Thanks to the Editor by the comments and suggestions in order to improve our article.

The Editor said as a first issue:

"Firstly, from your analysis it is unclear what the causes are of differences in drought recovery found between the catchments. You mention the importance of soil characteristics, but do not show that the soils are more important than the effect of higher precipitation and lower evapotranspiration (as mentioned by yourself in the paper), the effect of rainfall intensity (as mentioned by reviewer 1), the effect of topography and wetlands (as mentioned by reviewer 2), the effect of differences in vegetation type, antecedent conditions, etc."

Answer:

The differences in the hydrological behaviour of the catchments during drought periods were studied by means of a sensitivity analysis as suggested by the Editor. The hydrological conceptual model PDM was used in order to shed light in what could be the most important factor or cause in the drought recovery.

The Editor said as part of the first issue:

"In the abstract and manuscript text confusing statements can be found, claiming the difference is an effect of soil only (abstract, p.1 & p.23), an effect of soil and vegetation type (p.19), an effect of vegetation & evaporative demand (p.20), an effect of potential evaporation & rainfall (p.20), and effect of soil and evaporative demand (p.23). This should be properly analysed and discussed consistently. The effect of soil is counterintuitive, because larger storage normally results in longer drought recovery. So this also needs more discussion."

Answer:

The 'confusing statements' listed have been deleted and the content of the article had also changed drastically in order to take into account the suggestions of the Editor.

The Editor said as part of the second issue:

"Secondly, both reviewers expressed their concern about your use of a model in this study and the validity of the modelling results. In your revised manuscript you did not address these concerns satisfactorily. For example, major point 2 of reviewer 1 has not been answered. Contrary to what you state in reply to that point and in the manuscript, the model does not represent observed flow and soil moisture correctly, especially not during drought. Reviewer 2 recognises that modelling paramo hydrology is difficult, but that does not warrant your claim that the "discrepancy between simulations and observations is low". Also point 2 of reviewer 2 has not been addressed completely. It is still unclear from the manuscript what the model results add to the observational data analysis. There are valid reasons for using a model, but those have not been explored and discussed in your manuscript. In reply to a point about hydrological drought made by reviewer 1, you state that you used the model to investigate drought propagation and hydrological drought recovery, but if you have observational data of precipitation, soil moisture and discharge, you do not need a model for that. Additionally, contrary to your reply to this point by reviewer 1, your Figure 5 does not provide any analysis of drought propagation or hydrological drought recovery. A quantitative comparison of drought propagation and recovery between the catchments and between soil moisture drought and

hydrological drought is a needed addition to the current results. This can also help in providing a better answer to point 1 of reviewer 1, which needs a much more elaborate consideration."

Answer:

As we mentioned before, the content of the article has changed drastically. For instance, the plot scale measurements are not used anymore as it was in the first version of the article. It is because we recognize the scaling issues involved when we try to infer based on that measurement about the hydrological behaviour at the catchment scale. For this reason, the PDM model is used in this version to estimates the actual evapotranspiration and the soil water storage especially during the drought periods. The drought analysis was done based on the simulations of PDM, the point measurements of soil water content (plot scale) are used as a first evidence of the onset of drought events.

The Editor said as a third issue:

"Thirdly, the results are very thin and should be extended. In the Introduction you mention that "the hydrological drought is compared and related to the soil water drought". This is, however, not the case. Hydrological drought is never quantified in this study. This should be included."

Answer:

The soils moisture drought as well as the hydrological drought were quantified in this new manuscript.

The Editor said a four issue:

Finally, there is no discussion in the manuscript. Reviewer 2 pointed out a number of topics that should be discussed in the manuscript. Although you added a few lines of text to the results section, the points raised by the second reviewer require an in-depth discussion of the hydrology of the paramo environment.

In relation with the second reviewer and the hydrology of the paramo ecosystem, the latest improvements about this issue have been properly cited in the article. For instance, Buytaert and Beven, 2011 wrote an interesting article on hydrological modelling of the paramo where it is called "tropical alpine wetlands". In this research, the effect of the topography is incorporated in TOPMODEL by means of a conceptual representation with "a large residence time" or another parameter (tc). In other words, the overland flow has a delay. This parameter tries to conceptualize the hydrological processes observed in the wetlands, the water is storage and the hydrological response at the catchment scale is delayed as consequence of this natural mechanism. Therefore, is just a parameter, the physical process has not modelled. In fact, nothing was done in order to properly include the effect of the connectivity of the landscape. However, this issue is part of our ongoing research. We have installed several piezometers in a wetland in the same experimental area (Calluancay). The results are under analysis and the physical process will be incorporated in a hydrological model framework following the approach proposed by Fenicia et al., 2007 and Kavetski and Fenicia 2011.

Buytaert, W. and Beven, K.: Models as multiple working hypotheses: hydrological simulation of tropical alpine wetlands, Hydrological Processes, 25(11), 1784–1799, doi:10.1002/hyp.7936, 2011.

Fenicia, F., Solomatine, D. P., Savenije, H. H. G. and Matgen, P.: Soft combination of local models in a multi-objective framework, Hydrology and Earth System Sciences Discussions, 4(1), 91–123, doi:10.5194/hessd-4-91-2007, 2007.

Kavetski, D. and Fenicia, F.: Elements of a flexible approach for conceptual hydrological modeling: 2. Application and experimental insights, Water Resources Research, 47(11), W11511, doi:10.1029/2011WR010748, 2011.

To solve these issues a few things need to be done:

- Improve the model for the drought periods, for example by calibrating on the Nash-Sutcliffe value of the logarithm of the discharge values.
- Use the model to extend timeseries of soil moisture (Figure 3), so that you can compare the recovery of other drought events.
- Use the model to do sensitivity analysis, by changing the input (e.g. precipitation or potential evaporation during drought recovery) or the soil type.
- Do a proper analysis of drought propagation and hydrological drought recovery, using a drought analysis method and a quantification of drought recovery.
- Quantify the period of vegetation stress in both catchments to calculate vegetation recovery to drought (point 1 reviewer 1).
- Discuss the uncertainties related to the observation, data analysis and modelling of paramo hydrology. This needs to include the selection of the "representative locations for TDR measurement", the added value of using a model, the difficulties related to modelling, the scaling used for soil moisture, the quantification of drought recovery, the different factors influencing the difference in recovery between the catchments, the significance of the results for understanding paramo hydrology, etc.

Thanks for the suggestions. One by one has been incorporated in the article.

If these major issues are not handled satisfactorily in a revised manuscript I will reject the paper for publication in HESS. In addition to these essential modifications, there are a number of other issues that need to be addressed.

- Your answer to point 1 of reviewer 1 and your clarification of the term "resilience" in the manuscript are satisfactory, but from the revised manuscript I do not see the need to use such a complex and confusing term ("resilience"), when there is a more simple and easy to understand term ("recovery"). I would urge you to take out the resilience theory description and every mention of the word resilience from the title and the manuscript. Also because it leads to erroneous statements such as "the páramo vegetation and soil are more *resilient to drought recovery* as compared to the lower grass vegetation and soil".

- The word "resilience" has been deleted and the word "recovery" is used in order to avoid confusion.

-
- There is a lack of clarity about the time periods of analysis. In the abstract, for example, the periods 2007-2013, 2010-2012 and 2009 & 2010 are mentioned, but it is unclear which time periods were used in which part of the analysis and for which time period the mentioned results are applicable. The same is true for the main text and the Conclusions.
  The observation period for Calluancay is from 2007 up to 2012. While, for Cumbe the observation periods is from 2009 up to 2012. This is clearly detailed in a new table.

- Similarly, the use of catchment names is confusing. For example, in the Introduction on page 3 the Paute catchment is mentioned, a long time before the catchments are introduced in Section 2.1.
- The experimental catchment are located in the highlands of the Paute river basin. We mention this name because previous researches have been done also in the same catchment and easily we can find in the literature the references. Therefore, our results can be used for comparison with the literature.

-
- You should take out the paragraphs about El Nino in the Introduction. As you rightly state, for your study, it is the lack of rainfall that matters and not whether it is caused by El Nino or

by something else. The text about El Nino is not relevant.

All the sentences where the “El Nino” was mentioned has been deleted.

- As I mentioned before, the Introduction is too long and should be shortened. These suggestions above might help with that.

The introduction has been reduced following the suggestion of the Editor.

The hypothesis mentioned on page 6 does not correspond with the objectives explained in the introduction. Where does this hypothesis come from? Do you need it? Is it new? Can it be proven? Would one of the two methods, experimental monitoring vs. mathematical models, not be sufficient? And what is “drought recovery resilience in land cover and soil systems”? In the Conclusions, “the first aim was to estimate the actual evapotranspiration based on continuous time series of soil water content measurements”. This does not correspond to the Introduction and is not followed by a second aim.

The hypothesis mentioned on page 6 has been deleted in order to be consistent with the text

- How is recovery defined? On page 6 you mention that it is “the time needed to recover to its pre drought state of water content once that rainfall has started in a continuous way to exceed the vegetation water demand”. So how is that quantified? What is the pre-drought state of water content? When is P-ET positive in “a continuous way”? You analysed the recovery from the 2010 soil moisture drought from observations in Section 4.2. In Section 4.3, you mention recovery for the 2011 drought (Figure 5), but do not quantify it, not for soil moisture drought nor for hydrological drought. You also mention that the “recovery by the vegetation after drought is good”. How was this recovery quantified?

As I mentioned before, the point measurements of soil water content are not used in the new version of the article. Hence, the drought analysis applied here is based on the threshold method widely used in drought studies. We analysed the complete time series of precipitation, soil water storage (simulated by PDM model) and the stream discharge. Which means, the drought events of 2009, 2010, 2011 and 2012.

Furthermore, a number of textual issues need to be resolved:

- p.10, Qo: how is overland flow measured?
- p.15, lines 21-24: move up to paragraph 3.2
- p.22, line 32: what do you mean with “the proportion of potential water use in the páramo”?
- Check for spelling and grammar errors.

The soil water balance in the root zone at the catchment scale was deleted of the text. Because, it was based on the assumptions of the plot measurements can be a proxy for the average soil water storage at the catchment scale. But, after the analysis we recognize the number of plots is not enough to cover the requirements of a scaling approach. So the textual issues are not present in the new version.

Analysis of the drought recovery ~~resilience~~ of Andosols on southern Ecuadorian Andean páramos

V. Iñiguez [1, 2, 3], O. Morales[1], F. Cisneros[1], W. Bauwens[2], G. Wyseure[3]

[1]{Programa para el manejo del Agua y del Suelo (PROMAS), Universidad de Cuenca, Cuenca, Ecuador}

[2]{Department of Hydrology and Hydraulic Engineering, Earth System Sciences Group, Vrije Universiteit Brussel (VUB), Brussels, Belgium}

[3]{Department of Earth and Environmental Science, KU Leuven, Leuven, Belgium}

Correspondence to: vicente.iniguez@ucuenca.edu.ec

Abstract

The neotropical Andean grasslands above 3500 m a.s.l. known as "páramo" offer remarkable ecological services for the Andean region. Most important is the water supply -of excellent quality- to many cities and villages established in the lowlands of the inter-Andean valleys and to the coast. However, the páramo ecosystem is under constant and increased threat by human activities and climate change. In this paper we study the ~~resilience~~ capacity recovery of its soils for drought periods ~~during~~ observed during ~~the period 2007~~2009 ~~-~~ and 201~~2~~~~3~~. In addition, field measurements and hydrological conceptual modelling at the catchment-scale are comparing two contrasting catchments in the southern Ecuadorian Andes. Both were intensively monitored ~~during two and a half years (2010-2012)~~ in order to analyse the temporal variability of the soil moisture storage. A typical catchment on the páramo at 3500 m a.s.l. was compared to a lower grassland one at 2600 m a.s.l. The main aim was to estimate the severity of the drought periods by means of drought analysis and the ~~resilience capacity of the soils during a drought period and the~~ recovery during a subsequent wet period. Local soil water content measurements in the top soil (first 30 cm) through TDR (plot scale) ~~were used as a proxy for the catchment's average soil moisture storage. The local measurements~~ were compared to the average soil water storage as estimated by the probabilistic soil moisture (PDM) model (catchment scale) in order to reveals the impact of different scales over the drought analysis. This conceptual hydrological model with 5 parameters was calibrated and

validated for both catchments. At the plot scale, ~~–t~~The study reveals ~~the~~ an apparently ~~extraordinary resilience~~high ~~-~~capacity recovery of this type of shallow organic soils during the droughts in 2009 and 2010. During these droughts, the soil water content dropped from a normal value of about 0.80 to ~ 0.60 cm^3 cm^{-3}, while the recovery time was two to three months. This did not occur at lower altitudes (Cumbe) where mineral soils needed about eight months to recover from the drought in 2010. The soil moisture depletion observed in the mineral soils was similar to the Andosols (~~25~~27%), decreasing from a normal value of about 0.~~52~~ 54 to ~ 0.39 cm^3 cm^{-3}, but the recovery was slower. However, at the catchment scale the differences in the capacity recovery are not significant. The precipitation is the main factor in the hydrological response at the catchment scale. ~~Although, the rainfall pattern during the subsequent wet season was quite similar in both catchments (with 860 mm at Calluancay and 710 mm at Cumbe), the recovery of the páramo ecosystem was faster. This can be explained by the larger soil water storage capacity of Andosols and a lower atmospheric evaporative demand by the páramo at higher altitudes.~~ Finally, the drought analysis reveals small deficits for the soil moisture droughts in both experimental catchments.

1 Introduction

In the northern Andean landscape, between ca. 3500 and 4500 m a.s.l., an "alpine" neotropical grassland ecosystem -locally known as "páramo"- covers the mountains. Their major ecological characteristics have been documented by several authors (e.g. Buytaert et al., 2006a; Hofstede et al., 2003; Luteyn, 1999). The páramo is an endemic ecosystem with high biodiversity. Its soils contain an important carbon storage and provide a constant source for drinking water for many cities, villages, irrigation systems and hydro-power plants. During the last years, a high vulnerability of these systems to changes induced by human activities and climate change in mountainous regions has been recognized. Most of the research in páramos has been focused on its hydrological capacity as well as the soil characteristics under unaltered and altered conditions (Buytaert et al., 2007a; Farley et al., 2004; Hofstede et al., 2002; Podwojewski et al., 2002). These researches recognize the key role of the páramos in the water supply in the Andean region. The hydrological capacity is mainly related to the characteristics of its soils. Shallow organic soils -classified according to the World Reference Base for Soil Resources (WRB) as Andosols and Histosols (FAO et al., 1998)- are the two main groups of soils that can be found in this Andean region. In addition, but less frequently,

also Umbrisols, Regosols and other soils may be found. These soils are characterized by high levels of organic matter. They have an immense water storage capacity which reduces flood hazards for the downstream areas, while sustaining the low flows all year round for domestic, industrial and environmental uses.

