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Discussions

Interactive comment on "Multi-scale temporal variability in meltwater contributions in a tropical glacierized watershed" *by* Leila Saberi et al.

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1 Response to Reviewer 2

We would like to thank the reviewer for their time to review our paper. In this response, we have addressed all the reviewer's comments by providing clarifications and indicating how we will edit the manuscript. The reviewer's comments are copied here with italic font style.

This paper is an excellent, in-depth exploration of multiple methods to constrain the role of meltwater in downstream hydrology, granted at a very small scale. The innovative contribution is the use of different time scales to demonstrate the interplay between melt regimes, precipitation patterns, and groundwater dynamics. There is tremendous opportunity to expand the relevance of this work in the future by applying a similar suite of methods to data from further downstream, or nested catchments.

We are encouraged by the reviewer's positive comments and will carefully address all the issues raised.

A few overarching issues that should be more clearly addressed in the discussion/conclusions:

1. The 7.5 km^2 basin study area has offered valuable insights because of the data collection and monitoring that can be done at this scale, but it is important to acknowledge how your insights and results may translate downstream, given that your interpretations of the hydrology and implications of glacier recessions on discharge are being presented for an area in immediate proximity to the glacier terminus.

We will discuss potential downstream implications of our work through two edits to the manuscript.

First, we will explain that we did extend our mixing model analysis downstream of Gavilan Machay to the Boca Toma diversion point for an irrigation system. We found that the surficial glacial meltwater contribution dropped to about 4-15% of the discharge at

Boca Toma. Although this amount of meltwater appears to comprise a minor proportion of discharge, an earlier investigation by La Frenierre (2014) on downstream water usage showed that farming communities cannot afford to lose any of the water. Already, the irrigation system consistently fails to deliver its current full allocations. Furthermore, if groundwater at Gavilan Machay contains glacial meltwater, as our simulations suggest, the actual total amount of meltwater contribution could be even higher than the 4-15% estimated for surficial meltwater. A lack of model input data outside of the Gavilan Machay sub-catchment prevented further extension of the model to Boca Toma.

Second, we will discuss the potential outcome of extending measurements and the model implementation over nested watersheds covering successively larger downstream areas. We expect that a characteristic relationship may emerge between watershed size and meltwater discharge, similar to the exponential relationship found between relative groundwater (versus meltwater) contribution and glacierized area in the multi-watershed study in the Cordillera Blanca of Peru by Baraer et al. (2015). Our results on Volcán Chimborazo did not match their exponential prediction, indicating that the characteristic curves depend on climate and geologic setting. In fact, looking within our small study watershed, estimates of groundwater contribution over the stream network reveal a nonlinear relationship with subcatchment area that contains sharp increases where geologic features likely create localized discharge points (we will add the figure to the Supplementary Information). This indicates that extrapolations downstream depends on geological conditions that control groundwater.

Reference:

La Frenierre, J., 2014, “Assessing the Hydrologic Implications of Glacier Recession and the Potential for Water Resources Vulnerabilities in Volcán Chimborazo, Ecuador”, PhD Dissertation, Ohio State University, 2014.

2. The differentiation, or lack thereof, between snow and glacier melt should be more explicitly discussed. How big a role does snow (melt) play in the catchment, and what *data to you have that informs this? To explore this, and relevant to many of your interpretations, a cursory estimate of the precipitation partition in the catchment could be interesting - what percent of precip falls as snow vs. rain based on your temperature and precip data? Given that information and your discharge measurements, do you have a sense of relative contribution of snowmelt vs. glacier ice melt, or even how much of the discharge from the glacier terminus could also be liquid precip routed through that pour point?*

We will edit the manuscript to clarify the distinction between snow and glacier melt in both the mixing model analysis and watershed model simulations.

For the mixing model, the meltwater end-member was represented using the hydrochemistry of a water sample collected just below the glacier tongue. Even during our dry season sampling, some of the meltwater could include melting of snow from the previous seasons, and so our estimates of meltwater contribution using the mixing model approach would include both glacier and snowmelt.

