Detailed comments from Editor and the author's response:

Editor’s comment:

-The abstract needs more new results (like in conclusions) and a concluding discussion sentence. The recovery results mentioned in the abstract are not in the manuscript anymore, which I think they should be.

Answer:

The abstract and conclusions were reviewed. The recovery results mentioned in the abstract were included in the results and discussion section.

Editor’s comment

-“Capacity recovery”? Should this be “recovery capacity” or just “recovery”?

Answer:

We decided to use just “recovery”

Editor’s comment

-Methods section: please reorder the subsections 3.1 and 3.2 in a more logical sequence and rephrase the titles, e.g. 3.2 “Catchment modelling”, 3.2.1 “Calibration & validation”.

Answer:

The methods section was reordered following a more logical sequence and the titles were modified.

Editor’s comment

-3.1: You do not use Eq. 1 or the methods mentioned in this section in the rest of the manuscript.

Answer:

The Eq. 1 was deleted and the related text. The Eq. 1 was used in the soil water balance at the plot-scale, but this approach was removed from the manuscript. Was a mistake to leave the Eq. 1, but it was corrected.

Editor's comment

-P.12, I. 1-3: should this text be removed since you deleted this part from the analysis? Instead you can write that Ks & Kv cannot be measured and need to be determined indirectly by modelling actual ET. You should also add a sentence about why you want to know ks and Kv, i.e. to compare the catchments.

Answer:

Yes, it should be removed and it has been done. The text was deleted and the modifications were done.

Editor's comment

-P.12, I. 6-7: is model used to assess the impact of soil moisture on ET? I think you use it for other purposes.

Answer:

Yes, the PDM model was used it for other purpose. To simulate the soil water storage and so, used to assess the impact of the soil water droughts.

Editor's comment

-P.13, I. 26: did you use observed or simulated Q in the drought analysis? Also specify that in the figure.

Answer:

We used observed Q in the drought analysis. This has been clearly specified in the figures.

Editor's comment

-3.3.1: the recovery analysis explained in this section (I.25-27) is not followed by results in the Results section. Did you do a recovery analysis on the model simulations? Then that should be discussed with the results of the recovery analysis on the observations, mentioned in the abstract. Both should be included in the Methods and the Results sections.

Answer:

Yes, we did a recovery analysis and so, the Methods and the Results sections were updated in order to explain the approach and the results obtained.

Editor's comment

-3.3.2: the description of the recovery analysis (I.10-13) is unclear. How is the recovery period from vegetation stress quantified exactly?

Answer:

First, the vegetation stress period was identified by means of the time series of precipitation and potential evapotranspiration. For this purpose, month have potentially water shortage for the vegetation when the potential evapotranspiration exceeds the rainfall:

$$E_p > P$$

And, a stress period is defined as result of the total sum of consecutive months where vegetation stress is identified. Modelling by PDM was used to estimate E_a and was compared with the E_p. The beginning of the recovery period is when P exceeds the E_p (onset of the rainy season). The end of the vegetation stress recovery is assumed when E_a reaches the maximum value.

Editor's comment

-3.3.3: How are the scenario results compared to original simulation?

Answer:

The scenario results and the original simulation were shown in one figure in order to visualize the differences. Positive or negative deviations from the original simulation revealed the impact of each factors (precipitation, potential evapotranspiration and soil) on the soil water storage and stream discharge. The analysis was focussed during the drought recovery periods.

Editor's comment

-4.2: This section should be split up in multiple sections, one on general model results, one on ET and some parts that should go in the Methods or Discussion section:

Answer:

We are agree in that, the section 4.2 should be split up in multiple sections. And it has been done.

Editor's comment

-P.16, I.21-26 & I.29-30: this part should go in the Methods section

Answer:

This part is now in the Methods section.

Editor's comment

-P.17, I.6-9: Sn is out of range, discuss this.

Answer:

It was a mistake, the S_{rt} values shown correspond to the first manuscript. Now, the table was corrected. The calibration was different as compared with the first version (the calibration was focussed in low flows) and so, the range of feasible values changed.

Editor's comment

-P.17, I.19-30: Move this paragraph to the Discussion section. Last sentence is unclear statement.

Answer:

This paragraph was moved to the results and discussion section. The last sentence was deleted.

Editor's comment

-P.18, I.1-13: first part of this paragraph should be moved to before modelling results, second part should go to Discussion section.

Answer:

This modification has been done in the manuscript.

Editor's comment

-4.3: change title, e.g. "Drought severity"

Answer:

The title was modified

Editor's comment

-Remove "on the other hand" in several sentences.

Answer:

The phrase: "on the other hand" was removed from manuscript.

Editor's comment

-4.5: these new results need a figure (p.19 I.28 – p.20 I.4) and/or a table (p.20 I.5-15) to visualise the results. Also the vegetation stress recovery needs to be compared with the soil moisture drought recovery.

Answer:

The new results were shown in one figure per catchment and appropriately discussed in the manuscript. The vegetation stress recovery was also compared with the soil moisture drought recovery in both catchments.

Editor's comment

-P.20, I.16-25: why do you need the CDD analysis? Why is it mentioned in this paragraph?

Answer:

The CDD analysis and related text were removed from the manuscript.

Editor's comment

-P.20, I.1-2: what are these numbers? Total P & ET over the modelling period? Or per year?

Answer:

Those numbers were removed from the manuscript. However, those number corresponds to the total P & E_p over the modelling period (scenario analysis).

Editor's comment

-Table 3: does this show normal NS or NS based on log Q?

Answer:

Table 3 shows NS based on log Q. This was included in the caption.

Editor's comment

-Figs. 3-5: clarify which variables are simulated and which observed

Answer:

The Figs. 3-5 were modified in order to differentiate which variables are simulated or which observed.

Editor's comment

-Fig. 6: chose clearer colour scheme and make a better legend / give more information in the caption.

Answer:

The Fig. 6 was modified completely with a clear colour scheme and more information was included in the caption.

Editor's comment

-For drought recovery, you might want to look for inspiration at this recent paper in HESSD by (Parry et al., 2016) (in review).

Parry, S., Wilby, R. L., Prudhomme, C. and Wood, P. J.: A systematic assessment of drought termination in the United Kingdom, Hydrology and Earth System Sciences Discussions, (January), 1–33, doi:10.5194/hess-2015-476, 2016.

Answer:

Thanks for the suggestion.

A list of all relevant changes made in the manuscript

The sections which were modified substantially are:

-Abstract

-Methods

-Results and discussion

-Conclusions

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

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Abstract

The ~~neotropical~~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 along ~~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 ~~capacity~~ recovery of its soils for drought periods observed during 2009 and 2012. 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 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 recovery during a subsequent wet period. Local soil water content measurements in the top soil (first 30 cm) through TDR (plot scale) 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, the study reveals an apparently 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 (27%), decreasing from a normal value of about 0.54 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. 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~~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 67% of the annual rainfall (Buytaert et al., 2006a). During wet periods the volumetric soil water ~~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~~contains many ~~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 advance~~ment~~ 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) predicted an increase in the mean annual precipitation and temperature in the region that is of interest to our study. ~~On the~~

~~other hand~~Therefore, the carbon storage and the water yield could be reduced by the higher temperatures and the larger~~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).

~~On the other hand~~Additionally, 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).

It is claimed that t~~T~~he hydrological regulation and buffering capacity ~~of the páramo~~ is linked to~~resides in~~ its soils (Buytaert et al., 2007b).~~.~~ 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 hydrological and soil water drought as defined by Van Loon (2015).

The major point in our research is to analysis the recovery speed of the páramo soils after drought periods. Indeed, our hydrological perspective serves -in the first place- the downstream users.

The observation period includes the droughts of 2009, 2010, 2011 and 2012 together with intermediate wet periods.

In this paper ~~The~~ hydrological drought is compared and related to ~~this~~ soil water drought by ~~by means of an~~ analysing~~s of~~ the drought propagation. ~~For this purpose,~~ T~~t~~wo experimental catchments –one with and one without páramo– were investigated.~~ by means of a hydrological model. In addition,~~ T~~t~~he 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~~. In the two catchments ~~The experimental work included the measurement of~~ rainfall, climate, flow and soil moisture by TDR in experimental plots was measured. ~~(TDR probes installed in experimental plots, one for each catchment). For the modelling,~~ A~~a~~ parsimonious conceptual hydrological model –using T~~t~~he Probability Distributed Moisture simulator (PDM), a parsimonious conceptual hydrological model,~~ was~~ was calibrated and validated for each experimental catchment. The PDM model allowed~~s~~ to analys~~s~~e the temporal and spatial variability of the soil water content as well as the maximum storage capacity at the catchment scale.

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

2 Materials

2.1 ~~The s~~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) subpáramo is predominant; it occupies only 7.6% of the catchment. In the Cumbe catchment, 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~~ M~~m~~onitoring of hydro-meteorological 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 were~~are~~ part of a larger hydrological monitoring network maintained by PROMAS. Water levels were~~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 was~~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~~were measured with a 15 minute time interval by an automatic weather station. These stations were used to estimate the potential reference evapotranspiration according to the FAO-Penman-Monteith equation.

