Author’s response – Point to point reply to comments and relevant changes made (highlighted in bold) in the revised manuscript version

Anonymous Referee #1

The paper presents a comparison of mean transit time (MTT) between multiple watersheds in a tropical montane region aiming to evaluate factors controlling stream transit time. The issue addressed in the paper is one of the main concern in understanding hydrological process including sources, flow paths and storages. The paper shows that slope and permeability observed soil-bedrock interface other than land cover are the key factors controlling MTT in the tropical montane area. The paper is well written with significantly new knowledge. I recommend its publication on the Hydrology and Earth System Sciences after properly addressing the following issues:

Reply: Thank you very much for your positive recommendation. Please find our replies to your comments below.

(1) P10989L4, the authors state that short MTT were most strongly related to depth to soil-rock interface particularly for slopes dominated by depth > 2m. The result is derived by a series of divide-points including 0.5m, 1m, 2m. Is there any reason for such classification?

Reply: In the L2-L4 of the discussion paper we stated “a strong positive relation was observed between MTT and depth to soil–bedrock interface (particularly for hillslopes dominated by depths to bedrock > 2 m; Fig. 5f)”, i.e. longer MTTs were related to deeper soil-bedrock interfaces. We have re-phrased this sentence in the revised manuscript to make it more clear (Section 3.2, L400-402). The classification was based on the range of soil-bedrock depths observed. Hence, we decided to divide this variable in the following 4 classes: very shallow (<0.5 m), shallow (>50-100 cm), moderate deep (100-200 cm) and relatively deep (>200 cm) soil-bedrock depths, to test their influences on stream MTT. We have incorporated this information in the revised manuscript (Section 2.5, L279-281).

(2) In the paper, three functions (g (τ)) have been used to estimate transit time model including Gamma, Exponential and Dispersion. Although model parameters have been listed in Table4, it is perhaps not clear to the readers without specific formulas displayed.

Reply: We have now made clear in the Results (Section 3.2, L385-386) of the revised manuscript that the TTD model that we reported for a particular catchment in Table 4 was the one that best fitted the observed baseflow data. We also have referred to the readers to the supplementary information for the corresponding formulas of the models used by adding a footnote in Table 4.

(3) Conclusion part, the influencing factors for MTT in variable-area watersheds should be further justified.

Reply: We have included this information in the revised version (Conclusions, L584-587).
Anonymous Referee #2

This manuscript aims to assess the control of physical properties on mean stream water transit times in a tropical setting. Although the analyses in the paper are very simple and basic techniques are used, little data from these environments are currently available and this work makes an important contribution in that sense. I would recommend the work for publication, considering the following points below:

Reply: We would like to thank you for your positive recommendation and helpful comments. Please find our replies to your comments below.

The authors comprehensively discuss their results in light of other findings elsewhere. However, there is little discussion on the methods used and the caveats that come with these. There are three major issues that would be good if discussed.

1) Overall, there is a focus on base flows as these were sampled only. However recent work has shown that there can be a strong variability between MTTs of low and high flows. There is no mention of this in the discussion. I think this should be highlighted there and how this relates to potentially holding/breaking down relationships between physiographical properties and MTTS during storms vs base flow.

Reply: In catchments where runoff generation processes are dominated by near-surface or shallow lateral flow pathways, it will be important to carry out stream water samplings during high and low flow conditions to obtain representative estimates of MTTs. However, previous hydrological work at our research site has shown that baseflow is the dominant streamflow component (~ 90%). Furthermore, isotope and chemical-based hydrograph separation for a series of storms and for catchments dominated by different land covers showed that deep subsurface flow (mainly ground water sources) rather than near-surface or shallow lateral flow is the dominant pathway for runoff generation. The high permeability of the volcanic soils (Andisols) and the underlying substrate characterizing this region, as also shown in this paper, promotes vertical soil water percolation and recharge of deeper sources, leading to catchment rainfall-runoff responses dominated by groundwater discharge (Muñoz-Villers and McDonnell, 2012, 2013). The above supports why our sampling focused on stream baseflow. We have now made this clear in Methods section (L171-175) in the revised version, citing the above-mentioned references. From this point of the text onwards, we have used consistently the term baseflow MTTs.

2) One other key point is that the authors found no distinct differences in the isotope signatures of the streams, yet their model results have a large range of implied MTTs. How does this affect the uncertainty in the results? And is this simply a result of the different models which were used (which have different bias)?
**Reply:** For the calculation of MTTs, input data for the lumped TTD models consist of isotope time series of rainfall, meanwhile the isotope time series of baseflow are used for calibration. Hence, this procedure is different from the statistical method because it uses the temporal variation observed in isotope baseflow data to fit a TTD model and estimate a MTT from it.

In this study, we used the most basic TTD models, which require only one or two distribution parameters to be optimized; note that the used models have been successfully applied in other studies (e.g. McGuire et al., 2005). **We have added this information in the revised manuscript (Section 2.3, L219-221).**

As shown in Table 4, in 7 out of the 12 catchments baseflow MTTs were best estimated using the Exponential model. In two headwater catchments (MAT and SEC), baseflow MTT was best estimated using the Gamma model, which is a variant of the Exponential model. Using the Gamma model, we obtained MTT estimates of 2.6 years for the MAT and 2.7 years for the SEC; using the Exponential model, these estimates would have been 2.9 and 3 years, respectively. Hence, we obtained very similar MTT results using either the Exponential or Gamma model; this is because the optimized values of the $\alpha$ parameter (0.6-0.9) in the Gamma model approximated to 1 (i.e. the gamma distribution with $\alpha = 1$ is equivalent to an exponential distribution (c.f. McGuire et al., 2005). Furthermore, since these nine catchments included those with the lowest and highest MTTs, it is unlikely that the obtained range of MTTs is an artifact of model selection. Finally, MTT estimates for the remaining three catchments as obtained with the Dispersion model were generally close to the overall average MTT.

It should be noted that the TTD model that we reported for a particular catchment was the one that best fitted the observed baseflow data. **We have emphasized this in the revised manuscript (Section 3.2, L385-386).**

Furthermore, the selected models were identified as reliable TTDs because they provided predictions with relatively high fitting efficiencies and small uncertainty ranges. Parameter uncertainty was evaluated through the Nash-Sutcliffe $E$ value (see Section 2.3), and Table 4 reports the values of the model parameters and the uncertainty bounds. In all cases, the obtained $E$ values are indicative of a good predictive skill (> 0.5 to 0.7). Moreover, the overall efficiency of the TTD models was evaluated using the RMSE. In this case, the RMSE of the models was between 0.8 and 1.5 ‰, which indicates a good analytical reproducibility of the observed baseflow isotope data, considering that the isotopic composition range was from -50.2 to -41.0‰ across all catchments.

3) Many of the sampled subcatchments are nested and only stream samples for isotope data were taken. There is no indication of the relative contributions of runoff from the different parts of the catchment. For example, if the headwaters are contributing more than other subcatchments (could very well be considering the differences in precipitation), then this could bias the results in favour of the processes in those areas.

**Reply:** Due to accessibility problems and financial constraints, most of the headwaters and subcatchments in this area, as in other tropical regions, remain ungauged. Hence, we followed this approach because it relies primarily on tracer data, and hence is
useful to broadly characterize the hydrological behavior of the studied catchments (McGuire and McDonnell 2006).
Without measuring streamflow in the different catchments, it is difficult to say which ones could potentially contribute more than others. However, most precipitation falls where the first and second-order catchments are located (2,100-2,400 m asl), and it appears that this is where most groundwater recharge occurs, as inferred from previous water balance studies (Muñoz-Villers et al., 2012). To properly answer this question, more research work and effort should be done to quantify the stream flow contributions from different catchments, and to investigate the connectivity that could exist among sites.

The terrain analysis comprises of many standard techniques, hence I think section 2.4 can be condensed significantly. I would recommend to use either ‘watershed’ or ‘catchment’ consistently throughout the manuscript.

Reply: Despite some of the methods used to describe the terrain analysis are standard, we consider it important to explain to the readers how we defined the terrain parameters in terms of datasets and resolutions used, GIS software and processing. Although this may have made section 2.4 a bit longer, we think its length is still sufficiently short (19 lines).
Following the reviewer’s recommendation, we have used the term ‘catchment’ consistently throughout the revised manuscript.

Some other minor comments:

10976, L7: change to ‘and related these to catchment’
Reply: We have made this change in the revised version (Abstract, L23).

10976, L20-22L This sentence not clear. It suggests there is an effect of scale, while the results have shown there isn’t. Greatest difference between scales, or within the two groups?
Reply: We have re-phrased this sentence to make its meaning clear in the revised manuscript (Abstract, L36-37).

10977, L17: needs rephrased. Change ‘first’ to ‘for the first time’?
Reply: We have made this change (Introduction, L63).

10978, L8-9: are these of the same order of magnitude as Munoz-Villers and McDonnell 2012?
Reply: They were larger catchments from ~2 to 77 km². We have added this information in the revised version (Introduction, L81).

