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Hydrogeomorphology influence on pan-tropical transit times

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Resumen

Los trópicos son una de las regiones más diversas y dinámicas de la Tierra. A pesar de su importancia, nuestra comprensión de los procesos hidrológicos tropicales sigue siendo un desafío significativo, en su mayoría debido a la monitorización limitada. En este estudio, utilizamos conjuntos de datos isotópicos de alta resolución (diaria) de la entrada y salida de siete cuencas pan-tropicales en Australia, Costa Rica y Ecuador, para estimar y comparar tiempos de tránsito del agua con variables hidrogeomorfológicas. Utilizando el método de la integral de convolución con una distribución gamma como función de transferencia, las cuencas pan-tropicales mostraron tiempos de tránsito entre 49 y 497 días, eficiencias de Kling Gupta alcanzadas de hasta 0.92. El parámetro alfa de la distribución gamma estuvo por debajo del patrón global previamente identificado de alrededor de 0.5 en 5 de las 7 cuencas. Un enfoque de ranking de bosque aleatorio (RF) identificó la capacidad de almacenamiento de agua y la cantidad anual de precipitación como los controles más importantes de los tiempos de tránsito. Además, la distribución de los tiempos de tránsito según lo indicado por el parámetro alfa se explicó mejor por la evapotranspiración anual, y la cobertura de suelo Andosol (%). Nuestros hallazgos identificaron los controles clave de los tiempos de tránsito y su distribución en cuencas tropicales de respuesta rápida en comparación con otras zonas geomorfológicas y climáticas, resaltando el valor de los tiempos de tránsito como un descriptor simple de la cuenca.

Palabras clave: trópicos, distribución de tiempos, isótopos estables, integral de convolución, distribución gamma



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Abstract

The tropics are one of the most diverse and highly dynamic regions on Earth. Despite their importance, our understanding of tropical hydrological processes remains a significant challenge mostly due to limited monitoring. Here, we used high-resolution daily input-output isotope data sets from seven pan-tropical catchments ranging in size from 3 to 990 km², located in Australia, Costa Rica, and Ecuador to estimate and compare streamflow transit times (TTs) with potential explanatory hydrogeomorphological variables. Pan-tropical catchments resulted in short TTs from 49 to 497 days using a simple lumped convolution integral model with a Gamma distribution as transfer function (best-fit Kling Gupta efficiencies up to 0.92). The gamma distribution alpha parameter was in 5 out of 7 catchments below the previously identified global pattern of around 0.5. A random forest (RF) ranking approach identified water storage capacity, the presence of sedimentary rocks (%), and the annual precipitation amount as the most important TT controls. In addition, the TT distribution as indicated by the alpha parameter was best explained by annual evapotranspiration, the soil texture, and the Andosol soil cover (%). Our findings identified the key TT and TT distribution controls in fast responding tropical catchments compared to other geomorphic and climate zones emphasizing the value of TT as a simple catchment descriptor.

Keywords: tropics, time distribution, stable isotopes, convolution integral, gamma distribution



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Hydrogeomorphology influence on pan-tropical transit times

1. Introduction

The tropics play a crucial role in providing ecosystem services such as water production, carbon capture, and biodiversity (Barlow et al., 2018). However, the hydrological systems of the tropical region are highly dynamic, complex and challenging to understand and predict due to their heterogeneity. The high temporal and spatial rainfall variability, for example, results in extreme water and material fluxes (Macdonald et al., 2019; Wohl et al., 2012). Tropical systems have also co-developed under a diversity of geologic, climate, soil and biological conditions, contributing to highly variable characteristics. Additionally, population growth continuously changes the distribution of land cover and land use (Barlow et al., 2018; Bonell, 2005; Buytaert et al., 2002; Cai et al., 2019). The aforementioned factors and their complex interaction pose significant challenges to water management in the region (Blöschl et al., 2019). The challenges of water provisioning, hydrometeorological risk management, hydropower and aquatic ecological integrity are further exacerbated by a lack of understanding of the fundamental hydrological processes across the tropics (Wohl et al., 2012). Despite progress in certain countries, for example in terms of modelling (Arciniega-Esparza et al., 2023), a science and data-based water management is still hindered in many developing tropical countries due to the lack of crucial hydrometric data and monitoring.

Tracers emerged as an economic alternative and additional source of information to hydrometric data that can be particularly useful assessing the temporal response and transit times in tropical catchments (Birkel et al., 2016; Timbe et al., 2014). More generally, tracers provide insights into catchment transit times, stream water sources, flow pathways, and water storage (Knapp et al., 2019; McGuire & McDonnell, 2006; Stewart & McDonnell, 1991). Many studies focused on relating input-output tracer information with lumped convolution integral models (Maloszewski & Zubert, 1982) to estimate the mean transit time (MTT) as a catchment descriptor (see review by (McGuire & McDonnell, 2006)). The MTT showed to be strongly influenced by topography (McGuire et al., 2005), hydroclimate (Birkel et al., 2016), soil physical characteristics (Hrachowitz et al., 2009), urban impermeable surface area (Soulsby et al., 2014), and geologic controls (Cartwright et al., 2020), among other factors in different climatic and geomorphic settings.

Recognizing that transit times are non-stationary in nature (e.g., Klaus et al., 2015; Rinaldo et al., 2011 and a recent review by Benettin et al., 2022), new methods have emerged such as the Storage Age Selection (SAS) approach (Benettin et al., 2017) the young water fraction (Kirchner, 2016) or tracer-aided rainfall-runoff models that do not depend on an a priori TT distribution (see review by Birkel & Soulsby, 2015). However, the stationary lumped convolution integral models still find applications due to their simplicity and due to the almost universal gamma distribution (Godsey et al., 2009) converting the resulting catchment transit time distributions into useful descriptors, particularly for catchment comparative studies (Hrachowitz et al., 2010; Tetzlaff et al., 2009).

Although transit times have been estimated in tropical catchments, very few studies have reported potential relationships between catchments properties (i.e.: geology, hydrological variables, soil properties, etc.) and the TTD estimations. In humid tropical rainforests in Costa Rica, it was found that these systems are dominated by young waters with ages from hours to 3.3 years in drought situations, emphasizing the rapid rainfall-runoff and material transport dynamics (Birkel et al., 2016; Correa et al., 2020). In the cloud forest region of Mexico, MTTs of around 1.2 to 2.6 years were related to slope and permeability. The latter suggests that deep and long subsurface flow paths contribute to sustain base flow, particularly during dry periods (Muñoz-Villers et al., 2016). In Ecuador, the high regulation capacity and constant water supply of the páramo ecosystem depends on the catchment slope and the soil type, where shallow subsurface flow dominates resulting in short MTTs of less than 1 year (Larco et al., 2023; Mosquera et al., 2016). On the other hand, in a tropical montane catchment in eastern Kenya, a MTT of up to 4 years was estimated, mainly due to substantial groundwater contributions to streamflow throughout the year (Jacobs et al., 2018). However, a more systematic and comparative study on tropical transit times is still missing, but feasible with more higher resolution (daily) stable isotope time series made available.

Therefore, this study tested the gamma distribution as a lumped convolution integral model transfer function to examine how its parameters vary in different catchments with variable landscape characteristics and climate conditions (Beven, 2010; McDonnell et al., 2010). We used data from tropical catchments in South America, Central America, and Australia to enhance our current knowledge of tropical hydrology, with the following specific objectives:

- i) estimate transit times and distributions of different pan-tropical catchments,
- ii) relate the TTDs to catchment characteristics in a catchment comparison exercise and,

- iii) analyze the most important hydrogeomorphic drivers of transit times and their distributions.

2. Data

2.1. Pan-tropical study catchments

The pan-tropical region refers to the geographical area that extends approximately ± 20 degrees northern and southern latitude from the equator and encompasses regions situated within the tropical belt of the Earth (Cai et al., 2019). In this region we analyzed hydrometric and isotopic data from seven catchments located in Australia (i.e., Howard and Atika), Costa Rica (i.e., Caño Seco, Quebrada Grande, Alberto Manuel Brenes-RBAMB and Tempisque) and Ecuador (i.e., Zhurucay) (Figure 1 and Table 1). The altitude range of all analyzed catchments was between 12 and 3788 m a.s.l., while their areas varied from 1.5 to 990 km².

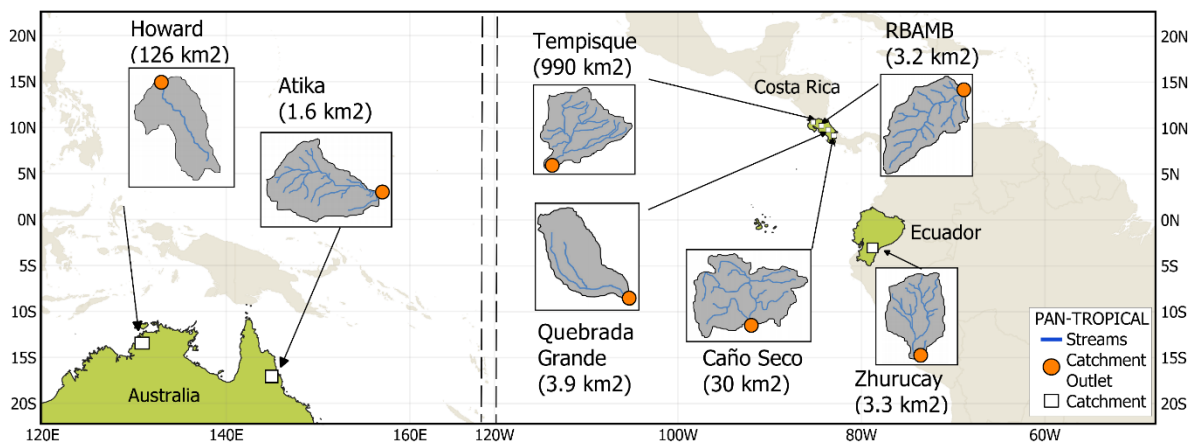


Figure 1. Pan-tropical study catchments in Costa Rica; Ecuador and Australia using the pan-tropical band $\pm 20^\circ$ (Cai et al., 2019).

