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

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

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

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

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

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

Abstract

The neotropical Andean grasslands above 3500 m a.s.l. known as "páramo" offer remarkable ecological services for the Andean region. Most important is the water supply -of excellent quality- to many cities and villages established in the lowlands of the inter-Andean valleys and to the coast. However, the páramo ecosystem is under constant and increased threat by human activities and climate change. In this paper we study the resilience of its soils for drought periods during the period 2007-2013. In addition, field measurements and hydrological conceptual modelling at the catchment-scale are comparing two contrasting catchments in the southern Ecuadorian Andes. Both were intensively monitored during two and a half years (2010-2012) in order to analyse the temporal variability of the soil moisture storage. A typical catchment on the páramo at 3500 m a.s.l. was compared to a lower grassland one at 2600 m a.s.l. The main aim was to estimate the resilience capacity of the soils during a drought period and the recovery during a subsequent wet period. Local soil water content measurements in the top soil (first 30 cm) through TDR were used as a proxy for the catchment's average soil moisture storage. The local measurements were compared to the average soil water storage as estimated by the probabilistic soil moisture (PDM) model. This conceptual hydrological model with 5 parameters was calibrated and validated for both catchments. The study reveals the extraordinary resilience capacity of this type of shallow organic soils during the droughts in 2009 and 2010. During these droughts, the soil water

content dropped from a normal value of about 0.80 to ~ 0.60 cm^3 cm^{-3}, while the recovery time was two to three months. This did not occur at lower altitudes (Cumbe) where mineral soils needed about eight months to recover from the drought in 2010. The soil moisture depletion observed in the mineral soils was similar to the Andosols (25%), decreasing from a normal value of about 0.52 to ~ 0.39 cm^3 cm^{-3}, but the recovery was slower. Although, the rainfall pattern during the subsequent wet season was quite similar in both catchments (with 860 mm at Calluancay and 710 mm at Cumbe), the recovery of the páramo ecosystem was faster. This can be explained by the larger soil water storage capacity of Andosols and a lower atmospheric evaporative demand by the páramo at higher altitudes.

1 Introduction

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

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

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

Land cover changes have also occurred in páramo. In the seventies, some areas of páramo were considered appropriate for afforestation with exotic species such as *Pinus radiate* and *Pinus patula*. The main goal was to obtain an economical benefit from this commercial timber. The negative impact of this afforestation and the consequences on the water yield of the páramo have been described by Buytaert et al. (2007b). Also, the productivity was often rather disappointing, due to the altitude.

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

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

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

Important dry periods and droughts in the páramo took place between 2005 and 2012. According to the monthly Niño-3.4 index published by the National Oceanic and Atmospheric Administration (NOAA) (which is used to calculate the Ocean Niño Index -ONI- values), the periods of November 2009 up to February 2010 and from August 2010 up to February 2011 were classified as a moderate El Niño(+) and La Niña(-) events respectively (Yu and Kim, 2013; Yu et al., 2011). The maximum sea surface temperature (SST) anomalies registered in the Pacific Ocean (Region 3.4 Average) during those periods were +1.42 and -1.46 respectively. A strong El Niño or La Niña event is considered when the absolute value of the SST is between 1.5 and 2. A value higher than 2 (+/-) points to a very strong event. Of course the main issue is the lack of rainfall regardless whether it coincides with El Niño or not. The drought periods in the páramo had a negative impact on the water supply and on the economy of the whole region that depends on water supply from the Andes. For instance, the water levels in the reservoir of the main hydropower project in the Ecuadorian Andes –the Paute Molino project– reached their lowest values as a consequence of the drought between December 2009 and February 2010. This caused several, intermittent, power cuts in many regions of Ecuador. The power plant's capacity is 1075 MW. In that period the Paute Molino hydropower provided around 60% of Ecuador's electricity (Southgate and Macke, 1989).

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

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

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

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

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

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

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

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

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

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

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

The hydrological drought is compared and related to this soil water drought. For this purpose, the water balance components of two experimental catchments –one with and one without páramo– were investigated by means of experimental measurements and by means of a hydrological model. The experimental work included the measurement of rainfall, flow and soil moisture. For the modelling, a parsimonious conceptual hydrological model –using the Probability Distributed Moisture simulator (PDM)– was calibrated and validated for each experimental catchment. The PDM model allows to analyse the spatial variability of the soil water content as well as the maximum storage capacity at the catchment scale. Therefore, the representativeness of the point measurements of soil water content can be assessed by means of this model.

