperate upland regions have shown that pre-event water typically contributes at least 50% of storm flow water (Buttle 1994). Here, the amount of event water peaked 15 hours after the first discharge peak and 5 hours after the second discharge peaked. In either case, pre-event water appears to be the primary driver of initial rises in stream water levels, and event-water reaches the stream at a lag. This lag could be due to piston flow as precipitation infiltrates into the shallow subsurface before exiting laterally into the stream channel. Alternatively the lag could be due to the effects of spring flow, as perennial springs flow more significantly with increased precipitation inputs and ephemeral springs, consisting primarily of event water, begin flowing after a rise in the groundwater levels (Buttle 1994).

3.5 Spring flow

Spring flow sampling provides insight into the influence of precipitation on springs, and thus the streams. Of the total of 28 springs, approximately 15 were continuous and 13 were ephemeral. On 13 March 2013, one full sampling campaign was conducted of all 28 springs, when all springs were flowing. All stable isotope ratios collected from these springs scattered along the LMWL (Figure 2) indicating that these ratios are representative of local precipitation. These ratios provide evidence that the source of spring water is a shallower groundwater system originating from precipitation rather than a separate deeper groundwater system from outside the watershed.

One additional sampling campaign was conducted on six of the primary perennial streams from 27 – 29 November 2013. On 27 November, a preliminary sample was conducted of all six streams ($\delta^{18}O$ ratios ranged from –6.69‰ to –2.39‰). On 28 November, sampling was conducted at the beginning and middle of a significant precipitation event (114.9 mm). Post-event sampling was conducted on 29 November. As the springs increased in flow, at the beginning of the event during the rising limb of the hydrograph, samples became more depleted relative to the pre-event samples likely due to precipitation as the values were depleted compared to spring water (–8.36‰ for $\delta^{18}O$). As flow started to subside, samples became more enriched, and in the day after the event, samples were more enriched than during the storm (Figure 11). Based on these observations, the springs do not appear to significantly influence the stream water signal during regular flow, but springs do influence the storm flow signals.

4.0 Conclusions

Examining the influences of seasonality on precipitation, we found strong evidence to support that seasonality does influence isotopic ratios of precipitation in this region in Costa Rica. While the tropical humid climate yields weak rainfall seasonality, stable isotopes in precipitation are more enriched during the dry season than during the rainy season. The general climate patterns of Costa Rica and the shifting ITCZ have significant seasonal influence on these compositions. Correlations between precipitation and wind speed, wind direction, and calendar month indicate that the source of the air mass yielding the precipitation event has the largest influence on isotope compositions in precipitation. We did not see any correlation with the amount effect at any time scale (event-based or monthly), which generally is the accepted explanation of variations in isotope compositions in precipitation in the tropics, based on monthly composite samples. Results of this study are important for providing baseline information about isotope seasonality at the study site, and variations in the future can show how climate change influences precipitation in the region.

Isotope ratios of stream water, groundwater, and springs were consistent with patterns seen in precipitation. Within this microwatershed, connectivity between hydrologic components was high, as all hydrologic components plotted along the LMWL and were highly correlated with each other. However, neither groundwater and stream water compositions clearly fluctuated between seasons as precipitation did, as their compositions were more stable than precipitation, likely related to the mean transit time of approximately one year for both components. Groundwater and stream water had more enriched compositions at the end of 2013, during the rainy season, when compared to the same time period in 2012. This suggests that precipitation is an important contributor to these components, as precipitation was also enriched during the rainy season in 2013, compared with 2012. Stable isotopes improved understanding of watershed hydrology at the study site and are a useful tool for studying flow pathways and stream flow generation.

In this subsurface flow driven system, isotope findings contributed to our understanding of flow pathways the proportion of base flow versus spring flow. Isotope correlations from stream water and base flow hydrograph separations indicate that while a connection with precipitation exists, there is an approximate 15 hour lag during storm events to the time that precipitation reaches stream water, suggesting that with precipitation traveling laterally via the subsurface. Base flow hydrograph separation using stable isotopes in the study watershed reveals that pre-event water dominates the storm flow. Stable isotope compositions in spring flow provide evidence that springs are originating from local (watershed) water and are generated from a shallow groundwater system.

Future work using a dual isotope approach would help quantify the hydrologic response of the watershed, to confirm the subsurface flow paths that we suggest based on isotope data. This approach also may allow greater understanding of seasonal variations in hydrologic components in other regions. Additional work is still needed to explain the processes driving spring flow generation to examine the primary source of spring flow, to analyze the contribution of event water versus pre-event water to ephemeral spring flow. A lack of information on spring flow exists in the literature, and further study on the seasonal variations of spring flows in tropical and temperate regions is necessary.

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Tables

Table 1: Information on field sampling conducted for stable isotopes at the study site.

Hydrologic Component Sampled	Sampling period	Frequency of Sampling	Location(s)/Elevations
Precipitation	Sept. 2011 – Dec. 2013 (upper two elevations sampled after Dec. 2011)	Event-basis	1040 m.a.s.l. 1128 m.a.s.l. 1210 m.a.s.l.
Groundwater	Dec. 2011 – Dec. 2013	Weekly	WTL-1 (1029 m.a.s.l.) WTL-2 (1032 m.a.s.l.) WTL-4 (1122 m.a.s.l.) WTL-5 (1204 m.a.s.l.)
Stream water	Nov. 2011 – Dec. 2013	Weekly	Flume – ASA (1018 m.a.s.l.) ASC (1042 m.a.s.l.) ASB (1120 m.a.s.l.) ASD (1191 m.a.s.l.)
	1 Nov. 2011	Hourly	Flume
	26 Nov. – 3 Dec. 2012	Hourly during the day; every two hours at night	Flume
	9 – 13 Dec. 2013	Hourly from 4 a.m. to 8 p.m. plus one sample at midnight	Flume
Overland flow	9 Nov. 2012	Once	Random grab samples where observed
Spring flow	29 Mar. 2013	Once	28 springs in watershed
	Sept. – Nov. 2013	Three times	6 main springs

Table 2: Seasonal precipitation data throughout the study period comparing precipitation amount, $\delta^{18}O$ ratios, $\delta^{2}H$ ratios, *d*-excess, and LMWL. Annual data are presented for 2012 and 2013.

Dates	Season	Precipitation			$\delta^{18}O$ (‰)			$\delta^{2}H$ (‰)			*d*-excess (‰)	LMWL	
		Total amount (mm)	Average event size (mm)	Maximum event size (mm)	Average	Min	Max	Average	Min	Max	Average	Slope	Intercept
Nov 2011 – Jan 2012	Trans	855	13	69	–6.74	–13.95	–2.08	–39.0	–99.5	9.3	14.88	8.9	20.7
Feb – Apr 2012	Dry	633	15	118	–2.27	–4.52	–1.16	0.0	–20.8	11.4	18.20	9.9	22.6
May – Oct 2012	Rainy	1431	13	182	–8.96	–18.52	–3.93	–56.5	–136.4	–12.1	15.18	8.4	18.5
Nov 2012 – Jan 2013	Trans	790	15	54	–3.37	–8.33	–1.00	–7.1	–49.9	13.7	19.91	8.5	21.6
Feb – Apr 2013	Dry	420	13	85	–2.90	–15.49	–0.45	–1.5	–114.2	13.1	21.68	8.6	23.5
May – Oct 2013	Rainy	1231	11	52	–6.90	–15.76	–0.29	–42.6	–117.8	13.4	12.56	8.0	12.2
Annual	2012	2974	16	182	–5.53	–18.52	–1.16	–27.0	–136.42	11.44	17.28	8.5	19.9
Annual	2013	2006	14	113*	–6.13	–15.76	–0.29	–34.72	–117.8	13.66	14.34	8.4	17.0

Notes: trans = transitional; *the maximum event size (113 mm) occurred in November 2013, which was not reported for seasonal data.

Table 3: Data for groundwater wells at the study site, including elevation, mean transit time (τ), and average isotope ratios for 2012 and 2013.

Groundwater Well	Elevation (m)	τ (days)	2012			2013		
			d¹⁸O mean (‰)	d²H mean (‰)	*d*-excess (‰)	d¹⁸O mean (‰)	d²H mean (‰)	*d*-excess (‰)
WTL-1	1029	345	–6.60	–36.6	16.26	–5.96	–33.7	13.90
WTL-2	1032	367	–6.77	–37.4	16.76	–6.23	–36.1	13.67
WTL-4	1122	279	–6.54	–35.8	16.49	–5.64	–30.1	14.97
WTL-5	1204	374	–7.22	–41.0	16.74	–6.71	–38.8	14.86

Table 4: Seasonal isotope ratios for groundwater and stream water at the study site for the sampling period.

Season	Months	Year	Groundwater		Stream water	
			d¹⁸O average (‰)	d²H average (‰)	d¹⁸O average (‰)	d²H average (‰)
Dry	Feb-Apr	2012	–7.36	–41.9	–6.83	–38.1
Rainy season	May-Oct	2012	–6.79	–38.0	–7.17	–39.7
Transition	Nov-Jan	2012-2013	–6.50	–35.0	–6.90	–38.4
Dry	Feb-Apr	2013	–6.39	–34.8	–7.00	–38.6
Rainy season	May-Oct	2013	–5.99	–34.6	–6.35	–37.5
Transition	Nov	2013	–6.04	–34.9	–6.30	–37.3
Annual		2012	–6.77	–37.6	–6.97	–38.9
Annual		2013	–6.14	–34.7	–6.46	–37.6

Table 5: Data for stream sample locations at the study site including elevation of sample locations, mean transit time (τ), and average isotope ratios for duration of sampling period. τ was calculated for all stream samples together.

Stream location	Elevation (m)	τ (days)	2012			2013		
			d^{18}O mean (‰)	dD mean (‰)	*d*-excess (‰)	d^{18}O mean (‰)	dD mean (‰)	*d*-excess (‰)
Flume (ASA)	1018	378	–6.82	–38.4	16.16	–6.35	–36.6	14.14
Lower (ASC)	1042		–6.93	–38.1	17.33	–6.48	–37.8	14.01
Middle (ASB)	1120		–6.85	–38.2	16.58	–6.44	–37.2	14.31
Upper (ASD)	1191		–7.40	–41.6	17.53	–6.74	–39.6	14.36

Figures

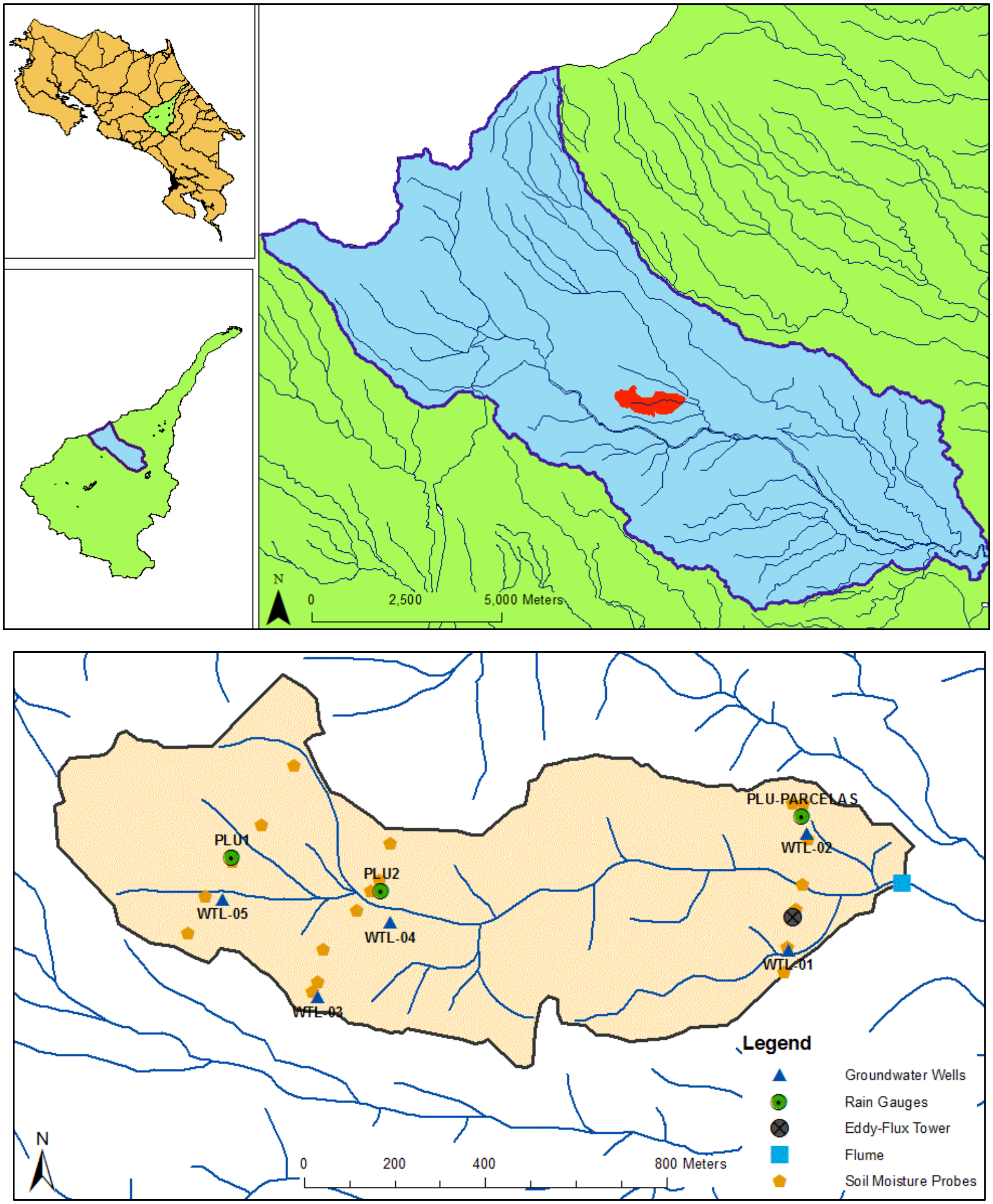


Figure 1: Location of a) Reventazón watershed (green) in Costa Rica, b) Turrialba watershed (blue), c) the Mejías Creek microwatershed study site (red), and d) study watershed experimental setup.

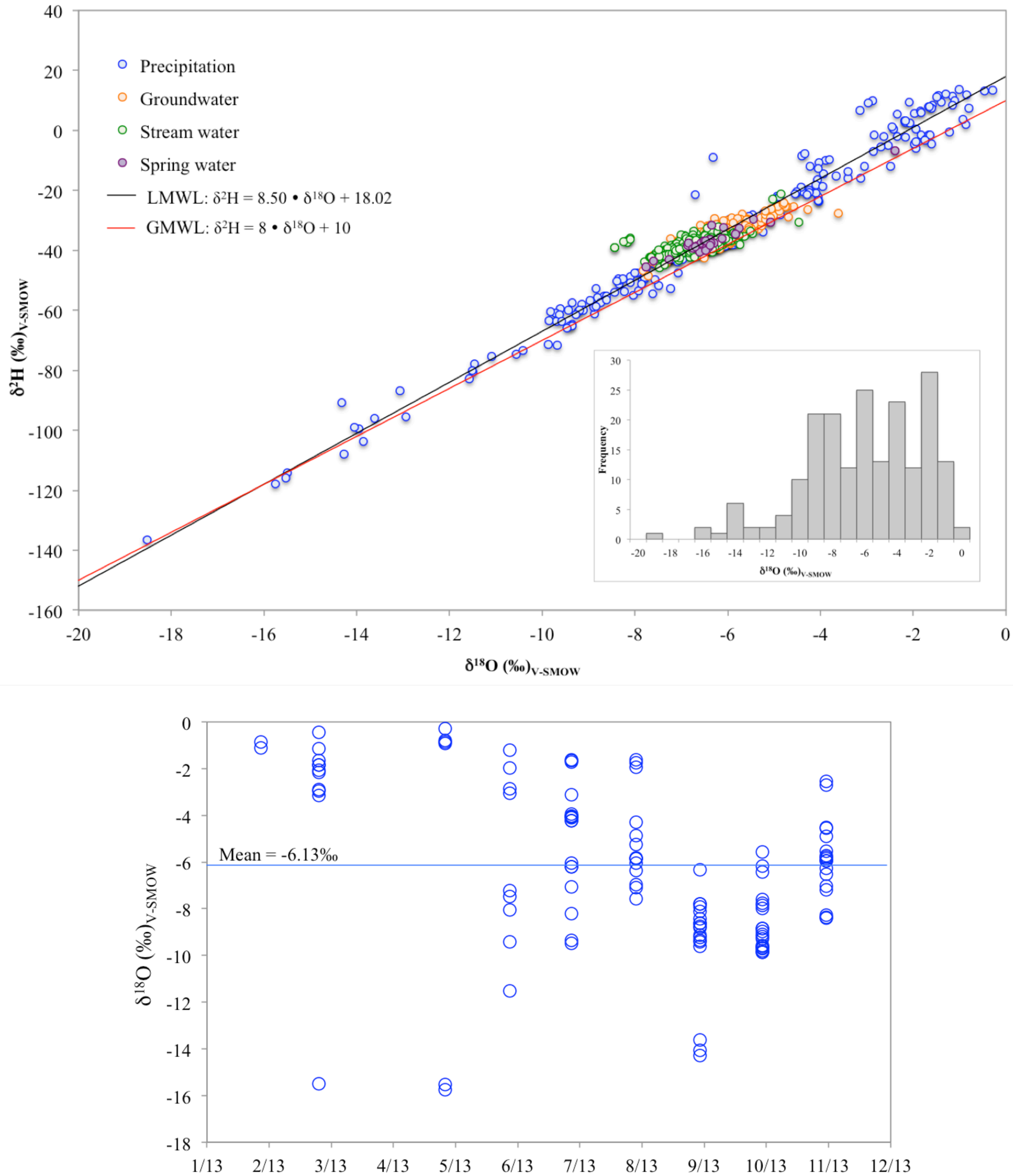


Figure 2: Top: LMWL for Aquiares study site with GMWL (Global Meteoric Water Line) (Craig 1961) for comparison in red. Inset shows distribution of $\delta^{18}O$ ratios. Bottom: Temporal variation of $\delta^{18}O$ ratios by month during 2013.

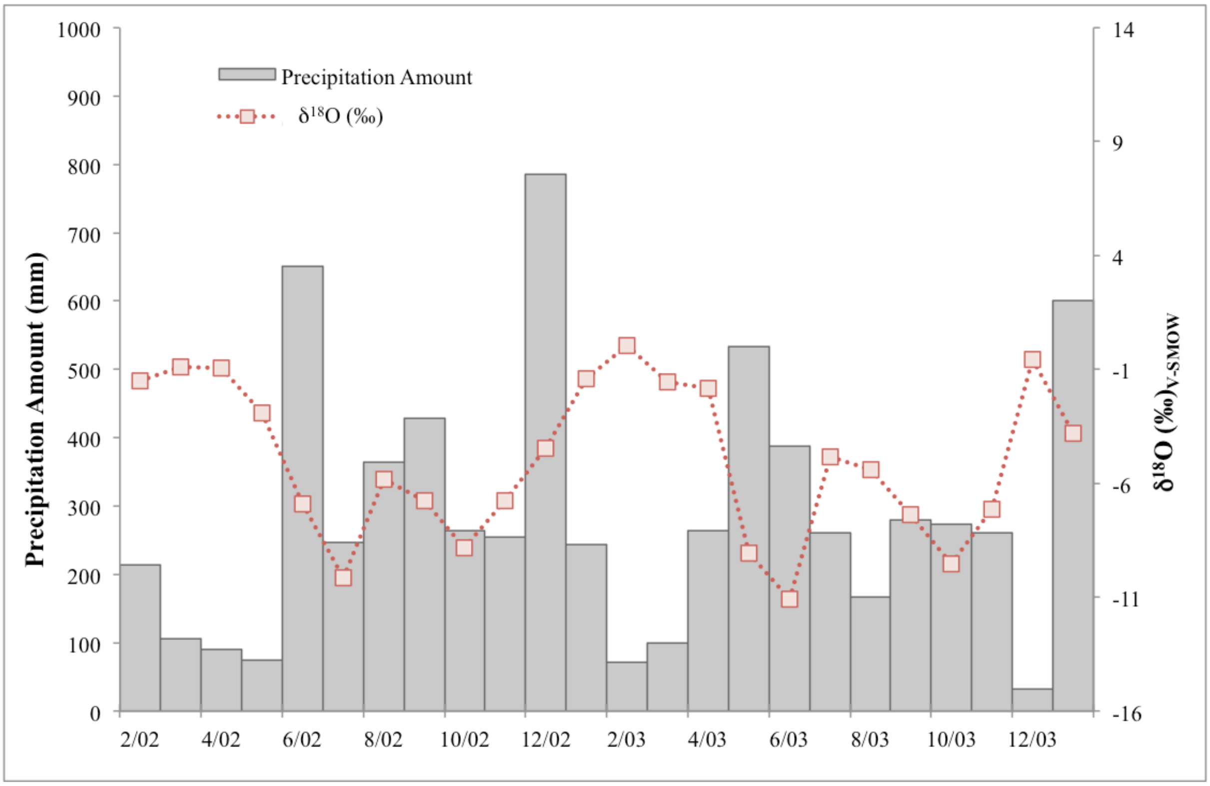


Figure 3: Monthly integrated δ^{18}O ratios in precipitation compared with average monthly precipitation amounts from historic GNIP data.

