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Identifying controls of the rainfall–runoff response of small catchments in the tropical Andes (Ecuador)

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SUMMARY

Tropical mountain regions are characterized by strong spatial climate gradients which together with the limited amount of data and knowledge of the underlying processes hinder the management of the water resources. Especially for regional-scale prediction it is important to identify the dominant factors controlling the rainfall–runoff response and link those to known spatial patterns of climate, soils, and vegetation. This study analyzes the rainfall–runoff relation of 13 intensively monitored micro-catchments in the Andes of southern Ecuador. The results of this study show that streamflow in the southern cordillera of the Ecuadorian Andes, above 2500 m a.s.l., primarily consists of subsurface flow. The yearly amount of streamflow is controlled by the annual rainfall depth, whereas the temporal distribution is mainly governed by the lateral saturated hydraulic conductivity, the soil water retention and the antecedent soil moisture content. Anthropogenic effects were found insignificant, with the exception in one of the studied micro-catchment. Effect of land use changes in most of the micro-catchments did not reflect in the shape of the flow duration curve because either the spatial extent of human impact was small and/or the overall basin slope was less than 20%.

1. Introduction

The tropical Andes is hydrologically one of the most diverse regions in the world. The convergence of several climate systems, combined with steep topography, results in extreme hydro-climatic gradients. Precipitation easily surpasses 5000 mm on the slopes of the Amazon basin and the Colombian Chocó region, while many regions in the interandean valley have a semi-arid and arid climate (Vuille et al., 2000; Buytaert et al., 2011). Similarly, gradients of soil types and vegetation are driven by temperature and precipitation gradients, as well as geological variability, volcanic activity and human interference (Buytaert et al., 2006b). These gradients give rise to a rich variety of hydrological systems with a very different behavior, ranging from perennially wet cloud forest and tropical mountain wetlands to intensive farming systems.

Many of the natural Andean ecosystems, particularly neotropical alpine wet páramo, grassland and montane cloud forest, provide essential environmental services, of which biodiversity conservation, carbon storage and water supply are the most important (Buytaert et al., 2011). Strong urban growth, the concentration of agriculture in the dry interandean valley, and the mountainous topography all contribute to the steadily increasing demand of water for domestic and industrial uses, irrigated agriculture and the generation of hydropower. Notwithstanding their socio-economic and environmental importance, catchments in South America are in general ungauged or poorly gauged, which explains why the hydrology of the high Andean mountain range is still not satisfactorily understood.

Additionally, the length and quality of available timeseries are short and of poor quality, containing many gaps. Monitoring for research purposes is limited to doctoral and small funded research projects. Only a few catchments in the Ecuadorian Andes region have been studied in depth, and unfortunately data collection mostly stopped when the project finished or funding dried up. Combined with the extreme variability and gradients of Andean hydrology, data-scarcity hinders extrapolation of hydrological understanding from gauged to ungauged catchments (Buytaert and Beven, 2009).

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This study only focuses on micro-catchments, to avoid in the data analysis and interpretation the effect of spatial variability, typical for the medium-sized and large basins in the Andean mountain range. In addition data records of larger basins are very few or limited to timeseries of rainfall and discharge. After pre-processing of the available datasets the timeseries of precipitation and streamflow of the 13 selected micro-catchments were found consistent and sufficiently long for analysis. The objective of the study was to search in which way streamflow is conditioned by micro-climate, precipitation pattern, slope, land cover and soil properties, amongst other catchment properties. Only the selected date period of the data series are presented.

2. Methods

Detailed information of the characteristics of the 13 analyzed micro-catchments is summarized in Tables 1–3. In the following a brief description is given of the methods and equipments uses for data collection and processing.

To account for the spatial rainfall variability as a function of altitude and extent of the micro-catchments two rainfall gauges were installed, respectively in the upper and lower part of each of the micro-catchments M1–M11 with exception of the catchment M3 where four rain gauges were installed. Rainfall data of the micro-catchments M1–M11 were recorded with HOBO RG3 tipping buckets with a resolution of 0.2 mm. In the study basins M12 and M13, precipitation and fog data from four precipitation stations were provided by the Bendix research group from January 2005 to October 2008. Details on equipment and protocol of rainfall and fog collection and data processing are given in Bendix et al. (2008). The data for all catchments were aggregated to 1-hourly rainfall and used for the calculation of the monthly and annual rainfall and extreme value analysis. Due to the small differences in precipitation depth between the rain gauges in the micro-catchments M1–M11 it was decided to apply the Thiessen polygon method for calculating the basin precipitation. For reason of elevation differences in the M12 and M13 catchments, basin precipitation was calculated using the area weighted elevation approach.

Streamflow in the micro-catchments M1–M11 was recorded with a Thompson (V-notch) weir, and in the catchments M12–M13 the water level was measured in a natural stable cross section. Each gauging site was equipped with pressure transducers or capacitance probe sensors, recording the water level with a 5 min interval and an accuracy of ±1 mm; frequent control measurements were made at different flood stages. The Kindsvater–Shen relation (US Bureau of Reclamation, 2001) was used for conversion of the water level to discharge for M1–M11. Potential and polynomial empirical stage–discharge relationships were developed using discharge measurements to estimate continuous discharge series for M12 and M13. The lowest measurable flow in the gauging stations is 0.0138, 3.3 and 21 l/s for M1 to M11, M12 and M13 respectively. Due to gaps in the data only shorter datasets could be used than the available timeseries which varied from 2.5 years (M12–M13) to 10 years (M6–M7). The window of rainfall and streamflow data used is listed in Table 3, second column. Timeseries were selected for periods with comparable rainfall record.

To verify if the rainfall and streamflow data of the micro-catchments collected in different periods are comparable, the selected window of rainfall data of each catchment were verified with the available long term daily rainfall data base (1964–2008) provided by the national hydro-meteorological institute of Ecuador (INAMHI). The extreme value analysis of the short data window and long data series did not show significant differences. Based here on, the authors concluded that the streamflow patterns of the 13 micro-catchments are not affected by the fact that data were collected in different times windows in the period 2001–2010.

A Chapman (1991) recursive digital filter for exponential recessions was used to separate the hydrograph into its components. The method is based on the analysis of the observed hydrograph

Table 1
Main catchment characteristics.