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

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

2 Materials

2.1 The study area

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

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

The second catchment, Cumbe, drains an area of 44 km^2. The highest altitude reaches 3467 m a.s.l., whereas the outlet is at an altitude of 2647 m. This altitude range of almost 1000 m defines a typical Andean mountain landscape with steep slopes and narrow valleys where the human intervention is also evident. This catchment is below the 3500 m and therefore contains a negligible area of páramo. The most prominent land cover is grassland (38.1%) along with arable land and rural residential areas (26.9%). A sharp division between the residential areas and the small scale fields is absent. Mountain forest remnants are scattered and cover 23% of the area, often on the steeper slopes. At the highest altitude (>3300 m) sub-páramo is predominant; it occupies only 7.6% of the catchment. In the Cumbe, about 4.4% of the area is degraded by landslides and erosion.

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

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

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

2.2 The monitoring data

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

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

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

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

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

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

2.3 The physical characteristics of the soil

In both catchments, the soil moisture content of the top soil layer was measured by means of time domain reflectometry (TDR) probes at representative sites in the vicinity of the weather stations. In each catchment there was one plot equipped with 6 TDR's with a data-logger. As TDR-sensors with data-logger per plot require a very large investment, the locations for the TDR measurements were carefully selected based on a digital terrain analysis, the soil and land cover maps and field surveys (soil profile pits). So, we selected representative locations.

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

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

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

3 Methods

3.1 The water balance based on the experimental data

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

$$\frac{\Delta S_r}{\Delta t} = P - E_\mathrm{a} - Q_\mathrm{o} - Q_\mathrm{l} + C_\mathrm{r} - D_\mathrm{p} \qquad (1)$$

Where:

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

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

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

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

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

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

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

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

In the Cumbe catchment 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.

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

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

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

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

$$\frac{\Delta S_c}{\Delta t} = P - E_a - Q \tag{1a}$$

Where:

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

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

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

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

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

3.1.1 The potential evapotranspiration

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

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

Where:

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

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

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

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

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

e_s = the saturation vapour pressure [kPa],

e_a = the actual vapour pressure [kPa],

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

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

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

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:

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

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 [^{o}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 the evapotranspiration of another vegetation type by means of a vegetation coefficient k_v. During dry periods, with water stress, the vegetation extracts less water as compared to the vegetation requirement. The relative reduction of the evapotranspiration due to this may be expressed by a water stress coefficient k_s.

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

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

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

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

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

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

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

3.2 The actual evapotranspiration estimated by hydrological modelling

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

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

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

3.3 Comparison between the experimental water balance and the PDM model

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

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

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

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

After calibration/validation of the PDM model parameters based on the discharge the simulated PDM average soil water content can be compared to the measured soil water content.

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

$$S_{\mathrm{r}} = \frac{S_{\mathrm{o}} - S_{\min}}{S_{\max} - S_{\min}} \quad (7)$$

Where:

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

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

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

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

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

4 Results and discussion

4.1 The potential evapotranspiration derived from soil water observations

4.1.1 The potential evapotranspiration

The potential reference evapotranspiration (E_p) for the period from 16 July 2010 until 15 November 2012 was calculated by the FAO-Penman-Monteith approach with the solar radiation estimated by Hargreaves-Samani. The daily average of E_p for Calluancay and Cumbe was 2.35 and 3.04 mm day^{-1} respectively. The temporal variation of E_p is depicted in Fig. 2. It reveals a sinusoidal pattern with higher atmospheric evaporative demand during the drier months (from August to March) and a lesser demand during the subsequent wet periods (from April to July). E_p ranged between 0.76 and 4.17 mm day^{-1} for Calluancay and between 1.56 and 4.62 mm day^{-1} for Cumbe. The difference can be attributed to the altitude difference between both catchments, with 900 m difference in elevation. The daily average minimum and maximum temperatures in Calluancay were 3.0 and 10.2 ^{o}C respectively. While, in Cumbe they were 7.8 and 17.4 ^{o}C. In addition, the wind speed is different in both catchments. Calluancay is very exposed to prevailing winds while Cumbe is relatively sheltered. The daily average wind speed for Calluancay and Cumbe are 4.2 (max: 11.9) and 0.9 (max: 2.6) m s^{-1} respectively.

