Land use change impacts on the hydrology of wet Andean páramo ecosystems

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Abstract This paper presents the research performed in the wet Andean páramo ecosystem in order to study the land use change impacts on its hydrology, using small paired catchments. The research results revealed that pine plantations produce a decrease of annual water yield as a consequence of increased evapotranspiration. On the other hand, livestock grazing does not seem to affect the hydrological response, primarily due to the low animal density. The main impact of cultivation is the reduction in the regulating function of the catchment, with a large increase in the magnitude of peak flows and a reduction of base flows. Furthermore, research results revealed that vertical infiltration through the soil is dominant under wet conditions, whereas preferential flow within the organic horizon to the underlying mineral horizon is dominant during low intensity rains. Only during long rain events saturated excess surface flow is observed; otherwise near surface lateral flow in the organic layer occurs. There is no evidence of Hortonian flow.

Key words páramo; land use changes; mountain hydrology; Andes; Ecuador

INTRODUCTION

The páramo is a neotropical alpine wetland ecosystem covering the upper Andean region of Venezuela, Colombia, Ecuador and Peru (Luteyn, 1992; Hofstede, 1995; Medina & Vásconez, 2001). As a result of its high water yield the majority of the main cities in the northern Andes (e.g. Bogota, Cali, Quito) benefit from páramo for domestic and industrial water supply, irrigation and the generation of hydro-electrical power. However, the demand for water strongly increases due to population growth and rising living standards. In Ecuador alone over 3 million people directly benefit from the páramo's water supply. Nevertheless, over the last decades human activity has been altering the natural land use of the páramo. Cattle grazing, cultivation, afforestation, building activities and road construction are the most common anthropogenic interferences. The paper's main objective is to summarize the research results of the hydrological impacts of the conversion from natural páramo to cattle grazing, cultivation and afforestation, obtained by the Universidad de Cuenca during the last 8 years.

METHODS

To minimize the differences due to climate, geology, topography and soils, the experimental small catchments were chosen in pairs, with similar altitudinal range and shape, and as close to each other as possible for reducing the differences in climate and rainfall catch. A comparative analysis was conducted of three pairs of catchments with different land cover such as páramo vegetation (tussock grasses mainly), cultivation of potatoes, pine plantation, and extensive cattle grazing. Flow duration curve and water balance were used to quantify the land use impact on the hydrological response and annual water yield (proportion of rainfall that is converted to discharge).

GENERAL CATCHMENT DESCRIPTION

The research was carried out on seven catchments with areas ranging between 0.63 and 5.01 km^2. Six study catchments are located in the Paute River basin (Amazonian affluent) and one catchment in the Jubones River basin (Pacific Ocean affluent), all located on the East-facing slope of the Western Cordillera (2900–3960 m a.s.l.) in South Ecuador. The catchments were divided into three paired groups according to their land use and human impacts. The first pair (M1 and M2 catchments) represents the effects of cultivation and intensive grazing. The second one (M3, M4 and M5) represents extensive grazing with annual burning, and the last one (M6 and M7) is representative of the afforestation effects (for details see Table 1).

Table 1 Major properties, hydro-meteorological characteristics and water balance of the catchments.

