

Impacts of land use on the hydrological response of tropical Andean catchments

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Abstract:

Changes in land use and land cover are major drivers of hydrological alteration in the tropical Andes. However, quantifying their impacts is fraught with difficulties because of the extreme diversity in meteorological boundary conditions, which contrasts strongly with the lack of knowledge about local hydrological processes. Although local studies have reduced data scarcity in certain regions, the complexity of the tropical Andes poses a big challenge to regional hydrological prediction. This study analyses data generated from a participatory monitoring network of 25 headwater catchments covering three of the major Andean biomes (*páramo*, *jalca* and *puna*) and links their hydrological responses to main types of human interventions (cultivation, afforestation and grazing). A paired catchment setup was implemented to evaluate the impacts of change using a 'trading space-for-time' approach. Catchments were selected based on regional representativeness and contrasting land use types. Precipitation and discharge have been monitored and analysed at high temporal resolution for a time period between 1 and 5 years. The observed catchment responses clearly reflect the extraordinarily wide spectrum of hydrological processes of the tropical Andes. They range from perennially humid páramos in Ecuador and northern Peru with extremely large specific discharge and baseflows, to highly seasonal, flashy catchments in the drier punas of southern Peru and Bolivia. The impacts of land use are similarly diverse and their magnitudes are a function of catchment properties, original and replacement vegetation and management type. Cultivation and afforestation consistently affect the entire range of discharges, particularly low flows. The impacts of grazing are more variable but have the largest effect on the catchment hydrological regulation. Overall, anthropogenic interventions result in increased streamflow variability and significant reductions in catchment regulation capacity and water yield, irrespective of the hydrological properties of the original biome. Copyright © 2016 The Authors. *Hydrological Processes*. Published by John Wiley & Sons Ltd.

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INTRODUCTION

Andean ecosystem degradation and water resources

The tropical Andes delivers a large portfolio of ecosystem services but remarkably an abundant and sustained supply of clean fresh water (Buytaert *et al.*, 2006a; Roa-García *et al.*, 2011). Groundwater in these

regions is difficult to extract (Buytaert *et al.*, 2007), which results in a predominant use of surface water sources that are particularly vulnerable to environmental changes (Bradley *et al.*, 2006), hydrological extremes (Bradshaw *et al.*, 2007), increasing water demand (Buytaert and De Bièvre, 2012) and a very dynamic land use as a result of rural development (Buytaert *et al.*, 2006a).

Anthropogenic disturbance in the tropical Andes started as early as 7000 years ago, but it has intensified after the colonial period in the 16th century and particularly extended since the early 20th century (Bruhns, 1994; White and Maldonado, 1991, as cited by Molina *et al.*, 2015; Etter and van Wyngaarden, 2000, as cited by Roa-García *et al.*, 2011; Sarmiento, 2000; Harden, 2006). Changes in land use are largely driven by population growth, including livestock grazing in extensive areas (Molina *et al.*, 2007), cultivation of mostly cereals and tubers (Sarmiento, 2000) and afforestation with exotic species introduced as a way to improve their economic viability (Farley *et al.*, 2004). An example of the latter is unsuccessful efforts of local authorities to replicate a positive experience from Cajamarca, Peru, where degraded lands were restored mostly using *Pinus patula* (approximately 60%), *Pinus radiata* and *Eucalyptus globulus*. However, the increase in subsurface flow associated with forests (Tobón, 2009) contrasts with negative impacts on local biodiversity (Hofstede *et al.*, 2002) and total water yield (Buytaert *et al.*, 2007).

The severe ecosystem degradation contrasts strongly with the lack of knowledge about the strong spatiotemporal gradients of local climate and hydrological processes that govern them (Célleri and Feyen, 2009). Much of the global surface is ungauged or poorly gauged (Fekete and Vörösmarty, 2007), but tropical regions in particular are characterized by data scarcity (Wohl *et al.*, 2012). This is exacerbated by the tendency of national hydrometeorological networks to cover inadequately remote headwater areas (Célleri *et al.*, 2010). As a result, the hydrological impacts of land use and that of many other anthropic activities in the region, such as watershed management, conservation and investment (e.g. Asquith and Wunder, 2008; Tallis and Polasky, 2009; Garzón, 2010) have not been evaluated properly.

Over the last decades, hydrological research in the tropical Andes has increased (e.g. as reviewed by Célleri and Feyen, 2009; Célleri, 2010). However, most studies have focused on the wet páramo ecosystems (Buytaert *et al.*, 2006a; Crespo *et al.*, 2010; Molina *et al.*, 2015) and high Andean forests (Bruijnzeel, 2004; Tobón, 2009; Crespo *et al.*, 2012), while other biomes such as dry páramo, jalca and puna are underrepresented. The extreme variety of meteorological boundary conditions, vegetation types, soils, geology and topography leads to similarly diverse and non-stationary hydrological

processes at multiple scales (e.g. Vuille *et al.*, 2000; Bendix *et al.*, 2006; Mora and Willems, 2012), which complicates further hydrological predictions in unmonitored regions. It is therefore paramount to increase the number, representativeness and quality of monitoring sites to cover the broad diversity of Andean ecosystems (Célleri *et al.*, 2010).

Hydrological processes in Andean catchments

The tropical Andes can be divided broadly in five major landscape units (Cuesta *et al.*, 2009): páramo, puna, Andean forests, inter-Andean valleys and mountain deserts or salt flats. They are distinguished by thermal limits and latitude (Josse *et al.*, 2009, Figure 1). The páramo, jalca and puna are mountainous highlands that span above the forest line (3000 to 3500-m altitude) and the permanent snow line (4500 to 5000-m altitude) (Buytaert *et al.*, 2006a; Sánchez-Vega and Dillon, 2006; Célleri *et al.*, 2010). The páramo biome covers the upper Andean region of western Venezuela, Colombia, Ecuador and northern Peru, where the transition to the puna originates the jalca formations. Humid puna extends from eastern Peru until the north-eastern Bolivian Cordillera, whereas dry puna is located from western Peru until the southwest of Bolivia and northern Argentina and Chile.