4.1.2 The vegetation coefficient

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

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

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

4.1.3 The water stress coefficient and the critical soil water content

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

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

Other important fact is that our soil water measurements and the simulation never reached the wilting point; which was 0.43 and 0.30 $cm^3\ cm^{-3}$ for Andosols and Dystric Cambisols, respectively (Fig.3 and Fig. S2 for the water retention curves in supplementary material). The minimum soil water content values during the drought periods in páramo was not lower than 0.62 cm^3 cm^{-3}. Field observations in November 2009, revealed that the plants apparently showed signs of deterioration in the first centimetres but after removal of the top layer (normally composed of dead leaves) the plants itself show little visual deterioration. Nevertheless, the depletion of the soil moisture storage during dry weather conditions clearly lead to stress and reduced the transpiration rate. The effect was quantified by the stress coefficient "k_s". In both cases (Calluancay and Cumbe), values never lower than 0.50 were estimated. As this vegetation has specific adaptations to high-radiation and cold environment the recovery by the vegetation after drought is good. We also think that tillage, burning and artificial drainage might have a larger and more irreversible impact on the soil water holding capacity of the Andosol as compared to a "natural" drought.

4.2 The actual vegetation evapotranspiration derived from soil water observations

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

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

The water balance in the two experimental catchments and its components expressed as cumulative volume over the period from July 2010 until February 2012 are given in Table 1 and Fig. 4. From this analysis it is clear that the páramo vegetation and soil are more resilient to drought recovery as compared to the lower grass vegetation and soil. Especially the recovery after the drought period is much shorter. The lower potential evapotranspiration is an important reason. Both the reference crop evapotranspiration and the vegetation coefficient are lower, so that páramo consumes less water. According to our experimental results, during wet periods the proportion of the stream discharge that can be regarded as potential water use is 54%. In addition the rainfall is slightly higher, so the runoff coefficient in páramo during the wet period remains at 0.68 of the rainfall and is still as high as 0.50 during the dry period. For the lower Cumbe catchment these coefficients are much lower: 0.21 and 0.23 for the wet and dry periods, respectively. Although the soil characteristics are very important for sustaining the base flow the different vegetation requirements are the crucial factors that explain these differences. Furthermore, the evaporative demand is higher in Cumbe as compared with Calluancay, due to the altitude difference. As a consequence, the length of recovery period for the drought event in 2010 was three months for the organic soils while in the mineral soils it took eight months (Fig. 3).

4.3 Actual catchment evapotranspiration estimated by hydrological modelling

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

Therefore, the time periods from 16 April 2011 until 16 January 2012 and from 17 January 2012 until 16 October 2012 are used as calibration and validation period respectively. These periods do not include the aforementioned extreme events. The selected periods for calibration and validation resemble the average climatic conditions of the southern Ecuadorian Andes (Buytaert et al., 2006b; Celleri et al., 2007).

The Table 3 and Fig. 5 summarizes the results for the PDM model. The performance of the model for the calibration period is good for Cumbe (Nash-Sutcliffe efficiency 0.82), but not for Calluancay (0.67). The bias is also lower in Cumbe as compared with Calluancay. The validation period gives a larger bias for both catchments. In addition, the analysis revealed that the temporal variability of the average soil moisture storage simulated by the PDM model mimics the pattern of the observed soil moisture measurements (Fig. 5). As result, the differences or discrepancies between the simulated soil water by a conceptual model and observed soil moisture storage at the point location are relative low. The differences might be due to non-linearities in the reduction of actual evapotranspiration as compared to the potential vegetation demand.

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

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

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

5 Conclusions

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

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

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

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

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

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

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

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

Acknowledgements

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

References

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Gunderson, L. H.: Ecological Resilience—In Theory and Application, Annual Review of Ecology and Systematics, 31(1), 425–439, doi:10.1146/annurev.ecolsys.31.1.425, 2000.

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

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

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

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

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

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

Koch, K., Wenninger, J., Uhlenbrook, S. and Bonell, M.: Joint interpretation of hydrological and geophysical data: electrical resistivity tomography results from a process hydrological research site in the Black Forest Mountains, Germany, Hydrological Processes, 23(10), 1501–1513, doi:10.1002/hyp.7275, 2009.

Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M. F. and Nepstad, D.: The 2010 Amazon Drought, Science, 331, 554, doi:10.1126/science.1200807, 2011.

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

Marengo, J. a., Nobre, C. a., Tomasella, J., Oyama, M. D., de Oliveira, G. S., de Oliveira, R., Camargo, H., Alves, L. M. and Brown, I. F.: The drought of Amazonia in 2005, Journal of Climate, 21(3), 495–516, doi:10.1175/2007JCLI1600.1, 2008.

Marengo, J. a., Tomasella, J., Alves, L. M., Soares, W. R. and Rodriguez, D. a.: The drought of 2010 in the context of historical droughts in the Amazon region, Geophysical Research Letters, 38(12), 1–5, doi:10.1029/2011GL047436, 2011.

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

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

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

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

Phillips, O. L., Aragão, L. E. O. C., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C. a, van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T. R., Bánki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A. C. A., Cardozo, N. D., Czimczik, C. I., Feldpausch, T. R., Freitas, M. A., Gloor, E., Higuchi, N., Jiménez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D. a, Nepstad, D., Patiño, S., Peñuela, M. C., Prieto, A., Ramírez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A. S., Steege, H. Ter, Stropp, J., Vásquez, R., Zelazowski, P., Alvarez Dávila, E., Andelman, S., Andrade, A., Chao, K.-J., Erwin, T., Di Fiore, A., Honorio C, E., Keeling, H., Killeen, T. J., Laurance, W. F., Peña Cruz, A., Pitman, N. C. a, Núñez Vargas, P., Ramírez-Angulo, H., Rudas, A., Salamão, R., Silva, N., Terborgh, J. and Torres-Lezama, A.: Drought sensitivity of the Amazon rainforest., Science, 323(5919), 1344–1347, doi:10.1126/science.1164033, 2009.

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

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

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

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

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

Southgate, D. and Macke, R.: The Downstream Benefits of Soil Conservation in Third World Hydroelectric Watersheds, Land Economics, 65(1), 38, doi:10.2307/3146262, 1989.

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

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

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

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

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

Vuille, M., Bradley, R.S., Keimig, F.: Climate Variability in the Andes of Ecuador and Its Relation to Tropical Pacific and Atlantic Sea Surface Temperature Anomalies, Journal of Climate, 13, 2520–2535, doi:10.1175/1520-0442(2000)013<2520:CVITAO>2.0.CO;2, 2000.

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

Yu, J.-Y., Kao, H.-Y., Lee, T. and Kim, S. T.: Subsurface ocean temperature indices for Central-Pacific and Eastern-Pacific types of El Niño and La Niña events, Theoretical and Applied Climatology, 103(3-4), 337–344, doi:10.1007/s00704-010-0307-6, 2011.

Yu, J.-Y. and Kim, S. T.: Identifying the types of major El Niño events since 1870, International Journal of Climatology, 33(8), 2105–2112, doi:10.1002/joc.3575, 2013.

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

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

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

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

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

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

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

Table 2. The calibrated parameters of the PDM model.

Parameters	Description	Feasible range	Calluancay	Cumbe
c_{max}	Maximum storage capacity	30-120 [mm]	101.2	44.2
b	Degree of spatial variability of the storage capacity	0.1-2.0 [-]	1.82	0.21
f_{rt}	Fast routing store residence time	1-2 [days]	1.7	1.1
s_{rt}	Slow routing store residence time	10-50 [days]	14.3	32.5
$\%(q)$	Percentage flow through fast flow	0.25-0.75 [-]	0.58	0.42