In the wet páramos that we investigated –and which have a low seasonal climate variability– the high water production can be explained by the combination of a somewhat higher precipitation and -more importantly- a lower water consumption by the vegetation. In these conditions, the role of the soil water storage capacity would not be significant. This is in contrast with páramos with a more distinct rainfall seasonal variability (as e.g. in the western part of the highlands of the Paute river basin), where the hydrological behaviour of the páramo ecosystem is more influenced by the water holding capacity of the soils (Buytaert et al., 2006a). Rainfall ranges between 1000 and 1500 mm $year^{-1}$ and is characterized by frequent, low volume events (drizzle) (Buytaert et al., 2007b). The annual runoff can be as high as of the annual rainfall (Buytaert et al., 2006a). During wet periods the soil moisture content ranges between 80% and 90%, with a wilting point around 40%. So the soil water holding capacity is high as compared to mineral soils. This is a very important factor in the hydrological behaviour of the páramo. This larger storage is important during dry periods and explains the sustained base flow throughout the year. The soil physical characteristics such as porosity and microporosity –which is much higher than what is commonly found in most soil types– explains an important part of the regulation capacity during dry periods. The water buffering capacity of these ecosystems can also be explained by the topography, as the irregular landscape is home to abundant concavities and local depressions where bogs and small lakes have developed (Buytaert et al., 2006a).

Nevertheless, the páramo area is under threat by the advancement of the agricultural frontier. Additionally, flawed agricultural practices cause soil degradation and erosion. Former studies on soil water erosion reveal significant soil loss in the highlands of the Ecuadorian Andean as result of land use changes (Vanacker et al., 2007) but also tillage erosion is responsible for this soil loss and for the degradation of the water holding capacity (Buytaert et al., 2005; Dercon et al., 2007).

Land cover changes have also occurred in páramo. In the seventies, some areas of páramo were considered appropriate for afforestation with exotic species such as *Pinus radiate* and *Pinus patula*. The main goal was to obtain an economical benefit from this commercial

timber. The negative impact of this afforestation and the consequences on the water yield of the páramo have been described by Buytaert et al. (2007b). Also, the productivity was often rather disappointing, due to the altitude.

The potential impact of the climate change over alpine ecosystems has also been reported by Buytaert et al., 2011and Viviroli et al., 2011. Mora et al. (2014) predict an increase in the mean annual precipitation in the region that is of interest to our study. On the other hand, the carbon storage and the water yield could be reduced by the higher temperatures and the higher climate variability. However, the uncertainties on the potential impact of the climate change remain high (Buytaert and De Bièvre, 2012; Buytaert et al., 2010).

~~Another important factor for the region are the El Niño Southern Oscillation events. The Amazon river basin, with its headwaters in the Andes, has indeed faced severe droughts in 2005 and 2010 (Lewis et al., 2011; Phillips et al., 2009). These dry periods have been attributed to the severe El Niño Southern Oscillation events and northwest displacement of the intertropical convergence zone (ITCZ) (Marengo et al., 2008, 2011).~~

~~The El Niño Southern Oscillation events not only have an impact on the eco-hydrology of the forest area of the Amazon River basin but also in its headwaters on páramos. Indeed, the droughts in the páramo have been observed during the months with less rainfall (from September to December), which coincide with the displacement of the ITCZ and by the Pacific and Atlantic anomalies (Buytaert et al., 2006b; Vuille et al., 2000). Thus, the climate variability in the mountains is exacerbated by these climate global events.~~

~~Important dry periods and droughts in the páramo took place between 2005 and 2012. According to the monthly Niño 3.4 index published by the National Oceanic and Atmospheric Administration (NOAA) (which is used to calculate the Ocean Niño Index – ONI- values), the periods of November 2009 up to February 2010 and from August 2010 up to February 2011 were classified as a moderate El Niño(+) and La Niña(-) events respectively (Yu and Kim, 2013; Yu et al., 2011). The maximum sea surface temperature (SST) anomalies registered in the Pacific Ocean (Region 3.4 Average) during those periods were +1.42 and -1.46 respectively. A strong El Niño or La Niña event is considered when the absolute value of the SST is between 1.5 and 2. A value higher than 2 (+/-) points to a very strong event. Of course the main issue is the lack of rainfall regardless whether it coincides with El Niño or not.~~ On the other hand, ~~T~~the occurrence of drought periods in the páramo have had a negative impact on the water supply and on the economy of the whole region that depends on water

supply from the Andes. For instance, the water levels in the reservoir of the main hydropower project in the Ecuadorian Andes –the Paute Molino project– reached their lowest values as a consequence of the drought between December 2009 and February 2010. This caused several, intermittent, power cuts in many regions of Ecuador. The power plant's capacity is 1075 MW. In that period the Paute Molino hydropower provided around 60% of Ecuador's electricity (Southgate and Macke, 1989).

The hydrological regulation and buffering capacity of the páramo resides in its soils. Therefore the present study investigates the response of páramo soils to drought and compares with other soils on grasslands at lower altitude in the same region. The drought analysed is a ~~soil moisture~~ hydrological drought as defined by Van Loon (2015)~~, who classifies the droughts into the following four categories:~~

~~"***Meteorological drought*** *refers to period with a precipitation deficiency, possibly combined with increased potential evapotranspiration, extending over a large area and spanning an extensive period of time*."~~

~~"***Soil moisture drought*** *is linked to a deficit of soil moisture (mostly in the root zone), reducing the supply of moisture to vegetation."~~

~~"***Hydrological drought*** *is a broad term related to lower than usual surface and subsurface water resources. This can be observed by below normal groundwater levels, lower water levels in lakes, declining wetland area, and decreased river discharge as compared to normal situations."~~

~~"***Socioeconomic drought*** *is associated with the impacts of the three above mentioned types."~~

~~On the other hand, resilience is a widely used concept in many areas of natural, human, medical and engineering sciences. This leads to a wide range of definitions and interpretations depending on the scientific domain. Broadly speaking we can classify the definitions into two groups:~~

- ~~**Robustness definitions**: the ability or resistance of the subject under study to withstand a level of disturbance without entering into an unwanted state as compared to the state before the disturbance~~
- ~~**Recovery definitions**: The rapidity of the subject under study to regain initial pre-stressed state after the exposure to a level of disturbance.~~

~~The latter definition is also called the "engineering resilience" and requires a quantitative and system analysis approach. The first definition is most common in medicine and psychology. Both definitions are used in different situations and sciences and have their merits.~~

~~In ecosystems research the **robustness** definition is often preferred. For instance, in the review article on ecological resilience by Gunderson, (2000); "*In this case* [ecological resilience using the robustness definition]*, resilience is measured by the magnitude of disturbance that can be absorbed before the system redefines its structure by changing the variables and processes that control behaviour. This has been dubbed ecological resilience in contrast to engineering resilience*".~~

~~In order to avoid confusion with "robustness resilience", the definition of "recovery resilience" will be used. Since t~~The major point in our research is to analysis the recovery speed of the páramo soils after drought periods ~~the use of "recovery resilience" ("engineering resilience") is fully appropriate~~. Indeed, our hydrological perspective serves -in the first place- the downstream users.

~~So, the recovery resilience to drought is defined here as the time needed to recover to its pre-drought state of water content once that rainfall has started in a continuous way to exceed the vegetation water demand. The pre-drought state of soil water content is estimated from longer term periods whereby rainfall exceeds the vegetation requirements.~~ The observation period includes the droughts of 2009, 2010, 2011 and 2012 together with intermediate wet periods. ~~The analysis is done with special focus on the 2010 drought.~~

The hydrological drought is compared and related to this soil water drought by means of an analysis of the drought propagation. For this purpose, ~~the water balance components of~~ two experimental catchments –one with and one without páramo– were investigated ~~by means of experimental measurements and~~ by means of a hydrological model. In addition, the results from the hydrological model and drought analysis in terms of soil water storage were compared with the data gathered from experimental plots implemented in each catchment. The experimental work included the measurement of rainfall, climate, flow and soil moisture (TDR probes installed in experimental plots, one for each catchment). For the modelling, a parsimonious conceptual hydrological model –using the Probability Distributed Moisture simulator (PDM)– was calibrated and validated for each experimental catchment. The PDM model allows to analyse the spatial variability of the soil water content as well as the

maximum storage capacity at the catchment scale. ~~Therefore, the representativeness of the point measurements of soil water content can be assessed by means of this model.~~

In this context, the hydrological model used in the research (PDM model) is the link between the soil moisture storage (as indicator for soil water drought) and the stream discharge (as indicator for the hydrological drought).

~~Our main hypothesis is that experimental monitoring combined with mathematical models enables the quantification of drought recovery resilience in land cover and soil systems in the Andes above 2600 m a.s.l.~~

2 Materials

2.1 The study area

The catchments under study are located in the southwest highlands of the Paute river basin, which drains to the Amazon River (Fig. 1). These highlands form part of the Western Cordillera in the Ecuadorian Andes with a maximum altitude of 4420 m a.s.l. The study area comprises a mountain range from 2647 until 3882 m a.s.l. Two catchments have been selected from this region: Calluancay and Cumbe.

The Calluancay catchment has an area of 4.39 km^2 with an altitude range between 3589 and 3882 m a.s.l. and a homogeneous páramo cover. The páramo vegetation consists mainly of tussock or bunch grasses and very few trees of the genus *Polylepis*. These trees are observed in patches sheltered from the strong winds by rock cliffs or along to some river banks in the valleys. Furthermore, in saturated areas or wetlands huge cushion plants are surrounded by mosses. This vegetation is adapted to extreme weather conditions such as low temperatures at night, intense ultra-violet radiation, the drying effect of strong winds and frequent fires (Luteyn, 1999). The land use of Calluancay is characterized by extensive livestock grazing.

The second catchment, Cumbe, drains an area of 44 km^2. The highest altitude reaches 3467 m a.s.l., whereas the outlet is at an altitude of 2647 m. This altitude range of almost 1000 m defines a typical Andean mountain landscape with steep slopes and narrow valleys where the human intervention is also evident. This catchment is below the 3500 m and therefore contains a negligible area of páramo. The most prominent land cover is grassland (38.1%) along with arable land and rural residential areas (26.9%). A sharp division between the residential areas and the small scale fields is absent. Mountain forest remnants are scattered

and cover 23% of the area, often on the steeper slopes. At the highest altitude (>3300 m) sub-páramo is predominant; it occupies only 7.6% of the catchment. In the Cumbe, about 4.4% of the area is degraded by landslides and erosion.

A small village, "Cumbe", is located in the valley and on the lower altitudes of the catchment. This village has ca. 5550 inhabitants. The water diversions from streams in Cumbe are ca. 12 [L s^{-1}] in total, mainly for drinking water. The village has no waste water treatment and used water is discharged via septic tanks. Additionally, during dry periods two main open water channels for surface irrigation are enabled. The water diversion and its rudimentary hydraulic structures have been built upstream of the outlet of the catchment. These irrigation systems deliver water to the valley area occupied by grasslands and small fields with crops.

Several types of soils can be identified in Cumbe and Calluancay, which are mainly conditioned by the topography. Dercon et al. (1998, 2007) have described the more common toposequences in the southern Ecuadorian Andes according to the WRB classification (FAO et al., 1998). Cumbe has a toposequence of soils from Vertic Cambisols, located in the alluvial area, surrounded by Dystric Cambisols at the hillslopes in the lower and middle part of the catchment. Eutric Cambisols or Humic Umbrisols extend underneath the forest patches between 3000 and 3300 m a.s.l. The highest part of the catchment -from 3330 until 3467 m a.s.l.- is covered by Humic Umbrisols or Andosols.

In contrast, Calluancay is characterized by two groups of organic soils under páramo: Andosols (in the higher and steeper parts) and Histosols (in the lower and gentler parts of the catchment). The soils were formed from igneous rocks such as andesitic lava and pyroclastic igneous rock (mainly the Quimsacocha and Tarqui formations, dating from the Miocene and Pleistocene respectively), forming an impermeable bedrock underneath the catchment. In the Cumbe catchment, the highlands and some areas of the middle part (about 55% of the area) are characterized by pyroclastic igneous rocks (mainly the Tarqui formation). The valley area (37% of the basin) is covered by sedimentary rocks like mudstones and sandstones (mainly the Yunguilla formation, dating from the upper Cretaceous). Only 8% of the Cumbe catchment comprises alluvial and colluvial deposits, which date from the Holocene (Hungerbühler et al., 2002).

2.2 The monitoring data

An intensive monitoring with a high time resolution was carried out in the study area during 28 months.

The gauging station at the outlet of Cumbe consists of a concrete trapezoidal supercritical-flow flume (Kilpatrick and Schneider, 1983) and a water level sensor (WL16 - Global Water). Logging occurs at a 15 minute time interval. Regular field measurements of the discharge were carried out to cross-check the rating curve. Initially a smaller catchment, similar in size to the Calluancay, was also equipped within the Cumbe catchment but a landslide destroyed and covered this flume. So, unfortunately no data were collected.

The measurements at Calluancay are part of a larger hydrological monitoring network maintained by PROMAS. Water levels are logged every 15 minutes at two gauging stations, which consist of a concrete V-shaped weir with sharp metal edges and a water level sensor (WL16- Global Water). The first station is installed at the outlet of the catchment. The second gauging station monitors an irrigation canal to which water is diverted from the main river. The gauging station was installed where the canal passes the water divide of the catchment. So, the total discharge can be evaluated.

For the Calluancay, rainfall is measured by a tipping bucket rain gauge (RG3M-Onset HOBO Data Loggers) located inside the catchment and with a resolution of 0.2 mm.

Three similar rain gauges were installed in the larger Cumbe catchment and located at the high, middle and lower part of the catchment. The areal rainfall for Cumbe was calculated with the inverse distance weighing (IDW) method, using the R implementation of GSTAT (Pebesma, 2004).

In each experimental catchment an automatic weather station measured the meteorological variables such as air temperature, relative humidity, solar radiation and wind speed at a 15 minute time interval. These stations were used to estimate the potential reference evapotranspiration according to the FAO-Penman-Monteith equation.

2.3 The physical characteristics of the soil

In both catchments, the soil moisture content of the top soil layer was measured by means of time domain reflectometry (TDR) probes at representative sites in the vicinity of the weather stations. In each catchment there was one plot equipped with 6 TDR's with a data-logger.

As TDR-sensors with data-logger per plot require a very large investment, the locations for the TDR measurements were carefully selected based on a digital terrain analysis, the soil and land cover maps and field surveys (soil profile pits). In Calluancay, the soil information was created by former studies carried out in the study area by PROMAS between 2007 and 2009. In this period, a soil map (scale 1:10 000) -which cover the whole altitudinal range of paramo (3500-3882 m a.s.l.)- was generated based on soil descriptions of 2095 vertical boreholes and 12 soil profile pits. In each soil profile pits a complete set of chemical and physical analysis were done. Meanwhile, in Cumbe 13 soil profile pits were carried out during the field campaign as part of the present research. To this purpose, 4 cross section transects were established. Thus, the field survey in Cumbe was designed to cover the whole altitudinal range (2647 – 3467 m a.s.l.). ~~So~~Therefore, this soil information was incorporated in the analysis and used in the~~we~~ selection~~ed~~ of representative locations for the TDR in each catchment~~.~~

The TDRs were installed vertically from the soil surface with a length of 30 cm and logged at 15 minute time intervals. In Calluancay, every fortnight soil water content was also measured by sampling from November 2007 until November 2008. In this catchment the TDR time series was from May 2009 until November ~~2013~~2012. In Cumbe, the TDR-time series extends from July 2010 until November 2012.