The latitudinal variability of physical characteristics, such as soil conditions, is less influential compared with the effect of the Pacific Ocean and the Amazon plains that induce more conspicuous differences in hydrological responses for respectively the Western and Eastern Cordilleras (Josse *et al.*, 2009). Additionally, Andean forests and, occasionally, glaciers are located respectively below and above gradual limiting lines with the highlands and are therefore associated with them especially on the common fringes (Cuesta *et al.*, 2009; Soruco *et al.*, 2015).

No existing scientific studies were found on the hydrology of punas and jalcas; thus, most of the currently available hydrological knowledge relates to wet páramos. These highlands feature typical high tropical mountain climate patterns (Buytaert *et al.*, 2006a; Viviroli *et al.*, 2007). Regions located closer to the equator have low seasonal variability, with solar radiation and mean air temperature almost constant throughout the year. But diurnal temperature cycles are highly marked and can range between 0 and 20 °C (Buytaert *et al.*, 2006a, 2007; Córdova *et al.*, 2015). Luteyn (1992); Buytaert *et al.* (2006a) and Molina *et al.* (2015) have reported annual precipitation amounts between 500 and 3000 mm year⁻¹, with an exceptionally high spatiotemporal variability (Buytaert *et al.*, 2006b; Célleri *et al.*, 2007). In contrast, characterizing reference evapotranspiration has been limited by the scarce availability of meteorological data. Although some values have been reported (e.g. 646 mm year⁻¹,

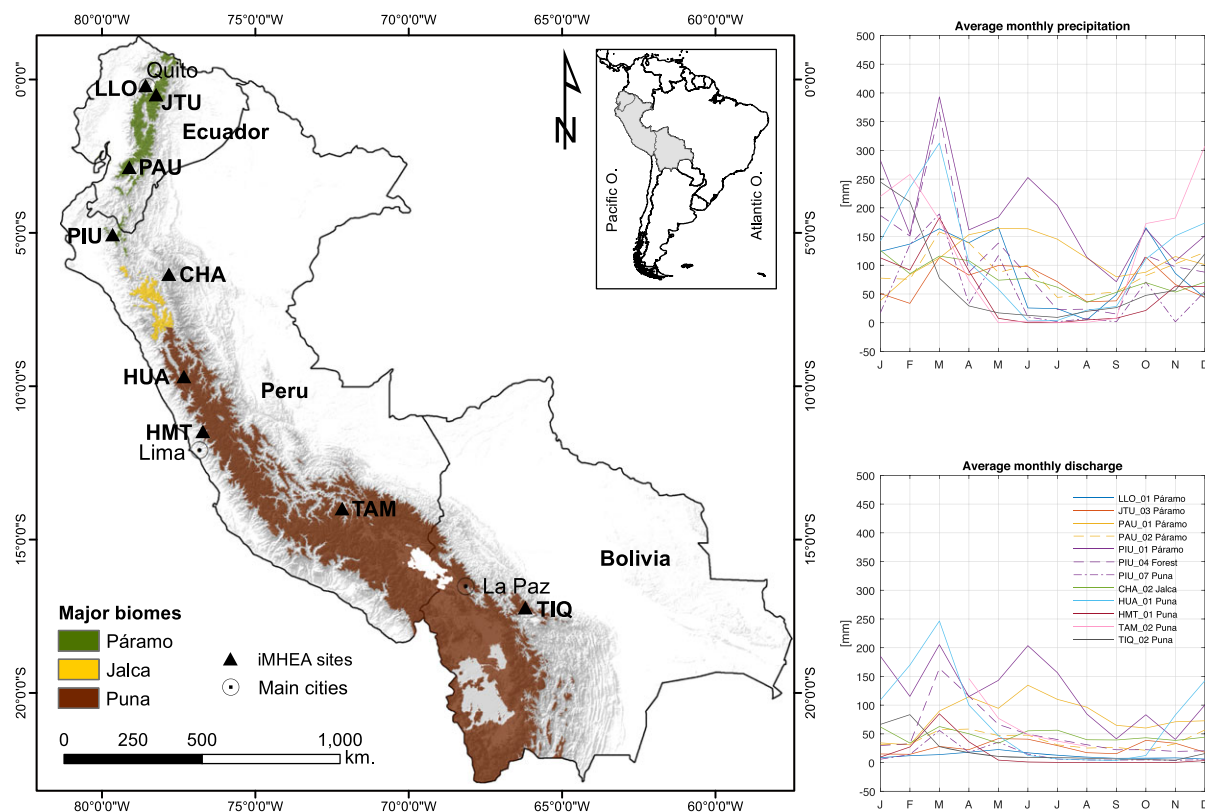


Figure 1. (Left) Map of the tropical Andes, major high Andean biomes and location of the iMHEA observatories. (Right) Monthly precipitation and discharge of reference catchments averaged over their monitored periods

Buytaert *et al.*, 2007; 723 mm year⁻¹, Córdova *et al.*, 2015), errors are thought to be as high as 30% with limited data (Córdova *et al.*, 2015).