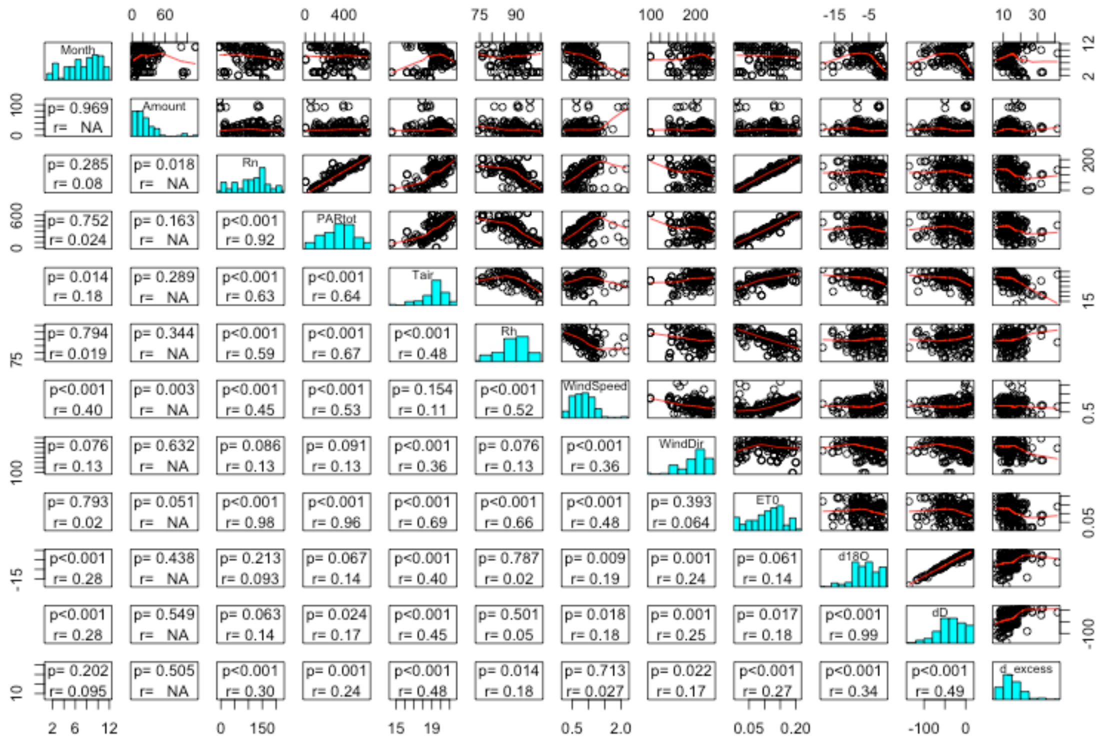
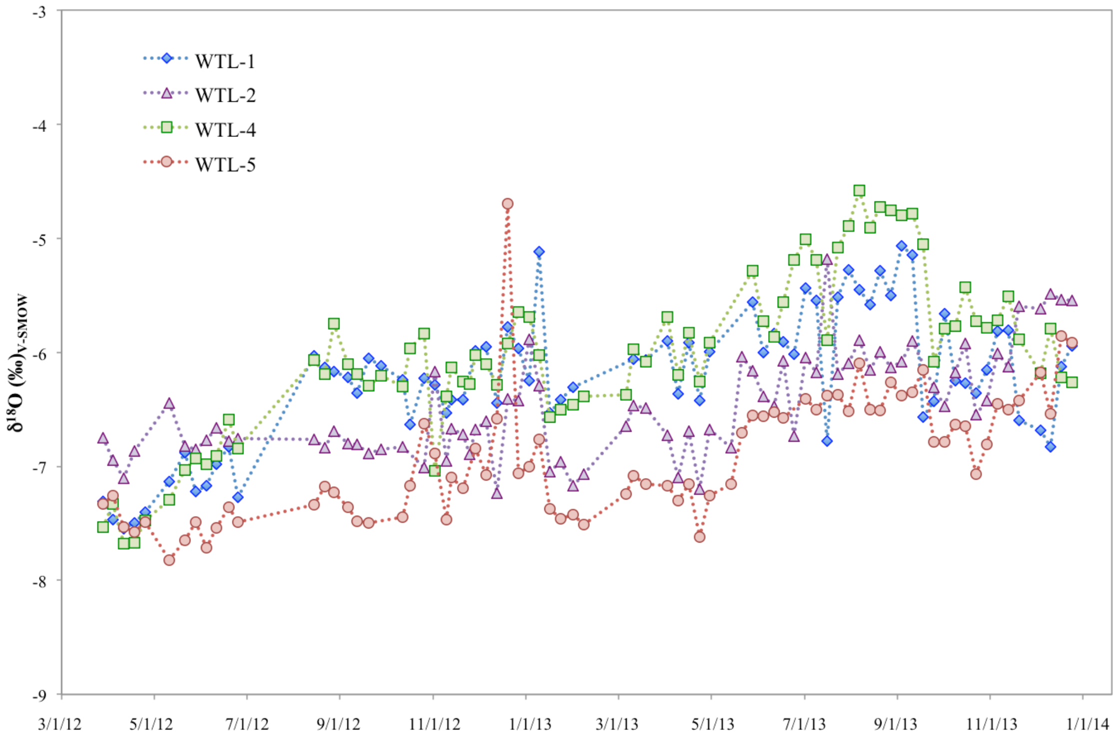


Figure 4: Correlation matrix of meteorological factors and stable isotope ($\delta^{18}O$ and $\delta^{2}H$) ratios in precipitation. The lower panel contains Pearson coefficients and associated p-values, and histograms show distribution of data. Only factors that were correlated with $\delta^{18}O$, $\delta^{2}H$, or *d*-excess are included in this matrix. Month = calendar month of precipitation sample, Amount = precipitation amount, Rn = net radiation, PARtot = Photosynthetically Active Radiation total, Tair = surface air temperature, Rh = relative humidity, WindSpeed = wind speed, WindDir = wind direction, ET0 = Potential ET, d18O = $\delta^{18}O$ value, dD = $\delta^{2}H$ value, d_excess = deuterium excess.



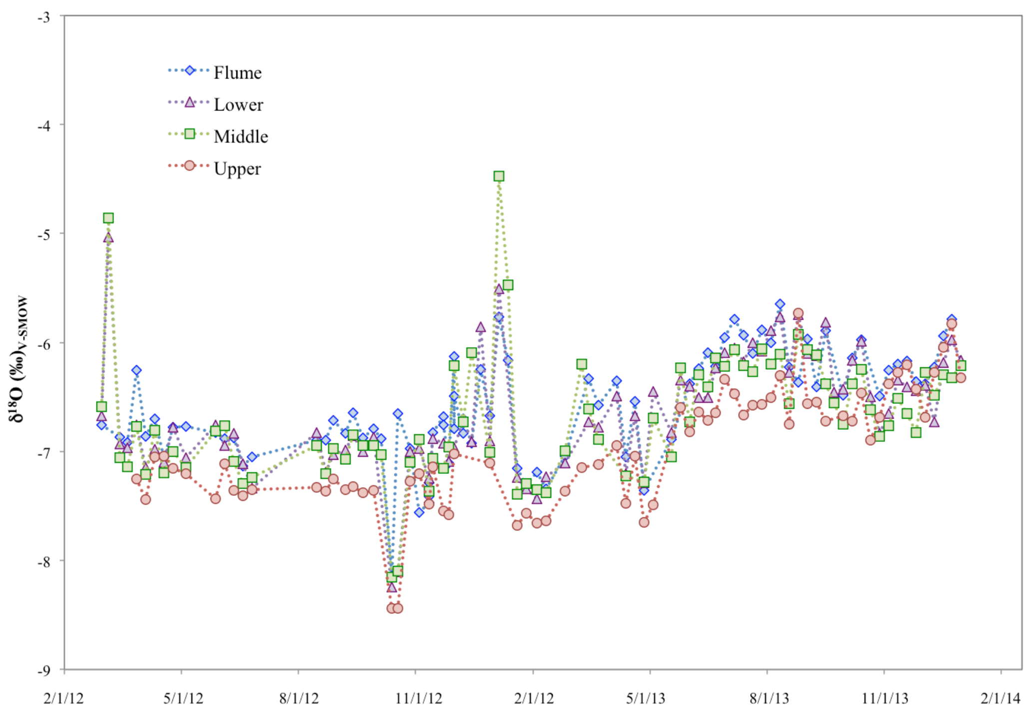


Figure 5: Comparison of $\delta^{18}O$ ratios in groundwater (op), collected weekly between March 2012 and December 2013, and stream water (bottom), collected between February 2012 and December 2013, at the study site.

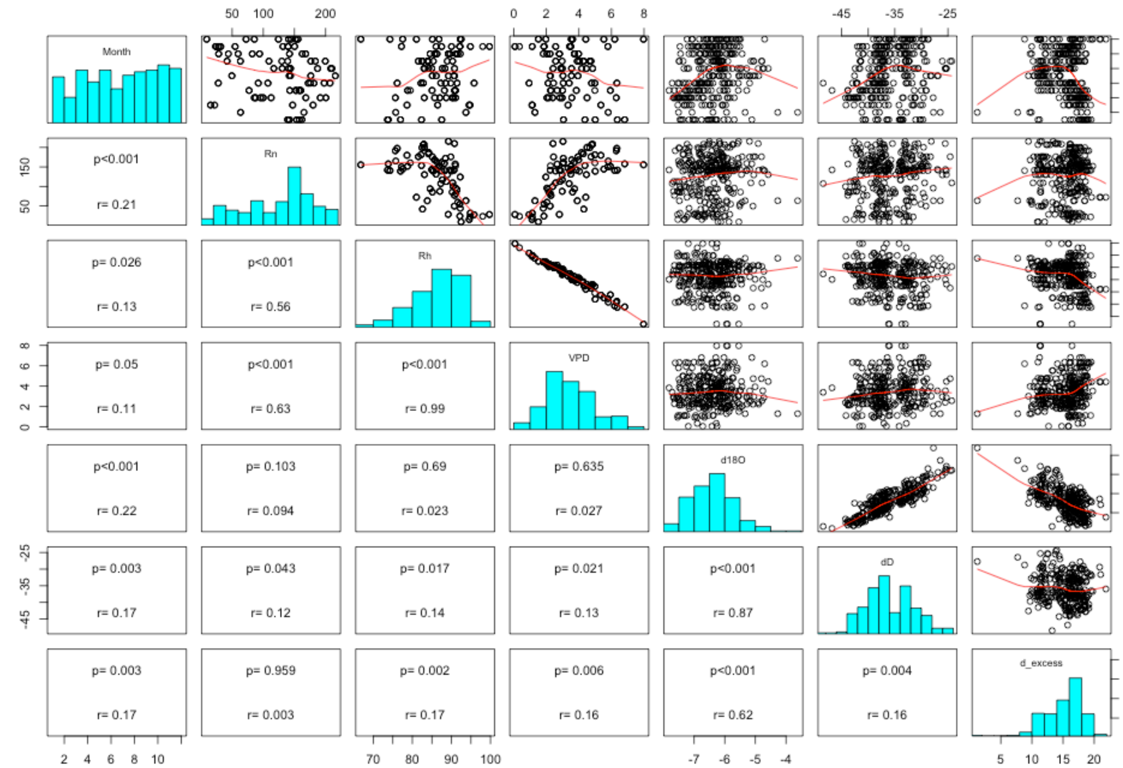


Figure 6: Correlation matrix of meteorological factors and stable isotope ($\delta^{18}O$ and $\delta^{2}H$) ratios in groundwater. The lower panel contains Pearson coefficients and associated p-values, and histograms show distribution of data. Only factors that were correlated with $\delta^{18}O$, $\delta^{2}H$, or *d*-excess are included in this matrix. VPD = vapor pressure deficit; all other abbreviations can be found in Figure 4.

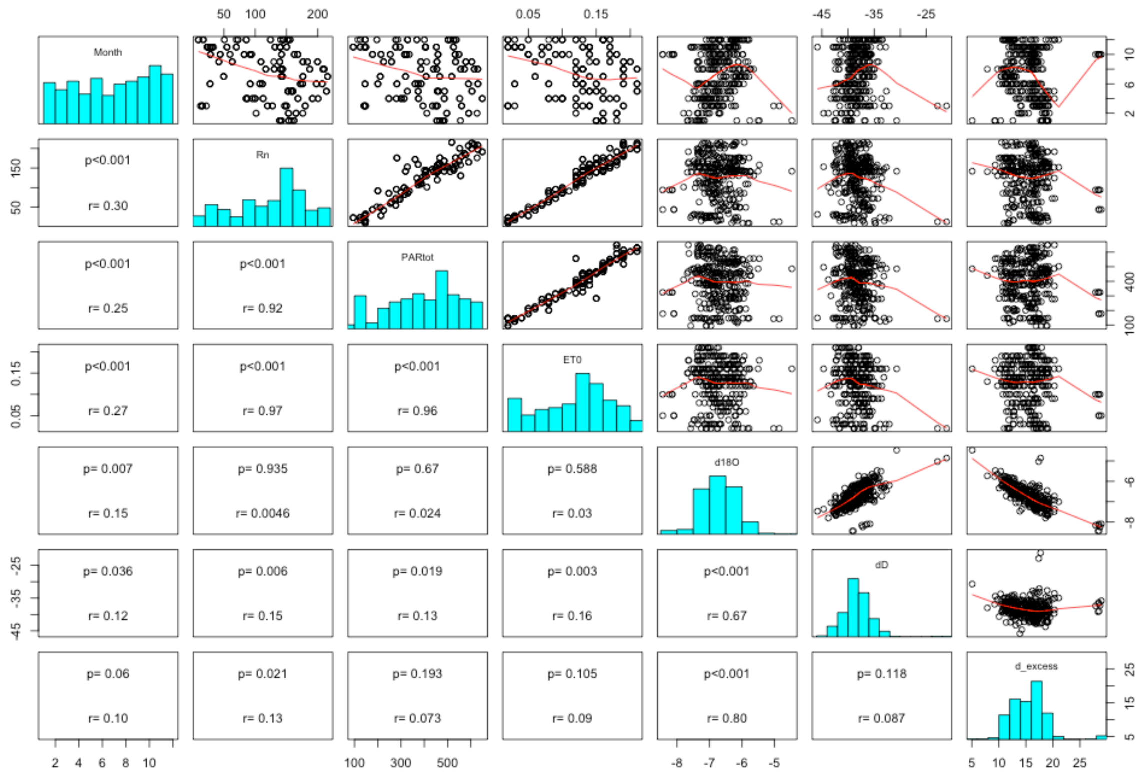


Figure 7: Correlation matrix of meteorological factors and stable isotope (δ^{18}O and δ^{2}H) ratios in stream water. The lower panel contains Pearson coefficients and associated p-values, and histograms show distribution of data. Only factors that were correlated with δ^{18}O, δ^{2}H, or *d*-excess are included in this matrix. All abbreviations can be found in Figure 4.

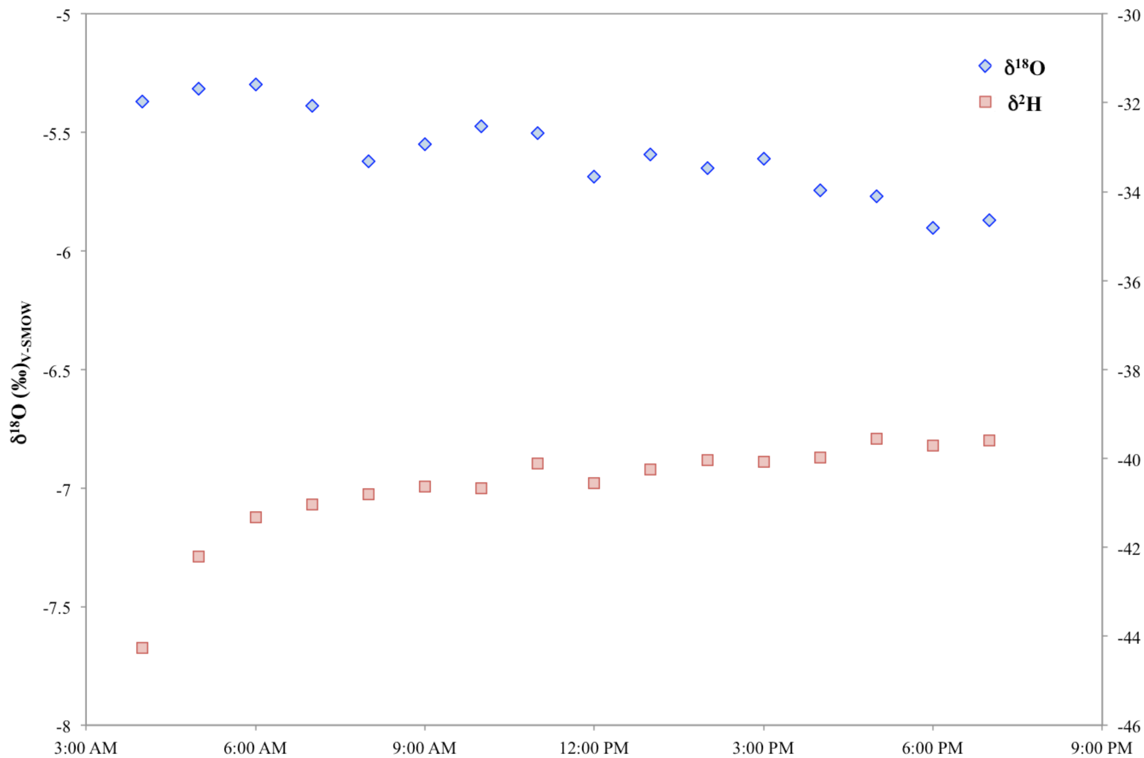


Figure 8: Hourly $\delta^{18}O$ and $\delta^{2}H$ ratios in stream water on 1 November 2012 at the study site.

