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Hydroclimatic controls on non-stationary stream water ages in humid tropical catchments

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ABSTRACT

Streams in humid tropical countries provide a wide range of ecosystem services, yet a good understanding of their hydrological functioning is severely limited by lack of data. The transit time of water is a fundamental characteristic of catchment functioning and can often be related to water quality dynamics, thus providing potentially important information for water managers in these environments. In this study, we applied the widely used lumped convolution integral model in a moving window approach to acknowledge the time-variance of transit time distributions (TTD) and resulting moments such as the mean transit time (MTT). We show that for a two-year (2012–2014) rainfall-runoff stable isotope record from almost daily sampling in a humid tropical 30 km^2 catchment in southern Costa Rica, the MTTs are generally short (<one year), but exhibit distinct inter and intra-annual patterns. The drier year (2012–13), which was under the influence of El-Niño causing less precipitation, exhibited MTTs up to one year. In contrast, the wetter year (2013–14) resulted in MTT estimates <100 days. Similar patterns were found at an intra-annual scale: the dry season MTTs were on average 185 days and only 15 days during the wet season. This can be explained by high rainfall volumes (>3 m/year) and events occurring throughout the year, the seasonality of rainfall and distinct moisture origin (Pacific, Atlantic and land surface), the likely dominance of quick near-surface flow paths and relatively low subsurface storage of the underlying volcanic and sedimentary rocks. The moisture origin of rainfall was found to be the most dominant driver of time-variable TTDs as indicated by the changing average wind directions following the transition from the dry into the wet season. This isotope study revealed a highly dynamic system that is likely to be sensitive to environmental change.

1. Introduction

Despite the usefulness and long history of tracer applications in the hydrological sciences (Leibundgut et al., 2009), tracer studies in humid tropical environments are sparse compared to many other environments, mainly due to funding restrictions and data limitations (Bonell and Bruijnzeel, 2005). This is especially true for the use of stable water isotopes as natural tracers that can help identify catchment hydrological processes, assess water resources and understand water quality issues (Kendall and McDonnell, 1998; IAEA, 2001). The latter is important in many humid tropical countries and particularly in Latin America, where water is generally abundant but water quality is severely affected by poor land and water management (STAF, 2012). The International Atomic Energy Agency (2006) summarized the isotope studies that were developed in these regions, and showed that these focussed mainly on water resources assessment, while hydrological process studies that use isotope techniques are rare. In part, economic and analytical constraints limited the use of isotope techniques in Latin America. However, relatively new and more economic laser-based isotope analyzers (Lis et al., 2008) now have the potential to facilitate widespread use of isotope tracers in hydrological process studies across tropical Latin-American countries. Nevertheless, recent isotope studies in the humid tropics of Latin America seem to be driven by concerns over particular threatened ecosystems (e.g. montane cloud forests, paramo). Such work includes Muñoz-Villers and McDonnell (2012) and Goldsmith et al. (2012) who report detailed hydrological process studies using stable isotope techniques in a montane cloud forest catchment in Mexico. Crespo et al. (2012) and Goller et al. (2005) report on similar

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ecosystems in Ecuador. Routine sampling efforts across many different systems in the humid tropics remain rare, but are crucial for a wider hydrological system understanding, as advocated by McDonnell and Beven (2014).

In many places, sampling of isotope tracers in rainfall and streamflow is frequently used to assess the distribution of water transit times (TTD) and its moments such as the mean transit time (MTT) as a proxy for the relative importance of flow paths that could be related to water quality and as a catchment metric for comparison purposes (e.g. Tetzlaff et al., 2009). To characterize water age, the available approaches range from simple lumped convolution integral models that assume steady state and a priori defined flow path distributions (Maloszewski and Zuber, 1982) to a suite of new modelling tools that derive non-stationary water age distributions for a variety of catchment systems (e.g. Davies et al., 2013; Heidbüchel et al., 2012; Hrachowitz et al., 2013; Birkel et al., 2015; Benettin et al., 2015; Rinaldo et al., 2015). The lumped convolution integral models were initially developed for groundwater systems where assumptions of steady-state are less problematic than for variable surface water systems. Other factors that contribute to the overall uncertainty of this method are coarse, e.g. weekly or less frequent, sampling resolutions (Timbe et al., 2015) and the limitation of stable isotopes to detect water ages beyond 4–5 years resulting in parameter identifiability issues (Stewart et al., 2010). Nevertheless, despite the series of over-simplistic assumptions, lumped convolution integral models are still useful tools that provide insights into relative MTTs between catchments or time periods (Birkel et al., 2012a), in particular when time-variable TTD and resulting MTT are explicitly taken into account (Hrachowitz et al., 2010). New theory on water transit time has further helped to reconsider that stationary conditions are rarely met in natural catchment systems (Botter et al., 2011; Rinaldo et al., 2011).