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

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

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

Figure 1. The study area

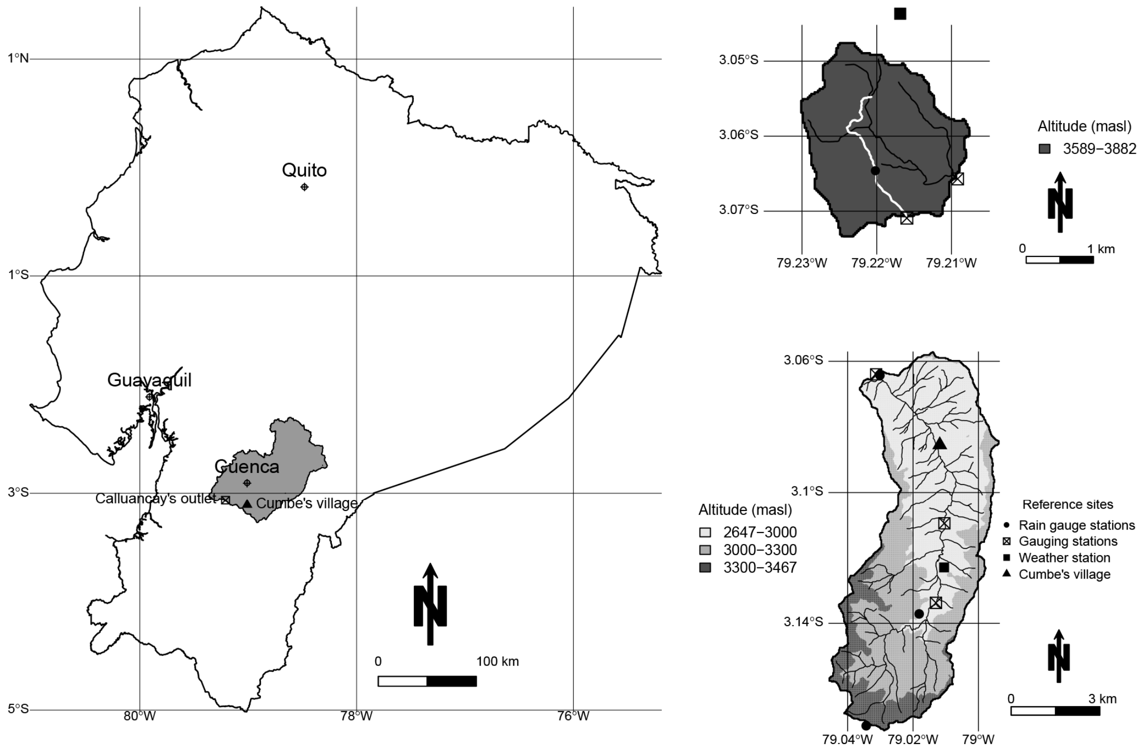

Figure 2. The potential evapotranspiration E_p for Calluancay (black) and Cumbe (grey).

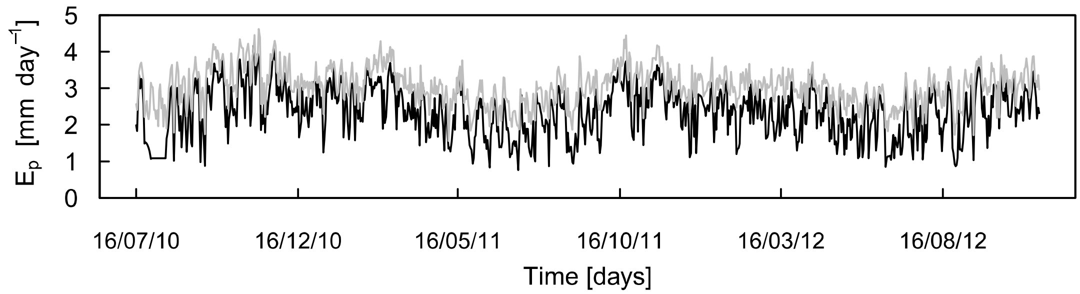

Figure 3. The soil water content data for Calluancay (a) and Cumbe (b). The drought periods are shaded in grey. The blue lines show the soil water content simulated by means of the soil water balance in the root zone for each catchment during the period from on 16 Jul 2010 up to on 1 Feb 2012. In Supplement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