2.3 Measurement of~~The physical characteristics of the~~ soil water content

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 available from~~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 covered the whole altitudinal range of páramo (3500-3882 m a.s.l.)- was generated based on soil descriptions of 2095 vertical boreholes and 12 soil profile pits. For~~In~~ each soil profile pit~~s~~ a ~~complete set of~~ physico-chemical ~~and physical~~ analysis of each layer were executed~~done~~. Within the~~Meanwhile, in~~ Cumbe catchment 13 soil profile pits were dug~~carried out~~ ~~during the field campaign~~ as part of the present research. ~~To this purpose, 4 cross section transects were established.~~ Thus, for both catchments a detailed soil map was available covering ~~the field survey in Cumbe was designed to cover~~ the whole altitudinal range (2647 – ~~3467~~ 3882 m a.s.l.). Based~~Therefore,~~ on this detailed soil information ~~was incorporated in the analysis and used in the selection of r~~representative locations for the TDR measurements in each catchment were selected.

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 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 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 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, 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:~~

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

~~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.~~

~~3.1.1~~1.1.1 ~~The potential evapotranspiration~~

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

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

~~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 [°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 °C^{-1}],~~

~~γ = the psychrometric constant [kPa °C^{-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:~~

~~$R_{\mathrm{s}} = R_{\mathrm{a}}\, c\, (T_{\mathrm{max}} - T_{\mathrm{min}})^{0.5}$ (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 [°C],~~

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

~~3.1.21.1.1 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:~~

$$\cancel{E_a = k_s \cdot k_v \cdot E_p} \qquad \cancel{(4)}$$

~~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.~~

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

~~3.2~~3.1 ~~The actual evapotranspiration estimated by hydrological~~Catchment modelling

The hydrological PDM model (Moore and Clarke, 1981; Moore, 1985) is a conceptual rainfall – runoff model, which consists of two modules. The first one is the~~a~~ soil moisture accounting (SMA) module which is based on a distribution of soil moisture storages with different capacities ~~used to~~ accounting for the spatial heterogeneity in a~~the~~ catchment. The probability distribution used is the Pareto distribution. The SMA module simulates the temporal variation of the average soil water storage. The second part of the model structure is the~~a~~ routing module, which consists of two linear reservoirs in parallel in order to model~~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.~~

~~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 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 fast runoff generation (Buytaert and Beven, 2011). Lateral subsurface flow has a slower response. Therefore, t~~T~~he stream discharge ~~(Q)~~ at the outlet of the catchment thus comprises mainly fast overland flow and slow lateral flow. ~~In other words, fast and slow flow pathways respectively.~~

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

As~~Based on th~~ clay is the most important ~~e~~ 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 o~~the combination of~~f~~ ~~flows:~~ overland either due to limited infiltration or to saturation and of shallow 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:~~

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

~~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.~~

T~~t~~he PDM model was~~has been~~ implemented within a MATLAB toolbox using the~~with the~~ options of calculating the actual evapotranspiration E_a as a function of the potential evaporation rate E_p, and the soil moisture deficit by (Wagener et al., 2001):

$$E_a = \left\{1 - \left[\frac{(S_{max} - S(t))}{S_{max}}\right]\right\} \cdot E_p \qquad (\cancel{5}1)$$

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 as~~can be~~ compared to~~with~~ the potential vegetation evapotranspiration ~~Eq. (4)~~ is an indicator of the drought~~n order to assess the impact of the vegetation and~~ stress ~~coefficients~~.

3.1.1 The potential evapotranspiration

The FAO-Penman-Monteith approach (Allen et al., 1998) was~~is~~ used to estimate the potential evapotranspiration of a reference crop (similar to short grass) under stress free conditions without water limitation:

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

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 [°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 °C^{-1}],
γ = the psychrometric constant [kPa °C^{-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 by the meteorological stations in our experimental catchments were not consistent and considered~~appeared~~ to be unreliable. ~~Therefore, the FAO-Penman-Monteith estimation for E_p was used with t~~Therefore the~~e~~ solar radiation was estimated by ~~means of t~~the Hargreaves-Samani equation (Hargreaves and Samani, 1985) using the daily maximum and minimum air temperature:

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

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 [°C],

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~~ T~~t~~he potential evapotranspiration of a~~another~~ vegetation~~ type~~ without drought stress can be~~was~~ calculated by multiplying the reference crop evapotranspiration by ~~means of a v~~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. During stress free periods k_s equals to one and the lower the stress coefficient the more stress the vegetation experiences.

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

$$E_\mathrm{a} = k_\mathrm{s} \cdot k_\mathrm{v} \cdot E_\mathrm{p} \qquad (4)$$

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 close to the equator, this seasonality may be neglected as the grasses are slow-growing and perennial.

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

For the purpose of this study the global effect of both coefficients will be estimated and the Eq. (4) can be combined into one coefficient K:

$$E_\mathrm{a} = K \cdot E_p \qquad (5)$$

In order to determine K the actual and potential evapotranspiration need to be estimated.

~~3.2.1~~3.1.3 ~~Implementation of the PDM model~~Calibration and validation of PDM model

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 was~~is~~ done in order to define the feasible parameter range. The sampling strategy applied was~~is~~ an optimal Latin Hypercube sampling with a genetic algorithm according to (Stocki, 2005) and (Liefvendahl and Stocki, 2006). Afterwards, the obtained parameters of the PDM model were optimized by means of the Shuffled Complex Evolution algorithm (Duan et al., 1992).

The time periods from 29 November 2007 until 06 August 2009 and from 20 May 2010 until 27 November 2012 were~~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. The selected periods for calibration and validation contained~~resemble~~ the typical~~average~~ climatic conditions of the southern Ecuadorian Andes- (Buytaert et al., 2006b; Celleri et al., 2007).

The Nash and Sutcliffe efficiency (NSE) was used as objective function (Nash and Sutcliffe, 1970) for ~~.The~~ calibration. As~~ procedure was focussed onin~~ low flows under drought were important~~and hence,~~ the logarithmic ~~of the~~ discharges~~ values~~ were used for the calculation of the NSE~~in the objective function~~. ~~The Nash and Sutcliffe efficiency was used as objective function (Nash and Sutcliffe, 1970).~~

It is important to mention that ~~T~~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 internally calculated~~ derived~~ variables include effective rainfall, actual evapotranspiration, simulated discharge and average distribution characteristics~~ 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 was~~can be~~ compared to the observed~~measured~~ soil water content, measured by TDR in one experimental plot in each catchment. ~~The comparison is carried out just to see if the PDM model parameters have physical meaning. However,~~ T~~t~~he average soil water content simulated by PDM was~~ill be~~ used in the drought analysis.

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~~ T~~t~~he soil water ~~storage~~ content always remained higher than~~was never extracted up to~~ wilting point. The volumetric water storage at wilting point, which is in Andosols and Histosols still as high as~~around~~ 40%, was~~is~~ therefore not actively represented in the model and can be considered as dead storage from the PDM modelling point of view.

~~3.3~~3.2 Drought analysis

T~~The threshold level approach will be used to identify and quantify t~~he severity of drought periods were identified and quantified by a threshold level approach ~~. 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). ~~T~~Thresholds were~~o this~~ set for ~~purpose,~~ the time series of precipitation (P), observed stream discharge (Q) and ~~the~~ average soil water content simulated by PDM (S~~M~~) ~~are analysed~~ according to ~~the following approach~~ ~~(~~Van Loon et al., (2014):

-~~In this study~~ a ~~monthly~~ threshold for each month of the year was based on the 80th percentile of ~~monthly~~ duration curves of P, S and Q ~~(after~~ applying a 10 day moving average~~), SM and Q~~. Th~~e~~ise threshold was subsequently~~is however~~ smoothed by ~~means of~~ a 30 day moving average. Last ~~This type of s~~smoothing ~~is required to~~ removed the stepwise pattern and avoided artefact droughts at the beginning or end of a month (Van Loon, 2013).

-Drought characteristics are determined based on a deficit index:

$$d(t) = \begin{cases} \tau(t) - x(t) & if\ x(t) < \tau(t) \\ & or \\ 0 & if\ x(t) \geq \tau(t) \end{cases}$$ (~~7~~6)

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

$$D_i = \sum_{t=1}^{T} d(t)\,.\Delta t \qquad (\cancel{8}7)$$

in which D_i is in mm. The deficit is standardized ~~divided~~ by dividing 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 average soil moisture water storage 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 ($P_{\text{day}} < 1$ mm) is the index employed to measure the drought conditions (Griffiths and Bradley, 2007).~~

~~3.3.1~~3.2.1 Drought propagation and drought recovery analysis

Here, we analysed~~is~~ the translation -as a chain of hydrological processes- from~~of the~~ meteorological drought over~~through the hydrological cycle and its impact in the soil water storage (~~ soil ~~moisture~~ water drought into~~) and over the hydrological response of the catchments (~~hydrological drought for the catchment~~)~~. The time series of P, Q and S was in one figure per catchment. This allowed a visual inspection of the propagation, onset and recovery of droughts and to compare the behaviour of the different time series.

The Fig. 2 shows a conceptual graph for -the estimation of the drought recovery. This diagram is similar to the formulated by ~~(~~Parry et al., (2016), who have proposed an approach to systematic assessment of the drought recovery period or drought termination. Such graphs allow to determine the duration t_d in days of a drought. The drought starts when the variable drops under the threshold and ends when the normal state is reached again. The duration of drought recovery, t_{dr}, starts from the lowest point to the end of drought. The slope of the variable between the lowest point and the end estimates the rate of recovery. This rate can be expressed as percentage of the recovery per day with respect to the normal value for the variable.