For Cumbe and Calluancay, the TDR probes were calibrated based on gravimetric measurements of soil moisture content, using undisturbed soil samples (r^2 = 0.79 and 0.80 respectively). In addition, the curves were regularly cross-validated by undisturbed soil samples during the monitoring period.

The soil water retention curves were determined based on undisturbed and disturbed soil samples collected near to the TDR probes. In the laboratory, pressure chambers in combination with a multi-step approach allowed to define pairs of values for moisture (θ) and matric potential (h). The soil water retention curve model proposed by van Genuchten (1980) was fitted on the data.

3 Methods

~~3.1 The water balance based on the experimental data~~

~~The soil water balance of the root zone in each catchment over a selected time interval is estimated by the following equation:~~

$$\frac{\Delta S_r}{\Delta t} = P - E_a - Q_o - Q_i + C_r - D_p \quad (1)$$

~~Where:~~

~~ΔS_r = the storage variation in the root zone during the time interval [mm],~~

~~Δt = the length of the time interval [days],~~

~~P = the precipitation intensity during the time interval [mm day^{-1}],~~

~~E_a = the actual evapotranspiration rate during the time interval [mm day^{-1}],~~

~~Q_o = the overland flow during the time interval measured at the outlet of the catchment [mm day^{-1}],~~

~~Q_i = the lateral flow during the time interval [mm day^{-1}],~~

~~C_r = the capillary rise from a water table during the time interval [mm day^{-1}],~~

~~D_p = the deep percolation rate during the time interval [mm day^{-1}].~~

3.1 Catchment hydrology

Here, we try to infer about the main hydrological processes present in the experimental catchments. This is based on field observations, measurements and literature. We focus in the rainfall-runoff processes and in the components of the soil water balance of the root zone in each catchment. Therefore, we start with ~~In the~~ Cumbe catchment where some water is diverted from the river for irrigation. As a result the flow at the outlet is reduced by the amount of irrigation. This irrigation is mainly concentrated in the valley and is rather informal by small farmer constructed offtakes without major hydraulic structures. In addition there are no irrigation associations present and therefore an estimation of this withdrawal is very

difficult. Therefore, a significant uncertainty during dry periods is expected in the stream discharge data *(Q)* at the outlet of the catchment.

Based on geological data, in Calluancay the deep percolation (D_p) and capillary rise (C_r) fluxes are considered to be negligible since the soils overlay bedrock consisting of igneous rocks with limited permeability. In páramos, saturation overland flow is the dominant flow process of runoff generation (Buytaert and Beven, 2011). The stream discharge (Q) at the outlet of the catchment thus comprises mainly overland flow and lateral flow.

In Cumbe, a surface-based electrical resistivity tomography test (Koch et al., 2009; Romano, 2014; Schneider et al., 2011) revealed no significant shallow groundwater for the alluvial area. In addition, the flat alluvial area near the catchment outlet is very small (2.7 % of the catchment area). Therefore, ~~the terms~~ D_p and C_r are also regarded to be negligible.

Based on the soil texture in Cumbe (clay) it is inferred that the infiltration overland flow is the dominant flow process of runoff generation. ~~–~~As a result, the stream discharge in Cumbe consists, as in Calluancay, by two kinds of flows: overland and lateral flow.

Considering that the overland flow (Q_o) and the lateral flow constitute the observed river flow, Q, the water balance in our two catchments can thus be written as:

$$\frac{\Delta S_c}{\Delta t} = P - E_a - Q \qquad (1~~a~~)$$

Where:

ΔS_c = the average storage variation in the soil of the catchment during the time interval [mm],

P = the precipitation intensity during the time interval [mm day^{-1}],

E_a = the actual evapotranspiration rate during the time interval [mm day^{-1}],

Q = the total runoff leaving the catchment during the time interval [mm day^{-1}].

The Eq. (1) is a classical mathematical expression used in many conceptual hydrological models and will be analysed afterwards in the item related to hydrological modelling. But, as a first step in order to apply Eq. (1), the potential evapotranspiration has to be estimated.

~~If we consider that P and Q are measured and we assume that the change of storage can be estimated based on the TDR measurements in our sampling points (as shown in the results section), the actual evapotranspiration is the only unknown in this equation.~~

~~During wet periods the water content in the root zone remains constant at field capacity. The continuity equation may then be reduced to:~~

~~$$E_a = P - Q \quad (1b)$$~~

3.1.1 The potential evapotranspiration

The FAO-Penman-Monteith approach (Allen et al., 1998) is used to estimate the potential evapotranspiration of a reference crop (grass):

$$E_p = \frac{0.408\Delta(R_n - G_h) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

Where:

E_p = the potential reference evapotranspiration [mm day^{-1}],

R_n = the net radiation at the crop surface [MJ m^{-2} day^{-1}],

G_h = the soil heat flux density [MJ m^{-2} day^{-1}],

T = the mean daily air temperature at 2 m height [^{o}C],

u_2 = the wind speed at 2 m height [m s^{-1}],

e_s = the saturation vapour pressure [kPa],

e_a = the actual vapour pressure [kPa],

$e_s - e_a$ = the saturation vapour pressure deficit [kPa],

Δ = the slope of the vapour pressure curve [kPa $^oC^{-1}$],

γ = the psychrometric constant [kPa $^oC^{-1}$].

The suitability of the FAO-Penman-Monteith approach for high altitudinal areas has been evaluated by Garcia et al. (2004). They found that the FAO-approach gives the smallest bias (-0.2 mm day^{-1}) as compared to lysimetric measurements.

The measurements of the solar radiation in our experimental catchments were not consistent and appeared to be unreliable. Therefore, the FAO-Penman-Monteith estimation for E_p was used with the solar radiation estimated by means of the Hargreaves-Samani equation (Hargreaves and Samani, 1985) using the daily maximum and minimum air temperature:

$$R_s = R_a \, c \, (T_{max} - T_{min})^{0.5} \qquad (3)$$

Where:

R_s = the solar radiation [MJ m^{-2} day^{-1}],

R_a = the extra-terrestrial solar radiation [MJ m^{-2} day^{-1}],

c = an empirical coefficient [-],

T_{max}, T_{min} = the daily maximum and minimum air temperature respectively [^oC],

According to Hargreaves and Samani (1985) "c" has a value of 0.17 for inland areas.

3.1.2 The actual evapotranspiration

The FAO-Penman-Monteith approach is used to calculate the potential evapotranspiration of a reference crop (normally grass) under stress free conditions without water limitation (E_p). This reference crop evapotranspiration can be converted to the evapotranspiration of another vegetation type by means of a vegetation coefficient k_v. During dry periods, with water stress,

the vegetation extracts less water as compared to the vegetation requirement. The relative reduction of the evapotranspiration due to this may be expressed by a water stress coefficient k_s.

The actual evapotranspiration, E_a, can thus be calculated as:

$$E_a = k_s \cdot k_v \cdot E_p \quad (4)$$

In general, k_v is time-dependent, as it is linked to the growth cycle of the vegetation and thus to the season. For the páramo, this seasonality may be neglected as the grasses are slow-growing and perennial. ~~In our study we therefore calculate a constant k_v by considering wet periods (during which k_s=1) and using Eq. (4), in combination with the equations 1b (for calculating E_a) and 2 (for calculating E_p). Hereby, the wet periods were identified based on the TDR measurements of the soil water content.~~

Below the critical water content, E_a becomes less than the vegetation requirement and the soil water stress coefficient ~~may be calculated as~~ can be estimated based on the soil water contents (Seneviratne et al., 2010):

~~$$k_s = 1 - \frac{\theta_{crit} - \theta_{act}}{\theta_{crit} - \theta_{wp}} \quad (5)$$~~

~~Where θ_{crit} is the critical soil water content, θ_{act} is the actual soil water content and θ_{wp} is the permanent wilting point of the soil.~~

~~With k_v derived during wet periods as described above, k_s can now be estimated as a function of the actual soil moisture content by considering the (daily) water balance during dry periods. To do so, we combine the equations 1a, 4, 2 and 5. If we consider that the permanent wilting point can be derived from the soil water retention curve, based on the soil and vegetation characteristics, the critical soil water content is the only parameter that needs to be determined.~~

3.2 The actual evapotranspiration estimated by hydrological modelling

The actual evapotranspiration estimation ~~based on local soil water measurements is compared to the actual evapotranspiration~~ at catchment-scale is calculated by the PDM model (Moore and Clarke, 1981; Moore, 1985). This hydrological model will be used to assess the impact of the soil moisture on the evapotranspiration. The PDM is a lumped rainfall-runoff model and its structure consists of two modules. The first is a soil moisture accounting (SMA) module which is based on a distribution of soil moisture storages with different capacities used to account for heterogeneity in the catchment. The probability distribution used is the Pareto distribution. The second part of the model structure is a routing module which consist of two linear reservoirs in parallel in order to consider the fast and slow flow pathways respectively. As in our study we consider small basins at a daily time step, the routing component is not so critical. The PDM model has been implemented within a MATLAB toolbox with the option of calculating the actual evapotranspiration E_a as a function of the potential evaporation rate E_p, and the soil moisture deficit (Wagener et al., 2001):

$$E_a = \left\{1 - \left[\frac{(S_{max} - S(t))}{S_{max}}\right]\right\} \cdot E_p \quad (6)$$

Where, S_{max} is the maximum storage and $S(t)$ is the actual storage at the beginning of the interval. A description of the model parameters is provided in Table 2.

The actual evapotranspiration estimated by PDM model can be compared with the potential evapotranspiration -Eq. (4)- in order to assess the impact of the vegetation and stress coefficients.

3.2.1 ~~Comparison between the experimental water balance and the~~Implementation of the PDM model

~~The comparison between the experimental local water balance and the PDM model is carried out for the time period between July 2010 and November 2012, since that is the period for which the hydrological data are available for both catchments.~~

A split sample test is performed in order to assess the performance of the PDM model and so, calibration and validation periods are established (Klemeš, 1986). The collected data contain wet and dry periods.

To implement the PDM model, an exploratory sensitivity analysis is done in order to define the feasible parameter range. The sampling strategy applied is a Latin Hypercube sampling with a genetic algorithm (Stocki, 2005). Afterwards, the parameters of the PDM model were optimized by means of the Shuffled Complex Evolution algorithm (Duan et al., 1992).

The measured soil moisture data are not used as input variables to the model. However, as most hydrological models the PDM model generates internally state and output variables. These internal derived variables include effective rainfall, actual evapotranspiration, simulated discharge and average distribution characteristic values of the soil moisture storage including their average.

After calibration/validation of the PDM model parameters based on the discharge the simulated PDM average soil water content can be compared to the measured soil water content. The comparison is carried out just to see if the PDM model parameters have physical meaning. However, the average soil water content simulated by PDM will be used in the drought analysis.

~~The soil water storage data will be scaled in order to make the comparison by means of the Eq. (7).~~

$$S_r = \frac{S_o - S_{min}}{S_{max} - S_{min}} \quad (7)$$

~~Where:~~

~~S_r = the time series of soil water storage scaled (0-1) [-],~~

~~S_o = the time series of soil water storage with its original values [mm],~~

~~S_{min} = the daily minimum soil water storage value [mm],~~

~~S_{max} = the daily maximum soil water storage values [mm].~~

In the PDM, there is no explicit modelling of soil surface evaporation, and therefore it cannot estimate the soil water storage below the wilting point. The model is calibrated on runoff and the soil water storage was never extracted up to wilting point. The volumetric water storage at wilting point, which is in Andosols and Histosols around 40%, is therefore not actively represented in the model and can be considered as dead storage from the modelling point of view. ~~The scaling is therefore justified in order to compare the temporal pattern.~~

3.3 Drought analysis

The threshold level approach will be used to identify and quantify the severity of drought periods. This approach has been used in several researches around the world (Andreadis et al., 2005; Van Lanen et al., 2013; Van Loon et al., 2014). To this purpose, the time series of precipitation (*P*), stream discharge (*Q*) and the average soil water content simulated by PDM (*SM*) are analysed according to the following approach (Van Loon et al., 2014):

-In this study a monthly threshold based on the 80th percentile of monthly duration curves of *P* (after applying a 10 day moving average), *SM* and *Q*. The threshold is however smoothed by means of a 30 day moving average. This type of smoothing is required to remove the stepwise pattern and avoid artefact droughts at the beginning or end of a month (Van Loon, 2013).

-Drought characteristics are determined based on a deficit index:

$$d(t) = \begin{cases} \tau(t) - x(t) & if\ x(t) < \tau(t) \\ 0 & if\ x(t) \geq \tau(t) \end{cases} \quad (7)$$

Where, $x(t)$ is the hydrometeorological variable on time t and $\tau(t)$ is the threshold level of the hydrological variable on time t. The units are mm day^{-1} and time t is measured in days. The deficit of drought event i (D_i) is then given by

$$D_i = \sum_{t=1}^{T} d(t) \,.\, \Delta t \quad (8)$$

in which D_i is in mm. The deficit is standardized divided by the mean of the hydrometeorological variable $x(t)$. A physical interpretation of standardized deficit is the number of days with mean flow required to reduce the deficit to zero (Van Loon et al., 2014).

The standardized deficit is also applied to the soil moisture simulated by PDM. The deficit approach is physically meaningless for state variables, however, it still gives an acceptable indication of the severity of a drought event.

In addition to the standardized deficit, we use for precipitation the consecutive dry days (CDD) as an extreme climate indicator. So, the maximum number of CDD ($P_{day} < 1$ mm) is the index employed to measure the drought conditions (Griffiths and Bradley, 2007).

3.3.1 Drought propagation

Here, we analysis the translation -as a chain of hydrological processes- of the meteorological drought through the hydrological cycle and its impact in the soil water storage (soil moisture drought) and over the hydrological response of the catchments (hydrological drought). The recovery after drought periods are analysed in the context of the drought propagation. Since, we are interested in the recovery of the soils after the droughts, the average soil water storage -simulated by PDM- during wet periods is considered the normal value. Based on this value, the time and speed of recovery of the soils will be analysed.

3.3.2 Vegetation stress and recovery

The vegetation stress periods are identified based on times series of potential evapotranspiration (E_p) and P. To do that, a similar procedure implemented by the FAO is considered here. The FAO defines the growing period as a period during a year when the precipitation exceeds the half potential evapotranspiration or in other words when there is enough water to cover the crop requirements (Allen et al., 1998). The opposite is considered as a dry period. So, a vegetation stress period in our catchments is identified when half potential evapotranspiration exceeds precipitation for a specific period of time (e.g., 10-days or monthly data). In the present research, monthly data are used in order to establish the stress periods. After the drought periods, when the wet season starts the P reaches values to cover the deficit of soil water and the vegetation starts to recovery. These periods are also identified based on the monthly data of P and E_p.