Catchment	Area (km^2)	Altitude (m a.s.l)	Slope (%)	Shape	Geology	Soil distribution (%)	Vegetation cover (%)	Landuse
Ortigas (M1)	0.99	2305–2880	43	SO	Saraguro Fm.: lavas and andesitic volcanoclastic	Andosol (74), Leptosol (26)	Upper montane forest (76), pasture (20), cropland (4)	N, EG, PT
Rio Grande (M2)	5.49	2230–3280	48	SO	deposits	Andosol (58), Leptosol (42)	Upper montane forest (28), shrubs (39), pasture (33)	EG, N
Panama (M3)	10.01	2050–3080	44	SO	Pisayambo Fm.: pyroclastic deposits	Andosol (12), Cambisol (46), Leptosol (42)	Upper montane forest (29), pasture (57), cropland (14)	EG, N, M
Marianza pajonal (M4)	1.00	2980–3740	42	SO	Saraguro Fm.: lavas and andesitic volcanoclastic	Andosol (>85), Histosol (<15)	Upper montane forest (14), tussock grass (86)	N
Marianza pinos (M5)	0.59	3240–3700	37	CO	deposits	Andosol (>85), Histosol (<15)	Pine forest (>90), tussock grass (<10)	PF
Huagrahuma (M6)	2.58	3690–4100	45	SO		Andosol (100)	Tussock grass (100)	N
Soroche (M7)	1.59	3520–3720	20	SO		Andosol (100)	Tussock grass (70), cropland (30)	PT, IG
Quinuahuaycu (M8)	5.01	3590–3880	19	EOR	Quimsacocha Fm.: volcanic and	Andosol (81), Histosol (19)	Tussock grass (78), cushion plants (20), shrubs (2)	N
Calluancay (M9)	4.39	3590–3870	18	CO	volcanoclastic rocks	Andosol (88), Histosol (12)	Tussock grass (69), shrubs (20), cushion plants (11)	EG
Zhurucay (M10)	1.34	3680–3900	18	EOR		Andosol (85), Histosol (15)	Tussock grass (71), shrubs (2), cushion plants (26)	EG
Bermejos (M11)	21.64	3708–3960	19	EOR		Histosol (70), Andosol (30)	Tussock grass (30), cushion plants (70)	N
San Ramon (M12)	4.62	1743–3150	61	CO	Chiguinda unit: paleozoic metamorphic	Histosol (60), Cambisol (30), Regosol (10)	Upper montane cloud forest (80), sub-páramo (18), shrubs (2)	N
Zurita (M13)	11.38	2025–3075	55	SO	rocks	Histosol (50), Regosol (30), Cambisol (20)	Upper montane cloud forest (73), sub-páramo (15), pasture (12)	W, EG

TG, tussock grasses; S, shrubs; CP, cushion plants; PT, potatoes; M, maize PF, pine forest. IG, intensive grazed; EG, extensive grazed; N, natural. W, wood; SO, stretched oval; CO, circular to oval; EOR, elongated oval to rectangular; M1–M3: Pacific coastal climate; M4–M11: inter-valley climate zone; M12–M13: Amazonian climate.

Table 2
Properties per horizons of the main soils in the studied catchments.

Soil type	Horizon thickness (cm)	Bulk density (g cm^{-3})	pH	SOM (%)	Ks (mm h^{-1})	pF = 0 (cm^3 cm^{-3})	pF = 2 (cm^3 cm^{-3})	pF = 4.2 (cm^3 cm^{-3})	Sand (%)	Silt (%)	Clay (%)
ANDOSOL (páramo cover)											
Ah1	18–40	0.2–0.5	4.3–4.8	15–35	12–38	0.66–0.90	0.64–0.82	0.39–0.64	37–80	8–62	12–27
Ah2	20–31	0.2–0.8	4.4–4.8	13–36	10–28	0.70–0.86	0.61–0.84	0.36–0.57	21–63	17–50	20–29
A	16–53	0.2–0.9	4.5–5.7	7–31	5–36	0.74–0.81	0.72–0.78	0.30–0.43	24–33	34–55	21–41
ANDOSOL (forest cover)											
O	15–30	0.2	5.6	19	105	0.77	0.71	0.58	50		35–15
A	13–30	0.4–0.6	4.0–6.0	16–29	22–60	0.71–0.93	0.65–0.89	0.48–0.49	28–42	45–47	11–27
Bw	40–50	0.3	5.6–6.0	1–8	23–60	0.64–0.76	0.59.0.76	0.33–0.59	41–68	27–37	5–22
LEPTOSOL											
O	20–25	0.5–0.6	5.6–6.0	11–18	28–32	0.66–0.72	0.59–0.68	0.18–0.47	38–42	43–50	12–15
Ah	15–20	1.0	5.8	6–20	32	0.64	0.59	0.33	38	50	12
HISTOSOL (páramo cover)											
H1	15–20	0.1–0.2	4.6–5.1	23–60	8–15	0.85–0.90	0.84–0.90	0.13–0.39	56–84	6–30	10–34
H2	30–35	0.1–0.3	4.4–5.0	21–66	5–9	0.81–0.88	0.79–0.87	0.12–0.33	64	6–20	4–16
A	14–55	0.1–1.0	4.8–5.1	24–57	3–91	0.56–0.86	0.50–0.83	0.15–0.74	38	2–42	7–20
HISTOSOL (forest cover)											
O	10–20	0.1–0.2	4.2–4.4	33–44	160–167				42	38	20
H	10–20	0.1–0.3	4.8	28	83–91	0.76	0.5	0.23	37	42	21
Ah	10–15	0.2–0.8	5.1	13	11	0.68	0.46	0.20	30	49	21
CAMBISOL											
O	10–16	0.1–0.2	4.2–4.4	33–44	160–167				42	38	20
A	14–40	1–1.1	4.8–5.4	4–28	54–91	0.55–0.76	0.50–0.52	0.23–0.26	29–38	42	20–28
Bw	15–80	1.0–1.3	5.1–5.7	0.3–13	11–23	0.68–0.70	0.46–0.63	0.19–0.36	19–30	42–49	21–38
REGOSOL											
O	10–16	0.1–0.2	4.2–4.4	33–44	160–167				42	38	20
Ah	14–20	1–1.1	4.8–5.4	3.7–28	54–91	0.55–0.76	0.50–0.52	0.23–0.26	29–38	40–42	20–28

pH, soil acidity expressed as amount of H+ cations in soil solution; SOM, soil organic matter in%; Ks, saturated hydraulic conductivity; pF, soil matric potential expressed as the $\log_{10}$ (cm water column) respectively at saturation, field capacity and wilting point; Sand, Silt and Clay, main particle size classes in percent.

Table 3
Average terms of the catchment water balance.

Catchment	Used data window	P (mm d^{-1})	Q_{total} (mm d^{-1})	$Q_{average}$ (m^3 s^{-1})	P-Q_{total} (mm d^{-1})	Q_{slow} %	Q_{quick} %	RC
M1	06/09/2005–15/07/2008	4.7	2.2	0.025	2.5	96.4	3.6	0.46
M2	20/02/2006–01/01/2008	3.6	2.4	0.154	1.2	67.9	32.1	0.68
M3	23/11/2005–12/03/2008	3.5	1.7	0.200	1.8	67.4	32.6	0.50
M4	21/10/2005–27/06/2007	3.3	1.6	0.019	1.7	87.2	12.8	0.49
M5	19/10/2006–23/09/2008	3.5	1.0	0.007	2.5	91.5	8.5	0.28
M6	13/08/2003–29/10/2008	4.0	2.9	0.088	1.0	75.9	24.1	0.74
M7	11/05/2002–29/09/2003	3.0	1.9	0.034	1.1	60.9	39.1	0.63
M8	10/11/2006–11/11/2008	3.5	2.6	0.150	0.9	67.8	32.2	0.74
M9	10/11/2006–11/11/2008	3.8	2.4	0.122	1.4	69.0	31.0	0.64
M10	26/10/2006–11/11/2008	3.4	2.5	0.039	0.9	65.8	34.2	0.74
M11	25/10/2006–11/11/2008	2.9	1.8	0.452	1.1	61.6	38.4	0.62
M12	23/04/2007–24/08/2008	10.4	8.4	0.451	2.0	69.9	30.1	0.81
M13	23/04/2007–24/08/2008	7.3	5.8	0.761	1.5	89.0	11.0	0.79

RC, fraction of the rainfall leaving the catchment as streamflow (runoff coefficient); M1–M3, Pacific coastal climate; M4-M11, inter-valley climate zone; M12–M13, Amazonian climate.

shape and the magnitude of the recession constant of the flow-components (Vázquez and Feyen, 2003). The flow separation was implemented using the Water Engineering Time Series PROcessing tool (WETSPRO) developed by Willems (2009). Herein a generalization of the Chapman filter is applied consisting in a time variant fraction of the total flow related to the filtered flow component (Willems, 2000). In this study the intermittent flow (also called the subsurface flow) and baseflow component were aggregated and called *slow flow* because the duration of the recession periods were in general too short to accurately separate intermittent flow from baseflow (Vázquez and Feyen, 2007).

