Summary of the modifications to the text, tables and figures:

Below, we have copied the relevant sections of the three reviews (copied sections are given in italics). We addressed each comment separately, and our reply is given below each copied 'reviewer' section. The changes are marked in yellow in the text, and we also indicate in our comments below where we made changes to the text (page and line of the 'revision, changes marked' document).

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)
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Received and published: 3 July 2015

General Comments

This paper provides an analysis of the relationship between vegetation cover and streamflow in the tropical Andean Pangor catchment, which has experienced a unique land conversion trajectory that includes conversion of natural vegetation to agriculture as well as exotic afforestation. The authors use long-term hydroclimate data and a data-adaptive time series decomposition technique to evaluate trends in hydroclimate data relative to the land use change trajectory. The timing in hydroclimate trends is paired with timing in land conversion to infer impacts of land cover change on the water budget of the catchment. I appreciate the data-based (not modeling) focus of the analysis, as well as the analysis of 'real' (instead of extreme experimental) land use change. The complexity of the analysis methods is appropriately suited to the data used.

Overall, I greatly enjoyed reading this paper! Most of the comments below make suggestions that are intended to aid in clarifying explanations of the methods and results. The abstract needs some work to provide clarity on the study design and data. By the end of the Introduction and Methods sections, I'm still not entirely clear on the focus of the analyses - what questions are asked and answered, and which methods are used for specific parts of the analysis. This becomes clear in the Results section, where the headers point out that the analysis is two-fold: analysis of land use change, and then analysis of hydroclimate trends. The descriptions of the methods used are mostly clear, but I lacked that guiding framework/outline of the analysis when reading them. The Methods section in particular could be clarified with improved introductory sentences for each paragraph. Detailed comments below.

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 (see Page 2, line 17-18).

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 (see page 2, line 30; page 3, line 4).

Reply : With regard to the anthropogenic impact on water resources in the Andes, we added a reference to work by Harden et al. (2013) see page 3, line 9.

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 (page 6, line 20-22).

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), see page 6, line 29-31.

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 ($m^3 s^{-1}$) into equivalent water depth (mm), see page 7, line 5-10.

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

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 (page 7, line 21-25).

“First, the mean annual evapotranspiration, $\overline{ET_{yr}}$, was estimated as the difference between the mean areal average annual precipitation, $\overline{P_{yr}}$, and mean annual equivalent water depth, $\overline{WD_{yr}}$, for the time period 1974-2008, thereby assuming that long-term changes in soil water storage, ΔS, can be neglected.”

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 hydro-meteorological 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: (page 7, line 18; page 7, line 31-32; page 8, line 1-2).

> “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 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.”

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.

> 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 (page 8, line 4-25).

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)?

> 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_i. Only significant IMF_i are averaged, here defined as those IMF_i 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 (page 8, line 25-31; page 9, line 1-8).

Page 5227, Line 20: what type of "perturbation" - Gaussian white noise?

> 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 (page 8, line 17-18; page 8, line 21-22).

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?

> 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 (page 12, line 22-24).

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?

> 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), see page 11, line 1-7.
>
> We slightly reordered the method section, to improve the logical flow of the text

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.

> 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).

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?

> 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 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 (page 12, line 5-7; page 12, line 11-14).
>
> 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), see page 8, line 19-31; page 9, line 1-4.

Page 5232, Line 4-5: re-state some numbers from Table 3 instead of saying "major".

> We have rephrased the first sentences of this paragraph, and make explicit reference to the amount of land cover change observed in the catchment (page 13, line 5-16).

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.

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 (page 14, line 14).

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 change, even if soil infiltration remained the same.

> 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: (page, 14, line 21-27)

> “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 ", see page 1, line 18

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 (page 1, line 20)

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”, see page 1, line 21

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 it’s not stated.

> We have rephrased this sentence to clarify the temporal scale of the analysis (page 1, line 21).

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

> The name of the catchment is added in the text (page 1, line 22)

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.

> It is now specified in the text that the changes refer to the period 1963-2009 (page 1, line 24).

Page 5220, Line 8-9: the use of "∼" 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.

> We have rephrased this sentence (see page 1, line 25 to page 2, line 3).

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?

> 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 catchment area (or 39 km²) in 46 years’ time, (2) deforestation of native forests by 11% (or -31 km²) corresponding to a mean rate of 67 ha yr^{-1} and (3) afforestation with exotic species in recent years by about 5% (or 15 km²). Over the time period 1963-2009, about 50% of the 64 km² of native forests was cleared and converted to agricultural land. See page 1, line 23-28

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

Done (page 2, line 4)

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)

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.”, see page 2, line 5-6; page 15, line 5-6.

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.

We have checked the text, as now use systematically similar language when we refer to land cover change trajectories.

Introduction

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

"play a pivotal role to supply" was replaced by "are an important source of ", see page 2, line 9

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

Done (page 2, line 15)

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). See page 2, line 14-20.

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", see page 3, line 25.

Page 5222, Line 25: change to "of the Ecuadorian Andes" (added "the")

Done (page 4, line 4).

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.

 # Regional Setting

Page 5223, Line 1: delete "at"
> Done (page 4, line 14)

 # 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 (page 6, line 14)

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.

Page 5226, Line 2: "aggregated to monthly" (replace "at")
> Done (page 7, line 16)

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

Page 5226, Line 27: "until" instead of "till"
> Done (page 8, line 9)

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

Page 5228, Line 8: delete "here" (in general, "here" is used frequently in this context throughout the paper, and it's not necessary)
> Done (see page 9, line 22)

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.
> 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. See page 9, line 24.

Page 5228, Line 18: "the partial" (add "the")
> We have rephrased this part: (see page 9, line 27-30; page 10, line 1-2)
>
> "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 for each of these ecosystems, following the methods described below."

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 (page 9, line 18-19).

 # 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", see page 11, line 12.

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. See page 1, line 23-27.

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 section to clarify the methodological approach (see reply to comments above). See page 8, line 4-8.

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

Done (page 12, line 11-14)

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

Done (page 12, line 31)

 # Figures

Figure 1: Make symbols, map inset, and labels all larger.

We have made a new figure with the location of the study area.

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.

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

Done.

###
Cheers!
Morgan Levy, UC Berkeley

Reviewer #2

j. restrepo (Referee)

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Received and published: 6 July 2015

This is a well written and presented paper assessing Climate change and human land conversion impacting stream flow and precipitation in the Ecuadorian Andes. The methods and results are well addressed and presented and conclusions have huge importance on policy making in tropical drainage basins of Andean countries. This paper proves what is happening in many river basins in the Andes: climate change is not the main trigger of decreasing or increasing water flows. Land cover change is the main stressor impacting water resources.

This an excellent paper that deserves to be published in its current version.

Many thanks for your encouraging words.

Anonymous Referee #3

Received and published: 8 July 2015

GENERAL COMMENTS

The authors investigate the nature and causes of hydrological changes in an Andean headwater catchment. The importance of this work is clearly demonstrated in the introduction, and what follows is a valuable analysis of climate and land use change as it pertains to changes in catchment discharge. The conclusions can inform watershed management and sustainability of water supply, with implications outside the study area. From my reading of the paper, the primary objectives are to answer the following research questions: have changes in precipitation led to changes in the hydrograph (reductions in total Discharge and changes in partitioning between quick flow and baseflow)? What changes in land use have occurred over the period of the study? What changes in land use are most responsible for altered catchment discharge?

The methods and analysis are appropriate given the aim of the study and limitations of data availability. However, the methods rely on a number of assumptions which introduce uncertainty and/or bias that could be affecting the conclusions. In the Specific Comments section I suggest ways the authors can clarify their approach and evaluate some of the uncertainties present in their assumptions. The writing is clear and easy to read, but there are a couple clarification and organizational changes I suggest in the Specific Comments section below.

> We thank reviewer #3 for his constructive review, based on a profound knowledge of the area and the research topic. Given the spatial and temporal scale of our analysis, it is not possible to get into all details of the hydrological processes as a limited amount of information is available for a catchment that is heterogeneous in topography, land cover and geomorphology. However, we feel that our approach is valid as it provides insights in the potential effect of land cover change on streamflow, which is currently an under-studied subject at the catchment scale.
>
> We have made the necessary changes to our water budget approach, and now evaluate also the potential impact of horizontal precipitation on streamflow (see below).

SPECIFIC COMMENTS
On organization:

- *I had to read the paper through to understand the research objectives of the authors. I suggest they add a couple sentences to the introduction specifically stating their objectives, such that the methods, results, and conclusions directly follow from the objectives.*

> We have added two sentences at the end of the introduction where we reiterate our research objectives: “The main objective of this paper is to quantify the potential long-term effect of land cover change on streamflow in the Tropical Andes. By analysing multi-decadal time-series of hydrometeorological data, we specifically tested the relative sensitivity of streamflow to climate and land cover change.”, see page 4, line 7-11.

- *The results from the ET model should be placed in the results section, prior to the discussion.*

> Our discussion starts with the analysis of change in the partial water balance based on the land cover change analysis and ET model results. We prefer to keep the results of the ET model here, to avoid repetition between the results and discussion section and to enhance the quality of the discussion.

The analyses are appropriate for the case study, but the authors should provide additional context with which to assess their assumptions, analysis, and conclusions.

> We made several improvements to the text, tables and figures based on the comments of reviewer#3.

1. The authors separate quickflow and baseflow using monthly streamflow timeseries. What are the timescales of quickflow in the catchment? If they are considerably less than a month, it would be more appropriate to conduct this analysis using daily streamflow data.

> Thanks for remarking this. There was an error in the text which caused this confusion. The separation of the streamflow into quick and slow flows was done on the daily data. This is clarified in the text. See page 7, line 5-10.

2. Given that all land use maps contain some uncertainty, it is valuable to the reader to know how accurate the maps are. For the remote sensing classification, the authors use a method previously developed in a separate paper but do not discuss any accuracy assessment. I suggest reporting the accuracy of the described method and describe how it would apply to their case study. Then, what kind of error can the reader expect in the results? What were the limitations to conducting an accuracy assessment?