~~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~~3.2.2 Vegetation stress and recovery

Drought indices have been used by several researchers in order to quantify drought characteristics (Dai, 2011; Van Loon, 2015; Tsakiris et al., 2013). Most of them are based on Precipitation P and potential evapotranspiration E_{p}. For instance, the Standardized Precipitation Index (SPI) (Lloyd-Hughes and Saunders, 2002) or the Standardized Precipitation and Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2013) are widely used in drought studies. But, due to the lack of a long historical time series of climate data for our experimental area, this type of indices cannot be applied. Nevertheless, based on the available monthly time series of P and E_{p} a comparison can be done between catchments.

~~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.~~

For this purpose, month have potentially water shortage for the vegetation when the potential evapotranspiration exceeds the rainfall:

$$E_p > P \qquad (8)$$

And, a stress period is defined as result of the total sum of consecutive months where vegetation stress is identified. Modelling by PDM was used to estimate E_{a} and was compared with the E_{p}.

After the ~~drought ~~stress periods, when the wet season starts~~ the~~ P reaches values to cover the deficit of soil water and the vegetation starts to recover~~y~~. These periods are also identified based on the monthly data of P and E_p~~.~~ and contrasted with~~–~~ E_a estimations. When E_a reaches the highest value -normally during the wet season- that month marks the end of the vegetation recovery.

~~3.3.3~~3.2.3 Sensitivity analysis

A sensitivity analysis was~~is~~ carried out by the~~means of~~ PDM model in order to reveal~~s 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 (páramo).~~

~~The sensitivity analysis implemented is relatively simple, ~~T~~t~~he 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 based on meteorological data~~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.

The scenario results, simulated stream discharge Q_{sim} and average soil water storage S are displayed in plots for each catchment in order to establish the main differences. Positive or negative deviations from the original simulation (calibration) will reveal the impact of the climate over the soil water storage and stream discharge. The analysis of the scenario results is focus in the drought recovery periods in order to compare the behaviour of the soils during different climate conditions.

4 Results and discussion ~~and discussion~~

~~4.1~~ 4.1. ~~The P~~potential evapotranspiration

Con formato: Título 2, Sin viñetas ni numeración

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~~3. 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 °C respectively, ~~. W~~while, in Cumbe they were 7.8 and 17.4 °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 was~~are~~ 4.2 (max: 11.9) and 0.9 (max: 2.6) m s^{-1} respectively.

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

Con formato: Título 2, Sin viñetas ni numeración

~~4.1.1~~ Modelling the discharge and the actual evapotranspiration~~results~~

Con formato: Título 2

~~The time periods from 29 November 2007 until 06 August 2009 and from 20 May 2010 until 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. 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. ~~3~~ 4 summarizes the results for the PDM model. The performance of the model for the calibration period is good in both catchments (Nash-Sutcliffe efficiency, NSE= 0.83). ~~The calibration procedure was focus in low flows and hence, the logarithmic of the discharges values were used in the objective function.~~ Lower values of NSE were obtained during the validation periods~~,~~. The~~s~~ calibration focussed on low flows. More storm runoff events were observed during the validation period as a consequence the poorer fit of large flows led to lower NSE~~that time as compared with the calibration period~~.

T~~t~~he average soil moisture storage simulated by the PDM model was compared to the observed soil moisture measurements on representative plots (Fig. ~~3~~4). Similar dynamics are observed. However~~This result is a first insight, which can be incorporated in future investigations on~~ a more precise up-scaling (from plot to catchment) would benefit from ~~. Here, there are not enough number of~~ more plots per catchment~~in order to apply an up-scaling approach~~.

Table 2 shows the calibrated parameter set for both catchments. The maximum storage capacity c_{max} is as expected higher at Calluancay.~~Initially, a relatively high difference in the value~~ The~~of~~ parameter "b" is quite different between the 2 catchments~~ revealed~~. Thise difference~~s in the sensitivity of th~~ of~~e parameter~~ "b" can be partially attributed to the fact that Cumbe is much larger and less homogeneous ~~,~~and therefore the variety of soils ~~hydrological response~~ is larger which was reflected in the coefficient representing the variability of soil water storage capacity. The residence time for fast routing is very similar as expected with relatively small catchments. The residence time for slow routing is more different. We know according to recent research by ~~(~~Guzmán et al.~~,~~ (2016) that runoff from hillslopes in the Cumbe catchment infiltrates into the alluvial aquifer, which drains into the river and causes a slow reaction. Calluancay also showed somewhat more contribution of fast flow. This can be explained by the occurrence of saturated overland flow originating from the bogs and wetland parts of the páramo.

Con formato: Subíndice

~~On the other hand~~T~~t~~he daily average values of E_a, as estimated by the PDM model~~s~~ for Calluancay and Cumbe, was~~are~~ 1.47 (range 0.19 to 3.33) and 1.70 (range 0.18 to 3.58) mm day^{-1} respectively. The PDM model, however, does not regard a critical soil moisture value for vegetation stress and therefore there are no constraints on the evapotranspiration during dry periods. As a result, E_a is overestimated by the model during these events.

~~Finally, t~~The impact of both -the vegetation and stress coefficients- ~~or k_v and k_s respectively~~globally represented by K coefficient was determined by means of a comparison between E_a and E_p. For Calluancay and Cumbe, the impact of the aforementioned coefficient~~s~~ 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. ~~(~~Buytaert et al.~~,~~ (2006c) determined two values of K for natural and altered páramo vegetation during a period without soil water deficit (k_s equal to 1), 0.42 and 0.58 respectively. Meaning that, if a comparison is done, the average value of K for páramo is higher than the previous research, a 60 and 16% respectively. While, the K value for Cumbe is in line with the literature for grasslands (Allen et al., 1998).

~~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 is~~was~~ 0.43 and 0.30 cm^3 cm^{-3} for Andosols (Calluancay) and Dystric Cambisols (Cumbe), respectively (Fig.~~3~~ 4 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.~~

The average daily actual evapotranspiration rate of 1.47 and 1.70 mm day^{-1} corresponds with former studies in páramo and grasslands respectively (Allen et al., 1998; Buytaert et al., 2006a). With the E_a estimated, the *K* coefficients were calculated in order to assess the combined effect of the vegetation and soil water stress. The differences between the catchment is no more than a 16% when average values are compared. Those values were of 0.67 and 0.58 for páramo vegetation and grasslands respectively.

The relatively ~~high~~low values of *K* coefficients could be partially explained by the plant physiology. The tussock grasses (mainly *Calamagrostis* spp. and *Stipa* spp.) in páramo are characterized by specific adaptations to extreme conditions. 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 evapotranspiration. In Cumbe the grazing pastures are characterized by plants of type C3 (*Pennisetum clandestinum*) which are also highly tolerant to drought. Therefore, the water uptake is mainly regulated by the plants during dry periods.

This is clearly observed in the volumetric water content θ as measured by TDR ~~-~~(Fig. 4). Field observations in November 2009, revealed that the plants showed some visual signs of deterioration in the first centimetres but after removal of the top layer, which is always containing dead leaves, the plants itself showed little visual deterioration. Nevertheless, the depletion of the soil moisture storage during dry weather conditions clearly lead to stress and reduced the transpiration rate. 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 this "natural" drought.

~~4.2~~ 4.3 ~~Impact of the d~~Drought~~s~~ severity

Con formato: Título 2, Sin viñetas ni numeración

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~~4). During the drought events in 2009 and 2010, the soil water content in páramo dropped substantially. ~~And so~~Thus, 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,~~ In order to characterize the drought events at catchment scale, ~~the~~a standardized deficit as well as its duration were calculated for each catchment~~s~~. The results are shown in the figure ~~4~~5. 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. So, seemingly the drought events characteristics are similar and independent of the climate. This in line with the literature. For instance, based on a global map of Köppen-Geiger climate types (Wanders et al., 2010) and using a similarity index SI (Kim et al., 2003), ~~(~~Van Lanen et al.~~, ~~(2013) concluded that independent of the climate type, similar combinations of duration and standardized deficit volume were found in a large number of drought events. They analysed 1495 locations around the world and a data set over the period 1958 to 2001.

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~~5. Just a slight higher value of slope for soil water storage in Calluancay (páramo) 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. In addition, in Calluancay the standardized deficit and duration in soil water storage are highly correlated. While, in Cumbe, a high correlation is observed in precipitation. In lesser extent, a correlation is observed in discharge for both catchments. The occurrence of hydrological drought events decreased due to high buffering capacity of the soils. This can explain~~s~~ the lack of a high correlation of the standardized deficit and duration in discharge, which has been widely documented in other studies (Van Loon et al., 2014; Peters et al., 2006).