2.2. Hydrometeorological Data

Existing daily rainfall and discharge data, as well as temperature, relative humidity and evapotranspiration estimates were recompiled for the above presented pan-tropical catchments (footnotes of Table 1). The mean annual precipitation, streamflow, and actual evapotranspiration, exhibited ranges of 958 to 5116 mm year⁻¹, 400 to 2100 mm year⁻¹ and 461 to 1338 mm year⁻¹, respectively. Mean annual air temperature varies from 6 to 27 °C. The different tropical climates of our study catchments were identified using the updated Köppen-Geiger classification (Beck et al., 2018; Köppen, 1936; Peel et al., 2007) and include tropical savanna-Aw (i.e., Howard, Tempisque), tropical rainforest- Af (i.e., Atika, Caño Seco, Quebrada Grande, Alberto Manuel Brenes RBAMB), and tropical alpine biome without dry

season and cold summer-Cfc (i.e., Zhurucay). For more details on hydrometeorological characteristics of the study catchments see Table 1.

1 **Table 1.** Location, altitudinal range, area and sampling period of the study catchments, together with climate (mean annual precipitation (P),
 2 mean annual streamflow (Q) and mean annual actual evapotranspiration (AET) and mean annual air temperature (T)), and geology (lithology,
 3 rock type and % cover)

	Catchment	Location (degrees)	Altitude (m a.s.l.)	Area (km ²)	Sampling Period	*P (mm)	Q (mm)	**ET (mm)	T (°C)	*** Climate	Geology		
											FORMATION: Dominant Lithology	Class	Coverage (%)
Australia	Howard	12°30'S 131°05'E	0-40	126	2015- 2018	1820 [1880]	758.5	1060 ¹	27	Aw ⁸	DARWIN: Sandstone, Claystone ¹⁵	Sedimentary	100
	Atika	16°49'S 145° 41'E	13-508	3.7	2019- 2021	2265 [1992]	618	1348 ²	25	Af ⁹	HODGKINSON: Mudstone, siltstone, conglomerates ¹⁶	Metamorphic	100
Costa Rica	Caño Seco	8°40'N 82°51'W	907- 1475	30	2012- 2014	2124 [3052]	1325	799 ³	20	Af ¹⁰	TERRABAN: Lulitas, liltstones, pyrite sandstones, tuffaces, conglomerates, turbidities ¹⁷	Sedimentary	58.9
											FILA DE CAL: Shallow limestone of reef platform ¹⁸	Sedimentary	0.1
	Quebrada Grande	1°6'0"N 84°3'W	1765- 2350	3.9	2016- 2019	5117 [4000]	1596	612 ⁴	27	Af ¹¹	AGUACATE: Andesite, basalts, gaps, tuffs ¹⁹	Igneous	41
	RBAMB	10°14'2"N 84°37'5"W	870- 1470	3.2	2013- 2017	2790 [2589]	2100	455 ⁵	19	Af ¹²	QUEBRADA GRANDE: Basalts, Andesites ²⁰	Igneous	100
	Tempisque	10.6°N 85.45°W	0-1900	990	2015- 2021	1800 [1920]	700	1100 ⁶	27	Aw ¹³	TERTIARY: Basalts, Andesites, pyroclastics flow ²¹	Igneous	100
											Volcanic rocks ²² Sediments ²³	Igneous Sedimentary	90 10
Ecuador	Zhurucay	3°04'S 79° 14'W	3400- 3900	3.3	2017- 2019	958.6 [1345]	433	461 ⁷	7.6	Cfc ¹⁴	QUIMSACocha: Basaltic flows with plagioclases, feldespars ²⁴	Igneous	50
											TURI: Tuddaceous andesitic breccias, conglomerates, stratified sands ²⁵	Igneous	30
											QUATERNARY: Sediments ²⁶	Sedimentary	20

*Mean Annual precipitation: long-term historic in brackets: [1989-2018] Australia, [> 5 years] Atika, [> 10 years] Caño seco, [1992-2003] Quebrada Grande River, [> 5 year] RBAMB, [1998-2020] Tempisque, [1964-2008] Zhurucay. **Evapotranspiration method: **1** (AET) Eddy covariance flux tower, **2** (AET) (FAO-56), **3** (PET) (Hargreaves); **4** (AET) Penman-Monteith. **5** (PET) Penman-Monteith, **6** (AET) MODIS satellite, **7** (AET) Eddy covariance flux tower. *** Köppen-Geiger Clasification: **8** (Birkel et al., 2020), **9** (Duvert et al., 2022) **10** (Méndez & Molina Montero, 2016), **11** (Mayer-Anhalt et al., 2022), **12** (Martínez-Cuenca et al., 2020), **13** (Nauditt et al., 2022), **14** (Kannan et al., 2020). **15** (Cook et al., 1998; Doyle, 2001; Duvert et al., 2020); **16** (Bass et al., 2014; Blewett, 2012; Lim et al., 2022); **17,18,19** (Méndez & Molina Montero, 2016), **20** (Mayer-Anhalt et al., 2022; Sánchez-Murillo et al., 2019); **21** (Bergoeing, 2007; Correa et al., 2020; Dehaspe et al., 2018; Solano-Rivera et al., 2019); **22,23** (Erlich et al., 1996; Guzmán Arias & Calvo-Alvarado, 2012); **24,25,26** (Coltorti & Ollier, 2000; Longo & Baldock, 1982; Panagos et al., 2022; Pratt et al., 1997).

2.3. Rainfall and streamflow isotope data

Streamflow samples in the Howard catchment were collected using 50 ml centrifuge tubes, with a weekly frequency during wet seasons and monthly during dry seasons, as reported by Birkel et al. (2020). Rainfall was collected daily using a dip-in rainfall sampler (RS-1C, PALMEX, Zagreb-Croatia) designed to avoid evaporation (Gröning et al., 2012). All waters were filtered through 0.45 μm membrane on-site, then kept on ice and refrigerated upon arrival to the laboratory. Stable isotope analysis was conducted using a Cavity Ring-Down Spectroscopy (CRDSL Picarro L2130-i) with standard errors reported ($\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

In the Atika catchment (Lim et al., 2022), streamflow samples were collected using an automatic water sampler (3700, Teledyne ISCO, Nebraska-USA) every week during non-events and every 2 hours during events. Rainfall samples were collected daily using a rainfall sampler (RS-1C, PALMEX, Zagreb-Croatia). All water samples were stored in dark brown glass bottles at room temperature in the laboratory prior to stable isotope analysis. Stable isotope analysis was conducted using a Cavity Ring-Down Spectroscopy (CRDSL Picarro L2130-i) with standard errors reported ($\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

The Caño Seco (Birkel et al., 2016) streamflow samples were collected manually every two days using a plastic funnel. Rainfall was collected daily using a passive sampler from a tipping bucket rain gauge. In all water samples, a mineral oil was applied, and they were filled into standard 3ml analytical vials and stored at 5°C. Stable isotope analysis was conducted using a Liquid-Water Isotope Analyzer (DLT-100 Los Gatos) with standard errors reported ($\pm\sigma$: $\pm 0.4\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

The Quebrada Grande (Mayer- Anhalt et al., 2022), streamflow samples were automatically collected daily using a Sigma 900 MAX (HACH, Iowa-USA) water sampler during 2016-2017, and manually with weekly frequency from 2017-2019. Rainfall was collected daily using an on-site manual rainfall sampler (RS-1C, PALMEX, Zagreb-Croatia). All samples were stored in 30 ml bottles at 5°C without headspace and were hermetically sealed to avoid exchange with atmospheric moisture. Prior to analysis, all samples were filtered using a 0.45 μm syringe polytetrafluorethylene (PTFE) membrane. Stable isotope analysis was conducted using a Cavity Ring-Down Spectroscopy (CRDSL Picarro L2120-i) with standard errors reported ($\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

The RBAMB (Birkel et al., 2021) and Tempisque (unpublished) streamflow was sampled daily with an autosampler (3700, Teledyne ISCO, Nebraska-USA) and weekly, respectively, while

rainfall was collected daily at both sites using a rainfall sampler (RS-1C, PALMEX, Zagreb-Croatia). All water samples were stored using 3-l plastic bottles using a funnel and inlet tube. Water samples were stored in 50-ml polypropylene, sealed with screw caps and later stored in a fridge at 5°C, then filtered through 0.45 μm syringe polytetrafluorethylene (PTFE) membrane. Stable isotope analysis was conducted using a Cavity Ring-Down Spectroscopy (CRDSL Picarro L2120-i) with standard errors reported ($\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

In Zhurucay (Pesántez et al., 2023), streamflow was sampled every 4 hours using an autosampler (PVS4100D, Campbell, Utah-USA). Rainfall was collected for every 2.08 mm of rain. The collected water was stored in 2mL amber glass bottles, covered with parafilm, and kept away from the sunlight. Stable isotope analysis was conducted using a Cavity Ring-Down Spectroscopy (CRDSL Picarro L2130-i) with standard errors reported ($\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$).

We report all the isotope analysis equipment and its standard errors in Annex A. All rainfall samples were collected daily with some sub-daily event sampling at RBAMB and Zhurucay. The sub-daily samples were aggregated to a representative daily sample and standard model application across the tropical study catchments.

