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Groundwater in fractured granite: implications for tropical dry forest development and water sustainability

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Abstract. Seasonality is one of the most important features of Tropical Dry Forests (TDFs), then water scarcity must be overcome by perennial sources dependent of groundwater flows. Groundwater recharge processes in TDFs are controlled by (i) the seasonal dynamics of the components of the water cycle through their interaction with the soil and underlying geological environment, and (ii) the phenological rhythms of the vegetation that simultaneously influence infiltration and evapotranspiration. The daily hydrological dynamics of a TDF that grow atop fractured granite with a thin layer of sandy soil were studied in three basins subject to conservation in the Pacific coast of southern Jalisco, Mexico along the 2019–2020 hydrological year. Automated climatological and streamflow instrumentation was used to obtain data for a detailed analysis of the rain-streamflow response and new instruments were placed to measure interception and soil moisture. Results show that annual precipitation was 1.179 mm (above the average of 832 mm) distributed in 80 highly variable events. The phenological stage of the vegetation and the accumulation of litter strongly influenced interception. Thin sandy soils (~ 0.30 m) controlled the rapid infiltration of 85 to 98 % of the precipitation that reached the ground along seasons, reducing the effect of evapotranspiration by percolation, aided by the fact that most of the precipitation events were nocturnal. The rain-streamflow response showed that groundwater discharge in the streams represented up to 70 % of the percolation volume and the remaining 30 % correspond to groundwater flow and temporary storage in the fractured medium. These two processes may explain the zonation of two subtypes of vegetation, their phenology and survival in the dry months. The deciduous tropical forest (DTF) in the study area developed in groundwater recharge zones, while the sub-deciduous tropical forest (SDTF) emerged in the discharge zones, where evapotranspiration values of up to 0.140 mm d^{-1} were obtained from the diurnal variations of the base flow. Analyses of daily data highlight the importance of the fractured medium and its temporary saturation, where residence times may made water available in the ecosystem during dry periods. Improving our understanding of these processes will help guide the sustainability of provision of groundwater by the conservation of hydrological ecosystem services in the basins for anthropogenic activities in the region reducing hydrological vulnerability to dry periods and climate change.

1 Introduction

Tropical dry forests (TDFs) are biomes amply distributed worldwide (Murphy and Lugo, 1986; Blackie et al., 2014). Given that seasonality is one of the most important climatic features of these biomes, with more than six months with no precipitation (Murphy and Lugo, 1986; Bullock and Solis-Magallanes, 1990; Borchert, 1994), ecosystems, people and their economic activities must adapt to water scarcity, looking for perennial sources as springs and wells, all of them dependent of groundwater flows (Poeter et al., 2020). Groundwater recharge processes in TDFs and therefore, freshwater sources in the neotropics, depend largely on their conservation and sustainable management (Portillo-Quintero et al., 2015).

It is widely believed that these ecosystems are sensitive to changes in precipitation regimes due to climate change, but many questions remain to be addressed, especially since subsurface processes have been analysed far less than surface ones, and some areas of the landscape are more susceptible than others (Farrick and Branfireun, 2013; Allen et al., 2017). Hydrological balance studies have found high infiltration rates and a relation between the occurrence of runoff to subsurface flows, or to the displacement of stored groundwater, rather than to Hortonian surface flows (Cervantes-Servín et al., 1988; Farrick and Branfireun, 2014; 2015). Likewise, research has shown that many tree species in TDFs tend to depend to a greater extent on water stored in the surface layers of the soil or in the unsaturated zone (Querejeta et al., 2007; Ruiz et al., 2010).

Climatic data alone are insufficient to explain the phenology of TDFs, since site-dependent differences in water availability, not seasonal precipitation, are the main environmental cause of variation in the water status of trees and species distribution (Murphy and Lugo, 1986; Bullock and Solis-Magallanes, 1990; Borchert, 1994). The soils of TDFs are extremely variable with respect to the parent material and in terms of their depth and organic matter content, and they tend to be poorly fertile (Rivero-Villar et al., 2022). The plants in a TDF present diverse morphological and functional adaptations to the pronounced irregularity in water availability from both precipitation and the subsoil (Borchert, 1994; Portillo-Quintero et al., 2015). Foliage phenology is one of the most dynamic components of TDFs, but topographic, edaphic, and climatic conditions all exert a great influence on the degree of leaf loss (Borchert, 1994; Kalacska et al., 2005; Méndez-Alonzo et al., 2013). Although studies have been conducted to obtain an integrated understanding of the effects of climatic and phenological dynamics on key processes, such as productivity, nutrient cycling, regeneration and resilience of the TDFs (Allen et al., 2017; Maass et al., 2018; Martínez-Yrízar et al., 2018; Muñoz-Villers et al., 2018), little is known about hydrological dynamics as a whole, or how all the components of the hydrological cycle interact to provide some ecosystem services (Maass et al., 2005; Farrick and Branfireun, 2013; 2014; 2015; Portillo-Quintero et al., 2015).

The Chamela region lies on the coast of the Pacific Ocean in the southern area of the state of Jalisco, Mexico (Fig. 1), on the granitic batholith of the Cretaceous “Jalisco Block”. Data on various topics have been collected on the characteristics of the TDFs in this region; for example, their resilience and recovery capacity after the passage of hurricanes has been studied, finding a high correlation between positive recovery and the occurrence of precipitation in the dry season or above average annual rainfall in the post-riot months (Martínez-Yrízar et al., 2018). These characteristics have important implications for

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the ecosystem, when we consider that a tendency toward a greater occurrence of precipitation in the dry season has been found (Murray-Tortarolo et al., 2017), a phenomenon that needs to be studied in greater detail.