~~4.3~~ 4.4 Drought propagation

Con formato: Título 2, Sin viñetas ni numeración

The figure ~~5~~ 6 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. The~~is~~ data set is over the period ~~correspond to~~ 2009~~, 2010, 2011 and~~ to 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~~ February and June (Buytaert et al., 2006b; Celleri et al., 2007). ~~Nevertheless~~And, between August 2009 and March 2010 a drought period was observed due to lower~~anomalies in the~~ precipitation. This event had the longest episode with low rainfall~~is the most clearly observed along~~ during the whole time series. The soil water storage in both catchments had~~s~~ a crucial role in the propagation of the droughts. For instance, in Cumbe the meteorological drought event of 2009-2010 was~~is~~ almost completely buffered by the soil water storage and hence, the hydrological drought was~~is~~ delayed. The opposite ~~occur~~occurred~~s~~ in Calluancay, where the soil water storage at that time was~~is~~ not sufficient~~enough~~ to overcome the period with low~~deal with the anomalies of~~ precipitation. The~~ and the~~ propagation of the drought was~~is~~ also observed simultaneously~~immediately~~ in the stream discharge (the hydrological drought). A different pattern is observed between 2010 and 2012. The buffering capacity of soils in Calluancay was higher as compared to Cumbe, since a reduced number of hydrological drought events were observed during that period in Calluancay. The recovery of the soil water storage occurs during the wet season and was caused~~ revealed by a series o~~ by~~f~~ several but intermittent storm events, which led to~~derived in~~ an irregular pattern of the soil water storage.

Con formato: Normal, Sin viñetas ni numeración

4.5 ~~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.~~

Con formato: Título 2

4.5 Soil water drought recovery

For the 2009-2010 drought event observed in Fig. 6, the duration of the soil water drought recovery for Calluancay and Cumbe was equal to 126 and 176 days respectively. While, the meteorological drought durations were equals to 182 and 238 days respectively. The anomalies calculated were of -59% in Calluancay and -66% in Cumbe.

The soil water storage in both catchments decreased up to about 3 mm at the beginning of the drought recovery. The speed of recovery expressed as percentage per day (which is the difference in soil water storage values between the end of drought and the beginning of the drought recovery by divided by the time in days) was of 0.73 and 0.53 % recovery day^{-1} for Calluancay and Cumbe respectively. This means that, the soil water recovery in Calluancay was a 37% faster as compared to Cumbe. The climate pattern observed for this event explained~~s~~ partially the differences between the rates of recovery. A higher evaporative demand was observed in Cumbe as well as less rainfall. Dividing the precipitation amount by the duration of the drought recovery for each catchment, the differences between the catchments became around 10%. The ratio between P and E_p in Calluancay was 50% higher than in Cumbe. For Calluancay and Cumbe, the soil water droughts started in August and July respectively. These months correspond to the dry season (July – November).

For the 2010-2011 soil water drought event, the drought recovery durations for Calluancay and Cumbe were 88 and 90 days respectively. The anomalies were of -61% (Calluancay) and -38% (Cumbe). The speed of recovery was relatively similar in both catchments despite of the differences in the anomalies. The recovery rates were equals to 1.02 (Calluancay) and 0.94 % recovery day^{-1} (Cumbe). This was almost identical. In this drought event, E_p was significant less than P, as compared with the first drought event. This meant~~s,~~ more available water and less deficit. This fact and the difference in the anomalies can explain the similar recovery rate in both catchments for this event.

For the two major drought events the number of intermittent events were no more than 3. These events had not significant impact in the drought pattern.

From Fig. 6, two small soil water drought events in 2011 were observed for Calluancay and just one event in Cumbe. These dry periods occurred within the wet season and so, the duration is no more than 50 days in both catchments (46 and 13 days for Calluancay and 34 days for Cumbe). The recovery rates for those events were equals to 3.03, 8.76 and 5.00 % recovery day^{-1}. The anomalies calculated for those events were different -47.3, -40.6 for Calluancay and -72.1% for Cumbe. The latest event was buffered almost completely by the soil water storage of Cumbe. This is confirmed by Fig. 6, a small hydrological drought event is generated by the anomaly observed in the precipitation. In a similar way, in Calluancay, the second event observed in that period was buffered by the soil water storage and hence, a hydrological drought event was not generated.

In 2012, one minor soil water drought event was identified in Calluancay. The anomaly was equal to -44.7%. The drought recovery was reached in 8 days. The recovery rate was equal to 8.31% recovery day^{-1}. The duration of the drought was as short as 18 days.

4.5

~~4.4~~ 4.6 Vegetation stress and recovery

Con formato: Título 2, Sin viñetas ni numeración

The vegetation stress periods were identified when the ~~half of~~ potential evapotranspiration exceeds the precipitation. Monthly data of E_p and P were used in the identification of the vegetation stress periods. As result, ~~in~~ for Calluancay the months ~~of~~ from August~~, September and October~~ 2009 up to January 2010 reveal clearly a deficit of water (Fig. 7a). This was confirmed by the modelling results, E_a was reduced substantially during this period as compared with E_p. In addition, the end of the soil water drought happened in February 2010 (Fig. 6a) and so, the vegetation stress recovery started~~The recovery start slowly in November 2009~~ and the soil water content progressively increased~~s~~ during the wet season~~ from February to Jun 2010~~. The complete recovery was reached in June 2010 when E_a was 92% of the E_p (maximum value reached in the wet season).

~~But, once again in~~ Between ~~September~~August and November 2010, another vegetation stress period was identified ~~October and November 2010 a deficit of water is detected and therefore~~. ~~this corresponds to the second period of vegetation stress~~. ~~However,~~ T~~t~~he vegetation stress recovery ~~is faster because between~~period was between December 2010 and April 2011 ~~the deficit is covered completely for~~by the onset of the wet season. The maximum monthly value of E_a was equal to 86% of E_p for this recovery ~~.~~period. While, the soil water drought recovery was reached in February 2011. In this month, E_a was equal to 76% of E_p.

In 2011, ~~only~~ August and October reveal~~s~~ed a deficit of water with a~~which is~~ quick~~ly~~ recovery due to sufficient~~with the~~ precipitation during ~~of~~ November 2011 and~~and December 2011~~ February 2012 (here the maximum monthly E_a was equal to 93% of E_p). While, in 2012 ~~only~~ the similar period between July to September suffered a~~reveal~~ed~~s~~ deficit ~~of water~~. A~~a~~ partial recovery was observed ~~between~~ in October and November 2012.~~.~~

Finally, in Cumbe the vegetation stress was~~is~~ higher as compared ~~with~~ to Calluancay (Fig.7b). 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 recorded in Cumbe was only~~just~~ 6.5 mm, while ~~that~~ in Calluancay it was 24.2 mm. In February 2010, the end of the soil water drought recovery was observed and so, this marked the beginning of ~~T~~the vegetation recovery period. The recovery was reached completely ~~from February up to July~~ on June 2010 and so, E_a was equal to 91% of E_p (but with anomalies in March and April 2010) just before the onset of the second drought period.

The second ~~period of~~ vegetation stress period was identified between~~from~~ August 2010 ~~up to~~and ~~October~~ January 201~~0~~1. ~~The corresponded recovery period was from November 2010 up tp April 2011~~Intermittent recoveries are observed during February and April 2011. In fact, these months were the end of the soil water drought recovery respectively. The E_a estimated for those months was equal to 74 and 86% of E_p.

The third vegetation stress period~~s~~ w~~ere~~as observed ~~in~~ from August ~~and October~~to December 2011. For this event, ~~The corresponded~~ the recovery period was reached completely ~~from November 2011 up to~~in February 2012 (only two months of recovery) and so, the E_a was equal to 86% of E_p. The last vegetation stress period was from ~~July~~ March up to ~~September~~

November 2012. ~~Afterwards, the recovery period was partially observed by the availability of data between October and November 2012.~~ This marked the end of our monitoring period so we cannot provide an estimation of the complete recovery period.

~~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.~~

~~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~~ 4.7 Sensitivity analysis

Con formato: Título 2, Sin viñetas ni numeración

Here, we studied~~y~~ two relatively simple scenarios, in both cases we kept~~ep~~ the parameter set obtained during the calibration procedure. ~~In other words~~This means, the soil characteristics were~~are~~ not modified. Only precipitation and potential evapotranspiration were~~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~~ Fig ~~6~~ 8 revealed~~s~~ that the most important factor was~~is~~ the precipitation as compared ~~with~~ to the potential evapotranspiration. The stream discharge was~~is~~ drastically

Con formato: Izquierda

reduced during the wet season in April 2012, as ~~result~~ consequence of the increase in the deficit of soil water storage. ~~However,~~ A significant difference ~~are~~ was not observed in the drought periods of 2009-2010 or 2011 despite of the increase in the rate of E_p and by a reduction in the input of rain. The opposite occurred in Cumbe, mainly due to the increase in the precipitation amount and by ~~the~~ a reduction in the ~~rate of~~ potential evapotranspiration rate. So, the stream discharge was~~is~~ substantially increased along the whole period, as consequence of the reduction of~~. This is also an effect of a less deficit of~~ soil water storage deficit. This illustrates the importance whether the rainfall minus potential evapotranspiration shows a surplus or deficit.

4.8 Drought characteristics

Con formato: Título 2, Sin viñetas ni numeración

The combinations of durations and standardized deficits for the drought events revealed no difference between the catchments. Initially, we can infer that the drought events are independent of the climate. The maximum standardized deficit estimated was no more than 9 days. This mean that no more than 9 days with mean flow are required to reduce the deficit to zero (Van Loon et al., 2014). While, the sensitivity analysis revealed that the precipitation is the main factor and has a direct influence over the hydrological response of the catchments, especially during the drought recovery.