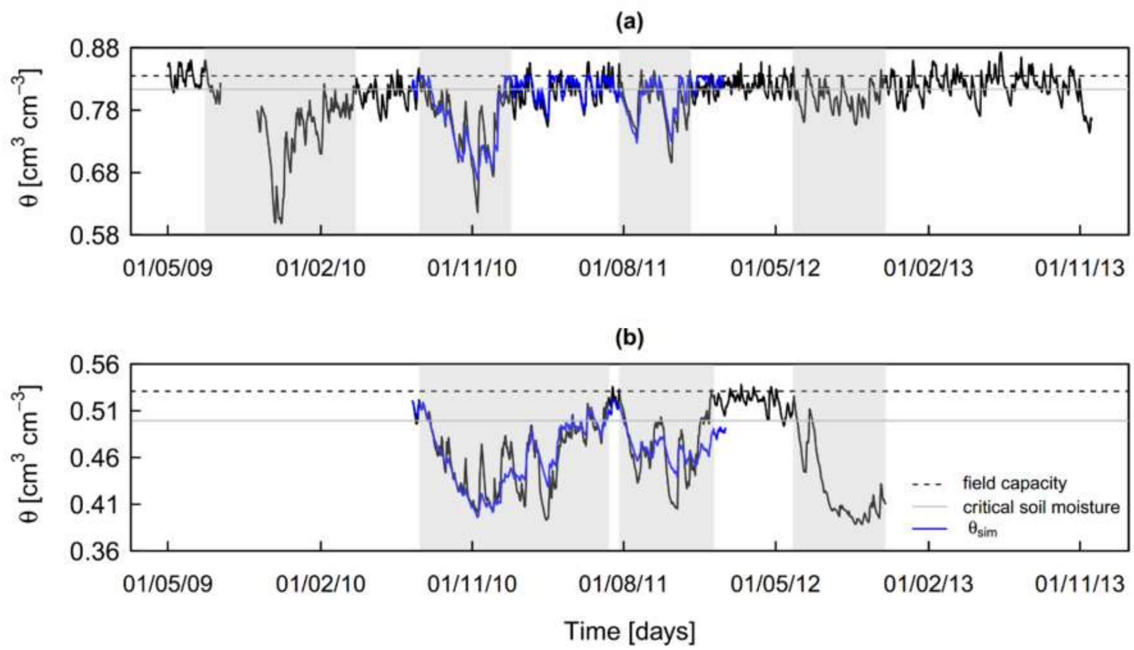

Figure 4. Water balance components for (a) Calluancay and (b) Cumbe. The curves in Calluancay show a non-linear behaviour and so suggest a seasonality for this páramo area. This climate pattern is enhanced by the occurrence of drought events. A high evapotranspiration is revealed in Cumbe. Most of this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

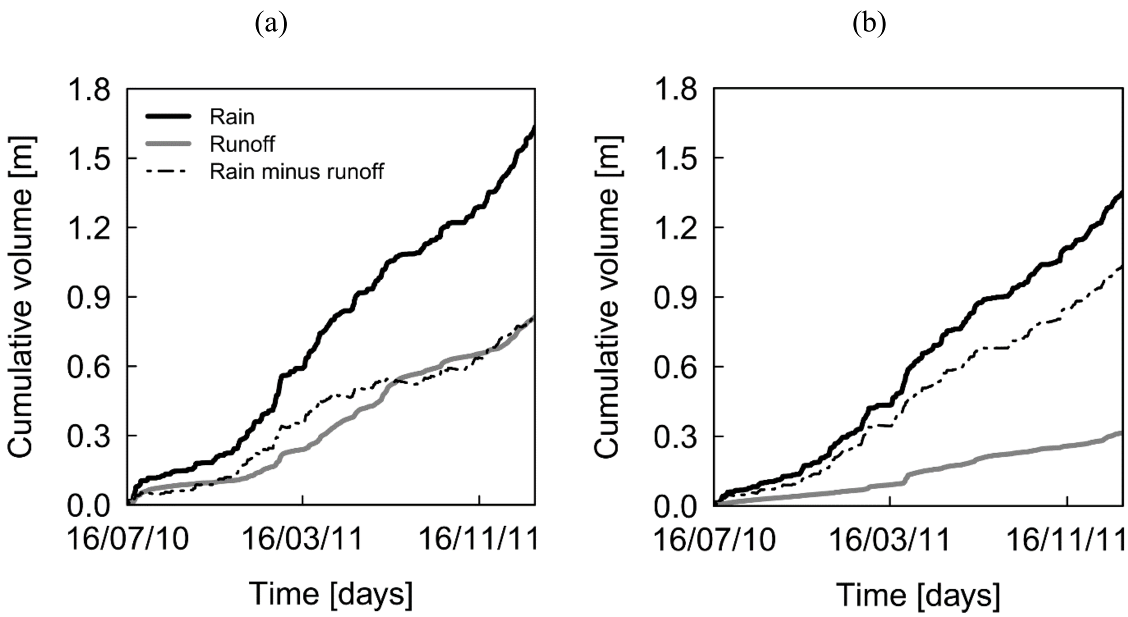

Figure 5. Representative sample of rainfall (top), runoff (middle) and soil moisture (bottom) time series. The scaled soil moisture storage in the root zone is shown in the bottom inset in the plot in solid and dashed black lines for measured and modelled respectively.