In our watershed model simulations, we aimed to distinguish glacier from snowmelt, but we realized from the reviewer's comment that we did not explain this clearly in the text. When we referred to the "With melt" and "No melt" model scenarios, we meant "With glacier melt" and "No glacier melt", respectively, because the two scenarios actually have the same amount of snowmelt; the only difference is that the former has an added glacier melt amount of water - determined with the temperature index model calibrated to discharge measurements. Apart from this glacier melt amount, both scenarios include the same meteorological inputs and thus same snowmelt amount. Through this approach, the melt contribution that we determined by differencing the two scenarios should only represent glacier melt. We will clarify this.

The reviewer does make the good suggestion that we should discuss the relative snowmelt and glacier melt amounts in the model. The model Flux-PIHM simulates the partitioning of precipitation inputs between rain and snow based on air temperature. Over the 2016 period, the model predicted that about 12% of precipitation falls as snow in the watershed. The simulated snowmelt amount is 15% of the total meltwater. On average, snow melt contributes 8% of stream discharge, while glacial melt contributes 52%.

We acknowledge that although we aim to distinguish between glacier melt and snowmelt in the model, there is uncertainty in the partitioning due to a lack of separate data constraints. Our snowmelt simulation is highly sensitive to any errors in the lapse-rate based spatial extrapolation of precipitation and temperature in the watershed, and so it is possible that our calibrated glacier melt includes some amount of snowmelt that is not captured in the Flux-PIHM simulation. We will edit the text to acknowledge this.

Specific comments:

P3 L23-24: which 4 major river systems?

The four major river systems are: the Río Mocha (NE flank), Río Colorado (NW flank), Río Guano (SE flank), and Río Chimborazo (SW flank). The names of the watersheds will be added to the manuscript.

P5 L5: Do you know if historically any other glaciers generated perennial surface discharge?

There are no historical streamflow data for any of Chimborazo's glacierized watersheds that are close enough to the mountain to be able to discern a glacier melt signature. Discussions with local water users by La Frenierre (2014) did not yield clear information about historic glacier meltwater flows. Aside from the general observation, stream and spring discharges are lower now than they have been in the past.

Reference:

La Frenierre, J., 2014, "Asessing the Hydrologic Implications of Glacier Recession and the Potential for Water Resources Vulnerabilities in Volcán Chimborazo, Ecuador", PhD Dissertation, Ohio State University, 2014.

P6 L10-12: Lack of any rainy/wet season samples is a limitation.

We agree. We will acknowledge this shortcoming of the hydrochemical mixing model results more explicitly, as well as explain that the model simulations fill this gap to examine wet season in addition to dry season conditions. As we mention (p. 3, lines 6-7), mixing model analyses of melt contributions typically have been applied in the dry season in the better-studied outer tropics. We followed suit for a couple of reasons. First, melt contribution is often of greatest interest for water resource management during times of low precipitation. Second, dry season samples are easier to interpret in mixing models, because there is no need to consider precipitation as an additional end-member, which can consist of different hydrochemical signatures depending on the accumulation of solutes during runoff generation.

Section 3.2.2: Having run same analytes in different labs in different years potentially introduces error or uncertainty. How confident are you in comparing different lab results? E.g. were detection limits the same, were any lab comparisons done?

We had this same concern and had thus checked for consistency by comparing the concentrations of the different cations and anions across the different sampling periods. We found that the bulk concentrations (e.g., sum of cations in Figure 2(a) and (c)) at a certain location were similar, and that the spatial trends for each analyte were consistent across sampling periods - e.g., the concentrations generally increased moving downgradient in each sampling period. There were some systematic biases for certain analytes - e.g., February 2017 had Cl^- concentrations at all locations that were higher by a relatively consistent difference compared to other sampling periods. However, this type of systematic bias between sampling periods is unimportant, because each implementation of the mixing model is carried out only with data within a certain sampling period, ensuring that we are not combining potentially incompatible data. We will explain this in the revised manuscript and include individual analyte plots over location for each sampling period in the Supplementary Information.