The soil water drought propagation analysis showed the buffering capacity of the soil water storage. The buffering capacity of the soils was important in the drought of 2010-2011 and partially in the previous event 2009-2010. Comparing the drought analysis for soil water storage and stream discharge clearly showed that they were linked. The seasonality observed in the rainfall climate during the monitoring period is also reflected by the temporal variability of the soil water storage with some delay due to buffering.~~.~~

In the drought event of 2009-2010, the vegetation stress observed in Cumbe lasted seven consecutive months of water deficit as compared to six months of Calluancay. The onset of the drought coincided with the dry season. The vegetation recovery occurred during the wet season in both catchments and when the maximum actual evapotranspiration reached 93% of the potential vegetation evapotranspiration.

After the drought event of 2009-2010 in Calluancay and Cumbe, the vegetation recovery was reached in three and five months, respectively. For Calluancay, the three months were consecutive, while in Cumbe the recovery occurred with intermittent periods of stress. -In the second drought event 2010-2011, the recovery was equal to five and six months for Calluancay and Cumbe respectively.

Finally, point measurements of soil water content in both catchments revealed high differences during drought events (Fig. 4). A faster recovery was observed in páramo as compared to the grasslands of Cumbe. Nevertheless, whether soil water storage simulations -catchment scale- are used instead of plot measurements, the differences in the speed of recovery is no more than a 37% (drought event 2009-2010).

5 Conclusions

The páramo ecosystem has a pivotal role in the hydrology and ecology for the highlands above 3500m in~~of~~ the Andean region. The páramo is the main source of ~~drinking~~ water for human consumption, ~~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 capacity recovery of the páramo soils during drought events.~~ Therefore, we compared~~analysed~~ the hydrological response of a~~A~~ typical catchment on ~~the~~ páramo at 3500 m a.s.l. ~~was compared~~ to one with ~~a~~ lower grassland ~~one~~ at 2600 m a.s.l.~~the páramo soil~~ during drought events ~~observed~~ in 2009, 2010, 2011 and 2012. The analysis was carried out based on the calibration and validation of a hydrological conceptual model, the PDM model and compared to soil water measurements in plots. ~~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.~~

Based on the threshold method the soil moisture droughts occurred 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, a~~At the plot scale the differences between the ~~capacity~~ recovery of the soils were~~are~~ relatively large~~high (Fig. 3)~~. The measured water content in páramo soils ~~apparently reveals~~ showed a ~~more~~ quicker 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 was not as pronounced~~reveals that the differences are not significant~~. Only for the prolonged drought event of 2009-2010 the differences were larger. The main factor in the hydrological response of these experimental catchments is the precipitation relative to potential evapotranspiration. As the soils never became extremely dry or close to wilting point the soil water storage capacity has a secondary influence. The altitude with lower temperatures has a lower water demand for vegetation. The~~A~~ rainfall minus potential vegetation evaporation has therefore more impact as compared to the influence of the ~~a clear impact in the~~ soil water storage capacity.

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.

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Con formato: Inglés (Reino Unido)

~~**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 1. The main characteristics of the experimental catchments

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[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~~ 75 [mm]	64.8	54.5
b	~~Degree of S~~spatial variability of the storage capacity	0.1-2.0 [-]	0.74	0.17
f_{rt}	Fast routing store residence time	1-2 [days]	1.5	1.4
s_{rt}	Slow routing store residence time	~~10~~35-~~50~~120 [days]	58.3	98.2
$\%(q)$	Percentage ~~flow through~~ fast flow	0.25-0.75 [-]	0.51	0.41

Tabla con formato

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

	Calibration		Validation	
Catchment	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 based on the logarithms of stream discharges

Figure 1. The study area

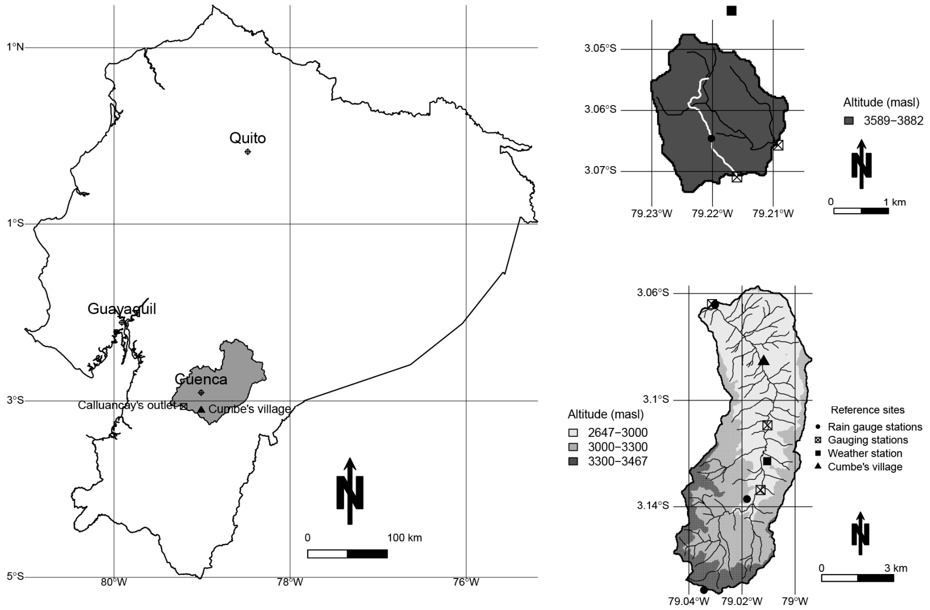


Figure 2. Conceptual diagram for estimation of the soil moisture drought recovery metrics. The t_d and t_{dr} are the durations in days of the soil moisture drought event and drought recovery period respectively. Drought recovery is represented by a brown line. Grey arrows mark intermittent events above the threshold. Green line marks the assumed normal value of soil water storage.

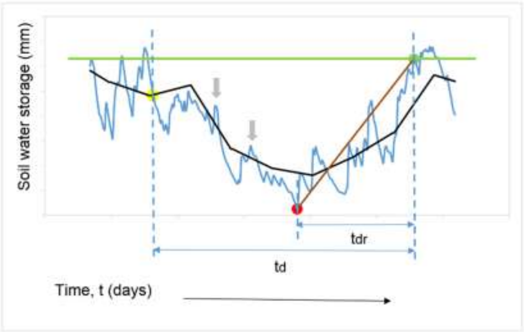
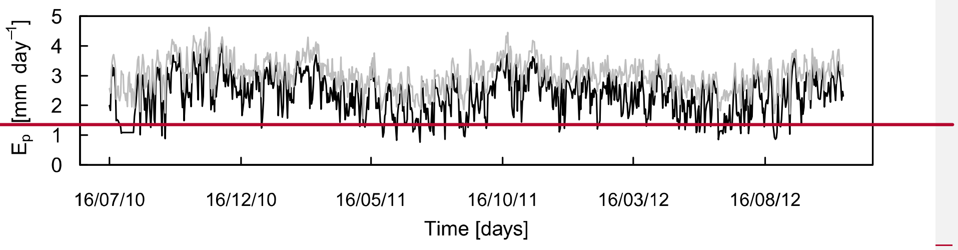


Figure ~~2~~3. The potential evapotranspiration E_p for Calluancay (black) and Cumbe (grey).