Because soil properties are very similar for all studied catchments, they are not presented as punctual data or grouped by catchments. Instead, Table 2 depicts value ranges for the presented soil properties, providing primarily information of the organic horizon. Data on the C horizon, due to incompleteness of data and because this horizon in general is a thin, weathered layer on top of the bedrock, are not listed. However, data of the hydraulic conductivity of the C horizon, whenever available, are mentioned in the text. The saturated hydraulic conductivity listed in Table 2 is the horizontal saturated conductivity (Ks) measured with the inversed auger-hole method (Kessler and Oosterbaan, 1974). The Ks data of M5 were derived from literature.

To identify patterns in the multitude of soil and hydrological data, and to express the data in such a way as to highlight their similarities and differences the principal component analysis (PCA) was applied. The objective of PCA is reducing the possibly correlated variables into a smaller number of uncorrelated variables and to transform the data to a new coordinate system such that the greatest variance by any project of the data comes to lie on the first coordinate, called the first principal component. Analogue the second greatest variance is placed on the second coordinate, and so on. Reducing the number of dimensions to three main principal components enabled to group the micro-catchments into distinct clusters, characterized by clear differences in the dominant processes controlling the conversion of rainfall into streamflow. The analysis was conducted using the correlation matrix of 17 variables including precipitation, discharge and various soil parameters. After reduction of the correlated variables a threshold value for the eigenvectors of ±0.2 was used as to define the main contributing variables within each of the principal components.

3. Case study catchment description

The area of the 13 studied micro-catchments varies between 0.59 and 22 km^2. They are located in Ecuador between 2°24′ and 3°58′ south latitude and in the altitude range of 1743–4100 m above sea level (see Fig. 1 and Table 1). The micro-catchments M1, M2, M3 and M10 drain to the Pacific Ocean while the other micro-catchments M4–M13 with exception of M10 are tributaries of the Amazonian River Basin. The shape of the micro-catchments M1 (0.99 km^2), M2 (5.49 km^2) and M3 (10.01 km^2) (Group 1: Pacific climate zone) is stretched oval. The altitude range and average surface slope of those three catchments are very similar, ranging between 2050 to 3280 m a.s.l. and 43% to 48%, respectively (see Table 1). The basin area of the micro-catchments M4–M11 (Group 2: Inter-valley climate zone) varies between 0.59 and 21.64 km^2. The catchment shape is stretched oval for the micro-catchments M4, M6 and M7; circular oval for the basins M5 and M9; and elongated oval to rectangular for M8, M10 and M11. Based on the topographic characteristics the micro-catchments in this group can be split into two subgroups. The micro-catchments in the first subgroup, M4–M6, are steep with surface slopes varying between 37% and 45% and altitude range from 2980 to 4100 m a.s.l. The largest difference in elevation (760 m) within a micro-catchment is found in M4. The micro-catchments in the second subgroup consist of the catchments M7–M11 with an altitudinal range between 3520–3960 m a.s.l. and average surface slope of 18–20%. The catchment shape is circular to oval for M12 (4.6 km^2) and stretched oval for M13 (11.3 km^2) (Group 3: Amazon climate zone), the altitude ranging between 1743 and 3150 m a.s.l. with an average surface slope of 61% and 55% for M12 and M13, respectively.

3.1. Climate

In the micro-catchments M1–M3 (Group 1) mean annual precipitation varies between 500 and 1900 mm, based on long-term rainfall record (1970–2008). The inter-annual seasonality is unimodal, influenced by the Pacific coastal regime. The wet season stretches from December to May, comprising 60–80% of the annual precipitation and a dry season from June to November, commonly with months without rain and a maximum observed continuous dry period of 78 days. Ninety percent of all monitored precipitation rates are less than 15 mm h^{-1}. The temperature ranges from 9 to 22 °C at 2254 m a.s.l., with December being the coldest and October the warmest month. According to Bacuilima et al. (1999) the

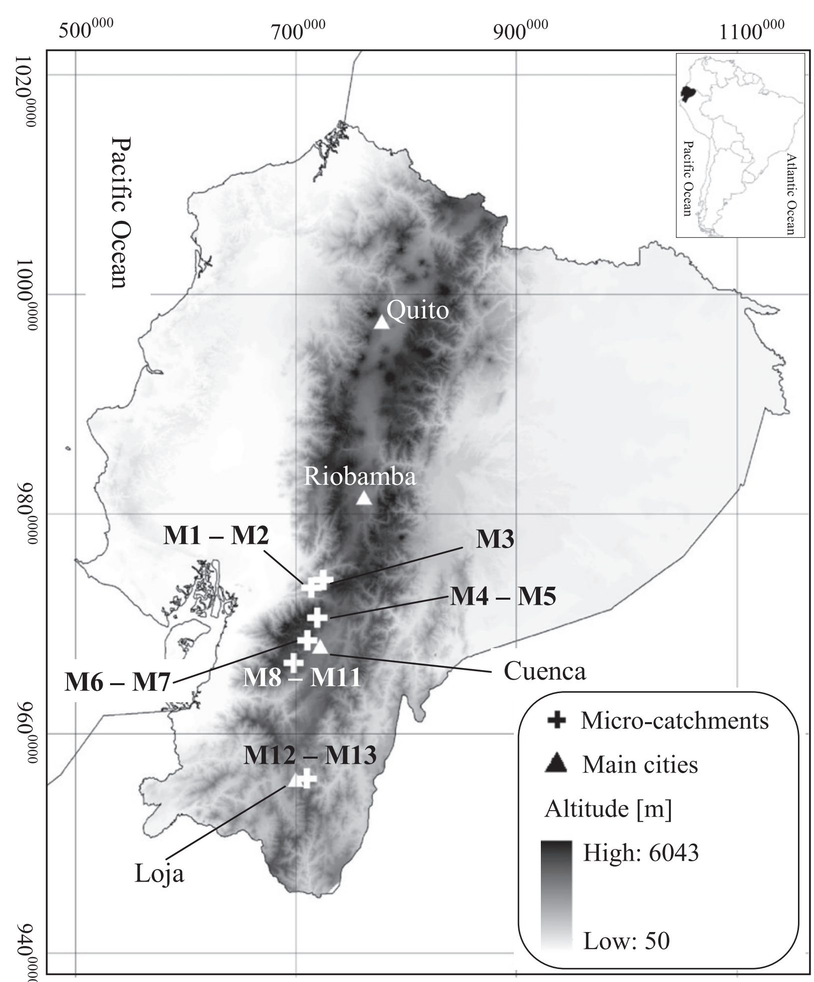

Fig. 1. Geographical location of the 13 study micro-catchments (UTM coordinates).

temperature lapse rate in the region varies between 0.5 and 0.7. Air humidity is relatively high with values between 40% and 100%. More details are given in Crespo et al. (2008).