10979, L11: change to ‘the majority of monitored headwaters are located’
Reply: We have made this change (Section 2.1, L113).

10980, L3: ET not known as this elevation?
Reply: Indeed, no data on ET are available for this elevation.

10981, L13: What kind of correlation? Can you show what the measure of fit is?
Reply: It was a linear regression with an $r^2$ of 0.95. **We have added this information in the revised version (Section 2.2.2, L170).**

10982, L4: Explain why this is the best method?! e.g. why not nearest gauge, something along the lines of elevation corrected Thiessen polygons

**Reply:** We actually followed the McGuire et al. (2005) approach, matching the average isotope signature of baseflow with that of rainfall, and so to identify the elevation at which most recharge occurs. **This information has been added in the revised version (Section 2.3, L190-192).** Furthermore, this approach was supported by the fact that both the TG and SECP sites are located at those elevations in the LG watershed where probably most groundwater recharge occurs, as determined by previous water balance studies (Muñoz-Villers et al., 2012). This information was already mentioned in the text (L198-200).

10982, L12: Why this approach when many others around? Does it fit your data best?

**Reply:** MTT studies often suffer from short isotope time series of rainfall, which yield nonunique model calibrations or uncertainty in the parameter estimates of the transit time distribution. To deal with this, the majority of the investigations extend their input time series using different methods (i.e. temperature records, seasonality in rainfall, or data from nearby long-term stations). At our site, precipitation shows a marked seasonal pattern (Holwerda et al., 2010; Muñoz-Villers et al., 2012). Rainfall isotope signatures also show a strong and consistent variation with rainfall amount (Goldsmith et al., 2012). **We have added this information in the revised version (Section 2.3, L201-205).** Thus, we decided to generate a warm-up period required for the model simulations, repeating our measured 2-year rainfall time series 15 times following the approach of Hrachowitz et al. (2009, 2010); note that we already tested this method in previous MTT work at our site (cf. Muñoz-Villers and McDonnell, 2012).

10984, L6: not 'created' but 'derived'

**Reply:** We have made this change (Section 2.5, L255).

10984, L14: which criteria were used for selection?

**Reply:** This information is provided in Section 2.5, L257-259.

10984, L16: change ‘description’ to ‘descriptions’

**Reply:** We have made this change (Section 2.5, L264).

10984, L17: n = 3 in total or 3 at each site?

**Reply:** Three undisturbed soil core samples at each site. We have clarified this in the revised version (Section 2.5, L266).

10985, L15-16: How does this relate to long term (or even 2006-2010) data? Could there be bias in your data as a result?

**Reply:** The average of 3,476 mm measured at the SECP site (2,100 m) is somewhat higher (9 %) than the average of 3,183 ± 306 (SD) mm measured at that same site between November 2005 and November 2009 (Goldsmith et al., 2002). No other data than those given here are available for the other sites. Nevertheless, the rather small
difference with the 2005-2009 data suggests that the two years of data used in this analysis are representative of the longer term pattern. We have added this information in the revised manuscript (Section 3.1, L298-303).

10985, L24: p value results of which test? Reply: Anova statistical test. We have complemented and re-phrased the information regarding the statistical methods in the revised version (Section 2.5, L287-293).

10986, L5: lagged by how much? Reply: We have omitted this text in the revised manuscript.

10986, L8: not statistically significant at all sites? And again, which test results? Reply: Yes, not statistically significant at all sites. We have made this clear in the revised version (Section 3.1, L318). For the second question, please see our reply to the previous comment.

10986, L10: But many of your sites are nested. Have you considered that this could be a result e.g. of the headwaters contributing the majority of water? Do you have any indication of how much water is coming from which parts of the catchments spatially? Reply: Please see our reply to your similar comment above.

10987, L10: the highest proportion of what? Reply: Of the above mentioned slope categories. We have made this clear in the revised version (Section 3.3, L351).

10987, L14-15: This sentence should be moved to methods - and explain why this is important? Reply: We have moved this sentence to the Methods section (Section 2.4, L245). The explanation given was to inform the readers what the measures/numbers indicate.

10991, top sentence needs rephrased Reply: We were not sure which sentence the reviewer is referring to.

10992, L17: change ‘has’ to ‘have’ Reply: We have made this change.

Figure 1: This Figure is currently all a bit busy and it is difficult to make out the subcatchments. Why not focus on the study area only as the lower part of the catchment is not relevant for the study here. Also, what do the elevation labels refer to in A? Reply: We included the lower part of the catchment to show the entire extent of the LG watershed. The elevation labels in Figure A are presented to give information about the elevation from the bottom to the top of the catchment. In response to the comment, we have increased the size of the figures and labels, and we have also re-arranged its content to make it easier to read.
Figure 2-3: Swap order of Fig 2 and 3 - in the text you first refer to Fig 3, then 2.

Reply: We have made this change.

Short comment by G. Mosquera

Dear authors, I think it would be quite interesting to discuss the selection of the best TTD for each catchment. Table 4 shows what the reader should assume as the best TTDs for each of them, but a thorough discussion about why different TTDs were selected for different catchments is lacking. Perhaps it would also be interesting to show the parameter space of all or at least the best TTD/s at least for one catchment in order show why one or another TTD was selected as the best (e.g., Figure 6 in Hrachowitz et al., 2009). Additionally, perhaps the analysis of the probability and cumulative density functions would help to better understand the hydrology of the system as a whole (e.g., why one of the smallest catchments shows the longest MTTs) (See for example Figures 8, 9, 14, and 15 in Timbe et al., 2014).

Reply: We thank you for your comment. As we mentioned in our reply to Reviewer #2, the TTD model that we used for a particular catchment was the one that best fitted the observed baseflow data. We have made this clear in the revised manuscript.

Note that the criteria used to select the TTDs are described in Section 2.3. Also note that in the majority of cases we used the Exponential model or the variant (Gamma model) (please see our Reply to reviewer #2). With regard to include a thorough discussion about the selected TTDs, we think that this is out of the scope of this paper. As our objective and research questions stated, we quantified stream MTTs and related these to catchment characteristics to understand and identify the key factors controlling baseflow MTTs across the different catchments. Please note that (probable) answers to the question ‘why one of the smallest catchments shows the longest MTTs’ are provided in Results (Section 3.2 and 3.3), Discussion (Section 4.2) and Conclusions.

Comments by the Editor

1. Please consider adding the base flow in the title as the focus is the base flow MTT, see the comment and your reply to Referee #2.

Reply: We appreciate the recommendation; however, we feel it is justified that we keep the title as it is, since in the manuscript we informed the readers that our streams are almost completely dominated by baseflow and for that reason samples for isotope analysis were taken during baseflow conditions.

2. The conclusion is too much similar to abstract. Please add more details to the conclusion part, like how the identified physiological properties control the MTT

Reply: We have followed the suggestion. We have incorporated more details of our results in the Conclusions. We also re-phrased and re-arranged this section in the revised version (L571-589).
References


Manuscript title
Factors influencing stream water transit times in tropical montane watersheds

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Abstract

Stream water mean transit time (MTT) is a fundamental hydrologic parameter that integrates the distribution of sources, flow paths and storages present in catchments. However, in the tropics little MTT work has been carried out, despite its usefulness for providing important information on watershed functioning at different spatial scales in (largely) ungauged basins. In particular, very few studies have quantified stream MTTs and related these to catchment characteristics in tropical montane regions. Here we examined topographic, land use/cover and soil hydraulic controls on baseflow transit times for nested catchments (0.1–34 km²) within a humid mountainous region, underlain by volcanic soil (Andisols) in central Veracruz (eastern Mexico). We used a 2 year record of bi-weekly isotopic composition of precipitation and stream baseflow to estimate MTT. Land use/cover and topographic parameters (catchment area and form, drainage density, slope gradient and length) were derived from GIS analysis. Soil water retention characteristics, and depth and permeability of the soil-bedrock interface were obtained from intensive field measurements and laboratory analysis. Results showed that baseflow MTT ranged between 1.2 and 2.7 years across the 12 study catchments. Overall, MTTs across scales were mainly controlled by catchment slope and the permeability observed at the soil-bedrock interface. In association with topography, catchment form and the depth to the soil-bedrock interface were also identified as important features influencing baseflow MTTs. The greatest differences in MTTs were found both within groups of small (0.1–1.5 km²) and large (14–34 km²) catchments. Interestingly, longest stream MTTs were found in the headwater cloud forest catchments.

Key words: stable isotopes, baseflow, catchment transit times, topography, land cover, Andisols, Mexico

1. Introduction

The demand for fresh water is rapidly increasing in the humid tropics due to population growth. Nevertheless, in these regions — particularly the montane tropics — relative little process-based hydrological studies have been performed to quantify the states, stocks, flows and residence times of water. These areas are especially prone to land degradation and deforestation for conversion to agricultural and pasture lands (Asner et al., 2009). Notably, tropical montane
cloud forests (TMCF) are unique and hydrologically important ecosystems (Bruijnzeel, 2004), but are among the world's most threatened terrestrial ecosystems (Cayuela et al., 2006; Hamilton et al., 1995; Pope et al., 2015). Yet the hydrological impacts associated with land degradation and forest conversion at different scales remain poorly understood, thus hampering the development of effective local and regional strategies for water resources protection and management.