3. Methods

3.1. Catchment Characterization

3.1.1. Landscape variables

The landscape characteristics such as the soil types and their relative percentage cover in each catchment were determined from the literature. Soils described in another soil classification system (e.g., Australian soil classification) were reclassified according to Krasilnikov et al. (2009) for a standard comparison with the Food and Agriculture Organization of the United Nations guides (FAO) (Driessen, 2001). The Howard catchment exhibits dominant Dermosols, Cambisols 73% and Fluviosols 27% (Brocklehurst, 2012). The Atika presents brown and red Dermosols as dominant soil types (Cambisols) (Murtha, 1986). Caño Seco's dominant soils are Andosols 66% and Alisols 34% (Méndez & Molina Montero, 2016). In Quebrada Grande, Andosols are the principal soil type with 100% cover (Mayer-Anhalt et al., 2022). RBAMB presents Andosols 80% and Cambisol 20% (Correa et al., 2020; Dehaspe et al., 2018). In Tempisque, Entisols (Regosols) 56% and Inceptisols (Cambisol) 34% predominate (Guzman & Calvo, 2013), and Zhurucay presents Andosols 74%, Histosols 22% and Leptosols 4% (Quichimbo et al., 2012).

The soil texture class was determined based on previous results from on-site soil profile descriptions. Furthermore, we compared the local measurements with the approach by Ross et al. (2018), who performed a global classification of soils using a 250 m grid size, with an emphasis on hydrologic and texture characteristics (FAO, 2006). Topographic variables such as average slope in percent, area in square kilometers and mean altitude in meters were estimated based on digital elevation models (DEMs) from Atika (Lim et al., 2022), Howard (Birkel et al., 2020; Duvert et al., 2020), Caño Seco (Birkel et al., 2016; Méndez & Molina Montero, 2016), Quebrada Grande (Mayer- Anhalt et al., 2022), RBAMB (Birkel et al., 2021), Tempisque (Venegas-Cordero et al., 2021) and Zhurucay (Mosquera et al., 2016) (Table 3).

3.1.2. Geological variables

The geology of Howard catchment constitutes of the Darwin formation with Quaternary-Claystone and a sedimentary lithology (Cook et al., 1998; Doyle, 2001; Duvert et al., 2020). Atika belongs to the Devonian-Hodkinson formation conformed of primarily metamorphic rocks (Blewett, 2012; Lim et al., 2022). The Caño Seco belongs to three formations, the Terraba-Miocene (Denyer & Kussmaul, 2000), Fila de Cal-Eocene (Moya Arguedas, 1990) and Aguacate-Pliocene (Moya Arguedas, 1990) with dominant sedimentary and igneous lithology respectively. Quebrada Grande belongs to the Cenozoic-Miocene with dominant igneous lithology (Sánchez-Murillo et al., 2019). The RBAMB belongs to Tertiary formations with dominating igneous rocks (Bergoeing, 2007). The Tempisque exhibits Cenozoic- quaternary geology with igneous and sedimentary rocks (Erlich et al., 1996). The Zhurucay catchment belongs to the Quimsacocha-Miocene and Turi-Miocene formations, quaternary deposits with igneous and sedimentary rocks (Coltorti & Ollier, 2000; Longo & Baldock, 1982; Pratt et al., 1997). More details on the dominant lithology are presented in Table 1.

3.1.3. Hydrological variables

Hydrometeorological variables such as the runoff coefficient, annual precipitation, annual actual evapotranspiration, and annual streamflow were obtained from the daily hydrometeorological data sets. Delta storage was estimated from the annual water balance as the difference between the input (precipitation) and outputs (evapotranspiration, streamflow), in percentage. We further used the seasonality index (SI) (Eq-1):

$$SI [-] = \frac{1}{R_i} \sum_{j=1}^{12} \left| M_{ij} - \frac{R_i}{12} \right| \quad \text{Eq-1}$$

where, R_i is the annual rainfall for the year i , M_{ij} is the monthly rainfall for month j . SI ranges from 0 (Non seasonal, all months with equal rainfall) to 1 (Extremely seasonal, all annual

rainfall occurs in one month) (Walsh & Lawler, 1981). The replicability index (RI) to assess variability of rainfall regimens (Eq-2):

$$RI [-] = \frac{SI_a}{SI_{mean}} \quad \text{Eq-2}$$

where, SI_a is the seasonality Index at year a, SI_{mean} is the mean seasonality index of the whole period. High values for wet and dry months frequently occur at the same period every year. Small values indicate highly variable timing of wet and dry seasons (Walsh & Lawler, 1981). Percentage of days with zero precipitation (Eq-3):

$$Day0 [\%] = \frac{\# Days_{p=0}}{\# Total days} \quad \text{Eq-3}$$

$\# Days_{p=0}$ it the numbers of days of the whole monitored period with zero precipitation. $\# Total days$ is the total number of days over the monitored period. Precipitation not registered by the rain gauge with respect to the total number of days over the monitored period. Coefficient of variation in daily precipitation PVAR (Eq-4):

$$PVAR [mm/mm] = \frac{\sigma_p}{P_{mean}} \quad \text{Eq-4}$$

where σ_p is the standard deviation of daily precipitation, P_{mean} is the average of the daily precipitation. Standard deviation of daily precipitation over the mean daily precipitation. Months with zero precipitation (Eq-5) relative to the entire analysis period:

$$Month0 [\%] = \frac{\# Months_{p=0}}{\# Total Months} \quad \text{Eq-5}$$

where, $\# months_{p=0}$ is the number of months with zero precipitation. $\# Total Months$ is the number of total months of the whole period available. Monthly precipitation not registered by the rain gauge with respect to the total number of months over the monitored period. Coefficient of variation in daily precipitation (Eq-6):

$$PMVAR [-] = \frac{\sigma_{MP}}{P_{Mmean}} \quad \text{Eq-6}$$

where, σ_{MP} is the standard deviation of the monthly precipitation. P_{Mmean} is the average monthly precipitation. [-] dimensionless. Standard deviation of monthly precipitation over the mean monthly precipitation.

3.2. Transit Time estimations

We used the lumped convolution approach to estimate TTs in pan-tropical catchments. The simple convolution integral transit time model (Eq-7) estimates stream isotopes ratios with

corresponding transit time, using a transfer function $g(\tau)$ (Amin & Campana, 1996; Maloszewski & Zuber, 1982). This model converts the input of daily isotopic composition of precipitation into an approximation of the stream isotope ratios $\delta_{out}(t)$. The daily evapotranspiration was subtracted from the daily precipitation amount for the input function $\delta_{in}(t-\tau)$, assuming no fractionation of surface waters. This assumption is supported by the stream water isotope samples plotting consistently close to the calculated Local Meteoric Water Lines (LMWL) (See Figure 3).

Two transfer functions were applied here. 1) The gamma distribution model (GM) Eq-8 which is more flexible and a general version of the exponential model. The product of the two parameters ($\alpha(-)$ is the shape parameter and $\beta(days)$ the scale parameter) gives the MTT $\tau(days)$ of the system (Hrachowitz et al., 2009). The Gamma model GM equation is:

$$GM = \frac{\tau^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} \exp\left(-\frac{\tau}{\beta}\right) \quad \text{Eq-7}$$

where the parameters α and β ranged from 0.01 to 4 (-) and from 0 to 1825 (days) respectively. Due to the limitations of stable water isotopes to detect transit times exceeding 5 years (Stewart et al., 2010), the scale parameter was limited to 1825 days (5 years).

2) The exponential model (EM) Eq-8 as a special case of the Gamma model represents a well-mixed system and assumes contributions from all flow paths. This model uses one parameter τ and is described in Eq-8:

$$EM = \frac{1}{\tau} * \exp\left(-\frac{t}{\tau}\right) \quad \text{Eq-8}$$

where τ ranged from 0 to 1825 days.

For all catchments, we used a warm-up period prior to calibration that consisted in 5 times the measurement record resulting in a standardized calibration approach (Hrachowitz et al., 2013). The gamma model and exponential model were calibrated for the periods shown in Annex B. A qualitative validation compared our TT results to TTs reported for the same catchments.

The calibration and evaluation of the TTD models was performed using the Differential Evolution algorithm (DEoptim R package) developed by Ardia et al. (2011). The algorithm was implemented in R (R Core Team, 2021) and the performance of the gamma and exponential model was evaluated using the Kling-Gupta Efficiency criterion (KGE) (Gupta et al., 2009). The KGE ranges from $-\infty$ to 1, where unity indicates an ideal optimization. The calibration

procedure used a maximum of 10 000 iterations with a stop criterion for KGE of 0.01, and the simulations were presented with 90% percentiles uncertainty bands for the best performing 100 parameters sets. Efficiency values greater than 0.3 were considered acceptable (Knoben et al., 2019).

3.3. Statistical analysis

We initially conducted a correlation analysis relating the estimated MTTs and TTD characteristics with hydroclimatic and landscape parameters using the non-parametric Spearman's rank correlation analysis (Wissler, 1905): 1) Landscape (soil type, soil texture and topographic features), 2) geological (rock type), and 3) hydrological (meteorological indices) parameters. The robustness of correlations was checked following these assumptions (Osborne & Waters, 2002; Williams et al., 2013): linearity, assessed by examining whether the mean of the residuals of each correlation is equal to or approximately zero (Pedhazur, 1997); normality, assessed using the Shapiro test to determine the normal distribution of the residuals (King & Eckersley, 2019); homoscedasticity, checked using the Score Test for Non-Constant Error Variance (ncv) (Cook & Weisberg, 1983); and the independence of the variables with the Durbin Watson test (Savin & White, 1977). All correlations and the hypotheses test were conducted using *lawstat* (Gastwirth et al., 2023) and *gvlma* (Peña & Slate, 2006) libraries using the R statistical programming language (R Core Team, 2021).