The climate of the micro-catchments M4–M11 (Group 2), located on the east slope of the western cordillera in the altitude range of 2980–4100 m a.s.l., is influenced by the Pacific coastal regime from the west and the continental and tropical Atlantic air masses from the east (Vuille et al., 2000). The resulting precipitation pattern is bimodal, with a major wet season in December to February and a less pronounced wet season from August to September (Buytaert et al., 2006a), interrupted by short dry spell periods having a maximum length of 16 days. The mean annual precipitation, based on the long-term record of 1964–2008 (INAMHI), varies between 900 and 1600 mm, with 10% of the rains having an intensity larger than 10 mm h^{-1} (Buytaert et al., 2006a). The temperature decreases at an average rate of 0.5–0.7 °C per 100 m (Bacuilima et al., 1999; van der Hammen and Hooghiemstra, 2000; Castaño, 2002), with the mean temperature being around 7 °C at 3500 m a.s.l. (Buytaert, 2004). Daily solar radiation and temperature are almost constant throughout the year, while the interday variability is quite marked. Intraday temperature variations can be as large as 20 °C. A more detailed description of the climate is available in Buytaert et al. (2006a, 2007) and PROMAS/IAMGOLD (2009). Fog interception is negligible as reported by Buytaert et al. (2007), on the basis of which it is assumed that fog captured by the páramo ecosystem not really contributes to the soil water reservoir.

The climate in the micro-catchments M12 and M13 (Group 3) is influenced by the air masses from the east, the Amazonian basin (Beck et al., 2008). The precipitation pattern is unimodal with relative constant seasonality and moderate to low inter-annual variability. The main wet season is from April to September with a maximum of 10 days without rain (Fleischbein et al., 2005). According to Rollenbeck (2006) precipitation is strongly correlated with altitude, and intensities are low with 90% of all monitored rain rates below 10 mm h^{-1}. Precipitation is primarily caused by advective orographical clouds. In the period 1964–2008 annual precipitation varied from 900 to 4300 mm (INAMHI) with an average of 2200 mm at an altitude of 1960 m; wind speeds being low and cloud cover less dense at this elevation. Average rainfall increases to 4700 mm (monitoring period 1994–2004) at the Cerro del Consuelo station located at the border of the catchment (3200 m a.s.l.) (Rollenbeck, 2006; Bendix et al., 2008). Horizontal rain and cloud/fog water deposition contributes considerably to the total ecological water input representing up to 41.2% of the basin water yield (Bendix et al., 2008). The mean annual temperature at 1952 m a.s.l. is 15.2 °C. The coldest months are June and July, with a mean temperature of 14.4 °C; the warmest month is November with a mean temperature of 16.1 °C. The average temperature gradient between the station at 1952 m and 2927 m a.s.l. is 0.66 °C per 100 m, and the mean humidity is 86% (period 1998–2004) (Fleischbein et al., 2006).

3.2. Land cover and use

Micro-catchment M1 represents the pristine condition in Group 1 with 74% of the basin covered by upper montane forest (*Asteraceae, Boraginaceae*, *Coriaceae, Euphorbiaceae*, *Junglandaceae*, *Fabaceae*, *Melastomataceae*, *Scrophulariaceae*, *Solanaceae*, *Verbenaceae*) (Bruijnzeel, 2001; Crespo et al., 2008). Canopy height is in general 5–10 m, occasionally exceeding 15 m (Bussmann, 2005), amply covered by lichens and epiphytes (Balslev and Øllgaard, 2002). According to Bendix et al. (2008) fog interception is negligible at this altitude. The micro-catchment M2 is very representative for the anthropogenic degraded condition; forest is cut, and burned, and farmers use the land for cultivation and grazing. When pasture and cropland are exhausted the land is abandoned and left to natural regeneration. Catchments are mainly covered by small shrubs (*Melastomataceae*, *Asteraceae*) (39%); some patches of upper montane forest (28%) and pasture (*Penicetum clandestinum*) (33%). The micro-catchment M3 represents the most human affected condition with 57% of its area covered with pasture (*Penicetum clandestinum*) and 14% cropland (annual rotation of potatoes, corn and vegetables). Montane forest occupies the remaining 29% of the area, primarily in steep and inaccessible zones and near the river bed.

The micro-catchments in Group 2 belong to the páramo ecosystem (neotropical alpine grassland) covering the Andes region above 3500 m a.s.l. (Luteyn, 1992; Hofstede, 1995; Medina and Vásconez, 2001). The landscape above 3500 m a.s.l. is typically composed of relatively flat to concave valleys. Below 3500 m the land is steeper covered by cloud forests. The micro-catchments M4, M6 and M8 have low human impact limited to free roaming cattle. Those catchments are covered with páramo vegetation consisting of tussock grass, low shrubs and upper montane forest (Table 1) (Buytaert et al., 2006b). The M11 catchment is a wetland covered by cushion plants and the M8 and M9 micro-catchments are covered by tussock grass, with an animal density of 0.5–2 heads per hectare. These catchments are annually burned and grazed. In the micro-catchment M7 grazing with an animal density of 2–3 heads per hectare, artificial drainage and cultivation of potatoes take place. Cultivation is continuous throughout the year, without a specific growing season, covering 30% of the catchment. In the rest of the catchment, original grass vegetation has been replaced by more nutritious species which are intensively grazed by cattle. Micro-catchment M5 is planted with *Pinus patula*. The forest is about 20 years old with a tree density of 1000 stems ha^{-1} and covering over 90% of the catchment. A more detailed description of the catchments can be found in Buytaert et al. (2006b, 2007) and PROMAS/IAMGOLD (2009).

Micro-catchment M12 (Group 3) is for 80% covered with pristine montane cloud forest, with trees up to 20 m high. Dominant plant species are of the families *Lauraceae*, *Euphorbiaceae*, *Melastomataceae* and *Rubiaceae* (Homeier et al., 2002). In the upland area of the micro-catchment (3140 m a.s.l.) vegetation mainly consists of sub-páramo shrubs, adapted to higher wind speeds, lower temperatures and low nutrient availability (Beck et al., 2008). The micro-catchment M13 (Group 3) is representative for mixed conditions with moderate human impact. Anthropogenic impacts consist of extensive wood cutting, gravel mining in the river bed, a draining gravel road and extensive grazing. The catchment is primarily covered with montane cloud forest (73%), sub-páramo (15%) and extensive pastures (*Setaria sphacelata*) (Werner et al., 2005).

3.3. Geology

The micro-catchment M3 is located on the Pisayambo Fm. composed of compacted pyroclastic deposits with balsaltic, andesite and rhyolitic composition dating from the Pliocene age. The geology of the micro-catchments M1, M2 and M4–M7 belongs to the Late Oligocene to Early Miocene Saraguro Fm. with lavas and andesitic volcaniclastic deposits compacted by glacier activity during the last ice age (Coltorti and Ollier, 2000; Hungerbühler et al., 2002). The hydraulic conductivity of the Piasayambo and Saraguro Fm. is low (Buytaert et al., 2005), and their lithology similar (Kennerley, 1980). The micro-catchments M8–M11 are located on the Quimsacocha Fm. (Pratt et al., 1997). Covered by volcanic and volcanoclastic rocks, the formation consists of basalt flows with plagioclase, feldspar phenocrysts and andesitic pyroclastic deposits. According to IAMGOLD (2006) the age of the deposits is not defined; hydraulically they are nearly impermeable and possess a low density of fissures in the top layer of the formation. The micro-catchments M12 and M13, located in the Cordillera Real on the Amazonian side, correspond to the Chiguinda unit, which is mainly composed of Paleozoic metamorphic rocks such as semipelite, phyllite and quartzite with low alteration (Litherland et al., 1994; Hungerbühler, 1997; Bendix et al., 2008). Observations and findings (Buytaert et al., 2005; Buytaert et al., 2007; Bücker et al., 2010; PROMAS/IAMGOLD, 2009) tend to suggest that (i) the geological impact on the runoff generation process is minimal, (ii) in most of the catchments only a minor fraction of the water in the soil reservoir percolates into the bedrock, and (iii) in local depressions of the bedrock a non-permanent water table is found.