Figure 2: 2(a) and 2(c) read like results.

We agree, and in fact, Fig. 2(a) and (c) with concentration results are not discussed until the beginning of Section 3 Results and Discussion (Page 10, Line 31). We originally thought to combine these concentration results with mixing model configuration in Fig. 2(b) in Methods so that the reader can easily align the two. However, the reviewer's comment makes us realize that readers might prefer to see the concentration results in a separate figure in the Results section. We will accordingly move 2(a) and (c) to a separate figure than 2(b).

P8 L20: grammar – 'is be unique'

Thank you for catching this. It will be corrected in the manuscript.

P10 L10: how were T, P, and RH interpolated?

We used temperature and precipitation lapse rates, as described earlier in Section 3.1. Relative humidity measured at the Boca Toma station was applied over the entire watershed, because we did not have measurements elsewhere. We had inadvertently omitted the explanation about relative humidity and will add it to the Methods section. Although relative humidity does vary in reality, model sensitivity tests showed discharge simulations to be far less sensitive to relative humidity inputs than precipitation and temperature. We will revise the line mentioned in this comment to remind the reader that the interpolation approach was provided in the Methods section.

P11 L4-7: unclear here how you ultimately selected tracers for the mixing model. E.g. were thresholds applied to bivariate plots?

We will clarify that we chose as tracers those analytes that visually showed the mixed sample falling on a line between its two source samples based on the bivariate plots in Figures S3-S6. For example, for a tributary, the outflow sample should fall on a line between its two inflow sources. This comparison is done for all reaches and tributaries within a sampling period.

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P11 L13-17: Any hypothesis on why groundwater discharge was so low in Feb 2017? Are there temps or precip events that inform this anomaly?

We intended to explain this in the text, but we now realize there was a typo. We meant to write: "However, the absolute contribution, determined by applying estimates of melt fractions to average observed weekly discharge measurements around the sampling time, was lowest in February 2017, because of significantly less total [NOT groundwater] discharge compared to the other sampling periods (Figure 3(b))." The lower total discharge was likely due to lower precipitation and temperature during the weeks around the sampling period compared to during the other sampling periods (Figure S1). We will edit the manuscript to correct the typo and to point the reader to Figure S1.

Figure 4 caption, line 4: "corresponding to the"

We will make this correction to the caption of Figure 4.

P14 L13-15: how do these melt factors compare to the literature?

They fall within the range of melt factors calculated for other glaciers in the tropics (3.5-9.9 mm we $^{\circ}C^{-1}d^{-1}$) reported in Fernandez and Mark (2016). We will add this.

Reference:

Fernandez and Mark, 2016, "Modeling modern glacier response to climate changes along the Andes Cordillera: A multiscale review". Journal of Advances in Modeling Earth Systems, DOI:10.1002/2015MS000482.

P14 L24: reference for historic geodetic mass balance estimates?

We will add the explanation that glacier volume change of debris-covered ice was estimated by differencing a GPS-validated photogrammetric digital elevation model in 1997 (Jordan et al., 2008) and terrestrial laser scanner (Riegl LMS-Z620) surveys in 2012 and 2013 (La Frenierre, 2016). We note that this estimate was not directly used in our model simulations but instead only served as a comparison point for our calibrated melt estimate.

References:

Jordan, E., J. Gonzales, K. Castillo, J. Torres, L. Ungerechts, F. Velez, D. Blanco, and M. Cruz. 2008. "Ortofotomapa Del Chimborazo Y Su Valor Como Diagnóstico Para Cambios Climáticos En Relación Con Otros Glaciares Tropicales." In Glaciares, nieves y hielos de América Latina. Cambio climático y amenazas, edited by Arenas, C. D. L., and Cadena, J.R., 239–60. Bogota, Columbia: Instituto Colombiano de Geología y Minería.

La Frenierre, J (2016), "Rapid downward deflation of a tropical-debris covered glacier: an analysis from Volcán Chimborazo, Ecuador". American Geophysical Union (AGU) Fall Meeting, San Francisco, December 2016.

P14 L30: missing close parentheses - "full details)."