3.3.3 Sensitivity analysis

A sensitivity analysis is carried out by means of PDM model in order to reveals which is the most important factor in the recovery of the soils after drought periods. The factors are climate -precipitation and potential evapotranspiration- and soils. The vegetation is also important because prevents soil erosion and promotes the infiltration. But, in terms of water storage its capacity is relative small as compared with the soils. In other ecosystems -like in forest- the storage capacity and role in the hydrology could be significant. For these reasons, the vegetation factor is not considered in the sensitivity analysis. In addition, the land cover in both catchment are relatively similar (two different types of grasslands). The main difference of the vegetation resides in the shape of the leaves and the adaptations to cold weather in the case of Calluancay (paramo).

The sensitivity analysis implemented is relatively simple, the parameters set obtained during the calibration procedure -which basically reassembles the soil water storage characteristics for each catchment- is the first factor (S). The second and third factors are precipitation (P) and potential evapotranspiration (E_p). Two scenarios were regarded: 1) For Calluancay, the parameters which defined the S were not modified in the model but P and E_p observed in Cumbe were used as input data in order to assess the impact on S. The same scenario was applied to Cumbe, the S defined by the parameters set calibrated were not modified but P and E_p registered in Calluancay were regarded as input data to the model of Cumbe. 2) The S and P in both catchments were not modified but the E_p was exchanged.

4 Results and discussion

~~### 4.1 The potential evapotranspiration derived from soil water observations~~

4.24.1 ~~4.1.1~~ The potential evapotranspiration

The potential reference evapotranspiration (E_p) for the period from 16 July 2010 until 15 November 2012 was calculated by the FAO-Penman-Monteith approach with the solar radiation estimated by Hargreaves-Samani. The daily average of E_p for Calluancay and Cumbe was 2.35 and 3.04 mm day^{-1} respectively. The temporal variation of E_p is depicted in Fig. 2. It reveals a sinusoidal pattern with higher atmospheric evaporative demand during the

drier months (from August to March) and a lesser demand during the subsequent wet periods (from April to July). E_p ranged between 0.76 and 4.17 mm day^{-1} for Calluancay and between 1.56 and 4.62 mm day^{-1} for Cumbe. The difference can be attributed to the altitude difference between both catchments, with 900 m difference in elevation. The daily average minimum and maximum temperatures in Calluancay were 3.0 and 10.2 ^{o}C respectively. While, in Cumbe they were 7.8 and 17.4 ^{o}C. In addition, the wind speed is different in both catchments. Calluancay is very exposed to prevailing winds while Cumbe is relatively sheltered. The daily average wind speed for Calluancay and Cumbe are 4.2 (max: 11.9) and 0.9 (max: 2.6) m s^{-1} respectively.

~~4.1.2 The vegetation coefficient~~

~~The time series during a wet period ranging between November 2007 and November 2008 (about a year) was used to estimate the vegetation coefficient, k_v for Calluancay. During this time period, the water content shows values greater or equal to field capacity (0.835 cm^3 cm^{-3}) (Table 1). So, this period is water stress free and k_s was set to 1. For this wet period, k_v was estimated as 0.63. Similar but somewhat lower values in the range of 0.42 to 0.58 have been reported in the literature (Buytaert et al., 2006c). Variations in water use are sometimes explained by extensive livestock grazing, frequent burns of páramo and fertilization, which lead to a more vigorous and green vegetation with a larger k_v. Normally the páramo contains a lot of dead brown leaves with a low vegetation coefficient.~~

~~For Cumbe, the wet period observed between February and April 2012 was used to estimate k_v. The soil moisture values for that period are near to the field capacity (0.531 cm^3 cm^{-3}). Therefore, this wet period can equally be considered water stress free. The vegetation coefficient was estimated to be 0.82. This value is consistent with the values established in the literature for grazing pastures (Allen et al., 1998), which are rather extensive and rough without high levels of fertilizer or cattle density.~~

~~Finally, the evapotranspiration derived from wet periods as identified by the soil water measurements in Calluancay and Cumbe was: 1.27 (range 0.53 to 2.35) and 2.51 (range 1.93 to 3.02) mm day^{-1} respectively.~~

4.1.3 The water stress coefficient and the critical soil water content

The values of the k_v coefficient estimated during wet stress free periods for both páramo vegetation (Calluancay) and for grazing pastures (Cumbe) are used during the drought period in 2010, to estimate the water stress coefficient and the critical soil water content. The latter are calculated by considering the soil water balance approach at the root zone during the pre-mentioned dry period. Based on the soil water observations, a suitable dry period was selected for each catchment. The water balance equation can be applied for Calluancay and Cumbe from July 2010 until February 2012. These periods show a negligible difference in root zone storage variation between start and end (Fig. 3).

Therefore, the water balance approach can be applied in both catchments. The critical water content in Calluancay was found to be 0.81 $cm^3 \cdot cm^{-3}$. This value is very close to the field capacity, as determined in the laboratory (Fig. 3a). The Andosols have typically an extreme high water retention capacity (Buytaert et al., 2006a). The critical moisture in Cumbe was 0.50 $cm^3 \cdot cm^{-3}$. This value is also near to the field capacity, as determined in the laboratory (Fig. 3b). Critical soil moisture values between ca. 50-80% of field capacity are reported in the literature (Seneviratne et al., 2010). However, most of them correspond to mineral soils in the context of crop water requirements and therefore those values cannot be applied for the present study. High critical soil moisture could be partially explained by the plant physiology. It is important in páramo because the tussock grasses (mainly *Calamagrostis* spp. and *Stipa* spp.) are characterized by specific adaptations to extreme conditions. For instance, the plants have scleromorphic leaves which are essential to resist intense solar radiation (Ramsay and Oxley, 1997). In addition, the plants are surrounded by dead leaves that protect the plant and reduce the water uptake. In other words, the combination of the xerophytic properties and other adaptations to a high radiation environment together with the dead leaves lead to a lower water demand as compared to the reference crop evapotranspirations. In Cumbe the grazing pastures are characterized by plants of type C3 (*Pennisetum clandestinum*) which are highly resistant to drought. Therefore, the water uptake is mainly regulated by the plants during dry periods. This is clearly observed in the TDR data (Fig. 3). The time series of soil water content reveal a constant rate of water uptake during dry periods.

Other important fact is that our soil water measurements and the simulation never reached the wilting point; which was 0.43 and 0.30 $cm^3 \cdot cm^{-3}$ for Andosols and Dystric Cambisols, respectively (Fig.3 and Fig. S2 for the water retention curves in supplementary material). The

minimum soil water content values during the drought periods in páramo was not lower than 0.62 cm^3 cm^{-3}. Field observations in November 2009, revealed that the plants apparently showed signs of deterioration in the first centimetres but after removal of the top layer (normally composed of dead leaves) the plants itself show little visual deterioration. Nevertheless, the depletion of the soil moisture storage during dry weather conditions clearly lead to stress and reduced the transpiration rate. The effect was quantified by the stress coefficient "k_s". In both cases (Calluancay and Cumbe), values never lower than 0.50 were estimated. As this vegetation has specific adaptations to high radiation and cold environment the recovery by the vegetation after drought is good. We also think that tillage, burning and artificial drainage might have a larger and more irreversible impact on the soil water holding capacity of the Andosol as compared to a "natural" drought.

4.3 The actual vegetation evapotranspiration derived from soil water observations

For Calluancay, the lowest value of k_s that was observed amounts to 0.62 (11 November 2010). For the same day, in Cumbe the k_s was 0.50. In other words, the water uptake by the roots was reduced by 38% in the páramo and by 50% for the pasture in Cumbe. This is a clear indication of the magnitude of the 2010 drought. A similar reduction was observed for the drought event in 2009 as the soil moisture content was slightly lower as compared to 2010 (Fig. 3a). In addition, the probability of human caused fires in páramo is higher during dry periods. This could affect the resilience of the soils especially during the subsequent wet period, since the vegetation is the main factor influencing the infiltration of the water.

So, for the whole period, which includes the drought of 2010, the daily average of E_a, for Calluancay and Cumbe is 1.42 (range 0.48 to 2.37) and 2.09 (range 0.99 to 3.04) mm day^{-1} respectively.

The water balance in the two experimental catchments and its components expressed as cumulative volume over the period from July 2010 until February 2012 are given in Table 1 and Fig. 4. From this analysis it is clear that the páramo vegetation and soil are more resilient to drought recovery as compared to the lower grass vegetation and soil. Especially the recovery after the drought period is much shorter. The lower potential evapotranspiration is an important reason. Both the reference crop evapotranspiration and the vegetation coefficient are lower, so that páramo consumes less water. According to our experimental results, during

~~wet periods the proportion of the stream discharge that can be regarded as potential water use is 54%. In addition the rainfall is slightly higher, so the runoff coefficient in páramo during the wet period remains at 0.68 of the rainfall and is still as high as 0.50 during the dry period. For the lower Cumbe catchment these coefficients are much lower: 0.21 and 0.23 for the wet and dry periods, respectively. Although the soil characteristics are very important for sustaining the base flow the different vegetation requirements are the crucial factors that explain these differences. Furthermore, the evaporative demand is higher in Cumbe as compared with Calluancay, due to the altitude difference. As a consequence, the length of recovery period for the drought event in 2010 was three months for the organic soils while in the mineral soils it took eight months (Fig. 3).~~

~~4.4~~4.2 Actual catchment evapotranspiration estimated by hydrological modelling

~~An initial inspection of the discharge and rainfall data revealed that the drought period of 2010 was followed by a wet period induced by a flood event on April 10, 2011. On the other hand, 2012 was relatively normal with the classic bimodal pattern (wet and dry period) (Celleri et al., 2007).~~

~~Therefore, t~~The time periods from ~~16 April 2011~~ 29 November 2007 until ~~16 January 2012~~ 06 August 2009 and from ~~17 January 2012~~ 20 May 2010 until ~~16 October 2012~~ 27 November 2012 are used as calibration and validation period respectively for Calluancay. In the case of Cumbe the calibration and validation periods were respectively from 21 April 2009 until 17 April 2011 and from 18 April 2011 until 13 December 2012. ~~These periods do not include the aforementioned extreme events.~~ The selected periods for calibration and validation resemble the average climatic conditions of the southern Ecuadorian Andes (Buytaert et al., 2006b; Celleri et al., 2007).

The Table 3 and Fig. 5 summarizes the results for the PDM model. The performance of the model for the calibration period is good ~~for Cumbe~~in both catchments (Nash-Sutcliffe efficiency 0.~~82~~83)~~, but not for Calluancay (0.67)~~. The calibration procedure was focus in low flows and hence, the logarithmic of the discharges values were used in the objective function. In fact, this partially explains the low values of Nash-Sutcliffe during the validation periods, since that more storm runoff events are observed during that time as compared with the calibration period. ~~The bias is also lower in Cumbe as compared with Calluancay. The~~

validation period gives a larger bias for both catchments. In additionNevertheless, the analysis revealed that the temporal variability of the average soil moisture storage simulated by the PDM model mimics the pattern of the observed soil moisture measurements (Fig. 5). This result is a first insight, which can be incorporated in future investigations on up-scaling (plot to catchment). Here, there are not enough number of plots in order to apply an up-scaling approach. As result, the differences or discrepancies between the simulated soil water by a conceptual model and observed soil moisture storage at the point location are relative low. The differences might be due to non-linearities in the reduction of actual evapotranspiration as compared to the potential vegetation demand.

The calibrated maximum storage capacity in Calluancay is two times higher as compared to the value for Cumbe (Table 2). This confirms the water holding capacity of the Andosols, despite the fact that the soils are shallow. The spatial variability of the topsoil moisture storage is also high in páramo, which is congruent with the field observations carried out during soil surveys. In Cumbe the spatial variability of the topsoil moisture storage is lower. The values of the parameter *b* for both catchments, that reflect the spatial variability of the storage capacity, also reflect this. The lower spatial variability is probably also the reason why the simulated and observed soil moisture storage agrees better in Cumbe (Fig. 5b). These results are in line with the literature (Brocca et al., 2012). The point measurements of soil moisture can thus be confirmed as representative for the catchment's average soil moisture storage or general wetness condition. Furthermore,Table 2 shows the calibrated parameter set for both catchments. tInitially, a relatively highhe difference in the value of parameter "b" is revealed. The differencess in the sensitivity of the parameter "b" can also be partially attributed to the fact that Cumbe is much larger, and therefore the hydrological response is longer., which is revealed by the dotty plots of the parameter "b" (see Fig. S3 in supplement material).

Other important aspect revealed by the figures 5a and 5b is the drought period recorded in 2011 for both catchments. In these graphs, a representative sample of rainfall (top), runoff (middle) and soil moisture (bottom) time series is displayed. And so, it is clear to see the propagation of the drought as a chain of processes , starting with a deficit of rainfall or dry days (meteorological drought), which are reflected by low values of stream flow observed or simulated (hydrological drought) and finally the impact in the soil moisture storage (soil

~~moisture drought). The recovery phase is also observed in those graphs when the subsequent wet periods appear.~~

~~Finally~~On the other hand, the daily average values of E_a, as estimated by the PDM models for Calluancay and Cumbe, are ~~1.34~~ 1.47 (range ~~0.17~~0.19 to ~~2.79~~3.33) and ~~1.77~~1.70 (range ~~0.34~~0.18 to ~~3.50~~3.58) mm day^{-1} respectively. ~~The mean values are similar to those obtained by the water balance equation and soil moisture observations. However, the range of variation is different for both methods. More variation is observed in the time series of E_a estimated by the PDM model. This is more evident in the Cumbe catchment (see Fig. 6).~~ The PDM model does not regard a critical soil moisture value and therefore there are no constraints on the evapotranspiration during dry periods. As a result, E_a is overestimated during these events.

Finally, the impact of both -the vegetation and stress coefficients- or k_v and k_s respectively was determined by means of a comparison between E_a and E_p. For Calluancay and Cumbe, the impact of the aforementioned coefficients over the E_a is in average 0.67 (range 0.09 to 1.00) and 0.58 (range 0.06 to 1.00) respectively.

High values of the coefficients could be partially explained by the plant physiology. It is important in páramo because the tussock grasses (mainly *Calamagrostis* spp. and *Stipa* spp.) are characterized by specific adaptations to extreme conditions. For instance, the plants have scleromorphic leaves which are essential to resist intense solar radiation (Ramsay and Oxley, 1997). In addition, the plants are surrounded by dead leaves that protect the plant and reduce the water uptake. In other words, the combination of the xerophytic properties and other adaptations to a high-radiation environment together with the dead leaves lead to a lower water demand as compared to the reference crop evapotranspirations. In Cumbe the grazing pastures are characterized by plants of type C3 (*Pennisetum clandestinum*) which are highly resistant to drought. Therefore, the water uptake is mainly regulated by the plants during dry periods. This is clearly observed in the TDR data or θ (Fig. 3). The time series of soil water content reveal a constant rate of water uptake during dry periods.

Other important fact is that our soil water measurements never reached the wilting point; which was 0.43 and 0.30 cm^3 cm^{-3} for Andosols and Dystric Cambisols, respectively (Fig.3 and Fig. S2 for the water retention curves in supplementary material). The minimum soil water content values during the drought periods in páramo was not lower than 0.62 cm^3 cm^{-3}.