Stream water mean transit time (MTT) is an important hydrologic metric that integrates the variety of flow paths, storages and runoff sources potentially existing in catchments. In humid temperate environments, MTTs estimated from stable isotopes have been used to broadly characterize the hydrological and biogeochemical behavior of catchments (McDonnell et al., 2010), providing important information on catchment resistance and resilience to climate change scenarios (Carey et al., 2010). In these same environments, significant progress has been made in exploring the linkages between baseflow MTTs and catchment characteristics, and the dominant factors controlling stream MTT variability across scales and regions. For example, McGuire et al. (2005) showed for the first time, the dependence of stream water mean residence time on catchment topographic indices (hillslope length and gradient) for multiple nested watersheds in Western Oregon, USA. Further, Broxton et al. (2009) found that stream water isotope variability and estimated MTTs were both related to watershed aspect and slope in the Valles Caldera watershed, New Mexico, USA. In Central Japan, Asano and Uchida (2012) showed that base flow MTT was mainly controlled by the depth of the hydrologically active layer (i.e. depth of the soil-bedrock interface), which was not necessarily related to catchment topography. Perhaps the most extensive work to date has been done in North East Scotland, where several studies have identified soil properties (soil type and permeability) as the main control on stream MTTs (Geris et al., 2015; Rodgers et al., 2005; Soulsby et al., 2006; Tetzlaff et al., 2009a). With the exception of the investigations carried out by McGlynn et al. (2003) in the Maimai watersheds in New Zealand, and more recently by Hale and McDonnell et al. (2016) in the Alsea Watershed Study in the Oregon Coast Range, USA, which both showed strong positive relations between MTTs and catchment area, most studies to date have shown that landscape evolution and organization dictates rainfall-runoff processes in humid temperate environments.

In the humid tropics, isotope-inferred stream MTT studies have provided insights into the hydrological functioning of small forested catchments (< 0.3 km²); Muñoz-Villers and
McDonnell, 2012), and their sensitivity to land use conversion (< 1.8 km²; Roa-García and Weiler, 2010). At larger scales (> 2 to 77 km²), the studies carried out in Ecuador by Crespo et al. (2012) and Timbe et al. (2014) have reported MTT values for various flowing water bodies (springs, creeks, tributaries and rivers), but as yet, the factors controlling the stream water transit times in this and other montane regions of the humid tropics remain to be explored.

Here we build upon previous isotope work at our site in central Veracruz, Mexico, where large water storage capacities have been estimated (~ 3 yr) for an old-growth TMCF upland catchment based on baseflow MTT (Muñoz-Villers and McDonnell, 2012). The present study is the first in the humid tropics that we are aware of that explores the relationship between stream water MTT and landscape characteristics across catchments ranging different size areas (from 0.1 to 34 km²). Our tropical montane watersheds are underlain by volcanic soil substrates (Andisols). MTT was determined using a 2 year record of rainfall and stream water isotope data. We used metrics such as land cover, topographic parameters and hydrologic properties of the soil-bedrock profile to identify the factors controlling stream MTTs in this environment. Specifically we addressed the following research questions:

1. What are the stream mean transit times across catchment scales?
2. How do catchment area, topography and subsurface hydrologic properties relate to stream transit times?
3. Does land cover have an effect on stream MTT variability?
4. Is there a dominant factor controlling stream water transit times in this mesoscale catchment?

2. Materials and Methods

2.1 Study site

The 5th-order Los Gavilanes (LG) river catchment (41 km²; 19° 28' N - 97° 01' W) is located on the eastern (windward) slopes of the Cofre de Perote mountain. It is the main stream water supply for the city of Coatepec and surroundings (~80,000 inhabitants). The landscape of this region is complex and strongly dissected by perennial streams draining catchments of different sizes. For this study, 12 catchments were selected, ranging in area from 0.1 to 34 km².
and located between 1300 and 3000 m a.s.l. (Figure 1a). Table 1 summarizes the physical characteristics of the study catchments.

The mid and upper parts of the LG catchment (1800–3000 m a.s.l.), where the majority of monitored headwaters are located, are characterized by short steep hillslopes covered mostly by pine-oak forest, mature and secondary tropical montane cloud forest, and pasture (Figure 1b,c). The lower portions of the LG catchment (1300–1800 m a.s.l.) are characterized by more gentle terrain covered by pasture, fragments of cloud forests on the steeper slopes and shaded coffee plantations below 1400 m.

The general climate in the LG catchment is temperate humid with abundant summer rains (Garcia, 1988). About 80% of the annual rainfall falls as convective storms during the wet season (May–October), when the region is under the influence of the easterly trade wind flow. Maximum ground water recharge and catchment runoff also occur during this season (cf. Muñoz-Villers and McDonnell, 2013). The relatively dry season (November–April) is characterized by light rains and/or fog and drizzle associated with the passage of cold fronts (Holwerda et al., 2010). Fog interception occurs exclusively during this time of year, and accounts for ≤ 2% of the annual rainfall for the upper part of the LG catchment (Holwerda et al., 2010; Muñoz-Villers et al., 2012, 2015).

The local climate varies markedly with elevation. At 1210 m a.s.l. (lower part of the LG catchment), the annual mean daily temperature is 19 °C. Corresponding mean annual rainfall and reference evapotranspiration (ET0) are 1385 and 1120 mm, respectively (Holwerda et al., 2013). At 2100 m a.s.l. (middle part), the annual mean daily temperature is 15 °C, and mean annual rainfall and ET0 are 3185 and 855 mm, respectively (Goldsmith et al., 2012; Muñoz-Villers et al., 2012). Finally, at 3000 m a.s.l. (upper part), mean annual temperatures range between 5 and 10 °C, and mean annual rainfall is 1900 mm (SMN, 2014).

Andisols derived from volcanic ashes are the dominant type of soil across the LG catchment. These soils are characterized by low bulk density, high permeability, high water retention capacity and high organic matter content (Gomez-Tagle et al., 2011). Soil profiles are usually deep, well developed and multilayered (A, A/B, Bw, Bw/C), with silt loam and silty clay loam as the dominant textures (Gómez-Tagle et al., 2011). The parental material is permeable, consisting of moderately weathered andesitic breccias, underlain, in turn, by semi-permeable
saprolite that has been weathered from fractured andesitic-basaltic bedrock (cf. Muñoz-Villers and McDonnell, 2012).

2.2 Field data collection and analysis

2.2.1 Rainfall measurements

To quantify daily precipitation and its spatial variation along the altitudinal gradient, rainfall was measured at 1560, 2100 and 2400 m a.s.l. (Figure 1a). For the sites at 1560 m (hereafter RA) and 2100 m (SECP), stand-alone tipping bucket rain gauges of the type RG2M (Onset) and Casella CEL, respectively, were used (both with a resolution of 0.2 mm). For the site at 2400 m, rainfall was measured with an ARG100 tipping bucket rain gauge (Environmental Measurements; 0.2 mm) as part of a meteorological station (TG; Figure 1a). The signals from the stand-alone gauges were stored in an HOBO pendant event logger (Onset), whereas for the gauge in the weather station a CR1000 data logger (Campbell Scientific) was used. Measurements at SECP were made continuously from July 2006 to November 2010, whereas measurements at RA and TG covered the period of isotope sampling (see below).

2.2.2 Collection and analysis of rain and stream water samples

To establish the records of δ²H and δ¹⁸O isotope composition of precipitation and streamflow, samplings during non-storm conditions were carried out over two hydrological years (May 2008 – April 2010). Paired with the tipping bucket rain gauges, samples of bulk rainfall were collected using a sampler consisting of a 95 mm diameter funnel assembled to a 40 mm diameter and 400 mm long transparent collection tube. The tube contained a float to minimize evaporation. In addition, the rain water collector was inserted into a 75 mm diameter PVC pipe wrapped with bubble foil insulation to protect the collected water against sunlight and minimize temperature variations. Rainwater sampling intervals ranged between 1 and 25 days, depending on rainfall amount and frequency. For logistical reasons, rainwater collection at the RA site was only possible from March 2009 to April 2010. The missing isotope data (10 months) were completed using a linear regression with data from the SECP site ($r^2 = 0.95$).
Previous hydrological work at our research site has shown that baseflow is the dominant streamflow component (~ 90%). Furthermore, isotope and chemical-based hydrograph separation for a series of storms and for catchments dominated by different land covers showed that rainfall-runoff responses are mainly dominated by ground water sources (Muñoz-Villers and McDonnell, 2012, 2013). For these reasons, we focused our stream sampling on baseflow. Grab samples of base flow were collected every 2 weeks at the outlets of the 12 study catchments. These included nine sampling points representing headwaters up to 4th-order streams (numbers 1-9; Figure 1a), two main tributaries of the LG river (10 and 11) and the main river (12).