The generation of knowledge on climatic and hydrological aspects in Chamela has a history of more than 40 years. Long term meteorological and streamflow data have been collected by installing permanent meteorological stations and spillways equipped with water level sensors (Maass et al., 2018). Specifically, studies have been carried out to measure interception (Cervantes-Servin, 1988), evapotranspiration by energy balance (Barradas and Fanjul, 1985; Burgos, 1999), phenology and the water relations of plants (Fanjul and Barradas, 1987; Huante et al., 2002; Méndez-Alonzo et al., 2013; Paz et al., 2015; Pineda-García et al., 2015), and soils and their water relations (Zarco-Arista, 1994; Galicia et al., 1995; Cotler et al., 2002). Joint hydrological dynamics have been addressed in only two studies (Burgos, 1999; Maass et al., 2018) on an annual scale that considered the geological environment to be impermeable. Recently Orozco-Uribe et al. (2023) demonstrated that groundwater infiltration and recharge are factors of much greater importance than previously estimated in this region. Considering the vegetation distribution pattern and its highly seasonal phenology, they proposed a conceptual model in which the rapid infiltration of rainwater into the soil through underlying fractured rock gives rise to local underground flows that manifest as baseflow in the main streams.

This paper describes a study done to explore key components of the conceptual model proposed by Orozco-Uribe et al. (2023). This comprises the instrumentation, collection, and analysis of daily data to evaluate precipitation processes and their partition into 1) interception (canopy, throughfall, stemflow and litter); 2) the rain-streamflow response; 3) variation in soil moisture content; 4) infiltration; and 5) evapotranspiration. The study covered the four seasons of the hydrological year. Based on the results, we discuss the importance and implications of water flows for the resilience of vegetation to drought, their distribution, and the contribution of hydrological ecosystem services in this local ecosystem to the management and sustainability of water in the region. The study area includes three basins (B1, B2, B3) that have slight differences on a local scale but are deemed representative of the physical and biotic characteristics of the system on the regional scale. Long-term ecological studies (LTES) have been carried out in the area for over four decades (Sarukhán and Maass, 1990; Maass et al., 2002), situated between the coordinates 19.503996° N / -105.034542° W and 19.494327° N / -105.035181° W, on lands subject to conservation by the Chamela Biology Station, operated by the National Autonomous University of Mexico (UNAM), in the Chamela–Cuixmala Biosphere Reserve. The basins combined surface area is 62.35 hectares (Fig. 1) that lie in the geological block known as "Cerro El Colorado", among hills with convex slopes near the Pacific coast (Galicia et al., 1995; Rodríguez-Hernández, 1999; Cotler et al., 2002). The climate is Aw0i; that is, warm subhumid with rain in summer, the driest of the subhumid types (García-Oliva et al., 2002). Average annual precipitation is 832 mm ± 277 mm (Takano-Rojas et al., 2023). The two main vegetation subtypes correspond to deciduous tropical forest (DTF) or low deciduous forest (< 10 m), distributed on the hills, with sub deciduous tropical forest (SDTF) or medium sub deciduous forest (10 to 15 m), along the banks of rivers and streams (Miranda and Hernández-X., 1963; Rzedowski, 1978).

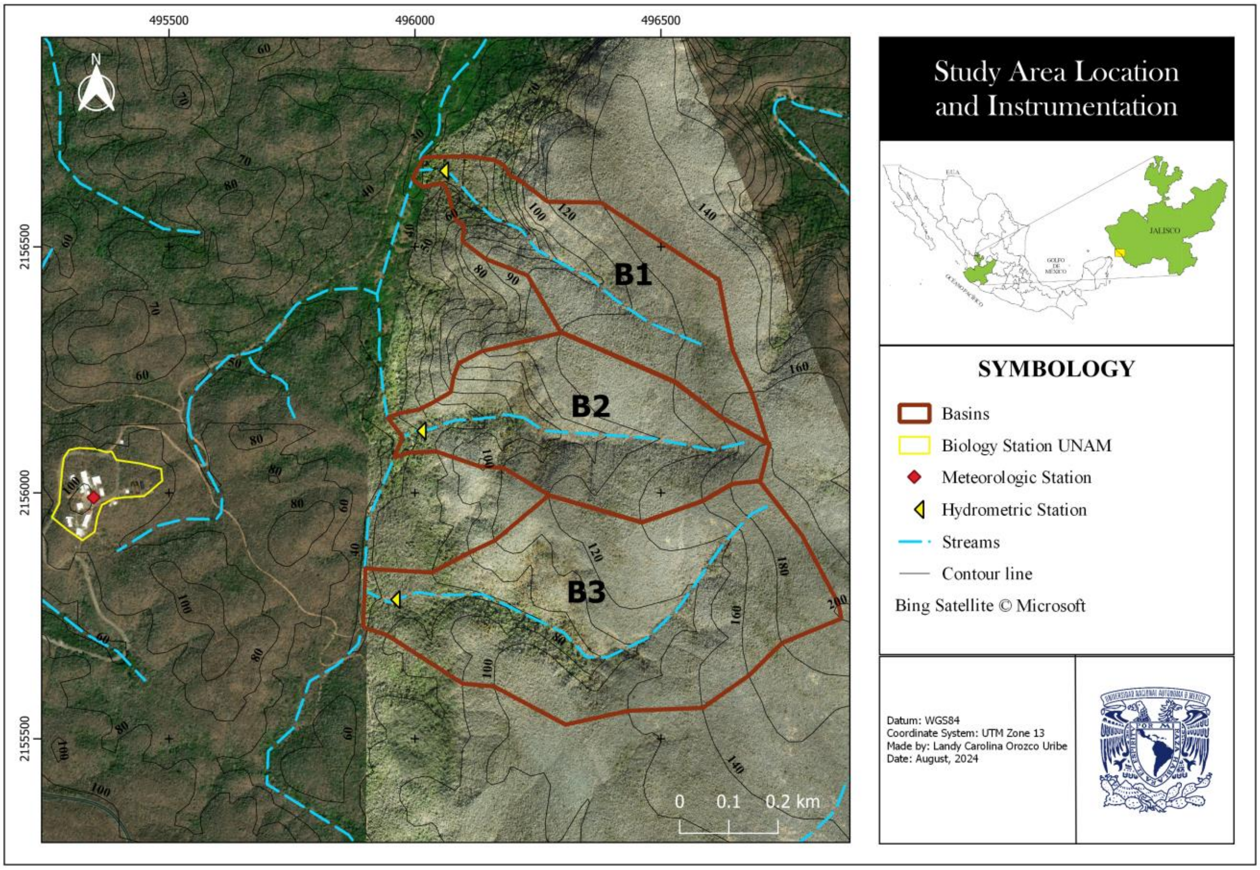

Figure 1. Location map, relief and instrumentation used in the three basins on a satellite image (Bing Satellite, 2024 ©Microsoft) and orthophoto generated by the LiDAR flight (section with higher resolution) that shows the phenological state of the vegetation in the dry season.