3.4. Soils

The main soil types in the study catchments are Andosol, Leptosol, Histosol, Cambisol and Regosol (FAO/ISRIC/ISSS, 1998). Table 1 depicts the soil distribution per catchment, and Table 2 summarizes per horizon the soil properties. The cold and wet climate and the low atmospheric pressure, characteristic for highlands, favor organic matter accumulation. This, together with the volcanic ash accumulation, is responsible for the dark, humic and acid soils, with an open pore structure, classified as Andosols. Andosols typically have a high organic matter content (13–36%), low bulk density (0.2–0.8 g cm^{-3}) and high water retention capacity (0.64–0.93 cm^3 cm^{-3} at saturation) (Buytaert, 2004). The depth of the organic horizon varies between 40 and 104 cm. The sequence of Ah1, Ah2, A, and C horizons are typically for Andosols under páramo, below forest the Ah1 horizon is replaced by an O (organic litter) horizon. The horizons are acid with a pH ranging between 4 and 6.

Leptosols are shallow with the O or Ah horizon lying directly on top of the parent material. Both horizons have fairly similar properties, are 15–25 cm deep, have a pH of 5.6–6.0, an organic matter content in the range of 6–20%, and a bulk density varying between 0.5 and 1.0 g cm^{-3}. Histosols typically contain a high fraction of non-decomposed plant fibers, particularly in the páramo belt (Beck et al., 2008). The main properties of the soils are very high organic matter (21–66%), low bulk density (0.1–0.3 g cm^{-3}), and high water retention between saturation and field capacity. The higher situated Histosols (above 3500 m a.s.l.) are on average 90 cm deep, typically composed of a H1, H2 and A horizon with high organic matter content. The Histosols under cloud forest (below 3500 m a.s.l.) are less deep with main horizons O, H, Ah and C (Makeschin et al., 2008; Wilcke et al., 2002).

The 120 cm deep Cambisols under pasture (M3) are characterized by three horizons (A, Bw and C) with decreasing saturated hydraulic conductivity, respectively 54.6, 23.4 and 16 mm h^{-1}. The bulk density varies between 1.0 and 1.3 g cm^{-3}. The soil organic matter content decreases with depth, fluctuating between 4% and 28% in the A and 0.3–13% in the Bw horizon. As a consequence of the overall lower organic matter content, the water retention capacity in both horizons is less than in the organic rich horizons of the Andosols and Histosols (see Table 2). The Cambisols in the M12 and M13 catchments are typical Dystric or Humic Cambisols with the horizon sequence O, Ah, Bw and C under forest (Wilcke et al., 2002). As observed by Makeschin et al. (2008) the change in land cover from forest to shrub and pasture strongly reduces the thickness and the properties of the O horizon. Huwe et al. (2008) reported a significant reduction in the saturated hydraulic conductivity under pasture. Regosols are only present in the M12 and M13 catchments, mainly situated below 2100 m a.s.l. The typical horizon sequence of Regosols under forest is O, Ah and C, with the O horizon significantly reduced under shrubs or ferns and completely lost under pasture (Makeschin et al., 2008). The horizon properties are very similar to the properties of the Cambisols; however the Ah horizon is less developed (14–20 cm thick).

4. Results and discussion

4.1. Streamflow pattern

Analysis of the rainfall timeseries reveals that rainfall throughout the year is fairly uniformly distributed in the micro-catchments belonging to Groups 2 and 3. The rainfall timeseries of the micro-catchments in Group 1 reflect the presence of a rainy and dry season. Intensity of most storm events, below 10 mm h^{-1} for the micro-catchments in Groups 1 and 2 and below 15 mm h^{-1} for the catchments in Group 3, is less than the saturated hydraulic conductivity of the top layer, which for Group 1 and 2 varies between 8 and 32 mm h^{-1} and Group 3 between 160 and 167 mm h^{-1}. Similar results were found by Buytaert et al. (2007), Crespo et al. (2008, 2010) and PROMAS/IAMGOLD (2009). Given the low to moderate rainfall intensities it is very unlikely that Horton overland flow occurs. Fleischbein et al. (2006) also excluded the occurrence of Horton overland flow based on the results obtained from a field survey nearby the M12 and M13 micro-catchments. Blume et al. (2007) and Buytaert et al. (2007) came to the same conclusion for a forested and páramo catchment in the south of Chile and Ecuador.

Figs. 2a–2d depict the 1-h flow duration curve (FDC) of the studied micro-catchments. The *x*-axis lists the probability of non-exceedance and the *y*-axis the total streamflow expressed in m^3 s^{-1} km^{-2}. The FDCs of the catchments in Group 1 (Pacific climate zone), 2 (Inter-valley climate zone) and 3 (Amazon climate zone), except M3, have similar shapes. This suggests that the same processes control the runoff generation notwithstanding the difference in climate and catchment properties. As can be derived from Table 3 streamflow is dominated by the slow flow component, representing 60.9–96.4% of the total flow, confirming that overland flow occurs only very occasionally. The larger hydraulic conductivity of the top soil in M1, M4 and M5 is responsible for the fact that slow flow represents respectively 96.4%, 87.2% and 91.5% of the total flow. The slow flow component in M13 represents a larger fraction of the average total flow than in M12, respectively 89.0% versus 69.9%, notwithstanding similarity in catchment properties. This is likely due to the larger lateral flow contribution of the C horizon and the cracks in the upper zone of the bedrock for low streamflow in M13 than M12, as suggested by Bücker et al. (2010), and the higher precipitation in M12 which enhances the quick flow contribution as fast lateral flow through the organic horizon. The fraction of the slow flow in the remaining micro-catchments (M2, M3 and M6–M11) varies between 60.9% and 75.9% of the total flow, very much in concordance with other studies (Célleri, 2007; Germer, 2008; Mortatti et al., 1997; Fujieda et al., 1997).

Above the non-exceedance probability level of 70% the observed distribution of high flows is almost the same in M1–M3. Differences in streamflow distribution below this level can be attributed to the following:

(i) The average annual rainfall in M1 is higher than in M2 and M3 (4.7 mm d^{-1} versus 3.5 a 3.6 mm d^{-1}) compensating the interception losses caused by the relative high degree of basin area covered by forest but still resulting in more runoff.
(ii) The lower flow-values for M3 as compared to M1 and M2, below the 70% non-exceedance probability, can be explained by the difference in geology and the anthropogenic impact (71% of the area in M3 is pasture and cropland versus 24% and 33% in M1 and M2). M3 is underlain by the Pisayambo Fm. whereas M1 and M2 are situated on the Saraguro Fm. It is possible that locally the top of the Pisayambo Fm. is semi-pervious capturing a fraction of the infiltrating precipitation. Unfortunately data to confirm this are not available.