All water samples were collected in 30 ml borosilicate glass vials with polycone sealing cap to prevent evaporation. The samples were analyzed for δ²H and δ¹⁸O on a laser liquid-water isotope spectrometer (Version 2, Los Gatos Research, Inc.) in the Hillslope and Watershed Hydrology Lab at Oregon State University, USA. The isotope values are expressed in permil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW). The precision of δ²H and δ¹⁸O measurements was 0.3 and 0.1‰, respectively.

2.3 Transit time model

Biweekly δ²H signatures of stream water and rainfall were used to estimate base flow mean transit time (MTT) and transit time distribution (TTD) for each of the study catchments. First, 2-week volume-weighted means (VWMs) of rainfall isotope composition were calculated for each of the three sampling sites. Second, we followed the McGuire et al. (2005) approach to compare the average isotope signature of baseflow for each study catchment with that of rainfall, and so to identify the elevation at which most recharge occurs. For this, we calculated 2-yr averages, and determined for each catchment which of the rainfall time series had its average δ²H value closest to the average δ²H baseflow value. The overall mean δ²H base flow value was -44.9‰ (range: -50.2 to -41.0‰ across all catchments), whereas rainfall at TG, SECP and RA had volume-weighted mean δ²H values of -43.0, -37.6 and -33.5‰, respectively. Hence, for all of the study catchments, MTT simulations were carried out using the rain isotope data from either TG or SECP. Further, this approach was supported by the fact that both the TG and SECP sites are located at those elevations in the LG catchment where most groundwater recharge occurs, as determined by previous water balance studies (Muñoz-Villers et al., 2012).
The $\delta^2$H precipitation data collected over 2 hydrological years (May 2008 – April 2010) may be too short to properly constrain stream base flow MTT estimates (cf. Hrachowitz et al., 2009). However, precipitation at our site shows a marked seasonal pattern (Holwerda et al., 2010; Muñoz-Villers et al., 2012). In addition, rainfall isotope signatures shows a strong and consistent variation with rainfall amount (Goldsmith et al., 2012). Therefore, to generate an artificial warm-up period required for the MTT model simulations, we followed the approach of Hrachowitz et al. (2009) and repeated our measured 2-year rainfall time series 15 times (cf. Muñoz-Villers and McDonnell, 2012). We then used a lumped parameter convolution model to predict the $\delta^2$H output for the stream water as a weighted sum of its respective past $\delta^2$H measured input in precipitation (Maloszewski and Zuber, 1993). Mathematically, the stream water outflow composition at any time, $\delta_{\text{out}}(t)$, consisted of past inputs lagged $\delta_{\text{in}}(t-\tau)$ and weighted by the transfer function $g(\tau)$, representing its lumped TTD (Maloszewski and Zuber, 1982):

$$
\delta_{\text{out}}(t) = \int_0^\infty g(\tau) \delta_{\text{in}}(t-\tau) d\tau
$$

where $\tau$ are the lagged times between the input and output tracer composition. The weighting function or TTD describes the travel time of the water from the ground surface to an outflow location (i.e. the catchment outlet) (McGuire and McDonnell, 2010).

In this study, we used the most basic TTD models (Exponential, Gamma and Dispersion), which require only one or two distribution parameters to be optimized and have been successfully applied in other studies (e.g. McGuire et al., 2005). The performance of different TTD functions for each of the 12 study catchments was evaluated using the transfer function hydrograph separation model TRANSEP (McGuire and McDonnell, 2010; Weiler et al., 2003). This model utilizes the Generalized Likelihood Uncertainty Estimation (GLUE) methodology (Freer et al., 1996) based on Monte Carlo simulations to determine the identifiability of the individual parameters. Our Monte Carlo analysis of each TTD consisted of 10,000 runs. Model performance was assessed using the Nash–Sutcliffe efficiency $E$ (Nash and Sutcliffe, 1970), based on the best agreement parameter value, where a value of 1 would indicate a perfect fit. Parameter uncertainty was defined as the range between 10th and 90th percentile value for the best 20% performing parameter sets based on $E$ (McGuire and McDonnell, 2010; Seibert and
McDonnell, 2010). The overall performance of the TTD models was evaluated using the root mean square error (RMSE).

### 2.4 Terrain analysis

To evaluate whether landscape characteristics had an influence on base flow MTT, several metrics describing catchment topographic and morphometric features were calculated in ILWIS 3.3, a raster and vector GIS system. Catchment area was obtained by delineating and extracting each catchment boundary using a digital contour elevation map (10 x 10 m resolution). Land cover was obtained from a regional land cover/use raster map (20 x 20 m) elaborated by Muñoz-Villers and López-Blanco (2008), using satellite images and ground truth verification data. For vegetation cover, each catchment was classified in one of the following 4 categories: (1) > 90% covered by TMCF; (2) > 60% covered by any type of forest (pine-oak, TMCF); (3) > 90% covered by pasture; and (4) even mixture (~50-50%) of pasture and any type of forest.

Catchment form factor (a measure of catchment shape), drainage density, slopes and hillslope length were calculated using topographic maps (scale 1: 20,000) and a 10 x 10 m digital elevation model (DEM). Catchment form factor ($R_f$) and drainage density ($D_d$) were calculated following Horton (1932). Hillslope length was obtained as the average distance between catchment ridge top and valley bottom. Horizontal and vertical gradients of each pixel in the DEM were used to calculate the mean and the percentage distribution of slopes in each catchment, using for the latter the following six classes: $0$-$5$; $5$-$10$; $10$-$20$; $20$-$30$; $30$-$45$; $>45°$.

### 2.5 Soil sampling and analysis

Field surveys, soil samplings and subsequent laboratory analysis were conducted from May 2011 to May 2012. First, hillslope forms (ridge top, mid and valley bottom) were derived in GIS using topographic analysis algorithms (Jenness, 2006) and then overlaid with catchment boundaries. From the intersection of the polygon units thirty-two soil toposequences were selected, distributed mostly in the mid and lower portions of the LG catchment because access to the upper part was very difficult. At each toposequence, soil auger-holes up to $2.2$ m deep were performed from ridge top to valley bottom to determine the organization of soil layers along the
hillslope. Soil penetration resistance was also measured down to 2 m using a dynamic cone penetrometer, following the design and method of Herrick and Jones (2002).

At selected toposequences, soil profile pits of approximately 1.5 m x 1.5 m x 2 m (length, width and depth, respectively; 43 in total) were excavated for detailed soil descriptions following the method of Schoeneberger et al. (2002). In addition, undisturbed soil core samples (n = 3) at the soil-bedrock interface in each soil profile pit were taken to determine saturated hydraulic conductivity \( K_s \) in the laboratory using the constant-head method. Further, a pedotransfer function, correlating the observed \( K_s \) and penetration resistance values, was used to extrapolate \( K_s \) of the least permeable layer to the catchment scale.

In each soil pit, soil samples from the A and B-horizons (solum) were collected for laboratory analysis. Bulk density was determined from samples taken with cylindrical stainless steel cores of 100 cm\(^3\) in each horizon (n = 3), and dried at 105 °C until constant weight. For soil moisture content at field capacity, undisturbed samples from 5 x 1 cm rings (diameter and height; n = 3) were collected, then weighed after reaching saturation and equilibration (normally within 48 hours), and placed in a pressure-plate apparatus at 30 kPa. From water retention at field capacity and bulk density values, the amount of water held in the solum (in mm) was calculated. All laboratory analyses were performed in the Soil Laboratory of the Instituto de Ecología A.C., Xalapa, Veracruz.

Based on the observed range of depths to soil-bedrock interface (DSBI), this variable was divided in 4 classes: very shallow (< 50 cm depth), shallow (> 50-100 cm), moderate deep (100-200 cm) and relatively deep (> 200 cm). Soil \( K_s \) and water retention (WR) capacity categories were defined for each site and hillslope sequence. The \( K_s \) classes were obtained from the Soil Hydrology Group of the National Engineering Handbook, Part 630 (NRCS-USDA, 2007), and partly modified based on the HOST classification system (Boorman et al., 1995). The WR capacity classes were defined on ad hoc ranges. Based on relationships between the soil hydrologic properties and geoforms, the data was extrapolated to the entire LG catchment.

Finally, to evaluate differences in the isotopic composition and deuterium excess (\( d\)-excess = \( \delta^2H \) – 8*\( \delta^{18}O \); Dansgaard, 1964) values for rainfall and stream water across sites, we used ANOVA t-tests. Statistical relationships between baseflow MTT, depth and permeability at the soil-bedrock interface, soil water retention and landscape characteristics (land cover and topographic variables) were tested using Spearman’s rank order correlations. All statistics were
evaluated at the 0.05 confidence level and conducted in Sigma plot (version 12, Systat Software Inc.).