The hydrological response of reported Andean catchments is strongly related to their soil conditions. Buytaert *et al.* (2005) showed that the hydraulic conductivity of wet páramo soils prevented soil moisture to drop below 60 vol %, reducing the probability of water stress occurrence. Previously, Buytaert *et al.* (2004) analysed the recession curves of a natural catchment finding three main responses attributed to overland flow, interflow and baseflow on the basis of their residence time. The study also found that interflow was less important, and later, Buytaert *et al.* (2007) and Crespo *et al.* (2010) pointed the virtual absence of infiltration excess overland flow. A particular characteristic of most of the studied high Andean catchments is the presence of underlying impermeable bedrock that minimizes deep infiltration and groundwater storage (Buytaert *et al.*, 2007), but some regions also present deep permeable soils and sustain important aquifers (Buytaert *et al.*, 2006a; Favier *et al.*, 2008). Runoff ratios between 0.50 and 0.70 have been reported in natural wet páramos (Buytaert *et al.*, 2007); while more recently, Mosquera *et al.* (2015) have found that water yield increases with the extent of wetlands, likely because of saturation excess flow occurrence.

Additionally, Buytaert and Beven (2011) also highlight the importance of threshold-triggered and non-stationary hydrological processes, such as disconnected water storages found within the catchment microtopography, or changing evapotranspiration, infiltration and routing produced by growing vegetation. Lastly, in areas covered by fog, horizontal precipitation and cloud water interception may account for 10% to 35% of total precipitation, particularly in forested catchments (Bruijnzeel, 2004; Tobón, 2009; Pryet *et al.*, 2012). However, no studies were found relating to the studied biomes.

To address this regional knowledge gap, this paper presents an analysis of data generated from a network of paired catchments in the tropical Andes to regionalize human impacts on their hydrological response and water yield. This research builds upon several years of extensive study by the Regional Initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA, Célleri *et al.*, 2010). Using 25 catchments distributed from Ecuador to Bolivia, the main objective of this paper is to include previously underrepresented ecosystems (jalca and puna) in a region-wide analysis of the impacts of land use across tropical Andean biomes. We make use of hydrological indices to test the generalization of results in areas generally facing data-scarcity yet intense use. These

results may be used to improve water resources management and the effectiveness of watershed interventions, as well as to support emergent research in the Andean region.

METHODOLOGY

Regional setting

Emerging from a local awareness about the need for better information on watershed interventions in the Andes, a partnership of academic and non-governmental institutions pioneered in participatory hydrological monitoring (Céleri *et al.*, 2010; Buytaert *et al.*, 2014). The collaborative nature of iMHEA allows for (i) standardizing monitoring practices by a unique protocol; (ii) ensuring quality and support from research groups to local stakeholders through the entire monitoring process; (iii) local responsibility for equipment and civil structure safety and maintenance, data downloading and project co-funding by development institutions; and (iv) promoting linkages with hydrometeorological and environmental authorities, policy makers and society involved in water governance in the region.

The local partners of iMHEA have been monitoring a set of 25 catchments distributed along the tropical Andes (Figure 1, Table I). The catchments, sized between 0.5 and 7.8 km², are located between 0 and 17° South and cover an elevation range from 2682 to 4840-m altitude. Sites are rural with no urbanization and not affected by water abstractions or stream alterations. Most of the catchments have a natural land cover of tussock and other grasses, interspersed with wetlands, shrubs and patches of native forest. Shapes are typically oval tending to circular or stretched and slopes are steep and uneven. The main land uses are for conservation, grazing, afforestation and cultivation, which are those addressed in this study.

Monitoring setup to assess land use change impacts

Quantifying the impacts of land use and cover change (LUCC) on the water cycle is complicated by the difficulty of distinguishing the effects of such changes from those that are due to natural climatic variability or other confounding factors (Ashagrie *et al.*, 2006; Bulygina *et al.*, 2009). Assessing these impacts relies on analysing signals of change over time or contrasting differences in hydrological responses between two or more catchments (McIntyre *et al.*, 2014).

Hydrologically, each method has different disadvantages. In long-term analysis, even though the same catchment is monitored before and after the change, natural climatic variability may influence differently during the two considered periods (Lørup *et al.*, 1998).

This is addressed in the second approach by monitoring paired catchments under the same climatic conditions and different watershed interventions. However, this may complicate the attribution of observed differences to the uniqueness of catchments, as land use is not the only factor that affects their hydrological response (Bosch and Hewlett, 1982; Thomas and Megahan, 1998; Beven, 2000; McIntyre *et al.*, 2014). Nevertheless, on balance, the paired catchment approach delivers more rapid answers by ‘trading space for time’ (e.g. Buytaert and Beven, 2009, 2011; Singh *et al.*, 2011; Sivapalan *et al.*, 2011), allowing for faster input in often urgent policy decisions. Additionally, the approach can be made more robust by considering a large number of catchments covering a wide range of ecosystems, land uses and physical and climatic characteristics.

In our paired catchments, streamflow has been measured using a compound sharp-crested weir (a V-shaped section for low flows and a triangular–rectangular section for high flows) equipped with pressure transducers at the outlet of each catchment. Water level recordings are taken at a regular interval of maximum 15 min and typically 5 min. Precipitation has been measured with a minimum of two tipping-bucket rain gauges at an installed height of 1.50 m (resolutions of 0.254, 0.2 or 0.1 mm) distributed in the catchment areas to account for small scale spatial variability (Buytaert *et al.*, 2006b; Céleri *et al.*, 2007). Table II shows the different monitoring periods of the catchments.

Data analysis

A preliminary survey of catchment physical features was performed before selection and to consider their influence on the hydrological response. Contour lines at 40-m vertical resolution were available for the characterization of elevations and slopes. Because only a limited number of catchments is equipped with a meteorological station, reference evapotranspiration was estimated using Worldclim temperature data (Hijmans *et al.*, 2005) and the Hargreaves formula (Hargreaves and Samani, 1985; Allen *et al.*, 1998).

