

## ***Interactive comment on “Long-term effects of climate and land cover change on freshwater provision in the tropical Andes” by A. Molina et al.***

**A. Molina et al.**

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Summary of the modifications to the text, tables and figures: Below, we have copied the relevant sections of the review (copied sections are given in italics). We addressed each comment separately, and our reply is given below each copied ‘reviewer’ section.

Interactive comments on “Long-term effects of climate and land cover change on freshwater provision in the tropical Andes” by A. Molina et al.

Reviewer #1 M. Levy (Referee) [mcleavy@berkeley.edu](mailto:mcleavy@berkeley.edu)

Thank you for taking the time to read carefully through the manuscript. Your comments really helped us to improve the quality of the analysis and discussion !

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### **### Specific Comments ###**

Page 5221, Line 3-5: This paragraph could be supplemented with additional literature.

Reply : We added reference to the work by Grau and Aide (2007) on land use change in mountain regions in Latin America, and to recent work by Curatola Fernández et al. (2015) on forest cover change in southern Ecuador.

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Page 5221, Line 15 and 26: The citations following these statements could be supplemented with additional and/or more recent literature.

Reply : We added reference to a recent paper by Poveda et al (2011) on the hydro-climatic variability over the Andes, and to a paper by Vuille (2013) on climate change and water resources in the Andes. Reply : With regard to the anthropogenic impact on water resources in the Andes, we added a reference to work by Harden et al. (2013).

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Page 5225, Line 10-11: Can you state why it is necessary to gap-fill the data? Reply : We added a short sentence to indicate that gaps were filled in order to obtain continuous time series data for EEMD analysis.

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Page 5225, Line 19-21: By the “observed relationship” do you mean a linear relationship, or something else? Reply : We now refer to previous work by Mora and Willems (2012) on the spatial variability of precipitation in the Ecuadorian Andes, and have rephrased the sentence to indicate that a positive linear relationship between elevation and precipitation is assumed based on previous work by Mora and Willems (2012) and Buytaert et al. (2006).

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Page 5225, Line 26: Can you state how you did this (like in the caption for Table 3)?  
Reply: We have added two sentences to clarify the conversion from daily discharge ( $\text{m}^3 \text{ s}^{-1}$ ) into equivalent water depth (mm).

"The daily discharge was then converted to daily water production of the catchment by multiplying the daily discharge ( $\text{m}^3 \text{ s}^{-1}$ ) by 86400 to convert the values to  $\text{m}^3$ . The equivalent water depth, WDd (mm), was then calculated by dividing the daily water production by the total catchment area ( $\text{km}^2$ ) and multiplying by one thousand to convert the values to mm to allow direct comparison with precipitation records."

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Page 5226, Line 11: Can you state here briefly that you can neglect change in storage at annual time scales in this region (you provide a discussion of this on Page 5228, but would be nice to mention it here.) Reply : Correct. We have clarified in the text that we assume long-term changes in soil water storage to be negligible in these soil systems. "First, the mean annual evapotranspiration, , was estimated as the difference between the mean areal average annual precipitation, and mean annual equivalent water depth, for the time period 1974-2008, thereby assuming that long-term changes in soil water storage,  $\Delta S$ , can be neglected."

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Page 5226, Line 20: Consider adding "at annual time scales." to the end of this sentence, and then describe how the annual time scale quality check relates to the usability of the data at monthly time scales (the time scale at which you decompose the data). Reply : We have clarified that our quality check suggests that we can use the hydrometeorological data for time series analyses at annual time scales; and also inserted one sentence at the beginning and end of the paragraph where we indicate : "Although it may be preferred to perform data quality assessment at the monthly time scale, the hydrometeorological datasets that were available for this study do not facilitate such task given the response time of the hydrological system." "These two assessments

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show that the quality of the hydrometeorological data is acceptable, so that they can reliably be used for analyses of inter-annual variability and long-term change. In this study, we refrain from discussing the seasonal or intra-annual variability in streamflow and precipitation."

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Page 5227, Line 14-23: This paragraph could be written more clearly, and the first sentence could be rewritten to summarize it's purpose. Is this paragraph intended to summarize the EEMD procedure, or to describe processes additional to the EEMD that are specific to this analysis? I remain confused about what the "non-significant trends" (Line 15) actually are (assuming simulated P and WD), or if you are saying the process described is the means by which the significance of P and WD trends is evaluated. It remains unclear in what capacity the actual P and WD data are used, and in what capacity simulations/samples of those data are used.

Reply: We agree with the reviewer that this paragraph was not very clear. We now explain the methods more clearly, by introducing first the principles of EMD and EEMD. Then, we explain how we derived the significant trends, by contrasting the observed time series by a synthetically generated random signal.