3. Results

3.1 Isotopic composition of rainfall and stream water

From May 2008 to April 2010, mean annual precipitation varied from 2670 mm at RA (1560 m), 3476 mm at SECP (2100 m) to 3264 mm at TG (2400 m). The average of 3,476 mm measured at the SECP is somewhat higher (9%) than the average of 3,185 ± 305 (SD) mm measured at that same site between November 2005 and November 2009 (see above). Nevertheless, the rather small difference suggests that the two years of data used in this study are representative of the longer rainfall pattern. For the other sites, no other data than those given here are available.

Rainfall showed a clear seasonal pattern, with 80% on average falling during the wet season (May–October). During the same period, a wide range of variation in the biweekly rainfall isotope values was found across elevations. The largest variation (118 ‰ for $\delta^2$H and 17 ‰ for $\delta^{18}$O) and most negative (depleted) values (-110 ‰ for $\delta^2$H and -16 ‰ for $\delta^{18}$O) were observed at the highest altitude (2400 m). With decreasing altitude, rainfall isotope values became more positive (enriched) and their range of variation smaller (Figure 2a). However, differences in rainfall isotopic composition among elevations were only suggested for $\delta^{18}$O ($p = 0.031$). Mean annual deuterium excess ($d$-excess) values of rainfall increased from 15 to 17 ‰ with elevation, but differences among sites were not significant ($p \geq 0.05$).

Across all sites, $\delta^2$H and $\delta^{18}$O rainfall signatures in the wet season (-32.3 ± 25.7 ‰ and -5.9± 3.2 ‰ SD, respectively) were significantly depleted as compared to the dry season (-15.6 ± 13.6 ‰ and -4.3± 1.7 ‰; $p \leq 0.05$) (Figure 3). Stream water isotopic composition followed the seasonal pattern as observed for precipitation; however values were damped (range: -49.4 to -41.8 ‰ for $\delta^2$H and -8.1 to -7.2 ‰ for $\delta^{18}$O; Figure 3) as compared to rainfall (range: -106 to 10 ‰ for $\delta^2$H and -15 to -1 ‰ for $\delta^{18}$O, respectively). For all stream water sites, differences in isotope composition between the dry and wet seasons were not statistically significant ($p \geq 0.05$).

Unlike rainfall, there were no distinct differences in the isotope signatures of the streams, despite the altitude difference of more than 1000 m between the upland headwaters and the downstream LG river tributaries (Figure 2b). During the wet season, $d$-excess values in the
streams were rather constant across all sites, whereas during the dry season values were slightly
enriched at lower elevations as compared to upper elevations (Table 2).

Figure 2c shows that all samples of precipitation and stream water fall along the local
meteoric water line (LMWL), with d-excess values consistently above 10 ‰ (range of rainfall:
10.7 to 24.2 ‰, and streams: 10.4 to 22.5 ‰). The fact that the rainfall and stream baseflow
samples had very similar d-excess ranges indicates that the catchment water input-output was
little affected by evaporation.

3.3 Land cover, topography and soil hydraulic properties

Our GIS analysis showed that approximately 70 % of the LG catchment was covered by
some type of forest. Eight out of the 12 study catchments were located in the middle and upper
portions of the LG catchment, which are characterized by moderate to steep terrain. These eight
catchments ranged in size between 0.1 and 14 km², and were covered predominantly by mature
and secondary TMCF (> 50%; Table 3). Forest was also the dominant land cover in one of the
two tributary catchments (Huehueyapan) and in the LG catchment itself. In these two
catchments, the upper part was dominated by pine-oak (> 2500 m), the middle part by TMCF and
pasture, meanwhile coffee plantations and forest fragments characterized the lower part (< 1400
m). Two out of the 12 catchments were dominated by pasture (having areas of 0.1 and 1.5 km²),
and only one catchment (1.9 km² of area) was covered by even portions of forest and pasture.

Hillslope lengths were shortest (113 m on average) in the smallest catchments (0.1–1.5
km²), and longest (273 m) in the largest ones (14–34 km²; Table 3). Slopes of intermediate
length (217 m) were found in the 4–9 km² catchments. Mean slope was 32 ± 5° across all
catchments. The dominant categories of slopes were 10-20° and 20-30°. Within these groups, the
headwater mature and secondary cloud forest catchments (MAT and SEC; < 0.25 km²) showed
the highest proportions of the above mentioned slope categories. The pasture headwater
catchment (PAS; 0.1 km²) had the highest percentage (46 %) of gentle slopes (0-10°), meanwhile
the 20 km² Huehueyapan tributary catchment showed the highest proportion (33 %) of very steep slopes (> 30°).

The catchment form factor ($R_f$) ranged between 0.071 (CATM1 and CATM5) and 0.231 (SEC). Drainage density ($D_d$) ranged from 1.3 to 8.0 km km⁻². Low $D_d$ values ($2.4 ± 0.4$ km km⁻²) were found at the larger catchments (14-34 km²) whereas higher $D_d$ values ($5.3 ± 2.4$ km km⁻²) characterized the smaller catchments (0.1-9 km²; Table 3).

Soil depth and water retention (WR) capacity of the solum were greatest in hillslopes located in the middle portion of the LG catchment; maximum WR values were observed in the headwater mature (MAT) and secondary (SEC) forest catchments, and in other small catchments < 0.5 km² dominated by TMCF (Category 15; Figure 4a). Catchments with areas of approximately 2 km² were dominated (≥ 50 %) by soil depths and WR capacities ranging between 1.0 and 1.5 m and 580 and 850 mm, respectively (Category 14). Shallower soil depths (from 0.5 to 1 m) and reduced WR values (from 310 to 510 mm; Category 13) characterized the slope areas (46 % on average) of the larger catchments (9-34 km²). CATM5 showed the highest proportion of area (33 %) covered by very shallow soils and relatively low water retentions (Category 12).

Across all sites, the depth to the soil-bedrock interface (DSBI) ranged from 0.5 to more than 2 m, and soil saturated hydraulic conductivity ($K_s$) at the interface ranged from 1 to nearly 40 mm hr⁻¹. However, for the majority of the catchments, the DSBI was between 1.0 and 1.5 m (~ 65 % of the catchment area on average), with corresponding $K_s$ values between 1 and 15 mm hr⁻¹ (Category 2C; Figure 4b). Notably, the SEC was dominated by DSBI between 1 and 2 m (70 % of the catchment area); at some locations in this catchment DSBI was greater than 2 m, with permeabilities at the soil-bedrock interface higher than 36 mm hr⁻¹ (Categories 2A and 1A). In contrast, the Huehueyapan catchment showed the highest percentage of area (30 %) covered by very low DSBI values (0.5 – 1.0 m on average) of all catchments, but $K_s$ ranged from 4 to 36 mm hr⁻¹ (Categories 4C and 3B).

Table 3

Figure 4

3.2 Stream baseflow MTTs and their relationship with catchments characteristics
Estimated baseflow mean transit time (MTT) ranged between 1.2 and 2.7 years across the 12 study catchments. Note the TTD model that we reported for a particular catchment was the one that best fitted the observed baseflow data (Table 4). The root mean square error (RMSE) and Nash-Sutcliffe efficiency value ($E$) for these model results ranged from 0.8 to 1.5‰ ($\delta^2$H) and 0.42 to 0.69, respectively. Table 4 provides further details on the values of the TTD parameters and the uncertainty bounds.

Catchment form, slope, land cover and depth to soil-bedrock interface explained each about 50% of the variance of baseflow MTT across catchments (Figure 5). The positive correlation found between form factor ($R_t$) and baseflow MTT suggests that catchments with narrow and elongated shapes lead to shorter transit times (Table 5; Figure 5a). Long MTTs were positively correlated with moderately steep catchments (particularly where slopes between 20 and 30° predominated; Figure 5c). Conversely, short MTTs were most strongly related to catchments with high proportions of gently slopes (between 5 and 10°). Interestingly, catchments covered by areas with very steep slopes (> 30°) showed very poor correlations with MTTs. Weak correlations were also obtained with catchment drainage density and mean slope length.

Soil WR categories determined along the hillslope transects did not explain much of the variation in baseflow MTTs. Instead, a strong and positive relation was observed between MTT and DSBI; specifically longer stream transit times were related to catchment hillslopes where deep (> 2 m) soil-bedrock interfaces dominated (Figure 5f). Conversely, low and negative correlations were obtained with shallower depths (< 1 m; Table 5). Regardless of the DSBI classes, observed $K_s$ values remained generally high across all sites (5–30 mm hr$^{-1}$; on average).

Land cover explained a significant variation of the baseflow MTT (Table 5; Figure 5e); catchments covered by more than 60% of forests (Categories 1 and 2) had on average longest MTTs (1.9 ± 0.4 (SD) yr) compared to catchments dominated by ≥ 90% of pasture or evenly mixed covers with pasture and forest (1.5 ± 0.2 yr; Categories 3 and 4).