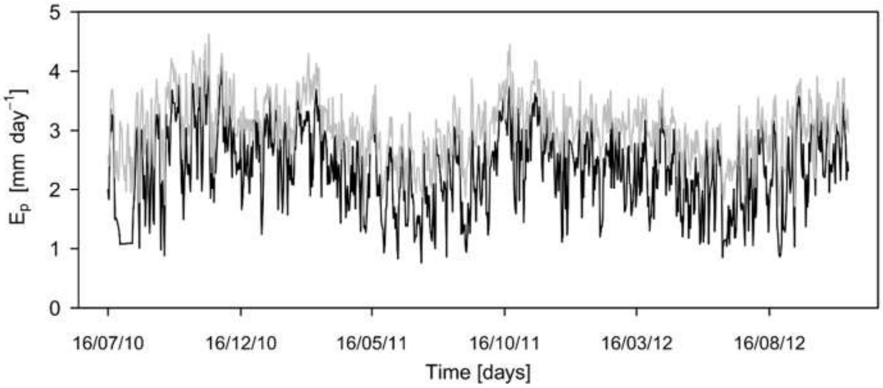
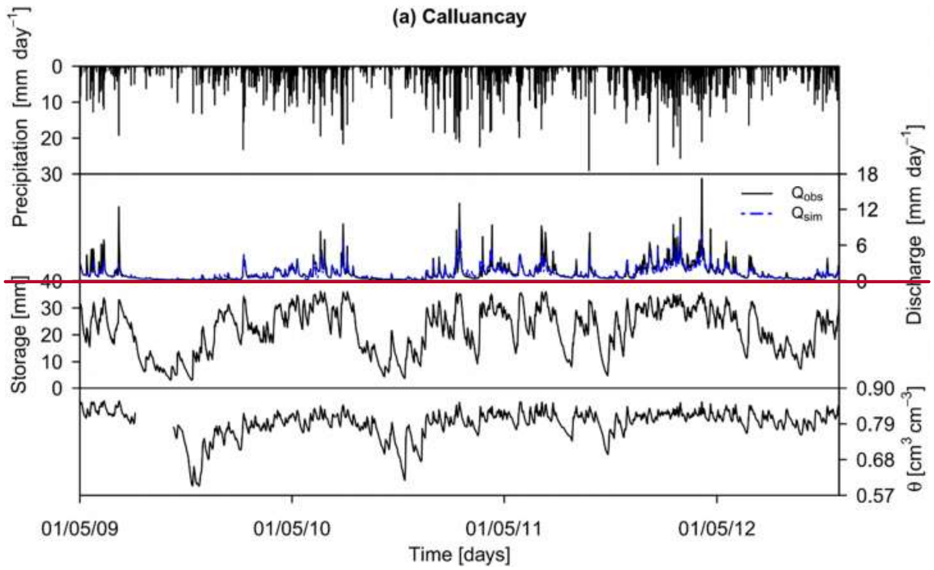
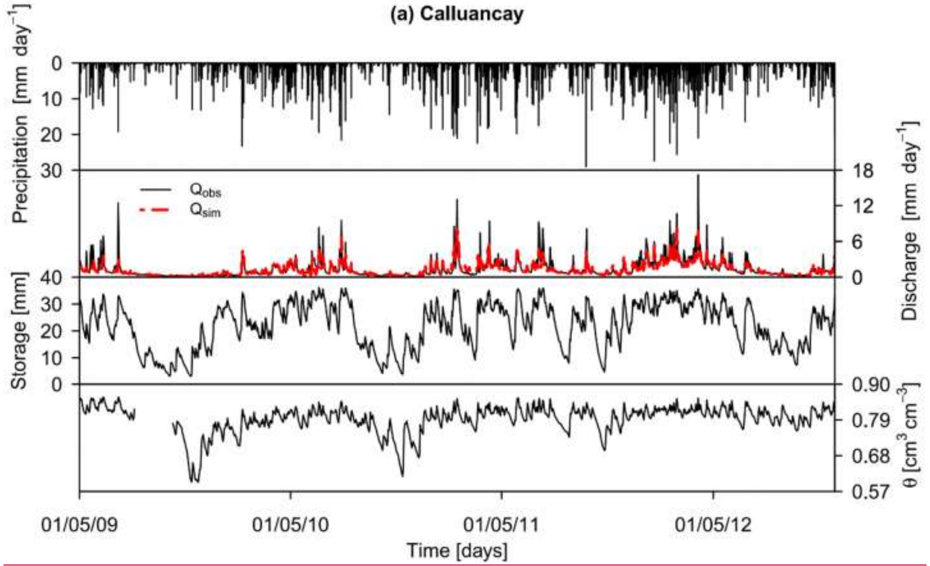
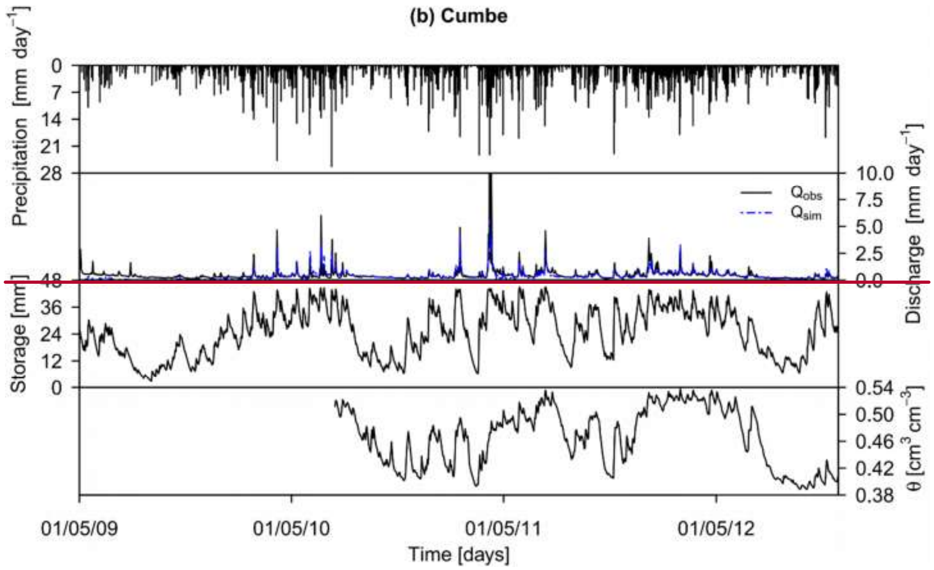


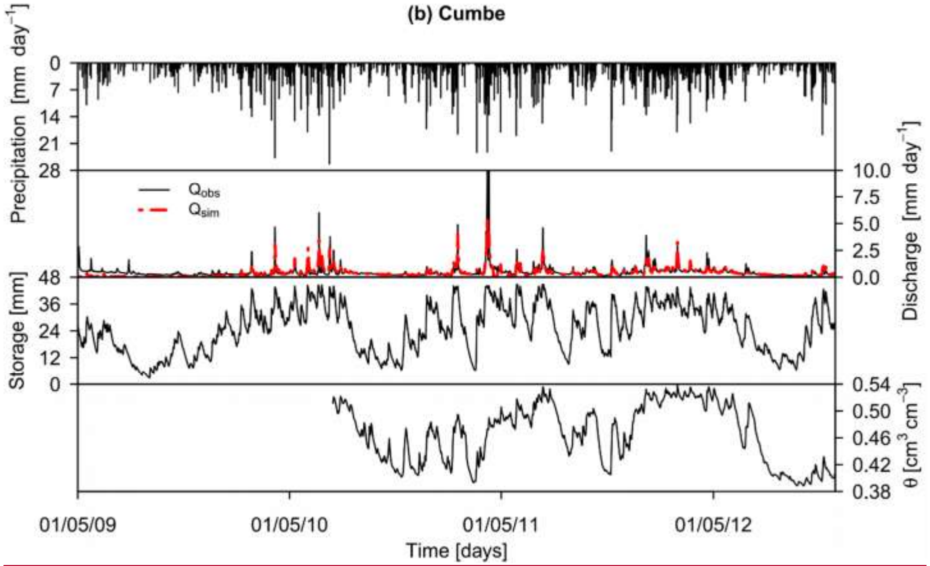
Figure ~~3~~4. Results from the hydrological modelling with PDM model. In first panel the precipitation. In the second panel ~~(~~stream discharge observed and simulated Q_{obs} and Q_{sim} respectively. ~~and~~ In the third panel the average soil water storage simulated~~)~~. Finally, in the bottom inset of the plot, ~~and~~ the soil moisture measured in an experimental plot.


(a) Calluancay
Precipitation [mm day^{-1}]
0
10
20
30
40
Q$_{obs}$
Q$_{sim}$
18
12
6
0
Discharge [mm day^{-1}]
Storage [mm]
30
20
10
0
0.90
0.79
0.68
0.57
θ [cm^3 cm^{-3}]
01/05/09
01/05/10
01/05/11
01/05/12
Time [days]


(a) Calluancay
Precipitation [mm day^{-1}]
0
10
20
30
40
Q$_{obs}$
Q$_{sim}$
18
12
6
0
Discharge [mm day^{-1}]
Storage [mm]
30
20
10
0
0.90
0.79
0.68
0.57
θ [cm^3 cm^{-3}]
01/05/09
01/05/10
01/05/11
01/05/12
Time [days]

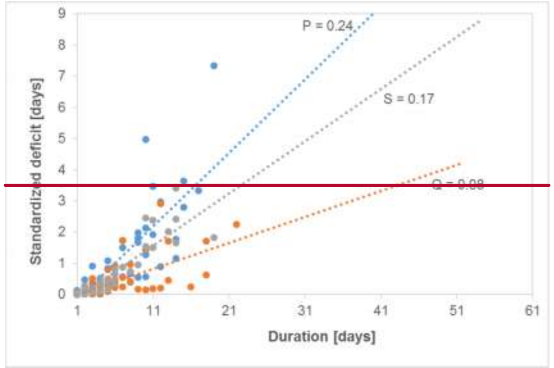


(b) Cumbe
Precipitation [mm day^{-1}]
0
7
14
21
28
Discharge [mm day^{-1}]
10.0
7.5
5.0
2.5
0.0
Q$_{obs}$
Q$_{sim}$
Storage [mm]
48
36
24
12
0
θ [cm^3 cm^{-3}]
0.54
0.50
0.46
0.42
0.38
01/05/09
01/05/10
01/05/11
01/05/12
Time [days]

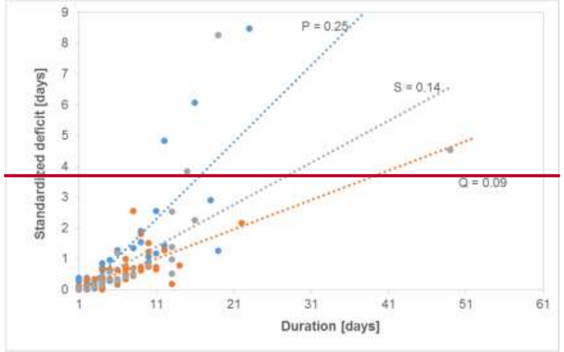


(b) Cumbe
Precipitation [mm day^{-1}]
0
7
14
21
28
Discharge [mm day^{-1}]
10.0
7.5
5.0
2.5
0.0
Q$_{obs}$
Q$_{sim}$
Storage [mm]
48
36
24
12
0
θ [cm^3 cm^{-3}]
0.54
0.50
0.46
0.42
0.38
01/05/09
01/05/10
01/05/11
01/05/12
Time [days]

Figure ~~4~~5. Standardized deficit for the drought periods. (a) Calluancay and (b) Cumbe (in blue P, precipitation; in grey S, soil water storage simulated and in orange Q, stream discharge observed).