Field observations in November 2009, revealed that the plants apparently showed signs of deterioration in the first centimetres but after removal of the top layer (normally composed of dead leaves) the plants itself show little visual deterioration. Nevertheless, the depletion of the soil moisture storage during dry weather conditions clearly lead to stress and reduced the transpiration rate. The effect was quantified by the vegetation and stress coefficients. As this vegetation has specific adaptations to high-radiation and cold environment the recovery by the vegetation after drought is good. We also think that tillage, burning and artificial drainage might have a larger and more irreversible impact on the soil water holding capacity of the Andosol as compared to a "natural" drought.

4.3 Impact of the droughts

Despite of the soil moisture measurements correspond to a plot-scale still gives a good indication of the severity of the drought periods (Fig. 3). During the drought events in 2009 and 2010, the soil water content in páramo dropped substantially. And so it was possible to establish the amount of water of the topsoil which is available during these dry periods. The reservoir can deliver a water volume equivalent to 0.24 cm^3 cm^{-3} (this represents the maximum soil water content change) during extreme climate conditions such as the droughts in 2009 and 2010. In normal conditions the maximum change observed in the soil water content in páramo is no more than 0.05 cm^3 cm^{-3}.

On the other hand, for each drought period, the standardized deficit as well as its duration are shown in the figure 4. From this figure is clear to see that the deficit is no more than 9 days for both catchments. In other words, 9 days with mean flow are required to reduce the deficit to zero for the whole set of events. In addition, the duration of the drought events is relatively similar for both catchments with only few outliers as for the case of Cumbe. This result is confirmed by the values of the slopes of the linear regression models, significant differences are not observed by means of the figure 4. Just a slight higher value of slope for soil water storage in Calluancay (paramo) as compared with Cumbe (grassland) is revealed in this figure. However, it is important to mention that the values of slopes reflect the effect of the drought propagation through the hydrological cycle. A reduced increase of deficit with duration is observed in both catchments.

4.4 Drought propagation

The figure 5 shows the drought propagation plots for Calluancay and Cumbe. This figure confirmed the results about the standardized deficit and duration for each drought event as well as the seasonality observed during the monitoring period. This period correspond to 2009, 2010, 2011 and 2012. A series of relatively consecutive small drought periods are observed in the time series of precipitation, which were recorded during the dry season. The dry season normally occurs between August and November and the wet season are concentrated between March and June. Nevertheless, between August 2009 and March 2010 a drought period was observed due to anomalies in the precipitation. This event is the most clearly observed along the whole time series. The soil water storage in both catchments has a crucial role in the propagation of the droughts. For instance, in Cumbe the meteorological drought event of 2009-2010 is almost completely buffered by the soil water storage and hence, the hydrological drought is delayed. The opposite occurs in Calluancay, where the soil water storage at that time is not enough to deal with the anomalies of precipitation and the propagation of the drought is observed immediately in the stream discharge (the hydrological drought). The recovery of the soil water storage occurs during the wet season and revealed by a series of several but intermittent storm events which derived in an irregular pattern of the soil water storage. In both catchment, the soil water storage has a similar pattern and is not possible to find significant differences. Therefore, a sensitivity analysis was done in order to observe what could be the most important factor in the recovery after the droughts. This is present in the following item.

4.5 Vegetation stress and recovery

The vegetation stress periods were identified when the half of potential evapotranspirtion exceeds the precipitation. Monthly data of E_p and P were used in the identification of the vegetation stress periods. As result, in Calluancay the months of August, September and October 2009 reveal clearly a deficit of water. The recovery start slowly in November 2009 and progressively increases during the wet season from February to Jun 2010. But, once again in September, October and November 2010 a deficit of water is detected and therefore this corresponds to the second period of vegetation stress. However, the recovery is faster because between December 2010 and April 2011 the deficit is covered completely for the onset of the wet season. In 2011, only October reveals a deficit of water which is quickly recovery with

the precipitation of November and December 2011. While, in 2012 only September reveals deficit of water which is also recovery between October and November 2012.

Finally, in Cumbe the vegetation stress is higher as compared with Calluancay. From July 2009 up to January 2010 (7 consecutive months of vegetation stress) the deficit of water was significant. For instance, in August 2009 the recorded precipitation in Cumbe was just 6.5 mm, while that in Calluancay was 24.2 mm. The recovery was reached from February up to July 2010 just before the onset of the second drought period. The second period of vegetation stress was from August up to October 2010. The corresponded recovery period was from November 2010 up tp April 2011. The third vegetation stress periods were observed in August and October 2011. The corresponded recovery period was reached from November 2011 up to February 2012. The last vegetation stress period was from July up to September 2012. Afterwards, the recovery period was partially observed by the availability of data between October and November 2012.

These values are in part confirmed by the consecutive dry days calculated for the whole time series of precipitation in both catchments. For Calluancay, the maximum number of CDD was determined for the period between August and November 2009. In this time, two maximums of 16 and 19 days respectively were detected. In 2010, other two maximums of CDD were observed, 18 and 22 days. In 2011, just one maximum of 18 days was observed in October. Meanwhile, in Cumbe the maximum observed was of 16 days (between October and November 2009). In the following year, two maximums were observed of 10 and 12 days (between August and November 2009). In March 2011 a maximum of 19 days was detected and clearly observed its impact in the soil water storage (Fig. 5). Finally, in July and August 2012 two maximums were calculated with 13 and 11 days respectively.

4.6 Sensitivity analysis

Here, we study two relatively simple scenarios, in both cases we keep the parameter set obtained during the calibration procedure. In other words, the soil characteristics are not modified. Only precipitation and potential evapotranspiration are exchanged between the catchments in order to assess the impact in the soil water storage by means of simulations with the hydrological model. The input values for the PDM were:

-Calluancay, observed values of P = 2723 mm and E_p = 2146 mm,

-Cumbe, observed values of P = 2199 mm and E_p = 2788 mm.

These values were exchanged between the catchments. The period analysed was from 20 May 2010 until 27 November 2012.

The figure 6 reveals that the most important factor is the precipitation as compared with the potential evapotranspiration. The stream discharge is drastically reduced during the wet season in April 2012, as result of the increase in the deficit of soil water storage. However, significant difference are not observed in the drought periods of 2009-2010 or 2011 despite of the increase in the rate of E_p and reduction in the input of rain. The opposite occur in Cumbe, mainly due to the increase in the precipitation amount and by the reduction in the rate of potential evapotranspiration. So, the stream discharge is substantially increased along the whole period. This is also an effect of a less deficit of soil water storage.

5 Conclusions

The páramo ecosystem has a pivotal role in the hydrology and ecology for the highlands of the Andean region. The páramo is the main source of drinking water and irrigation and for hydropower projects. The hydrological capacity of the páramo is primarily attributed to its organic soils. Shallow organic soils with exceptional high retention and infiltration capacity regulate the surface and subsurface hydrology in this mountainous ecosystem. Nonetheless, in the recent past, human activities and climate change have induced a negative pressure on its ecological services. In addition, from 2005 the whole region has faced several drought events with an adverse ecological and economic impact. In this context, the present study is focused on the analysis of the ~~resilience~~ capacity recovery of the páramo soils during drought events. Therefore, we analysed the hydrological response of the páramo soil during drought events observed in 2009, 2010, 2011 and 2012. The analysis was carried out based on ~~the soil water balance in the root zone~~ the calibration and validation of a hydrological conceptual model, the PDM model. ~~Two experimental catchments from the highlands of the Paute river basin were selected and monitored during ca. 28 months.~~ A typical catchment on the páramo at 3500 m a.s.l. was compared to a lower grassland one at 2600 m a.s.l. The observation periods were of ca. five and three and half years respectively.

~~Initially, the first aim was to estimate the actual evapotranspiration based on continuous time series of soil water content measurements. To this purpose, two parameters have been estimated, a vegetation coefficient k_v and the critical soil water content θ_{crit}.~~

~~The vegetation coefficient k_v is used to estimate the crop water requirement in the FAO-Penman-Monteith equation. k_v represents the proportion of water use by a vegetation as compared to the reference crop, under wet, stress free conditions. θ_{crit} is a threshold value from which the potential evapotranspiration is reduced linearly in function of the availability soil water content.~~

~~The estimated coefficients k_v during the wet periods where the potential vegetation evapotranspiration is observed for both páramo vegetation and grazing pastures were 0.63 and 0.82 respectively. These data are consistent with the literature. The k_v value is slightly higher than reported in previous studies in the case of páramo vegetation, but obviously frequent burning and human intervention on this páramo generate more vigorous vegetation and so more demand for water. The critical soil water content for Andosols and Dystric Cambisols were 0.81 and 0.50 $cm^3 \cdot cm^{-3}$. The daily average actual evapotranspiration in páramo is low, 1.42 mm day^{-1}. While, for grazing pastures the E_a is 2.09 mm day^{-1}. From the water balance, the proportion of potential water use in the páramo of Calluancay is 54%.~~

~~During the drought events in 2009 and 2010, the soil water content in páramo dropped substantially. And so it was possible to establish the amount of water of the topsoil which is available during these dry periods. The reservoir can deliver a water volume equivalent to 0.24 $cm^3 \cdot cm^{-3}$ (this represents the maximum soil water content change) during extreme climate conditions such as the droughts in 2009 and 2010. In normal conditions the maximum change observed in the soil water content is no more than 0.05 $cm^3 \cdot cm^{-3}$. As consequence the real evapotranspiration can be reduced up to 38% of its potential by stress conditions.~~

~~Thus, despite having suffered an extreme drought in 2009, the páramo soils recovered of another drought in 2010. During last period an extreme drought event was recorded in the entire Amazon River basin. In the páramo, three months of precipitations were enough to recover its normal moisture conditions. This did not occur at lower altitudes where mineral soils (Cumbe) needed about eight months in total to achieve this recovery. The combination of two factors explains the recovery of the páramo ecosystem, a big soil water storage capacity of Andosols and a low atmospheric evaporative demand due to altitude and the typical vegetation. These factors play a pivotal role in the resilience capacity to droughts~~

~~especially in páramos with seasonal patterns as in Calluancay. Therefore, the páramo ecosystems have a high resilience to droughts.~~

~~In this context, point measurements of soil moisture in the topsoil (30 cm) were in line with the catchment's average soil moisture storage as estimated by the PDM model. The storage parameters of the PDM are also in line with field observations and literature. The E_a, is however overestimated by the PDM model as compared to the water balance based on soil water measurements.~~

~~Finally, the present research has shown the value of soil water measurements at representative sites as they correspond well to the soil storage as estimated in a conceptual model. A more realistic estimation of the actual evapotranspiration can be done on the basis of the soil water content measurements. As continuous soil water data logging by TDR requires large investments the locations have to be selected with great care so that this point measurements can be considered a reliable proxy for the catchment's average soil moisture storage.~~

Based on the threshold method the soil moisture droughts occur mainly in the dry season in both catchments as a consequence of several anomalies in the precipitation (meteorological drought). Just one soil moisture drought was observed during the wet season (in 2011). The deficit for all cases is small and progressively reduced during the wet season. This conclusion is confirmed by the identification of the vegetation stress periods. These periods correspond mainly to the months of September, October and November which coincides with the dry season. In this context, the maximum number of consecutive dry days were reached during the drought of 2009 and 2010, 19 and 22 days, which can be considered a record in páramo. In these periods, the soil moisture content observed in the experimental plot reached also the lowest values recoded until now, 0.60 cm^3 cm^{-3} in November 2009.

On the other hand, at the plot scale the differences between the capacity recovery of the soils are relatively high (Fig. 3). The páramo soils apparently reveals a more quick recovery as compared with the mineral soils present in Cumbe. But, at the catchment scale, the soil water storage simulated by PDM model and the drought analysis reveals that the differences are not significant. The main factor in the hydrological response of these experimental catchments is the precipitation. A reduction of the precipitation has a clear impact in the soil water storage.

Acknowledgements

We thank the VLIR-IUC programme and IFS for its financial support during this research. And also thanks to the anonymous referee and Dr. Wouter Buytaert by their comments in order to improve the present manuscript.

References

Allen, R., Pereira, L. S., Raes, D. and Smith, M.: Crop evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome., 1998.

Andreadis, K. M., Clark, E. a., Wood, A. W., Hamlet, A. F. and Lettenmaier, D. P.: Twentieth-Century Drought in the Conterminous United States, Journal of Hydrometeorology, 6(6), 985–1001, doi:10.1175/JHM450.1, 2005.

Brocca, L., Tullo, T., Melone, F., Moramarco, T. and Morbidelli, R.: Catchment scale soil moisture spatial–temporal variability, Journal of Hydrology, 422-423, 63–75, doi:10.1016/j.jhydrol.2011.12.039, 2012.

Buytaert, W. and Beven, K.: Models as multiple working hypotheses: hydrological simulation of tropical alpine wetlands, Hydrological Processes, 25(11), 1784–1799, doi:10.1002/hyp.7936, 2011.

Buytaert, W. and De Bièvre, B.: Water for cities: The impact of climate change and demographic growth in the tropical Andes, Water Resources Research, 48(8), W08503, doi:10.1029/2011WR011755, 2012.

Buytaert, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J. and Hofstede, R.: Human impact on the hydrology of the Andean páramos, Earth-Science Reviews, 79(1-2), 53–72, doi:10.1016/j.earscirev.2006.06.002, 2006a.

Buytaert, W., Celleri, R., Willems, P., Bièvre, B. De and Wyseure, G.: Spatial and temporal rainfall variability in mountainous areas: A case study from the south Ecuadorian Andes, Journal of Hydrology, 329(3-4), 413–421, doi:10.1016/j.jhydrol.2006.02.031, 2006b.

Buytaert, W., Cuesta-Camacho, F. and Tobón, C.: Potential impacts of climate change on the environmental services of humid tropical alpine regions, Global Ecology and Biogeography, 20(1), 19–33, doi:10.1111/j.1466-8238.2010.00585.x, 2011.

Buytaert, W., Deckers, J. and Wyseure, G.: Regional variability of volcanic ash soils in south Ecuador: The relation with parent material, climate and land use, Catena, 70(2), 143–154, doi:10.1016/j.catena.2006.08.003, 2007a.

Buytaert, W., Iñiguez, V. and Bièvre, B. De: The effects of afforestation and cultivation on water yield in the Andean páramo, Forest Ecology and Management, 251(1-2), 22–30, doi:10.1016/j.foreco.2007.06.035, 2007b.

Buytaert, W., Iñiguez, V., Celleri, R., De Bièvre, B., Wyseure, G. and Deckers, J.: Analysis of the Water Balance of Small Páramo Catchments in South Ecuador, in Environmental Role of Wetlands in Headwaters SE - 24, vol. 63, edited by J. Krecek and M. Haigh, pp. 271–281, Springer Netherlands, Dordrecht, The Netherlands., 2006c.

Buytaert, W., Vuille, M., Dewulf, A., Urrutia, R., Karmalkar, A. and Célleri, R.: Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management, Hydrology and Earth System Sciences, 14(7), 1247–1258, doi:10.5194/hess-14-1247-2010, 2010.