Baseflow MTT showed no relation to catchment area (Table 5; Figure 5b). However, at the smallest scale (< 0.3 km$^2$), major differences in the MTT were found (1.5 to 2.7 yr). At the intermediate scale (4–9 km$^2$), differences in MTTs (1.4 to 1.9 yr) were small among catchments. At the larger scale (> 14 km$^2$), some more variation in the baseflow MTTs was observed (1.2 to 2 yr). The 20 km$^2$ Huehueyapan showed the shortest baseflow transit times (1.2 yr) compared to
other large catchments examined—this was also the lowest MTT estimated across all the study catchments.

Table 4
Table 5
Figure 5

4. Discussion

4.1 How do our baseflow MTTs compare to those found in other tropical montane streams?

Our stable isotope data showed that wet season rainfall is the main catchment stream water source in this tropical montane region. This is similar to findings in other humid tropical environments (Crespo et al., 2012; Roa García and Weiler, 2010; Scholl and Murphy, 2014), but contrasts with results for temperate regions where seasonality in flow regime is usually much more pronounced and, consequently, stream water tends to reflect input sources from different seasons (Brooks et al., 2012; Mueller et al., 2013; Peralta-Tapia et al., 2015). Our estimates of base flow transit times ranged between 1.2 and 2.7 years across the 12 study catchments. These rather long transit times suggest deep, and presumably long subsurface flow paths, contributing to sustain catchment baseflows across scales (0.1 to 34 km²) and seasons.

Comparing our results with those obtained by Roa-García and Weiler (2010) for three adjacent headwater catchments differing in size (0.6–1.8 km²) and land cover (forest versus pasture) in central-western Colombia, our baseflow MTTs for the cloud forest catchments (~ 2.7 yr; 0.1–0.3 km²) are almost twice the value obtained for their forest-dominated catchment (1.4 yr). Further, for two pasture-dominated catchments, these authors obtained MTTs that differed considerably (0.1 and 1.4 yr), which they attributed to differences in soil permeability.

Furthermore, the relatively short stream MTTs in the Andean catchments were attributed to the relatively low hydraulic conductivities that characterize the volcanic soils (Acrudoxic Hapludans) of that region, limiting rain water percolation and promoting near-surface flow (Roa-García and Weiler, 2010). This contrasts with our sites, where deep subsurface flow rather than shallow lateral flow is the dominant flowpath for runoff generation (Muñoz-Villers and McDonnell, 2012, 2013)
In southern Ecuador, Crespo et al. (2012) used a simple sine-wave approach to estimate the baseflow MTTs for a 74 km² nested mesoscale watershed (the San Francisco river basin), underlain mostly by Histosols. They found MTTs on the order of 0.7–0.9 yr for nine cloud forest catchments (1.3–74 km²). Further, for a 0.8 km² pasture catchment, they reported a MTT of 0.8 yr. Shallow lateral subsurface flow and high catchment runoff ratios (76–81 %) due to relatively low topsoil and subsurface permeabilities (14–166 mm hr⁻¹) characterized the hydrology of that montane area (Crespo et al., 2012). In contrast, soil hydraulic conductivities at our site were higher (~ 400 mm hr⁻¹ on average across land covers; Muñoz-Villers et al., 2015), leading to lower (annual) rainfall-runoff ratios (35–50 %), and hydrological responses mainly driven by groundwater sources, which likely explain the much larger catchment water storage capacities of our systems.

For eight of the catchments in the San Francisco river basin previously investigated by Crespo et al. (2012), Timbe et al. (2014) obtained much higher MTTs values by fitting several TTD models. For seven cloud forest dominated catchments (1.3–77 km²), they reported an average MTT value of 2.1 yr, while for a pasture catchment they obtained a MTT value (3.9 yr) that was twice the average value for the forests. However, the authors did not provide an explanation of why they found longer MTTs and contradictory results (i.e. higher MTT in the pasture than in the forests) compared to the earlier work by Crespo et al. (2012).

4.2 Factors determining baseflow MTTs in this tropical montane watershed

It is well known that topography plays an important role in the transit time of water through catchments (Tetzlaff et al., 2009a), particularly in montane environments (cf. McGuire et al., 2005). Our findings are consistent with previous work and show that longest baseflow MTTs are related to rounded shapes of catchment (0.19–0.23), where moderate slope gradients (20–30°) predominate. In contrast, catchments with elongated forms—regardless of their internal slope assemblages—produced the shortest MTT estimates. Our interpretation is that in narrow forms, the hydrological connectivity between hillslopes and the stream is higher than in catchments with more rounded shapes. This in turn would increase the frequency of water table formation and response to precipitation leading to shorter water travel times. Related work on this was carried out by Hrachowitz et al. (2009) in the Scottish Highlands, who evaluated the influence of topography on stream MTT. In their study, form factor ratios and drainage densities
were computed for 20 different catchments (< 1 to 35 km$^2$). Their work showed that elongated
forms of catchments were roughly distinguished from rounded shapes. Drainage density,
however, characterized much better the catchments topography of that region showing a strong
and inverse relationship with stream MTTs. They found high drainage density values associated
to high percentages of responsive soil cover (peat soils) as rapid water routed via overland flow
enhances connectivity between hillslopes and stream channel network. In our study site,
drainage density was inversely related to slope length (data not shown) and showed no
correlation with soil type as Andisols dominate entirely the hillslopes of our catchments.

We also explored the influences of land cover on baseflow MTT. Our findings showed
that catchments covered predominantly by forests had longer MTT estimates compared to
catchments dominated by pasture. We attributed this to topographic differences among sites
more than land cover effects since most forested areas are themselves located on steep terrain.
This is supported by results obtained by Muñoz-Villers and McDonnell (2013), who investigated
the streamflow dynamics at the mature and secondary TMCF and pasture headwater catchments.
They found on average 50 % lower baseflow in the pasture at the end of the dry season compared
to forests, explained by lower recharge of subsurface water storages due to smaller catchment
gradients (cf. Sayama et al., 2011; Tetzlaff et al., 2009b) in the pasture, and lower surface soil
infiltration capacities caused by animal grazing compaction (30 ± 14 mm hr$^{-1}$ versus 696 ± 810
mm hr$^{-1}$). Thus, the fact that forested catchments have steeper slopes and higher topsoil
infiltration capacities might be a more likely explanation for their higher subsurface water
storage capacities.

In general, very few studies have investigated the effect of land cover on catchment
stream MTTs. Mueller et al. (2013) studied the influence of shrub cover area on MTTs in four
micro catchments in the Swiss Alps. They found that soil and bedrock hydraulic characteristics
had a stronger control on stream transit times rather than land cover. High subsurface flow
promoted by fast soil water percolation through fractured bedrock, which can contain karstic
rock in deeper layers, dominated the catchment water storage, mixing and release in this alpine
environment. More recently, Geris et al. (2015) investigated the relative influence of soil type
and vegetation cover on storage and transmission processes in a headwater catchment (3.2 km$^2$)
in northeast Scotland. Forested and non-forested sites were compared on poorly drained
Histosols in riparian zones and freely draining Podzols on steeper hillslopes. Their results
showed that soil permeability properties linked to soil type rather than vegetation influences were dominant features on water storage dynamics at the plot and catchment scales.

Our study determined the depth and permeability of the soil-bedrock interface through intensive and extensive measurements in the subsurface over numerous hillslope transects across the LG catchment. This is rather unlike most studies that have derived flow path depths and source contributing areas to stream discharge from surface topography based on digital terrain models (Hrachowitz et al., 2010; McGuire et al., 2005; Tetzlaff et al., 2009b) or from geochemical tracers such as SiO$_2$ (Asano and Uchida, 2012). Our approach showed that hillslopes with deeper soils along with high hydraulic conductivities at the soil-bedrock interface allowed more subsurface water transmission and storage, leading to longer catchment baseflow transit times. In this case, longest stream MTTs (ca. 3 yr) were obtained in the mature and secondary TMCF headwater catchments, associated to their highest percentage of area covered by deep soil-bedrock profiles related in turn to their moderate steep relief, and greatest subsurface permeabilities. Previous work at these sites showed that the very high permeability of the Andisols (1000 mm hr$^{-1}$ at 0.1 m to 4 mm hr$^{-1}$ at 1.5 m depth; Karlsen, 2010) and underlying volcanic substrate promote vertical and fast soil water percolation and recharge of deeper sources, as the preferred flow path mechanism controlling catchment water storage and storm runoff responses (Muñoz-Villers and McDonnell, 2013).

Across all catchments, the observed range of saturated hydraulic conductivities at the soil-bedrock interface was from 5 to 30 mm hr$^{-1}$, suggesting little impedance for water to continue percolating vertically below the soil profile and to recharge ground water reservoirs. This could explain the generally long MTTs found across sites (1.8 yr on average). Further, we observed greatest depths to bedrock at mid and ridge top hillslope positions (data not shown). Thus these topographic features seem to be the main contributing areas to subsurface water recharge. While soil water retention capacities were also greatest at mid and ridge top slope positions, they did not explain much of the variation in baseflow MTTs.