~~(a) Calluancay~~



~~(b) Cumbe~~

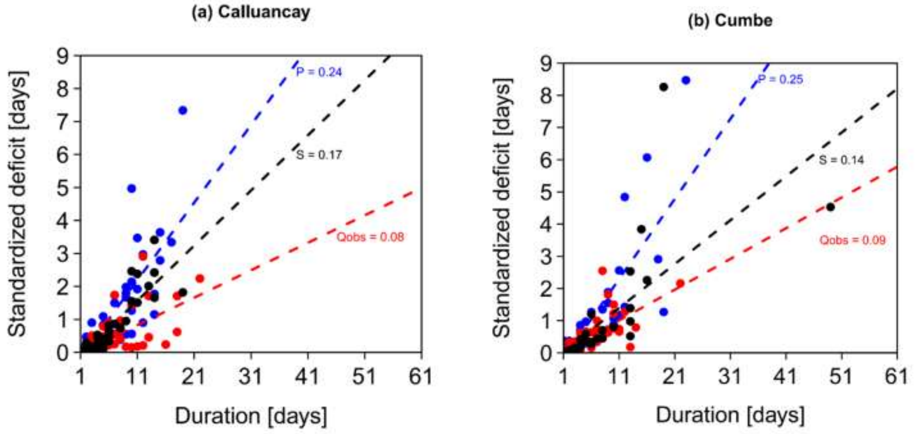
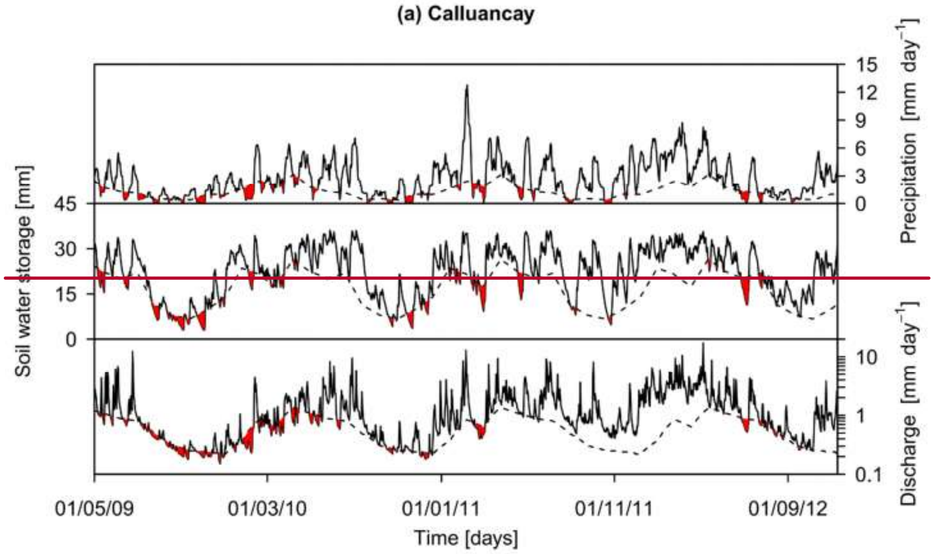
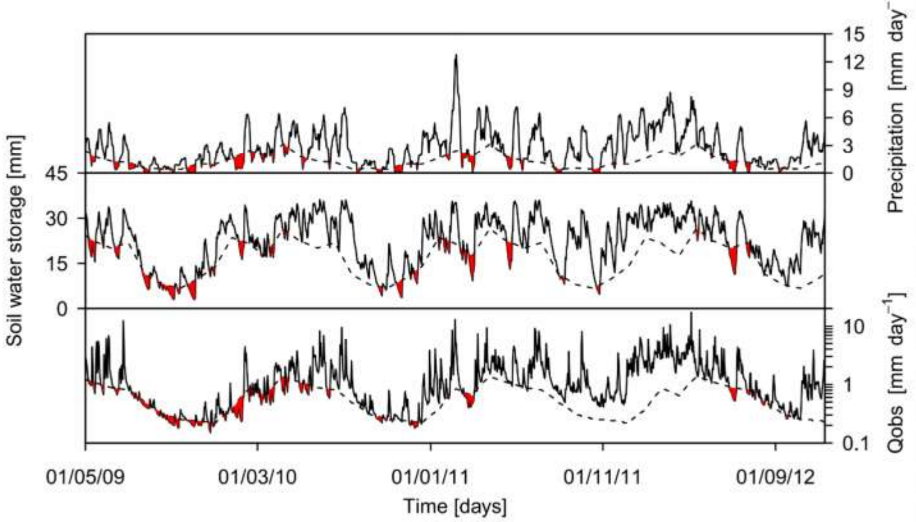


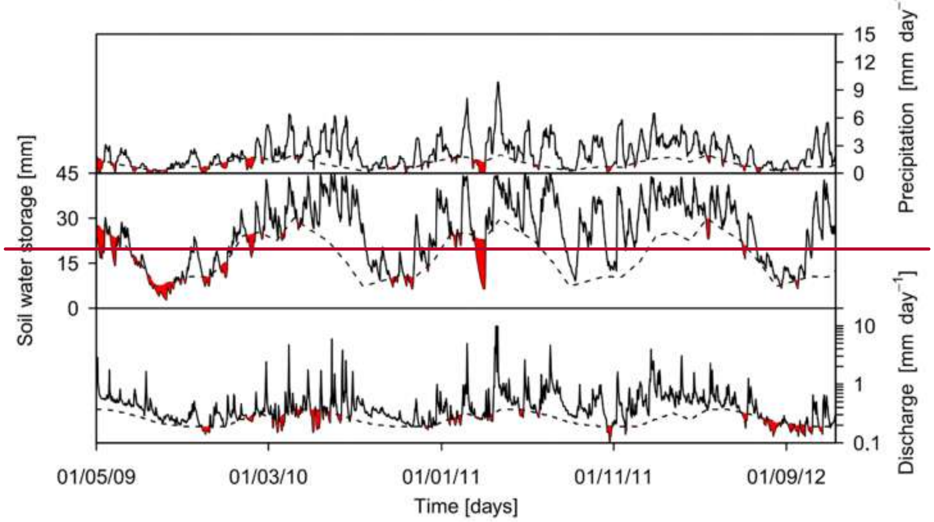
Figure ~~5~~6. Drought propagation for each experimental catchment. Discharge corresponds to the observed data. Soil water storage is the storage simulated by PDM model.



(a) Calluancay



(b) Cumbe



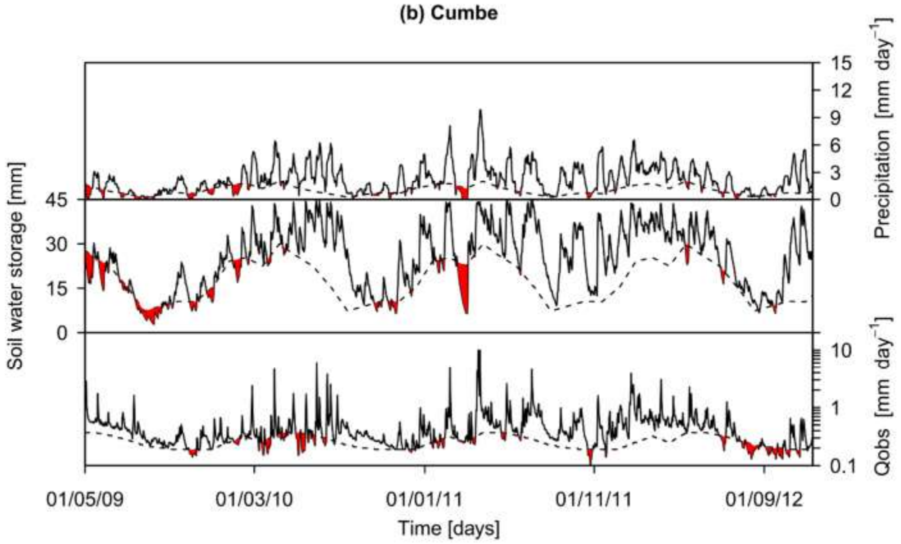
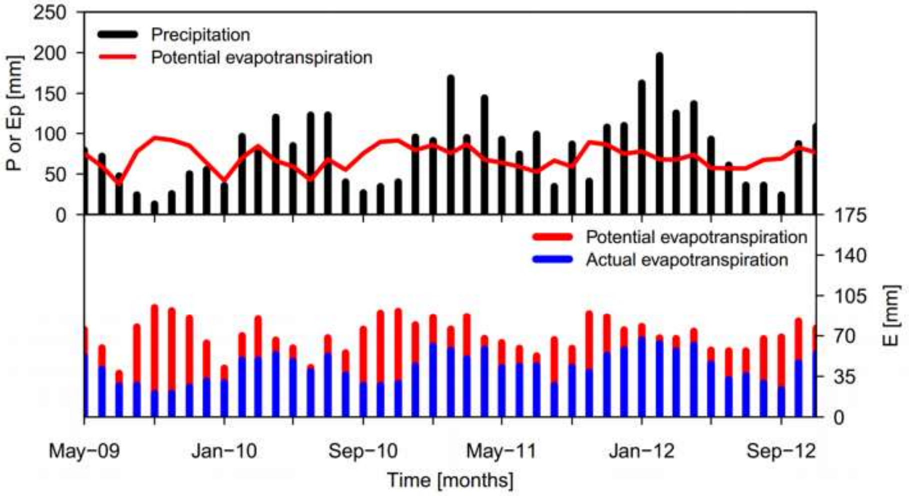