> In the previous version of the paper, we did not provide full details on the accuracy assessment of the land cover maps. We now report the accuracy of the methods that we used, and refer to our previous work on land cover monitoring – where necessary: (page 5, line 28-30; page 6, line 1-9)
>
> "The accuracy of the land cover change analysis is function of the errors on the individual land cover maps. Land cover maps for 1963 and 1977 were extracted by manual on-screen digitalisation on high resolution copies of aerial photographs. As such, the accuracy of the land cover maps mainly depends on the horizontal positional accuracy of the orthorectified photographs, and is systematically below the spatial resolution (30 m) of the aggregated land cover maps (Vanacker et al., 2003; Guns et al., 2014). A thorough validation of the land cover classification was realized for the 2001 satellite derived map (Balthazar et al., 2012), based a stratified sampling of 300 points for which the reference class was identified on very high resolution aerial photographs. The error matrix reveals an overall classification accuracy of 94% (Balthazar et al., 2012). Given the temporal dependence of land cover time series, the uncertainty on the amount of bi-temporal land cover change is not the limiting factor in our analysis."

3. The residual trend of water depth from the empirical mode decomposition declines from 1974-1990, after which it is nearly stationary (Figure 5, bottom panel). I assume, based on the other analyses, that this does not necessarily entail that the decline in discharge occurred entirely before 1990. Please confirm and/or clarify. If the opposite is true and streamflow is mainly stationary after 1990, it would entail that changes in discharge cannot be attributed to tree plantations which were weren't introduced until the 1990s. This also relates to the statement on p5231, line 11, describing "two periods of change".

> We now provide more details on the results of the EEMD in section 4.2. ("Long-term trends in precipitation and streamflow"). Two periods of change can be identified, and the strongest decrease in streamflow is observed before the beginning of the 1990s. It is correct that the residual flow trend is rather flat from the 1990s onwards. This does not imply that the pine plantations have no effect on the overall water balance, as the precipitation records shows an increasing trend till the early 2000s (so net effect is negative). See page 12, line 1-14.

We have provided more information on the rate of change in the text, particularly in section 4.2., and have revised section 5.1. based on your comments.

4. *In the catchment water balance, horizontal precipitation (HP) is ignored because in 2009 the land cover of montane cloud forests, the primary land use where HP occurs, was small compared with the total catchment area. But the change in montane cloud forest land use over the course of the study period (10.9% of catchment area) is larger than the total size of exotic tree plantations in the catchment (5.3%). As the authors note, previous work has indicated that horizontal precipitation can account for 5% to 20% of total precipitation. If one were to assume HP is equal to 20% of measured precipitation for cloud montane forest and 0 for other land cover, average annual rainfall of 1400 mm, and 10.9% of the watershed was converted from cloud montane forest to other land cover, then the average annual water loss would be close to 30 mm across the catchment, a number that is comparable with the total water loss to ET from tree plantations (Table 3). Would such assumptions be reasonable? This type of sense check would be valuable for the reader.*

In the previous version of the paper, we made abstraction of the "extra' moisture input from interception of fog and clouds, and no quantitative estimate of the contribution of horizontal precipitation exists for the Ecuadorian Andes. We agree with the reviewer that horizontal precipitation can be important, and have adapted our method. We now include the potential effect of a reduction in occult precipitation after forest clearance, and have reorganized our discussion accordingly. See page 13, line 27-30; page 14, line 1-9.

5. *Some concerns related to ET: (a) The equation for evapotranspiration for montane cloud forest reduces to the equation for the total catchment water balance (ET = P - WD). Is this an appropriate assumption? Furthermore, reporting values for throughfall and stemflow are unnecessary and confusing. (b) The strong correlation between P and ET in Figure 2 suggests the catchment is water limited (PET > P), with ET reaching values of nearly 3000 mm/yr. However, the authors suggest that plants rarely undergo water stress in this region, potentially suggesting an energy-limited catchment (P > PET). The value of PET is given from INAMHI as 1000 mm/yr which is comparable with average annual P. Each of these scenarios would have different implications for water balance modeling. (c) As a cross-check for the applicability of the models, I suggest comparing results from the two methods for estimating E (direct water balance and hybrid approach on p5229).*

(a) If we would have information on the water yield for a catchment that is only covered by montane cloud forest, we would be able to estimate the ET as P – WD (as suggested by the reviewer). This is not possible in our case-study, as we do not have spatially disaggregated data on the hydrological response of individual land cover type. Therefore, we used a direct water balance to estimate the losses by evapotranspiration of montane cloud forest (see 3.4 Estimation of the long-term water balance), and we calculated transpiration losses, interception evaporation and evaporation from bare soil separately following Fleischbein et al. (2006). See page 9, line 11-30; page 10, line 1-12.

(b) The long-term average potential evaporation of the area is estimated to be between 1000 and 1100 mm, according to previous records of potential evaporation (as determined by pan evaporation measurements) by INAMHI (2009). Here, we take the potential evaporation (*PE*) as determined by INAMHI (2009) as the reference crop evapotranspiration, and do not apply an empirical correction factor (of 0.85 based on average wind speed, fetch and humidity following Allen et al., 1998) to convert *PE* into ET_o. The reason is twofold: (1) there is a good correspondence between the long-term *ET* (1097 mm) as estimated from the catchment water balance and *PE* (1000 - 1100 mm, INAMHI, 2009), and (2) the validation of evapo(transpi)ration data and models for the Southern Ecuadorian Andes indicates that ET_o determined by the Penmann-Monteith method corresponds within 10% with the measured values of *PE* by INAMHI (Baculima et al., 1999). This estimated crop reference evapotranspiration is lower than the mean annual precipitation over the catchment (P_{yr} estimated at 1656 mm, see Table 2). At the catchment scale, there is no evidence of water limited conditions from these measurements, although it is possible that water limited conditions occur at certain locations during the dry season. Given that the comparison of long-term ET_{yr}, PE and estimated ET_0 do not suggest water limited conditions, we consider our approach of water balance modelling to be valid.

(c) We have compared the results of the two methods to estimate *ET* losses in the forest: (1) direct water balance, and (2) so-called "hybrid" approach by Reviewer #3, used for estimation of ET for agricultural land, páramo grasslands and pine plantations. In the latter method, we take Kc for evergreen broadleaf forest = 1 following the literature. The results are very similar, which is logical as the estimate of ET_o is very close to the long-term estimate of ET_{yr} derived from the catchment water balance.

6. In the conclusions, the authors suggest that reductions in catchment water yield could result mostly from increases in tree plantations. I suggest this statement be further placed into context. If a layperson were to read the conclusions, he/she might think that converting montane cloud forest to traditional crops would solve the problem. However, this would be incorrect given the ET model provided by the authors because crops transpire at 95% the rate of tree plantations, so there would be little change in ET after making this land use conversion.

Good point, and we have adapted our conclusions by including the partial water balance for páramo and cloud forest ecosystems. The latter was adapted based on your suggestions, and shows that a reduction in horizontal precipitation after forest clearance can have important consequences for the overall catchment water budget.

TECHNICAL CORRECTIONS

p5229, line 6: what is meant by "dry vegetation"?

We have rephrased this sentence into "where Et_{yr} is the transpiration loss or soil water uptake (mm yr^{-1}), Ei_{yr} the evaporation from wetted vegetation surface (interception evaporation) (mm yr^{-1})", see page 10, line 7-8.

p5229, line 12: While water depth may be a lumped parameter for the catchment, the authors already have a method for calculated precipitation distributed throughout the catchment. Therefore, there is additional information with which to spatially disaggregate P if so desired.

Correct. We have rephrased this sentence to clarify our idea. As we do not have information to spatially disaggregate WD_{yr}, we use lumped values for P_{yr} and WD_{yr}.
"P_{yr} and WD_{yr} were established for the entire catchment, as no detailed hydrological information is available to further spatialize WD_{yr}.", see page 9, line 18-19.

p5229, line 15: It's incorrect to refer to this equation as the Penman Monteith method. The Buytaert et al. (2006) paper references (Allen et al., 1998), which defines a specific FAO Penman Monteith equation for reference ET. The "Penman-Monteith" naming convention refers to estimating reference ET using the Penman-Monteith equation, contrary to this article in which it is retrieved directly from INAMHI.

Correct. We have rephrased this sentence. See page 10, line 13-14.

Table 2, Figure 4c, 5, 6: For the figures I suggest using "streamflow water depth" instead of "water depth" in the captions, so readers can flip to the figures without necessarily referring to the text to know what "water depth" means.

Thanks for this suggestion. We have checked the captions of Tables and Figures, and clarified that we refer to "streamflow water depth" where necessary. Also, we systematically use the term "water depth" in text, tables and figures when we refer to streamflow measurements only.

Figure 6: I suggest rewording the beginning of the caption to "Rainfall and streamflow with EEMD residual trends" because "residuals in rainfall" could be conflated with subtracting the mean from the rainfall timeseries. Also, I assume the trend in baseflow is not from the EEMD analysis because it is not monotonic. This should be clarified.

> We have reworded the caption as suggested by the reviewer. All residual trends are from EEMD analysis (also the trend in baseflow). It is important to distinguish between the residual and the trend. The residual is always monotonic. However, the trend can be the sum of both the residual and the last IMF(s) (if the latter is/are significant). In this case the trend is not monotonic (as observed in Fig. 6b).

Multidecadal change in streamflow associated with anthropogenic disturbances in the Tropical Andes

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Abstract

Andean headwater catchments are an important source of fresh water for downstream water users. However, few long-term studies exist on the relative importance of climate change and direct anthropogenic perturbations on flow regimes in these catchments. In this paper, we assess change in streamflow based on long time series of hydrometeorological data (1974-2008) and land cover reconstructions (1963-2009) in the Pangor catchment (282 km²) located in the Tropical Andes. Three main land cover change trajectories can be distinguished during the period 1963-2009: (1) expansion of agricultural land by an area equal to 14% of the catchment area (or 39 km²) in 46 years' time, (2) deforestation of native forests by 11% (or -31 km²) corresponding to a mean rate of 67 ha yr^{-1} and (3) afforestation with exotic species in recent years by about 5% (or 15 km²). Over the time period 1963-2009, about 50% of the 64 km² of native forests was cleared and converted to agricultural land. Given the strong temporal variability of precipitation and streamflow data related to El Niño-Southern Oscillation, we use empirical mode decomposition techniques to detrend the time series. The long-term increasing trend in rainfall is remarkably different from the observed changes in streamflow, which exhibit a decreasing trend. Hence, observed changes in streamflow are not the result of long-term change in precipitation but very likely result from anthropogenic disturbances associated with land cover change.