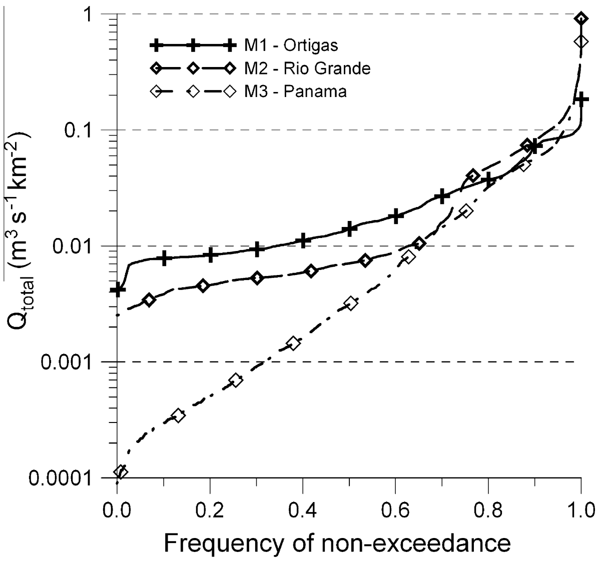

Fig. 2a. 1-h FDCs of the micro-catchments M1, M2 and M3 (Group 1) situated in the Pacific climate zone.

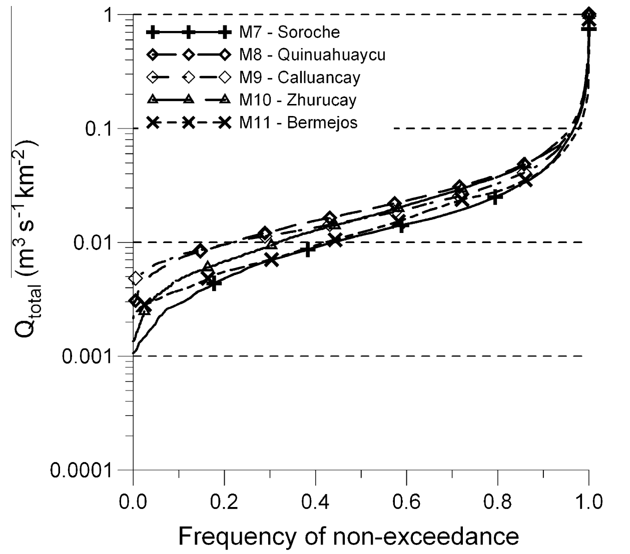

Fig. 2c. 1-h FDCs of the micro-catchments M7, M8, M9, M10 and M11 (Group 2) situated in the inter-valley climate zone.

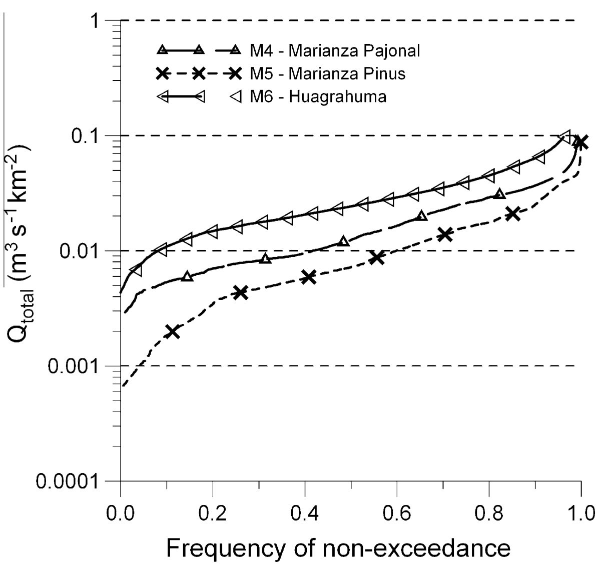

Fig. 2b. 1-h FDCs of the micro-catchments M4–M6 (Group 2) situated in the inter-valley climate zone.

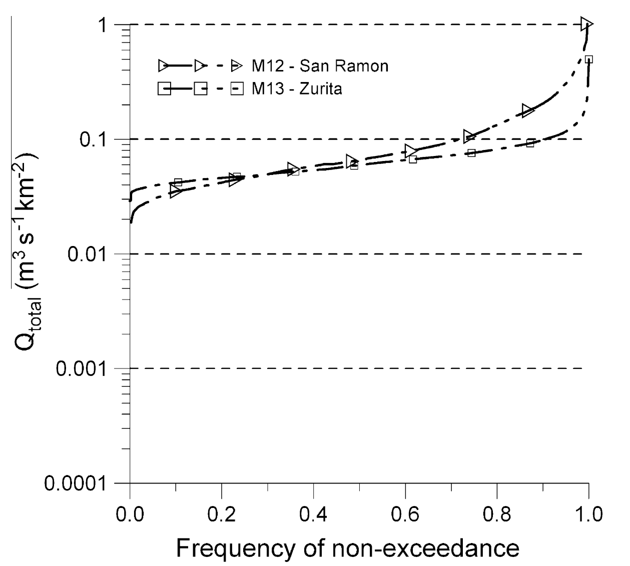

Fig. 2d. 1-h FDCs of the micro-catchments M12 and M13 (Group 3) situated in the Amazon climate zone.

In addition in M3 a considerable fraction of the runoff water is tapped for irrigation water in the dry season reducing the runoff volume. Furthermore the soil physical properties degrade by the conversion of forest and shrub land to pasture or cropland (see Table 2). Similarly Bruijnzeel (2004), Buytaert (2004) and Vignola (2005) reported that intensive grazing and crop farming negatively affect the soil water retention capacity. Morales (2008) and Tobón et al. (2006) stated that human impact is the main cause of a drop in discharge during dry spell periods as a consequence of a drop in soil water retention and hydraulic conductivity.

The FDCs of the micro-catchments in Group 2, although alike were split in two subgroups, respectively the micro-catchments M4–M6 (Fig. 2b) and the micro-catchments M7–M11 (Fig. 2c). Comparing both figures it is clear that the FDCs of the subgroup M7–M11 are situated within a narrow range; the FDCs of the subgroup M4–M6 are much more different. The largest differences between both subgroups are: (i) the average basin slope which for the first subgroup varies between 37% and 45%, and between 18% and 20% for the second subgroup, and (ii) there is a higher variability in the partitioning of the flow between slow and quick flow across M4–M6 than within M7–M11. Difference in behavior of the micro-catchments M4–M6 as compared to the catchments M7–M11 can be explained by the fact that minor differences in rainfall and basin properties are more strongly reflected in the FDC due to the steep average slope of those catchments, on average 40% versus 20%. The mild slope of the micro-catchments M7–M11 masks local differences in precipitation pattern and basin properties. The higher flow-values of M6 in Fig. 2b is the consequence of the overall higher rainfall in this micro-catchment as compared to the other micro-catchments in Group 2, being the consequence of the higher situation of this micro-catchment in the Andes mountain range. On the other hand the fact that in Fig. 2b the FDC of M5 is positioned lowest can, as stated by Buytaert et al. (2007), be explained by the high degree of afforestation, 90% of the basin is covered with *Pinus patula*. Pine strongly intercepts precipitation which during dry spell periods evaporates reducing the fraction of rainfall contributing to runoff.