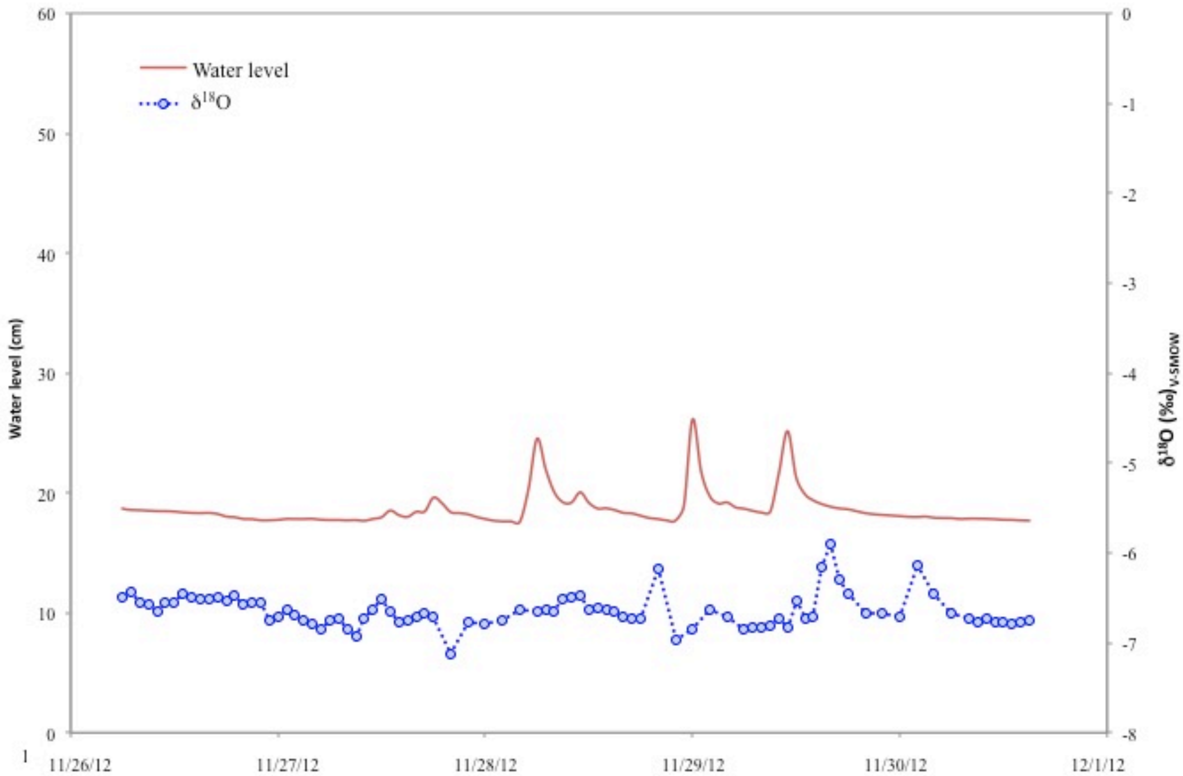


Figure 9: Hourly $\delta^{18}O$ ratios in stream water, compared with water level at the flume, from 26 November – 1 December 2012.

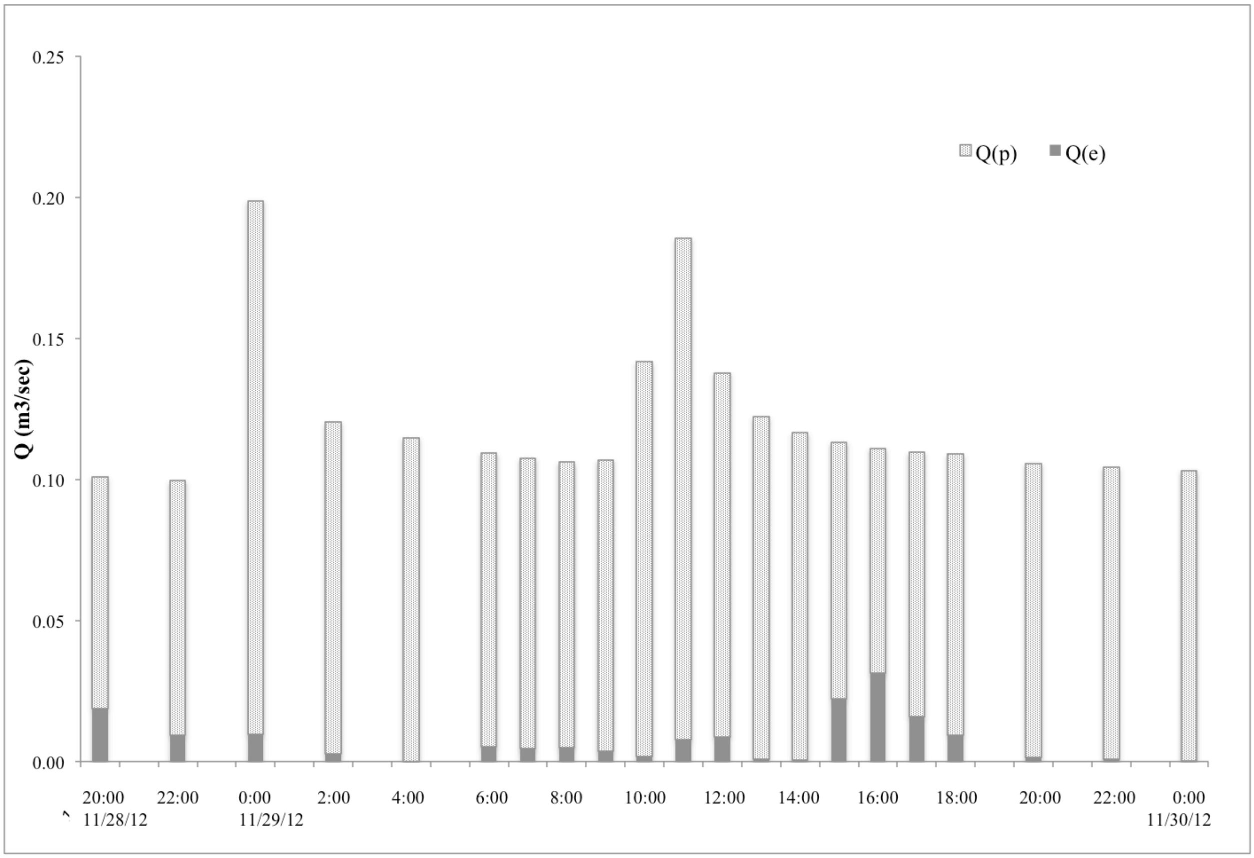


Figure 10: Base flow separation from δ^{18}O ratios during a storm event from 28 - 29 November 2012 (storm peak occurred on 28 November between 21:00 and 22:00 with 9.5 mm precipitation). Q(p) signifies pre-event storm water flow, and Q(e) is event water flow.

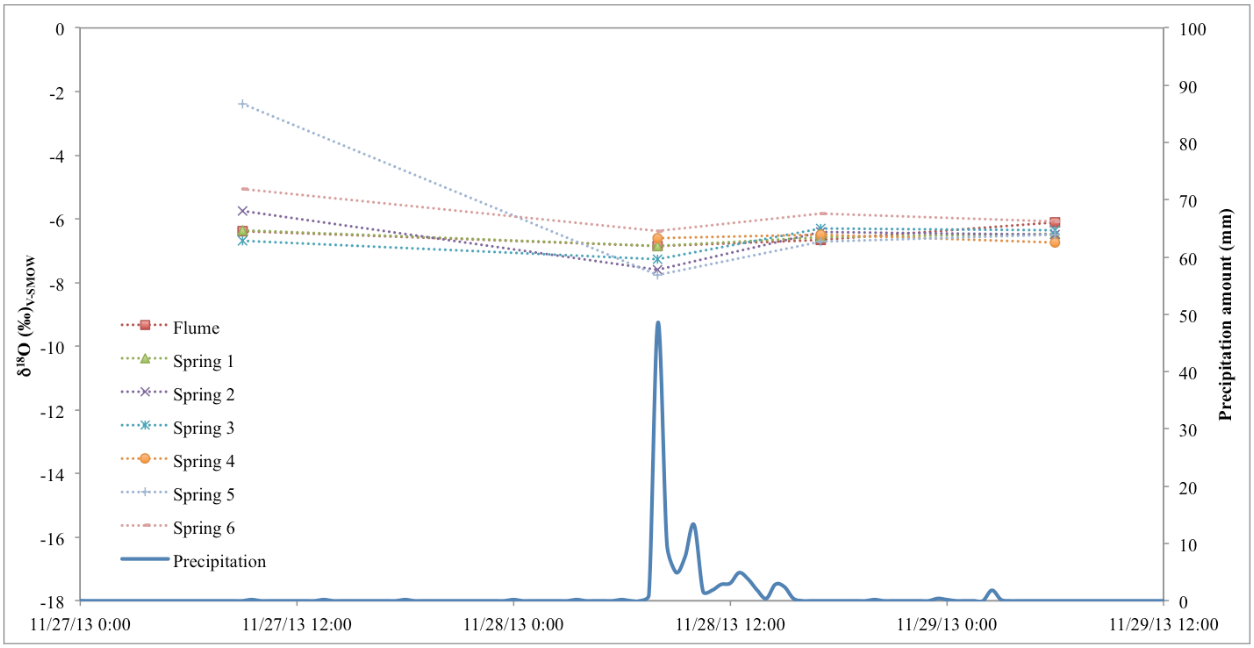


Figure 11: $\delta^{18}O$ ratios of six springs and flume sampled during a storm event, with precipitation amounts shown for comparison.

Chapter 3: Response of a distributed hydrologic model simulating spring flow in a tropical coffee watershed

Abstract

The processes governing the hydrologic mechanisms behind spring flow are not well understood. Spring flow is important for drinking water and can be a significant contribution to stream flow, thereby potentially influencing flood occurrences. However, model simulations typically do not include a spring flow component. Our study is unique in that it explicitly includes spring flow, including ephemeral springs, in simulation efforts. Our goal was to simulate water balance partitioning in a tropical watershed to understand hydrologic response, and particularly subsurface flow pathways. In this study, a physically based distributed model, the Soil Moisture Routing (SMR) Model, was used to simulate water balance partitioning, explicitly including spring flow, within a microwatershed (<1 km^2) in a coffee agroforestry system in Costa Rica. The results were used to assess whether distributed model simulations could accurately represent the hydrologic behavior of the watershed and of its springs. Results from model simulations were compared to hydrologic processes observed on site with installed equipment, including stream flow, meteorological conditions, precipitation, groundwater, soil moisture, and ephemeral spring flow. SMR yielded strong statistical results with a Nash-Sutcliffe coefficient of 0.84 for stream flow. Although stream flow was slightly greater than measured values in the watershed, ephemeral spring flow amount was equivalent to estimated values. Springs can be included in distributed models and strengthened our simulation efforts. Results showed that springs enabled further hydrologic partitioning and that origins of spring flow are from a shallow fast-response groundwater system.

1.0 Introduction

In Costa Rica, flooding is one of the most common natural disasters, causing significant economic hardship for communities through loss of property, infrastructure, and life (Bower 2013; Waylen and Laporte 1999). During storm events, many small watersheds also face the detrimental impacts of contaminant loading to streams through non-point source pollution (Agnew et al. 2006; Kundzewicz and Krysanova 2010; Sheridan et al. 1999; Tong and Chen 2002). The hydrologic response of a watershed is an important factor for influencing both flooding and contaminant loading (Grayson et al. 1992a). These occurrences are indicative of a fast response to precipitation within watersheds, as overland flow and rapid water flow to streams occur. With changing climate, more extreme events, such as increased amounts of precipitation and associated flooding, are expected to occur (Haines et al. 2006; Huntington 2006; Kundzewicz and Krysanova 2010; Wohl et al. 2012). Analyzing hydrologic flow processes in tropical watersheds is critical to assess the influences on stream flow and to mitigate some of the detrimental impacts from flooding and water pollution.

Variable source areas, or saturated areas that can change between storm events within the watershed, are significant sources of overland flow in humid regions (Beven and Kirkby 1979; Dunne and Black 1970; Frankenberger et al. 1999; Hewlett and Hibbert 1967; Mehta et al. 2004; Walter et al. 2000). These saturated areas can arise due to subsurface lateral flow, slope, or depth to a restricting layer (Frankenberger et al. 1999; Hewlett and Hibbert 1967). Variable source areas have important implications for water quality (Walter et al. 2000) and flooding. Ephemeral springs are a specific type of variable source areas, as their runoff changes significantly over time. Generally, springs occur on steep slopes where subsurface lateral flow above the water table exits the land surface (Smakhtin 2001). Springs are common in volcanic regions and can contribute a significant volume to stream flow (Whiting and Stamm 1995). In semi-arid environments, springs can cause extended base flows following storm events (Smakhtin 2001). Springs have the potential to greatly increase stream flow during storm events. However, the hydrologic processes driving spring flow are not well studied or documented (Buttle et al. 2012), and few models exist that simulate the complex spring flow generation processes.

Hydrologic modeling is an important tool for decision making and quantifying hydrologic processes (Borah and Bera 2004; Jain and Sudheer 2008) for drinking water and other uses (such as irrigation or hydropower), particularly in data-poor regions of the world

(Schmitt 2007). In these regions, a lack of field measurements and hydrologic data can hinder the study of hydrologic processes, but model simulations provide new insight into hydrologic understanding. The accurate simulation of hydrologic responses within watersheds is important for quantifying the water balance including evapotranspiration (ET) loss, runoff, and response to storm events, in addition to water management and planning for climate change (Bormann et al. 2009; Dunne 1983; Gómez-Delgado et al. 2011; Johnson et al. 2003). However, few models exist that simulate variable source areas (Brooks et al. 2007; Mehta et al. 2004; Moussa et al. 2007). While both spatially lumped and distributed models are used in hydrology, a distributed model is necessary to simulate the occurrence of variable source areas (Frankenberger et al. 1999). Distributed models are an important tool for identifying potential source areas of non-point source pollution (Brooks et al. 2004; Frankenberger et al. 1999; Grayson et al. 1992).

Physically based distributed models typically use Geographic Information Systems (GIS) to analyze spatially variable data across a watershed. One of the main benefits of distributed models is their ability to synthesize, view, and manipulate distributed information (Brooks et al. 2007). Additionally, functional relationships are used in distributed models parameterized with measured or readily available variables (Beven and Kirkby 1979). One of the main drawbacks of distributed, physically based models is that they often require large amounts of data and significant calibration to work for a given watershed (Bormann et al. 2009; Grayson et al. 1992a), but examples of models requiring minimal calibration exist (Brooks et al. 2007). Complex hydrologic systems are difficult to simulate when processes and variables change both spatially and temporally (Beven and Kirkby 1979). According to Grayson et al. (1992b), physically based models operate under the assumption that physically based relationships accurately reflect the processes occurring in a defined manner, the watershed operates as a sum of parts of the spatially distributed relationships, and the algorithms accurately reflect the process sequence enough to derive a correct representation of the watershed.

Previous work in the tropics has illustrated the value of models for explaining hydrologic processes in this region of the world, as well as informing management and decision-making. As one example, modeling is used to analyze soil loss, and efforts have helped identify potential areas of erosion (see Beskow et al. 2009; Gómez-Delgado et al. *in review*; Hoyos 2005; Labriere et al 2015; Schmitt 2007; Villatoro-Sanchez 2015). In Costa Rica, few studies have been conducted using modeling to understand hydrologic processes. Gómez-Delgado et al. (2011) simulated hydrologic partitioning of a single land use (coffee agroforestry) microwatershed in Costa Rica using a lumped model. Results indicated that a deep aquifer was the primary contributor to stream flow via base flow with minimal runoff.

To analyze hydrologic processes in Costa Rica, Spaans et al. (1989) and Toohey (2012) characterized plot and field scale responses to precipitation. Spaans et al. (1989) investigated soil characteristics, including porosity, bulk density, and saturated hydraulic conductivity, before and after forest clearing. Toohey (2012) studied soil characteristics at the point, plot, and field scale to compare how infiltration, percolation, and runoff differed at each scale. In addition, a "fill and spill" mechanism was identified in these soils, whereby precipitation would fill the soil profile and then eventually cause lateral flow or deep percolation (i.e., "spill") due to elevated K_{sat} and storage capacity. The "fill and spill" hypothesis was previously identified by Spence and Woo (2003) and Tromp-van Meerveld and McDonnell (2006), although they described this process as occurring through a soil-filled valley and a depression in bedrock layer on a hillslope, respectively.

A need exists for a more physical understanding of hydrologic processes, particularly subsurface flow, in tropical watersheds through field observations coupled with physically based models. In this study, therefore, we addressed the following research questions: 1) what is the balance of subsurface flow contributions to the stream between groundwater and springs? 2) can we model our conceptual understanding of how spring flow is generated in the study watershed? and 3) what other hydrologic processes influence stream flow in the watershed? We address these questions through the use of a distributed physically based model to simulate water balance partitioning in a tropical humid microwatershed. The availability of detailed actual ET data makes this study unique, whereas the majority of hydrologic studies rely on assumptions and estimates based on reference ET (Allen et al. 2005). Despite the need for more detailed ET data, few studies exist with measured ET due to the difficulties in installing instrumentation (Niedzialek and Ogden 2012). We modify an existing model by including runoff from semi-impervious surfaces (roads and paths) and a spring flow component to simulate the many ephemeral springs observed within the study watershed.

2.0 Materials and methods

2.1 Site description

The study was conducted in the Mejías Creek microwatershed, which is part of the Aquiares Coffee Farm in the town of Aquiares, Cartago, Costa Rica in the Central Caribbean region of the country (Figure 1). The study watershed is approximately 0.9 km^2 in size and forms part of the Turrialba watershed, which is part of the larger Reventazón watershed. The town of Aquiares lies on the southern slope of the Turrialba Volcano. Land cover at the study site is solely coffee agroforestry, predominantly covered by *Coffea arabica* coffee plants with tall *Erythrina poeppigiana* shade trees. More details on land cover are reported by Taugourdeau et al. (2014) and Charbonnier et al. (2013).

Elevation at the site ranges from 1020 to 1280 m.a.s.l., and slopes average approximately 20% with steeper slopes of 80% in the upper portions of the watershed. Soils within the study region are Andisols, according to the United States Department of Agriculture (USDA) soil taxonomy. Andisol soils originate from volcanic ejecta, are subjected to weathering and mineral transformations, and have high infiltration capacity and available water capacity (USDA 1999), and observations at the site corroborate soils have very high infiltration capacity (Benegas et al. 2014). This soil order is also characterized as having at least 60% andic soil properties in the upper 60 cm of the soil profile (USDA 1999), and the soil organic content is high at the surface (Kinoshita et al. *in review*). The study site is located in a tropical humid location, and therefore precipitation events occur throughout the rainy and dry seasons. The annual precipitation for the site averaged 3219 mm during the three years when this study was conducted (3178 mm in 2009, 3341 mm in 2010, and 3139 mm in 2011). Precipitation varies throughout the year with the highest amount falling during the rainy season in May through October.

The site is part of the CoffeeFlux project, established by the French institute CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement) and the Costa Rican institute CATIE (Centro Agronómico Tropical de Investigación y

Enseñanza) to monitor carbon, soil, and water ecosystem services within a coffee agroforestry watershed. The observatory contributes to the global network of FLUXNET micrometeorological sites and SOERE F-ORE-T network of observatories (France). Long-term hydrologic data have been collected on site since 2009. Meteorological measurements collected on site include precipitation, stream flow, relative humidity, air temperature, wind speed, wind direction, and radiation (more details in Gomez-Delgado et al. 2011).

2.2 Field measurements

Precipitation was measured on site with three ARG100 tipping buckets (R.M. Young Company, USA) connected to a CR800 datalogger (Campbell Scientific, USA). These tipping buckets were located along the central transect of the watershed at different elevations (1040, 1128, and 1210 m.a.s.l.) throughout the watershed (Figure 1d). Data were integrated every ten minutes. An eddy-flux tower is located on site, and actual ET data were recorded at a reference height of 26 m (Gómez-Delgado et al. 2011). Additionally, stream flow was measured with a 3.9 m long steel flume located near the watershed outlet. Water levels were measured every ten minutes with a pressure transducer (PDCR-1830, Campbell-Scientific, USA) placed in a stilling well connected to the flume. Four wells were placed throughout the watershed to measure groundwater levels with pressure transducers (Micro-Divers, Schlumberger Water Services, USA), and data were collected every half hour. Wells were installed to 4 m depth. More details are available in Gómez-Delgado (2010) and Gómez-Delgado et al. (2011).

Soil parameters were measured in the field and laboratory. Soil samples were collected in three test pits (upper, middle, and lower elevations) at two depths (0.5 m and 1 m) using a cylindrical core sampler. Samples were then measured in the laboratory (Center for Tropical Agriculture Research and Education [CATIE] Soil, Plant Tissue, and Water Laboratory) on pressure plates to calculate wilting point moisture content (θ_{wp}) (15 bar), field capacity moisture content (θ_{fc}) (0.33 bar), and saturated moisture content (θ_s) (0.1 bar). Values that were obtained from this analysis and used as inputs to the model are presented in Table 1. Moisture contents were comparable to those measured by Toohey (2012) in similar soils at a coffee farm located close to the study site. Porosity measurements collected by Benegas et al. (2013) were compared against θ_s values. Percent rock was measured by Defrenet et al. (*in review*) at the site through soil pits and sampling soils by depth down to 4.5 m. Saturated hydraulic conductivity, or K_{sat}, values were determined through onsite tests (Benegas et al. 2013) and results from similar field sites close to the study site (Toohey 2012). We used a value of 150 cm/day for soil horizon A and 120 cm/day for soil horizon B based on those measurements. The upper layer used values from measured ring infiltrometer and rain simulation studies (Benegas et al. 2013; Toohey 2012), and the lower layer was estimated at approximately 75% of horizon A.