(b) Cumbe
Precipitation [mm day^{-1}]
15
12
9
6
3
0
Soil water storage [mm]
45
30
15
0
Qobs [mm day^{-1}]
10
1
0.1
01/05/09
01/03/10
01/01/11
01/11/11
01/09/12
Time [days]

Figure 7. Time series of P, E_p and E_a in order to identify vegetation stress and recovery periods

(a) Calluancay



(b) Cumbe

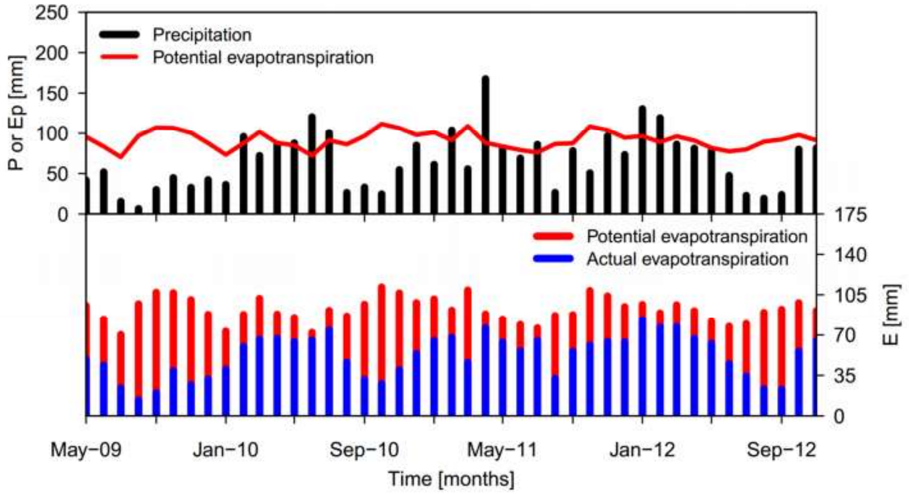
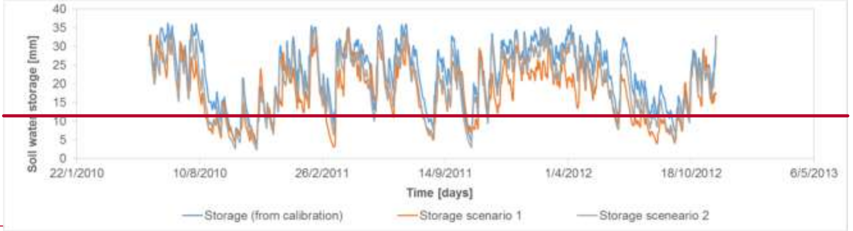
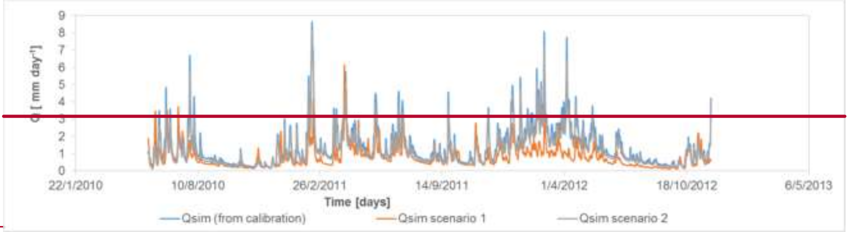


Figure ~~6~~8. Soil water storage and stream discharge for the experimental catchments as result of the two scenarios of climate. The simulated time series of storage and stream discharge (calibration) are included in the figure for comparison.

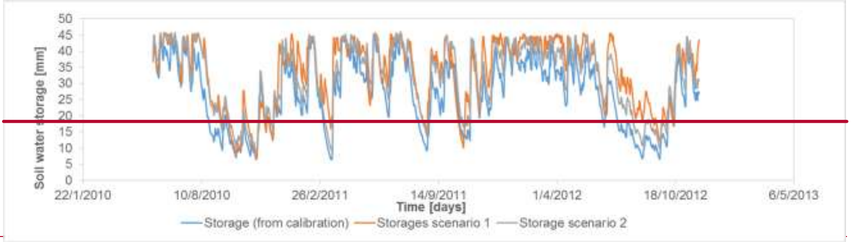
~~(a) Calluancay~~



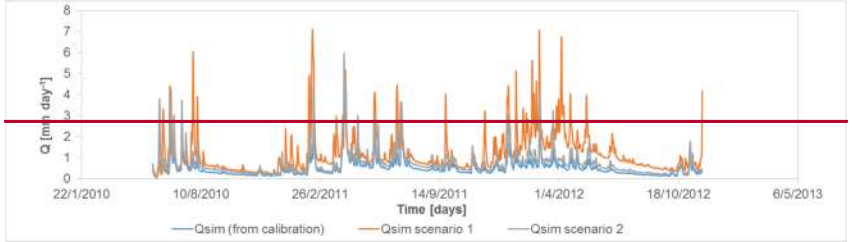


Con formato: Párrafo de lista, Numerado + Nivel: 1 + Estilo de numeración: a, b, c, … + Iniciar en: 1 + Alineación: Izquierda + Alineación: 0.25" + Sangría: 0.5"

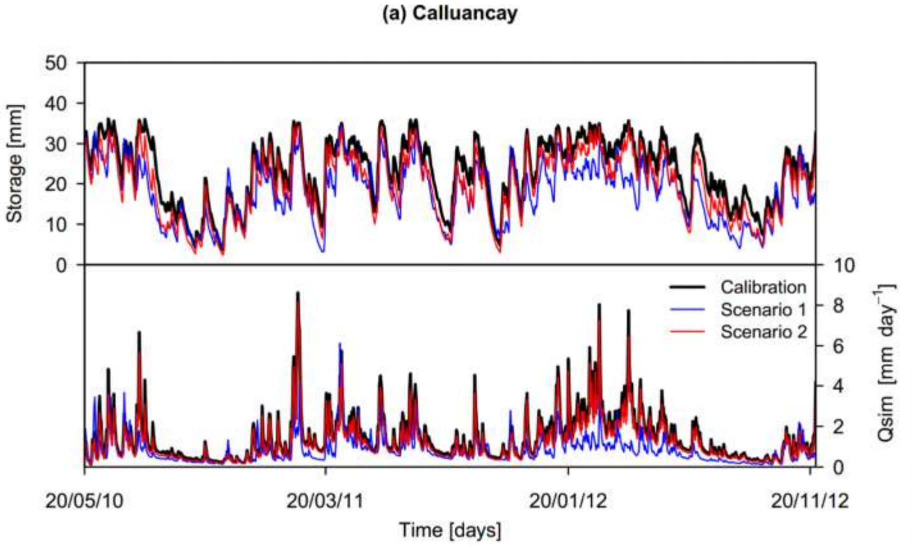
~~(b) Cumbe~~

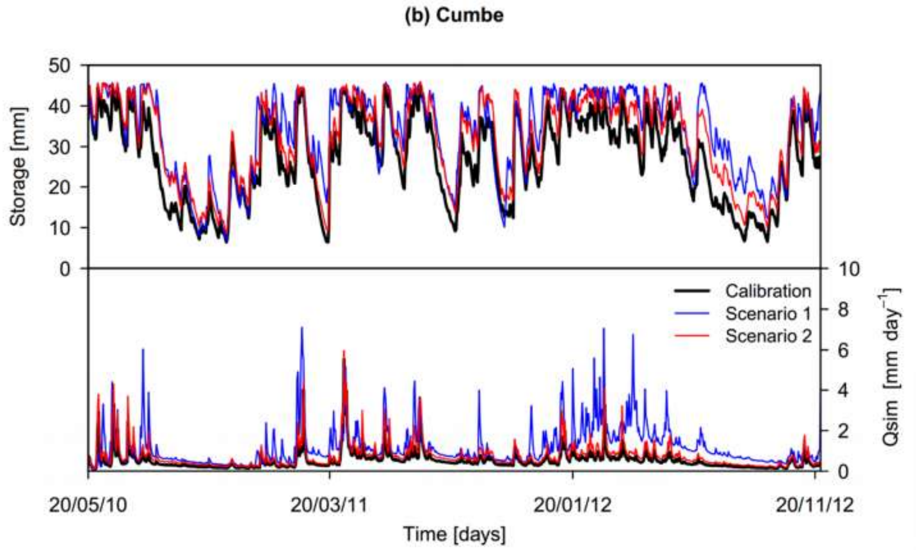


Con formato: Párrafo de lista, Numerado + Nivel: 1 + Estilo de numeración: a, b, c, … + Iniciar en: 1 + Alineación: Izquierda + Alineación: 0.25" + Sangría: 0.5"



Con formato: Párrafo de lista




(b) Cumbe
Storage [mm]
50
40
30
20
10
0
10
8
6
4
2
0
Qsim [mm day^{-1}]
Calibration
Scenario 1
Scenario 2
20/05/10
20/03/11
20/01/12
20/11/12
Time [days]