1 Introduction

Andean headwater catchments are an important source of fresh water for downstream water users (Urrutia and Vuille, 2009; Roa-García et al., 2011). Although the ecosystems in the Tropical Andes have been modified by anthropogenic disturbances for at least 7000 years (Bruhns, 1994), it is only since the early 20th century that natural habitats have undergone extensive transformation (White and Maldonado, 1991). The demand for agricultural land has led to an expansion of the agricultural frontier at the expense of natural ecosystems. 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).A major concern for sustainable development in the Tropical Andes is the increasing demand for freshwater ecosystem services (Harden, 2006; Ponette-Gonzalez et al., 2014). The rapid growth of various mega-cities located in the high Andes will further exacerbate the demand for water resources in the near future, from drinking water to water for sanitation, irrigation and agriculture, mining operations, and hydropower production. Changes in freshwater flow regimes are predicted to lead to future water scarcity (Bradley et al., 2006) as a result of the combined effect of climate change and variability (Bathurst et al., 2011; Urrutia and Vuille, 2009), and direct anthropogenic impact (Harden, 2006).

Both change and variability in local climatic conditions produce changes in hydrological conditions (Poveda and Mesa, 1997; Restrepo and Kjerfve, 2000; Poveda et al., 2011). In the Tropical Andes, the temporal variability of precipitation is strongly related to oceanic and atmospheric conditions over the Pacific Ocean and Amazon basin (Vuille et al., 2000; Marengo et al., 2004). The impact of El Niño-Southern Oscillation (ENSO) is clearly noticeable on the Western escarpment of the Andes in Ecuador and northern Peru (Tapley and Waylen, 1990; Rossel, 1997; Vuille, 2013), and decreases with altitude as the steep, high-altitude topography of the Andean range creates distinct microclimates (Mora and Willems, 2012).

Direct anthropogenic impact associated with land cover change is rapidly transforming the hydrological functioning of Tropical Andean ecosystems (Vanacker et al., 2003; Farley et al., 2004; Molina et al., 2012; Harden et al., 2013). The hydrological response is diverse, as changes in vegetation affect various components of the hydrological cycle including evapotranspiration (Nosetto et al., 2005), infiltration (Molina et al., 2007) and surface runoff (Bathurst et al., 2011; Restrepo et al., in press). The clearance of native forest for arable and grazing land induces rapid changes in soil physical properties reducing soil infiltration capacity (Bosch and Hewlett, 1982; Molina et al., 2007), and increasing surface runoff as a result of soil compaction and reduced evapotranspiration (Ruprecht and Schofield, 1989). As a consequence, the conversion of native forests to agricultural land often results in an increase of the annual water yield, but a reduction of the low flows (Bruijnzeel, 1990; Andréassian, 2004). In contrast, afforestation and/or reforestation of grasslands and arable lands lead to a reduction in soil moisture and total water yield as a result of greater canopy interception and evapotranspiration (Bruijnzeel, 2004; Scott et al., 2005; Farley et al., 2005; Buytaert et al., 2007).

In Tropical Andean ecosystems characterised by large inter- and intra-annual variability in hydrometeorological conditions, little is known about the relative importance of climate change and direct anthropogenic perturbations on streamflow. At large spatial scale (> 100 km^2), the patterns of land cover change are notoriously dynamic, both in space and time, and are commonly associated with climatic and altitudinal gradients. In this paper, we assess multi-decadal change in freshwater provision based on long time series of hydrometeorological data and land cover reconstructions. Given the strong temporal variability of precipitation and streamflow data related to El Niño-Southern Oscillation (ENSO), we use Hilbert-Huang transformation to detrend the time series of streamflow and precipitation data. The adaptive data analysis is based on empirical mode decomposition techniques that are appropriate for nonlinear and nonstationary time series data (Huang et al., 1998). After empirical mode decomposition, the remaining long-term trends in streamflow and precipitation are contrasted to the observed patterns of land cover change.

The study is realised in an exceptional setting, the Pangor catchment (c. 282 km^2) in the Ecuadorian Andes. Situated on the Western escarpment of the Ecuadorian Andes, the area is particularly affected by El Niño-Southern Oscillation cycles (Rossel, 1997). Land cover change resulted in a net loss of native forests and grasslands by about 20% of the total catchment area between 1963 and 2009 (Balthazar et al., 2015). The main objective of this paper is to quantify the potential long-term effect of land cover change on streamflow in the Tropical Andes. By analysing multi-decadal time-series of hydrometeorological data, we specifically tested the relative sensitivity of streamflow to changes in land cover and precipitation.

2 Regional setting

The Pangor catchment (78°50’-79°01’W, 1°43’ - 1°58’S) is located 200 km southwest of the capital of Ecuador, Quito (Fig. 1). The catchment has pronounced relief with elevation ranging between 1434 and 4333 m.a.s.l. over a distance of less than 30 km. Slopes are typically steep with slope gradients around 55%, but steeper in the dissected river valleys. The climate can be described as equatorial mesothermic semi-humid to humid (Pourrut, 1994), with precipitation and temperature increasing strongly with altitude. Mean annual precipitation at J. de Velasco station (3100 m.a.s.l.; Fig. 1) is about 1400 mm (1970-2009), with high inter-annual variability ranging from 475 mm (2002) to 3700 mm (1994); whereas at Chimbo DJ Pangor station (1450 m.a.s.l.) annual precipitation is only about 1000 mm (INAMHI, 2009).

The underlying geology consists of volcanic and meta-sedimentary rocks of Cretaceous to Early Tertiary age, with remnants of recent volcanic deposits at higher elevations. Soils have been classified as Andisols, Histosols and Mollisols following the USDA soil taxonomy (Gonzalez Artieda et al., 1986), and are characterised by a remarkably high water-holding capacity and soil organic matter content when undisturbed (Podwojewski et al., 2002). The landscape pattern now reflects several decades of land cover change. At mid and low altitudes, a complex patchwork of small agricultural plots, remnants of sub-alpine cloud forest, and patches of abandoned land with regeneration of natural shrub vegetation can be observed. Smallholder farming is the dominant agricultural activity, and crop rotation is a common practice where annual crops are alternated with pasture. Crop species vary with altitude, with maize (Zea mays) grown in association with common bean (Phaseolus vulgaris) at altitudes below 2600 m.a.s.l., and potato (Solanum spp.), faba bean (Vicia faba) and cereals (Triticum spp. and Hordeum vulgare) at higher altitudes. Large patches of montane cloud forest are only remnant on steep slopes in areas with very low accessibility. Above the natural treeline, the páramo grasslands are dominant, but plantation forests with exotic tree species (Pinus radiata and Pinus patula) now cover extensive areas (Balthazar et al., 2015).

3 Materials and methods

3.1 Land cover change detection

Land cover change for the period 1963-2009 was reconstructed based on panchromatic aerial photographs (IGM, Quito, Ecuador) and high resolution Landsat TM (15/10/1991) and ETM+ (3/11/2001, and 6/9/2009) images. A full coverage of aerial photographs at the scale of 1/60000 was obtained for November 1963 and 1977, and land cover mapping was realized following the orthorectification procedure described by Molina et al. (2012). Three Landsat scenes (1991, 2001, 2009, from the same season) with 1T level of pre-processing were acquired from the USGS archive, and images were atmospherically and topographically corrected with ATCOR3 (Balthazar et al., 2012). To support the definition of land cover classes, a WorldView II image of 2010 with a horizontal resolution of 0.5 m (PAN) and 2 m (MS) was used (Digital Globe).

A multi-source data integration method developed by Petit and Lambin (2001) was applied to reduce imprecision and inconsistency that may result from the comparison of heterogeneous datasets (Balthazar et al., 2015). Four land cover types were defined: AL: agricultural land dominated by pastures and annual crops; F: montane cloud and subalpine forests (including primary and secondary forests); P: páramo grasslands dominated by tussock grasses and dwarf shrubs, and PP: exotic forest plantations dominated by Pinus radiata and patula.

The accuracy of the land cover change analysis is function of the errors on the individual land cover maps. Land cover maps for 1963 and 1977 were extracted by manual on-screen digitalisation on high resolution copies of aerial photographs. As such, the accuracy of the land cover maps mainly depends on the horizontal positional accuracy of the orthorectified photographs, and is systematically below the spatial resolution (30 m) of the aggregated land cover maps (Vanacker et al., 2003; Guns et al., 2014). A thorough validation of the land cover classification was realized for the 2001 satellite derived map (Balthazar et al., 2012), based a stratified sampling of 300 points for which the reference class was identified on very high resolution aerial photographs. The error matrix reveals an overall classification accuracy of 94% (Balthazar et al., 2012). Given the temporal dependence of land cover time series, the uncertainty on the amount of bi-temporal land cover change is not the limiting factor in our analysis.

3.2 *Time series of precipitation and streamflow data*

Hydrometeorological data were obtained from the National Institute of Meteorology and Hydrology of Ecuador (INAMHI). Time-series of daily precipitation records are available for four meteorological stations located in or close to the Pangor catchment (J. De Velasco, Chimbo DJ Pangor, Pallatanga and Cañi-Limbe); daily streamflow data was obtained from the Pangor AJ Chimbo gauging station (Fig. 1). Hydrometeorological data of all stations is collected and recorded from manual readings, and data processing and quality control is realized by INAMHI. The time series are appropriate for studies of long-term trends in precipitation and streamflow, as they are of good quality (data gaps < 10%) and cover a prolonged period of time (1974 to 2008). Only during 1997 and 2003, there is a gap in the series of observed streamflow and precipitation data of more than 3 months. To obtain continuous time series data for EEMD analysis, the multiple linear regression method described by Mora and Willems (2012) was used to fill data gaps. This method estimates correlation coefficients between all pairs of hydrometeorological stations, for each current and preceding month, and applies a multiple linear regression equation to predict missing flow or precipitation data. Given the low density of rain gauges in the Pangor catchment, we applied the regionalization method proposed by Mora and Willems (2012) to obtain catchment-wide or areal average precipitation depths. Based on data of altitude, vegetation pattern and precipitation regime, four meteorological regions were delineated, and the closest rain gauge station was assigned to each region (Fig. 1). Additionally, an altitude correction factor was applied based on the observed positive linear relationship between mean annual precipitation and altitude (Mora and Willems, 2012). The areal average precipitation for the entire Pangor catchment was then calculated by summing the weighted precipitation (by surface area) of the four regions, and dividing this value by the sum of the weights. The areal average daily precipitation depths, P_d (mm), were aggregated into monthly data for the period 1974-2008.