High rates of hydraulic conductivity in the soils causes vertical infiltration of throughfall to occur relatively quickly, and virtually no overland runoff occurs with the exception of roads and paths. At the study site, a network of dirt roads and footpaths exist throughout the coffee farm. Although these areas are not paved, heavy compaction causes them to act like impervious areas during rain events. Field observations reveal that overland flow from these regions is an important contribution to stream flow during rain events. Road locations were digitized from overhead satellite imagery and verified with a Garmin GPS (Global Positioning System). Footpaths were recorded with a Garmin GPS only, as satellite imagery does not capture footpaths.

Ephemeral spring flow is a significant source of stream contribution during the rainy season and times of high precipitation. There are a total of 28 springs throughout the watershed, and about 10 of these streams are ephemeral. The ephemeral streams generally flow during periods of very high precipitation and the rainy season. Given soil conditions, including high hydraulic conductivity, spring flow was assumed to occur due to a shallow restrictive layer that creates excess saturation in upper portions of the watershed, which forces lateral flow to exit at the points of the spring. Spring locations were determined in the field and recorded with a Garmin GPS at the point where they exit the subsurface. In addition, we collected spring flow measurements of six springs using a Pygmy flow meter during the start and end of a storm to catch the rising and falling limbs of the hydrograph. Other springs were not measured with the Pygmy meter due to insufficient water depth.

3.0 Soil Moisture Routing Model

3.1 Model Description

The model used for this study is a modified version of the Soil Moisture Routing (SMR) model, a physically based distributed model that simulates the water balance on a daily time step (Brooks et al. 2007; Frankenberger et al. 1999; Johnson et al. 2003; Mehta et al. 2004). SMR is GIS-based and implemented through the open-source GIS program GRASS (Geographic Resources Analysis Support System; available at http://grass.osgeo.org). The model simulates water flow processes at the watershed scale and, in particular, variable source areas of overland flow. SMR uses physically based hydrologic equations on 10 m grid cells for elevation, soil type, and land cover. The model was developed primarily to examine the influence of variable source areas on watershed hydrology (Mehta et al. 2004).

Specific parameters in SMR include soil depth, organic matter, porosity, water content, and saturated hydraulic conductivity; inputs include climate data, precipitation and ET; and land cover information. Some of these parameters and the values that were used as inputs are presented in Table 1. SMR calculates the water entering and exiting each cell using a basic mass balance approach:

$$d \cdot \frac{d\theta}{dt} = P - ET + \frac{LF_{in} - LF_{out}}{A} - BF - R \qquad (1)$$

where *d* is the soil depth (cm) above a hydraulically restrictive layer, θ is volumetric moisture content (cm^3/cm^3), *t* is time (day), *P* is precipitation (cm), *ET* is evapotranspiration (cm), *LF* is lateral flow in from and out to surrounding cells (cm^3), *A* is area (cm^2), *BF* is percolation or base flow (cm), and *R* is runoff (cm) (Brooks et al. 2007; Frankenberger et al. 1999). A visual representation of this setup is presented in Figure 2.

3.2 Model components

We modified the variable source area concept in previous versions of SMR (Brooks et al. 2007; Frankenberger et al. 1999; Mehta et al. 2004) to include two important components of the study watershed: runoff from semi-impervious areas (roads and paths within the coffee fields) and spring flow. The model we used for this study incorporates the components and modifications described in this section.

Precipitation and evapotranspiration

Both precipitation and ET were measured on site, based on field protocol outlined previously. From precipitation, we subtracted canopy storage and evaporation to obtain throughfall. We assumed a maximum canopy storage amount, and evaporation of the canopy storage was calculated based on daily evaporation rates. Whereas previous iterations of the SMR model (Brooks et al. 2007; Frankenberger et al. 1999; Mehta et al. 2004) used estimated or measured potential ET, we used actual ET measurements. Using actual ET measurements, SMR calculated the amount of ET leaving each cell according to each cell's moisture content, thereby limiting the ET to the available amount; in few instances did this number differ slightly from the measured actual ET. We assumed that ET is limited by soil moisture at 80% of field capacity.

Subsurface lateral flow

The lateral flow out of each cell in the model is calculated using Darcy's Law assuming that slope of the land is equal to the hydraulic gradient:

$$Q_{l,out} = K_{eff} \cdot m \cdot w \cdot d \qquad (2)$$

where $Q_{l,out}$ is lateral flow out of each cell, K_{eff} is the effective hydraulic conductivity (cm/day), m is the slope of the cell, w is the width of the cell, and d is the depth of the cell. K_{eff} is calculated with Bresler's formula to determine unsaturated conductivity:

$$K_{eff} = K_{sat} \cdot e^{\frac{-13.0}{\theta_s} \cdot \left(\theta_s - \frac{S}{d}\right)} \qquad (3)$$

where K_{sat} is hydraulic conductivity, θ_s is saturated moisture content, S is storage amount, and d is depth of soil (Bresler et al. 1978). Based on the slope of neighboring cells, lateral flow out of the cell is routed to cells that are downslope. We assume that lateral flow in the unsaturated zone is insignificant (Brooks et al. 2007).

Percolation and runoff

The SMR model was not modified to address the components of runoff or percolation through the restrictive layer. Surface runoff occurs when the cell inputs exceed the cells outputs for the amount of cell storage, or when throughfall plus lateral flow into the cell exceed ET, lateral flow out, and percolation. Vertical flow occurs when storage within cells exceed field capacity (θ_{fc}). $K_{subsurface}$ is the parameter for vertical saturated hydraulic conductivity through the subsurface restrictive layer and was derived through calibration. We used different values according to whether a cell was in the contributing subsurface watershed to a spring outlet, here referred to as springshed, or in the remainder of the watershed. A $K_{subsurface}$ value of 6 cm/day was used for the entire watershed and 1 cm/day for the springsheds, since we assume that the subsurface layer in these areas is more restrictive and forces lateral flow to the spring outlet.

Base flow was calculated as a post-processing method, and we used a non-linear base flow reservoir with the following equation:

$$BF = \left(\frac{P_{Cum}}{b}\right)^{\frac{1}{a}} \quad (4)$$

where BF is base flow (cm/year/basin), P_{Cum} is cumulative percolation (cm/year/basin), a is recession constant a, and b is recession constant b. The non-linear reservoir coefficients were derived from observed recession data; for the Aquiares simulation, a = 60 and b = 0.2. Both linear and non-linear reservoirs were tested, as previous versions of SMR used linear reservoirs, but the non-linear reservoir provided the best fit to the observed recession data.

Semi-impervious runoff

As discussed previously, we included a semi-impervious runoff component for roads and footpaths within the coffee plots. To incorporate semi-impervious runoff into the SMR model, we set values for the initial abstraction of roads (2 mm) and footpaths (5 mm), or the amount that will infiltrate before becoming runoff. After the initial abstraction, the remainder of throughfall becomes overland flow. Because the SMR model used a 10 m grid, we determined the portion of cells that were covered by roads (3 m wide) and paths (1 m wide) and calculated runoff for only that portion of the cells.

Spring flow

We hypothesized that springs are generated by a shallow restrictive layer that forces lateral flow to exit the soil at the spring points (see Figure 3). We used GPS points from the field to identify spring locations. To determine the springshed areas, we delineated the contributing subsurface watersheds to each spring point based on topography and calibrated the springshed depth. Within these contributing areas, we used varying depths to the restrictive layer, assuming that the layer itself came closer to the surface near the spring point, or that the soil remained saturated at the elevation of the spring point. Moving upward from the spring point, the soil depth was increased by 4 cm for each 10 m. This method was most representative of our conceptual understanding of field conditions and allows for saturation at shallow depths near the spring outlet, forcing spring flow to exit the hillslope.

We modified the SMR model to calculate spring flow as runoff that occurs from within the springsheds. The $K_{subsurface}$ value for the spring areas was set at a lower number than the remainder of the watershed, because of our assumption that a shallow restrictive layer or perched water table forces runoff to occur.

Groundwater levels

For additional model verification, we simulated groundwater levels at the site by calculating the amount of storage for each cell. Using the existing groundwater well locations, we compared groundwater at cells with wells to observed data. We calculated the groundwater level using the following equation:

$$Pz = \frac{(S-fc)}{(Sat-fc)/d} \tag{5}$$

where Pz = groundwater level (cm), S = storage amount (cm), fc = field capacity amount (cm), d = soil depth (cm).

4.0 Model application

The modified SMR model was applied to the Mejías Creek watershed during the calendar years 2009 through 2011 on a daily time-step. As the majority of the input parameters were field-measured values, we calibrated $K_{subsurface}$ and soil depth in the springsheds using data from the year 2009 and verified the model with data from 2010 and 2011. We used daily input data for precipitation, actual ET, and calculated evaporation rates. Evaporation was calculated according to the method used by Penman (1948) for the stream channel, canopy evaporation, and ponding atop roads and footpaths.

4.1 Calibration

We used a combination of the N_S coefficient and observations of the water balance partitioning to assess results for the year 2009. The $K_{subsurface}$ value directly affects the storage within the cell and the percolation into the base flow reservoir. Due to the high rock content in these soils, $K_{subsurface}$ is not easily measured. When a single $K_{subsurface}$ value was used for entire study site, the model failed to simulate the high peaks correctly, overestimating peaks at low values (e.g., 0.1) and underestimating peaks at high values (e.g., 10). In addition, with one $K_{subsurface}$ value, the model did relatively well simulating base flow in the dry season but did a poorer job during the rainy season with a higher stream flow than observed values. Model performance improved by setting different values for the springshed and remainder of the watershed. The performance of the model dropped significantly when the springshed value was set extremely low (0.1). Stream flow experienced greater peak events, and these peaks were lagged by four days from the observed data in the watershed. We determined that the value of 6 cm/day for $K_{subsurface}$ resulted in the most accurate response for the watershed combined with a value of 1 cm/day for the springsheds.

For the soil depth in the springshed, we started with a shallow (i.e., 2-6 cm) soil depth at the spring location. Then, to test the most representative soil depth of the springsheds, we changed the incremental increase in soil depth from a 2 cm to 6 cm change for each 10 m cell's distance away from the spring. We found that a 4 cm and 6 cm increase in soil depth produced equally strong results. We selected a 4 cm increase in soil depth for the model simulations.

4.2 Sensitivity analysis

Soil depth varies across the site, although maximum soil depth in the watershed was measured at approximately 4.5 meters. Based on watershed conditions and field observations, we assumed this depth to be uniform across the site for purposes of modeling. However, we tested values from 3 to 5 m to see if significant changes in soil depth would have an influence on model results. We performed sensitivity analysis on the K_{sat} values, because measured values in the field showed a high variability. A range of values, between 10 cm/day and 1500 cm/day were used to test the sensitivity of the model to this parameter.

4.3 *Statistical assessment of modeling results*

We used four statistical tests to analyze simulated and observed stream flow responses at the watershed outlet. First, the Nash-Sutcliffe coefficient (N_S) was used to test model fitness and is defined as:

$$N_S = \frac{v_o n - \sum_{i=1}^{N}(x_i - y_i)^2}{v_o n} \quad (6)$$

where v_o is the variance of the observed values, n represents the number of data points, x_i is the observed value, and y_i is the simulated value (Nash and Sutcliffe 1970). The N_S values range from -1 to +1, with a value of 1.0 indicating exact agreement between observed and simulated values. The N_S coefficient is one of the most commonly used statistics to assess the accuracy of simulated results, although studies are more commonly using other criteria as well (Gupta et al. 1998; Jain and Sudheer 2009). We therefore used three other statistics in addition to the N_S.

The second statistical test used was the coefficient of determination, r^2, a measure of the proximity of modeled data to simulated data. The third test was the root-mean-square error, RMSE, which is related to the N_S coefficient and represents the standard deviation of difference between observed and simulated responses.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{n}} \quad (7)$$

where variables have been previously defined. RMSE values indicate average error in the model, expressed in cm $basin^{-1}$ day^{-1} with a value of 0 indicating no error. Finally, the mean difference, M_D, is the average or mean of the difference between the observed and simulated responses and describes the overall model bias in cm $basin^{-1}$ day^{-1}.

$$M_D = \frac{\sum_{i=1}^{N}(x_i - y_i)}{n} \quad (8)$$

5.0 Results

Model performance was assessed by comparing simulated and observed stream flow for each of the three years of data, as well as comparing simulated and observed groundwater for two years of observed data. Results from the SMR simulations are shown in Figure 4. In addition, spring flow output was compared against representative field measurements.

5.1 Observed hydrologic response in basin

Figure Figure 4 shows simulated and observed stream flow and precipitation. During the 2009 through 2011 years, a total of 966 cm of precipitation fell (318 cm for 2009, 334 for 2010, 314 for 2011). As evidenced from Figure 4, precipitation is relatively well distributed throughout the year. Total stream flow during this time period was 582 cm, or 60% of precipitation. Base flow sustains the stream flow during the year with peaks observed in the hydrograph following precipitation events. The largest peak flow event occurred on 12 January 2011 at 4.84 cm. Total measured ET was 226 cm, or 23% of precipitation.

Observed and simulated groundwater levels between June 2009 and April 2010 are also presented in Figure 5. WTL-2 (Figure 5a) exhibits a more stable response throughout the year, while WTL-4 (Figure 5b) appears to rapidly respond to precipitation inputs. We simulated groundwater levels with SMR and found that these levels were more responsive to precipitation, as seen in well WTL-4. The observed levels for WTL-2 mirror percolation levels that were simulated with SMR, which presents more stable groundwater levels throughout the year.

5.2 Water balance partitioning

Table 2 presents a detailed summary of the simulated mass balance components by year. SMR simulated that an average of 24% of precipitation exits the watershed as ET. Through our simulations, we calculated that a total of 67% of precipitation exits the watershed through percolation, or base flow, for all three years. When base flow is combined with overland flow, path and road runoff, and spring flow, a total of 76% of precipitation exits as stream flow, which is greater than the observed stream flow. Springs started to flow only with approximately 3 cm/basin/day or more of precipitation in the simulation.

5.3 Model validation and statistical assessment

Model validation was performed by analyzing results for data for 2010 and 2011 through statistical assessment and comparison of simulated data with observed stream flow, groundwater, and field measurements of spring flow. The amount of precipitation exiting the watershed as stream flow was similar in amounts between simulated and actual results, although simulated results were slightly higher as a percentage of throughfall. Observed data indicate that there is a watershed loss occurring in the system, and this amount varied between years, which could be the reason for the discrepancy. In simulated results, we assumed a 10% watershed loss in the system. Coefficients of the statistical analyses show that the model produced strong results (Table 3). For the 2009 calibration data the resulting N_S value was 0.83 (r^2 = 0.85). For the 2010 and 2011 validated data, the N_S values were 0.70 (r^2 = 0.91) and 0.90 (r^2 = 0.95), respectively. Also, the RMSE and M_D are low for all years.

5.4 Sensitivity analyses

By conducting the sensitivity analysis, we analyzed the thresholds that drive the model. Results of the sensitivity analyses are presented in Table 4. Results of the sensitivity analysis indicate that the model is not highly sensitive to the K_{sat} parameter according to statistical analysis. However, observations of the hydrologic response of the watershed provide insight into how this parameter influenced simulations. Low K_{sat} values (e.g., 10 cm/day) decreased spring flow significantly and caused base flow to underestimate stream flow for the dry season and overestimate for the rainy season. A high K_{sat} value (e.g., 2000 cm/day) resulted in greater base flow amounts with higher peaks.

For testing soil depth, we ran simulations with a 3 m and 5 m depths. We found that for the 3 m depths there was an increase in overland flow for the 2009 data. At 4 m, there was no overland flow simulated, as well as at 5 m. There was also a slight decrease in percolation amounts and slight increase in spring flow with the shallow depth.

When calibrating the model with the $K_{subsurface}$ value, the model is highly sensitive to this parameter. Lower $K_{subsurface}$ values (0.4 cm/day and lower) resulted in significantly reduced percolation (34% of incoming precipitation), but overland flow increased substantially with decreasing percolation. In addition, while moisture contents were measured at the site, we note that these values are highly variable throughout the field site and region. By adjusting some of these values, with a decrease in wilting point and field capacity, percolation values increased significantly. The model is very sensitive to moisture content values.

6.0 Discussion

6.1 Stream flow simulations

The SMR model produced results that were in good agreement with observed stream flow at the site, particularly when noting the results of statistical analyses. However, the overall amount of stream flow is overestimated with the SMR model, as simulation results reveal 76% of precipitation exits as stream flow, whereas observations suggest that 60% of precipitation exits as stream flow. The results for percolation are high (67% of precipitation), and with the addition of path and road runoff and spring flow the number increases above the observed amount. Further investigation of this discrepancy is needed.

6.2 Groundwater levels

SMR did a good job predicting shallow groundwater levels with a faster response to precipitation. However, we believe that two hydrologic responses are occurring within our study watershed, as identified by Gómez-Delgado et al. (2011), and comparing both WTL-2 and WTL-4 observed levels to deeper groundwater (i.e., percolation) and shallow groundwater (i.e., infiltrated water) exhibits this response. The observed levels at WTL-2 are steadier throughout the year and are indicative that a stable groundwater system is present, which matches our percolation simulated results. The observed levels at WTL-4 fluctuate and appear to have a faster response to precipitation inputs, which is indicative of a fast-response groundwater system that matches our simulated groundwater levels. The values for WTL-4 at the time of writing are similar in behavior, but further analysis on the actual soil depth where the perched water table starts developing will improve the fit with observed data.

6.3 Subsurface flow contributions

One of the primary research questions in this study was to determine the subsurface flow contributions between groundwater and springs in the watershed. Reference to Table 2 indicates that spring flow could contribute to approximately 6% of total stream flow for all three years, while base flow contributes 67% of total stream flow. Based on field observations, we estimate that ephemeral spring contribution is close to 5-10% of total spring flow, and therefore simulated results are close to the expected values. So, while overall stream flow is overestimated, it appears that too much water is allocated to base flow, or that the channel network itself experiences reinfiltration.

Additionally, one of the research questions for this study was whether we can model our conceptual understanding of how spring flow is generated in the study watershed. We hypothesized that shallow restrictive layers in the hillslope force water to exit the soil laterally as they saturate near the most shallow point (see Figure 3). In this region, the occurrence of spring flow seems to fit with the “fill and spill” mechanism observed by Tromp-van Meerveld and McDonnell (2006) and Toohey (2012). Tromp-van Meerveld and McDonnell (2006) showed that at a certain threshold value spill would occur on the site, while we observed that with a certain amount of precipitation (greater than 3 cm) springs will start to flow.

Observations and modeling indicate that ephemeral springs start flowing after significant precipitation. The inclusion of spring flow in the SMR model reveals the importance of this component to simulating flow peak events. As seen in Figure 4, spring flow has large peaks at the beginning of the years 2009 and 2011 in the transitional season, which comes immediately after the rainy season. The spring flow discharge likely is dependent on antecedent moisture conditions within the springsheds, and after more precipitation events in the rainy season the soil has less available storage so that springs can respond more quickly. Therefore, when a precipitation event occurs while the soil has a significant amount of available storage (i.e., during the dry season), the watershed experiences less spring flow than during the wet season.

6.4 Impervious surfaces

A second research objective was to determine what other hydrologic processes influence stream flow in the watershed. As seen in the previous section, stream flow is most significantly influenced by base flow and spring flow. However, in this watershed overland flow from semi-impervious areas is also a contributor. Relatively little (3%) of incoming precipitation becomes path and road runoff, and this amount is observed in the watershed during storm events. When erosion occurs from these areas, they may cause sedimentation in the stream channel. The amount that path and road runoff contributes is a relatively small component of stream flow but would be the largest contributor to erosion, since these surfaces are the primary area where there is overland flow. This information is important in the watershed provision of hydrologic environmental services in Costa Rica (as identified by Gomez-Delgado et al. *in review*), and the specific identification of areas that may cause erosion is a notable benefit of using a distributed model. Overland flow in other areas of the watershed does not contribute to overall stream flow.