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Page 5227, Line 17: With respect to "were randomly distributed" - does this mean the monthly values "are" randomly distributed according to some test, or does this mean that a random sample was generated using statistics of the monthly data (I'm assuming the latter)? If so, using samples from what distribution, or simply by randomly sampling the empirical distribution (the data)?

Reply : We have clarified this in the text. To extract the significant trend, the final IMFs and residual trend are extracted from the observed time series as the average of their corresponding ensemble members, IMF<sub>i</sub>. Only significant IMF<sub>i</sub> are averaged,

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here defined as those IMFi having a variability or energy that is higher than the 99th percentile of the variability of the trends derived from the random signal. To obtain random time series, we synthetically generated random signal using a random sample of the monthly data.

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Page 5227, Line 20: what type of "perturbation" - Gaussian white noise? Reply: Thanks for this comment. We have clarified this in the text: we used Gaussian white noise with an amplitude of 0.2 standard deviation of the original time series.

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Page 5228, Line 13-23: The purpose of the explained procedure is not entirely clear and could be improved. Why was a chi-squared test used, and why is it necessary for establishing the partial water balance, or is this related to another component of the analysis?

Reply: This was indeed confusing. We used chi-square analyses only to get the significance of the change in precipitation and streamflow between the period 1974-1991 and 1992-2008 (see section 4.3). We now make reference to the chi-square analyses in section 4.3, as this is a standard statistical technique that was routinely used here.

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Page 5228, Line 19-20: "reconstructed based on linear interpolation of existing land cover distributions" - is there precedent for this method, any references where this method was also used?

Reply: We used Markov chain analysis to simulate the land cover distributions for 1974 and 2008, based on the land cover transition probabilities that we extracted from the time series of 1963-1977 and 2001-2009. We have provided more details on the techniques in the text, and also provide a reference to earlier work by Petit et al. (2001). We slightly reordered the method section, to improve the logical flow of the text

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Page 5231, Line 4-10: The reporting of these very interesting findings and their significance could be improved. Perhaps it would be appropriate to change "climate change" (Line 5, and also the Abstract at Page 5234 Line 8, and title) to "precipitation change" because climate is not fully accounted for in this analysis; solar radiation and/or temperature data are not used. ET change (and therefore flow change) result from a combination of energy/temperature variability and vegetation cover - only vegetation cover is discussed.

Reply: We agree with this observation, and acknowledge that we do not have the full set of observational data to analyse all aspects of climate change (including changes in solar radiation, temperature and precipitation). Because of data scarcity, we made a pragmatic choice by concentrating on the changes in precipitation values only. We have changed "climate change" to "change in precipitation" throughout the text (abstract, introduction and conclusion).

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Additionally, from Figure 6, it is clear that the decomposed rainfall trend moves gradually upwards while the flow trend moves gradually downwards over the same time period - and that these changes correspond to a snapshot record of land cover over a long period of time. Stronger statements might not be warranted unless further discussion is provided. The use of the words "remarkable decrease", "increased sharply", and "decreased notably" either do not represent the findings according to Fig. 6, or obscure reporting of the nature and significance of the findings. Is there a quantitative measure of the significance in the trend change for both? Do you have any information on the degree to which measurement error does or does not affect interpretation of the trend or its significance?

Reply: Thanks for this suggestion. We have carefully checked the text, and have softened our statements on the significance of our findings. Besides, we have further

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elaborated section 4.2 where we present the long-term trends in streamflow and precipitation. From our analysis (and Fig. 6), it is clear that two periods of change can be identified: (1) before the 1990s, and (2) after the mid-1990s. Reply: All residual trends plotted on Fig. 6 are significant, following the adapted EEMD procedure by Brisson et al. (2015). We now provide more details on the significance of the residual and trend in the description of the EEMD techniques (section 3.3).

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Page 5232, Line 4-5: re-state some numbers from Table 3 instead of saying "major". Reply: We have rephrased the first sentences of this paragraph, and make explicit reference to the amount of land cover change observed in the catchment.

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Line 9-12: this statement seems strong ("as a result of [land change]") given that no energy or temperature data was used in the analysis - same comment as above. Correct. We have adjusted this statement, given the uncertainty on the ET estimates using empirical equations.

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Page 5233, Line 16-18: citation for this, or is this a finding from this study? We now provide reference to the work of Henry et al. (2012) on soil erosion measurements in a nearby catchment.