The time series of streamflow data (1974-2008) is based on daily water stage readings at Pangor AJ Chimbo gauging station (Fig. 1). Stage records (m) were converted into discharge records (m^3 s^{-1}) using the stage-discharge rating curve developed by INAMHI. The daily discharge was then converted to daily water production of the catchment by multiplying the daily discharge (m^3 s^{-1}) by 86400 to convert the values to m^3. The equivalent water depth, WD_d (mm), was then calculated by dividing the daily water production by the total catchment area (km^2) and multiplying by one thousand to convert the values to mm as to allow direct comparison with precipitation records. The daily water depths were split into quick and slow flows using the hydro-statistical toolkit WETSPRO (Water Engineering Time Series PROcessing tool). This procedure is based on subflow separation techniques, and applies a generalization of the original Chapman filter. The Chapman filter assumes exponential recession for the hydrological subflows and is derived from the general equation of a low pass filter (Willems, 2009). To condense the time series data, the daily water depths were aggregated to monthly time step.

To assess the consistency of the hydrometeorological datasets, two simple tests were carried out on the annual records of precipitation and equivalent water depth following Costa et al. (2003). 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. First, the mean annual evapotranspiration, $\overline{ET_{yr}}$, was estimated as the difference between the mean areal average annual precipitation, $\overline{P_{yr}}$, and mean annual equivalent water depth, $\overline{WD_{yr}}$, for the time period 1974-2008, thereby assuming that long-term changes in soil water storage, ΔS, can be neglected. This first estimate of $\overline{ET_{yr}}$ of 1097 mm **yr**$^{-1}$ or 3.0 mm **d**$^{-1}$ (resulting from the subtraction of 559 mm streamflow **yr**$^{-1}$ from 1656 mm precipitation **yr**$^{-1}$, 1974-2008) is consistent with published estimates of potential evaporation for this region of 1000 to 1100 mm yr^{-1} by the National Institute of Meteorology and Hydrology (INAMHI, 2009). Second, the annual evapotranspiration data, ET_{yr}, are highly associated with the areal average annual precipitation depths, P_{yr} (Fig. 2), which is characteristic for tropical Andean basins (Mora and Willems, 2012). These two assessments 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.

3.3 Empirical mode decomposition EMD

Given the nature of hydrometeorological data in Tropical Andean basins, which often display an abrupt pattern of amplitude and frequency modulation at different time scales, empirical mode decomposition, a technique developed by Huang et al. (1998), is an ideal method to extract physically meaningful signals in the nonlinear and nonstationary time series (1974-2008). The method separates non-linear oscillatory patterns of higher frequencies from those of lower frequencies, until a constant or monotonic trend is ultimately obtained (Wu and Huang, 2004. Peel and McMahon, 2006). In contrast to more traditional time series analysis techniques, such as Fourier transformation and wavelet analysis, EMD is not based on linear and stationary assumptions (Huang and Wu, 2008). Huang et al. (1999) demonstrated that EMD is generally successful in retrieving the physically meaningful signals hidden in time series. In some cases, however, the physically meaningful variability tends to spread into different IMFs (so-called mode-mixing problem as described by Huang and Wu, 2008). Wu et al. (2009) addressed this issue by performing noise assisted data analysis which consists in building an ensemble of IMFs (ensemble EMD or EEMD) by introducing Gaussian white noise into the original signal before performing the EMD analysis techniques.

The time series of monthly precipitation values and equivalent water depths covering the period 1974-2008 were decomposed into their intrinsic mode function (IMFi) components and the residual or trend. Gaussian white noise (having an amplitude of 0.2 standard deviation of that of the original signal) was introduced in the original time series following Wu et al. (2009). The final IMFs and residual or trend were then computed as the average of their corresponding ensemble members, IMF_i. Here, only the significant IMF_i and their residuals or trends were averaged following the methods developed in Brisson et al. (2015). The significance is defined by the original trend having variability higher than the variability of a trend derived from a randomised time-series. Here we propose a 3-step method to derive the significance of the trend. Firstly, the monthly values of the observed time series, *P* and *WD*, were randomly distributed. The resulting time series features a variability similar to the observed one, but without any meaningful trend. In total, 1000 random time series were generated from the empirical data. Secondly, following the process of the EEMD, a perturbation was added to the 1000 random time series. Finally, the trend in each random time series was derived using EMD. The original trend was defined to be significant if its variability is higher than the 99th percentile of the variability of the trends derived from the random perturbed time series.

Using EEMD analysis techniques, the time series of areal average monthly precipitation, streamflow and baseflow were decomposed into six ensemble intrinsic mode function components plus their significant residual or trend. In total, 34 years of hydro-meteorological data were processed.

3.4 Estimation of the long-term water balance

A budget approach was used to approximate the different components of the water cycle, including evaporation and transpiration (Bruijnzeel et al., 2006). First, the annual water balance for the entire catchment was approximated as:

$$P_{yr} + HP_{yr} = WD_{yr} + ET_{yr} + \Delta S \qquad (1)$$

where P_{yr} is the areal average precipitation (mm $\mathbf{yr}^{-1}$), HP_{yr} is the horizontal rainfall and cloud interception (mm $\mathbf{yr}^{-1}$), WD_{yr} is the equivalent water depth as derived from streamflow measurements (mm $\mathbf{yr}^{-1}$), ET_{yr} is the evapotranspiration (mm $\mathbf{yr}^{-1}$), and ΔS is the change in soil water storage in the catchment (mm $\mathbf{yr}^{-1}$). P_{yr} and WD_{yr} were established for the entire catchment, as no detailed hydrological information is available to further spatialize WD_{yr}. Long-term changes in soil water storage, ΔS, can be neglected, as soils are typically shallow on the Western escarpment of the Andes so that deep infiltration is limited. Horizontal rainfall, HP_{yr}, is also considered to be negligible for the catchment-wide water balance, as additional water input from the interception of cloud water and wind-driven rain is typically constrained to the belt of cloud forests (i.e. 11.6% of the catchment area in 2009). We can then estimate the annual evapotranspiration as

$$ET_{yr} = P_{yr} - WD_{yr} \qquad (2)$$

Second, 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 for each of these ecosystems, following the methods described below. In the tropical montane cloud forest, the annual evapotranspiration in the cloud forests was estimated as:

$$ET_{yr} = Et_{yr} + Ei_{yr} + Es_{yr} \qquad (3)$$

with $Ei_{yr} = P_{yr} - (Tf_{yr} + Sf_{yr})$ (4)

and $Et_{yr} = (Tf_{yr} + Sf_{yr}) - WD_{yr}$ (5)

where Et_{yr} is the transpiration loss or soil water uptake (mm yr^{-1}), Ei_{yr} the evaporation from wetted vegetation surface (interception evaporation) (mm yr^{-1}), Es_{yr} the evaporation from the soil surface (mm yr^{-1}, negligible under dense vegetation), Tf_{yr} throughfall and Sf_{yr} stemflow (mm yr^{-1}). Fleischbein et al. (2006) measured *Tf* and *Sf* for three catchments under the montane cloud forest in the southern Ecuadorian Andes. Results of *Tf* and *Sf* were on average respectively 59% and 1% of *P*.

For all remaining land cover types, the annual evapotranspiration was estimated from the potential evaporation following the methods described in Allen et al. (1998):

$$ET_{yr} = K_s \times K_c \times ET_o \qquad (6)$$

where K_s is a water stress factor, K_c is the crop coefficient and ET_o is the reference crop evapotranspiration. Here, we take the potential evaporation (*PE*) as determined by INAMHI (2009) as the reference crop evapotranspiration, and do not apply an empirical correction factor to convert *PE* into ET_o. The reason is twofold: (1) there is a good correspondence between the long-term *ET* (1097 mm) as estimated from the catchment water balance and *PE* (ranging between 1000 and 1100 mm, depending on altitude), and (2) the validation of evapo(transpi)ration data and models for the Southern Ecuadorian Andes indicates that ET_o determined by the Penmann-Monteith method corresponds within 10% with the measured values of *PE* by INAMHI (Baculima et al., 1999). Crop coefficients for natural grass vegetation and agricultural land were established for the southern Ecuadorian Andes (Buytaert et al., 2006), and K_c values are estimated at 0.42 for natural grassland and 0.95 for agricultural land. Pine plantations were attributed a K_c value of 1 based on the crop coefficient established by Allen et al. (1998) for conifers. The water stress factor, K_s, was set at 1, given that the annual *PE* (and ET_o) is lower than the long-term catchment average precipitation, P_{yr}.

Land cover data were used to estimate temporal changes in partial water balance over the period 1974-2008, as the main hydrological components are here parametrized based on land cover type. Land cover data for the Pangor catchment are discrete in time, and provide information for 1963, 1977, 1991, 2001 and 2009 based on panchromatic aerial photographs and high resolution Landsat images. A Markov chain model was used for the interpolation of the temporal land cover data for 1974 and 2008, using respectively land cover transition probabilities of 1963-1977 and 2001-2009 (Petit et al., 2001).

4 Results

4.1 Land cover dynamics (1963-2009)

Three main land cover change trajectories can be distinguished: (1) expansion of agricultural land by an area equal to 14% of the catchment area (or 39 km²) in 46 years' time, (2) deforestation of native forests by an area equal to 11% of the catchment area (or -31 km²) corresponding to a mean rate of 67 ha yr^{-1} and (3) afforestation with exotic species in recent years by about 5% (or 15 km²; Table 1; Fig. 3). Over the time period 1963-2009, about 50% of the 64 km² of native forests was cleared and converted to agricultural land. Small forest remnants are now scattered over steep terrain and/or in poorly accessible sites at higher elevations. Deforestation rates were highest in the 1960s, 1970s and 1980s with a net deforestation rate of 89 ha yr^{-1}, and slowed down to about 18 ha yr^{-1} for the period 1992-2009; similar to what was reported earlier for the Ecuadorian highlands (Vanacker et al., 2003; Guns and Vanacker, 2013). The pattern of afforestation stands in sharp contrast to the deforestation pattern (Fig. 3). Afforestation is mainly concentrated in the subalpine and alpine zones, and started in the early 1990s. About 2/3 of the total decrease in páramo grasslands (-23 km²) results from exotic forest plantations, and only 1/3 from conversion to agricultural land.