6.5 Hydrologic understanding of the study site

Previous work by Spaans et al. (1989) and Toohey (2012) has shown that a high infiltration capacity exists in this region due to soil characteristics. Additional hydrometric and modeling work by Gómez-Delgado et al. (2011) and Benegas et al. (2013) confirm high infiltration rates at the study site. In this study, we confirmed the high infiltration capacities but also provide further information. Using the physically based distributed SMR model, and incorporating spring flow, we were able to simulate peak flows in the watershed with good agreement between observed and simulated stream flow. A distributed model allowed us to improve on simulated peak flows from previous modeling efforts using a lumped approach (Gomez-Delgado et al. 2010). Simulating groundwater levels enabled us to confirm that two different groundwater responses are occurring within the study basin, with a more stable groundwater layer and a layer that is more responsive to precipitation.

Additionally, SMR provided important spatially explicit information on areas of runoff. This information is particularly useful in situations where watersheds are under consideration for hydrologic environmental services. For example, erosion is of potential concern for hydropower provision, and this distributed model can point to specific areas within a watershed experiencing overland flow that could benefit from further management to reduce erosion.

By including physically based hydrologic components, such as semi-impervious overland flow and spring flow, that were important in our watershed, the SMR model not only accurately simulated results but also provided further insight into the hydrologic processes governing the system. This model could be useful in other watersheds or to consider different land management scenarios. For instance, using this watershed and substituting the land use and estimating ET measurements for a new land use, users can assess the impact of different land uses or management practices on hydrologic processes within the watershed. In addition, this model could be used to assess the impact of changing precipitation regimes that will be seen with climate change.

7.0 Conclusions

The ability to accurately simulate watershed responses is critical for hydrologic understanding and planning for water management and climate change. In this study, we applied the physically based SMR model to a microwatershed in Aquiares, Costa Rica to characterize hydrologic processes in the study watershed. The use of a distributed model allowed the inclusion of spatially explicit information, including the location of semi-impervious areas that contribute to storm flow and ephemeral streams that contribute to stream flow during high flow periods but often are not captured in modeling. The inclusion of these hydrologic components allowed us to obtain strong results.

The main goal of this study was to investigate subsurface flow in a small watershed. Additionally, we addressed the balance of subsurface flow contributions to streams and whether we could model our conceptual understanding of spring flow generation in the watershed. According to statistical analyses, such as the Nash-Sutcliffe coefficients, the SMR model produced a good fit with observed data for three years of study. By conducting a sensitivity analysis and including spatially explicit information, including the locations of paths, roads, and springs, the results simulated peak flow during storm events and provided new insight into the hydrologic processes governing the watershed. Through this work, we found that we were able to model our conceptual understanding of spring flow generation in the study watershed. Additionally, we found that semi-impervious areas represent a relatively small area within the watershed but have the potential to significantly influence stream flow in this watershed.

This model with the incorporated additions could be tested in other watersheds and in other regions, to further refine the spring flow component. More work on the understanding the processes driving generation of spring flow is necessary. In addition, this model can be used to analyze the impacts of different management practices, land use conversion, and climate change regimes.

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Table 1: Description of parameter values used for SMR model simulation.

Parameter	Value	Notes
d	400 cm springs vary	Based on field measurements 200 cm for upper layer and 200 cm for lower layer; Spring watersheds varied by 4 cm every 10 m from spring
θ_{wp}	0.43 (upper) 0.43 (lower)	Measured through laboratory calculations; also measured by Toohey (2012)
θ_{fc}	0.55 (upper) 0.56 (lower)	Measured through laboratory calculations
θ_{s}	0.688 0.713	Measured; calculated from porosity
K_{sat}	150 cm/day 120 cm/day	Measured by Benegas et al. (2013) and Toohey (2012)
$K_{subsurface}$	1 cm/day (spring areas) 6 cm/day (watershed)	Determined through calibration
ϕ	0.688 (upper) 0.713 (lower)	Measured; calculated through bulk density measurements
RC	0.26 (upper) 0.37 (lower)	Measured in field

Note: d = depth; θ_{wp} = wilting point moisture content; θ_{fc} = field capacity moisture content; θ_{sat} = saturated moisture content; K_{sat} = saturated hydraulic conductivity; $K_{subsurface}$ = vertical hydraulic conductivity through restrictive layer; ϕ = porosity; and RC = rock content. For parameters where different values were used for the upper layer (0-200 cm depth) and the lower layer (200-400 cm depth), values are noted with "upper" and "lower."

Table 2: Mass balance components (cm/basin/year) for SMR model for each year of simulation compared with measured mass balance components.

Component	Amount (% of Throughfall)				Notes
	2009	2010	2011	All Years	
Throughfall	313 (100%)	330 (100%)	309 (100%)	951 (100%)	Equals precipitation minus canopy evaporation and storage
Total ET	79 (25.2%)	74 (22.3%)	73 (23.6%)	226 (23.7%)	
Percolation	207 (66.4%)	223 (67.6%)	203 (65.8%)	634 (66.6%)	
Overland flow	0 (0%)	0 (0%)	0.1 (0%)	0.1 (0%)	Only from coffee land cover
Path/Road runoff	9 (3.0%)	10 (3.0%)	9 (3.1%)	29 (3.0%)	
Spring flow	17 (5.3%)	19 (5.7%)	23 (7.5%)	58 (6.13%)	
Change in storage	-0.6 (-0.2%)	2.5 (0.8%)	-1.3 (-0.4%)	0 (0%)	
Mass balance difference	**0.3%**	**0.6%**	**0.4%**	**0.5%**	Equal to throughfall minus remaining components
Measured Hydrologic Components in Watershed					
Precipitation	318	334	314	966	Measured value
Actual ET	80 (25%)	76 (23%)	73 (23%)	229 (24%)	Measured value
Measured stream flow	205 (64%)	177 (53%)	201 (64%)	583 (60%)	Measured value

Note: Percentage in parenthesis represents percent of throughfall for each component.

Table 3: Statistical analysis of fit used to evaluate the SMR model for stream flow (Q: cm basin^{-1} day^{-1}).

Statistical Analysis	2009	2010	2011	All years
N_S	0.83	0.70	0.90	0.84
R^2	0.85	0.91	0.95	0.90
RMSE (cm basin^{-1} day^{-1})	0.17	0.22	0.19	0.20
M_D (cm basin^{-1} day^{-1})	-0.051	-0.177	-0.108	-0.112

Note: N_S = Nash-Sutcliffe coefficient, R^2 = coefficient of determination, RMSE = root-mean-square error, and M_D = mean difference between measured and simulated value.

Table 4: Sensitivity analysis performed on key hydrologic parameters for SMR model.

Parameter	Value	Statistical Fit (N_S)	Mass Balance Data (%)
K_{sat} (cm/day)	10	0.83	0.18
	50	0.82	0.19
	100	0.82	0.14
	200	0.82	0.21
	500	0.83	0.37
	1000	0.85	0.57
	2000	0.86	-0.08
d (cm)	300	0.87	0.37
	500	0.88	0.39

Note: K_{sat} = saturated hydraulic conductivity; d = soil depth; N_S = Nash-Sutcliffe coefficient

Figures

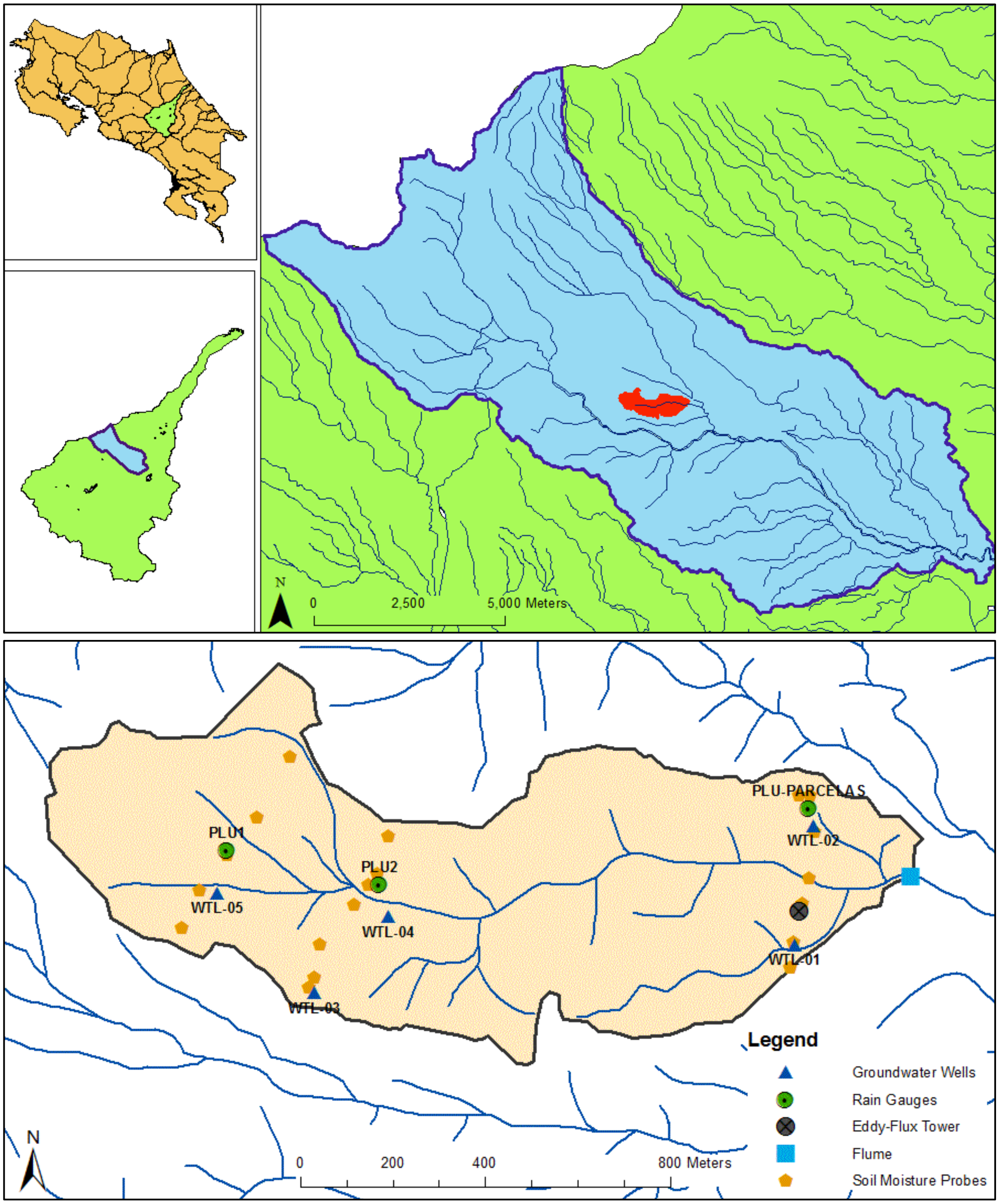

Figure 1: Location of a) Reventazón watershed (green) in Costa Rica, b) Turrialba watershed (blue), c) the Mejías Creek microwatershed study site (red), and d) study watershed experimental setup.

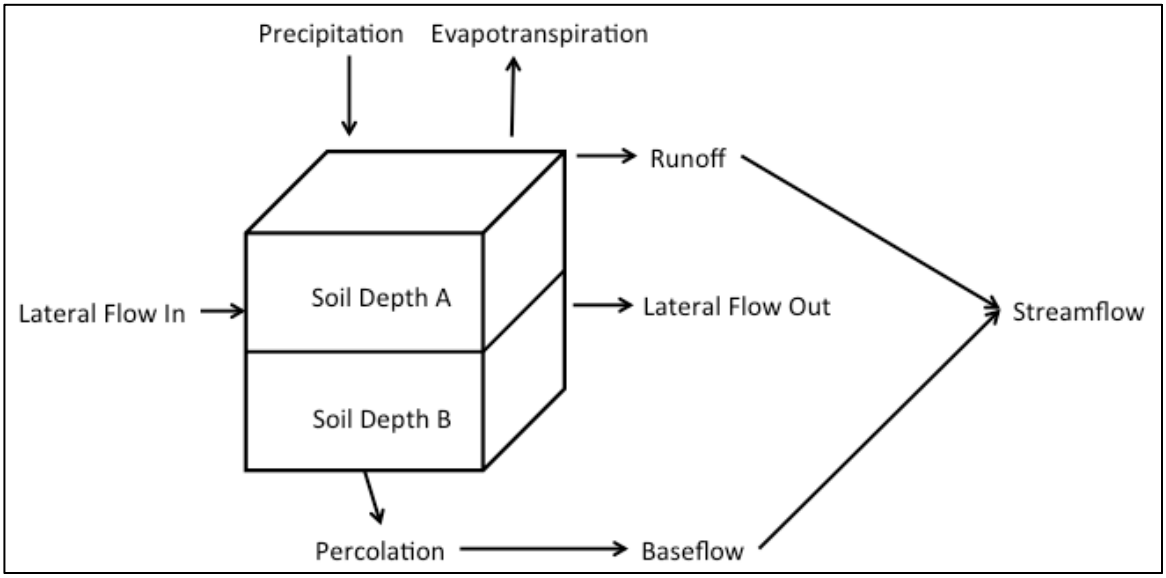

Figure 2: Conceptual diagram of SMR hydrologic model, adapted from Frankenberger et al. (1999a).

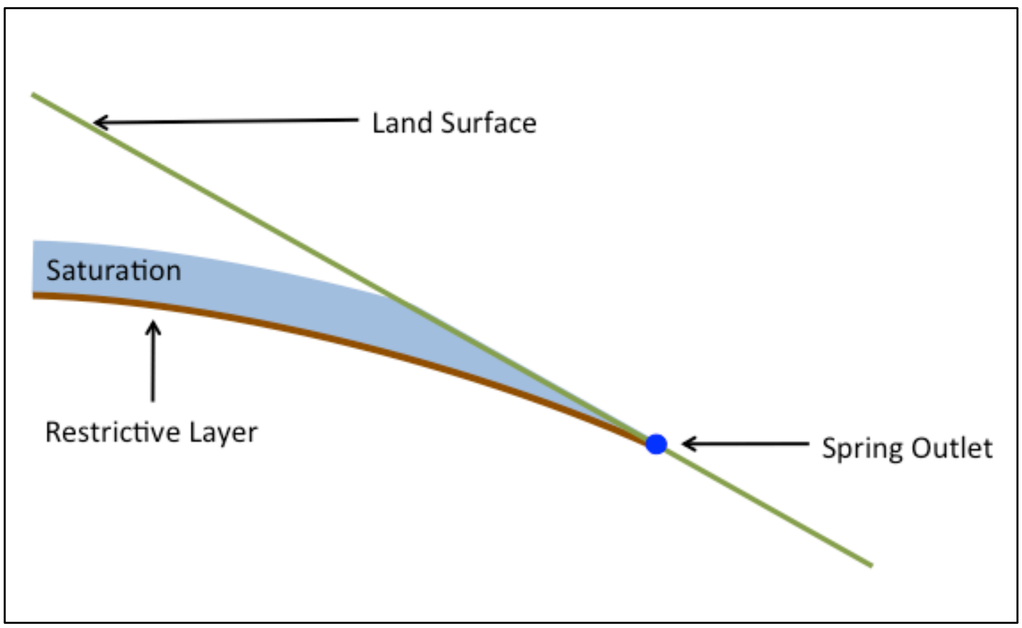

Figure 3: Side profile of hillslope with spring showing slope of spring restrictive layer.

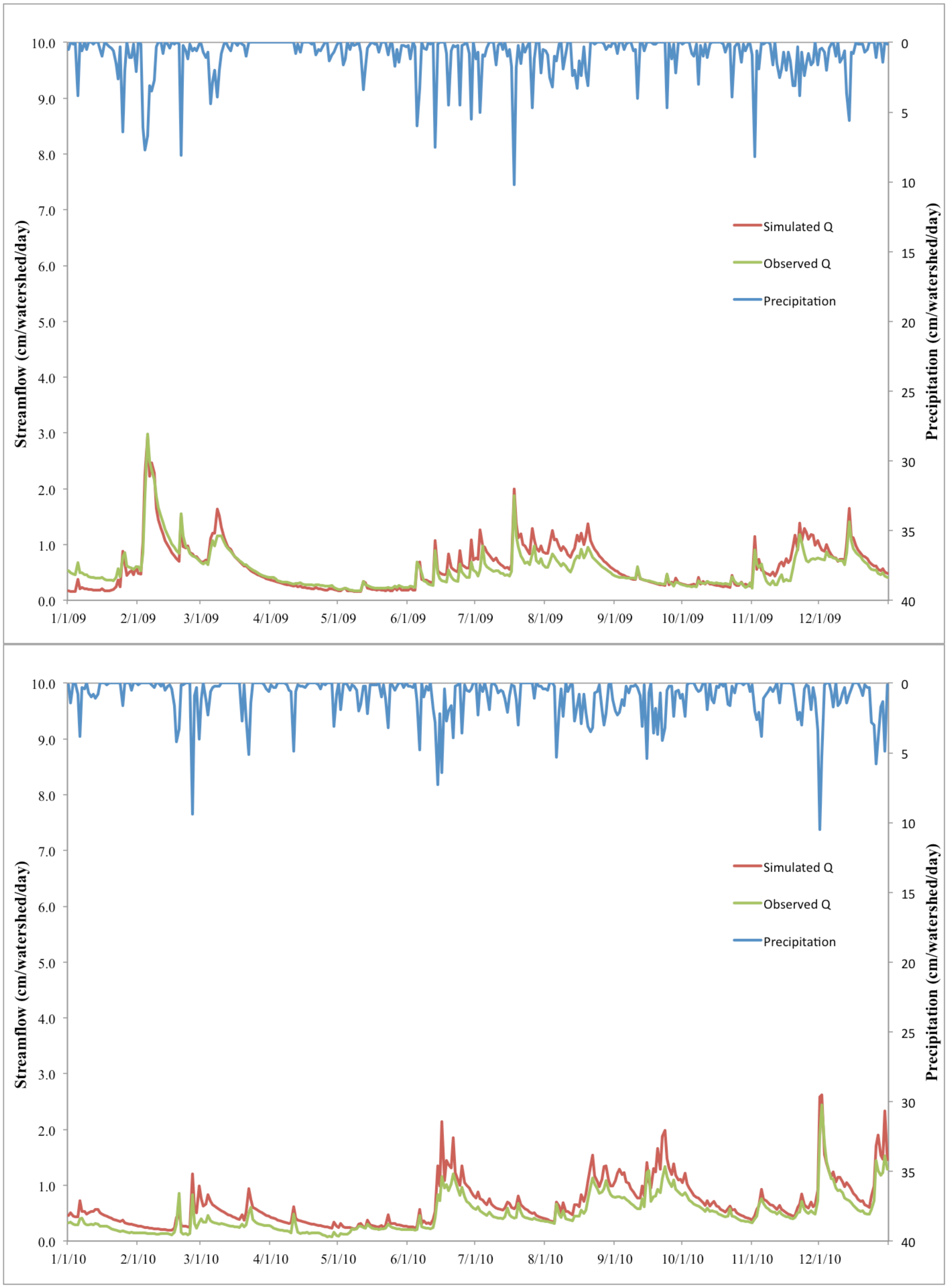

Figure 4: Observed versus simulated stream flow (cm/basin/year) and precipitation amounts for 2009 (a) and 2010 (b).