Furthermore, the identified drivers associated to MTTs and the TTD alpha parameter by correlation ($p\text{-value} < 0.1$), were ranked according to the relative importance using a random forest (RF) analysis (Liaw & Wiener, 2001). For the RF we used the increased mean square error (IncMSE) as a measure explaining the effect of an explanatory variable on the predicted result. Therefore, higher IncMSE values more positively impact on the target variables (MTTs and alpha values) (Breiman, 2001). The analysis was performed using the *randomForest* library implemented in R (Liaw & Wiener, 2001).

4. Results

4.1. Hydrogeomorphology and isotope characteristics of the tropical study catchments

The pan-tropical catchment characterization is based on the landscape and hydrometeorological variables presented in Table 2. Here, we give a brief summary of the main characteristics. Four of seven catchments presented Andosol (Caño Seco, Quebrada Grande, RBAMB, Zhurucay) and Cambisol (Howard, Atika, RBAMB, Tempisque) soil types with more than 66% and 20% of the catchment area, respectively. Soil types such as Alisols

34% (Caño Seco), Histosols 22% (Zhurucay), Regosols 56% (Tempisque), and Fluvisols 27% (Howard) were the least abundant. The predominant soil texture groups are A (Sand) and B (Sandy Loams, Loamy Sands) in most of the catchments. According to the catchment size classification by Singh (1991), our catchments range from micro-catchments $< 10 \text{ km}^2$ (Atika, Quebrada Grande, RBAMB, Zhurucay), small catchments $< 100 \text{ km}^2$ (Caño Seco) to medium catchment size $< 1000 \text{ km}^2$ (Howard, Tempisque). The largest catchments (Howard and Tempisque) exhibited on average “sloping land” (10% - 15%), while the smaller catchments (Atika, Caño Seco, Quebrada Grande, RBAMB, and Zhurucay) are also the more mountainous and “moderately steep” (15% - 30%). The mean altitude covered a range from 12 to 3,788 m a.s.l. (Table 2). The geology of most of the catchments is dominated by igneous rocks, with sedimentary rocks present to a lesser extent. The Atika is the only catchment with predominant metamorphic rocks (Table 2).

The mean annual precipitation, streamflow, and actual evapotranspiration in the catchments ranged from 959 to 5116, 433 to 2100 and 461 to 1060 mm year^{-1} , respectively. Such a wide range shows the high hydrometeorological variability that characterizes the tropics (Cai et al., 2019). The wettest catchment Quebrada Grande, in Costa Rica, received the largest amount of precipitation ($5116 \text{ mm year}^{-1}$) and the RBAMB the highest streamflow ($2100 \text{ mm year}^{-1}$). The Australian Atika catchment registered the highest actual evapotranspiration ($1348 \text{ mm year}^{-1}$). The Zhurucay exhibited the lowest precipitation and streamflow (959 and 433 mm respectively) among all catchments. Most catchments are relatively humid ($\text{RH} > 90\%$), except for the seasonally-dry Howard ($\text{RH} \sim 65\%$). The mean annual temperature of all catchments is around 19.7°C , except for the high-elevation Zhurucay (7.6°C). The runoff coefficients (RC) ranged from 0.27 to 0.75 with prominent overland and shallow subsurface flow. The water storage capacity in the catchments is relatively small (less than 10%) apart of the Quebrada Grande with a significant water storage capacity of 56% (Table 2).

The seasonality index reflected different tropical precipitation regimes from non-seasonal (Quebrada Grande, 0.2-0.39, $\text{Day0} < 30\%$) to more seasonal precipitation with a short dry season ($\text{SI: } 0.4\text{-}0.59$, $\text{Day0} < 60\%$) as in Caño Seco, RBAMB and Zhurucay. The Tempisque, Howard and Atika show a predominantly seasonal precipitation regime ($\text{SI: } 0.6\text{-}0.79$, $\text{Day0} < 30\%$, $\text{SI: } 0.8\text{-}0.99$, $\text{Day0} < 30\%$) with a long dry season of a minimum of four months. The replicability index shows high values when wet and dry months frequently occur at the same period every year (e.g., Howard). Conversely, small RI values suggest high variability in timing of the wet and dry season (e.g., Quebrada Grande). The percentage of months with zero precipitation (Month0) is less than 30% in all the catchments, and the coefficient of variation (PMVAR) is less than 1.27. The variability of daily precipitation (PVAR) is low in Tempisque

229 and Zhurucay, where $PVAR < = 0.6$, but high in Howard and Caño Seco, where $PVAR > 2$
 230 (Table 2).

231 **Table 2.** Catchment descriptors (hydrogeomorphology) used for correlation analysis with
 232 transit time estimations.

	Parameter	Howard	Atika	Caño Seco	Quebrada Grande	RBAM B	Tempisque	Zhurucay
Soil types	Andosol (%)	0	0	66	100	80	0	74
	Cambisol (%)	73	100	0	0	20	34	0
	Alisoles (%)	0	0	34	0	0	0	0
	Histosol (%)	0	0	0	0	0	0	22
	Regosol (%)	0	0	0	0	0	56	0
	Fluviosol (%)	27	0	0	0	0	0	0
*Soil Textu	A (%)	27	0	66	100	80	0	74
	B (%)	73	100	0	0	20	34	4
	C (%)	0	0	34	0	0	56	22
Topographic variables	slope (%)	10.00	27.00	20.79	16.90	22.30	10.50	18.00
	Area (km ²)	126.00	1.57	31.21	3.90	3.20	990.00	3.28
	Altitude (m a.s.l.)	12	20	1037	2222	1133.50	260	3788
**Geology	Igneous (%)	0	0	41	100	100	90	80
	Metamorphic (%)	0	100	0	0	0	0	0
	Sedimentary (%)	100	0	59	0	0	10	20
***Hydrometeorological variables	P (mm year ⁻¹)	1819.10	2265.0	2123.87	5116.90	2790.00	1880.00	958.60
	AET (mm year ⁻¹)	1060	1348	799	612	455	1100	461
	Q (mm year ⁻¹)	759	618	1325	1596	2100	700	433
	RH (%)	65.70	82.00	95.30	95.00	96.30	95.00	92.00
	T (°C)	26.70	25.00	19.90	27.00	19.70	27.00	7.60
	Delta Storage (%)	0.00	13.20	0.01	56.85	8.42	4.26	6.74
	RC (-)	0.42	0.27	0.62	0.31	0.75	0.37	0.45
****Seasonal and	SI (-)	0.93	0.84	0.58	0.24	0.46	0.78	0.45
	RI (-)	1.01	0.94	0.90	0.58	0.79	0.93	1.09
	Day0 (%)	63	0	59	21	43	40	43
	PVAR (-)	2.49	1.61	1.97	1.49	1.76	1.54	1.49

Month0 (%)	27	6	3	0	1	29	0
PMVAR	1.19	1.27	0.80	0.50	0.69	1.11	0.55

*A (Sa) sand; B (SaLo) Sandy Loam, (LoSa) Loamy Sand; C (ClLo) Clay loam, (SiClLo) Silty clay loam, (SaClLo) Sandy clay loam, (Lo) Loam, (SiLo) Silty Loam, (Si) Silty. Classification done according to (Ross et al., 2018). (-) Dimensionless.

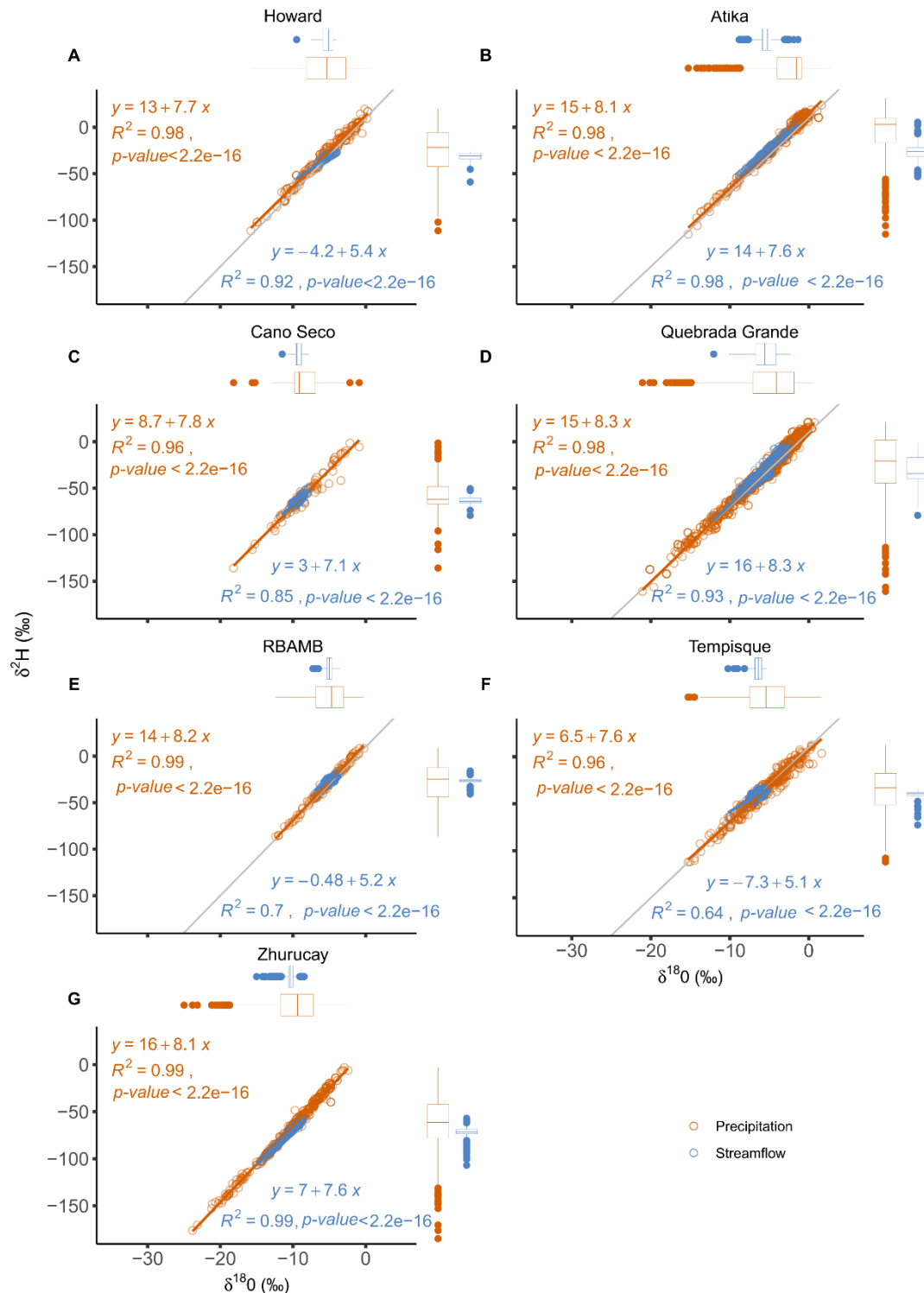
**Igneous (basaltic flows with plagioclases, feldspars, andesitic pyroclastics); Metamorphic (Mudstone, siltstone, conglomerates); Sedimentary (Shallow limestone of reef platform, lullitas, siltstones, sandstones, turbidities, pyrite).