The tipping bucket rainfall data were processed using a composite cubic spline interpolation on the cumulative rainfall curve (Sadler and Brusscher, 1989; Ciach, 2003; Wang *et al.*, 2008; Padrón *et al.*, 2015) and aggregated at intervals matching discharge time steps (i.e. daily, monthly and annual scales for hydrological indices and sub-daily scales for rainfall intensities). A 5-min scale moving window was used to calculate rainfall intensity curves for durations between 5 min and 2 days. The seasonality index (Walsh and Lawler, 1981) was calculated and normalized between 0 (non-seasonal) and 1 (extremely seasonal). Correlations between the

Table I. Major physiographic properties of the studied catchments.

Code	Ecosystem	Altitude	Area	Shape	Slope	Soils	Land use	Land cover
		[m]	[km ²]	^a	^b		^c	^d [%]
Units								
LLO Lloa								
LLO_01	Páramo	3825–4700	1.79	SO	SU	Andosol	EG, B	TG(90), SH(10)
LLO_02	Páramo	4088–4680	2.21	SO	U	Andosol, Histosol	EG, NF	TG(70), NF(10), WL(20)
JTU Jatunhuaycu								
JTU_01	Páramo	4075–4225	0.65	O	U	Andosol	IG	TG(100)
JTU_02	Páramo	4085–4322	2.42	O	U	Andosol	IG	TG(100)
JTU_03	Páramo	4144–4500	2.25	CO	U	Andosol, Histosol	N	TG(80), SH(20)
JTU_04*	Páramo	3990–4530	16.05	SO	U	Andosol, Histosol	IG, N, R	TG(70), SH(10), WL(5), NR(15)
PAU Paute								
PAU_01	Páramo	3665–4100	2.63	CO	U	Andosol	N	TG(100)
PAU_02	Páramo	2970–3810	1.00	O	SU	Andosol, Histosol	N, EG	TG(80), NF(20)
PAU_03	Páramo	3245–3680	0.59	CO	SU	Andosol, Histosol	PF	TG(10), PF(90)
PAU_04	Páramo	3560–3721	1.55	CO	U	Andosol	IG, CR	TG(70), CP(30)
PIU Piura								
PIU_01	Páramo	3112–3900	6.60	CO	U	Andosol, Histosol	N	TG(75), NF(15), L(10)
PIU_02	Páramo	3245–3610	0.95	CO	SU	Andosol, Histosol	IG	TG(75), NR(15), L(10)
PIU_03	Páramo	3425–3860	1.31	CO	SU	Andosol, Histosol	IG	TG(90), L(10)
PIU_04	Forest	2682–3408	2.32	O	SU	Andosol, Cambisol	NF	G(20), NF(80)
PIU_07	Dry puna	3110–3660	7.80	O	U	Andosol	IG	TG(45), SH(20), CP(35)
CHA Chachapoyas								
CHA_01	Jalca	2940–3200	0.95	O	U	Andosol, Inceptisol	PF	TG(20), PF(80)
CHA_02	Jalca	3000–3450	1.63	O	U	Andosol, Inceptisol	N	TG(90), NF(10)
HUA Huaraz								
HUA_01	Humid puna	4280–4840	4.22	CO	U	Andosol, Histosol	N, EG	TG(60), NR(25), WL(15)
HUA_02	Humid puna	4235–4725	2.38	O	U	Andosol, Histosol	EG	TG(55), NR(30), WL(15)
HMT Huamantanga								
HMT_01	Dry puna	4025–4542	2.09	O	U	Leptosol, Inceptisol	IG	G(75), NR(15), SH(10)
HMT_02	Dry puna	3988–4532	1.69	O	SU	Leptosol, Inceptisol	IG	G(85), NR(10), SH(5)
TAM Tambobamba								
TAM_01	Humid puna	3835–4026	0.82	O	U	Leptosol, Inceptisol	IG, PF	G(80), PF(20)
TAM_02	Humid puna	3650–4360	1.67	CO	SU	Leptosol, Inceptisol	N, NF	G(60), NF(40)
TIQ Tiquipaya								
TIQ_01	Humid puna	4140–4353	0.69	O	U	Leptosol, Inceptisol	IG, CR	G(70), NR(30)
TIQ_02	Humid puna	4182–4489	1.73	SO	U	Leptosol, Inceptisol	N	TG(90), NR(5), WL(5)

Notes

^a SO: Stretched oval; O: Oval; CO: Circular to oval.

^b U: Uneven; SU: Strongly uneven; S: Steep; VS: Very steep.

^c B: Burning; CR: Cultivation; EG: Extensive grazing; IG: Intensive grazing; N: Natural; NF: Native forest; PF: Pines; T: Tourism; R: Restoration.

^d TG: Tussock grass; G: Grass; SH: Shrubs; NF: Native forest; WL: Wetland; PF: Pines; L: Lagoon; NR: Nude rock/soil.

*Station JTU_04 is located at the outlet of the catchment that contains JTU_01 to JTU_03 and is not used in a pairwise comparison.

multiple local rain gauges were used to detect and correct errors, to fill data gaps and to obtain reliable averaged values.

The Kindsvater–Shen relation (USDI, 2001) was used to transform water level to streamflow, complemented with manual stage-discharge measurements. Flow duration curves (FDC) and corresponding percentiles were calculated based on the daily flows using the plotting position of Gringorten (1963). The slope between 33%

and 66% of the FDC is commonly used as an indicator of hydrological regulation (Olden and Poff, 2003). A steep slope is associated with high flashiness response to input precipitation, whereas a flatter curve represents buffered behaviour and larger storage capacity (Buytaert *et al.*, 2007; Yadav *et al.*, 2007). Although flow percentiles are associated with their probability of occurrence, information about when or for how long such flows happen is absent. Therefore, the average duration of hydrographs

Table II. Water balance and hydrometeorological features of the studied catchments.