Buytaert, W., Wyseure, G., De Bièvre, B. and Deckers, J.: The effect of land-use changes on the hydrological behaviour of Histic Andosols in south Ecuador, Hydrological Processes, 19(20), 3985–3997, doi:10.1002/hyp.5867, 2005.

Celleri, R., Willems, P., Buytaert, W. and Feyen, J.: Space–time rainfall variability in the Paute basin, Ecuadorian Andes, Hydrological Processes, 21(24), 3316–3327, doi:10.1002/hyp.6575, 2007.

Dercon, G., Bossuyt, B., De Bièvre, B., Cisneros, F. and Deckers, J.: Zonificación agroecológica del Austro Ecuatoriano, U Ediciones, Cuenca, Ecuador., 1998.

Dercon, G., Govers, G., Poesen, J., Sánchez, H., Rombaut, K., Vandenbroeck, E., Loaiza, G. and Deckers, J.: Animal-powered tillage erosion assessment in the southern Andes region of Ecuador, Geomorphology, 87(1-2), 4–15, doi:10.1016/j.geomorph.2006.06.045, 2007.

Duan, Q., Sorooshian, S. and Gupta, V.: Effective and efficient global optimization for conceptual rainfall-runoff models, Water Resources Research, 28(4), 1015–1031, doi:10.1029/91WR02985, 1992.

FAO, ISRIC and ISSS: World Reference Base for Soil Resources. No. 84 in World Soil Resources Reports. FAO, Rome., 1998.

Farley, K. a., Kelly, E. F. and Hofstede, R. G. M.: Soil Organic Carbon and Water Retention after Conversion of Grasslands to Pine Plantations in the Ecuadorian Andes, Ecosystems, 7(7), 729–739, doi:10.1007/s10021-004-0047-5, 2004.

Garcia, M., Raes, D., Allen, R. and Herbas, C.: Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano), Agricultural and Forest Meteorology, 125(1-2), 67–82, doi:10.1016/j.agrformet.2004.03.005, 2004.

van Genuchten, M. T.: A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, Soil Science Society of America Journal, 44, 892–898, doi:10.2136/sssaj1980.03615995004400050002x, 1980.

Griffiths, M. L. and Bradley, R. S.: Variations of twentieth-century temperature and precipitation extreme indicators in the northeast United States, Journal of Climate, 20(21), 5401–5417, doi:10.1175/2007JCLI1594.1, 2007.

Hargreaves, G. H. and Samani, Z. A.: Reference Crop Evapotranspiration from Temperature, Applied Engineering in Agriculture, 1(2), 96–99, 1985.

Hofstede, R. G. M., Groenendijk, J. P., Coppus, R., Fehse, J. C. and Sevink, J.: Impact of Pine Plantations on Soils and Vegetation in the Ecuadorian High Andes, Mountain Research and Development, 22(2), 159–167, doi:10.1659/0276-4741(2002)022[0159:IOPPOS]2.0.CO;2, 2002.

Hofstede, R., Segarra, P. and Mena, P.: Los páramos del mundo, Global Peatland Initiative/NC-IUCN/EcoCiencia, Quito., 2003.

Hungerbühler, D., Steinmann, M., Winkler, W., Seward, D., Egüez, A., Peterson, D. E., Helg, U. and Hammer, C.: Neogene stratigraphy and Andean geodynamics of southern Ecuador, Earth-Science Reviews, 57(1-2), 75–124, doi:10.1016/S0012-8252(01)00071-X, 2002.

Kilpatrick, F. and Schneider, V.: Use of flumes in measuring discharge, U.S. Geological Survey Techniques of Water Resources Investigations, Washington, USA., 1983.

Klemeš, V.: Operational testing of hydrological simulation models, Hydrological Sciences Journal, 31(1), 13–24, doi:10.1080/02626668609491024, 1986.

Koch, K., Wenninger, J., Uhlenbrook, S. and Bonell, M.: Joint interpretation of hydrological and geophysical data: electrical resistivity tomography results from a process hydrological

research site in the Black Forest Mountains, Germany, Hydrological Processes, 23(10), 1501–1513, doi:10.1002/hyp.7275, 2009.

Van Lanen, H. A. J., Wanders, N., Tallaksen, L. M. and Van Loon, A. F.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrology and Earth System Sciences, 17(5), 1715–1732, doi:10.5194/hess-17-1715-2013, 2013.

Van Loon, a. F., Tijdeman, E., Wanders, N., Van Lanen, H. A. J., Teuling, a. J. and Uijlenhoet, R.: How climate seasonality modifies drought duration and deficit, Journal of Geophysical Research: Atmospheres, 119(8), 4640–4656, doi:10.1002/2013JD020383, 2014.

Van Loon, A. F.: On the propagation of drought. How climate and catchment characteristics influence hydrological drought development and recovery, PhD Thesis, Wageningen University, Wageningen, the Netherlands., 2013.

Van Loon, A. F.: Hydrological drought explained, Wiley Interdisciplinary Reviews: Water, 2(4), 359–392, doi:10.1002/wat2.1085, 2015.

Luteyn, J. L.: Páramos: A Checklist of Plant Diversity, Geographical Distribution, and Botanical Literature. The New York Botanical Garden Press, New York., 1999.

Moore, R. J.: The probability-distributed principle and runoff production at point and basin scales, Hydrological Sciences Journal, 30(2), 273–297, doi:10.1080/02626668509490989, 1985.

Moore, R. J. and Clarke, R. T.: A distribution function approach to rainfall runoff modeling, Water Resources Research, 17(5), 1367–1382, doi:10.1029/WR017i005p01367, 1981.

Mora, D. E., Campozano, L., Cisneros, F., Wyseure, G. and Willems, P.: Climate changes of hydrometeorological and hydrological extremes in the Paute basin, Ecuadorean Andes, Hydrology and Earth System Sciences, 18(2), 631–648, doi:10.5194/hess-18-631-2014, 2014.

Pebesma, E. J.: Multivariable geostatistics in S: the gstat package, Computers & Geosciences, 30(7), 683–691, doi:10.1016/j.cageo.2004.03.012, 2004.

Podwojewski, P., Poulenard, J., Zambrana, T. and Hofstede, R.: Overgrazing effects on vegetation cover and properties of volcanic ash soil in the páramo of Llangahua and La Esperanza (Tungurahua, Ecuador), Soil Use and Management, 18, 45–55, doi:10.1111/j.1475-2743.2002.tb00049.x, 2002.

Ramsay, P. M. and Oxley, E. R. B.: The growth form composition of plant communities in the ecuadorian páramos, Plant Ecology, 131(2), 173–192, doi:10.1023/A:1009796224479, 1997.

Romano, N.: Soil moisture at local scale: Measurements and simulations, Journal of Hydrology, 516, 6–20, doi:10.1016/j.jhydrol.2014.01.026, 2014.

Schneider, P., Vogt, T., Schirmer, M., Doetsch, J., Linde, N., Pasquale, N., Perona, P. and Cirpka, O. a.: Towards improved instrumentation for assessing river-groundwater interactions in a restored river corridor, Hydrology and Earth System Sciences, 15(8), 2531–2549, doi:10.5194/hess-15-2531-2011, 2011.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Science Reviews, 99(3-4), 125–161, doi:10.1016/j.earscirev.2010.02.004, 2010.

Southgate, D. and Macke, R.: The Downstream Benefits of Soil Conservation in Third World

Hydroelectric Watersheds, Land Economics, 65(1), 38, doi:10.2307/3146262, 1989.

Stocki, R.: A method to improve design reliability using optimal Latin hypercube sampling, Computer Assisted Mechanics and Engineering Sciences, (12), 393–411, 2005.

Vanacker, V., Molina, A., Govers, G., Poesen, J. and Deckers, J.: Spatial variation of suspended sediment concentrations in a tropical Andean river system: The Paute River, southern Ecuador, Geomorphology, 87(1-2), 53–67, doi:10.1016/j.geomorph.2006.06.042, 2007.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, a. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M. and Woods, R.: Climate change and mountain water resources: overview and recommendations for research, management and policy, Hydrology and Earth System Sciences, 15(2), 471–504, doi:10.5194/hess-15-471-2011, 2011.

Wagener, T., Boyle, D. P., Lees, M. J., Wheater, H. S., Gupta, H. V. and Sorooshian, S.: A framework for development and application of hydrological models, Hydrology and Earth System Sciences, 5(1), 13–26, doi:10.5194/hess-5-13-2001, 2001.

Table 1. The main characteristics and the water balance of the experimental catchments[a].

Name	Altitude (m)	Area (km^2)	Monitoring period	Type of period	Soil moisture[b] ($cm^3 cm^{-3}$)	ETsim[e] ($mm\ year^{-1}$)	ET ($mm\ year^{-1}$)	Discharge ($mm\ year^{-1}$)	Rainfall ($mm\ year^{-1}$)	RC	Dominant land use
Calluancay	3589-3882	4.39	29 Nov 2007-12 Nov 2008[d]	WET	0.83 - 0.86	539	462	1000	1462	0.68	Páramo
			16 Jul 2010-1 Feb 2012[e]	DRY	0.62 - 0.86	431	529	525	1054	0.50	
Cumbe	2647-3467	44.0	2 Feb 2012-13 Apr 2012	WET	0.51 - 0.54	882	918	243	1161	0.21	Grazing pastures
			16 Jul 2010-1 Feb 2012	DRY	0.39 - 0.54	647	668	204	872	0.23	

[a] Climatic variables have been rescaled to yearly basis for comparison with literature. RC is the runoff coefficient.

[b] The average daily minimum and maximum soil moisture for each monitoring period.

[e] ETsim is the actual evapotranspiration estimated by the PDM model.

[d] Gaps in the soil moisture data (30 Nov 2007-18 Jan 2008, 14 Mar 2008-23 Mar 2008, 30 Apr 2008-19 May 2008, 26 Jun 2008-28 Jun 2008, 16 Oct 2008-20 Oct 2008).

[e] Gaps in the discharge time series of Calluancay (29 Oct 2010-23 Nov 2010, 13 Jan 2011-2 Feb 2011, 27 May 2011-28 Jun 2011). These gaps has been filled up using the PDM model.

Table 1. The main characteristics of the experimental catchments

NAME	Calluancay	Cumbe
Area (km^2)	4.39	44.0
Altitude (m a.s.l.)	3589 – 3882	2647 – 3467
Observation period	Nov 2007 – Nov 2012	Apr 2009 – Nov 2012
-Hydrometeorological variables:		
P (mm $year^{-1}$)	1095	783
E_p (mm $year^{-1}$)	831	1100
Q (mm $year^{-1}$)	619	181
-State variables:		
Soil water content (cm^3 cm^{-3})[a]	0.60 - 086	0.39 – 0.54

[a], the average daily minimum and maximum soil water contents for each observation period

Table 2. The calibrated parameters of the PDM model.

Parameters	Description	Feasible range	Calluancay	Cumbe
c_{max}	Maximum storage capacity	30-120 [mm]	~~101.2~~64.8	~~44.2~~54.5
b	Degree of spatial variability of the storage capacity	0.1-2.0 [-]	~~1.82~~0.74	~~0.21~~0.17
f_{rt}	Fast routing store residence time	1-2 [days]	1.~~7~~5	1.~~4~~1
s_{rt}	Slow routing store residence time	10-50 [days]	~~14.3~~58.3	~~32.5~~98.2
%(q)	Percentage flow through fast flow	0.25-0.75 [-]	0.51~~8~~	0.41~~2~~

Table 3. The Nash and Sutcliffe efficiencies ~~and the bias~~ for the PDM models*.

~~Catchment~~	~~Calibration~~		~~Validation~~	
	~~NS (-)~~	~~Bias (%)~~	~~NS (-)~~	~~Bias (%)~~
~~Calluancay~~	~~0.67~~	~~-10.0~~	~~0.74~~	~~-20.9~~
~~Cumbe~~	~~0.82~~	~~-3.0~~	~~0.66~~	~~-17.5~~

~~*Calibration period: 16 Apr 2011 - 16 Jan 2012, Validation period: 17 Jan 2012 - 16 Oct 2012. NS is the Nash-Sutcliffe efficiency.~~

Catchment	Calibration		Validation	
	NS (-)	Period	NS (-)	Period
Calluancay	0.83	29 Nov 2007 – 06 Ago 2009	0.53	20 May 2010 – 27 Nov 2012
Cumbe	0.84	21 Apr 2009 – 17 Apr 2011	0.63	18 Apr 2011 – 13 Dec 2012

*NS is the Nash and Sutcliffe efficiency

Figure 1. The study area

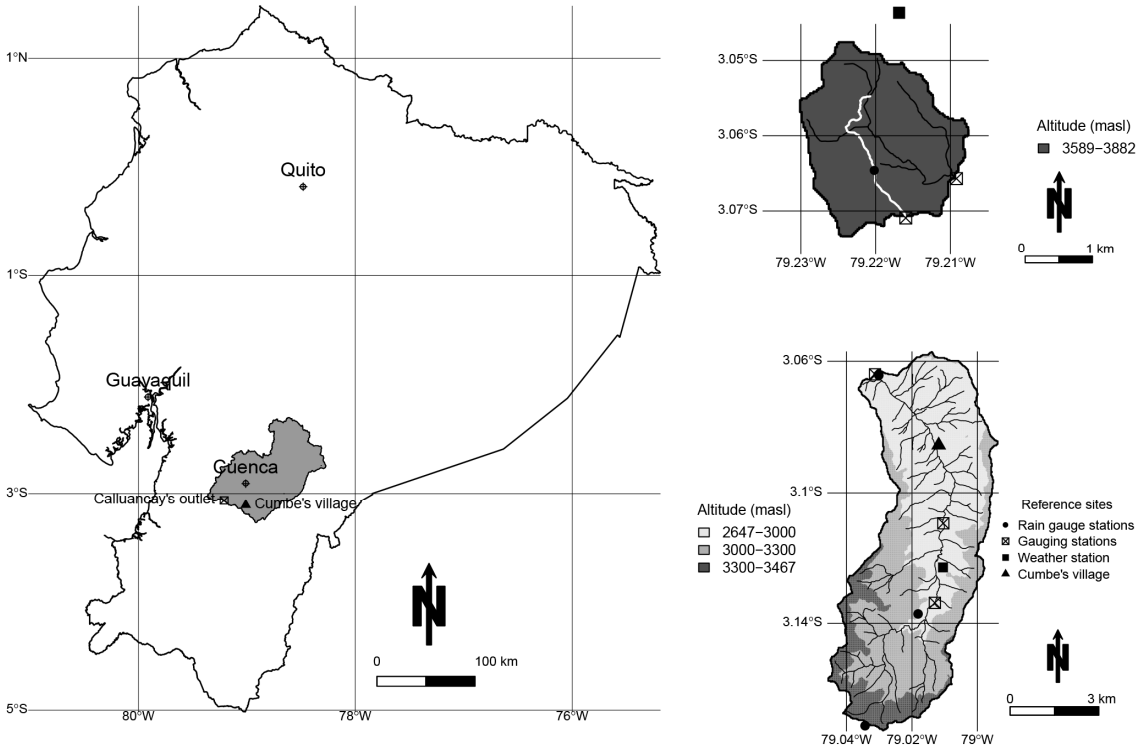
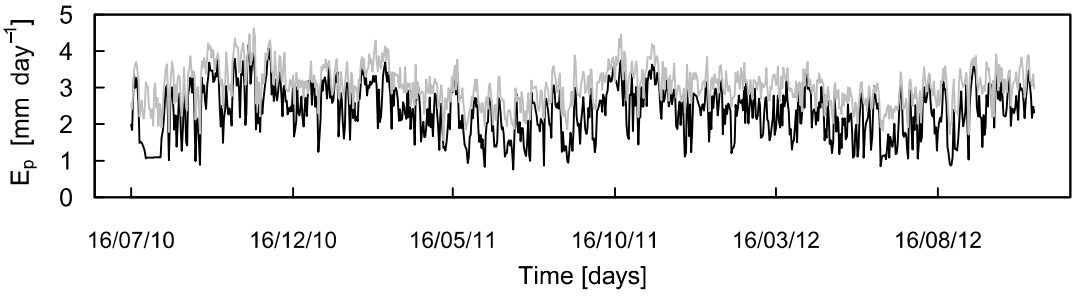


Figure 2. The potential evapotranspiration E_p for Calluancay (black) and Cumbe (grey).