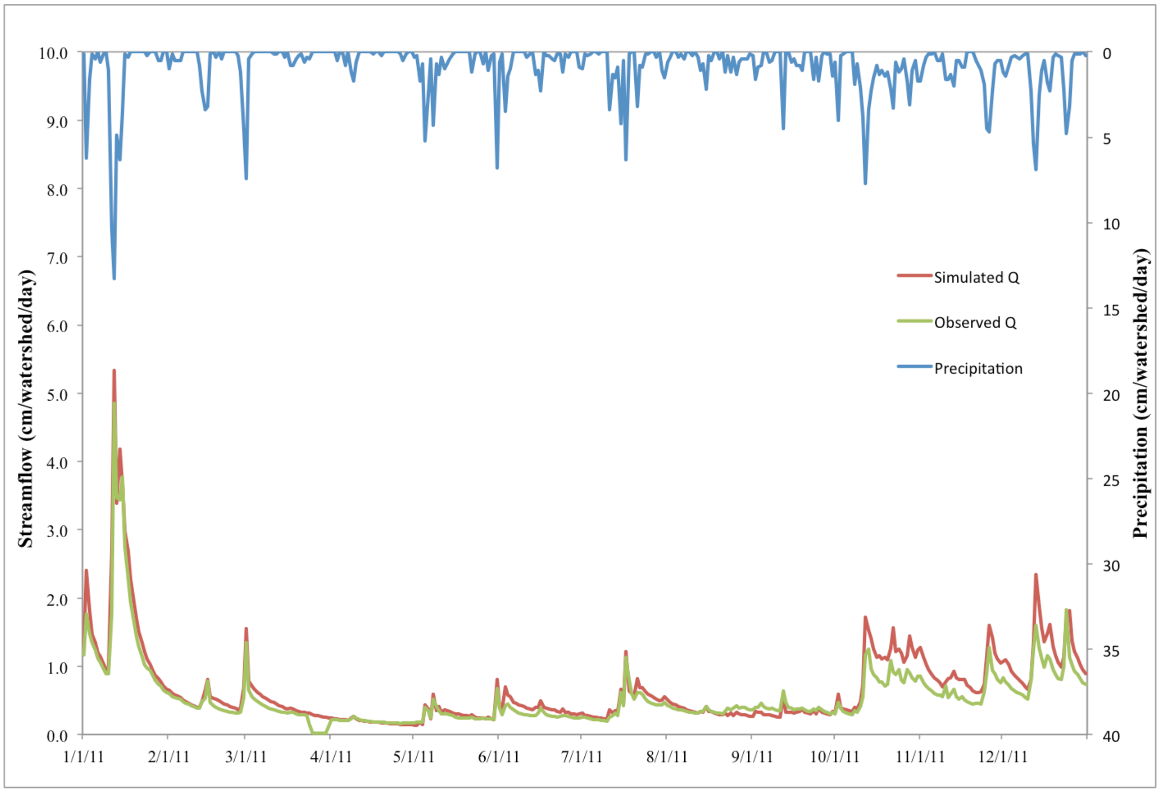

Figure 4 (cont): Observed versus simulated stream flow (cm/basin/year) and precipitation amounts for 2011 (c).

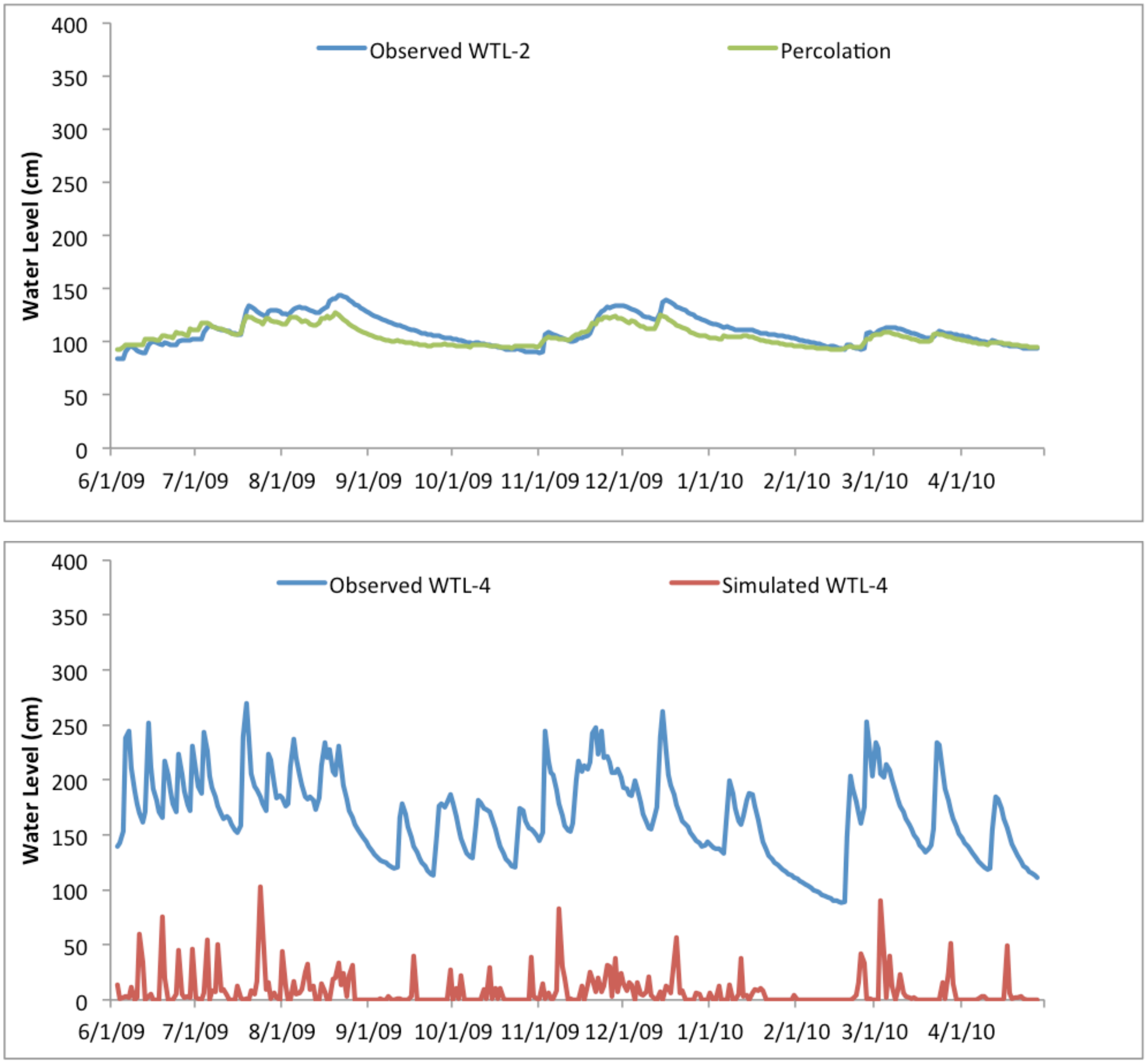

Figure 5: Observed groundwater levels at two well locations (WTL-2 and WTL-4) that exhibit different hydrologic responses. Observed levels for WTL-2 (a) match percolation levels, while WTL-4 (b) matches better with simulated levels with higher precipitation response.

Chapter 4: Reconciling resource management with the landscape: An approach to identify scale mis-fit in social-ecological systems

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Keywords: natural resource governance; scale; scale mis-fit; social-ecological systems; water resources

Abstract

Scale mis-fit occurs when natural resources are not managed at the spatial or temporal scale at which they are provisioned. Issues of scale mis-fit abound in social-ecological systems. They can hinder efforts to effectively manage resources and threaten resilience of the larger ecosystem, thus affecting societal well-being and livelihoods. Here, we present an approach to identify issues of scale mis-fit. Our approach can be used to define a specific natural resource problem, determine the scales at which relevant biophysical processes and management actions occur, assess spatial and temporal scale mis-fits, and identify potential solutions. We provide two case studies of drinking water resource management in Costa Rica and the Pacific Northwest United States as applications of our approach to natural resource management. While our case studies focus on a subset of water resources, the approach we present is broadly applicable to an array of social-ecological systems.

1.0 Introduction

Humans rely on natural resource provision for many facets of life, including sustenance, energy, livelihoods, recreation, and shelter. Effective management of natural resources is crucial to ensure their sustained use. Natural resource provision results from complex ecosystem interactions occurring across spatial and temporal scales, but resource use by society often occurs without understanding of the multi-scale biophysical processes that produce the resource or the complex response to management (Levin 1992). As a result, this lack of understanding is often exacerbated when management of natural resources occurs at different scales than those at which natural resources are provisioned and has been recognized within a variety of social-ecological systems (SES) and governance approaches (Ludwig and Smith 2005, Cumming et al. 2006, Dore and Lebel 2010, Termeer et al. 2010, Carmona-Torres et al. 2011, Apostolopoulou and Paloniemi 2012, Johnson et al. 2012, Paloniemi et al. 2012, Vervoort et al. 2012, Cumming et al. 2013).

Failing to manage natural resources at the appropriate scales can compromise both the long-term availability of the resource and the functioning of the larger SES (Lee 1993, Cumming et al. 2006, Wilson 2006, Dore and Lebel 2010, Moss and Newig 2010, Johnson et al. 2012, Fremier et al. 2013). Therefore, effective management of natural resources requires reconciling complex biophysical and social interactions that occur across different temporal and spatial scales within an SES (Gunderson and Holling 2002, Cash et al. 2006, Cumming et al. 2006) to fit management actions to the scales at which biophysical processes are provisioning the natural resource.

The SES perspective to natural resource management has emerged from the recognition that: (i) interactions and feedbacks between the biophysical processes that provision resources and actions related to their management commonly occur, (ii) unexpected changes in natural resource availability are common (e.g., due to natural and social system dynamics), and (iii) management actions aimed at adapting to changes in natural resource flows, rather than maintaining constancy, are necessary to sustain natural resource availability (Folke 2006). Thus, the SES framework requires holistic approaches to management that integrate system components (social and ecological) and their interactions to analyze and elucidate problems of natural resource sustainability (Liu et al. 2007, Ostrom

2009). Interdisciplinary SES approaches provide a unique opportunity to analyze complex environmental problems from varying perspectives and to investigate a problem more thoroughly (Newell 2001).

Scale mis-fit commonly exists and has been recognized within SES; however, systematic approaches to identify scale mis-fit are lacking. Therefore, we present an integrated approach to analyze natural resource problems using a scale mis-fit lens that deconstructs components of an SES while enhancing understanding of complex interactions within the system. Users of this approach determine the scales at which relevant biophysical and governance processes occur to identify spatial and temporal scale mis-fit and propose potential solutions to a natural resource problem in an effort to align management actions to the relevant biophysical scales.

We suggest that framing complex natural resource issues explicitly in terms of spatial and temporal scales may allow for new insights to identify, analyze, and resolve natural resource problems in SES. By defining a system based on the scales of biophysical processes that sustain natural resources and the scales of management actions that influence these processes, the complex interactions between the biophysical and human components of the SES can be reduced to fundamental elements underlying a specific natural resource problem. This clarity may reveal critical mis-fits in the scales of biophysical processes and management actions, highlighting possible improvements for natural resource problems. For example, natural cycles of forest loss and regeneration take much longer than historical management practices of wildfire suppression allowed. Recognizing this as a temporal scale mis-fit places more focus on defining management actions that allow forests to burn at a recurrence interval that better aligns with natural forest regeneration processes.

Our approach is designed for researchers, managers, and other practitioners to become aware of spatial and temporal scale mis-fits within various SES and identify solutions to address problems arising from them. The overall goal of this approach is to advance management by understanding the integrated biophysical and governance context of natural resource problems and applying that understanding to management actions. Systematically identifying sources of scale mis-fit and outlining solution options will assist users in achieving this goal. We recognize that no simple or single solution exists for resolving scale mis-fit complexity. However, this approach can be useful across a wide variety of SES to identify scale mis-fits and possible solutions without suggesting panaceas (Bovens and Hart 1996, Brunner et al. 2005, Ostrom et al. 2007).

1.1 Scale mis-fit definitions

Scale is a fundamental aspect of social, physical, and biological systems and is considered a unifying concept between different academic traditions (Silver 2008). Scale has previously been studied and defined in the literature (see Gibson et al. 2000, Young 2002, Cash et al. 2006, Cumming et al. 2006), and we adopt the definition “dimensions used to measure and study any phenomenon” (Gibson et al. 2000, p. 218) However, both within scientific literature and colloquially, scale is also used as an overarching term to refer to points along a spatial or temporal scale. We adopt this common terminology. For example, the terms “national scale” and “local scale” (i.e., jurisdictional boundaries) and the term “watershed scale” refer to different geographically defined areas on a spatial scale; different time frames (e.g., decades or minutes) refer to different points along a temporal scale. Box 1 presents several key definitions related to scale that we have adopted for this approach.

Here, biophysical processes are the interactions between two or more components of a natural system that contribute to the provisioning of a resource. We use the term biophysical explicitly to include both biological and physical components of an SES. The term management specifically refers to the actions of overseeing resource provision and usage. Management actions are the implementation of rules and regulations that are determined by governance processes, which occur through the larger social system (Parkes et al. 2010). Governance processes extend beyond formal government and include the actions of all individuals and institutions involved in making decisions and establishing rules and norms that influence a natural resource (Richards and Smith 2002, Graham et al. 2003, Armitage and Plummer 2010).

We define scale mis-fit as a discrepancy between the scales of biophysical processes and management actions (Box 1). Spatial and temporal scale mis-fits exist when adequate management actions do not occur at the spatial scales (i.e., geographic areas) or temporal scales (i.e., amount of time) most relevant to the biophysical processes provisioning the resource. Although governance processes occur at multiple scales, resolving scale mis-fit problems necessitates adequate management actions at the spatial and temporal scales most relevant for the biophysical processes specific to the natural resource problem of concern.

1.2 Sources and consequences of scale mis-fit

Scale mis-fit in SES may arise from a variety of causes. Note that the terms “mis-fit” and “mismatch” are often used synonymously; we prefer the term “mis-fit” because it does not imply the existence or feasibility of an exact match between scales and/or processes. Cumming et al. (2006) categorize sources of scale mis-fit (referred to by the authors as “scale mismatch”) as mainly social, ecological, or coupled social-ecological, clarifying that mis-fit can be caused by environmental factors, the organizations responsible for management, or interactions between them. These authors provide examples of environmental sources of scale mis-fit including natural cycles within ecological communities (e.g., due to disease outbreaks or predator-prey interactions) or unexpected environmental responses to management. They also describe social drivers of scale mis-fit as changes in land tenure, technology, human population growth, markets, infrastructure, and values. Others have further described the sources of scale mis-fit as rooted specifically in the governance system, such as imperfect knowledge about the biophysical system being managed (Hessl 2002, Apostolopoulou and Paloniemi 2012), constraints within the institutions charged with management (Paloniemi et al. 2012), short-term economic returns overshadowing environmental processes in policy development (Ludwig and Smith 2005, Dore and Lebel 2010, Ahlborg and Nightingale 2012, Paloniemi et al. 2012), and difficulty in adapting legislation and agency practices to meet environmental needs (Gibson et al. 2000, Young 2002). In our view, the primary source of scale mis-fit is a failure to fully understand and consider the scales of biophysical processes provisioning a resource and to subsequently align management actions and governance processes accordingly.

A lack of understanding or recognition of the most relevant scales at which biophysical processes provision a resource can hinder efforts to align resource management with these processes (Cash et al. 2006). For instance, Johnson et al. (2012) explored potential causes of sea urchin declines in Maine, USA in the late twentieth century. They concluded that the small-scale biophysical processes most important for maintaining sustainable sea urchin fishery levels (local migration of sea urchins to areas in which they were easily harvested) were not adequately incorporated into state-scale fishery co-management policies, resulting in persistent sea urchin decline. In another example in the western United States, management actions designed with a temporal understanding discordant with cross-scale ecological dynamics, including forest dynamics, grazer population dynamics, and fire regime, have also have been blamed for decline of forests (Holling 1986, Hessl 2002). Furthermore, since natural systems rarely follow socio-political boundaries, consequences of management actions in one region can have transboundary effects. For example, upstream river degradation can influence downstream water quality, flood occurrence, and fisheries (Fremier et al. 2013). While it is increasingly evident that effective resource management necessitates that social processes are consistent with the scales of related biophysical processes (Cleveland et al. 1996), scale mis-fit continues to exist within many SES and contribute to many environmental problems (Young 2002).

1.3 Toward an approach to identify and address scale mis-fit

Many examples of natural resource problems resulting from scale mis-fit in SES exist in the literature (Wilson 2006, Dore and Lebel 2010, Ahlborg and Nightingale 2012, Apostolopoulou and Paloniemi 2012, Johnson et al. 2012, Kane 2012, Vervoort et al. 2012). However, systematic identification and analysis of scale mis-fit is lacking. Moreover, identifying problems related to mis-fit prior to natural resource decline or system collapse is more effective to prevent and mitigate problems than retrospective analysis. Cumming et al. (2006) concluded that once identified, resolving scale mis-fit first requires an awareness of how scale contributes to problems within an SES, followed by the development of a range of potential solutions. We build on this conclusion by proposing that systematic problem definition should be the first step towards diagnosing and potentially resolving issues of scale mis-fit and presenting a process for identifying scale mis-fit.

Our approach to identify and analyze scale mis-fit integrates concepts from existing theoretical frameworks, mainly the policy sciences (Lasswell 1968, Clark 2002) and social-ecological resilience (Cumming et al. 2005, Walker and Salt 2006, Walker and Salt 2012). Both frameworks have been used to map biophysical and social processes within SES (Walker et al. 2002, Rutherford et al. 2009, Wilshusen 2009, Brunner and Lynch 2010, Walker and Salt 2012), and our approach incorporates insights from specific aspects of each of them. The policy sciences framework offers a problem definition process as a starting point for natural resource managers to guide their analysis and resolution of complex problems (Clark 2002, Lynch et al. 2013, Hammer 2013). Resilience theory, with its origins in describing non-linear behaviors in biophysical systems (Holling 1973), offers tools to assess complex dynamics in coupled SES (Walker and Salt 2006). These frameworks help define a system based on available knowledge and we propose applying this knowledge specifically to identify issues of scale mis-fit and potential ways of improving alignment of management actions to the relevant scales of resource-sustaining biophysical processes. In our approach, we reiterate the emphasis that both of these frameworks place on promoting participatory processes to engage multiple stakeholders in research and practical applications of analyzing these dynamics in SES (Clark 2002, Walker et al. 2002, Walker and Salt 2012).

Much of the published literature related to scale mis-fit in SES focuses primarily on the effects of scale mis-fit in natural resource provisioning (Gunderson and Holling 2002, Cumming et al. 2006, Moss & Newig 2010, Carmona-Torres et al. 2011, Ahlborg and Nightingale 2012, Johnson et al. 2012, Vatn and Vedeld 2012, Vervoort et al. 2012). Identifying effective solutions to problems within SES often requires addressing scale mis-fit, although tools to identify and analyze scale mis-fit are lacking. The only approach that we have found in the literature to identify scale mis-fit is presented by Ludwig and Smith (2005) based on Walker et al. (2002). Their four-step approach to address scale mis-fit uses resilience analysis in Australian rangelands. The steps include: (i) mapping the scales at which key processes and components of the SES occur, (ii) evaluating potential trajectories of the SES, (iii) assessing the effects of scale mis-fits driving uncertainty in trajectory predictions, and (iv) gauging how different methods for correcting scale mis-fits may affect management actions. We expand on this approach by beginning with focused problem orientation, followed by a systematic appraisal of the relevant scales for both the biophysical processes that provision a natural resource and the management actions pertinent to the stated problem.

2.0 An Approach to Identify Scale Mis-fit

Our stepwise approach to identify and address scale mis-fit in SES is presented in Box 2 as a series of six steps, where each step builds on understanding gained in previous steps. The approach is designed to focus on one specific natural resource problem, although many problems may exist within an SES. We see great value in using professionally facilitated, interactive processes engaging multiple stakeholders to complete these steps.

3.0 Scale Mis-fit in Water Resource Management

We found our approach useful for examining case studies in water resource management, where scale mis-fit exists prominently (Cash et al. 2006, Dore and Lebel 2010, Moss and Newig 2010) but has not been resolved effectively (Poff et al. 2003). As with other natural resources, the biophysical processes that influence water resources occur at multiple spatial scales ranging from small-scale molecular processes (e.g., interactions between chemical pollutants) to large-scale basin, continental, or global-level processes (e.g., groundwater flow and climate, flood, and drought regimes). Management actions often are not aligned with the scales of these biophysical processes. For example, political boundaries generally do not follow watershed boundaries, making watershed management more complex when crossing multiple jurisdictions. Moreover, defaulting to a focus at the watershed scale could ignore or fail to prioritize biophysical processes that occur at different scales, such as climate regimes or groundwater recharge, which do not generally adhere to topographic watershed boundaries (*sensu* Vatn and Vedeld 2012).