This study presents a preliminary analysis of a systematic two-year rainfall-runoff isotope record collected on a daily basis from a generally data sparse, but representative humid tropical catchment with a seasonal rainfall pattern in southern Costa Rica. Previous isotope studies in Costa Rica analyzed rainfall isotope patterns separately to mainly detect moisture sources (e.g. Rhodes et al., 2006 in a montane cloud forest; Sánchez-Murillo et al., 2013 at a national scale) and developed preliminary surface water isotope maps of major rivers (Lachniet and Paterson, 2002). However, these previous studies lack the integration of isotope techniques into a hydrological process study to improve understanding of catchment function. Therefore, the main aim of this study was to characterize the isotope dynamics and resulting temporal variability in transit times using a simple convolution integral model and identify the main controls to gain insights into the hydrological functioning of the study site, representing humid tropical conditions for which hydrological processes are generally poorly understood. The specific objectives were:

(a) to analyze the two-year daily time series of stable isotopes in precipitation and stream flow to characterize the TTD of a humid tropical catchment with a seasonal rainfall pattern.
(b) to apply lumped convolution integral models in a moving window approach to generate a time-variable set of TTDs and MTTs for wet and dry periods (i.e. years/seasons).
(c) to identify the potential drivers of time-variable TTDs in relation to hydroclimatic controls.

2. Study site and data

The 30 km^2 Caño Seco study catchment located in southern Costa Rica (8°40′N, 82°51′W) drains into the Pacific Ocean via a larger 120 km^2 catchment (Fig. 1a). The Caño Seco has a humid tropical climate (Chang and Lau, 1983), which is characterized by high rainfall (P) volumes exceeding 3 m/year and an average annual potential evapotranspiration (PET) of around 1 m/year (Table 1). Although intense convective rainfall events that build up during the morning hours and rain out early afternoon are common throughout the year, there are distinct dry (January to March) and wet (April to December) seasons with rainfall peaking in September/October (Fig. 1b). On average 83% of rain falls in the wet season between April and December. The mean annual temperature (T) is close to 20 °C and the mean annual relative humidity (RH) was measured at 86%. The distinct seasonality can also be found in lower relative humidity (on average up to 10% less during the dry season), slightly higher temperatures (up to 0.6 °C), higher radiation (I) and resulting increased PET towards the end of the dry season in March (on average up to 50 mm/month). The main driver of this climatic seasonality is the migration of the Intertropical Convergence Zone (ITCZ). During the dry season, when the ITCZ is located south of Costa Rica, air masses travel in a northeasterly direction across the country. During the wet season, P is controlled by the ITCZ moving northward, which results in cross-equatorial winds from the southern hemisphere change to become south-westerly and transport Pacific parental moisture to Costa Rica combined with a weakening of trade winds (Lachniet et al., 2007). Deep convection systems on the Pacific coast of Costa Rica develop as a result. Hurricanes generally only exert an indirect effect with increased rainfall in Costa Rica. The southern oscillation however, strongly influences climatic patterns with less P on the Pacific slope and increased rainfall in the Caribbean during the El Niño warm phase.

The catchment topography is characterized by a modest ~500 m elevation gradient and steeper slopes only in the upper areas (Table 1). The unusual geomorphology of a high-plain with the extensive and flat riparian area situated at 1000 m.a.s.l. is the product of active orographic uplifting of the maritime crust and volcanism (Bergoeing, 1998). These tectonic processes generated a complex fault system with a strong discontinuity between the upper and lower part of the catchment that caused the formation of an ancient lake and the subsequent accumulation in the valley bottom of eroded fine materials from the steeper hillslopes.

Therefore, a small part (<10%) of the steepest and highest western catchment is characterized by Quaternary calcareous marine sediments. The north-eastern part is dominated by older (Tertiary) volcanic rocks and the south-central part by slightly younger fluvial sedimentary rocks (Denyer and Kussmaul, 2000). Both formations are classified as relatively impermeable and possess poor aquifer properties with a relatively low water yield. The fluvial sedimentary rocks in combination with the deposits of the previously mentioned ancient lake results in water-logged clay-rich Ultisol ("red clay") soils dominating in the undulated adjacent and flat riparian area. The latter likely generate rapid surface runoff generation processes resulting in a flashy response of the river, which can be observed during rain events. The steeper hillslopes particularly towards the east are dominated by more porous volcanic Andisol soils that are more likely to laterally transport water and contribute to groundwater recharge.

From the original land cover of the catchment as primary rainforest, only a few patches remain (<20%), mainly on the upper hillslopes. Pasture and livestock grazing (30%) are the dominant land uses on the less steep lower hillslopes. The catchment is relatively sparsely populated (<3000 inhabitants), but intensive agriculture and urbanization (currently 40% and 10% respectively) are expanding, particularly in the flat lowland areas.

In October 2011 we deployed three Davis Vantage Pro2 meteorological stations (15 min recording interval) distributed throughout the catchment and installed a stilling well in a stable section of the Caño Seco river using an Onset Hobo U20 pressure transducer