4.2 Long-term trends in precipitation and streamflow (1974–2008)

The flow regime (1974-2008) largely mimics the yearly variation in precipitation, with maximum mean monthly streamflow in April (equivalent water depth of 86 mm) and low flow in September (25 mm). More than 60% of the annual flow is concentrated in the period between February and June. Annual values of precipitation and streamflow reveal strong inter-annual variation (Fig. 4). Using EEMD, the times series of monthly precipitation values and equivalent water depths were decomposed into six ensemble intrinsic mode function (IMFs 1-6) components plus the significant residual or trend (Fig. 5). The EEMD detrending analysis shows that the precipitation and streamflow regime changed significantly over time (Fig. 6), as the residual trend is not flat. Based on the EEMD analysis (1974-2008), we can conclude that the observed changes in streamflow are not the result of long-term precipitation change, as the direction of the residual trends in streamflow and precipitation is opposite. Despite increased precipitation, there is a remarkable decrease in streamflow (Table 1).

Over the period 1974-2008, the rate of change in streamflow and baseflow varied through time. Two periods of change can be distinguished based on the EEMD time series analysis with a transition occurring roughly at the beginning of the 1990s. Before the early 1990s, there is a notable decrease in monthly streamflow and baseflow while the precipitation amounts increase (Fig. 6). From the mid-1990s onwards, there is no systematic trend in streamflow, while the precipitation trend is still increasing (Fig. 6).

4.3 Changes in the hydrological cycle and its components.

For the two periods of change that were identified based on the results from EEMD (1974-1991, 1992-2008), flow duration curves were constructed based on the daily data (Fig. 7). The mean daily water depth is about 0.4 mm lower in the period 1992-2008 compared to 1974-1991, despite an increase in the mean daily precipitation of 0.5 mm (Table 2). The largest difference is observed for low water depths, with a decrease of the Q95 and Q90 by 77% and 75% respectively. The moderate water depths (Q10 to Q90) decreased by 24%, and the highest ones (Q1) by 15% only. Results of a chi-square analysis indicate that changes in mean annual precipitation, streamflow and evapotranspiration between the two periods are significant (p-value < 0.005). Streamflow and evapotranspiration exhibit the largest change with - 22 and + 33% respectively. Interestingly, the magnitude of increase in estimated *ET* is 3-fold greater than the increase in precipitation. When analysing the monthly distribution of streamflow, it is clear that the largest decrease in streamflow is observed during the dry season (JJAS), followed by the first (JFMAM) and second (minor) rainy season (OND; Fig. 8a). Similarly, the estimated mean monthly baseflow is systematically lower (3 to 11 mm) during the most recent period (Fig. 8b). During the dry season (JJAS), about 60% of the reduction in total flow can be attributed to the strong decrease in baseflow.

5 Discussion

5.1 Changes in water balance for montane cloud forest and páramo ecosystems

Land cover dynamics observed in the Pangor catchment are characteristic for the Tropical Andes, with conversion of montane cloud forests and páramo grasslands for agriculture and forestry. The time series of land cover data (1963–2009) revealed shifts in land cover dynamics in the early 1990s. From 1963 to 1991, agricultural land increased rapidly at an annual rate of about 1%, mainly as a result of deforestation of montane cloud forests at a rate of 2.08% per year; while few changes occurred in páramo grasslands. In the early 1990s, there is a shift from net deforestation to a net increase in forest cover, as a consequence of the deceleration of deforestation and strong increase in exotic-tree plantations (+15 km²) in páramo grasslands (Table 1; Balthazar et al., 2015).

Table 3 shows first order estimates of changes in the partial water balance in montane cloud forest and páramo ecosystems over the period 1974-2008. The observed land cover changes in montane cloud forest and páramo ecosystems are estimated to have resulted in a net loss of annual water yield by 74 mm (or about 13% of WD_{yr}) over the period 1974-2008.

The development of 15 km² of pine plantation in páramo ecosystems is estimated to have increased transpiration losses by about 8.6 hm³ or 31 mm (Table 3). Pine forests' water use is very high compared to native páramo vegetation as result of the large total leaf surface area and deep root systems (Buytaert et al., 2007), and it largely affects the soil water storage and retention in organic-rich páramo soils (Farley et al., 2004). In addition, the conversion of ~6 km² páramo grassland to agricultural lands is expected to have further increased the transpiration losses by 3.0 hm³ or 11 mm (Table 3). Despite high solar radiation in the tropical Andes, the water use of native plants in páramo ecosystems is very low because of the evaporative characteristics of páramo grass species. Páramo grass tussock specie can consist of up to 90% of dead leaves, resulting in low *ET* values.

On the other hand, in montane cloud forests, the conversion of 50% of the surface area of forest to agricultural land is expected to have had an impact on the annual *ET* through changes in plant evapotranspiration after forest removal (Table 3). However, changes in cloud interception as a consequence of the removal of forests can largely outweigh the former effects on the overall water yield, as suggested by Bruijnzeel et al. (2006) and Hamilton et al. (2008). With degradation or removal of cloud forests, the mass of moisture-intercepting leaf surfaces, including epiphyte biomass on branches and stems, is lost, and horizontal precipitation from fog or cloud is consequently also reduced. In our calculations, we assume that the contribution of horizontal precipitation to the overall water budget is up to 20% of ordinary rainfall based on Bruijnzeel (2004). As such, deforestation of native forests (by an area equal to 11% of the catchment area) might have engendered a net loss of annual water yield WD_{yr} by about 32 mm, mainly as a result of reduced atmospheric moisture input from fog or clouds (Table 3).

5.2 Soil hydrology following land cover conversions

Land cover conversions are often followed by a phase of intense soil degradation that further exacerbates the anthropogenic impact on surface hydrology (Hofstede et al., 2002). Soil erosion measurements based on fallout-radionuclides for the Chimbo catchment (Central Ecuadorian Andes) by Henry et al. (2013) clearly illustrate that soil erosion rates highly depend on land cover and management: Erosion rates in páramo grasslands are estimated at 9 t ha^{-1} yr^{-1}, and are significantly higher in forest plantations, pastures and croplands with erosion rates of resp. 21, 24 and 150 t ha^{-1} yr^{-1}. The latter values are similar to soil erosion estimates for highly degraded Andean environments in southern Ecuador (Molina et al., 2008; Vanacker et al., 2014). Accelerated soil erosion after land cover change has been shown to alter soil hydrological conditions, e.g. through a reduction of soil water infiltration rates and soil water retention capacity (Podwojewski et al., 2002; Molina et al., 2007). The analysis of flow duration curves established for the periods 1974-1991 and 1992-2008 indicates that the largest change in streamflow is observed for low flow depths (Fig. 7). About 60% of the reduction in total flow results from decreasing base flow (Fig. 8), which points to reduced soil water storage capacity in the Pangor basin (Fig. 8). This observation suggests that land cover change not only affects the hydrological cycle directly through changes in transpiration or net precipitation, but also indirectly through changes in soil hydrological conditions.

6 Conclusion

Land cover dynamics observed in the Pangor catchment are characteristic for the Tropical Andes, with rapid deforestation of native forests and afforestation with exotic tree species in more recent decades. Given the nature of hydrometeorological data in Tropical Andean basins, which often display an abrupt pattern of amplitude and frequency modulation at different time scales, EEMD is an ideal method to extract physically meaningful signals. The EEMD analysis shows that the observed changes in streamflow (1974-2008) are not the result of long-term change in measured precipitation. Despite increased precipitation, there is a remarkable decrease in streamflow that very likely results from anthropogenic disturbances that are associated with land cover change.

Over the period 1974-2008, the rate of change in streamflow varied through time. During a first phase (1974-1991), there is a notable decrease in monthly streamflow and baseflow while catchment average precipitation increases. The largest change in the catchment water balance is observed during this period of forest clearance at a rate of 2.08% per year. Model simulations using a partial water balance suggest that a 20% reduction in atmospheric moisture input from fog or clouds as occult precipitation in cloud forests can contribute to a net loss of annual water yield by 7% over the period 1974-1991. During a second phase (1992-2008), there is no systematic trend in monthly streamflow but a positive residual trend in catchment average precipitation, suggesting an increase in loss by evapotranspiration. At the same time, we observe a shift from net deforestation to net reforestation, as a consequence of the deceleration of deforestation and strong increase in pine plantations in páramo grasslands by an area equal to 5% of the catchment area. The development of 15 km² of pine plantation is estimated to have increased transpiration losses by about 31 mm or 5% of the annual water yield.

In conclusion, our analysis suggests that significant long-term change in streamflow can be associated with anthropogenic disturbances following land cover change. Land cover change not only affects the hydrological cycle directly through changes in transpiration or net precipitation, but also indirectly through changes in soil hydrological conditions. Our observations point to the importance of land use planning, to minimize the potential impact of land cover change on freshwater flow regimes in the Tropical Andes.

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Table 1. Proportions (in percent) of the four land cover types for 1963, 1977, 1991, 2001 and 2009, and amount of land cover change for period 1963-2009 as percentage of the catchment surface area (%).

Land cover type	**1963**	**1977**	**1991**	**2001**	**2009**	**Δ (1963 – 2009)**
Agricultural land (AL)	33.6	39.0	45.3	46.5	47.4	+ 13.8
Native forest (F)	22.5	18.5	13.8	12.8	11.6	- 10.9
Páramo grassland (P)	43.9	42.5	40.5	37.4	35.7	- 8.2
Exotic forest plantation (PP)	0.0	0.0	0.4	3.3	5.3	+ 5.3

Table 2. Long-term mean of the main surface hydrological components. $\overline{P_d}$ is the mean daily precipitation and $\overline{WD_d}$ the mean daily streamflow water depth derived from the hydrometeorological dataset for the periods 1974-1991 and 1992-2008. $\overline{ET_d}$ is the mean daily evapotranspiration, estimated following Eqn (2). All hydrological components are expressed in mm.

Period	$\overline{P_d}$ (mm)	$\overline{WD_d}$ (mm)	$\overline{ET_d}$ (mm)
1974-1991	4.3	1.7	2.6
1992-2008	4.8	1.3	3.5

Table 3. Changes in catchment water budget over the period 1974-2008 in (a) montane cloud forest and (b) páramo ecosystems. ET_{past} corresponds to the evaporative losses of the land units prior land cover change, ET to the evaporative losses after land cover change and ΔET to the overall change in evaporation due to land cover change during the period 1974-2008. The ET values are expressed in hm^3 to indicate the changes in partial water budgets for the land units undergoing land cover change. To allow direct comparison with the results from the long-term time series analyses at the catchment scale, ΔET is also expressed in mm by dividing the estimated water production of the land units (hm^3) by the total catchment area (km^2) and multiplyied by one thousand to convert the values to mm. For cloud forest ecosystems, ΔP corresponds to a hypothetical change in catchment average net precipitation, as a result of a reduction in the horizontal precipitation in cloud forests after clearance assuming that interception precipitation is 20% of the measured precipitation.

