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Flowpaths, source water contributions and water residence times in a Mexican tropical dry forest catchment

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SUMMARY

Runoff in forested tropical catchments has been frequently described in the literature as dominated by the rapid translation of rainfall to runoff through surface and shallow subsurface pathways. However, studies examining runoff generation in tropical catchments with highly permeable soils have received little attention, particularly in tropical dry forests. We present a study focused on identifying the dominant flowpaths, water sources and stream water residence times in a tropical dry forest catchment near the Pacific coast of central Mexico. During the wet season, pre-event water contributions to stormflow ranged from 72% to 97%, with the concentrations of calcium, magnesium, sodium and potassium closely coupling the geochemistry of baseflow and groundwater from the narrow riparian/near-stream zone. Baseflow from the intermittent stream showed a strongly damped isotopic signature and a mean baseflow residence time of 52–110 days was estimated. These findings all suggest that instead of the surface and near-surface subsurface lateral pathways observed over many tropical catchments, runoff is generated through vertical flow processes and the displacement and discharge of stored water from the saturated zone. As the wet season progressed, contributions from the saturated zone persisted; however, the stormflow and baseflow geochemistry suggests that the contributing area of the catchment increased. Our results show that during the early part of the wet season, runoff originated primarily from the headwater portion of the catchment. As the wet season progressed and catchment wetness increased, connectivity among sub-basin was improved, resulting in runoff contributions from across the entire catchment.

1. Introduction

Much of our current understanding of runoff generation processes in tropical systems has been produced from research in catchments of the humid tropics (Bonell and Bruijnzeel, 2005; Levia et al., 2011; Farrick and Branfireun, 2013). While it is generally recognised that rapid flow processes dominate runoff in forested tropical catchments, the specific water flowpaths, source areas and residence times of stream water often remain unclear (Buttle and McDonnell, 2004; Bonell and Bruijnzeel, 2005). This is especially true for tropical dry forests, where most research has often focused on quantifying the catchment scale water balance (de Araújo and González Piedra, 2009; Montenegro and Ragab, 2010). Tropical dry forests are defined by a distinct 3–7 month dry period and an average ratio of annual potential evapotranspiration to rainfall >1 (Murphy and Lugo, 1995; Miles et al., 2006) indicating a water limited climate. Understanding the water flowpaths in a catchment is necessary for the management of surface and groundwater resources. This is particularly important in tropical dry forests where land use change (Miles et al., 2006) coupled with the projected decrease in precipitation (Bates et al., 2008) are expected to reduce the already limited streamflow observed in these catchments (Farrick and Branfireun, 2014b).

In many tropical forest catchments, runoff is dominated by the rapid translation of rainfall to runoff. Many studies show stormflow to be composed of 40–75% event water (Sandström, 1996; Schellekens et al., 2004; Hughes et al., 2007; Ribolzi et al., 2007), most of which is translated downslope as saturation-excess overland flow (SOF) (Elsenbeer et al., 1994, 1995b), return flow (RF) through soil pipes (Schellekens et al., 2004; Negishi et al., 2007), through shallow lateral pathways near the soil surface (Schellekens et al., 2004) or infiltration-excess overland flow (HOF) (Bonell and Williams, 1986). These studies show that the hydraulic properties of the surface soil and shallow subsurface soil often determine the dominant runoff mechanism. Shallow confining soil layers with low hydraulic conductivities (K) impede vertical flow through the highly permeable surface soils, leading to

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shallow subsurface flow and SOF generation (Bonell and Gilmour, 1978; Elsenbeer and Vertessy, 2000; Godsey et al., 2004). Although lateral surface and near-surface flowpaths have been observed over much of the tropics, there has been increasing evidence for deep subsurface flow (Bonell and Bruijnzeel, 2005; Chappell and Sherlock, 2005; Scheffler et al., 2011; Salemi et al., 2013). These studies show that high *K* exists throughout the soil profile, resulting in predominantly vertical flowpaths. Flow through these vertical pathways often displaces near-saturated soil water or hillslope groundwater, resulting in runoff that can be composed of 72–99% pre-event water (Muñoz-Villers and McDonnell, 2012).

Most concepts regarding hydrological connectivity and variable source areas have originated primarily from research in humid temperate forest catchments (Bracken et al., 2013). These studies often show that connectivity between the riparian zone and hillslope is needed to generate substantial amounts of subsurface flow (Bracken and Croke, 2007), and the relative contribution from either source often varies on a seasonal (Ocampo et al., 2006; McGuire and McDonell, 2010) or event basis (McGlynn and McDonnell, 2003; Subagyono et al., 2005). In geographical regions where a distinct dry–wet season occurs, hillslope and riparian areas often remain hydrologically disconnected for extended periods of the year. As rainfall and antecedent wetness increase, the upslope expansion of saturated subsurface areas, often through a rise in the riparian and hillslope water table, connects these two landscape units (Ocampo et al., 2006). The improved connectivity results in a shift in the dominant source area from the riparian zone to the hillslope (Ocampo et al., 2006; Jencso et al., 2009). In wetter temperate catchments, with a more even annual rainfall distribution, hillslope – riparian connectivity is affected by the size of the storm event. Under small rainfall inputs, connectivity is low and most runoff is generated from the riparian zone, while large rainfall events improve connectivity with most runoff generated from the hillslope (McGlynn and McDonnell, 2003; Subagyono et al., 2005). Although hillslope – riparian connectivity is important for stormflow generation in temperate forests, in humid tropical forests where SOF and RF are the dominant mechanisms, hydrological connectivity often develops by surface drainage expansion. Zimmerman et al. (2014) showed that as antecedent wetness increased, SOF was generated at progressively higher upslope positions, which drained into ephemeral channels, essentially expanding the size of the source area contributions to runoff.