~~**Figure 3.** The soil water content data for Calluancay (a) and Cumbe (b). The drought periods are shaded in grey. The blue lines show the soil water content simulated by means of the soil water balance in the root zone for each catchment during the period from on 16 Jul 2010 up to on 1 Feb 2012. In Supplement there are dotty plots with the parameters optimized during the water balance.~~

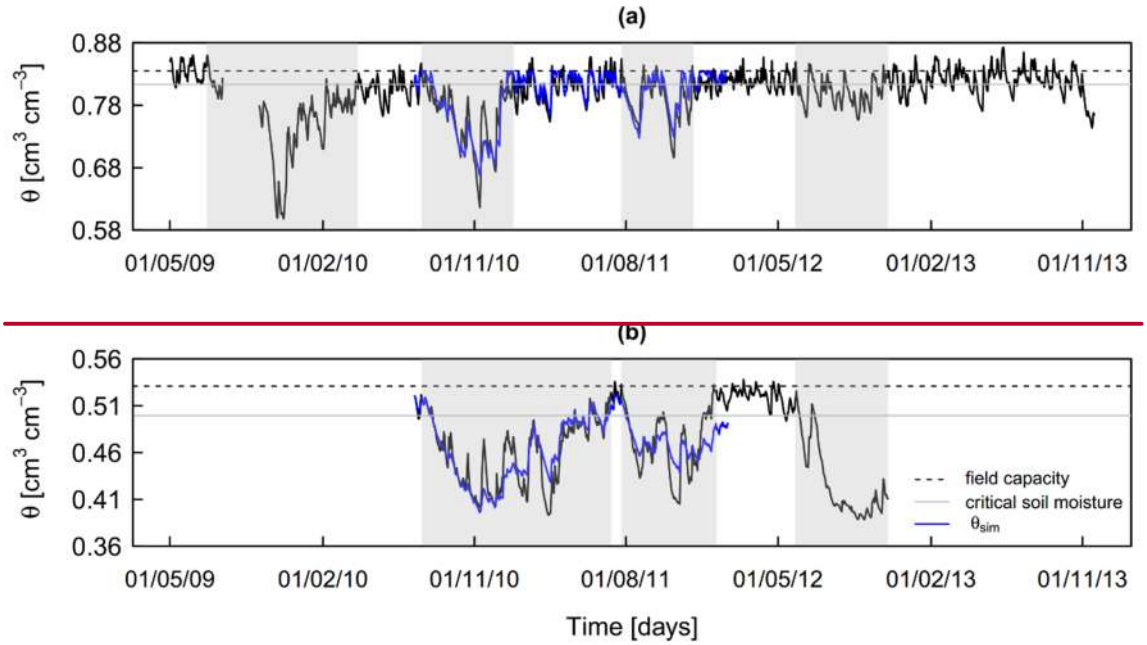


Figure 4. Water balance components for (a) Calluancay and (b) Cumbe. The curves in Calluancay show a non linear behaviour and so suggest a seasonality for this páramo area. This climate pattern is enhanced by the occurrence of drought events. A high evapotranspiration is revealed in Cumbe. Most of this E_a can be attributed to the irrigation systems which are operational during dry periods.

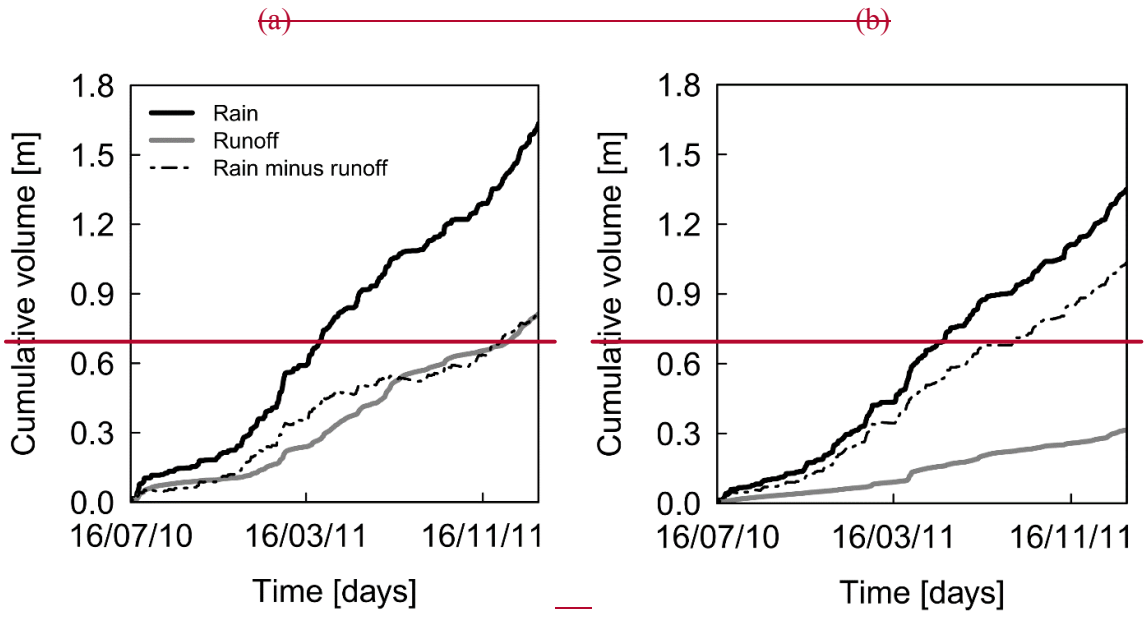


Figure 5. Representative sample of rainfall (top), runoff (middle) and soil moisture (bottom) time series. The scaled soil moisture storage in the root zone is shown in the bottom inset in the plot in solid and dashed black lines for measured and modelled respectively.

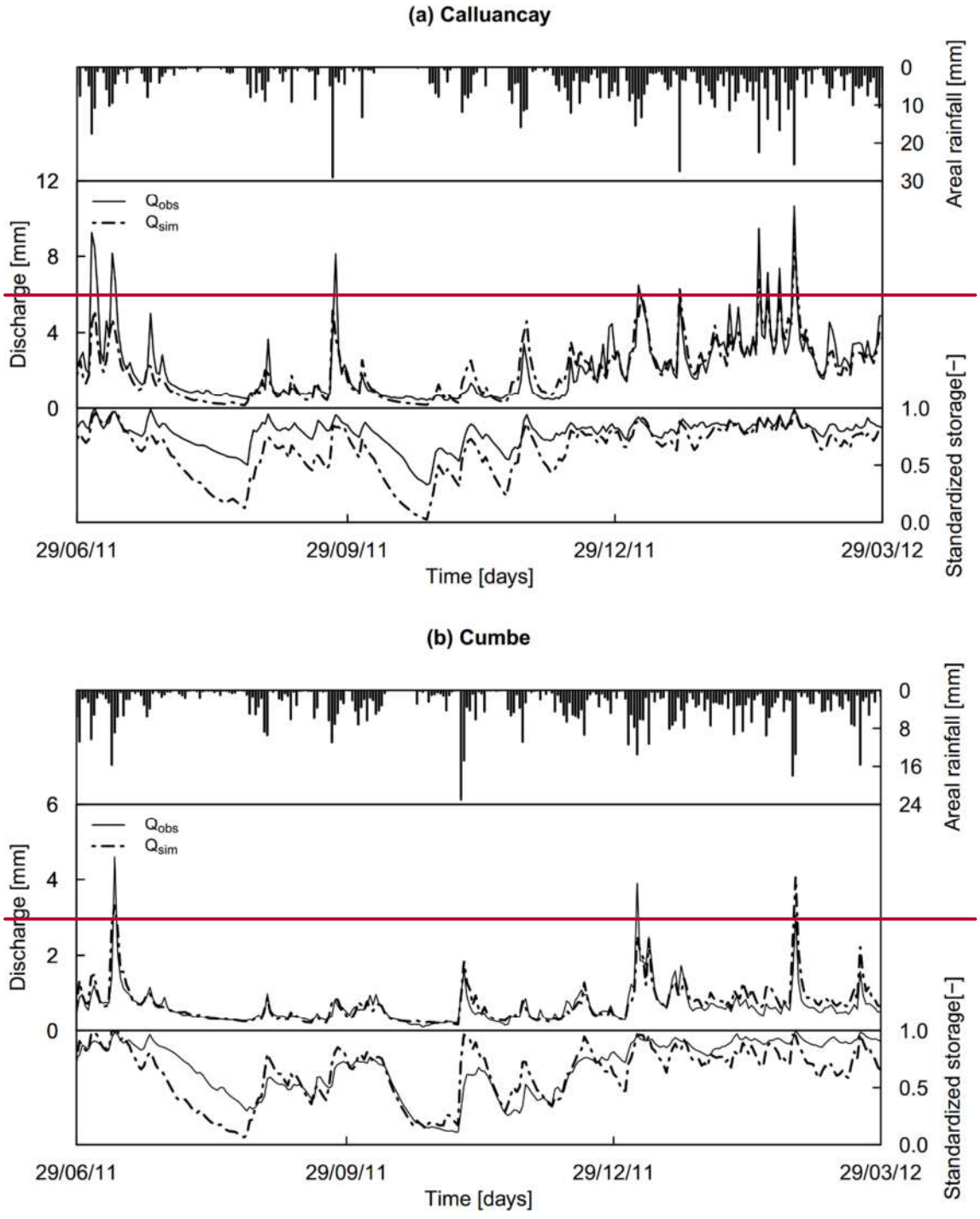
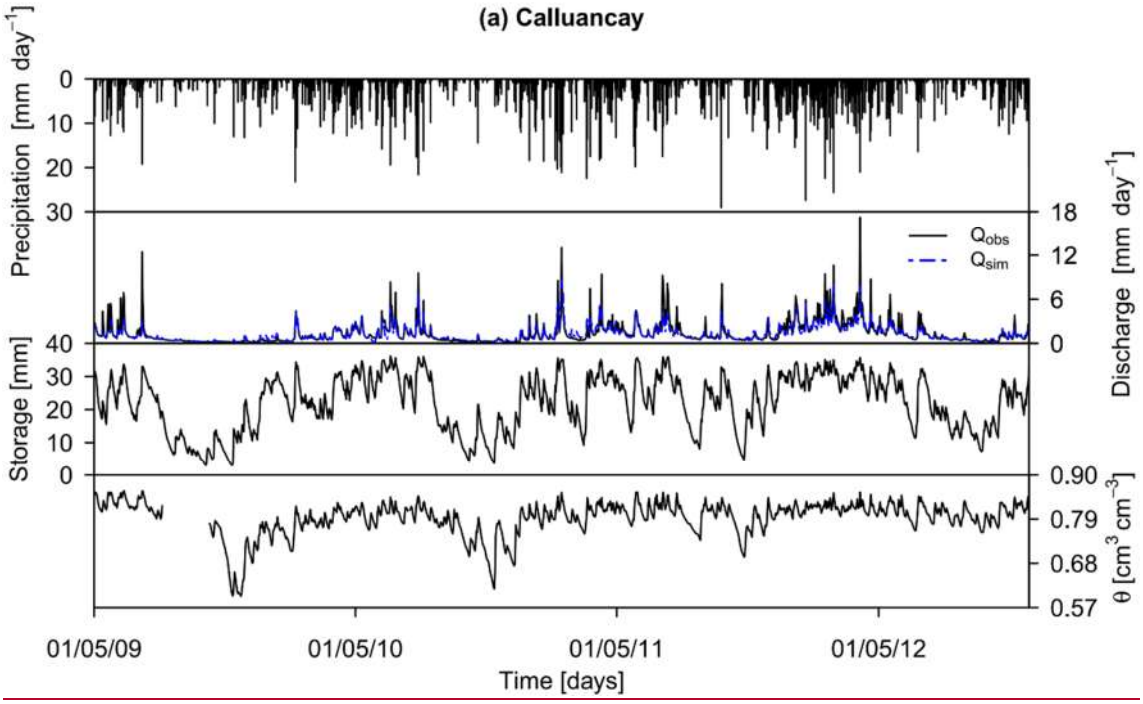


Figure 3. Results from the hydrological modelling with PDM (stream discharge and average soil water storage simulated) and the soil moisture measured in an experimental plot.