One example of an effort to address issues of scale in water resource management problems is Integrated Water Resource Management (IWRM). IWRM promotes both a watershed vision for management actions (Agarwal et al. 2000) and integration of governmental authority over various activities that impact the water resource (Cosens and Stow 2014). However, water resource problems are often very unique and cannot utilize one standard solution (Biswas 2004). While IWRM is an attempt to address water issues at the most appropriate biophysical spatial scale (i.e., the watershed), some point out that the watershed is not always the most appropriate scale of addressing governance processes (Cohen and Davidson 2011). In addition, despite the prevalence of scale issues in water resource systems, IWRM principles do not specifically address the issue of scale mis-fit. IWRM is designed to address fragmentation in management of human activities that affect the same connected water resource. While this may at times address scale issues, they are not the focus. Ultimately, given the multiple spatial and temporal scales that are involved in water resources, water management must address scale mis-fit issues to be effective and to produce long-term results. In addition, participatory methods that engage multiple stakeholders have been particularly effective in establishing opportunities to overcome scale mis-fit (Dore and Lebel 2010) and in enabling vertical integration, linking the levels of water governance (Knuppe and Pahl-Wostl 2011). We demonstrate how our approach promotes integration and multi-scale considerations in two water resource management case studies.

3.1 Case studies: Water resource management in Costa Rica and the Pacific Northwest USA

We present two case studies focused on drinking water management to demonstrate the utility of our approach in analyzing SES problems. By presenting these case studies, we aim to contribute to the continuing development of heuristic approaches to identify, understand, and resolve scale mis-fit. The first case is based in Costa Rica and was developed through interdisciplinary teamwork of four doctoral students in the Joint Doctoral Program between the Tropical Agricultural Research and Higher Education Center (CATIE) and the University of Idaho (UI). The second case is based in the western United States and draws from long-term involvement of the University of Idaho in scientific studies on regional water resources, as well as interdisciplinary studies by faculty and students in the UI Waters of the West Program. With both case studies, we present relevant background information before using our scale mis-fit approach to analyze the SES.

3.2 Costa Rica case study background

The Costa Rica case study focuses on drinking water quality in rural communities in the Cartago Province of central Costa Rica. This case study draws from findings from interviews with community organizations and government agencies involved in drinking water management and a survey and workshop with community drinking water organizations in the study region. Drinking water quality remains largely unknown, although potentially hazardous contaminants, such as agrochemicals, are used within the watershed and are likely entering community water sources. Throughout the country, local community-based drinking water organizations (CBDWOs, or ASADAs and CAAR in Spanish) are responsible for overseeing the management and provision of drinking water in rural communities. In this region, drinking water is piped directly from springs and most CBDWOs use chlorine treatments to reduce the risk of bacterial contamination. Water quality testing is conducted once every six months to two years, if at all. In addition, common land uses within the contributing area include agriculture and pasture, and contaminants from these practices threaten water quality. The Water Law (Costa Rica Government 1942) and the Environmental Law (Costa Rica Government 1995) mandate forested protection zones of 200 m and 100 m radii, respectively, around the spring. Most citizens are uncertain about which radius to use, and enforcement of the two laws is minimal. Moreover, these protection zones are not based on scientific evidence. The upstream area contributing to a spring (springshed) lies largely unprotected, while the majority of the protected area lies downstream of the spring in areas that do not contribute groundwater to the spring flow (Figure 1). Therefore, much of the springshed is not protected under the two laws. We use the term springshed to refer to the area of land in which water infiltrates into the ground and exits at a common spring source. We differentiate springshed from watershed, which is typically determined by topography, since springs mainly rely on only groundwater sources that may not follow topographic relief.

As a result of the discrepancy between the protection areas and the boundaries of the springsheds, CBDWOs often are not aware of the influence that the springshed has on water quality and do not monitor activities that occur in these regions. Due to limited or non-existent water quality testing, CBDWOs and users lack information about the quality of their drinking water sources. Potential threats that exist in the springshed interfere with the ability of CBDWOs to provide potable drinking water for local communities. In some cases these threats may pose hazardous to community members' health. Limited financial and human resources prevent communities and government agencies from conducting studies to identify where groundwater recharge occurs, to determine whether water contamination is occurring within the springshed, and to establish effective management plans.

3.2.1 *Six-step approach applied to the Costa Rica case*

Using the six-step approach presented in Box 2, we analyze the SES related to drinking water in the Cartago province of Costa Rica.

Step 1: Drinking water quality is a significant concern within rural communities of Costa Rica. Water quality monitoring is infrequent, and understanding of groundwater recharge zones for the springs is limited, preventing CBDWOs from identifying both potential contaminants and the human actions that are responsible for contamination. This uncertainty about water quality jeopardizes human health.

Step 2: Many biophysical processes influence the provision of clean drinking water, including climate processes (precipitation) and hydrogeologic processes (infiltration, groundwater flow, and spring water discharge). Precipitation occurs at a regional scale, while the interactions between infiltrated water, groundwater, and spring water occur at the scale of the springshed. Precipitation occurs on the order of minutes to hours, while infiltration and shallow groundwater flow to springs occur on the order of hours to months, depending on springshed size, soil parameters, and precipitation intensity and magnitude. In order to address the problem of focus, the relevant spatial scale is the springshed, while the relevant temporal scale is in the range of hours to days.

Step 3: Human activities primarily influence water quality through land use management practices. Within the springsheds, which are not protected by the Water Law (1942) or Environmental Law (1996), many concerning land uses occur, such as intensive agriculture and cattle grazing. Agrochemicals applied to crops and fecal coliforms from cattle manure can enter soils and flow to the spring on the temporal scale of hours to days.

Step 4: Several institutions are responsible for management actions and governance processes in this region. The National Institute for Water and Sewage (ICAA, or AyA in Spanish) is responsible for providing CBDWO administrative support; they also provide occasional training and limited financial resources. The Ministry of Energy and the Environment (MINAE) developed and enforces the Environmental Law (Costa Rica Government 1995) that stipulates the 100 m radius protection area around drinking water sources. The Water Law (Costa Rica Government 1942) stipulates the 200 m radius (Figure 1). The CBDWOs act on the local community scale to develop spring sources, maintain infrastructure for water delivery, collect fees, and finance maintenance of the system. Spatially, management actions are limited to areas directly around the springs, although very few springs are fully protected by the mandated 100 and 200 m radius zones. Temporally, the relevant management actions, water quality tests, generally occur on a scale from once every six months (most frequent) to once every two years (least frequent), or sometimes not at all.

Step 5: The relevant biophysical spatial scale is the springshed, where recharge contributes to spring flow. Land use within the springshed, including agriculture and cattle grazing, threatens water quality, but management actions to regulate these practices, when undertaken, usually only occur within the 100 to 200 m surrounding the springs. Of the limited management practices undertaken to mitigate the effects of land use on water quality, many are targeted in locations outside of the springshed, downslope of the spring in the area that does not contribute to spring flow. Therefore, there is a spatial scale mis-fit between the scale of drinking water management with the scale of the biophysical processes that provision the resource. Management actions also do not occur at the temporal scales most relevant for drinking water provisioning. Water quality tests are conducted infrequently, but potential threats to water quality (e.g., agrochemicals and fecal coliforms) are possibly occurring in the springshed, ranging on the order of minutes to days (Figure 2). Therefore, the limited testing that is conducted has a high probability of not identifying any acute contaminants that pass through the system; this results in a temporal scale mis-fit.

Step 6: To address these scale mis-fits, management actions are needed at the springshed scale, and governance processes should focus on establishing the springshed as the protection area for management focus. Delineation of springshed boundaries requires significant resources given the difficulty of determining the extent of groundwater contribution to springs. However, the watershed, based on topographic boundaries, may be initially considered, given the likelihood of significant overlap with the springshed. Also, the watershed is a more feasible and cost-effective scale to begin protecting. More frequent water quality monitoring aligned with the temporal scale of infiltration and shallow groundwater flow rates is also needed to identify potential rapid changes on the landscape that lead to contamination of drinking water supplies.

Potential short-term solutions include delineating watershed boundaries for all springs and conducting targeted sampling after rainfall events when occurrence of contaminants might be greatest. Two medium-term solutions could include 1) developing a monitoring plan to capture the appropriate spatial extent and temporal variability of the biophysical processes to sustain consistent, clean drinking water for the communities, and 2) forming regional bridging organizations (i.e., a watershed management group) among CBDWO water managers to promote water quality training, shared knowledge, communication, and collective garnering of financial resources. Two potential long-term solutions are to 1) modify existing laws and enforcement mechanisms to establish appropriate upslope spring protection areas and focus management actions at the watershed scale and 2) determine groundwater contributions to the springs for management at the springshed scale.

3.2.2 Overview of the six-step approach in Costa Rica

Applying the six-step approach to this SES in Costa Rica reveals a predominant issue of spatial scale mis-fit involved in drinking water management, as management actions do not exist at springshed levels. The spatial scale of biophysical processes responsible for water provisioning (i.e., the springshed) is not sufficiently considered in the design of Costa Rican drinking water management policy. Use of this approach indicates that several potential options exist for community members to address water quality in this region, including short-term efforts that can provide insight into the problem while longer-term solutions are refined and implemented. Results of our approach also emphasize the importance of monitoring water resource dynamics at the appropriate temporal scale. The strategy of focusing water protection efforts at the springshed scale, monitoring spring water quality more frequently, and sharing this information throughout a local CBDWO network would establish community knowledge to inform short-term actions in lieu of long-term policy that will require significant time to reform. Therefore, a change in the spatial and temporal scale of management actions would more closely align the governance actions with the biophysical processes for water provision in this particular case as well as in other cases facing similar issues.

3.3 Palouse Basin case study background

The Palouse Basin case study focuses on groundwater availability in the Palouse Basin located in the Inland Northwest of the United Sates (Figure 3). The majority of water from the basin is pumped from the Grande Ronde, a deep fractured basalt aquifer that provides groundwater for domestic and industrial users located in the Idaho and Washington states. Significant concern exists over aquifer levels, which have been declining at a rate of 20-45 cm per year for the past 60 years (see Figure 4; Beall et al. 2011, Moran 2011) with no direct evidence of aquifer recharge (Belknap 1999). Water allocation occurs at the state level in the United States (California Oregon Power Co. v. Beaver Portland Cement Co. 1935, Tarlock 2011), but the Washington/Idaho state line divides the Grande Ronde Aquifer. Idaho state law prohibits aquifer mining, defined as water pumping rates that exceed the rate of natural groundwater recharge (Idaho Statutes 42-237a(g)). Therefore, the occurrence of aquifer mining as defined by law cannot be determined without knowing the recharge rate, which has not been determined in this case. Washington state law is less specific but prohibits pumping beyond the source's yield capacity (RCW 90.44.070), which has not yet been scientifically determined for this aquifer. Continued need for a scientific answer to the questions of the exact size and recharge rate of the aquifer has diverted attention from developing plans to reduce pumping rates, reinforcing the spatial and temporal mis-fits.

With approval of Congress, federal law allows the creation of an interstate authority that crosses state lines and allows the region to control management of their water system as one unit. However, studies show that decision makers in the region have rejected this approach based on fear that federal approval will complicate management (Richartz 2011). The Palouse Basin Aquifer Committee (PBAC) was established in 1967 as a voluntary entity bridging the state divide and has been instrumental in facilitating voluntary conservation measures. However, PBAC lacks management and enforcement authority for conservation goals in the region.

3.3.1 Six-step approach applied to the Palouse Basin case

Using the six-step approach presented in Box 2, we analyze the SES related to the Palouse Basin.

Step 1: The resource of concern is groundwater from the Grande Ronde Aquifer. The water level of the aquifer has been declining significantly for the last 60 years. However, uncertainties remain over whether the aquifer is recharging and if the basin will experience a water shortage, since the recharge rate has not been scientifically determined. Existing local policies encourage voluntary conservation measures. State law requirements for curtailment of pumping on a "mined" aquifer have not been met in either state in which the aquifer occurs. Political will to develop alternative drinking water sources is lacking, as any viable surface water sources are shared by the two states.

Step 2: The biophysical processes that influence the aquifer include climate processes (precipitation) and hydrogeologic processes (primarily infiltration and aquifer recharge). Precipitation occurs at a regional scale, whereas infiltration and recharge occur on the aquifer scale. A shallow aquifer provides water to portions of one city and its recharge occurs on a scale of hours to months. The occurrence of recharge to the primary deep aquifer is unknown, but movement of recharge, if any, into production zones is clearly not occurring in a timeframe to prevent aquifer decline. In order to address the problem of focus, the relevant spatial scale is the aquifer, while the relevant temporal scale is unknown, but longer than the current period of record (60 years).

Step 3: Municipal groundwater pumping accounts for the most significant use of water from the aquifer and pumping rates increase with population growth. Groundwater pumping is likely occurring at a rate greater than recharge to the production zone given declines in the level of the aquifer over the last 60 years.

Step 4: The aquifer extends across the Washington-Idaho border and, as a result, is managed independently by the two states, invoking jurisdictional complexity. The PBAC, composed of representatives of the communities reliant on the aquifers and representatives of each state in an advisory capacity, was established to bridge efforts at the aquifer scale. The PBAC promotes information sharing and establishment of joint conservation goals, including the 1993 Groundwater Management Plan (GWMP). Although suggested management actions such as the GWMP are not legally binding, generally communities have complied. Although the rate of aquifer decline has slowed since implementation of the GWMP, aquifer levels continue to decline (Figure 4). In the state of Idaho, Statute 42-237a(g) prohibits aquifer mining exceeding the groundwater recharge rate (a standard that cannot be met if recharge is unknown), while Washington law (RCW 90.44.080) prohibits pumping an aquifer beyond its "safe yield." The relevant spatial scale of management actions includes the four cities that pump water from the aquifer and the state scale at which management is dictated. The temporal scale of management actions ranges from daily (pumping) to years (for development of city and university plans) to decades (for development and implementation of legislation).

Step 5: Currently there is no legally binding governance or management at the aquifer scale, which is the scale at which groundwater resources are provisioned, resulting in a spatial scale mis-fit. However, PBAC forms a bridging organization between the states of Idaho and Washington at this scale. The rate of aquifer recharge has not been determined and steady decline of the aquifer level over time suggests that the rate of extraction is greater than the rate of recharge at least to the production zone of municipal wells, indicating that a temporal mis-fit is occurring. The limited scientific investigations of recharge rate preclude imposing legal restrictions on pumping rates. The high cost associated with such research has inhibited the necessary scientific studies. Stakeholder attention primarily focuses on the state-defined spatial mis-fit and the need for further scientific study. However, application of this approach indicates that the temporal scale is far more important.

Step 6: Strategies to overcome scale mis-fit in the Palouse Basin must address the problem of declining groundwater reserves at the aquifer scale and at a temporal scale that matches the discrepancy between the recharge rate to the production zone and rate of groundwater decline. Adequate investment to develop new water sources is paramount. Continued effort to determine recharge rates is warranted, although they have proved unsuccessful to date. The basin may be better served by determining the maximum depth of production through test wells and consideration of the economics of pumping from that depth. Based on maximum depth of pumping, the timeframe for aquifer decline to this point (assuming current rate of decline) and thus the need for supplemental resources may be determined.

One potential short-term strategy to address these issues is the establishment of a facilitated forum where scientists and decision makers can discuss relevant issues and identify the roles of science and policy in addressing existing problems. Over several years, a medium-term strategy to incorporate university-based research to determine maximum economic pump depth and possibly aquifer recharge rates could provide student training and valuable knowledge to the regional groundwater problem. Efforts to identify alternative water sources and design, permit, and develop compliance measures for new water sources could move forward. Potential long-term strategies include determining a more robust means for communities to work together across the state line, potentially through empowering PBAC, and coordinating appropriate pumping levels of the aquifer based on scientific evidence.

3.3.2 Overview of the six-step approach in the Palouse Basin

Applying the six-step approach in the Palouse Basin reveals a spatial scale mis-fit in this SES. Given that a state line divides the Grande Ronde Aquifer, management occurs within jurisdictional boundaries that do not overlap with the most appropriate spatial scale, the aquifer scale, for regional groundwater resources. While the scale at which PBAC is focused aligns well with the biophysical scale at which water is provisioned in the Palouse Basin, the organization has no enforcement authority. However, this spatial scale mis-fit overshadows and tends to mask the temporal scale mis-fit, which lies at the heart of the problem. The main source of the water resource problems in this region is that the withdrawal rate exceeds the timeframe in which aquifer recharge occurs within the production zone. Since legislation in both states requires scientific determination of the general recharge rate in order to legally limit pumping, costly and lengthy studies are needed before adequate water conservation practices will be implemented. Using our approach in this case study helps users identify the temporal scale mis-fit occurring and place more focus on potential short-term solutions to mitigate the effects of waiting for necessary long-term solutions.

3.4 Applicability of the six-step approach for the case studies

The case studies demonstrate a useful approach to identify, further understand problems associated with, and discuss alternative solutions for scale mis-fit. In the Costa Rica case, by framing the management problem in terms of spatial and temporal scales, potential avenues for improving resource governance and defining management actions emerged. Our approach revealed feasible means to address water quality issues in drinking water. CBDWOs are spending human and financial resources to manage protection areas that do not contribute to the quality of spring water in the region. Resources would be more effectively used to protect those areas that have the most influence on drinking water quality. Delineating watersheds in lieu of springsheds provides an essential and feasible starting point for aligning the spatial scale of management actions with the spatial scale most relevant (and practical) for water resource provisioning. Ultimately, identifying the scale mis-fit between management actions and biophysical processes of an SES exposes potential vulnerability that may threaten the ability of an SES to provision an adequate supply of resources. Addressing this weakness could strengthen the SES to address ongoing large-scale issues including increasingly common problems associated with climate change and population growth.

Restatement of the Palouse Basin aquifer issue from a scale mis-fit perspective distilled the complex problem to an awareness of specific spatial and temporal mis-fit in water resource governance. Focusing on both spatial and temporal scales clarified the multi-scale nature of the problem and highlights the need for cross-scale collaborations. Using our approach revealed that a critical temporal mis-fit issue is likely masked by the obvious spatial mis-fit created by the political border dividing the aquifer. Significant attention is being placed on the political boundaries rather than focusing on the likely decline of the aquifer, precluding more appropriate sustainable management of groundwater resources. Our approach identified that more knowledge of the system could potentially improve mismanagement. The lack of management actions at the basin scale and the lack of a long-term, legally binding conservation plan contribute to uncertainty about the future availability of drinking water in the Palouse region.

These two cases provide examples of how our approach is useful for identifying and understanding issues of scale mis-fit within SES. The steps in our approach provide a process for navigating environmental problems by first focusing on a specific natural resource problem and then framing the problem explicitly in terms of the scales of both biophysical and governance processes, thereby making the problem more manageable to tackle without ignoring system complexity. When addressing complex problems with an interdisciplinary systems approach, it is often difficult to strike a balance between holistically understanding a problem that involves multiple interactions and feedbacks and deconstructing the problem into individual components. With this approach we intend to provide an entry point for breaking a problem down into manageable components through an analysis that acknowledges system complexity while identifying specific vulnerabilities. This approach is applicable to other contexts, both in water resource management and with other natural resource problems where spatial and temporal scales are of particular relevance and will be useful to researchers, managers, and other practitioners involved in natural resource management.

4.0 Discussion

This six-step approach to analyzing scale mis-fit has several unique aspects. First, a focus on scale facilitates mutual understanding among researchers and stakeholders with different disciplinary orientations. This focus is of particular importance given the need for interdisciplinary approaches to SES (Redman et al. 2004, Lang et al. 2012) that can be hampered by the inherent difficulty of interdisciplinary collaboration (Eigenbrode et al. 2007, Morse et al. 2007). Second, specifically emphasizing the scales of resource provision and management offers an opportunity to identify "critical causes," when they are related to scale, of natural resource problems that are not always intuitive or obvious in SES. Third, this approach explicitly places a concurrent emphasis on both spatial and temporal scales, as well as biophysical and governance systems, which are critical for effective natural resource management. Lastly, our approach encourages users to identify a range of possible solutions over different time frames rather than focusing on a single solution to resolve problems of scale mis-fit.

We also recognize the need to address potential weaknesses of this approach. For example, solutions to address scale mis-fit are often complex and not straightforward. After identifying an existing scale mis-fit, one cannot simply "align the scales" to "fix" the problem. For example, where a problem is identified in an SES, creating or changing legislation might better protect resources and prove to be necessary to address the scale mis-fit. However, as new legislation requires a long-term vision, waiting for changes in legislation without additional short-term actions to address problems could allow them to worsen. More importantly, uncertainty requires a more nimble approach than legislative action in a governance structure that fits the scale of today's problem but may prove inadequate in the future. Therefore, short- and medium-term mitigation strategies that address certain aspects of a problem could be explored concurrently with comprehensive long-term approaches. We propose that considering multiple solutions for different time frames will avoid issues that occur when focusing on one solution for a specific time frame.