	Conversion from…	Area (km^2)	ET_{past} (hm^3)	ET (hm^3)	ΔET (hm^3)	ΔET (mm)	ΔP (mm)
(a)	Native forest to agricultural land	21.4	23.5	22.4	-1.1	-4	-36
(b)	Páramo grassland to agriculture	5.7	2.4	5.4	+3.0	+11	
	Páramo grassland to plantations	14.9	6.3	14.9	+ 8.6	+31	

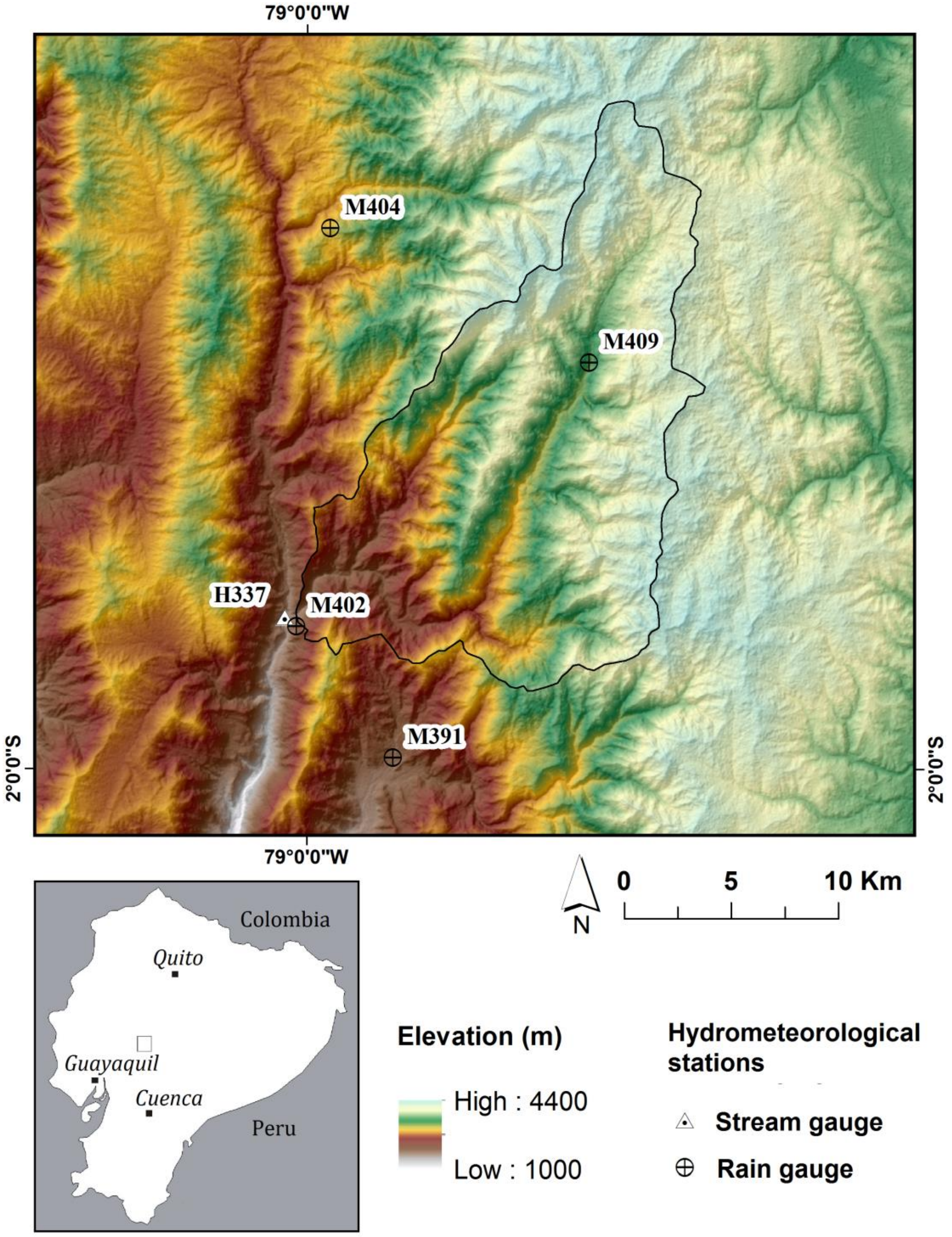

Figure 1. Location map of the Pangor catchment on the Western escarpment of the Ecuadorian Andes. The ASTER GDEM V2 30m resolution digital elevation model was draped over the hillshade model. The location of the gauging station (H337, Pangor AJ Chimbo) is shown with a triangle, and the rain gauges (M402: Chimbo DJ Pangor, M404: Cani-Limbe; M409: J. de Velasco, M391: Pallatanga) with a black cross. The inset map at the upper left shows the location of the study area within South America

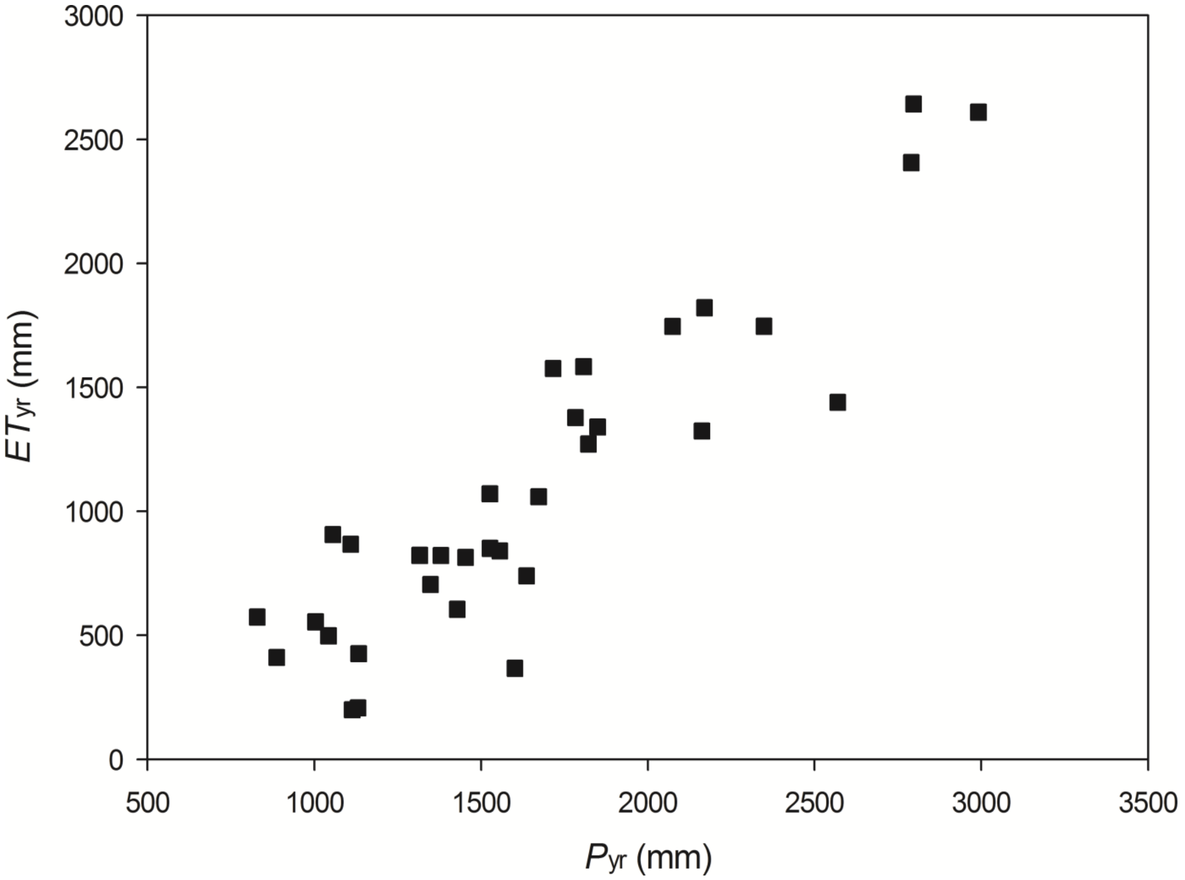

Figure 2. Scatterplot between areal average annual precipitation *Pyr* and annual evapotranspiration *ETyr*.

