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Interactive comment on "Insights on the water mean transit time in a high-elevation tropical ecosystem" *by* G. M. Mosquera et al.

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Referee 1:

Reply: We really appreciate the review provided by referee 1 (R1) and are glad that our work gives rise to quite interesting discussion of catchment heterogeneity and non-stationarity conditions in the context of robust MTT estimations. R1 comments focus on four main aspects: 1) site conditions, 2) aggregation bias, 3) model evaluation and performance, and 4) selected methodology. Hence, we provide responses to each of them separately below.

R1: The paper attempts to explore transit time distributions (TTD) in a high-elevation tropical ecosystem by using a detailed hydrologic and isotopic record from eight nested catchments located in southern Ecuador.

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Discussion paper

Reply: First, we want to emphasize that our system is characterized by unique hydrometeorological and landscape characteristics in comparison to other systems: i) mean annual precipitation, runoff, and evapotranspiration are similar across the entire catchment (1284±18 mm yr-1, 788±54 mm yr-1, 496±61 mm yr-1, respectively) (Mosquera et al., 2015), ii) precipitation is evenly distributed year-round with very low degree of seasonality (Padrón et al., 2015), iii) isotopic fractionation by evaporative effects is virtually negligible (Mosquera et al., 2016) as a result of the year-round high relative humidity (∼90%) (Córdova et al., 2015), iv) the soils are shallow and poorly developed across the entire catchment (∼1m deep), and v) the geology is relatively young and homogeneous (Coltorti and Ollier, 2000). We believe our system presents a high degree of homogeneity across the entire basin as a result of the mentioned landscape configuration and local hydrometeorological conditions. A description of these conditions will be included in the final version of the manuscript.

R1: Although the data are extremely interesting and unique in quality and location, the transit time analysis is performed through a method (the lumped convolution approach) which is likely to include an aggregation bias, especially for systems with a high degree of heterogeneity and non-stationarity (see the recent papers by Kirchner, [2016a,b]).

Reply: We appreciate the comment about how extremely interesting and unique our data are. Regarding our approach, we will first focus on the issue of heterogeneity. It is certainly true that heterogeneity is “a fundamental problem” in the investigation of catchment behavior, because the scale of investigation influences the type of hydrological processes that can be identified. This issue is very well captured in Figure 4 of Kirchner (2016a) which exemplifies how MTT estimations can be affected as a result of aggregation across scales in heterogeneous catchments. We recognized this issue since our study design by considering a nested monitoring configuration. This configuration allowed us to investigate the variability of hydrological processes across scales and to characterize the system’s degree of heterogeneity. As mentioned above, the characteristics of the Zhurucay basin, provide quasi-homogeneous conditions or

low degree of heterogeneity, which most likely significantly reduces the issue of aggregation bias in MTT estimations. The landscape homogeneity in our system is evident considering that the same TTD represent the subsurface hydrologic system's behavior at all catchments, with a relatively small range of variation of the estimated MTTs (0.51±0.17 yr). Thus, we consider that given the homogeneous catchment characteristics and small seasonality of local environmental conditions in our system, applying the LCA to our water stable isotopic dataset is a first step over which to build-up improved catchment functioning understanding. Regarding the nonstationarity issue (Kirchner, 2016b), we first want to clarify that using a certain methodology does not imply that other ones are ignored. The LCA is an approach that assumes steady-state conditions in the system, assumption acknowledged in our paper. However, as highlighted in manuscript title (i.e., "Insights"), our study aims to set a baseline for the application of modeling techniques using water stable isotopes in tropical ecosystems above the tree line, in which in general, there is very scarce hydrologic information. To our knowledge, this is the first contribution regarding the modeling of MTT in páramo ecosystems. Although recent advances in hydrologic research, such as the ones listed by R1, have provided theoretical evidence of the importance of recognizing the unsteady nature of hydrologic processes highlighting the possible shortcomings of the LCA, our paper is not a methodological contribution regarding MTT modeling theory but rather about understanding catchment functioning in a high-elevation tropical region. Indeed one of our future goals is to apply modeling techniques that explicitly recognize nonstationarity and storage dynamics in the hydrological behavior of this tropical ecosystem (e.g.,Birkel et al., 2015; Harman, 2015; Hrachowitz et al., 2013). These analyses, however, are beyond the scope of this paper. As mentioned above, our intention is to generate hydrologic knowledge in this understudied region. That said, we also believe our data set is valuable because it provides a concrete example to test the applicability, limitations, and constraints of different MTT modeling methodologies. In fact, based on the homogeneous and uniform hydrometeorological characteristics of our site, in contrast to many of the temperate regions in which time-variant MTT modeling has

been developed, we anticipate our dataset and the results from this study to allow for benchmark testing of MTT methodologies in regions with low climate seasonality. At the same time, we will acknowledge the growing recognition of the time-variant nature of transit times and make sure to reference and highlight the value of such modeling methodologies and recent findings related to them. It is relevant to note a recent application of conceptual modeling for the investigation of non-stationary conditions in a wet Scottish upland catchment where runoff generation processes mainly occur in the riparian Histosol soils with high storage capacity (Birkel et al., 2015), as in our study site. These authors detected non-stationary characteristics in water age distributions only during extreme weather conditions (extensive dry or wet periods) and attributed this behavior to the large mixing capacity of the Histosol soils, "which acts as an isostat moderating isotope variability and limiting the time variance of water age". The latter has been clearly observed in the Zhurucay basin, where the isotopic composition of the organic horizon of the Histosol soils remains virtually constant and matches the isotopic composition in the streams year-round (Mosquera et al., 2016). This, in combination with the nearly uniform climate characteristics in our site, supports the utility of steady-state approaches in our system.