Code	Monitoring period	Rainfall [mm year ⁻¹]	Discharge [mm year ⁻¹]	ET ₀ [mm year ⁻¹]	SINDX	DAYP0	PVAR	RR	QVAR	R2FDC	IRH	DLQ75	DHQ25
Units					[-]	[-]	[mm mm ⁻¹]	[-]	[mm mm ⁻¹]	[-]	[-]	[day]	[day]
LLO Lloa													
LLO_01	10/01/2013–27/01/2016	1128	115	972	0.32	0.52	1.95	0.10	0.54	-0.46	0.74	8.80	8.56
LLO_02*	10/01/2013–27/01/2016	1091	144	829	0.31	0.51	1.91	0.13	0.57	-0.60	0.71	14.00	9.58
JTU Jatunhuaycu													
JTU_01	14/11/2013–15/02/2016	641	59	798	0.23	0.35	1.99	0.09	0.31	-0.41	0.91	13.13	7.56
JTU_02	15/11/2013–15/02/2016	739	57	781	0.22	0.27	1.81	0.08	1.44	-0.99	0.46	8.87	4.18
JTU_03*	13/11/2013–16/02/2016	849	315	765	0.20	0.22	1.70	0.37	0.86	-0.59	0.63	7.52	4.74
JTU_04	19/11/2013–11/02/2016	767	214	817	0.22	0.27	1.85	0.28	1.05	-0.32	0.63	12.60	5.88
PAU Paute													
PAU_01*	24/05/2001–16/08/2005	1358	974	937	0.14	0.20	1.40	0.72	0.85	-0.70	0.63	19.60	5.13
PAU_02*	29/02/2004–31/07/2007	1092	467	1038	0.17	0.27	1.48	0.43	0.79	-0.73	0.62	10.45	8.16
PAU_03	29/05/2004–31/07/2007	1014	201	987	0.17	0.28	1.61	0.20	1.14	-1.12	0.47	8.60	15.39
PAU_04	27/10/2001–14/10/2003	1123	688	935	0.13	0.13	1.38	0.61	1.33	-1.05	0.43	7.33	3.10
PIU Piura													
PIU_01*	05/07/2013–12/12/2015	2239	1474	1275	0.19	0.24	1.58	0.66	1.09	-1.28	0.46	5.55	3.07
PIU_02	06/07/2013–13/12/2015	2677	1729	1178	0.21	0.26	1.62	0.65	1.15	-1.32	0.44	19.35	3.98
PIU_03	11/04/2013–23/10/2015	1869	1103	1165	0.22	0.23	1.68	0.59	1.85	-1.63	0.18	5.67	54.50
PIU_04*	23/06/2013–14/01/2016	1377	614	1374	0.31	0.40	2.12	0.45	1.05	-0.70	0.52	8.86	22.71
PIU_07*	11/07/2013–15/01/2015	640	173	1268	0.51	0.67	2.86	0.27	1.58	-0.48	0.40	15.22	11.42
CHA Chachapoyas													
CHA_01	18/08/2010–07/12/2015	634	118	1294	0.19	0.32	1.61	0.19	1.06	-0.71	0.52	4.11	5.23
CHA_02*	18/08/2010–07/12/2015	930	560	1266	0.15	0.25	1.43	0.60	0.57	-0.36	0.75	3.86	2.36
HUA Huaraz													
HUA_01*	10/09/2012–20/06/2014	1346	937	984	0.37	0.26	1.36	0.70	1.05	-2.06	0.43	39.50	9.29
HUA_02	10/09/2012–20/06/2014	1288	726	1015	0.36	0.26	1.32	0.56	1.12	-2.22	0.38	20.13	14.55
HMT Huamantanga													
HMT_01	28/06/2014–03/03/2016	645	168	902	0.48	0.69	2.47	0.26	2.72	-3.33	0.02	8.11	25.50
HMT_02*	26/06/2014–03/03/2016	613	138	964	0.50	0.68	2.60	0.23	2.51	-2.19	0.06	8.56	30.60
TAM Tambobamba													
TAM_01	12/04/2012–02/01/2013	1245	244	1250	0.49	0.66	2.38	0.20	0.98	-0.95	0.49	11.33	17.50
TAM_02*	12/04/2012–16/04/2013	1405	811	1299	0.48	0.63	2.36	0.58	0.67	-0.57	0.67	17.00	35.00
TIQ Tiquipaya													
TIQ_01	02/04/2013–25/01/2016	835	244	1146	0.42	0.59	2.36	0.29	2.17	-1.99	0.15	5.86	7.65
TIQ_02*	18/02/2013–25/01/2016	871	263	1102	0.45	0.61	2.36	0.30	2.12	-0.58	0.35	16.69	20.62

Notes

*Reference catchments. Average monthly precipitation and discharge for these are plotted in Figure 1. See Table III for the definitions of the analysed hydrological indices.

above or below a threshold helps complement this information.

In order to assess the impacts of cultivation, afforestation and grazing on the hydrological response and water yield, a set of indices is compared between reference and altered catchments and contrasted across biomes (Table III). Precipitation is summarized in the seasonality index (SINDX), annual ratio of days with zero precipitation (DAYP0) and daily rainfall variability (PVAR). For discharge, we use the runoff ratio (RR), daily flow variability (QVAR), slope of the flow duration curve (R2FDC), the hydrological regulation index (IRH), average low flow duration below the 25th flow percentile (DLQ75) and average high flow duration above the 75th flow percentile (DHQ25). To assess differences in streamflow flashiness and response to precipitation events, we also compare high-resolution sections of the monitored precipitation and discharge time series. Hydrological indices were calculated using the entire available dataset for each catchment, while a 30-day scale time window is used for visualization purposes highlighting representative effects of land use change on catchment regulation that are consistently observed in the complete analysis periods.