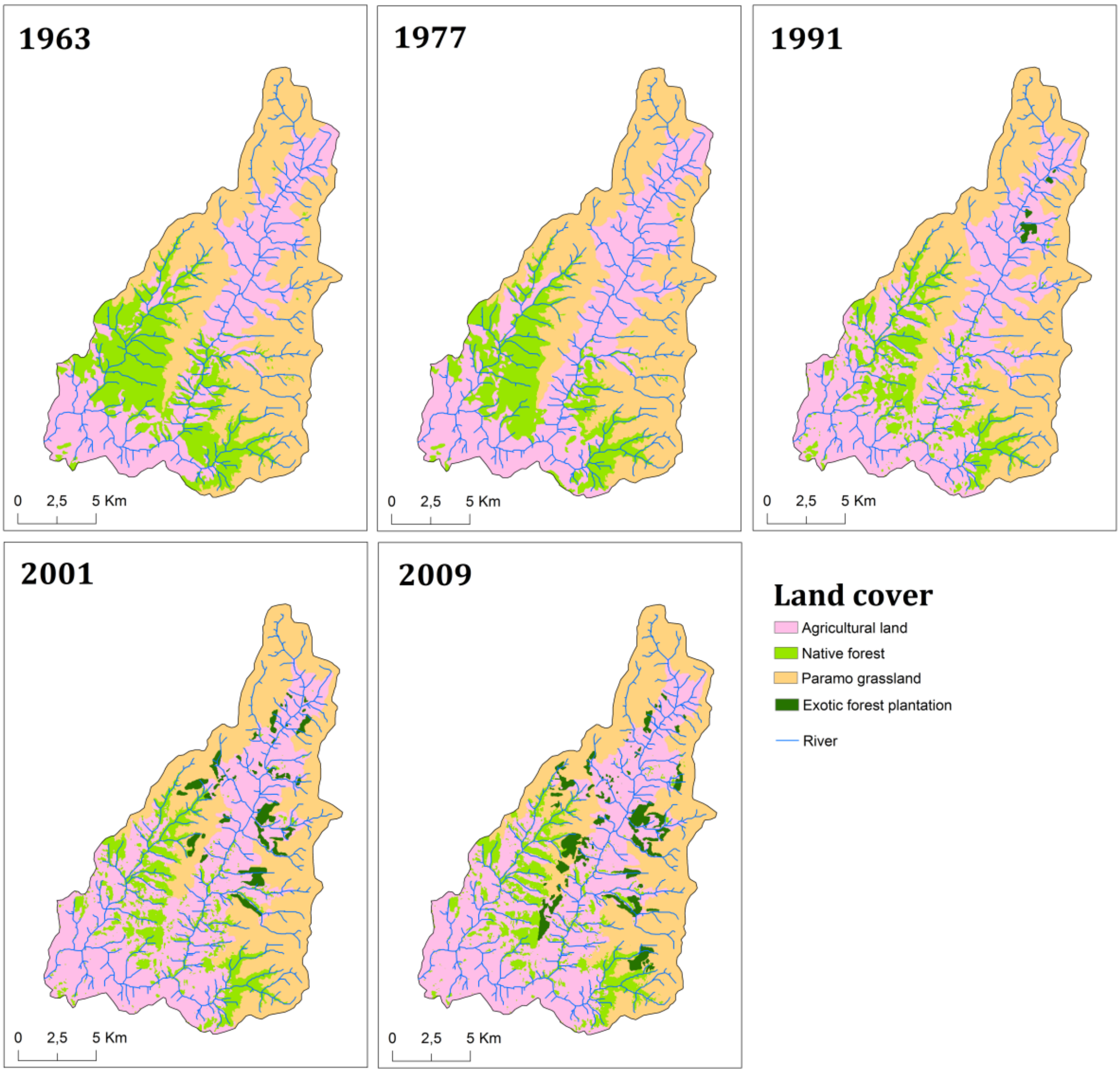

Figure 3. Land cover maps of 1963, 1977, 1991, 2001 and 2009 based on panchromatic aerial photographs and high resolution Landsat images. Four land cover types were identified: agricultural land, montane cloud and subalpine forests, paramo grasslands and exotic forest plantations.

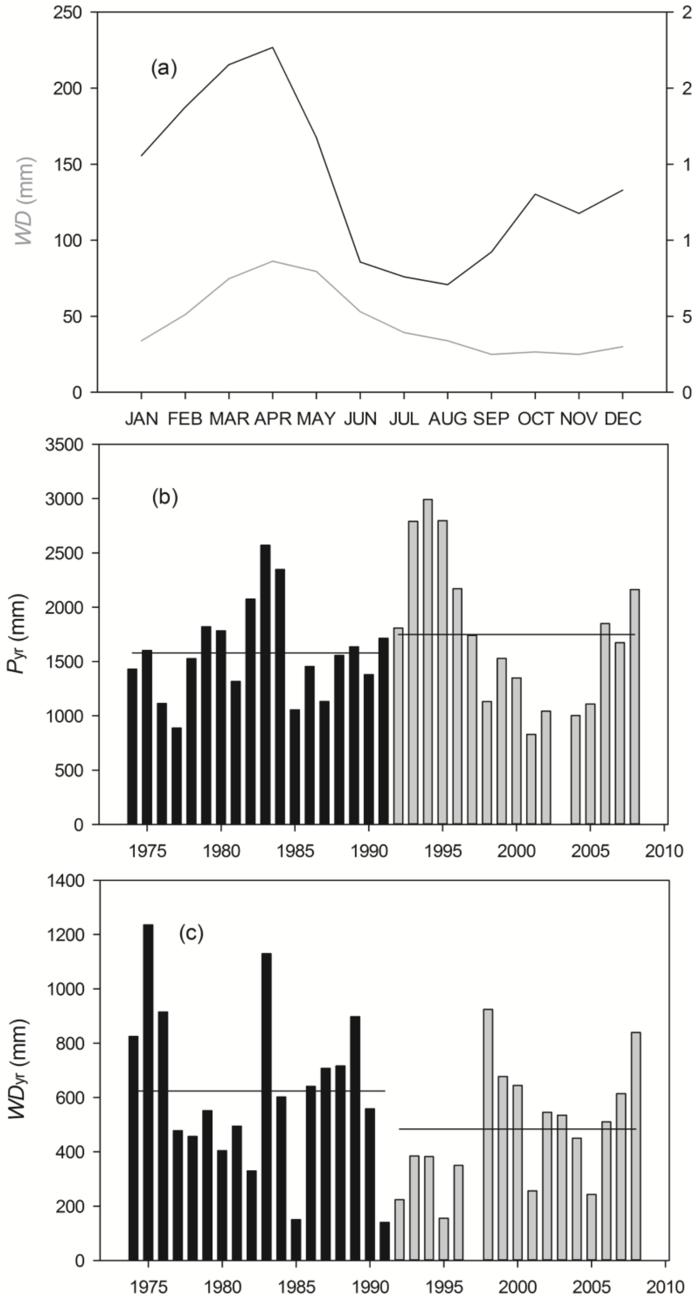

Figure 4. Hydrological characteristics of the study area. (a) Mean monthly streamflow (gray line, left y-axis) and average monthly rainfall (black line, right Y-axis) for the period 1974-2008, (b) time series of areal average annual precipitation and (c) equivalent water depth.

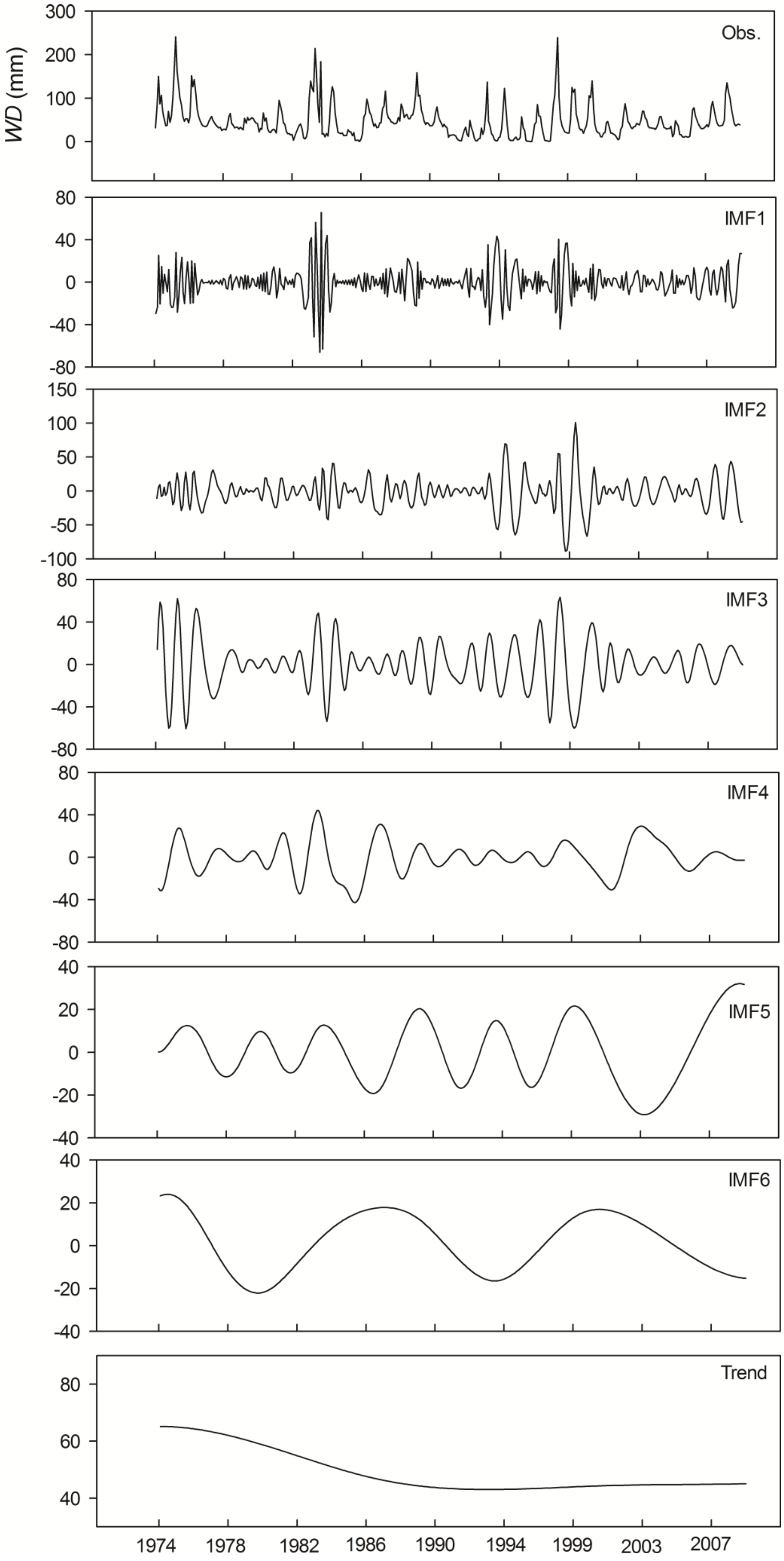

Figure 5. EEMD analysis of time series (1974-2008) of monthly water depths, with observed mean monthly streamflow (top panel), the six corresponding intrinsic mode functions and the residual trend (bottom panel).