2 Methods

Ecosystem processes have been monitored in the long term (> 40 yr) in forest plots of 2,400 m^2 (30 m × 80 m), in the central part of each basin; except B1, where two additional plots were stablished in the upper and in the lower part of the basin (Maass et al., 2002). These five plots were used in the present study to locate two instrumenting transects of 10 × 2 m (20 m^2) within each monitoring plots. A total of 9 transects were placed with a random direction on both slopes of each basin (the upper plot of B1 had only one transect). A soil moisture content sensor was placed (Fig. 1), along with throughfall and stemflow collectors (see below for details).

A daily balance for the 2019–2020 hydrological year was carried out on an Excel spreadsheet that covered each component of the water cycle. The storage from the previous day (S_{prev}) was updated with the new day's precipitation (P), canopy interception (I_{C}), litter interception (I_{L}), streamflow (Q), hydrograph separation into direct flow (Q_{D}) and baseflow (Q_{B}), infiltration (Inf), soil moisture content (θ), percolation ($Perc$), evapotranspiration in both the deciduous tropical forest

(ET_{DTF}) and sub deciduous tropical forest (ET_{SDTF}), and daily storage (*S*) for each subsequent day. The distribution of the two vegetation subtypes was determined from our analysis of an orthophoto generated by a LiDAR flight at a resolution of 1m, using the QGIS Desktop 3.22.3 program. The conceptual model developed previously from the interactions of the water cycle with phenology of vegetation, soil and geology (Orozco–Uribe et al., 2023) was applied. This model integrates the temporal phenological variation and the characteristics of the fractured geological environment. For practical purposes, groundwater storage at the beginning of the dry spring of 2019 was estimated to be zero. The methodology for obtaining data and/or calculating each one of the daily factors is described below.

2.1 Precipitation (*P*)

Precipitation events were recorded at 1 minute intervals at the "Chamela Atmospheric Observatory" of the UNAM's Network of Atmospheric Observatories (RUOA), located inside the Biology Station (Fig. 1), for the period from 01 March 2019 to 29 February 2020. An individual rainfall event was considered as one in which the precipitation pause recorded was ≥ 2 hours. If the event occurred between 6:00 and 11:59 a.m. LT, it was considered daytime, evening if it occurred between 12:00 and 17:59 p.m. LT, and nocturnal if it occurred between 18:00 p.m. and 5:59 a.m. LT. For practical purposes, intensity was classified using the glossary of the National Water Commission (CONAGUA) as follows: light (< 5 mm h^{-1}), moderate (5.1 to 15 mm h^{-1}), heavy (15.1 to 60 mm h^{-1}), and torrential (> 60 mm h^{-1}). To calculate the daily balance, the volume of the events that occurred during day *N* (mm) was summed and then transformed into volume (m^{3}) per the surface of the three basins.

2.2 Canopy interception (I_{C})

Canopy interception was calculated by subtracting the throughfall (*tf*) and stemflow (*sf*) measurements from the precipitation recorded using Eq. (1). Whenever possible, these components were measured directly after each precipitation event, but some events were accumulated, depending on such factors as volume, time of occurrence, and the effort required to reach the sites.

$$I_{\mathrm{C}} = P - tf - sf \tag{1}$$

2.2.1 Throughfall (*tf*)

Throughfall was measured transect-by-transect using a cylindrical collector 11 cm in diameter ($A = 95.03$ cm^{2}). This instrument was "nomadic"; that is, after each measurement it was relocated to a distinct point to record the variation of this factor for each event inside the same transect (Holwerda et al., 2006).

2.2.2 Stemflow (*sf*)

All individual woody plants in each transect were instrumented and separated into three diameter classes: 2 to 5, 5 to 10, and > 10 cm. For the plants in the first two classes, a plastic funnel was fixed to the stem or trunk with silicone and connected to a 3/8" hose that emptied into a collecting container of 2 or more litres (González-Martínez et al., 2017). The individual plants > 10 cm in diameter were equipped with a 1” hose cut in half and fixed around the trunk with epoxy foam. It was connected to a 3/8” hose that emptied into a collection container with a diameter of 10 cm and a capacity of 20 litres (Durocher, 1990).

2.3 Leaf litter interception (I_L)

The value of the interception by litter for each season was taken from the measurements made by Burgos (1999) which are 1.75, 0.89, 0.72 and 1.13 mm for dry spring, onset of rains, rains and winter respectively, and transformed into volume (m^3) for the surface area of the basins studied.

2.4 Infiltration (*Inf*)

Given the shallow and sandy characteristics of the soils described by Solís-Villalpando (1993), Zarco-Arista (1994), and Cotler et al. (2002), we used Eq. (2) considering that all the water not intercepted had the potential to be infiltrated, except for individual events where the intensity of the precipitation was torrential, or in those events where direct streamflow occurred.

$$Inf = P - I_C - I_L - Q_D \qquad (2)$$

2.5 Streamflow (Q)

Streamflow was measured using “V” outlets and “H” type channels located at the end of each basin, with a Solinst “level logger” sensor of water column model 3.001, with a precision of 0.1 mm in 2 minute intervals corrected from simultaneous values of barometric pressure.

2.6 Evapotranspiration (ET)

Evapotranspiration for the deciduous tropical forest (ET_{DTF}) was calculated using the rate values reported by Barradas and Fanjul (1985) and Burgos (1999), which are 0.4, 4.8, 3.5, and 1.9 mm d^{-1} for the dry spring season, onset of rain, rain, and winter, respectively, with an annual average of 2.7 mm d^{-1}. Because we did not count with direct ET measurements for the sub deciduous tropical forest, the evapotranspiration for this forest (ET_{SDTF}) was calculated by adding to the DTF values the volume calculated under saturation conditions, obtained from the flow reduction during the day registered in the hydrographs, following Cadol et al. (2012).