RESULTS

The natural hydrological regime

Table II and Figures 1 and 2 show results of the monitoring of precipitation and streamflow for the three major biomes in the highlands of Ecuador, Peru and Bolivia: páramo, jalca and puna. The studied catchments represent an extraordinary wide spectrum of characteristics and clearly reflect the dominant regional regimes of the tropical Andes.

In northern Ecuador, stations located on the eastern side of the Andes (JTU) have a stronger influence from the Amazon regime, resulting in a more pronounced dry season during the boreal winter (*DJF*). In contrast, dry months in the western slopes at similar latitude (LLO) occur during the summer (*JJA*). Despite their low seasonality ($SINDX < 0.32$), DAYP0 was as high as 0.52 in LLO, and daily precipitation was more variable than in other páramo catchments ($PVAR > 1.70$). However, daily discharges were considerably more stable ($QVAR < 1.44$).

The catchments located in the páramo of southern Ecuador and northern Peru exhibit a perennially wet, bimodal regime similar to that described by Bendix

Table III. Definition of the hydrological indices analysed in the study.

Abbreviation	Reference formula	Units	Definition
Indices related to meteorological features			
ET ₀	$0.0023(T_{\text{mean}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5}Ra$	[mm year ⁻¹]	Reference evapotranspiration based on monthly temperature estimates only.
SINDX	$(1/P_{\text{year}})(\sum P_{\text{month}} - P_{\text{year}} /12)(6/11)$	[-]	Seasonality index scaled between 0 (non-seasonal, all months with equal rainfall) to 1 (extremely seasonal, all annual rainfall occurring during one month).
DAYP0	$D_{P < RGres}/D_{\text{total}}$	[-]	Percentage of days with zero precipitation (i.e. not registered by the rain gauge resolution) with respect to the total number of days over the monitored period.
PVAR	σ_p/P_{mean}	[mm mm ⁻¹]	Coefficient of variation in daily precipitation over the monitored period, standard deviation divided by mean.
Indices related to streamflow features			
RR	$Q_{\text{year}}/P_{\text{year}}$	[-]	Ratio between average discharge volume and average rainfall volume over the monitored period.
QVAR	σ_Q/Q_{mean}	[mm mm ⁻¹]	Coefficient of variation in daily flows over the monitored period, standard deviation divided by mean.
R2FDC	$(\log_{10}(Q_{66}) - \log_{10}(Q_{33})) / (0.66 - 0.33)$	[-]	Slope in the middle third of the flow duration curve in logarithmic scale.
IRH	$\Sigma(Q_{Q < Q50}) / \Sigma(Q)$	[-]	Volume below the 50 th flow percentile (Q50) in the flow duration curve divided by total volume.
DLQ75	$\Sigma(D_{Q < Q75}) / N_{Q < Q75}$	[day]	Average duration of flows below the 25 th flow percentile (Q75) over the monitored period.
QHQ25	$\Sigma(D_{Q > Q25}) / N_{Q > Q25}$	[day]	Average duration of flows above the 75 th flow percentile (Q25) over the monitored period.

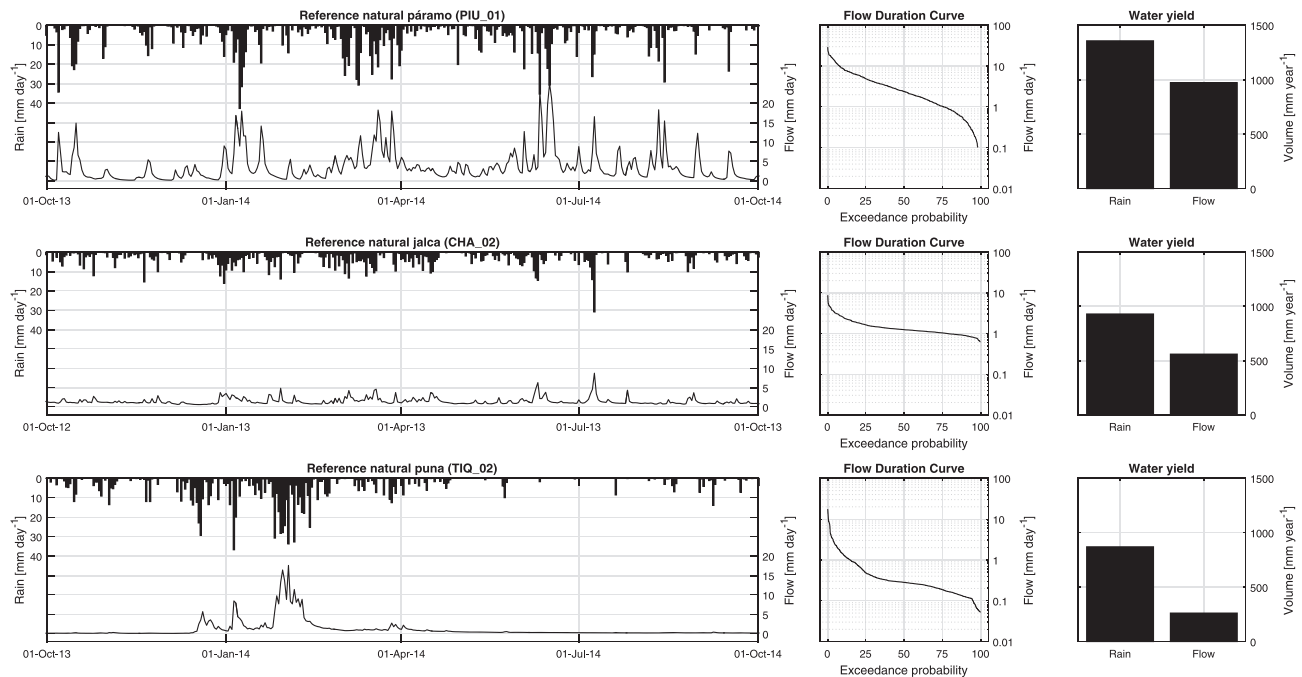


Figure 2. Hydrological response of different Andean biomes in a year. The left vertical axis corresponds to precipitation and the right vertical axis to streamflow. The flow duration curves and annual water yield are aggregated over the complete catchment monitored periods. Notice that the time series show different years