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Page 5233, Line 25-27: Is this referring to Figure 8 instead of Figure 7 (where peak mean monthly flows are the same between periods, but peak baseflow is different)? Are you attributing the increased flashiness to reduced soil water infiltration, or just proposing that reduced infiltration as a possible cause? It doesn't seem like enough evidence is provided to say that the flashiness is from reduced infiltration - increased rainfall could induce surface runoff in the period during which you also saw land use

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change, even if soil infiltration remained the same.

Reply: We agree with this comment, and have revised this section of the text. We do not make any further statement on changes in the flashiness of the river, but based our discussion on the results of the flow duration analyses: "Based on the results from flow duration analysis, we can infer that the effect of reduced soil water infiltration and retention after land cover change is noticeable on the overall water balance (Fig. 7). The overall decrease of baseflows accounts for about 60% of the reduction in total streamflow, and points to the decreased storage capacity of the Pangor basin (Fig. 8)."

### Technical Corrections ###

# Abstract

Page 5220, Line 1: "role to supply" is awkward. Suggestion: "Andean headwater catchments are an important source of fresh water for downstream water users."

"play a pivotal role to supply" was replaced by "are an important source of "

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Page 5220, Line 3: Suggestion for clarity: add "in these catchments." on the end of the sentence ending in "flow regimes."

The phrase "in these catchments." Has been added in the text

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Page 5220, Line 5: "freshwater provision" is vague. Does this term refer to provision of water to downstream users, or does it refer to in-stream flow?

"freshwater provision" was replaced by "streamflow"

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Page 5220, Line 6: Is time period listed for the hydrometeorological data (1974-2008) also the same as the "multi-decadal" period of the study? This might be assumed, but

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it's not stated.

Reply: We have rephrased this sentence to clarify the temporal scale of the analysis.

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Page 5220, Line 6-7: include the name of the basin in the abstract.

Reply: The name of the catchment is added in the text

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Page 5220, Lines 7-11: With respect to the list of land cover change trajectories: do these changes refer to net change over the study period, or end-year change relative to a baseline year, or some other specification? It would help to include this information in or directly after the previous sentence.

Reply: It is now specified in the text that the changes refer to the period 1963-2009.

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Page 5220, Line 8-9: the use of "áLij" is potentially confusing. If it means approximately, use "approximately" instead. Additionally, 'decline' is an unclear category relative to the other categories; consider "transition of native vegetation to another land cover type". Lastly, define/describe páramo.

Reply: The following changes were made: "approximately" was added instead of "á", "decline" was replaced by "reduction of the extent of", and "high alpine grasslands (páramo)" was added.

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Page 5220, Line 9: The meaning of (2) is unclear. Does this mean that agricultural land increased by an area equal to 14% of the basin area?

Reply: We have rephrased this part : "Three main land cover change trajectories can be distinguished: (1) expansion of agricultural land by an area equal to 14% of the

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catchment area (or 39 km<sup>2</sup>) in 46 years' time, (2) deforestation of native forests by 11% (or -31 km<sup>2</sup>) corresponding to a mean rate of 67 ha yr<sup>-1</sup> and (3) afforestation with exotic species in recent years by about 5% (or 15 km<sup>2</sup>). Over the time period 1963-2009, about 50% of the 64 km<sup>2</sup> of native forests was cleared and converted to agricultural land.

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Page 5220, Line 15: use ", which" instead of "that" Done

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Page 5220, Line 16-17: it is not clear if this sentence means that flow changes likely result 'from direct anthropogenic disturbances evident in land cover change', or literally - from anthropogenic disturbances that occur "after land cover change" (meaning the disturbances are different from the land cover change itself)? (This comment also applies to the Conclusion - Page 5234, Line 10)

Reply: Interesting comment. As discussed in 5.2 (soil hydrology following land cover conversions), anthropogenic disturbances to ecosystems are complex. Changes in land cover are likely to be one of most noticeable results of anthropogenic land conversions, and are associated with profound changes in biophysical properties.

Therefore, we have rephrased this sentence in the abstract and conclusion as : "...very likely results from anthropogenic disturbances that are associated with land cover change."

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Page 5220, Line 19: colonization by what? does this refer to the land use change trajectory (1) or (2)? If so, it would help to use similar language. Reply: We have checked the text, as now use systematically similar language when we refer to land cover change trajectories.

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## # Introduction

Page 5220, Line 22: same comment as Line 1.

"play a pivotal role to supply" was replaced by "are an important source of "

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Page 5221, Line 2: "has" instead of "have"

Done

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Page 5221, Line 4-5: does "demographic" just mean "population"? If so, use "population". The meanings of "internal and external migration" and "land reform programs" are unclear. Can you provide brief additional descriptions of these?