The FDCs of M12 and M13 (Group 3), situated in the Amazon climate zone, are shown in Fig. 2d. The flow values of both FDCs are larger than the flow values of the FDCs of all other micro-catchments in the survey simply due to the fact that the rainfall in the Amazonian region is 2–3 times as high. Furthermore, the shape of the FDCs of both micro-catchments is more flat indicating that rainfall is fairly uniform. The larger fraction of quick flow in M12 than in M13 is due to the higher annual rainfall in M12, 3799 versus 2672 mm.

4.2. Water yield and actual evapotranspiration

As depicted in Table 3, the average water yield of the micro-catchments in Group 1 (M1–M3), the Pacific climate zone, varies between 1.74 and 2.42 mm d^{-1}, representing 46–68% of the precipitation. The micro-catchments in the Amazon climate zone (Group 3, M12–M13) have a much higher water yield varying between 5.78 and 8.43 mm d^{-1}, equivalent to 79–81% of the rainfall. The average water yield of the micro-catchments situated in the inter-valley climate zone, Group 2 (M4–M11), varies between 0.99 and 2.94 mm d^{-1}, corresponding to 28–74% of the precipitation, respectively.

The average rest term of the water balance, considered as an approximation of the actual evapotranspiration, is highest for the catchments M1 (2.50 mm d^{-1}), M5 (2.51 mm d^{-1}), M12 (1.98 mm d^{-1}), M4 (1.68 mm d^{-1}) and M13 (1.54 mm d^{-1}). Foregoing can be explained by the high coverage of forest varying between 14% and 100% of the basin area, causing the interception of rainfall and fog followed by evaporation (Wilcke et al., 2008). The difference in evapotranspiration between M2 and M3 is due to the re-use of runoff water for irrigation in M3. The actual evapotranspiration of M1 closely matches the average evapotranspiration value of 2.68 mm d^{-1} reported by Bruijnzeel (2001) for lower montane cloud forest. The average actual evapotranspiration of the micro-catchments M6–M11 is lower varying between 0.9 and 1.4 mm d^{-1}. The lower level can be explained by the overall lower average annual rainfall and the low transpiration rate of tussock grass. The leaf morphology of tussock grass and the sunken position of the stomata are considered responsible for the lower level of physiology and transpiration (Ramírez et al., 2006). The average value of the evapotranspiration for M12 and M13 is smaller than the range published by Bruijnzeel (2001) for tropical lowland forest (2.43–4.40 mm d^{-1}) and larger than the range found for upper montane cloud forest (0.85–1.07 mm d^{-1}). Fleischbein et al. (2006) on the other hand reported an average value for the evapotranspiration of 4.06 mm d^{-1} for upper montane cloud forest, which is twice as large as the value derived in this study for M12. These authors conducted their experiments on two small catchments, respectively 8 and 9 ha large, in the vicinity of the M12 micro-catchment and used the same assumption for the water balance, i.e. actual evapotranspiration can be approximated as the rest term of the water balance. However, the difference is presumably due to the large gaps in the streamflow data; up to 80% of the monitoring period was missing and reconstructed using TOPMODEL (Fleischbein et al., 2006). This might have led to an underestimation of the outflow and consequently and overestimation of the rest term.

The difference between our data and the published data of Bruijnzeel (2001) and Fleischbein et al. (2006) is not unique. An analysis of the literature reveals that a large divergence exist between published average values of the evapotranspiration, partly because experimental conditions are not always comparable and literature is not always clear on the assumptions on which the rest term of the water balance is derived. For instance Hutley et al. (1997) found an average evapotranspiration value of 3.45 mm d^{-1} for a highly fog-influenced Australian subtropical rainforest, while Motzer (2003) reported for similar conditions an average value of 1.54 mm d^{-1}. The difference in reported values underlines the importance for the long-term monitoring of the water balance terms of properly selected representative catchments, but also a better representation of the high spatial variability of precipitation inputs.

4.3. Hydrological processes

For the assessment of the causal factors the correlation matrix between streamflow and the variables depicted in Tables 2 and 3 was examined. Unfortunately the analysis did not yield any significant correlation, not enabling to get a clear picture of the variables controlling the rainfall–runoff process. Given the likelihood that streamflow in the studied micro-catchments is the result of a group of variables a principal component analysis (PCA) was conducted. Table 4 lists the variables retained after elimination of the correlated variables and the eigenvector value for the 1st, 2nd and 3rd most important principal component. The three principal components explain 84% of the variance in hydrologic response. Of the three streamflow variables, Q_{total}, $\%Q_{quick}$ and $\%Q_{slow}$, only $\%Q_{slow}$ was retained in the analysis, given the belief that the lateral subsurface flow through the organic horizons is dominant in the transfer of rainfall into runoff. As illustrated in Table 4 the contributing variables to the first principal component (PC) explain 42% of the total variance. The variables retained and positively correlated in the 1st PC, ranked according to their importance as expressed by the eigenvector value, are precipitation, average surface slope, the saturated hydraulic conductivity of the top and bottom layer of the organic horizon, the bulk density of the top horizon and to a lesser extent the rest term of the water balance and the contribution of slow flow to the total streamflow. The significant variables associated with PC2, explaining 32% of the variance, are the runoff coefficient, precipitation and the saturated hydraulic conductivity of the top horizon; other retained variables in PC2 but negatively correlated are the bulk density of the soil profile, the saturated hydraulic conductivity of the C horizon, precipitation, evapotranspiration and $\%Q_{slow}$. PC3 still explains 10% of the variance in hydrologic response and is positively correlated to

Table 4
Eigenvectors of the variables retained in the three first principal components.

Variables	PC1 42%	PC2 32%	PC3 10%
Slope	**0.372**	−0.026	−0.157
BD > 20	−0.057	**−0.375**	**−0.385**
BD < 20	**0.348**	−0.192	−0.077
Ks > 20	**0.407**	0.102	−0.077
Ks < 20	**0.357**	**0.205**	−0.049
Ks-C	0.140	**−0.381**	**0.339**
AWC	−0.029	−0.182	**−0.754**
P	**0.372**	**0.216**	−0.052
RC	0.033	**0.457**	−0.053
ET	**0.276**	**−0.325**	0.010
$\%Q_{slow}$	**0.245**	**−0.291**	**0.346**

PC1, PC2 and PC3, principal components of the original variables; Slope in percent; BD, bulk density; Ks, saturated hydraulic conductivity; AWC, water content at saturation of the organic horizon; P, average annual precipitation; RC, runoff coefficient; ET, actual evapotranspiration, equal to the rest term of the water balance; $\%Q_{slow}$, average percentage of slow flow contribution to the total discharge; >20, below 20 cm depth in the organic horizon; <20, above 20 cm depth; C, C horizon; bold numbers have an eigenvector value larger than 0.20 or smaller than −0.20.

the saturated hydraulic conductivity of the C horizon and %Qslow, and negatively with the bulk density of the upper organic horizon and the soil water content at saturation of the organic horizons. Based on the retained variables and their positive, respectively negative correlation within each of the principal components the following physical meaning is attributed to each of the PC's:

(i) PC1 represents the wet basin condition, i.e. when the soils are near saturation or saturated following a period of intense rainfall. Under this condition the different horizons in the soil profile contribute to the lateral subsurface flow of which the flow is controlled by the gradient of the surface and the hydraulic conductivity of the subsequent horizons. The organic horizons are very permeable and therefore contribute most, explaining the fast rise of total streamflow and the large fraction of the slow flow in the total streamflow component.
(ii) PC2 stands for the wet to moderate dry conditions of the soil profile whereby the effect of rainfall becomes less significant. When evapotranspiration increases soil wetness reduces explaining the negative correlation, depleting first the litter and/or top organic horizon. Subsurface flow continuous primarily through the organic horizons, and limited through the mineral horizon as indicated by the negative correlation of PC2 with the bulk density and the saturated hydraulic conductivity of the C horizon. The fraction of slow flow in the total flow increases due to the reduction of overland flow. Runoff still can be important during wet periods. The soil physical parameters increasingly control the flow process.
(iii) PC3 describes the phenomenon under moderate to dry condition whereby the quick flow component is zero or negligible and the drainage to the river network entirely consists of slow flow, produced by the mineral C horizon and the cracks in the top layer of the bedrock, and to a much lesser extent by the lower organic horizons. This is confirmed by the negative correlation of PC3 with the water content at saturation in the organic horizons.