(2000) and Célleri *et al.* (2007). In the case of the páramo in Piura, this is characterized by a Pacific climate influence increased further by Amazonian air masses that penetrate the Andes through the Huancabamba depression (Figure 2). The seasonality is low ($SINDX < 0.30$, $DAYPO < 0.30$), which means that precipitation is well distributed throughout the year with high-intensity events occurring approximately every 3 months (January, March, June and October). This results in a low variability of streamflow ($PVAR < 1.60$, $QVAR < 1.10$) and high specific discharge.

In contrast, catchments located further south in the jalca and puna biomes only receive moisture from the Amazon basin because of the arid climate system of the Peruvian Pacific coast (Figure 2). These catchments tend to have monomodal precipitation regimes with a clear humidity gradient decreasing from east to west. Seasonality and rainfall intensities are much lower in the jalca of Chachapoyas ($SINDX < 0.20$, $DAYPO < 0.32$), which results in small, sustained streamflows with low variability during the entire year ($PVAR < 1.61$, $QVAR < 1.10$).

The puna catchments of southern Peru and Bolivia have the most pronounced seasonal regime ($SINDX > 0.30$, $DAYPO > 0.60$), with high intensities during the boreal winter. As shown in Figure 2 for the puna in Tiquipaya, this produces highly seasonal and variable discharge volumes falling nearly to zero during the driest months ($PVAR > 2.36$, $QVAR > 2.10$). The humid puna of Huaraz

in central Peru still shares precipitation characteristics similar to those of the páramo further north (i.e. large annual rainfall, $DAYPO < 0.26$, $PVAR < 1.61$), yet seasonality is larger and precipitation during dry months may be as low as 3 mm month^{-1} (Figure 1).

Natural Andean ecosystems are associated with FDC profiles with a low slope indicating good hydrological regulation capacity ($R2FDC \sim 0$, $IRH > 0.50$), often diminished because of LUCC. As can be seen in Figure 2, the jalca exhibited the most horizontal profile, followed by the páramo, while the curve in the puna revealed a larger difference between high and low flows. Additionally, average RRs of natural catchments are between 0.37 and 0.72 in the páramo, 0.60 in jalca and between 0.30 and 0.70 in the puna.

The impacts of land use change

Cultivation. Figure 3 shows that cultivated catchments respond to rainfall events with higher and more rapid peak flows, while the recession curves drop faster sustaining lower baseflows. This indicates a loss of hydrological regulation capacity, which is also reflected in a steeper FDC. While high flows remain very similar among pairs, mean daily flows are approximately half those of natural catchments, and low flows are lower with an average ratio of five. $QVAR$ is high in both the natural and cultivated puna yet larger when the páramo is intervened. Additionally, $DLQ75$ and $DHQ25$ are about

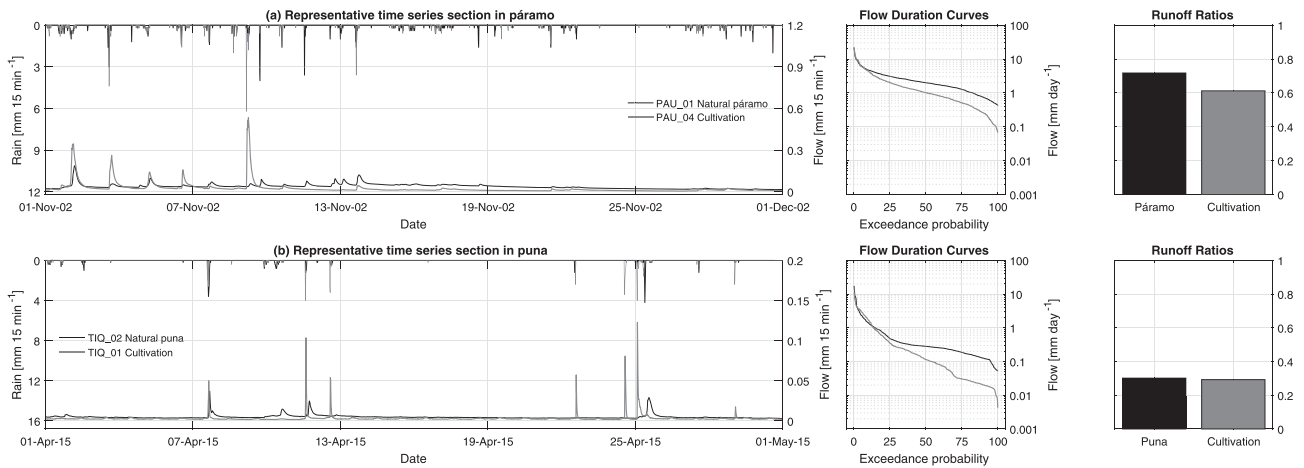


Figure 3. Impact of cultivation on the hydrological response of (a) páramo and (b) puna. The black lines represent the reference natural catchments and the grey lines their pairs. The high-resolution 30-day time series sections present comparable precipitation events and their correspondent streamflow responses. The flow duration curves and annual water yield are aggregated over the complete catchment monitored periods

60% lower in the cultivated catchments of both biomes, which may indicate a flashier streamflow regime under cultivation.