We have rephrased this sentence, and added more information on the land reform programs : "The magnitude and intensity of land use change has increased rapidly from the second half of the 20th century, as result of population growth, socio-economic development, rural-urban and international migration, and land reform programs (Vanacker et al., 2003; Grau and Aide, 2007; Curatola Fernández et al., 2015). The agrarian land reforms of the 1960s and 1970s led to a redistribution of the land ownership, but also promoted rapid colonization of so-called vacant lands, which were often covered by native forests (Balthazar et al., 2015).

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Page 5222, Line 14: does "commonly associated to" mean "commonly associated with" or "commonly attributed to" instead?

Thanks for this comment. We have replaced "commonly associated to" by "commonly associated with"

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Page 5222, Line 25: change to "of the Ecuadorian Andes" (added "the") Done —  
Page 5222, Line 25: combined present tense ("is rapid") and past tense ("resulted in") reads awkwardly. Additionally, by what standard is this rapid? a 20% change over 46 years might not be considered rapid. (Same comment on use of rapid in Page 5223, Line 20.)

We agree that this annotation was not very appropriate. We now refer to the raw data only, and have eliminated any subjective interpretation of the rate of change ("is rapid"), also in # regional setting.

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## # Regional Setting

Page 5223, Line 1: delete "at" Done

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## # Materials and Methods

Page 5225, Line 5-6: the statement following the semicolon needs to be a complete sentence, consider "...; daily streamflow data was obtained from the Pangor AJ Chimbo gauging station (Fig. 1)"

Done

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Page 5225, Line 12: is "either" correct? Mora and Willems (2012) says both are estimated. Thanks for remarking this. This was indeed not correct, and it should read as "for each current and preceding month". Changes are made in the text.

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Page 5226, Line 2: "aggregated to monthly" (replace "at") Done

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Page 5226, Line 23: "was used" instead of "was here used" Done

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Page 5226, Line 27: "until" instead of "till" Done

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Page 5227, Line 16-17: "used" instead of "here proposed". This section was rewritten, see reply to comments above.

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Page 5228, Line 8: delete "here" (in general, "here" is used frequently in this context throughout the paper, and it's not necessary) Done

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Page 5228, Line 10: what is meant by "narrow(ing)" - does this imply that the cloud forest is narrowing over the time of the study and this means something for interception? If it doesn't have anything to do with the interception assumption, maybe delete. Reply: We have deleted "narrow(ing)". It made reference to the changes in cloud forest extent over the period 1963-2009, but is a bit distracting in this part of the paper.

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Page 5228, Line 18: "the partial" (add "the")

Reply: We have rephrased this part: "Second, a detailed analysis of the long-term change in water balance was realized in the two ecosystems where major changes in land cover occurred (Table 1): the tropical montane cloud forest (defined as the landscape unit between 2200 and 3200 m.a.s.l. originally covered by cloud forest), and páramo ecosystems (here defined as the entire landscape unit of high altitude above the continuous forest line, 3200 m.a.s.l.). A partial water balance was computed

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for each of these ecosystems, following the methods described below."

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Page 5229, Line 11-12: This is already stated in a previous section, delete. And, include the subsequent sentence (Line 13-14) in the first mention of the definition of P and WD, and delete here.

Done. We deleted the definition of P and WD here (repetition), and now include our statement on the spatialization of hydrometeorological data in the beginning of section 3.4.

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## # Results

Page 5230, Line 3-4: Same question as before: expansion equal to 14% of basin area, or 14% of previous agricultural land? We have clarified this in the text: "by an area equal to 14% of the catchment area".

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Page 5230, Line 3-6: Aside from the question above, this summary (and the rest of the paragraph) is much clearer than what is provided in the abstract - consider using this wording in the abstract instead.

Thanks for this suggestion. We have rephrased this part of the abstract based on the text in the results' section.

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Page 5230, Line 23 - Page 5231, Line 2. These two sentences ("Given" to "trend") belong (also) in the Methods section. They're very clear, and motivate and introduce the use of EEMD. There's also a period missing after "(Fig. 5)".

We have moved this to the methods section. We have also rewritten the methods

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section to clarify the methodological approach (see reply to comments above).

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Page 5231, Line 10: insert "in streamflow and baseflow" between "change" and "decreased", otherwise it could be misinterpreted as referring to rainfall. Done

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Page 5231, Line 28: "contributed" should be "attributed". Done

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#### # Figures

Figure 1: Make symbols, map inset, and labels all larger. We have made a new figure with the location of the study area.

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Figure 3: Make the river line larger and/or a different color because it's hard to see. Done. We have provided a better figure for the land cover change analysis.

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Figure 7: Include the time scale of the WD values (daily) in the caption. Done.

— ## Cheers! Morgan Levy, UC Berkeley

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 5219, 2015.