2.7 Soil moisture content (θ)

The measurements of soil moisture content were carried out by inserting nine 30-cm long, GroPoint Profile TDT Time Domain Transmission probe sensors vertically into the ground to record average water content as a percentage (θ %) along 15 cm segments. Therefore, θ measurements were taken at two depth intervals: 0 to 15, 15 to 30 cm. Two sensors were placed in each plot (at the beginning of each transect), one on each side of the mainstream of the basin in question to include the heterogeneity of soils, topography, and exposures. In the upper plot of B1, only one device was placed due to the

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homogeneous topographic conditions. The sensors were placed on 19–20 June 2019. Insertion required moistening the soil, so a reading was taken upon completing the installation, followed by two more after 7 and 14 precipitation-free days, to obtain an initial value for dry soil. Subsequently, the sensor readings were taken punctually on each occasion that the collection of interception data was conducted. A GroPoint GP-DU SDI-12 Handheld Sensor Reader was used for this procedure.

2.8 Water storage (*S*)

To calculate the behaviour of water storage in the soil we considered two parameters: first, the maximum water retention capacity value of 26.8 % of the soil volume in 1 m^3 (Galicia et al., 1995); second, 30 cm of soil thickness along the basins (Cotler et al., 2002). In the daily balance, the volume of infiltration water per event was compared to the retention volume. If the first value was lower, the result was considered a retention volume, so to calculate the storage volume in the soil the next day, the *ET* value of the two subtypes of vegetation in the basins and the baseflow volume were subtracted as shown in Eq. 3). It is important to note that from this equation, when the infiltration volume was greater than the retention volume, or the sum of the previous day's storage volume and the infiltration volume exceeded the retention volume, then the surplus was classified as percolation volume stored ad or in transit in the fractured medium.

$$S = \left(S_{\mathrm{prev}} + P\right) - \left(I_{\mathrm{C}} + I_{\mathrm{L}} + Q + ET_{\mathrm{DTF}} + ET_{\mathrm{SDTF}}\right) \tag{3}$$

3 Results

Figure 2 presents the results of the distribution of precipitation over time, and its partition into interception (throughfall, stemflow), soil moisture, and streamflow for the hydrological year. A total of eighty precipitation events were recorded (Fig. 2a) with a cumulative value of 1,179 mm, well above the average of 832 mm for the study area. This surplus was due in part to the occurrence of winter events that totalled 161.2 mm. The continuity, volume, and intensity of the events was highly variable as 73 % of the precipitation occurred in the rainy season (August–November), favoured by the influence of regional cyclonic events (hurricanes, tropical storms). Most events were nocturnal (*n* = 47, 58.8 %) and of light intensity (*n* = 44, 55 %). The greatest accumulation of precipitation occurred during moderate intensity (total = 916.3 mm) and nocturnal events (total = 808 mm). No torrential events occurred during the study period.

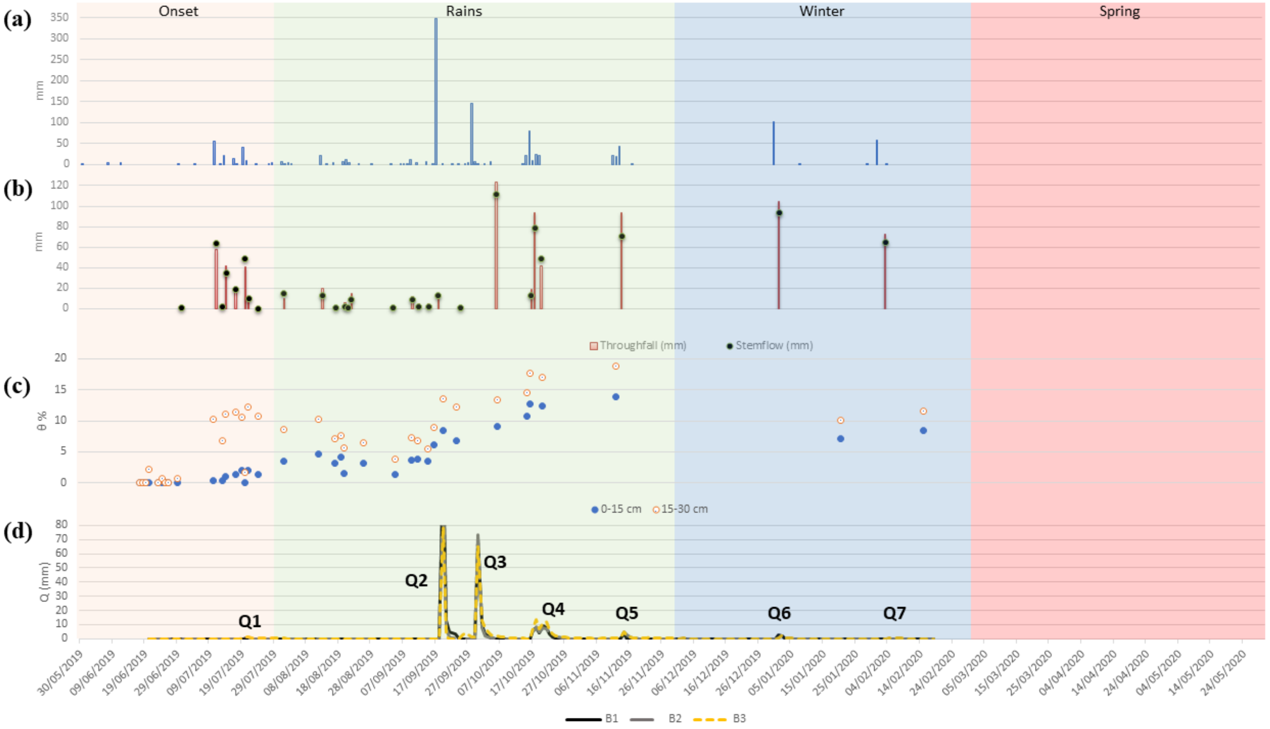

Figure 2. Comparison of data recorded and measured during the four seasons of the 2019–2020 hydrological year (background stripes). (a) Precipitation events; (b) throughfall (left scale) and stemflow (right scale) measurements; (c) average spot measurements of soil moisture at depths of 0.15 m and 0.30 m; (d) streamflow highlighting the number of events that occurred (Q#). The timescale is daily. Measurements of throughfall, stemflow and soil moisture were taken at least one day after the precipitation events. Precipitation and streamflow values for 18–19 September were cropped to allow a better visualization of the rest of the data (reaching 366.2 and 124.42 mm, respectively). There is a clear variability in the volume and intensity of the precipitation events, and in the influence on throughfall and stemflow. Streamflow events occurred when average soil moisture values at a depth of 0.3 m exceed 10 %.