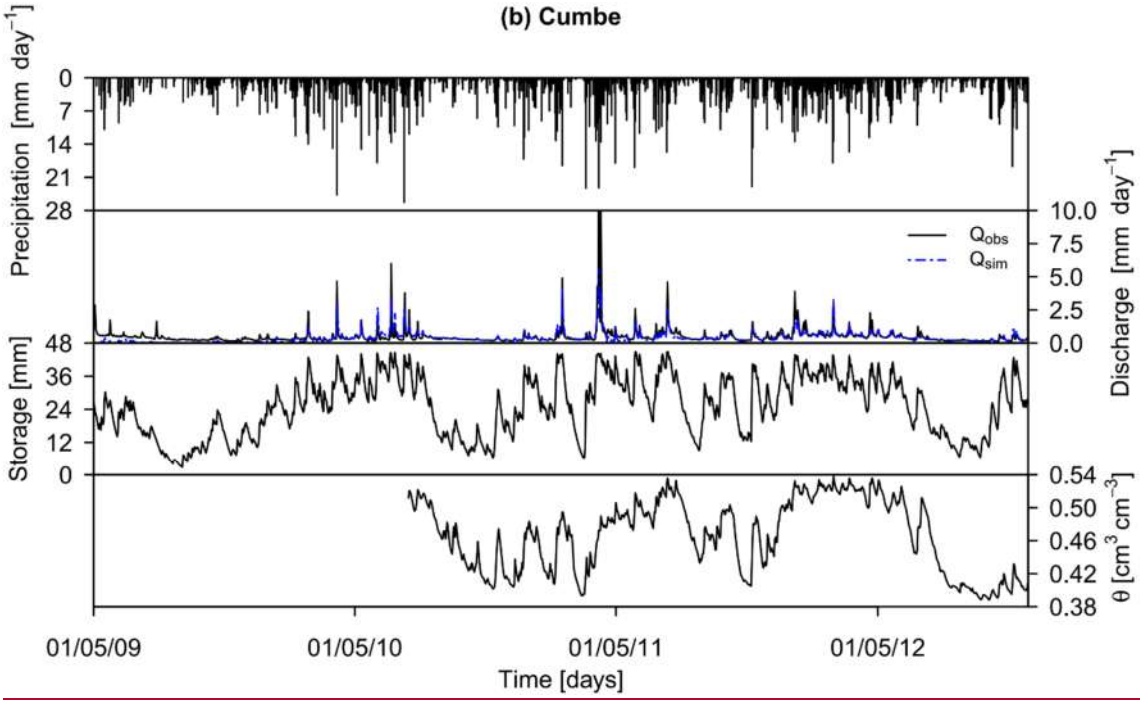
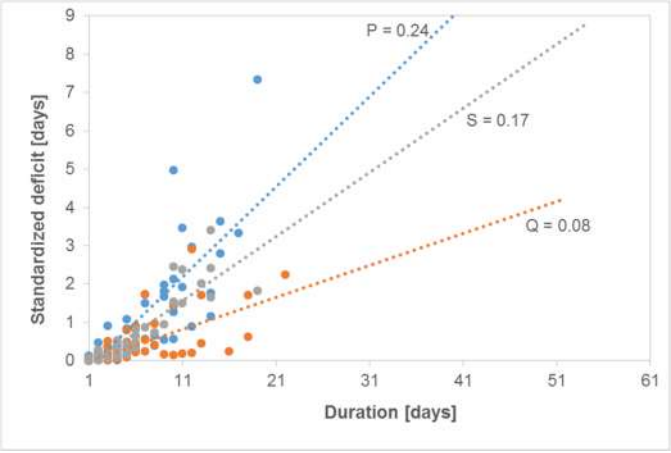
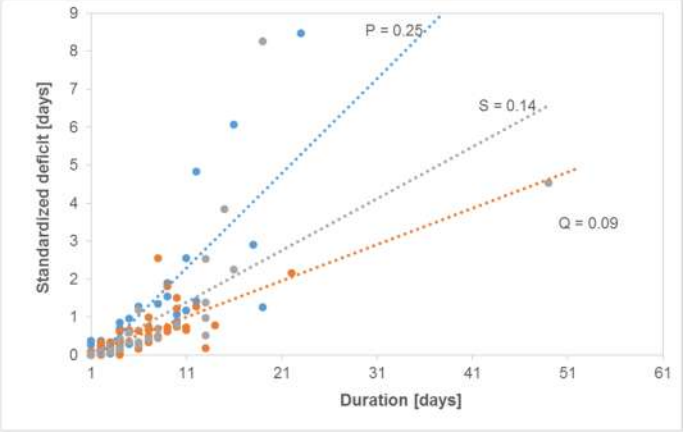


Figure 4. Standardized deficit for the drought periods. (a) Calluancay and (b) Cumbe (in blue P, precipitation; in grey S, soil water storage and in orange Q, stream discharge)

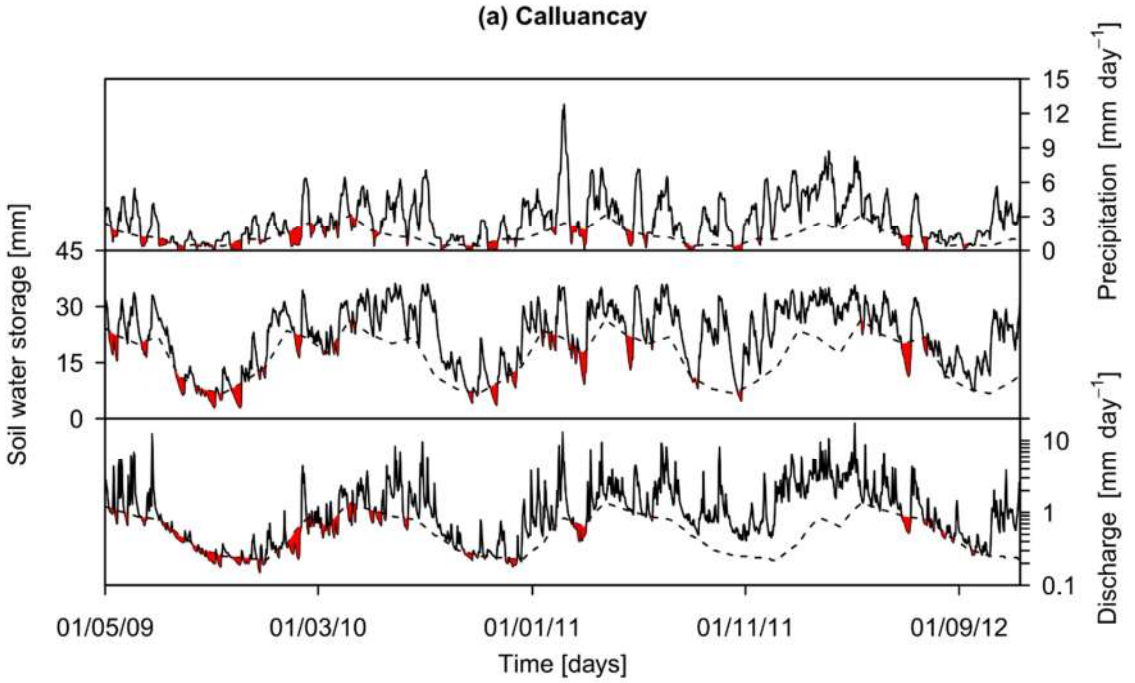


(a) Calluancay



(b) Cumbe

Figure 5. Drought propagation for each experimental catchment



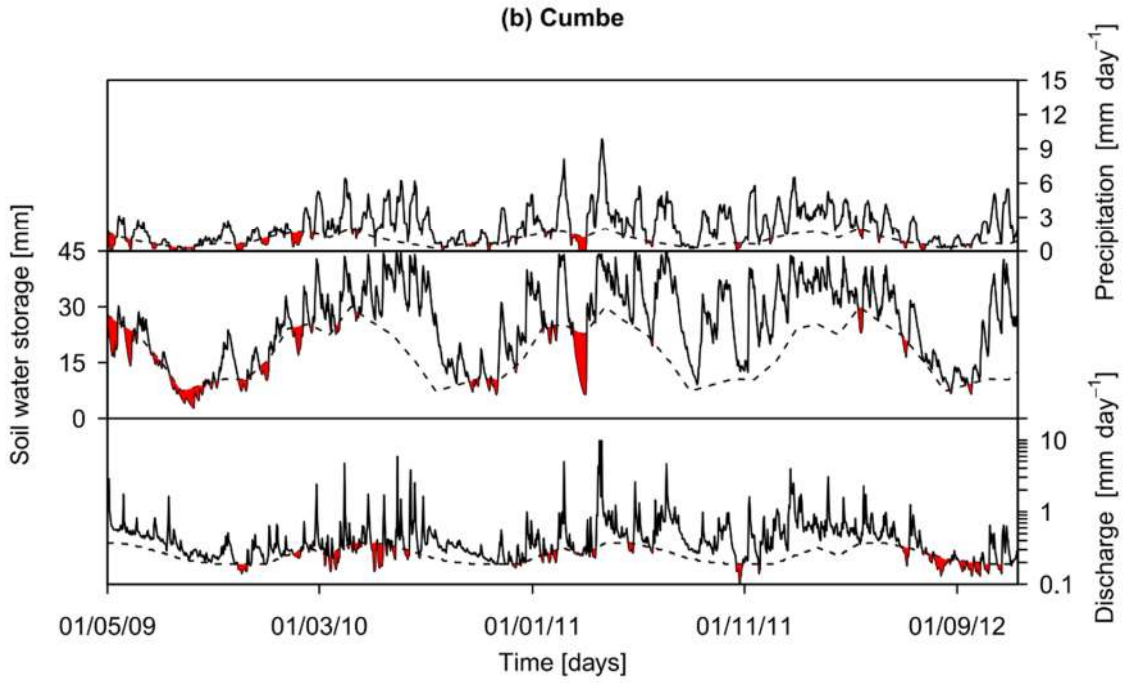
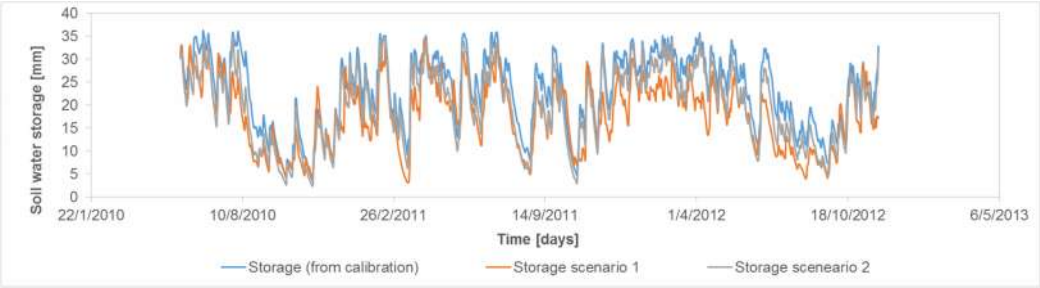
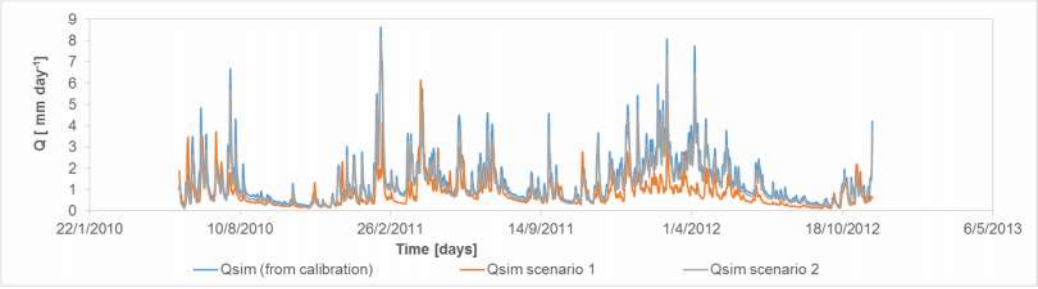


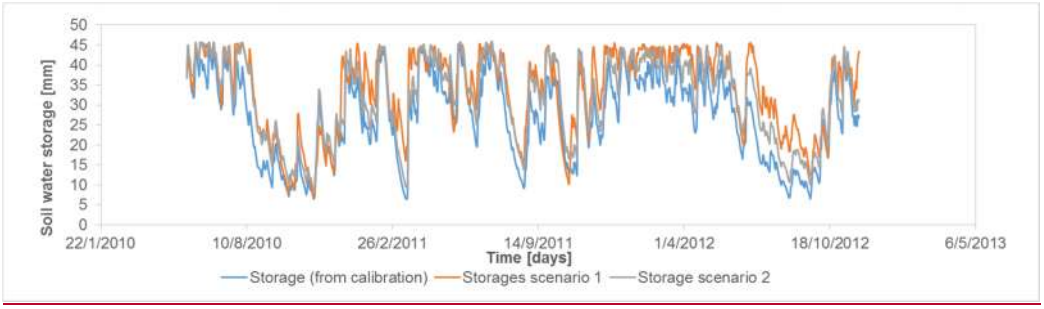
Figure 6. Soil water storage and stream discharge for the experimental catchments as result of the two senarios of climate

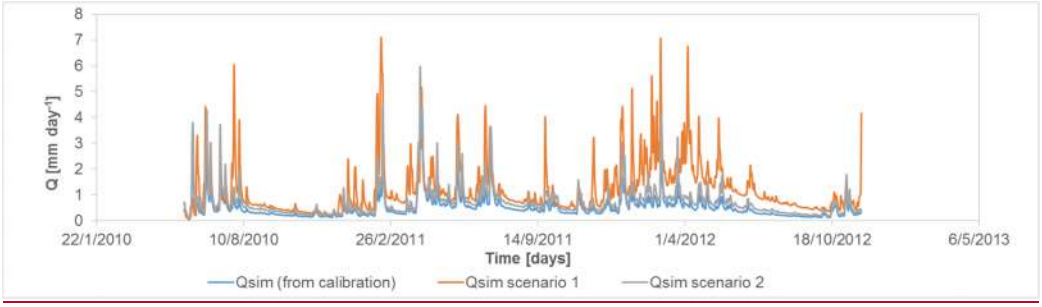
(a) Calluancay



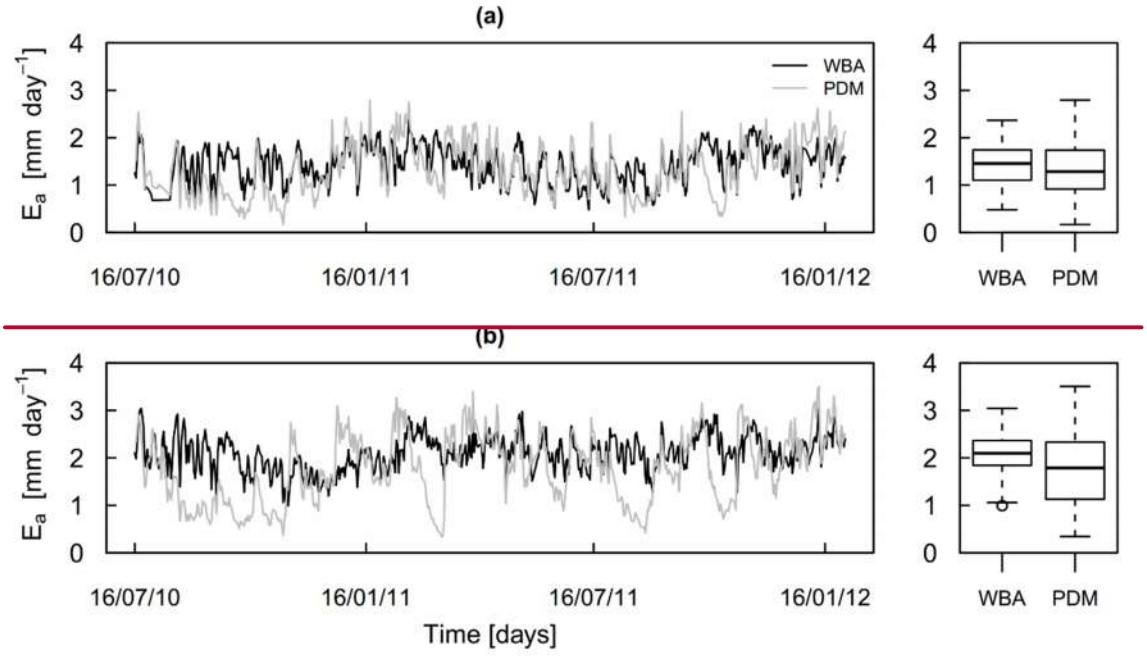


(b) Cumbe





~~Figure 6.~~ ~~The actual evapotranspiration (E_a) using the water balance approach (WBA) and the PDM model. **(a)** Calluancay and **(b)** Cumbe.~~



1

2

3