R1: In simple terms, even if the transfer function approach allows a fair simulation of the measured isotopic signal, the system mean transit time is not necessarily realistic, due to the structural uncertainties in the quantification of the older water components. This emerges in Figures 4 and 6, where different TTD (with different MTT) result in similar model performances.

Reply: With regards to the uncertainties related to the quantification of old water components, we consider this is not a significant issue in our system. Evidence of very low (insignificant) "old" water contributions (i.e., deep groundwater contributions to discharge) in the Zhurucay basin has been found by Crespo et al. (2011) and Mosquera et al. (2016) and by Buytaert and Beven (2011) in a nearby páramo catchment in South Ecuador. It appears that this results from the combination of relatively young

and homogeneous geology with the high storage capacity of the porous organic horizon of the páramo soils in combination with their low level of development (soils are generally less than 1 m deep). Results from our study support this interpretation. This is evidenced by the fact that the two TTDs functions (Gamma and two parallel linear reservoir) that incorporate an "old" water component yield parameter values that are not well constrained. Instead the exponential model provided a robust representation with a clearly defined parameter. In this sense, it must be highlighted that our procedure to identify the TTD that best describes our system hydrologic behavior did not only take into account the goodness-of-fit of the objective function but also the level of identification of the function parameters and a process-based interpretation of the results (see below). Regarding the similar performance of the model using different TTDs, Timbe et al. (2014) conducted a detailed analysis of the uncertainties related to the use of different TTDs in MTT modeling using the LCA. They also found that several TTDs provide high goodness-of-fit between predictions and observations, but poor parameter identifiability for some TTDs calibrated parameters, as has also been observed by other researchers (e.g., Hrachowitz et al., 2009). As such they recommend that for achieving meaningful MTT estimates from the LCA, it is at least needed to: 1) used several TTDs, 2) evaluate predictions uncertainty, and 3) assess parameter identifiability for each TTD function. Following these recommendations, we conducted an assessment of the performance of different TTDs, considering not only the best fit but also the uncertainty of the predictions, the parameter identifiability, and a process-based interpretation in light of the detailed hydrometric, isotopic, and biophysical landscape information which has been collected at our study site over the last five years (Córdova et al., 2015; Mosquera et al., 2015, 2016; Padrón et al., 2015; Quichimbo et al., 2012) to select the model that best describes the hydrologic functioning of the system. In addition, we will also include an analysis using a metric for model selection (Akaike information criterion, AIC). This analysis has confirmed the EM as the one that best describes the hydrologic functioning in our system.

R1: Moreover, the paper ignores the recent advances in hydrologic transport and TTD

(see the list of suggested literature), which are now widespread within the hydrologic community and have clarified the concept of TTD in the light of non-stationarity. The manuscript is clear, well written and easy to follow, but the methods pose some serious concern on the paper's conclusions.

Reply: We appreciate this comment. We will include in the paper a clear discussion about the recent time variant advances in hydrologic modeling. However as mentioned above, given the high degree of homogeneity of our system we believe that assuming steady-state conditions is justified as a first step over which to build-up improved catchment functioning understanding using hydrometric-tracer based hydrologic modeling in this understudied region. In addition we believe that limiting transit time modeling efforts only to recent methodologies prevents us to gain knowledge from different information provided by different approaches that ultimately, altogether, can help improve catchment functioning understanding by fulfilling/complementing information yielded by each of them. This is particularly critical in the case of MTT modeling under non-stationary conditions, an approach that is currently under development, and as result, there is yet no unified methodology that can be globally applied. Indeed there are very few applications of such methodology, most of which have yield results with high degree of uncertainty (Harman, 2015; Klaus et al., 2015; McMillan et al., 2012) or it is not even estimated (Davies et al., 2013; Heidbüchel et al., 2012; van der Velde et al., 2015), mainly as a result of expensive computation costs or high uncertainties related to the spatial variability of the input hydrometric and tracer field measurements. It is clear however, that given the mathematical limitations (Duvert et al., 2016; Seeger and Weiler, 2014), high-temporal resolution of tracer data required (Harman, 2015; Heidbüchel et al., 2012), and general unavailability of long-term tracer records (Hrachowitz et al., 2010; Klaus et al., 2015) also required for hydrological modeling under non-stationary conditions, the LCA is still a useful metric of storage and catchment functioning not only in understudied regions such as the tropics (e.g., Farrick and Branfireun, 2015; Muñoz-Villers et al., 2015; Timbe et al., 2014) but also elsewhere (e.g., Duvert et al., 2016; Hale and McDonnell, 2016; Hale et al., 2016; Hu