Interception (measured as the reduced values of throughfall and stemflow) was highly variable (Fig. 2b) with extreme values that ranged from 1 to 100 %. The maximum precipitation event of 18–19 September overflowed the collectors, so no measurements were taken. These values were more evident after the onset of the rains, when the vegetation showed a radical change in leaf cover (Fig. 3). The average interception value for the hydrological year was 8.92 %. Water reached the ground by either throughfall (88.28 %) or stemflow (2.8 %).

Figure 3. Extreme change in leaf cover in deciduous tropical forest from the first precipitation events at the onset of the rainy season. The change observed in a span of 4 days (13–17 July 2019), affected the canopy interception values.

There were 7 streamflow events during the study period (Fig. 2d). Their accumulated volume represented 24.3 % of the annual precipitation. The behaviour, volume, and duration of each streamflow event differed in each basin. The most important events, by average volume, occurred in the rainy season associated with four cyclonic precipitation events, followed by events of lesser magnitude related to convective precipitation that occurred at the beginning of the rainy season and in winter (*n* = 3).

The detailed analysis of the hydrographs allowed us to separate the components of the streamflow, due to the differences between the basins, the behaviour of streamflow also differs, such as the delay in the recording of direct streamflow peaks as well as in the formation and duration of baseflow. In particular, the baseflow in Q1 that slowly changed after the extinction of direct flow, revealed an important contribution of groundwater through the baseflow, which represented 85.76 % of total streamflow (2.26 % of *P*) (Fig.4). Baseflow was lower in all cases in B1 and higher in B3; whereas direct flow peaks at the beginning of the rainy season and in winter differed for each basin, as they were recorded first for B1 and later for B3. Recording was continuous in all three basins during the rainy season. The daily fluctuations of baseflow allowed us to calculate evapotranspiration values under saturation conditions for the sub deciduous tropical forest (SDTF).

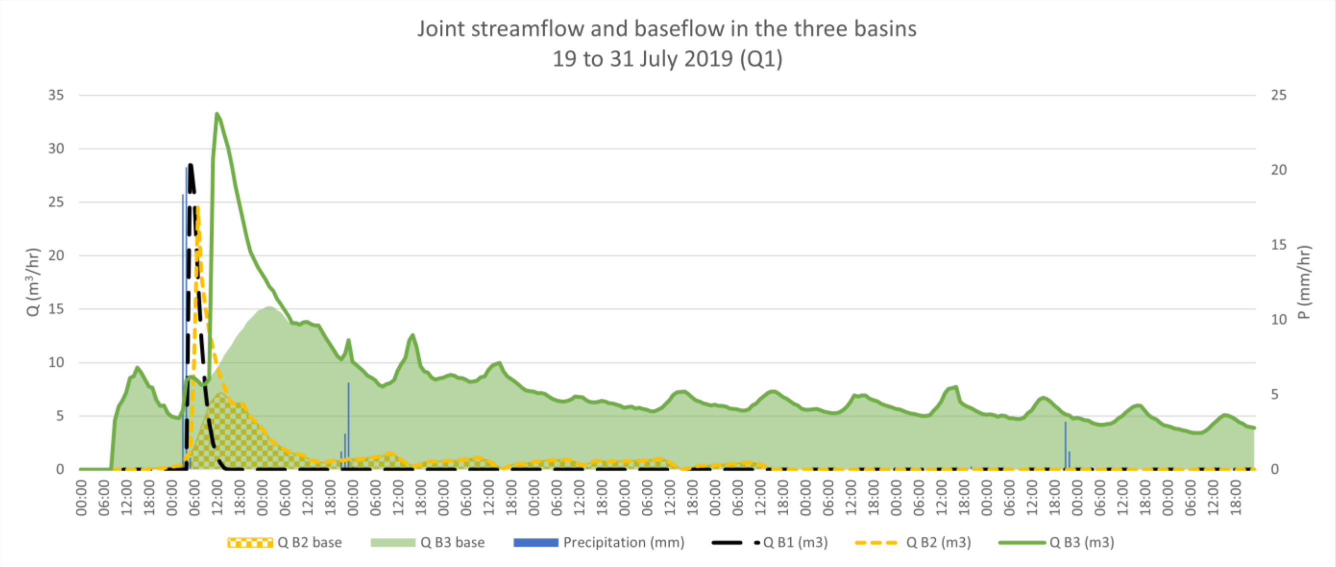

Figure 4. Streamflow event occurred from 19 to 31 July 2019, in the three basins. Peaks of direct streamflow are shown in all 3 basins. The formation of baseflow (shaded areas underneath lines) is also shown in basins 2 and 3.

Infiltration was calculated in a range of 85 to 98 % of the precipitation that reached the ground along the seasons. This is consistent with the behaviour of the hydrographs (Fig. 5), where infiltration exceeded the moisture retention capacity of the soil, forming percolation toward the fractured medium. About 70 % of the precipitation event was recorded as baseflow.