These findings are partly consistent with those obtained by Asano and Uchida (2012) in central Japan, who examined the baseflow MTT spatial variation for a 4.3 km$^2$ forested montane watershed underlain by granitic soils. They used the dampening of the isotopic signal as a proxy for the relative difference in MTTs among locations. They also used dissolved silica as a tracer to identify the contributing depth of the flow path to stream discharge. Their work showed that
the depth of hydrologically active soil-bedrock layer was the main factor determining catchment water storage. Longer baseflow MTT were associated to increased flow path contributions related in turn to hillslope length and topography. McGuire et al. (2005) also showed strong correlations between catchment terrain indices (flow path length) and mean stream residence times for seven catchments (0.085–62.4 km²) in the western Cascade Mountains of Oregon, USA, showing that landscape organization was the main factor controlling catchment-scale water transport.

While some investigations have reported that catchment area controls the variation in stream MTT (i.e. Hale and McDonnell, 2016; McGlynn et al., 2003), the majority of the work published to date has shown no relation between MTT and catchment size for catchments ranging between 0.1 and 200 km² (Crespo et al., 2012; McGuire et al., 2005; Mueller et al., 2013; Rodgers et al., 2005; Soulsby et al., 2006). Our findings support these latter studies and show that increasing catchment area does not lead to longer mean stream travel times.

We also found that baseflow MTTs were more variable in smaller catchments (0.1-1.5 km² sizes) where topography imposed its strongest effect (cf. Hrachowitz et al., 2010; Tetzlaff et al., 2009b). Further, longer MTT were found at the forest-dominated headwater catchments (≤ 0.25 km²; ~ 3 yr). This is similar to the findings obtained by Timbe et al. (2014) in a tropical montane cloud forest watershed underlain by Histosols in southern Ecuador, who reported longer and larger variation of MTTs in small streams (0.1 – 5 km²; ~ 3 ± 1.09 yr) in comparison to downstream tributaries and main river channels (10 – 77 km²; ~ 2 ± 0.08 yr). At the intermediate scale (4 – 9 km²), our differences in MTTs were small and associated probably to catchment topography. Unexpectedly, MTTs showed a slight convergent pattern at this scale (Figure 5b) (cf. Hrachowitz et al., 2010; Timbe et al., 2014). Beyond this scale (> 9 km²), catchment processes determining streamflow behavior seems to be different. For instance, the Huehueyapan watershed (20 km²) showed the shortest MTT (1.2 yr) across all catchments investigated. We attributed its low water storage capacity to its narrow form, combination of gentle and very steep slope areas (the latter limiting the development of soil on its hillslopes), and shallow depths to bedrock. Alternatively, the main outlet of the LG catchment (35 km²) has an MTT of 2.2 yr that nearly doubled the MTT value of its main tributary (Huehueyapan catchment). This might suggest that runoff processes of smaller catchments does not necessary combine to define MTT
at larger scales (> 14 km$^2$) (cf. Shaman et al., 2004), probably due to changes in geomorphology, related in turn to past landscape formation of this volcanic area.

5. Conclusions

This study provides an important first step towards a better understanding of the hydrology of tropical montane regions and the factors influencing stream water transit times in these environments. Our estimates of baseflow MTT ranged between 1.2 and 2.7 years across 12 catchments (0.1 to 34 km$^2$) in central Veracruz, Mexico, suggesting deep and presumably long subsurface flow paths contributing to sustain baseflows, particularly during dry periods. Our findings showed that catchment slope and the permeability observed at the soil-bedrock interface are the key factors controlling baseflow MTT in this tropical montane region. Longest stream MTTs were found in the cloud forest headwater catchments, related to their moderate steep slopes, and greater transmissivity at the soil-bedrock interface. Conversely, the MTT was shortest in one tributary of the main river outlet, which was mainly attributed to its high proportions of both gentle and very steep slopes. In association with topography, catchment form and the depth to the soil-bedrock interface were also identified as important features influencing baseflow MTT variability across scales. More specifically, longer baseflow MTTs appeared to be related to rounded shapes of catchments and deeper soil-bedrock interfaces. Greatest depths to bedrock were particularly observed in the mid and ridge top hillslope positions, thus these topographic locations seemed to be the main contributing areas for catchment subsurface water recharge. Major differences in MTTs were found both within groups of small (0.1–1.5 km$^2$) and large (14–34 km$^2$) catchments, related mostly to catchment slope and morphology, and to much lesser extent to land cover.

Author contribution


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hydrological flow paths, residence times and landscape influences in a nested mesoscale


Table 1. Topographic characteristics of the 12 catchments (0.1–34 km²) investigated

<table>
<thead>
<tr>
<th>#ID</th>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Stream order</th>
<th>Mean elevation (m a.s.l.)</th>
<th>Elevation range (m a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MAT</td>
<td>0.25</td>
<td>1</td>
<td>2160</td>
<td>2020-2300</td>
</tr>
<tr>
<td>2</td>
<td>SEC</td>
<td>0.12</td>
<td>2</td>
<td>2130</td>
<td>2040-2220</td>
</tr>
<tr>
<td>3</td>
<td>PAS</td>
<td>0.10</td>
<td>1</td>
<td>2400</td>
<td>2320-2480</td>
</tr>
<tr>
<td>4</td>
<td>CATM1</td>
<td>0.46</td>
<td>2</td>
<td>2230</td>
<td>1980-2480</td>
</tr>
<tr>
<td>5</td>
<td>CATM2</td>
<td>0.62</td>
<td>2</td>
<td>2230</td>
<td>1980-2480</td>
</tr>
<tr>
<td>6</td>
<td>CATM3</td>
<td>1.9</td>
<td>3</td>
<td>2380</td>
<td>2000-2760</td>
</tr>
<tr>
<td>7</td>
<td>CATM4</td>
<td>1.5</td>
<td>2</td>
<td>2240</td>
<td>1860-2620</td>
</tr>
<tr>
<td>8</td>
<td>CATM5</td>
<td>4.1</td>
<td>2</td>
<td>2050</td>
<td>1340-2760</td>
</tr>
<tr>
<td>9</td>
<td>CATM6</td>
<td>8.9</td>
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<tr>
<td>10</td>
<td>PUENTE ZARAGOZA</td>
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<td>1300-2760</td>
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<tr>
<td>11</td>
<td>HUEHUEYAPAN</td>
<td>19.7</td>
<td>4</td>
<td>2120</td>
<td>1300-2940</td>
</tr>
<tr>
<td>12</td>
<td>LOS GAVILANES</td>
<td>33.5</td>
<td>5</td>
<td>2120</td>
<td>1300-2940</td>
</tr>
</tbody>
</table>
Table 2. Annual, and wet and dry season means of the isotopic composition of rainfall (3 sites) and stream water (12 sampling locations) plus corresponding values of $d$-excess, as calculated from 2 years of data (April 2008 – May 2010)

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>VWM Annual</th>
<th>VWM Wet season</th>
<th>VWM Dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta^2$H</td>
<td>$\delta^{18}$O</td>
<td>$d$-excess</td>
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<tr>
<td>TG (2400 m)</td>
<td>-43.0</td>
<td>-7.5</td>
<td>17.0</td>
</tr>
<tr>
<td>SECP (2100 m)</td>
<td>-37.6</td>
<td>-6.7</td>
<td>16.0</td>
</tr>
<tr>
<td>RA (1560 m)</td>
<td>-33.4</td>
<td>-6.1</td>
<td>15.4</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Mean annual</th>
<th>Mean wet season</th>
<th>Mean dry season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta^2$H</td>
<td>$\delta^{18}$O</td>
<td>$d$-excess</td>
</tr>
<tr>
<td>MAT</td>
<td>-42.5</td>
<td>-7.3</td>
<td>15.9</td>
</tr>
<tr>
<td>SEC</td>
<td>-41.8</td>
<td>-7.2</td>
<td>15.8</td>
</tr>
<tr>
<td>PAS</td>
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<td>15.5</td>
</tr>
<tr>
<td>CATM1</td>
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<td>-8.1</td>
<td>15.4</td>
</tr>
<tr>
<td>CATM2</td>
<td>-47.2</td>
<td>-7.8</td>
<td>15.2</td>
</tr>
<tr>
<td>CATM3</td>
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<tr>
<td>CATM6</td>
<td>-41.8</td>
<td>-7.2</td>
<td>15.8</td>
</tr>
<tr>
<td>PUENTE ZARAGOZA</td>
<td>-42.1</td>
<td>-7.3</td>
<td>16.3</td>
</tr>
<tr>
<td>HUEHUEYAPAN</td>
<td>-46.1</td>
<td>-7.7</td>
<td>15.5</td>
</tr>
<tr>
<td>LOS GAVILANES</td>
<td>-43.3</td>
<td>-7.4</td>
<td>15.9</td>
</tr>
</tbody>
</table>
Table 3. Slope length and gradient, drainage density, form factor and land cover of the study catchments