River basin	Units	Paute		Paute		Jubones	Paute	
Small catchment		Huagrahuma (M1)	Soroche (M2)	Quinahuaycu (M3)	Calluancay (M4)	Zhurucay (M5)	Marianza 1 (M6)	Marianza 2 (M7)
Catchment properties								
Area	km^2	2.58	1.59	5.01	4.39	1.34	0.84	0.63
Soil		Andosol	Andosol	Andosol Histosol	Andosol Histosol	Andosol Histosol	Andosol Histosol	Andosol Histosol
Vegetation cover	%	TG(100)	P(30), TG(70)	TG(78), S(20),CP(2)	TG(69), S(20), CP(11)	TG(90), CP(10)	TG(80), S(20)	PF(>90), TG
Landuse		EG	P, IG	N	EG	EG	N	PF
Geology		Saraguro Fm.: lavas and andesitic volcanoclastic deposits		Quimsacocha Fm.: volcanic and volcanoclastic rocks			Saraguro Fm: lavas and andesitic volcanoclastic deposits	
Slope	%	45	20	22	19	21	42	37
Altitude	m a.s.l	3690–4100	3520–3720	3590–3880	3585–3870	3680–3900	2980–3810	3230–3710
Shape		SO	SO	SO	SO	SO	SO	CO
Hydro-meteorological characteristics								
Begin monitoring period	date	16/10/01	29/10/01	10/11/06	10/11/06	10/11/06	29/02/04	08/05/04
End monitoring period	date	30/10/08	23/01/04	12/11/08	12/11/08	12/11/08	23/09/08	23/09/08
Maximum discharge	l/s/km^2	614.98	873.25	1019.38	971.35	992.84	445.70	285.32
Minimum discharge	l/s/km^2	3.33	0.67	2.78	4.35	2.01	2.33	0.15
Average discharge	l/s/km^2	32.09	20.50	25.52	26.05	28.82	19.30	8.30
Water balance components								
Begin monitoring period	date	13/08/03	29/10/01[a]	11/11/06	11/11/06	11/11/06	23/09/07	23/09/07
End monitoring period	date	29/10/08	22/01/04	11/11/08	11/11/08	11/11/08	23/09/08	23/09/08
Precipitation	mm/ year	1450.89	1126.42	1143.31	1382.64	1253.82	1416.88	1406.60
Total discharge	mm/ year	1063.71	648.92	908.18	823.64	910.94	684.57	389.26
Rainfall-runoff	mm/ year	387.18	477.51	235.14	559.00	342.89	732.30	1017.34
Runoff coefficient		0.73	0.58	0.79	0.60	0.73	0.48	0.28

TG, Tussock grasses; S, Shrubs; CP, Cushion plants; P, Potatoes; PF, Pine forest. IG, intensive grazed; EG, extensive grazed; N, Natural. SO, stretched oval; CO, Circular to oval; [a] With gaps between 21/02/2002 – 11/05/2002 and 30/09/2003 – 14/10/2003

The catchment shape is stretched oval for the catchments M1 to M3, M5 and M6 and circular oval for the basins M4 and M7. Based on the topographic characteristics, the catchments can be split into: (a) catchments M2 to M5 with an altitudinal range between 3520 and 3900 m a.s.l., and an average slope of 19–22%, and (b) catchments M1, M6 and M7, which are steep with slopes varying between 37 and 45% and altitudes between 2980 and 4100 m a.s.l. The largest difference in elevation (760 m) within a catchment is found in M1.

The climate of the catchments 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 relatively dry season in August–September and a less pronounced dry season around December–February (Buytaert *et al*, 2005a). The mean annual precipitation ranges between 900 and 1600 mm based on the record period 1964–2005. Rainfall is characterized by short, frequent, low intensity (90% below 10 mm/h), and an equal distribution over the year (Buytaert *et al*., 2006a). Temperature decreases at an average rate of 0.5–0.7°C per 100 m (Bacuilima *et al*., 1999; van der Hammen & Hooghiemstra, 2000; Castaño, 2002), with the mean temperature being 7°C at 3500 m a.s.l. (Buytaert, 2004). Daily solar radiation and temperature are almost constant throughout the year, while the inter-day variability is quite marked. Intra-day temperature variations are in general larger than 20°C. Due to the similarity of each pair of catchments characteristics (same altitude and mountain range), climate variability was minimized (Buytaert *et al.*, 2007; PROMAS/IAMGOLD, 2009). A more detailed description of the climate is available in Buytaert *et al*. (2006a).

The catchments M1, M3 and M6 have low human impact, with land use being limited to extensive grazing by free roaming animals and are representative of the "natural" páramo in the region. Those catchments are covered with typical páramo vegetation consisting of tussock grass and low shrubs (Table 1; Buytaert *et al*., 2006b). On the other hand, M4 and M5 catchments are covered by tussock grass, with an animal density in the range of 0.5–2 heads per hectare. Those catchments are representative of annually burned and semi-intensive grazing conditions. In catchment M2, intensive grazing (2 to 3 heads per hectare approx.), artificial drainage and cultivation of potatoes take place. Cultivation occurs through the entire year, without a specific growing cycle and occupies about 30% of the catchment. In the remaining part of the catchment, the original grass vegetation has been replaced by more nutritious species for grazing. In M2, the area of intensive grazing occupies more than 50% of the catchment. Catchment M7 is planted with *Pinus patula*. Foresters in the area generally choose this species over *P. radiata* because of its resistance to *Dothistroma pini*. In the past, infections with *Dothistroma* have had devastating effects on *P. radiata* plantations (Hofstede *et al*., 1998). The forest is about 20 years old, has a tree density of about 1000 stems ha^{-1}, and occupies more than 90% of the catchment. A complete description of the catchments can be found in (PROMAS/IAMGOLD, 2009; Buytaert *et al*., 2006b, 2007).