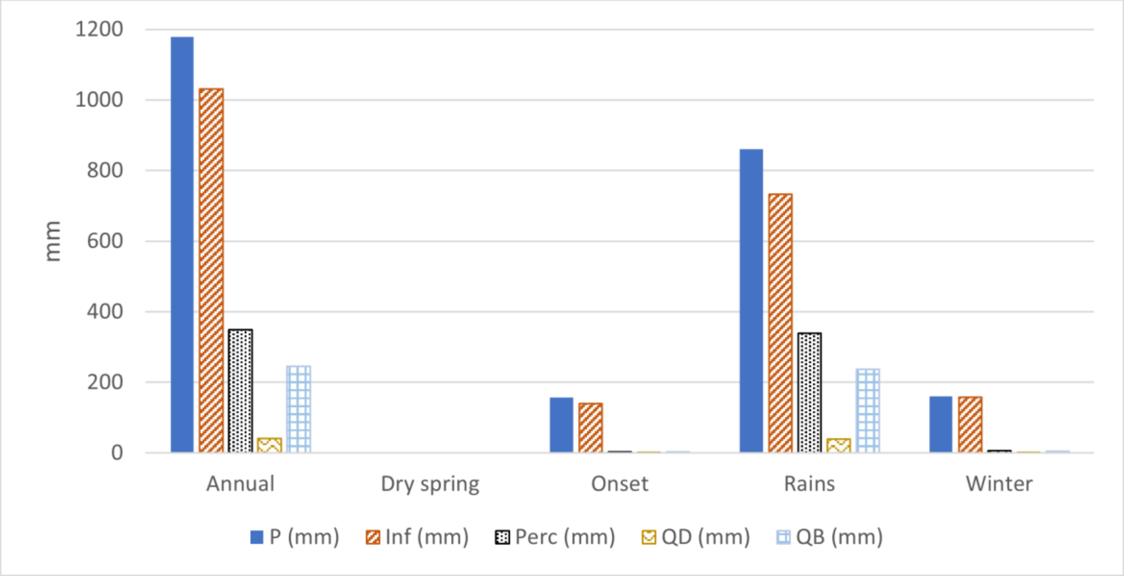

Figure 5. Partitioning of precipitation (P) into infiltration (Inf), percolation (Perc), direct flow (QD) and baseflow (QB), both annually and by season. Between 85 and 98 % of the precipitation reached the soil and infiltrated. Baseflow dominates the discharge in this figure, with a very low value of direct flow and a higher value of baseflow.

The behaviour of soil moisture was related to the volume and continuity of precipitation and infiltration events (Fig. 6). A correlation was observed between the occurrence of streamflow events and the specific recordings of humidity values above 10 % at a depth of 0.15 to 0.30 m (Figs. 2C, 2D).

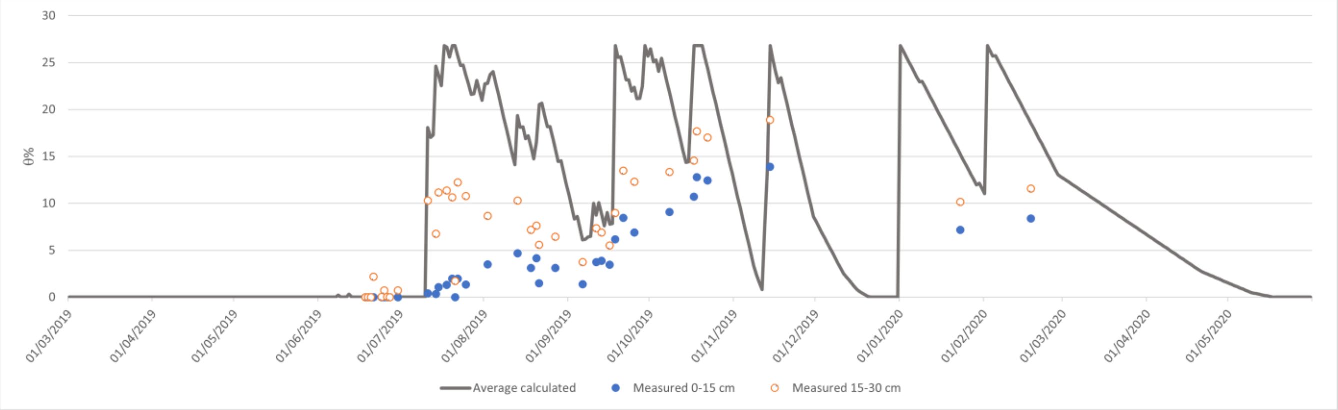

Figure 6. Variation of daily soil moisture content (average of all 9 measured sites). Maximum water retention volume fits the 26.8 % described by Galicia et al. (1995). The decrease in the *ET* due to the loss of leaves allowed humidity to be maintained in the soil for a longer period through the winter and spring (December–May).

Regarding the percolation water that could be stored or flow through the fractured medium (*S*), behaviours like those of the soil were observed, with relatively rapid decreases during the rainy season related to the effect of evapotranspiration and a slower decrease toward winter and dry spring of the following year (Fig. 7). Winter precipitation considerably increased the calculated percolation volume. Its permanence over time was related to the drastic decrease in the effect of evapotranspiration due to the loss of leaves in the vegetation.

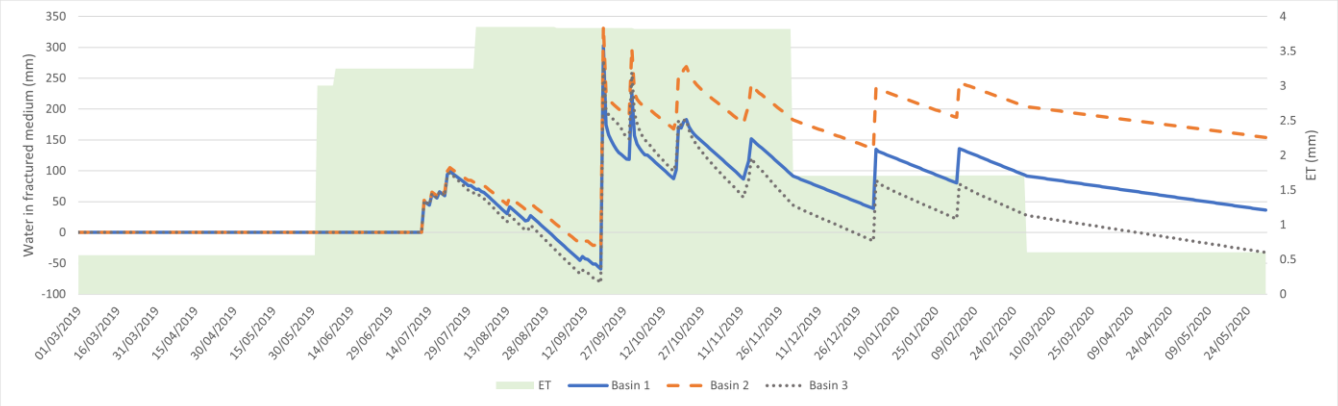

Figure 7. Joint volumes of water in the fractured medium (stored or flowing) calculated for each basin. The evapotranspiration values calculated for each season are shown as a reference (background shades). Although the beginning of this analysis does not contemplate a volume prior to the measurements, the positive values extended until the end of the dry spring of 2020 for basins 1 and 2.