et al., 2015; Seeger and Weiler, 2014). In this sense, we agree with Christian Birkel (referee 2, R2) comment: “there are merits in using the MTT to characterize catchment systems particularly considering the constraints and limitations working in tropical environments” and are convinced that this “experimentally derived dataset for this tropical ecosystem is unique and interesting to the HESS readership and beyond”, particularly taking into account the system′s particular characteristics. We believe this contribution will become a benchmark study over which to build-up further hydrological processes understanding not only in this remote understudied region, but also more generally, in regions with low climate seasonality and catchments with low degree of heterogeneity. Future efforts will built upon the monitoring infrastructure and datasets that continue to be collected in the Zhurucay River Ecohydrological Observatory, which will allow for continual improvement in hydrologic interpretation by eventually incorporating some alternative modeling techniques (e.g., Birkel et al., 2015; Harman, 2015; Hrachowitz et al., 2013).

DETAILED COMMENTS

Page 7, line 18: the authors say that kinetic fractionation by evaporation can be neglected, however looking at Figure 3 it seems that the majority of stream water samples plot below the LMWL. How can this behavior be explained?

Reply: The isotopic composition in stream waters corresponds to a mixture of rainfall waters which have resided different periods within the system. Therefore, for streams and soil waters it is not feasible to directly evaluate the existence of evaporation effect on fractionation using a relationship like the LMWL, useful for precipitation, which purely depends on the atmospheric conditions at the source of water vapor and further at the study site. Fractionation effects in stream waters due to evaporation can be assessed through the d-excess of individual water samples, with samples with d-excess values falling 5‰ or more below that of the LMWL indicating evaporation (Brooks et al., 2012). At the study site, Mosquera et al. (2016) found that the d-excess of stream waters for all individual samples were above 5‰ (average 11.56±0.96‰. These authors

attributed this to the high year-round relative humidity (∼90%) in the Zhurucay basin (Córdova et al., 2015). This explains why kinetic fractionation in streamflow water samples can be neglected. We will include a discussion about kinetic fractionation and will reference the work of Mosquera et al. (2016) in the final version of the manuscript

P. 9, l. 3: the variable tau in Eq. (1) and (2) is not the mean transit time. It is just the dummy variable in the integral, which spans the transit time domain [0, +inf].

Reply: Thank you catching this typo. We will correct this in the final version of the manuscript.

P. 10, l. 22-26: I did not get why the model is run twice to get the behavioral set of parameters.

Reply: We first run the model 10,000 times considering a wide range of parameter values. This provided and idea about the range of acceptable values. Based on the latter, we narrowed the parameter space and run the model again until 1,000 solutions or more, corresponding to at least 95% of the KGE objective function (i.e., at least 1,000 behavioral solutions), were obtained. These 1000 solutions allowed strong identification of the 90% confidence interval using the GLUE methodology. This procedure will be clarified in the final version of the manuscript.

P. 10, l. 28: the MI index seems to be very arbitrary depending on the choice of the prior parameter distribution. Segura et al., [2012] provide a partial explanation for their choice of the prior, which is here missing.

Reply: We appreciate this observation. Our initial choice of parameters ranges was selected based on the work of Timbe et al. (2014) in their analysis of uncertainties related to the use of the LCA for MTT estimations. We will clarify this in the manuscript.

P. 13, l. 27: the terminology “MTT probability density function” seems to refer to the pdf of MTT obtained from the posterior parameter distribution.

Reply: You are correct. The pdf and cdf we referred to in the text correspond to the

distributions described based on the fitted parameter distributions. We will clarify this in the text.

P. 14, l. 1-13: this is to me a clear example of the indetermination of the MTT. Different parameterizations of the TTD are able to provide good, similar simulations of the isotopic signal, but result in rather different MTT. While it is reasonable to choose a model because its parameters are more constrained in the simulation of a specific target, this does not allow to extrapolate that its MTT is the "right" one.

Reply: This issue is been already discussed above in the general comment and we just want to emphasize that we carefully considered the uncertainty of the predictions and the parameter identifiability, in addition to the results of the simulation of the isotopic signal against the objective function and will further include the results from the AIC model selection metric that support that the EM is the one that best describes our system, as suggested by R2. Additionally, we conducted a process-based interpretation of these results in light of the detailed hydrometric, isotopic, and biophysical landscape information which has been collected at the Zhurucay basin over the last five years (Córdova et al., 2015; Mosquera et al., 2015, 2016; Padrón et al., 2015; Quichimbo et al., 2012) for selecting the TTD that best suites the hydrologic conditions of the system.

P. 15, l. 21: what is meant by "completely" recovered? Is there a threshold (e.g. 99%) on the recovered mass?

Reply: This means that if the tracer would have been injected as a single pulse, how much it would take to completely leave the system. In effect, certain proportion of the total injection will be recovered at a certain time after the injection, For example, Figure 6 depicts that for the EM 80% of the tracer is recovered at around 20 biweeks. Analogous analysis have been reported by Hrachowitz et al. (2009) and McGuire et al. (2005).

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