***Runoff coefficient (RC); precipitation (p); evapotranspiration (et); streamflow(q); relative humidity (RH); temperature (T); percentage of storage water (Δ storage)

****Seasonality Index (SI); Replicability Index (RI); Percentage of days with zero precipitation (Day0), Coefficient of variation with daily precipitation (PVAR), Percentage of month with zero precipitation (Month0), coefficient of variation with monthly precipitation.

233

234 Figure 2 shows the Local Meteoric Water Lines (LMWL) for each site. The slope of the
 235 precipitation isotopic signal ranged from 7.7 to 8.3, with an average of 7.91 ± 0.27 , similar to
 236 the Global MWL. The intercept ranged from 6.5 to 16, with an average of 12.6 ± 3.6 ‰. The
 237 slope of the regression equations for the streamflow signal reflected the internal processes of
 238 each catchment, with values ranging from 5.1 to 8.3, and an average of 6.6 ± 1.34 , while the
 239 intercept range was between -7.3 to 16, with an average of 4 ± 8.84 ‰. The deuterium-excess
 240 parameter defined as $d = \delta^2\text{H} - 8 \cdot \delta^{18}\text{O}$ varied between 8.79 and 14.6 for precipitation and
 241 between 9.9 and 16 for streamflow. Generally, the LMWLs show limited evaporation
 242 processes or mixing with other water sources. The boxplots in Figure 2 show the isotopic
 243 variability in precipitation and streamflow for oxygen-18 ($\delta^{18}\text{O}$) and deuterium ($\delta^2\text{H}$). The direct
 244 comparison of precipitation with streamflow variability is indicative of the degree of catchment
 245 filtering where a similar variability reflects little to no mixing and filtering. The Atika and
 246 Quebrada Grande show the highest input to output ratio.



247

248 **Figure 2.** Precipitation and streamflow isotope variability (boxplots) and LMWLs of all pan-
 249 tropical catchments. Blue dots represent streamflow isotope signal. Blue lines represent the
 250 WL of streamflow. Orange dots are the precipitation isotope signal. Orange lines are the
 251 LMWL of precipitation samples. Gray line represents the Global Meteoric Water line (GMWL)
 252 $y = 8x + 10$ as a reference.

4.2. Transit time simulations and parameter uncertainty

The Howard, Caño Seco, and Tempisque catchments exhibited the longest MTTs (307 < MTTs < 495 days) compared to Atika, Quebrada Grande, RBAMB and Zhurucay (82 < MTTs < 252 days). When using the gamma model, the reported MTTs < 1.4 years were modelled with KGEs efficiencies ranging from 0.32 to 0.92 (Table 3). In comparison, the calibrated exponential model resulted in shorter MTTs < 0.4 years with lower KGEs efficiencies from 0.16 to 0.88. Table 3 summarizes the gamma and exponential model parameters, as well as the best-fit MTT's and KGE's.

Table 3. The best-fit MTT estimations of all study catchments using two different models. Gamma (GM) and exponential model (EM) with the retained parameter range and median, as well as the best fit MTT's, KGE efficiencies and references.

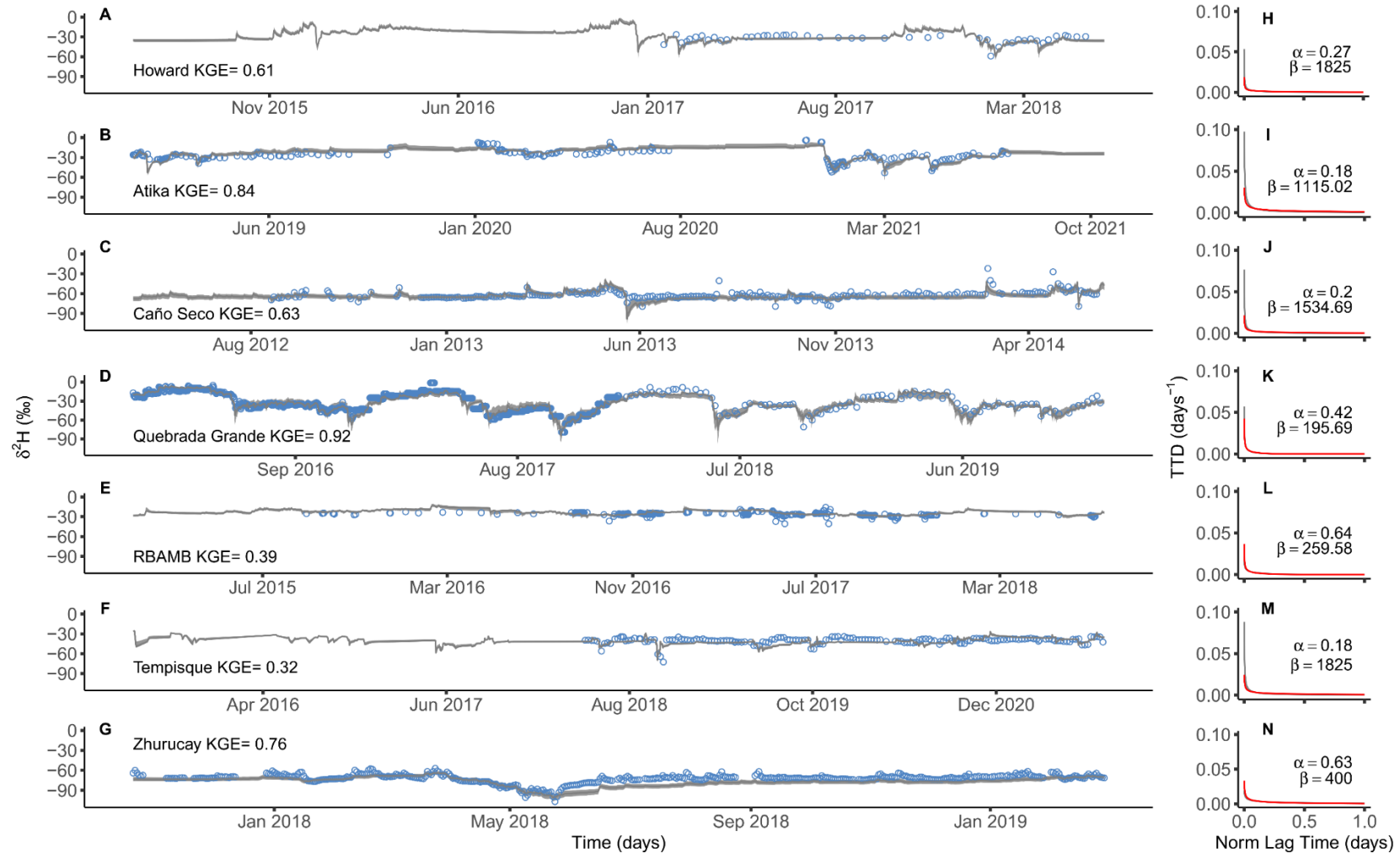
Catchment	GM				EM		REFERENCES MTT/TT (days)
	Alpha (Range) calibrated	Beta (Range) calibrated	MTT (Simulated) Best fit	KGE	MTT (Simulated) Best fit	KGE	
Howard-AUS	(0.2-0.3) 0.27	(944-1825) 1825	(283-497) 494.83	0.6 1	(113-124) 123.46	0.1 8	~511 (Birkel et al., 2020)
Atika-AUS	(0.12-0.18) 0.18	(1034-1318) 1115.02	(49 -228) 197.00	0.8 4	(28-113) 53.37	0.6 7	-- --
Caño Seco-CRI	(0.16-0.22) 0.19	(1213-1552) 1535	(274-340) 336.70	0.6 3	(109-113) 104.2	0.3 8	~213 (Mendez et al., 2016)
Quebrada Grande-CRI	(0.22-0.44) 0.42	(179-389) 195.70	(80-151) 81.74	0.9 2	(69-113) 72.52	0.8 8	~87 (Mayer-Anhalt et al., 2022)
RBAMB-CRI	(0.52-0.65) 0.64	(248-323) 259.57	(130-438) 165.69	0.3 9	(113-157) 156.20	0.3 7	~162 (Correa et al., 2020)
Tempisque-CRI	(0.16-0.22) 0.18	(1730-1825) 1825	(289-438) 322.19	0.3 2	(82-113) 85.53	0.1 6	-- --
Zhurucay-ECU	(0.6-0.66) 0.63	(382-412) 400	(229-264) 252.02	0.7 6	(113-230) 163.12	0.5 7	~188 (Mosquera et al., 2016)

-- No previous reported values.