The most common soils in the study area are andosols and histosols (Buytaert *et al*., 2006b; Borja *et al*., 2008) in FAO's World Reference Base for Soil Resources (FAO/ISRIC/ISSS, 1998). The cold and wet climate and the low atmospheric pressure favour organic matter accumulation in the soil. The resulting soils are dark and humic and have an open and porous structure. This accumulation is further enhanced by the formation of organometallic complexes strongly resisting microbial breakdown. Unlike their high organic matter content, the soils of the páramo differ significantly from regular peat soils, due to their stronger soil structure. They have a low bulk density of around 0.13–0.95 g/cm^3, a high organic carbon content between 1 and 44%, high water retention capacity near to 0.9 cm^3/cm^3 at saturation and hydraulic conductivity ranging between 10 to 60 mm/h (Buytaert, 2004; Buytaert *et al*., 2005b, 2006b).

The geology of the catchments M1, M2, M6 and M7 consists of the Late Oligocene to Early Miocene Saraguro formation with lavas and andesitic volcanoclastic deposits shaped and compacted by glacier activity during the last ice age (Coltorti & Ollier, 2000; Hungerbühler *et al*., 2002). The catchments M3 to M5 are located on the Quimsacocha formation. This area is covered by volcanic and volcanoclastic rocks. The volcanic sequence consists of lava intermixed with stretches of fenocristals of feldspates, plagioclastic and andesitics piroclasts of more recent date, consisting of calcareous tufa and pebbles. The age is not well defined but belongs most likely to the upper Miocene or earlier (IAMGOLD, 2005). The hydraulic conductivity of the bedrock is very low, particularly compared to the hydraulic conductivity of the thin layer of volcanic ashes that constitute the soil layer (Buytaert *et al*., 2005c, 2006b) and according to Buytaert *et al*. (2007), no groundwater is present.

MONITORING

The design of the monitoring network was constrained by multiple factors such as climate characteristics (spatial and temporal), basin residence time, and accessibility, among other factors. Regretfully, an integral experimental design has not been feasible due to budget limitations. Monitoring started in the early 2000s and the collected data enabled an assessment of the catchment response as a function of land use. Time series showed a number of gaps primarily due to sensor failures during extreme weather conditions.

Each catchment was provided with a V-notch weir (90°) and a pressure transducer (Global Water WL16) to estimate the streamflow. Water level recordings were made at 5 and 15 minute intervals depending on the catchment. The Kindsvater–Shen relation (US Bureau of Reclamation, 2001) was used to convert the water level to discharge. Additionally, three tipping bucket raingauges (Davis Rain Collector II and HOBO RG3M raingauge) were installed at each catchment. Meteorological stations were installed in catchments M2, M4, M5 and M6. Details about the hydrometeorological network configuration can be found in Buytaert *et al.* (2007) and PROMAS/IAMGOLD (2009). A summary of data and the starting date of the recordings are presented in Table 1.

RESULTS

Natural páramo hydrology

Soil properties (high infiltration and water storage), the cold and wet climate, the uniform rainfall pattern and low water consumption by natural vegetation result in a high annual water yield and flow regulation. Rainfall intensities are commonly lower than infiltration rates (Buytaert *et al*., 2006b). Thus, infiltration excess overland flow (Hortonian flow) is virtually non-existent (Iñiguez *et al*., 2008). The hydrological regime is dominated by a slow flow response (Buytaert *et al*., 2007). Vertical infiltration through the soil is dominant during the beginning of the rainfall events and dependent on the antecedent soil moisture conditions. By contrast, during low intensity rainfall events, preferential flow is dominant between the organic horizon and the underlying mineral horizon or the bedrock. Only during long rain events saturation excess surface flow is observed; otherwise near sub-surface lateral flow in the organic layer occurs during peaks (Iñiguez *et al*., 2008).