Results of the analysis and classification of the LiDAR orthophoto led us to calculate that of the 62.35 hectares that the basins cover, 46.37 hectares correspond to deciduous tropical forest (DTF) distributed in the high areas and slopes of the hills, and 15.7 hectares to sub deciduous tropical forest (SDTF), distributed along the streams and certain geological lineaments. The *ET* values taken from the literature were measured from DTF, where infiltration and groundwater recharge occur; thus, the analysis of the daily variations in the baseflow recorded in the hydrographs allowed us to relate them to the evapotranspiration under saturation conditions for the SDTF, associated with the groundwater discharge zones, and then define the annual and temporal values for each zone (Table 1). It is important to note that evapotranspiration is the only factor that remained relatively constant, so although its values are low in the dry spring and winter seasons, it exceeds the precipitation values recorded since we did not consider the possible existence and/or consumption of water in the fractured medium prior to the hydrological year analysed.

Table 1. Summary of annual and seasonal hydrological balance based on values measured and calculated daily. The differentiated distribution of precipitation by season and, therefore, of the rest of the factors of the hydrological cycle is shown. P, precipitation; I_C, canopy interception; I_L, leaf litter interception; *Inf*, infiltration; *Perc*, percolation; Q_{tot}, total streamflow; Q_D, direct streamflow; Q_B, baseflow; ET_{DTF}, evapotranspiration of the deciduous tropical forest; ET_{SDTF}, evapotranspiration of the sub deciduous tropical forest. All values are in mm.

Period	P	I_C	I_L	*Inf*	*Perc*	Q_{tot}	Q_D	Q_B	ET_{DTF}	ET_{SDTF}
Annual	1179.00	76.99	29.98	1031.18	349.83	286.54	40.79	245.75	648.71	221.59
Dry spring	0.20	0.20	0.00	0.00	0.00	0.00	0.00	0.00	41.27	11.40
Onset	156.80	7.16	9.14	139.90	3.80	4.44	0.59	3.85	145.95	50.80
Rains	860.80	69.63	18.60	733.11	338.86	275.81	39.41	236.39	346.64	120.13
Winter	161.20	0.00	2.24	158.17	7.17	6.30	0.79	5.51	114.85	39.26

4 Discussion

We aimed to explore the interactions among the physical characteristics of the basins and the phenology of the TDF, and their influence on the partitioning of rainwater. Overall, our results highlight the importance of the infiltration of up to 85 to 90 % of rainwater, from which 70 % was recharge of groundwater in the fractured media, where residence times may allow the sub deciduous tropical forest to survive, retain foliage and keep functioning well into the dry months that follow the rainy period of the hydrological year. Such high infiltration and temporary storage in the fractured media are key features to consider when planning sustainable water management programs, as both factors impact resilience of vegetation to droughts and of water storages against extractive actions.

Over half of the precipitation events recorded for the 2019–2020 hydrological year were of light intensity (< 5 mm h^{-1}) and nocturnal, findings that are consistent with the long-term data for over 40 years (Mass et al., 2018). The annual precipitation of 1,179 mm exceeded the average of 832 mm, mainly due to rains that occurred in the, usually rainless, winter season. This behaviour of the precipitation is important for partitioning the water into the categories of interception, infiltration through the thin layer of sandy soils (~ 0.30 m), evapotranspiration, and recharge of groundwater to the fractured media.

Interception plays an important role as the rainy season progresses due to the phenological response of the vegetation, which showed extreme variation (0 to 100 %), though the average annual values of 6.5 % for canopy interception were within the range reported by other authors (Cervantes-Servin, 1988; Barbosa-Moreno et al., 2016; Rodrigues-Pinheiro et al., 2017). While throughfall is the main route for the arrival of water to the soil, stemflow appeared to be a more stable and concentrated pathway, likely because the woody structures of the vegetation undergo fewer changes throughout the year (Durocher, 1990; Crockford and Richardson, 2000; Pérez-Suárez et al., 2014).

Measured soil water content increased during the rainy season proportionally to the magnitude and duration of the precipitation events and to the interception conditions. It showed local changes associated with the soil conditions and location of each probe in the basin, though precise temporal correspondence with precipitation was limited due to the lack of continuous automated registration, and averages were measured in the ranges of 0 to 15 and 15 to 30 cm, not in more discrete ranges. On the other hand, our calculation of θ based on the daily hydrological balance served as a reference as it considered the influence of interception and evapotranspiration at the basin scale. The θ values increased dramatically with the winter precipitation events, but then decreased slowly due, once again, to the phenological conditions of the vegetation, with reduced interception and evapotranspiration values. This behaviour is consistent with other soils in TDFs in Mexico (Farrick and Branfireun 2014, 2015).

Practically all the precipitation, mostly of light intensity and nocturnal, that is not intercepted, infiltrates rapidly through the thin sandy soils that show high secondary porosity due to biological activity (Cotler et al., 2002; Zarco-Arista 1994). These conditions increase the θ and the percolation reduce the effect of evapotranspiration toward the underlying fractured granite. Infiltration was calculated in a range of 85 to 90 % of the main rainfalls, a figure that represents the most important result, especially since earlier studies in the area considered the granitic rock to be impermeable.

The precipitation-streamflow response differed among the three basins, in principle reflecting differences in their capture area, albeit other factors as soil distribution and depth, the fracture conditions of the basal rock (Orozco-Uribe et al., 2023), topography, and vegetation cover, from which we separated direct streamflow and baseflow (Gupta and Larson, 1979). Groundwater (baseflow) represents 70 % of infiltration, a finding consistent with the light intensity and nocturnal characteristics of most of the precipitation events, the low rainwater interception, the fast infiltration, and the limited evapotranspiration. These results are consistent with the behaviour of other TDF watersheds and basins worldwide (Freeze, 1974; Farrick and Branfireun 2014; 2015; Tóth, 2016; Butz et al., 2018). Although the streams in our basins are intermittent, the baseflow in B3, the larger and less stepped basin, can last for over 2 to 3 weeks and, perhaps, months at shallow depths in the fractured granite, a condition that may benefit the survival and growth of trees in the SDTF.