The gamma model reliably represented the extremes of the isotopic signals (Figure 3: Panels A-G $KGE_{\text{gamma}} > 0.32$) and resulted in better fits compared to the exponential model (Annex C: Panels A-G, $KGE_{\text{exponential}} > 0.16$). Therefore, we used the GM MTT results in further

268 statistical analysis. The Probability Density Functions (PDFs) in Figure 3, panels H-N, were
269 plotted with the best-fit GM parameters (α and β), and a normalized scale [0,1]. The latter
270 resulted relatively similar to the global PDF ($\alpha = 0.5$ and $\beta =$ beta calibrated to the specific
271 site).

272



273

274 **Figure 3.** Fitted deuterium signal simulations in streamflow using a convolution integral approach with a gamma model as transfer function: A-G:
 275 Deuterium signal simulations in streamflow. Measured streamflow isotope signal as blue points. 90% uncertainty bands in gray obtained from the
 276 retained parameter sets during calibration. H-N: Probability Density Functions (best-fit α and β values) as gray line, and global PDF ($\alpha = 0.5$ and
 277 β calibrated to the specific site) in red.

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4.3. Relating transit times to pan-tropical catchment characteristics

The nonparametric Spearman rank correlation was used to relate the calibrated alpha parameters and the resulting MTTs (Table 3) from the GM of all catchments to the hydrogeomorphological catchment characteristics from Table 2. Such correlations revealed which variables were influencing water age and allowed inference on how (Table 4). The statistically robust and significant correlations (p-value < 0.1) are presented in Table 4 and Annex D. Figure 4 shows the positive correlations of the alpha parameter with Andosol soils (Figure 4-A, $r = 0.79$), soils texture (Figure 4-B, $r = 0.85$) and mean altitude (Figure 4-C, $r = 0.67$). Negative correlations resulted with the actual evapotranspiration (Figure 4-D, $r = -0.96$), percentage of months with zero precipitation (Figure 4-E, $r = -0.75$), and the coefficient of variation with monthly precipitation index (Figure 4-F, $r = -0.72$). The MTTs correlated with the percentage of sedimentary rocks coverage (Figure 4-I), seasonality index (Figure 4-L), and percentage of days with zero precipitation (Figure 4-M). Conversely, variables as the percentage of Andosols coverage (Figure 4-G), percentage of igneous rocks coverage (Figure 4-H), mean annual precipitation (Figure 4-J), and water storage catchment capacity (Figure 4-K) negatively correlated with MTTs (p-value < 0.098). The other variables only exhibited weak correlations with MTTs and the alpha parameter (Table 4).

Table 4. Spearman correlation coefficients with significance values of alpha (α) and MTT related to landscape, geology, and hydrologic variables.

Landscape variables	Soil Type	Alpha	MTT	Hydrologic Variables	Hydrometeorological	Alpha	MTT
	Andosol	0.79(0.036)	-0.7(0.077)		Runoff Coefficient (RC)	0.61(0.144)	0.21(0.645)
	Cambisol	-0.6(0.154)	0.34(0.452)		Mean Annual Precipitation (P)	0.11(0.818)	-0.75(0.052)
	Alisoles	-0.21(0.658)	0.41(0.363)		Mean Annual Actual Evapotranspiration (AET)	-0.95(8.1e-4)	0.39(0.383)
	Histosol	0.41(0.358)	0(1)		Mean Annual Streamflow (Q)	0.41(0.355)	-0.32(0.482)
	Regosol	-0.51(0.237)	0.2(0.661)		Mean Annual Temperature (T)	-0.54(0.215)	0(1)
	Fluviosol	0(1)	0.61(0.144)		Relative Humidity (RH)	0.34(0.461)	-0.36(0.427)
	*Soil texture Class				Delta Storage (Δsto)	0.23(0.613)	-0.93(2.5e-3)
					Seasonal and meteorological Index		
	A (Sa)	0.85(0.014)	-0.58(0.175)		Seasonality Index (SI)	-0.63(0.129)	0.68(0.094)
B (SaLo, LoSa)	-0.44(0.328)	0.23(0.613)	Replicability Index (RI)	-0.16(0.728)	0.57(0.18)		
C (ClLo, Lo, SiClLo, Si, SaClLo, SiLo)	-0.39(0.39)	0.45(0.307)					

Topographic Features					
Geology	Average Slope	0.05(0.908)	-	Days Zero Precipitation (Day0)	0.31(0.5) 0.72(0.068)
	Area	-	0.46(0.294)	Variation Coefficient of daily precipitation (PVAR)	- 0.15(0.756) 0.63(0.129)
	Mean Altitude	0.32(0.478)	0.64(0.119)	Months Zero precipitation (Month0)	- 0.75(0.054) 0.63(0.129)
	Dominant Rock types		-	Variation Coefficient of monthly precipitation (PMVAR)	- 0.72(0.068) 0.54(0.215)
	Igneous	0.54(0.21)	0.67(0.098)		
	Metamorphic	-	-0.2(0.661)		
	Sedimentary	-	0.93(2.7e-3)		

* (Sa) sand, (SaLo) Sandy Loam, (LoSa) Loamy Sand, (CIlo) Clay loam, (SiCIlo) Silty clay loam, (SaCIlo) Sandy clay loam, (Lo) Loam, (SiLo) Silty Loam, (Si) Silty. This classification was done according to (Ross et al., 2018). In bold all significant correlations (p-value < 0.1).

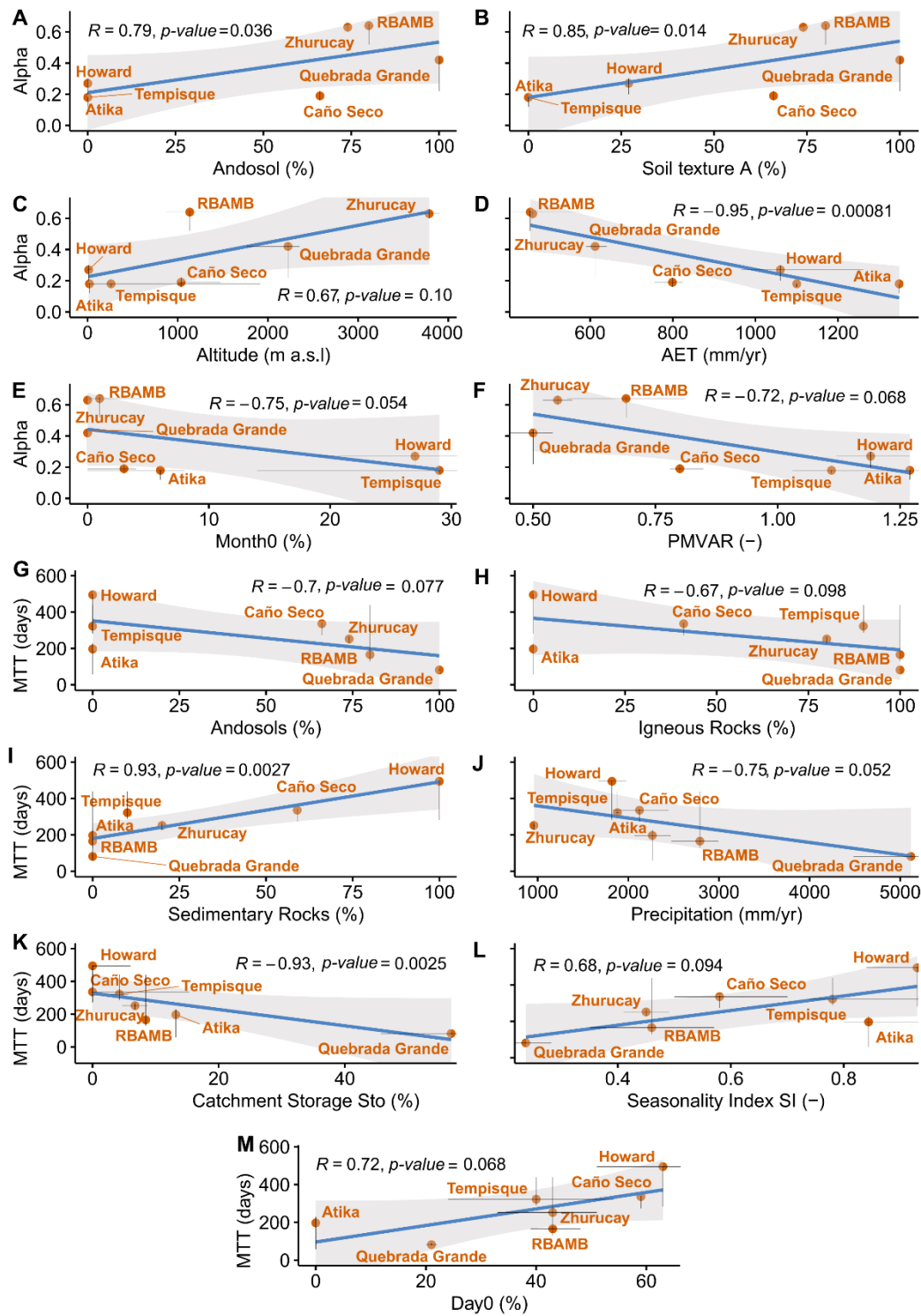


Figure 4. Spearman correlations. Alpha parameter (α) correlated with: A) percentage of Andosols, B) A group soil texture, C) altitude, D) mean annual evapotranspiration, E) percentage of months with zero precipitation, and F) coefficient of variation with monthly precipitation. MTT values correlated with: G) percentage of Andosols, H) percentage of igneous rock, I) percentage of sedimentary rock, J) mean annual precipitation, K) delta storage (term of the hydrological balance equation $\Delta\text{sto} = P - ET - Q$), L) seasonality index, and M) percentage of days with zero precipitation. X-axis and y-axis errors are represented with horizontal and vertical lines respectively on each point of the scatter plots.