We will correct this in the manuscript.

Figure 5 caption: clarification on "(a) average air temp below ELA (5050 m.a.s.l.) and over glaciers and simulated melt inputs" – does this mean T is averaged over ablation zone plus snow covered area?

Yes. We will edit the caption so that this is clearer.

Figure 5 caption, L4: 'distribution' should be 'contribution'

The change will be applied to the caption. Thanks.

P20 L10-11: what you suggest here is a buffer against lower extreme low flows during drought times, which somewhat contradicts your repeated assertion (e.g. P20 L14) that melt does not necessarily provide the buffer often credited to it. Reconciling these, perhaps with a clear acknowledgement in the conclusions that the buffer does exist for extreme low flow scenarios, but the modulating effect in other flow scenarios may not *be as strong of a control on streamflow as other studies suggest.*

Thank you, this is a very good point. You captured exactly what we meant. We will revise the manuscript to clarify our conclusion that the classic paradigm that melt buffers does not always apply, though it still can buffer against extreme low discharge periods.

P20 L26-27: these longer periods controlled by melt inputs are via infiltration and groundwater recharge, right?

Yes, that is right. We will revise the sentence to make this clearer.

Figure 8 caption, lines 1-2: reference here to glacial meltwater is misleading, since what you've characterized is glacier outflow that is a combo of ice and snow melt, right?

No, what we represented here is only the result of glacier meltwater, since the same snowmelt amount was present in both the "With melt" and "No melt" simulation scenarios. As stated in an above response, we realized that we should have called the "No melt" scenario "No glacier melt", because it only removed glacier melt. We will revise the text to specify "With glacier melt" and "No glacier melt", and clarify that both scenarios include the same amount of snowmelt.

P22 L9: "Recharge by meltwater"

Thanks. We will modify this in the manuscript.

P22 L22-23: Unclear what justifies the assertion that discharge could be reduced by half. Equilibrium discharge with glacier melt contributions and equilibrium discharge post-glaciers should be the same if precip is the same, barring other changes (e.g. increased ET). The peak water period in the middle is a different story, but this claim seems unsupported.

As mentioned in Section 2 Study Area, the glaciers on Chimborazo are already retreating fast and thus are not in equilibrium. This leads us to consider the glacial meltwater as originating largely from stored ice from earlier time periods. However, the reviewer makes a good point that even during peak water period (when ablation > accumulation), some of the meltwater could still originate from newly accumulated ice, such that post-glaciers, this amount of water would still fall as precipitation and contribute to discharge. We will edit our manuscript to clarify that without glaciers, but assuming the same precipitation, the potential future reduction of discharge by half is an upper limit, and that the reduction could be less if some of current-day precipitation goes to glacier accumulation. Similarly, we will acknowledge that the reduction could be less if the estimated current meltwater contribution includes snowmelt. Although our simulated scenarios aim to isolate the contributions of glacier melt and snowmelt (see our response to the preceding comment), the exact partitioning is not well-constrained by observations; further, the mixing model estimate of meltwater contribution may include snowmelt and/or melt of freshly accumulated ice (see our response to overarching issue #2).

P22 L24-25 Related to the previous comment and as mentioned at the beginning, the other huge caveat is that you are looking at a point 2km from a glacier terminus, so results absolutely cannot be implied to inform understanding of vulnerability of water resources. Extrapolating further downstream is a logical next step and I think expanding your methods downstream would be an incredibly valuable contribution to this understanding!!!

We agree that it would be extremely valuable to extend our work downstream, now that we have established this multi-method approach. As described in our response to the reviewer's overarching issue #1, we did apply the mixing model to the irrigation diversion point Boca Toma downstream from the Gavilan Machay discharge point. The findings and implications are provided in that first response. We were not able to extend the model over the entire Boca Toma watershed (26 km^2) due to the unavailability of weather input data for that other portion of the watershed outside of the Gavilan Machay watershed. Also, the other part does not have glacier melt, and so working on Gavilan Machay allows us to focus on the glacier contribution to the irrigation system.