Potential solutions and governance approaches need to be tailored for each resource and unique SES (Vatn and Vedeld 2012). Therefore, we envision that this approach will require in-depth, participatory discussions involving multiple stakeholders relevant for a specific case. Given that identifying solutions to scale mis-fit is complex, we would like to highlight that Step 6 is intended to encourage users of this approach to consider potential solutions to specifically address identified scale mis-fits. However, further work would be needed to identify a range of potential options that would satisfy multiple stakeholders' interests and to analyze the benefits and drawbacks of each solution. In addition, some factors influencing natural resource use, such as culture, history, religion, or economics, may not be explicitly addressed in this approach and may need further consideration in some cases. We encourage users to apply other relevant conceptual models, frameworks or analytical tools in conjunction with this approach specific to scale mis-fit.

5.0 Conclusions

Issues of scale mis-fit, when natural resources are not managed or governed at the scale at which they are provisioned, exist in a wide variety of SES. Lack of understanding the scales at which biophysical processes influence natural resource provisioning can lead to misalignment of management actions influencing resources. Identifying effective solutions to problems within SES often requires addressing scale mis-fit, although limited tools to identify and analyze scale mis-fit have been developed. We propose a systematic, approach for identifying, analyzing, and addressing scale mis-fit in environmental problems, based upon the premise that many natural resource problems are ultimately caused by a misalignment of the scales of management to the scales of resource provisioning.

The two case studies presented, from Costa Rica and the Inland Northwest region of the United States, highlight the applicability of our approach in two different social-ecological contexts related to water resource management. However, this approach for interdisciplinary investigation of spatial-temporal phenomena will be useful to analyze natural resource problems across a variety of SES contexts. We encourage others to test and refine this scale mis-fit approach for a range of natural resources issues, such as species, forest, and marine management, in various SES contexts to aid in its development and practical application. While identification of scale mis-fit is an imperative step towards reconciling natural resource management with biophysical processes occurring on the landscape, additional work is particularly necessary to identify and implement solutions to address scale mis-fit problems.

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Box 1. Key definitions and explanation related to scale mis-fit

Scale: "The spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon." (Gibson et al. 2000, p. 218) **Spatial scale**: The geographically-defined area where biophysical, management, or governance processes occur in a system. **Temporal scale**: The amount of time it takes for biophysical, management, or governance processes to occur in a system. **Scale mis-fit**: When adequate management actions do not occur at the spatial scales (i.e., geographic areas) or temporal scales (i.e., amount of time) most relevant to the biophysical processes provisioning the resource.

Box 2. A six-step approach to identify, analyze and address scale mis-fit.

Step 1. Define the problem related to the natural resource of concern.

a) What is the natural resource of concern in the system?
b) What is the specific problem related to this resource?

Step 2. Describe biophysical processes that provision the resource.

a) What biophysical processes are relevant for providing the resource?
b) Where do these processes occur on the landscape? (spatial scales)
c) How much time does it take for these processes to occur? (temporal scales)
d) What are the spatial and temporal scales most relevant to address the specified problem?

Step 3. Describe how humans influence biophysical processes contributing to the resource.

How do human activities influence the biophysical processes at the most relevant spatial and temporal scales (from Step 2d)?

Step 4. Describe management actions and governance processes that influence the resource.

a) What institutions (governmental and non-governmental) play a role in managing these human activities, and what management actions do they take?
b) What governance processes determine these management actions?
c) Where geographically are management actions focused? (spatial scale)
d) What time frames do management actions address? (temporal scale)

Step 5. Assess spatial and temporal scale mis-fits.

a) Do adequate management actions (Step 4) occur at the biophysically relevant spatial and temporal scales (Step 2)?
b) What spatial and/or temporal scale mis-fits exist?

Step 6. Identify potential solutions to address scale mis-fits.

a) What management actions are needed at the relevant spatial and/or temporal scales to address the scale mis-fits identified?
b) What governance processes are needed to achieve these management actions?
c) What barriers exist under current laws and policies and what process would be necessary to overcome these barriers?
d) What potential solutions could be implemented over short-, medium-, and long-terms?

Figures

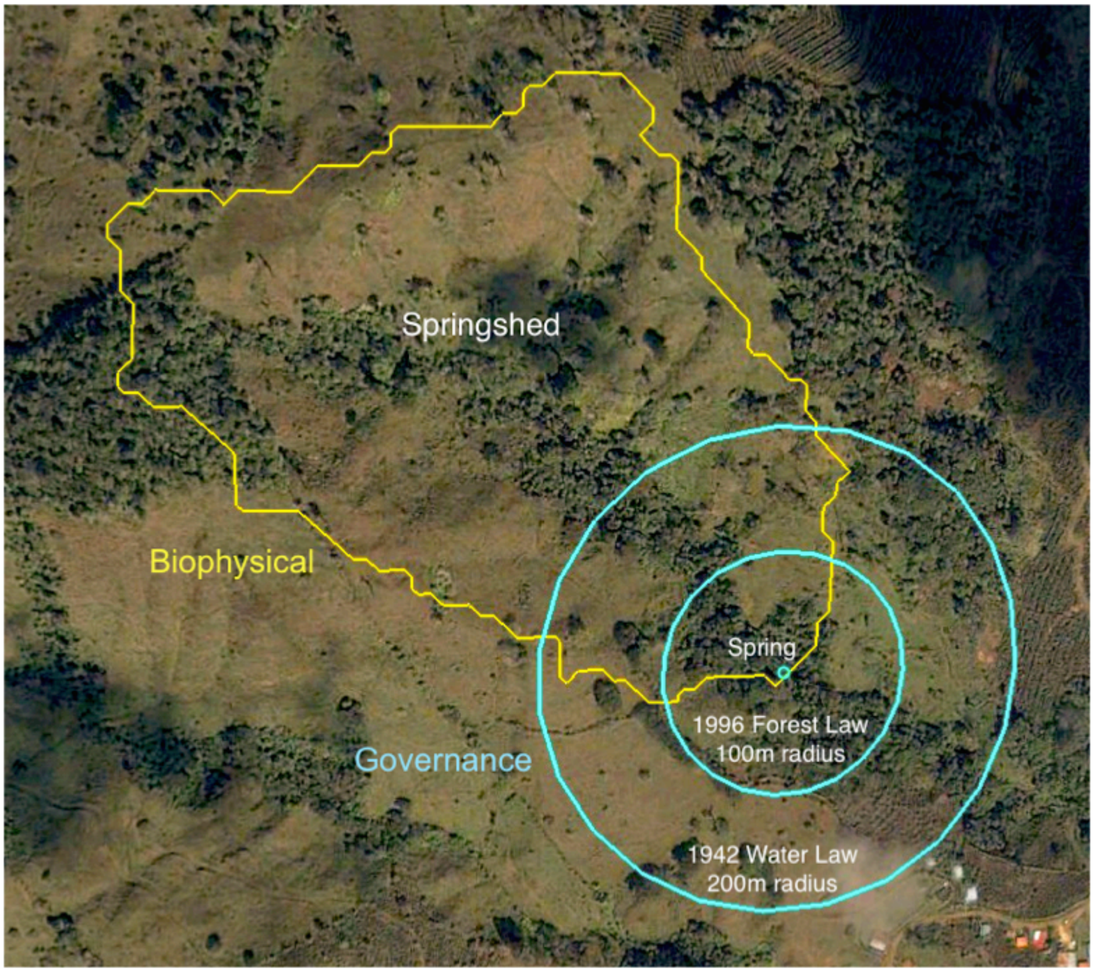

Figure 1. Illustration of a spatial scale mis-fit between the upstream area contributing to spring discharge (the potential springshed, yellow polygon) and the mandated protection buffers surrounding the spring (blue polygons) managed by a CBDWO in the Cartago Province of Costa Rica. Management actions primarily occur within the protection buffers, which do not fit the spatial scale of the biophysical processes that provision the drinking water (i.e., within the springshed) (Map data ©2013 Google, Digital Globe).

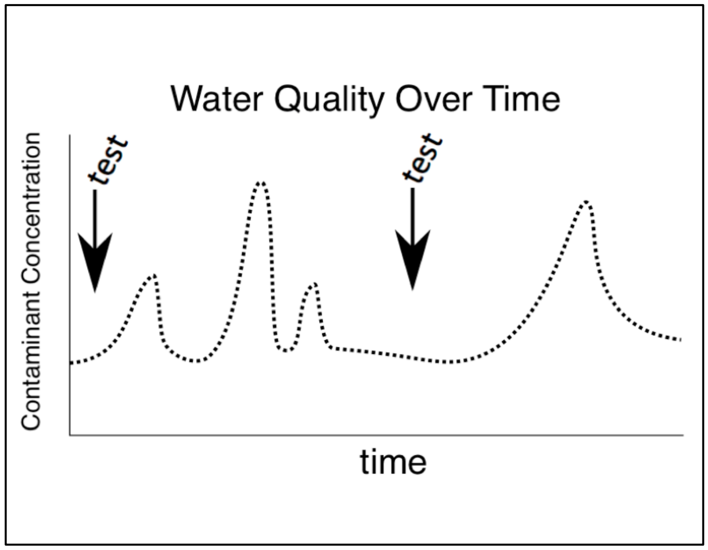

Figure 2. Conceptual illustration of a temporal scale mis-fit between the frequency of water quality testing and the probable changes in water contaminant concentration over time. CBDWOs in Costa Rica typically sample water for contaminants less than twice per year, and thus the tests are not likely revealing the suitability of the water for drinking.

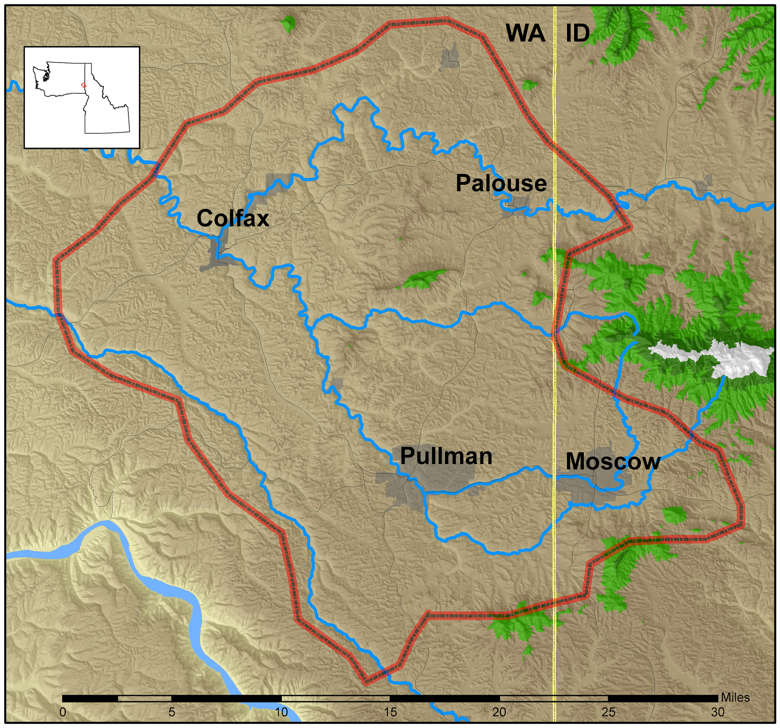

Figure 3. Palouse Basin showing boundary between Idaho and Washington (yellow line) and the approximate boundary of the Grande Ronde aquifer (red line) located within both states. The inset shows where the aquifer is located within both states.

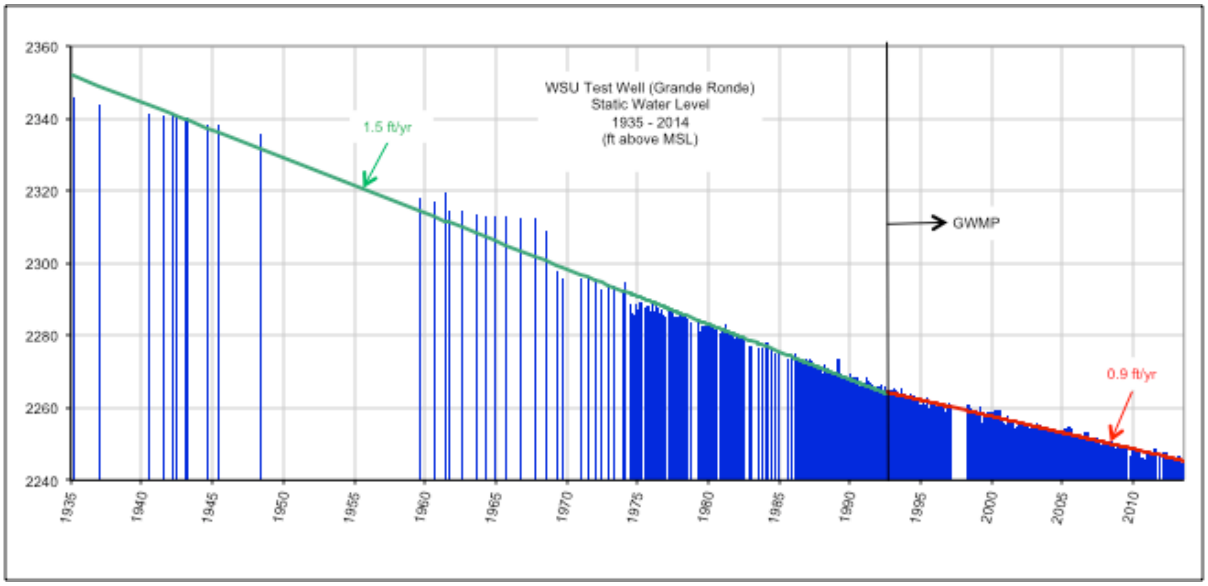

Figure 4. Static water levels in the WSU Test Well. Green and red regression lines show decrease of levels prior to and after 1993, respectively, when the Groundwater Management Plan (GWMP) was developed by PBAC.

Chapter 5: Dissertation Conclusions and Recommendations

The hydrologic response of watersheds to precipitation is important for watershed management, particularly in planning for flooding and water quality (Grayson et al. 1992). Characterizing subsurface flow pathways enables better understanding of how precipitation arrives at streams, thereby improving management efforts. Both permanent and temporary springs also can greatly impact overall stream flow, but springs have not been well studied and their behavior is poorly understood (Buttle et al. 2012). Analyzing hydrologic flow processes in tropical watersheds is important to assess the influences on stream flow and to mitigate some of the detrimental impacts from flooding and water pollution.

This interdisciplinary research was designed to better understand the hydrologic response of tropical watersheds and management efforts for drinking water. In this dissertation, I examined hydrologic processes using stable isotope analyses, physically-based modeling, and a case-study approach with interviews. Chapters 2 and 3 were based in the Aquiares Coffee Farm in Aquiares, Costa Rica and both analyzed subsurface flow pathways in a tropical agroforestry watershed. Chapter 4 was the result of an interdisciplinary team-based research project developed to analyze a case study of drinking water management of springs in the Cartago province of Costa Rica.

Chapter 2 served as a baseline study for isotope hydrology in Aquiares to understand what factors influence precipitation, and thus local hydrology, and how seasonality influences the hydrology of the region. In this chapter, I used stable isotopes, $\delta^{18}O$ and $\delta^{2}H$, collected in precipitation, groundwater, stream water, and springs over the course of two and a half years. Isotopes enabled improved analysis of subsurface flow pathways. We found that although the region does not exhibit strong seasonal hydrology, the isotope seasonality is strong due to the general climate patterns between seasons. Stable isotope values in precipitation also exhibited a strong correlation with several meteorological factors that are influenced by season. Stable isotope values in other hydrologic components (groundwater and stream water) were also strongly associated with precipitation. These results show the strong influence that climate has on precipitation and local hydrology.

Additionally, Chapter 2 provided more insight into subsurface pathways in a tropical agroforestry watershed. Base flow was the primary contributor to stream flow, and during storm events pre-event (or "old") water contributed predominantly to peak flows. We found an approximate 15 hour lag for precipitation (or "new" water) to reach the stream. Based on data and field observations, we concluded that this lag is due to precipitation infiltrating the soils, traveling laterally through the subsurface above the water table, and exiting to the stream. Due to the high infiltration capacity of soils in our study watershed, Andisols, overland flow was rarely observed on site. Groundwater samples revealed different responses between two sets of groundwater wells (WTL-2 and WTL-5, versus WTL-1 and WTL-4). Previous work at the site (Gómez-Delgado et al. 2011) revealed different hydrologic behavior of the groundwater: a faster response relative to precipitation inputs (in wells WTL-1 and WTL-4), and a more steady groundwater reservoir that yields more stable levels throughout the year (in wells WTL-2 and WTL-5). Results from sampling stable isotopes of springs indicate that the ephemeral springs appear to originate from "new" water, or the more fast-response groundwater system.

In Chapter 3, I used the physically-based Soil Moisture Routing (SMR) model to simulate local watershed hydrology. The use of a distributed model allowed the inclusion of additional spatially explicit information, such as the location of semi-impervious areas (roads and foot paths) that contribute to storm flow and ephemeral streams. Spring flow is an important component in many watersheds, as it contributes significantly to stream flow, yet is often not included in modeling efforts or studies of watershed hydrology. Modeling efforts illustrate the value in incorporating springs into physically-based models, as our results improved with their inclusion.

Based on simulation results, we confirmed that there are different behaviors occurring in different areas of the watershed, with one groundwater system that rapidly fluctuates in response to precipitation, as well as a more steady groundwater layer that is relatively stable throughout the year. We also simulated stream flow with good agreement to observed data. Including spring flow and semi-impervious areas proved that we can model our conceptual understanding of spring flow in the watershed and showed the importance of overland flow from a relatively small area.

In Chapter 5, I worked with an interdisciplinary team to conduct two case studies of drinking water management of the Cartago province of Costa Rica, in addition to the Palouse Aquifer Basin in Idaho and Washington. In Costa Rica, the majority of community-based drinking water organizations obtain their drinking water through springs. However, management efforts of these springs, which are vital for the health of community members, are hampered by a scale mis-fit that is occurring. We identified scale mis-fit as when natural resources are not managed at the spatial or temporal scale at which they are provisioned. Legislation in Costa Rica mandates a 100 m or 200 m (based on two pertinent laws) buffer protection zone around springs. The potential area of influence or recharge of these springs (the "springshed") does not occur in a circular zone, and thus scale mis-fit exists. Because concerning land use exists within the influencing areas (such as agriculture with pesticide use and pasture land), communities need to have the ability to manage these lands. However, legislation must change for communities to be able to shift their management efforts.

Based on the results of this dissertation, there are several areas of future work and recommendations for management. Throughout this research, the importance of understanding springs for both their contribution to hydrology and for water resource management was evident. Further work is necessary to quantify how ephemeral springs contribute to watershed hydrology and the factors that cause ephemeral springs to start flowing. We believe that the behavior of the ephemeral springs in the Aquiares watershed is characteristic of a "fill and spill" mechanism (Spence & Woo 2003; Tromp-van Meerveld & McDonnell 2006) that could be occurring in the subsurface layer of the springshed. Springs have the potential to greatly contribute to storm flow, and therefore understanding the mechanisms that cause them to flow could assist in planning for and management of flooding. More work is needed to further identify the mechanism that causes this spring flow to occur.

Additional work is still necessary to confirm subsurface flow pathways within watersheds, and a dual isotope approach would be useful in this regard. Understanding how precipitation infiltrates into the subsurface and the pathways that it follows to arrive at streams is important for understanding storm flow and stream response to precipitation. Through our work, we identified a shallow subsurface pathway where precipitation could be exiting laterally above the groundwater table to the streams. However, more work with isotopes at a finer temporal resolution would help identify and further characterize these pathways and associated distribution of the time lag response. Combining stable isotopes results with a physically-based model, such as SMR, would provide even more understanding of these pathways.

Finally, we see that more work is needed to improve management efforts in light of these results. Because flooding is a significant problem in this region of Costa Rica where soils typically have very high infiltration capacity, understanding the subsurface flow pathways that we identified in this research is important. Legislation also needs to improve to focus the level of management at the proper scale where the biophysical resources are being provisioned. Because communities in this region obtain the majority of their drinking water from springs, managing at the spatial scale of the contributing springshed is critical for protecting water resources. Only through improved legislation will communities be able to protect their drinking water resources at the appropriate scale.

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