Land use change effects

The comparative analysis revealed that the basin soils are very susceptible to irreversible structural changes caused by a change in land use. Those changes entail a drying effect, which significantly alters the soil water retention properties and thus the hydrological basin response (Buytaert *et al*., 2002). Cattle grazing with annual burning management, primarily due to the low animal density, does not seem to affect the hydrological response (Table 1). The water yield is reduced slightly with a maximum of 15% as shown in Fig. 1 and on the water balance section in Table 1. Pine plantation (*Pinus radiata*) results in a decrease of the water yield (nearly 50%) as a consequence of increased evapotranspiration, as shown in Fig. 2 (Buytaert *et al*., 2007). The comparison of flow duration curves shows a slight reduction of the water regulation capacity. However, the flow regime changes drastically, with both peak and low flows being severely reduced (Buytaert *et al*., 2006b, 2007). In the semi-cultivated and intensively grazed basin, an increase in peaks and a severe reduction in low flows, and thus a considerable loss of water regulation, is observed (Buytaert *et al*., 2005a). This is attributed to a higher hydraulic conductivity of soils, an introduction of artificial drains and soil compaction (Buytaert *et al*., 2007). Longer time series are needed to study the effects on the water yield, but apparently it is reduced. Additionally, field observations report a considerable increase in sediment production in the cultivated basin. In the other catchments sediment production is negligible.

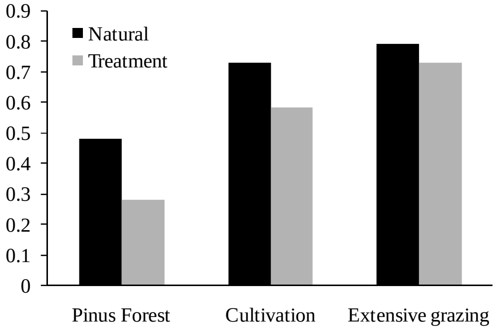

Fig. 1 Annual runoff coefficients for different land uses by pairs of catchments.

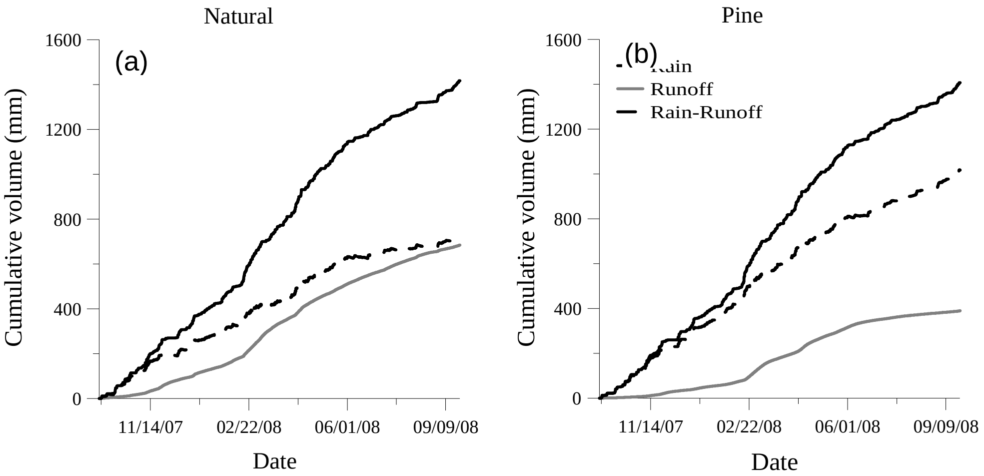

Fig. 2 Cumulative water balance of the catchments (a) M6 and (b) M7.

CONCLUSIONS AND FUTURE RESEARCH

Given the fragility of the soils and the socio-economic importance of the surface water draining from the páramo ecosystem, this study has provided evidence that land use changes, especially afforestation with *Pinus* plantations and cultivation, result in a strong reduction of water yield and water regulation capacity of Andean páramo catchments. Therefore changes in land use should be controlled and limited so as to safeguard the water resources of Andean highlands. From a hydrological point of view extensive grazing seems to be the most sustainable land use. These research results are being used by decision makers to devise national land use management policies drawn on scientific evidence.

Future research will include: (a) improvement of spatial rainfall measurements, (b) analysis of the effects of afforestation with *Polylepis* sp. on catchment hydrology, and (c) flow paths identification. Additionally, knowledge validation, upscaling of results to larger catchments and extrapolation to ungauged catchments will be the driving forces for research in the coming years.

Acknowledgements This research was feasible thanks to grants from DIUC (Direccion de Investigacion de la Universidad de Cuenca), IAMGOLD Ecuador S.A. (Quimsacocha Project) and a K. U. Leuven postdoctoral grant (PDM). The authors thank Dr Felipe Cisneros, Director of PROMAS of Universidad de Cuenca for providing data, and the technical staff of PROMAS for their assistance. Patricio Crespo was funded by the DFG doctoral grant, and Rolando Célleri and Pablo Borja by the SENACYT through the PIC-08-460 grant.

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