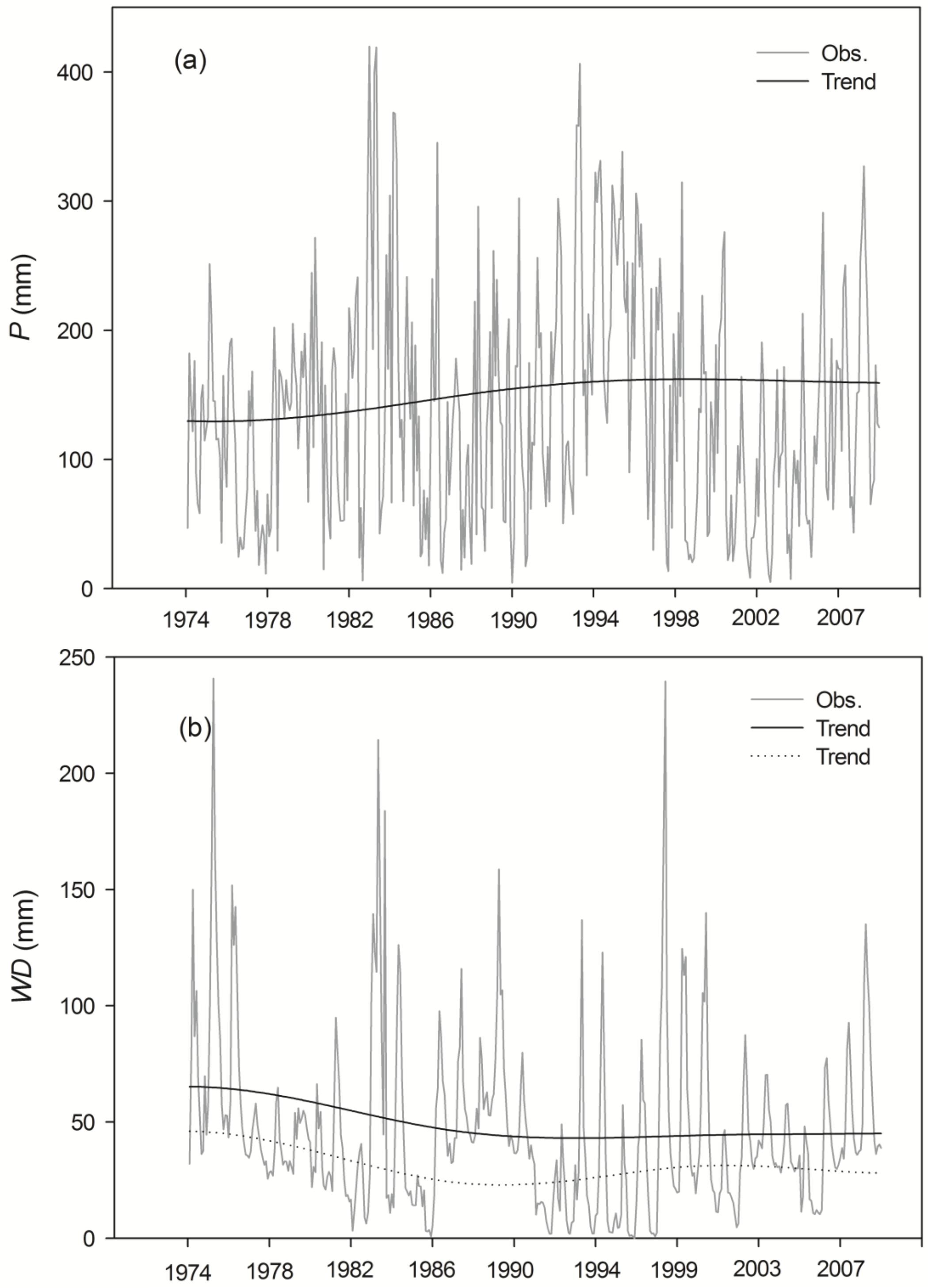

Figure 6. Long-term change (1974-2008) in rainfall, streamflow and baseflow and EEMD residual trend. (a) Observed areal average monthly rainfall (grey line) and residual trend (black line). (b) Observed monthly equivalent water depth (grey line) and trend in streamflow (continuous black line) and baseflow (dotted black line).

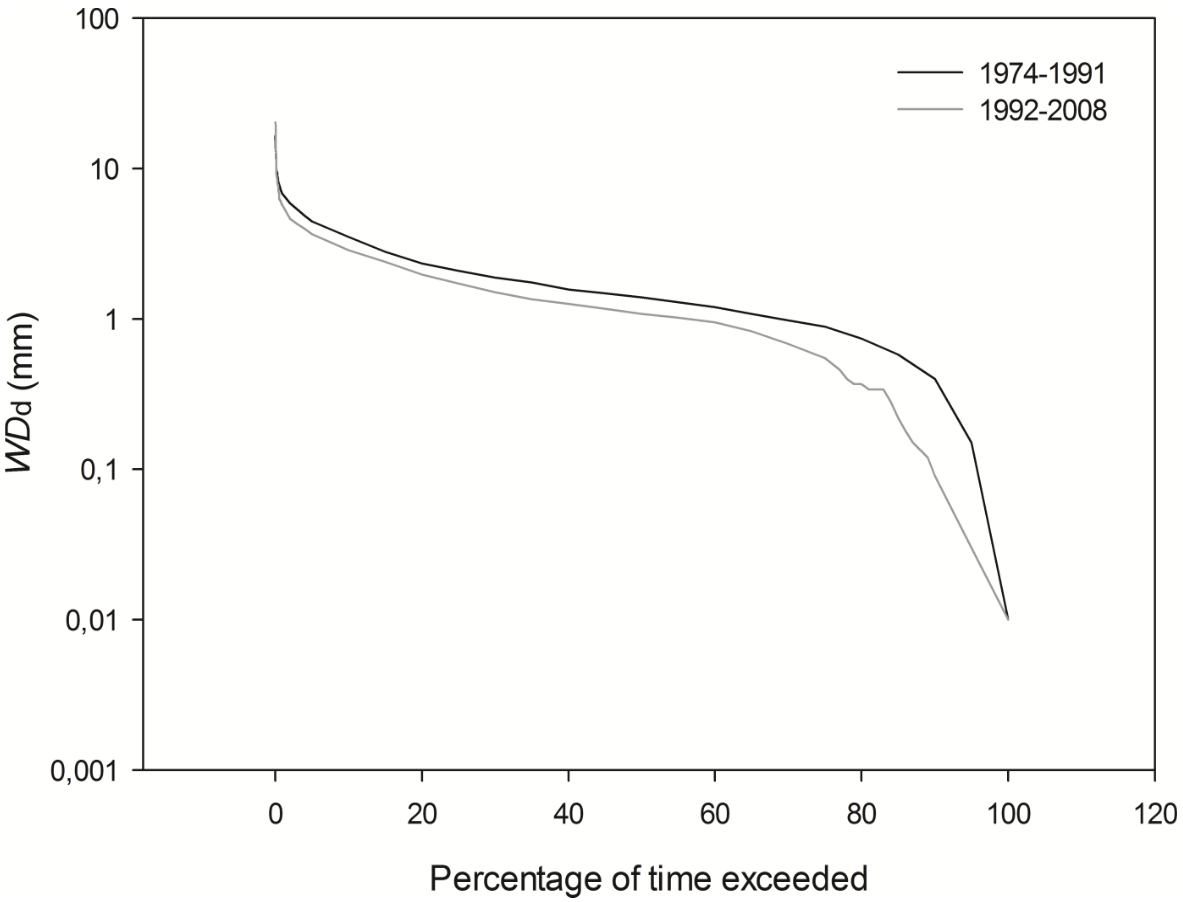

Figure 7. Flow duration curves based on daily observations of equivalent streamflow water depth for the period 1974-1991 (black line) and 1992-2008 (grey line).

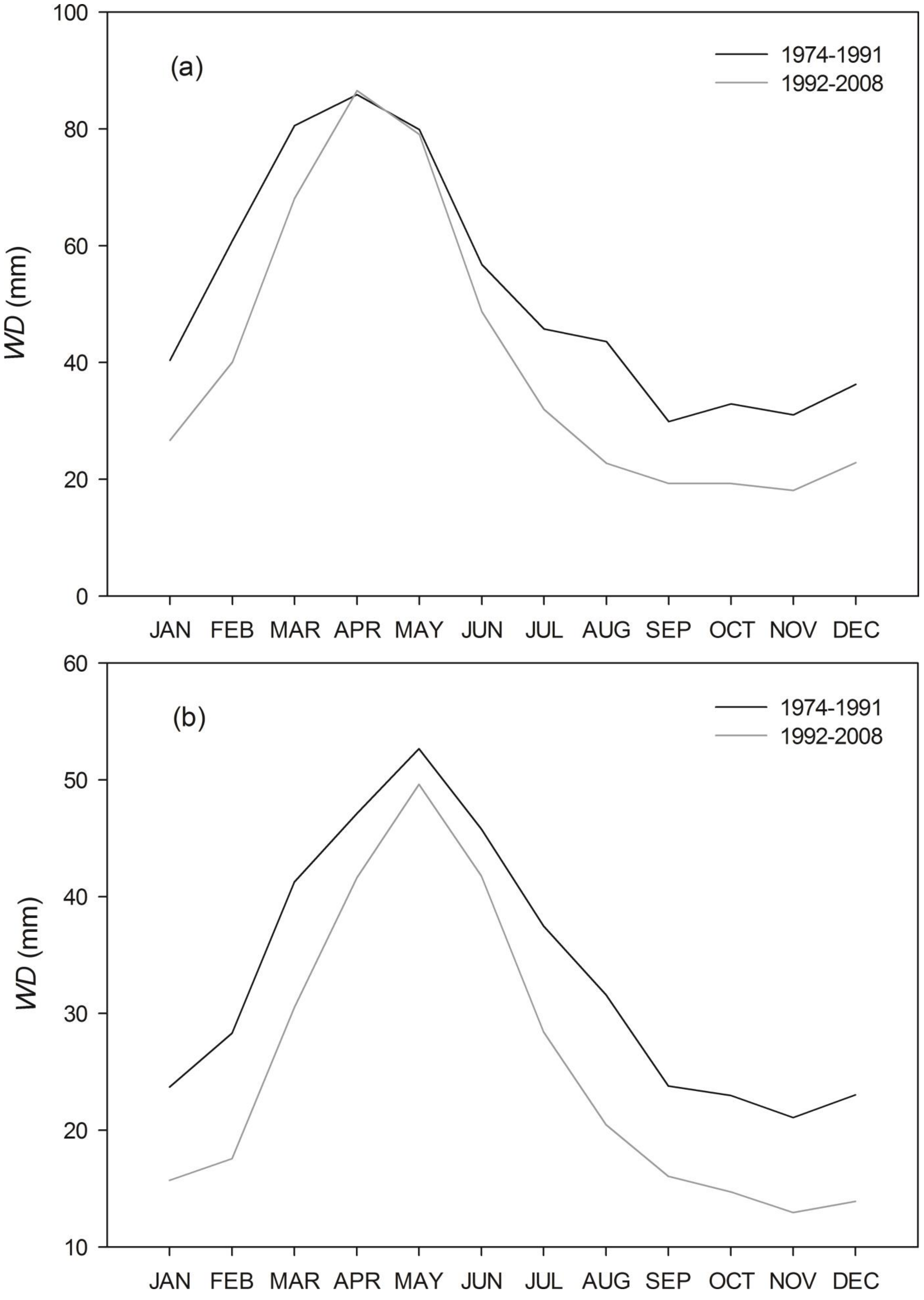

Figure 8. (a) Mean monthly streamflow and (b) mean monthly baseflow for period 1974-1991 (black line) and 1992-2008 (grey line).