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Mean slope length (m)</th>
<th>Drainage density (km km$^{-2}$)</th>
<th>Form factor (-)</th>
<th>% of cover per slope class</th>
<th>Land cover category and % of vegetation coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0-5°</td>
<td>5-10°</td>
</tr>
<tr>
<td>MAT</td>
<td>123</td>
<td>4.8</td>
<td>0.222</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>SEC</td>
<td>105</td>
<td>5.8</td>
<td>0.231</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>PAS</td>
<td>68</td>
<td>7.0</td>
<td>0.164</td>
<td>7</td>
<td>39</td>
</tr>
<tr>
<td>CATM1</td>
<td>80</td>
<td>7.9</td>
<td>0.071</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>CATM2</td>
<td>77</td>
<td>8.0</td>
<td>0.093</td>
<td>6</td>
<td>21</td>
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<tr>
<td>CATM3</td>
<td>190</td>
<td>2.6</td>
<td>0.122</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>CATM4</td>
<td>150</td>
<td>3.2</td>
<td>0.087</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>CATM5</td>
<td>208</td>
<td>6.8</td>
<td>0.071</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>CATM6</td>
<td>225</td>
<td>1.3</td>
<td>0.131</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>PUENTE ZARAGOZA</td>
<td>235</td>
<td>2.9</td>
<td>0.187</td>
<td>7</td>
<td>17</td>
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<tr>
<td>HUEHUEYAPAN</td>
<td>300</td>
<td>2.0</td>
<td>0.134</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>LOS GAVILANES</td>
<td>285</td>
<td>2.4</td>
<td>0.220</td>
<td>9</td>
<td>16</td>
</tr>
</tbody>
</table>
### Table 4. Stream baseflow MTTs, and corresponding model parameters and model efficiencies

<table>
<thead>
<tr>
<th>Catchments</th>
<th>MTT (days)</th>
<th>Model</th>
<th>Model parameters</th>
<th>Model efficiency</th>
</tr>
</thead>
</table>
| MAT        | 958        | Gamma ($\alpha$, $\beta$) | $\alpha$, $\beta$  
0.74 (0.70, 0.85),  
1299 (524, 1137) | $E$  
0.53 | RMSE ($\delta^2$H, %)  
1.5 |
| SEC        | 975        | Gamma ($\alpha$, $\beta$) | $\alpha$, $\beta$  
0.74 (0.59, 0.93),  
1326 (484, 2329) | 0.68 | 1.4 |
| PAS        | 548        | Exponential ($\tau_m$) | $\tau_m$  
548 (493, 609) | 0.57 | 1.0 |
| CATM1      | 531        | Exponential ($\tau_m$) | $\tau_m$  
531 (514, 550) | 0.58 | 1.0 |
| CATM2      | 636        | Dispersion ($\tau_m$, $D_p$) | $\tau_m$, $D_p$  
636 (463.824)  
0.66 (0.44, 0.89) | 0.66 | 1.1 |
| CATM3      | 624        | Dispersion ($\tau_m$, $D_p$) | $\tau_m$, $D_p$  
624 (536.734)  
0.85(0.68, 0.96) | 0.45 | 1.0 |
| CATM4      | 522        | Dispersion ($\tau_m$, $D_p$) | $\tau_m$, $D_p$  
522 (451.571)  
2.2 (1.4, 3.0) | 0.53 | 1.4 |
| CATM5      | 710        | Exponential ($\tau_m$) | $\tau_m$  
710 (555, 859) | 0.63 | 0.8 |
| CATM6      | 702        | Exponential ($\tau_m$) | $\tau_m$  
702 (550, 856) | 0.64 | 0.9 |
MTT is the mean transit time, $E$ is the Nash-Sutcliffe efficiency and RMSE is the root mean square error. Numbers in parenthesis are the 10th and 90th percentile values of the MTT estimates and the model parameters.

Refer to the supplementary information for the corresponding formulas of the TTD models.

<table>
<thead>
<tr>
<th>Location</th>
<th>MTT</th>
<th>Distribution (τ_m)</th>
<th>Example Values</th>
<th>E</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUENTE ZARAGOZA</td>
<td>633</td>
<td>Exponential (τ_m)</td>
<td>633 (520, 751)</td>
<td>0.64</td>
<td>0.9</td>
</tr>
<tr>
<td>HUEHUEYAPAN</td>
<td>424</td>
<td>Exponential (τ_m)</td>
<td>424 (371, 482)</td>
<td>0.63</td>
<td>1.2</td>
</tr>
<tr>
<td>LOS GAVILANES</td>
<td>788</td>
<td>Exponential (τ_m)</td>
<td>788 (646, 935)</td>
<td>0.42</td>
<td>1.0</td>
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</table>
Table 5. Spearman's rank correlation coefficients ($r_s$) between baseflow MTT and land cover, catchment area, topographic characteristics and subsurface hydrologic properties for the study catchments.

<table>
<thead>
<tr>
<th></th>
<th>$r_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land cover</td>
<td>-0.74</td>
</tr>
<tr>
<td>Area (km$^2$)</td>
<td>-0.09</td>
</tr>
<tr>
<td>Form factor (-)</td>
<td>0.56</td>
</tr>
<tr>
<td>Drainage density (km km$^{-2}$)</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean slope length (m)</td>
<td>-0.13</td>
</tr>
<tr>
<td>Slope 0-5°</td>
<td>-0.22</td>
</tr>
<tr>
<td>Slope 5-10°</td>
<td>-0.63</td>
</tr>
<tr>
<td>Slope 10-20°</td>
<td>-0.01</td>
</tr>
<tr>
<td>Slope 20-30°</td>
<td>0.57</td>
</tr>
<tr>
<td>Slope 30-45°</td>
<td>0.04</td>
</tr>
<tr>
<td>Slope &gt; 45°</td>
<td>0.06</td>
</tr>
<tr>
<td>DSBI &gt; 200 cm</td>
<td>0.48</td>
</tr>
<tr>
<td>100 &lt; DSBI ≤ 200 cm</td>
<td>-0.28</td>
</tr>
<tr>
<td>50 &lt; DSBI ≤ 100 cm</td>
<td>-0.15</td>
</tr>
<tr>
<td>DSBI ≤ 50 cm</td>
<td>-0.08</td>
</tr>
<tr>
<td>Soil WR per category</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-0.08</td>
</tr>
<tr>
<td>12</td>
<td>0.24</td>
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<tr>
<td>13</td>
<td>-0.18</td>
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<tr>
<td>14</td>
<td>0.30</td>
</tr>
<tr>
<td>15</td>
<td>-0.25</td>
</tr>
</tbody>
</table>
Figure 1. Location of the study site in central Veracruz, eastern Mexico, and maps of the Los Gavilanes catchment showing (A) the stream and rain water collection points; (B) slopes; and (C) land covers (see text for further explanation).
Figure 2. (A) Relationship between δ²H signatures of stream base flow and elevation of the catchment outlets (i.e. the sampling locations), and volume-weighted means (VWMs) of the deuterium composition of rainfall at the three elevations within the Los Gavilanes river catchment; (B) δ¹⁸O versus δ²H signatures of baseflow from the 12 catchments investigated; and (C) Isotope (δ¹⁸O versus δ²H) signatures of rainfall and stream baseflow. The local meteoric water line (LMWL; dashed line) is based on the 2008-2010 precipitation at TG, and reads: δ²H=8.36* δ¹⁸O + 20.37; the solid line represents the global meteoric water line (GMWL): δ²H=8* δ¹⁸O + 10.
Figure 3. Biweekly values of $\delta^2$H composition of stream baseflow for each of the 12 study catchments, and corresponding values of deuterium composition of rainfall at 2400 m (TG) for the period between May 2008 and April 2010. The shaded areas indicate the wet seasons.
Figure 4. Map of hydro-pedologic properties of the Los Gavilanes river catchment. (A) Soil water retention at field capacity in the solum. Category 11: < 180 mm; Category 12: ≥ 180 ≤ 310 mm; Category 13: ≥ 310 ≤ 580 mm; Category 14: ≥ 580 ≤ 850 mm; and Category 15: ≥ 850 mm. (B) Depth to soil-bedrock interface and corresponding saturated hydraulic conductivities (Ks). For depth < 100 cm, Ks categories A, B and C correspond to: $K_s > 36$; $14 < K_s \leq 36$ and $1 < K_s \leq 14$ mm hr$^{-1}$, respectively. For depth > 100 cm, A, B and C correspond to $K_s > 144$; $36 < K_s \leq 144$ and $4 < K_s \leq 36$ mm hr$^{-1}$, respectively.
Figure 5. Regressions between stream baseflow MTTs and topographic features, subsurface properties, land cover and catchment area for the study catchments.