Furthermore, the %IncMSE of the RF method identified the delta storage and AET as the most important drivers of MTT and the shape of the TT (alpha parameter), respectively (Figure 5). The second most important variables were the sedimentary rocks and the percentage of soil texture A within the catchment. The third most important variables related to MTT and alpha were mean annual precipitation and Andosol soil cover, respectively.

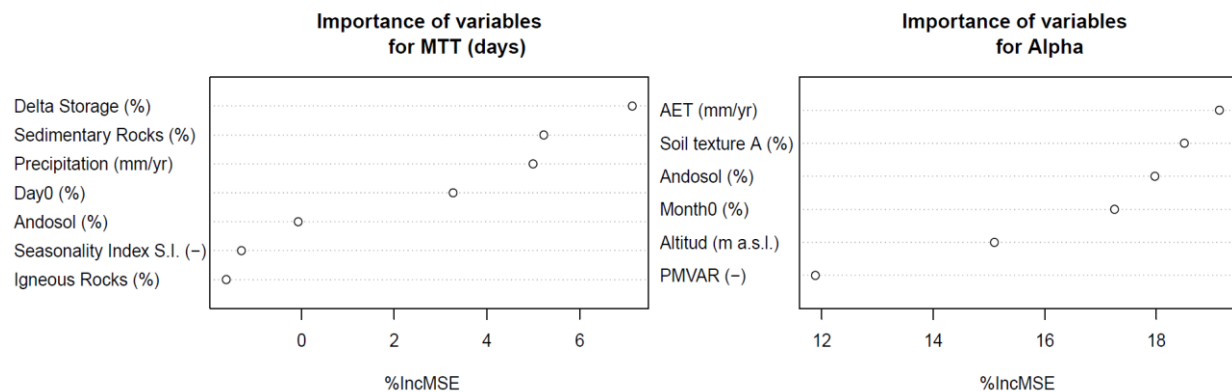


Figure 5. Ranking important explanatory variables of MTT and alpha based on the %IncMSE for all predictors used in a Random Forest model.

5. Discussion

5.1. Pan-tropical isotope characteristics and transit time estimates

All the pan-tropical study catchments exhibited relatively similar LMWLs and Evaporation Water Lines (EWL), with a slope close to those of the GMWL (range from 7.7 to 8.35 ‰ and 5.1 to 8.3 ‰, respectively), indicating limited evaporative fractionation processes (Figure 2). The intercept ranged from 6.5 to 16 ‰, in line with other tropical estimations, where the slope and the intercept values ranged from 6.5 to 9 and from -5 to 25 ‰, respectively (Putman et al., 2019). In addition to this, d-excess values found in precipitation of the study catchments (8.79 – 14.6), could be associated to non-equilibrium processes such as diffusion across humidity gradients in the tropics indicating evaporation processes for d-excess <10 and humidity recycling for d-excess >10 (Noone, 2012). Similar d-excess values have been previously found in tropical regions such as Costa Rica (8.7 – 13.3 ‰) (Sánchez-Murillo et al., 2017), and the Amazon rainforest (8 – 17 ‰) (Martinelli et al., 1996). Comparing the variability in precipitation isotopes with the streamflow variability can be indicative of catchment filtering processes most prominent for very damped or averaged out streamflow isotope variability (Tetzlaff et al., 2009). We found variability differences among the catchments but to a lesser degree compared to many other reported studies in the extra-tropics (Figure 2). The latter was reflected in transit time estimates of less than 1.4 years emphasizing the more generally quick response of these hydrological systems. These findings were consistent with previous studies that reported similar transit times but with different methods (Table 3). The gamma model was

able to reflect the dynamics of the isotope signal in streamflow ($0.32 > KGE > 0.92$), and superior compared with the exponential model ($0.16 < KGE < 0.88$) (Knoben et al., 2019). Furthermore, the daily sampling frequency particularly of the precipitation input was able to accurately estimate the rapid catchment responses if compared to previous studies that partly reported unidentifiable TTDs using weekly (Hrachowitz, et al., 2009) and bi-weekly (Mosquera et al., 2016; Muñoz-Villers et al., 2016) datasets.

In the Australian Howard catchment, we estimated a best-fit MTT of 494 days (~1.4 years) similar to those reported by Birkel et al. (2020). These longer TTs compared to the other tropical catchments is related to deeper and older groundwater contributing to streamflow as captured by a coupled tracer-aided conceptual rainfall-runoff model that estimated TTs from 1.4 to 3.6 years. In the Atika (Australia), the MTT was 197 days suggesting relatively faster water movement through the Cambisol soils (Lim et al., 2022), which respond quickly to rainfall with a fast infiltration and subsurface stormflow (soil texture class B, Sandy Loam and Loamy Sands) (Bass et al., 2014). Our results are consistent with these previous insights into the fast streamflow response to intense and frequent rainfall events caused by tropical cyclones and monsoon rainfall in the area (Lim et al., 2022).

In Costa Rican catchments, our MTT estimates resulted similar to previous work by Birkel et al. (2016), Correa et al. (2022) and Mayer-Anhalt et al. (2022), all with MTTs of less than one year. Such fast streamflow isotope responses to rainfall resulted from dominant near-surface flow paths with little evidence of deeper and older groundwater even in the larger Tempisque catchment (990km²). Nauditt et al., (2022) reflected on the quick response as a result of limited storage capacity due to the high drought risk in the Tempisque.

Our MTT estimate of ~252 days for the Zhurucay catchment in Ecuador was consistent with previous studies that suggested the prevalence of a “quasi” steady-state with MTTs shorter than 1 year and limited influence from groundwater (Larco et al., 2023; Mosquera et al., 2016; Pesántez et al., 2023).

5.2. Hydrogeomorphic drivers of pan-tropical transit times

We found that the shape of TTDs (alpha parameter) was strongly correlated with soil characteristics and actual evapotranspiration. A similar relationship with soil characteristics was also reported in the much cooler and wet climate of Scotland (Hrachowitz et al., 2009) indicating that soil and storage are primary TT drivers. Furthermore, pan-tropical alpha parameters remained close to and below 0.5, which indicates L-shape distributions with high initial values and a heavy tail (Figure 3). A wide range of North American and European catchments followed this pattern (Godsey et al., 2010; Hrachowitz et al., 2009) suggesting that

more solutes are flushed at short time lags and are present over much longer time scales (Hrachowitz et al., 2010). The latter behavior is directly related to the co-existence of fast near-surface and slower deeper substrate flow paths, which we can confirm with the most important storage, soil and precipitation variables related to MTTs. For example, Volcanic ash soils (Andosols, $r = -0.7$, $p\text{-value} = 0.077$) have high water holding capacity (Mosquera et al., 2021) that in combination with low intensity but long frequency precipitation (e.g., Seasonality Index < 0.58) favor relatively quick subsurface flow (Mosquera et al., 2015; Pesántez et al., 2023). Moreover, such soils with macropore flow reduce MTTs (Harman, 2015; Heidbüchel et al., 2020; Mosquera et al., 2020). Consequently, an increase in the percentage cover of these soils will result in shorter MTTs (Figure 3). Therefore, the combination of surface and shallow subsurface preferential flow paths in near-saturated soils above a relatively impermeable bedrock as in the case of the RBAMB and Zhurucay presented relatively higher alpha parameters ($0.42 < \alpha < 0.64$). On the other hand, catchments such as the Howard, Atika, Caño Seco, and Tempisque, with more freely draining soils, above coarser drift deposits and fractured bedrock resulted in lower alpha parameters ($\alpha < 0.42$). The significant correlation of altitude ($r = 0.67$, $p\text{-value} = 0.10$), actual ET ($r = -0.95$, $p\text{-value} = 0.00081$) and the alpha parameter suggested that the higher elevation catchments are more energy limited with lower ET compared to lowland catchments. A similar relation to ET and the exposure to energy in form of aspect was previously found by Broxton et al. (2009) in semi-arid catchments in Arizona. Linked to soil characteristics and the capacity of a catchment to conduct or store water were the significant correlations identified by random forest ranked most important controls on TTs and the gamma alpha parameter (Figure 5).

6. Conclusions

Despite the importance of the tropics as a global provider of environmental services, their complex and highly variable dynamics cause a considerable lack of eco-hydrological knowledge. This paper aimed at providing new information for pan-tropical catchments in terms of the hydrogeomorphological influence on transit times. Our analysis revealed potential relationships of TTs with landscape features (soil type), geological variables (igneous, and sedimentary rocks) and hydrological variables (precipitation, storage, seasonality and dry days). These findings suggest that pan-tropical catchments are more connected to subsurface processes and storage than it was previously thought.

TTs of pan-tropical catchments are shorter than 1.4 years indicating the expected relatively fast and dynamic flows and material transport. The gamma model estimated TTDs showed that more solutes are flushed at shorter time scales in contrast with the almost globally valid TTD of $\alpha = 0.5$. Our analysis revealed statistically significant correlations ($0.67 < r < 0.85$, p -

value < 0.1) associated with landscape features (storage capacity, soil characteristics and mean altitude), and ($-0.95 < r < -0.72$, p-value < 0.068) hydrologic variables (months with zero precipitation, precipitation, the coefficient of variation of monthly precipitation and actual evapotranspiration). Despite the stationary TTs used in this study, our findings provided more details about how physical variables influence the hydrological flow pathways of the tropics, which is essential for an appropriate water resources management and climate change adaptation strategies in tropical catchments.