Water residence time analyses using stable isotopes have emerged in the last two decades as an important tool that can provide insights into catchment runoff processes. As stream water residence time is strongly influenced by topographic (McGuire et al., 2005) and internal catchment features such as soil depth and subsurface geology (Soulsby et al., 2006; Katsuyama et al., 2010), it provides an excellent indication of the coupling among the flow paths, water sources and storage in a catchment (McGuire and McDonnell, 2006). Although the use of isotopic residence time analyses in catchment-scale hydrology has increased, it has generally been limited to humid temperate catchments (McGuire and McDonnell, 2006). Though Buttle and McDonnell (2004) suggest the use of residence time techniques in tropical forests catchments as a means to improve the understanding of the translation of rainfall to stream water, application of these techniques have been limited to a few studies (e.g. Crespo et al., 2012).

In this study we report the research on the rainfall–runoff response of a steep, tropical dry forest catchment with highly permeable soils. Farrick and Branfireun (2014b) suggested that given the high hydraulic conductivities, high soil porosities and the rapid soil moisture response to rainfall at depths one metre below the soil surface, runoff in this tropical dry forest catchment is generated as subsurface flow through the displacement of stored water in the saturated or near-saturated zone. In order to test this hypothesis, we used a combined hydrometric, isotopic and geochemical approach to examine the dominant flowpaths and source areas of stream water during the translation of rainfall to runoff. More specifically we (a) estimated the mean residence time of stream water; (b) estimated the relative contributions of event and pre-event water during stormflow and (c) characterised and compared the geochemical composition of stormflow with potential source areas.

2. Study area

The study was conducted in a 3.15 km^2 catchment in the lake Zapotlán watershed, approximately 100 km south-southwest of Guadalajara, Jalisco, Mexico; 5 km northeast of Ciudad Guzman, Jalisco, Mexico (19°N 103°W) (Fig. 1). The climate is Tropical Savannah (Köppen-Geiger: Aw) with a distinct wet and dry season (Peel et al., 2007) and the forest characterised as tropical dry according to the Holdridge biome classification (Holdridge, 1967). The average annual precipitation (1972–2003) is 813 mm, of which 95% falls between June and September (Ortiz-Jiménez et al., 2005). Rainfall is dominated by short duration, low intensity storm events (Farrick and Branfireun, 2014a). The strong wet–dry seasonality results in intermittent streamflow production from the catchment, with most flow occurring from July to October (Farrick and Branfireun, 2014b). Mean annual temperature is 19.6 °C with maximum temperatures occurring in July (Ortiz-Jiménez et al., 2005).

Elevation ranges from 1557 metres above sea level (Note that all elevations are in metres above sea level and will be referred to m henceforth) at the primary outflow channel to 2170 m at the headwater sub-basin. The catchment is steep with slopes ranging from 18° to over 52°. The study area is underlain by Pleistocene andesitic basalt–basaltic andesite and volcanic fine tuff. The channel width ranges from <0.20 m in the headwater sub-basins to 1.0–1.5 m at the primary outflow channel. The stream channels are deeply incised and steep with a 0.2–1 m wide riparian areas. The bedrock along the incised channels is weathered and highly fractured. The soil is classified as chromic cambisols with andic properties of volcanic origin (Gómez-Tagle, 2009). The soils at

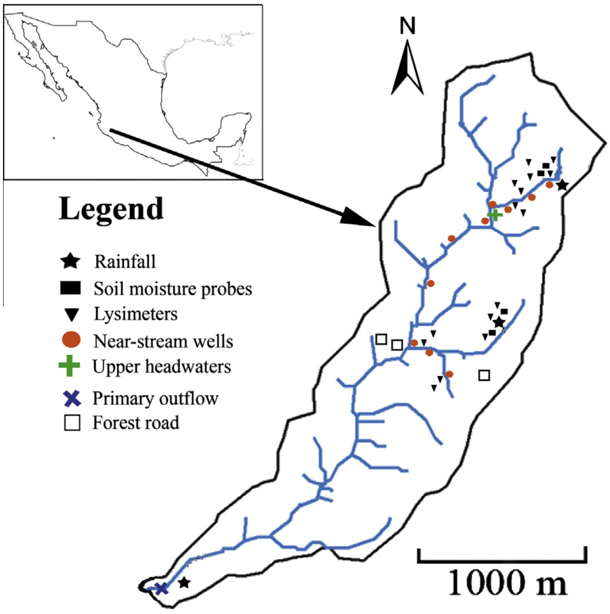

Fig. 1. Location of the study site and isotopic and geochemical water sampling locations across the catchment.