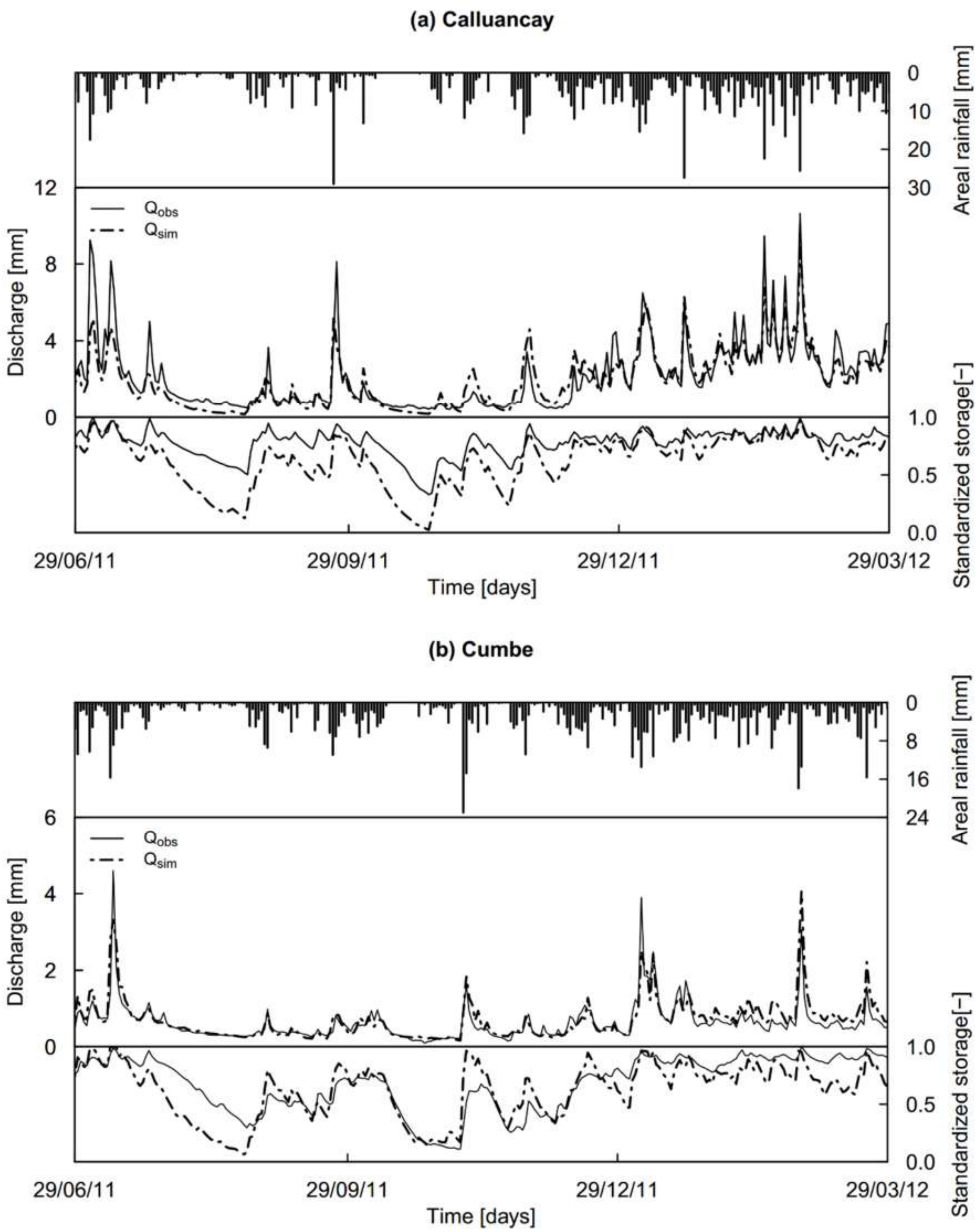

Figure 6. The actual evapotranspiration (E_a) using the water balance approach (WBA) and the PDM model. **(a)** Calluancay and **(b)** Cumbe.