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Annexes

Annex A. Data source and descriptive statistics of isotopic signatures

Statistical descriptions (i.e., n-number of observations, $\bar{x}$ -media, $\tilde{x}$ -median, sd- standard deviations, [min, max] range) of isotopic concentration in precipitation and streamflow of two conservative tracers: deuterium ($\delta^2\text{H}$) and oxygen-18 ($\delta^{18}\text{O}$). Samples were collected on daily time scale from the current catchments, which are constantly monitored by Costa Rica University-Costa Rica, James Cook University- Australia and University of Cuenca-Ecuador in cooperation with the IAEA. Data from RBAMB and Zhurucay catchments are available at an intra-hourly scale and were aggregated to daily scale for a standard daily treatment of the entire pan-tropical dataset of catchments.

Table A. Data source and descriptive statistics of isotopic signatures: Deuterium (^2H) and Oxygen-18 (^{18}O) were measured.

Catchment s		Howard	Atika	Caño Seco	Quebra da Grande	RBAMB	Tempisque	Zhurucay	
Equipment		*CRDSL Picarro L2130-i	*CRDSL Picarro 2130-i	**DLT- 100 Los Gatos	*CRDS Picarro L2120-i	*CRDS Picarro L2120-i	*CRDS Picarro L2120-i	*CRDS Picarro L2130-i	
Precipitation	$\delta^2\text{H}$	n	370	309	555	914	2024	484	4310
		$\bar{x}$	-29.6	-7.98	-57.96	-26.76	-26.56	-38.1	-72.85
		$\tilde{x}$	-26.33	2.44	-62.05	-20.64	-28.52	-36.2	-65.90
		sd	26.6	24.96	22.97	33.3	11.02	24.36	35.55
		[Min; max]	[-111.4; 22.56]	[-15.13; 30.93]	[- 135.91; -1.46]	[- 161.04, 21.23]	[-65.84; 21.22]	[-111.85; 12.28]	[-184.96; 0.01]
	$\delta^{18}\text{O}$	n	370	309	234	914	102	484	4310
		$\bar{x}$	-5.5	-2.81	-8.52	-5	-5.16	-5.88	-10.02
		$\tilde{x}$	-5.34	-1.55	-9.16	-4.1	-4.65	-5.72	-9.38
		sd	3.43	3.09	2.87	3.99	2.8	3.16	4.40
		[Min; max]	[-15.8; 0.29]	[-15.26; 2.88]	[-18.17; -0.89]	[-21.06; 0.69]	[-8.88; -3.80]	[-15.29; 1.16]	[-24.98; -2.43]
Streamflow	$\delta^2\text{H}$	n	47	163	247	395	223	171	3918
		$\bar{x}$	-32.7	-26.52	-63.00	-30.34	-26.21	-40.31	-73.04
		$\tilde{x}$	-31.08	-26.33	-64.17	-34.46	-26.06	-39.24	-71.72
		sd	5.82	11.83	4.47	13.70	3.32	4.91	7.27
		[Min; max]	[-58.94; -26.45]	[-53.28; 5.27]	[-79.37; -21.88]	[-79.23, -1.39]	[-40.69; -15.79]	[-72.60; -34.08]	[-108.63; -54.66]
	$\delta^{18}\text{O}$	n	47	163	234	395	200	171	3958
		$\bar{x}$	-5.33	-5.32	-9.30	-5.55	-5.02	-6.48	-10.58
		$\tilde{x}$	-5.09	-5.23	-9.46	-5.56	-5.02	-6.38	-10.42
		sd	1.04	1.54	0.58	1.58	0.52	0.77	0.95
		[Min; max]	[-9.5; -4.01]	[-8.82; -1.37]	[-11.49; -1.27]	[-12.04; -2.29]	[-7.26; -3.63]	[-10.23; -5.32]	[-15.29; -6.26]

*Standard errors reported by the analysis $\pm\sigma$: $\pm 0.5\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$. ** $\pm\sigma$: $\pm 0.4\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$. Tracer metrics used for comparison between catchments. $\bar{x}$ media, $\tilde{x}$ median, n number of observations, sd standard deviation.

Annex B. Data records of all catchments

Table B. Available data records of all catchments.

Study catchments	Dataset	Warming-up period	Calibration Period
Howard	May-2015 /May 2018	Dec-2016 /April 2017	May-2015 /May 2018
Atika	Jan-2019/Oct 2021	Nov-2020/April 2021	Jan-2019/Jul- 2021
Caño Seco	Jan-2012/Sep-2014	Jun-2013/Nov-2013	May-2012/May-2014
Quebrada Grande	Jan-2016/Dec-2019	Oct-2015/April-2017	Jan-2016/Dec-2019
RBAMB	Jan-2013/Jul-2018	March-2017/Sep-017	Jan-2015/Jul-2018
Tempisque	Jun-2015/Aug 2021	Jul-2020/April-2021	Jun-2015/Aug 2021
Zhurucay	Oct-2017/Feb-2019	May-2018/Feb 2019	Oct-2017/Feb-2019

Annex C. Exponential Model results

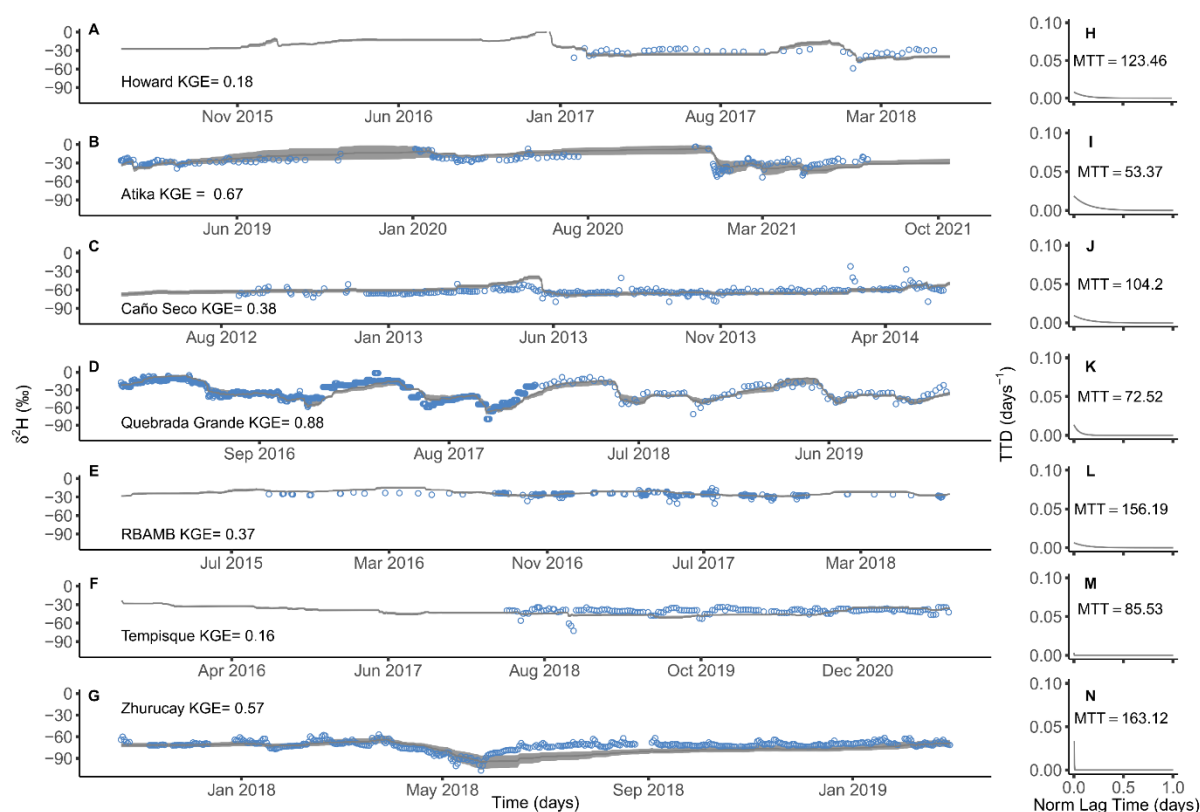


Figure C. Fitted deuterium signal simulations in streamflow using the convolution integral approach with exponential model as transference function: A-G: Deuterium signal simulations in streamflow. Isotopic signal of the streamflow in blue points. 90% uncertainty bands obtained from the isotopic signal of the precipitation are in gray color. H-N: Probability Density Functions (PDF plotted with the best MTTs values) in gray line.

Annex D. Correlation assumption

Table D. Speaman's correlations assumptions. Linearity with the mean of the residuals equal or around to zero as valid. Normality with p-value > 0.05 with a valid hypothesis Ho: The residuals have a normal distribution. Homoscedasticity with p-value > 0.05 with a valid hypothesis Ho: The variance of the errors is the same for any combination of values of the independent variables. Independency with p-value > 0.05 with a valid hypothesis Ho: The linear regression residuals are uncorrelated.

Correlations	Linearity Mean residual	Normality p-value > 0.05	Homoscedasticity p-value > 0.05	Independency p-value > 0.05
MTT-Andosols	-5.07e-15	0.93	0.39	0.10
MTT-Igneous	-2.03e-15	0.48	0.28	0.56
MTT-Sedimentary	-9.53e-16	0.14	0.26	0.81
MTT-Precipitation	-1.42e-14	0.22	0.33	0.79
MTT-Delta Storage	5.08e-16	0.23	0.47	0.74
MTT-Seasonality Index	3.04e-15	0.18	0.21	0.13
MTT-Day0	-6.08e-15	0.61	0.74	0.36
Alpha-Andosols	9.92e-19	0.66	0.23	0.53
Alpha-A(Sa)	9.93e-19	0.48	0.20	0.64
Alpha-Altitude	-5.94e-18	0.001	0.83	0.70
Alpha-AET	-6.93e-18	0.12	0.84	0.61
Alpha-Month0	6.93e-18	0.47	0.33	0.38
Alpha-PMVAR	-9.93e-19	0.99	0.34	0.92