Fig. 3 depicts the ordination plot of the micro-catchments as a function of PC1 and PC2. This plot reveals that the hydrologic response of the 13 micro-catchments can be grouped into three clusters (I–III). Cluster I contains the micro-catchments M12 and M13,

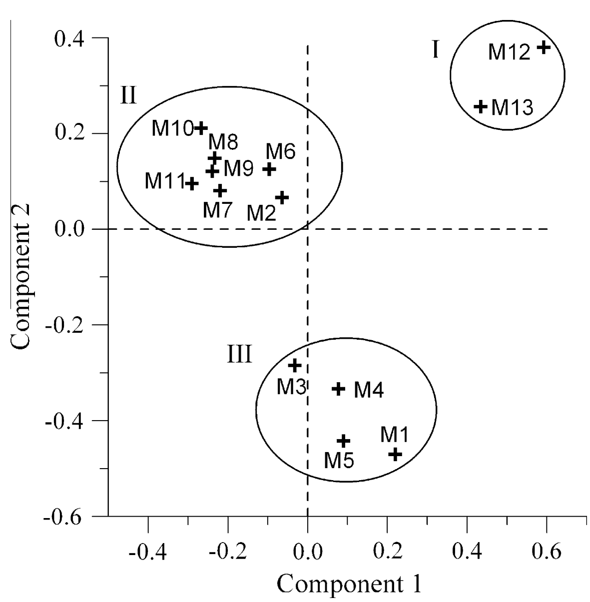

Fig. 3. Ordination plot of the study micro-catchments according to the principal components 1 and 2.

both situated in the San Francisco River Basin with Amazon climate, and with the average annual rainfall two to three times as large as the average annual rainfall recorded in all other studied micro-catchments. Both catchments, covered with upper montane cloud forest, have the highest average discharge and an average rest term of the water balance varying between 1.5 and 2.0 mm d^{-1}. The position of Cluster I in the ordination plot confirms that the runoff process in M12 and M13 is mainly controlled by rainfall and the soil physical factors. Rainfall is fairly uniformly distributed throughout the year, such that most of the rainfall infiltrates keeping the soil moisture content in wet to moderate wet condition favoring the subsurface flow through the litter layer and the underlying organic horizons. Elsenbeer (2001), Goller et al. (2005) and Fleischbein et al. (2006) subscribed the flow in catchments similar to the catchments M12 and M13 as "organic horizon flow", by which these authors refer to the fast lateral flow in the organic horizons.

Cluster II groups the micro-catchments M2 and M6–M11. These micro-catchments are with the exception of M2, situated in the inter-valley climate zone at the east flank of the cordillera. M2 is situated at the west flank where climate is dominated by the Pacific Ocean. Common for these catchments is the similarity in average actual evapotranspiration, ranging between 0.90 and 1.38 mm d^{-1}, and the relative large area under tussock grass and/or shrubs. The fraction under pasture and cropland is small to nonexistent. The position of this cluster in the ordination plot indicates that the hydrology of the micro-catchments in Cluster II mainly is controlled by the variables constituting PC2, it is climate characterized by rainfall and evapotranspiration, and the soil physical properties of the lower half of the organic horizons. The relative high contribution of the runoff coefficient in PC2 is the consequence of the relative high flows occurring during extreme wet conditions.

Cluster III is composed of the micro-catchments M1, M3, M4 and M5, which are, with the exception of M3, predominantly covered with upper montane forest, páramo and pine forest. M3 has a strong anthropogenic influence; 73% of the basin area has been converted to pasture and cropland. As stated above, a considerable fraction of the runoff water in this catchment is re-used as irrigation water. The 4 micro-catchment have in common that slow flow is a large proportion of the total flow, varying between 87 and 97%. Furthermore all 4 micro-catchments are steep with an average surface slope in the range of 37–44%. The position of this cluster in the ordination plot (Fig. 3) is slightly controlled by PC1 and strongly, but negatively, controlled by PC2. The steepness of the basins, the shallowness of the soils, the permanent vegetation, and the high permeability of the top soil suggests that subsurface flow dominates the rainfall–runoff process.

The original variables in the three PCs, explaining 84% of the variance, reveal that the magnitude of the runoff and its distribution are controlled by precipitation, slope, bulk density of the top layer, lateral saturated hydraulic conductivity of the upper and lower horizons, rest term of the water balance and $\%Q_{slow}$. Vegetation does not seem to have an effect on the rainfall–runoff process, except on the evapotranspiration when interception of rainfall and fog are important. Notwithstanding the sometimes high average basin slope, overland flow is not that significant as a consequence of flush vegetation, the low bulk density of the top layer of the Andosols and Histosols, and the high lateral saturated hydraulic conductivity. This and the fact that the basins are underlain by bedrock suggests that the infiltrating precipitation percolates relatively quickly to the bottom of the shallow to medium deep soil profiles, start filling up the soil layers from the bottom to the top, and as a layer saturates water starts flowing lateral by gravity towards the drainage network. That the soil composition is actually controlling the hydraulic response of the micro-catchments is confirmed by the main contributing variables in the 2nd and 3rd principal component. The analysis also reveals that human interference in the studied basins does not strongly modify the temporal streamflow distribution, although it affects the soil physical properties, the interception and the evapotranspiration. And even if it does modify the streamflow distribution, the affected area within the basin is relatively small with respect to the unaffected basin area or the density of the impact is limited (e.g. number of cattle per ha is still at the low side) as to become clearly visible in the shape of the FDC.

5. Conclusions

The hydrology of the studied micro-catchments is in addition to the average annual rainfall depth, rainfall regime and slope primarily controlled by the horizon sequence and the lateral saturated hydraulic conductivity of each horizon. It is realistic to assume that under dry-tropic conditions the slow flow component consists of the lateral flow in the C horizon and contributions of the top layer in the bedrock, if any, the so-called baseflow. Under wet conditions the slow flow component represents the lateral flow in the organic horizon(s) and litter layer, which could be considered as a form of intermittent flow. Overland flow most probably occurs primarily by saturation excess. Albeit it seems that in all studied micro-catchments, in addition to the magnitude of rainfall and variety of catchment properties, the hydrological response is dominated by the physical soil properties. The antecedent soil water content controls which layer of the soil profile mostly contributes to the slow flow component of streamflow, being in all studied micro-catchments the major contributor to total streamflow. It is most probable that those findings, representative for the area in which the 13 micro-catchments are situated, apply to the entire Andes Cordillera above 2500 m a.s.l. stretching from Riobamba to the border with Peru, a distance bird-flight of 600 km.

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