Our results indicate that the basins have two hydrological zones: one of groundwater recharge far above from the stream bottom where DTF develops, and other of discharge where groundwater reaches the soil surface near streams where SDTF developed, as discussed by Freeze and Cherry (1979). This zoning is critical for conservation and sustainability, as will be explained below. This suggest that different landscape units can have distinct functions in the hydrological cycle, with deciduous tropical forest (DTF) corresponding mostly to recharge zones, and sub deciduous tropical forest (SDTF) on the banks of rivers and streams functioning mostly as discharge zones. This zonation may have significant implications for sustainable water management in relation to such concepts as hydrological vulnerability (Jones Jr. et al., 2021), resilient landscapes (SIWI, 2024), and hydrolandscape ecology (USGS, 2016); where conservation strategies is crucial in the maintenance of local hydrological processes that influence groundwater recharge and discharge that sustain not only this ecosystems, but human activities in the regions where they develop, in this case under seasonal conditions, where practically more than half of the year no precipitation occur, and dependency is over groundwater (Saldaña-Espejel, 2008).

The finding of a long tail of low but positive values of water stored or in flow in the fractured media suggest the possibility that this water source may play a role in the spatial distribution of the two vegetation subtypes in our study area, as well as the growth and survival of the SDTF trees well into the dry season. In contrast, previous studies in this and other tropical dry forests have suggested that the survival of many woody species through the dry season depends heavily on winter rains that recharge the soil and prevent it from reaching the physiological limits of dehydration (Fanjul and Barradas, 1987; Borchert, 1994; Burgos, 1999; Díaz-Castellanos et al., 2022). Whether tree survival during the dry season depends on recharging winter rains or on water stored in the fractured media is still under investigation and may require direct measurements of the water sources actively used by the trees along the hydrological year. Nevertheless, for the year we studied, the fact that after the winter rains the soil water decayed more rapidly than the percolated water in the discharge zones, strongly suggests a role of groundwater in both, the distribution of the SDTF in the landscape, as well as the survival of those tardily deciduous or perennial trees during the seasonal droughts, particularly during the years with no winter rains as suggested by Rempe and Dietrich (2018).

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The general physiological and phenological characteristics of the two subtypes of vegetation in these basins indicate their close relation to contrasting humidity conditions in the subsoil leading to their zonation. The moisture retained by the soil sustains the evapotranspiration of a significant fraction of the species that constitute this ecosystem, especially herbaceous plants and trees with superficial roots, or mechanisms of water storage, which form an important component of the DTF that cover the high areas and slopes of the basins (Balvanera, 1999; Paz et al., 2015; Méndez-Toribio et al., 2017). However, the soils in the study area have a low moisture retention capacity, so the survival of many of the tree species in both the DTFs (Paz et al., 2015), and SDTFs may depend on the depth of their roots. This can be explained again, by referring to the formation of the percolation flows that contribute to water storage or flow in the fractured medium (Fanjul and Barradas, 1987; Rempe and Dietrich, 2018). The zonation of SDTF in the lower parts of the basins and along certain geologic lineaments would indicate groundwater discharge zones, where the analysis of the diurnal variations of the baseflow, allowed us to calculate the evapotranspiration for this subtype of vegetation under saturation conditions, a process that had not been measured previously in the basins.

It is necessary to consider anthropogenic processes in relation to all the features analysed herein, for together, and under conservation conditions, they are integrated to provide ecological services to society, including water recharge, soil restoration, carbon sequestration, strengthening of biodiversity, and enhancing the health of all living beings. Healthy ecosystems provide humans with healthy water, food, and environmental conditions (USGS, 2016; SIWI, 2024). In contrast, unfortunately, outside the conservation areas of the Chamela–Cuixmala Biosphere Reserve, the conditions of degradation of these elements are leading the region toward a potential crisis. This is particularly critical in a region marked by high water demand among the population, as scarcity is already beginning to generate social conflicts (Riensche et al., 2015). This underscores the need to protect local watersheds and basins and manage TDFs to ensure that the process of groundwater recharge is maintained or progressively recovered, as this will sustain more stable, permanent flows of water for both humans and ecosystems, while reducing hydrological vulnerability and the effects of climate change (Chisola et al., 2020: Jones Jr. et al., 2021).

Conclusions

The interaction between the physical characteristics of the basins and the phenology of TDFs, on the one hand, and their influence on the partitioning of precipitation, on the other, were studied in three basins that lie in a conservation area. Results highlight the importance of the infiltration of up to 85 to 90 % of rainwater, of which 70 % is groundwater in the fractures of the granitic rock where residence times allow the vegetation to survive dry periods. Groundwater thus, represents the main source of water for the survival of the TDF, so it must be the target of efforts to achieve sustainability in the region.

The detailed geographical scale of our analysis of these basins, allowed us to verify the influence of the surface, coverage, and slope that basins have on the hydrological dynamics analysed, despite their location in the same massif of fractured granitic rock. Most of the precipitation infiltrates due to the sandy nature of the thin soils with low moisture retention which permit the development of percolation flows that, in the discharge zone near the streams, contribute to the formation of the baseflow (groundwater) recorded in the spillways at the outlet of the basins. Some percolation may follow slow flow paths and be stored temporally as groundwater in the fractured medium, perhaps descending to greater depths to find its natural outlet.

Although the vegetation in the basins shows amazing adaptations to a seasonal environment, it is likely that its survival is crucially related to the presence of groundwater in the fractured medium, not solely moisture retained in the soil, due to the low retention capacity and high evapotranspiration properties identified. Our analysis shows positive values of water storage in the fractured medium at the end of the hydrological year that extends into the dry months following the rainy period. Likewise, the distribution of vegetation may be related to the formation and occurrence of distinct water flows, where the DTF would indicate recharge zones and the SDTF, the groundwater discharge zones.

This detailed analysis of hydrographs to separate direct and baseflows, and calculations of evapotranspiration values under saturation conditions, helped expand our knowledge of the study area in relation to the importance of the fractured medium in providing hydrological ecosystem services. Thus, we propose protecting local basins and TDFs in a way that will ensure that groundwater recharge is recovered progressively, as this will foster more stable, permanent flows for human use and ecological demands, while reducing hydrological and climatic vulnerability on distinct scales of application.

Author contribution

LCOU contributed with the experimental design and field data gathering. All authors contributed with data analysis, results, writing and detailed discussion and revision of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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