The impacts of agriculture on water yield are more difficult to identify, with only a slightly lower discharge in both biomes. After correction for rainfall volume differences, water yield in the natural and cultivated páramo differ in 142 mm year^{-1} (RR: 0.75 vs 0.66) but only 8 mm year^{-1} in puna (RR: 0.33 vs 0.28). However,

on average, such differences still lie within the broad range of natural catchments.

Afforestation. Figure 4 shows that the flow regime drastically changes under afforestation, reducing the entire flow distribution but increasing the steepness of the FDC. High and mean daily flows in afforested catchments are approximately four times lower, whilst low flows are even seven times lower (up to 10 times in

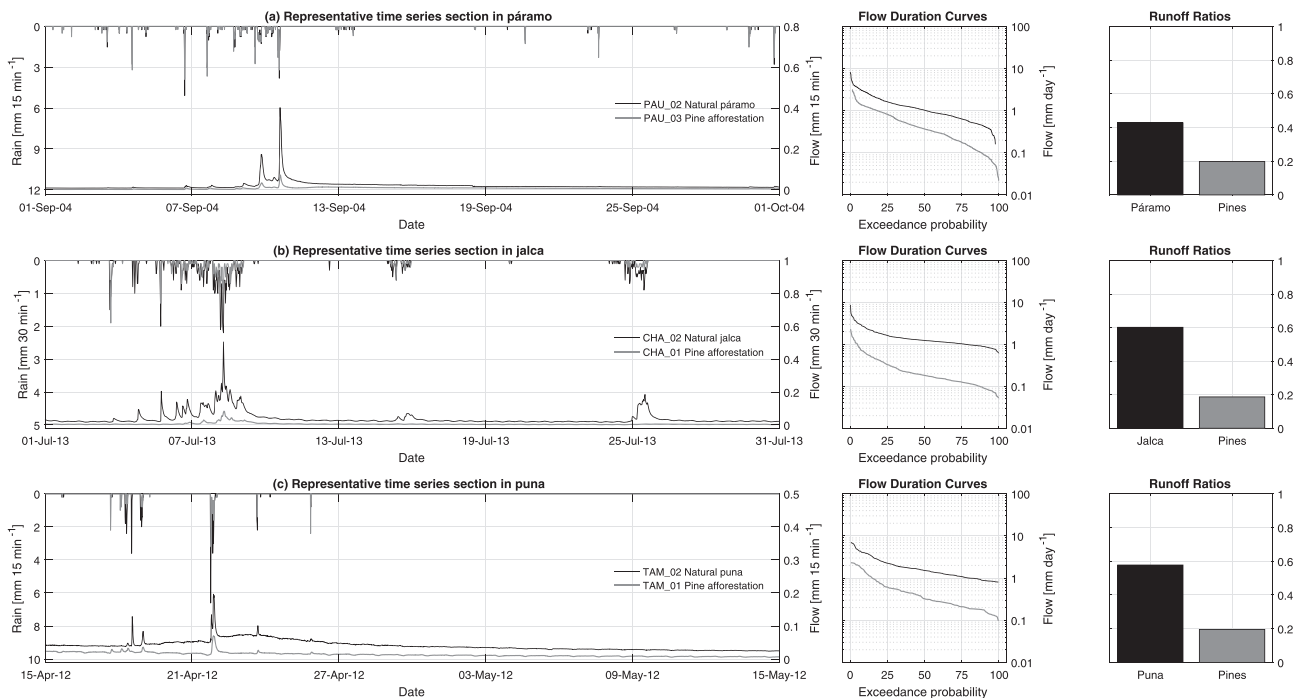


Figure 4. Impact of pine afforestation on the hydrological response of (a) páramo, (b) jalca and (c) puna. The black lines represent the reference natural catchments and the grey lines their pairs. The high-resolution 30-day time series sections present comparable precipitation events and their correspondent streamflow responses. The flow duration curves and annual water yield are aggregated over the complete catchment monitored periods

the jalca). This results consistently in a much lower water yield under afforestation compared with their neighbouring natural catchments. Corrected discharges differ by 250 mm year^{-1} (RR: 0.43 vs 0.20) in the páramo, 386 mm year^{-1} (RR: 0.60 vs 0.19) in the jalca and up to 536 mm year^{-1} (RR: 0.58 vs 0.20) in the puna.

Additionally, although the occurrence of sustained precipitation events increases streamflow in natural watersheds, this response is virtually absent in the afforested catchments. At the same time, we also find that QVAR is 50% higher under afforestation than under natural grasslands, reflecting a relatively higher variability in daily flows overall. Furthermore, whereas DLQ75 is slightly lower in the afforested catchments, suggesting an improvement in hydrological regulation, DHQ25 is twice as high in the afforested páramo and jalca but only half in the afforested puna.

Grazing. The impacts of grazing are more difficult to identify on aggregated statistics. Under low-intensity grazing in two páramo catchments with deep soils located in northwestern Ecuador (LLO_01 and LLO_02, Figure 5), the water yield is 115 mm year^{-1} (RR: 0.10) and 144 mm year^{-1} (RR: 0.13), respectively, and both present a very horizontal FDC profile (R2FDC > -0.60). Similarly, the corrected difference in water yield between a pristine páramo watershed (PIU_01) and its

neighbouring grazed pair (PIU_02) is only 28 mm year^{-1} (RR: 0.66 vs 0.65), and their overall flow distributions seem unaffected (R2FDC: -1.30 on average, Figure 5). Therefore, the major and more severe impacts of grazing are observed on the hydrological regulation of catchments with high-density livestock, which produce much faster and higher peaks as well as more rapid flow recessions than the highly buffered natural páramo.

Similar effects are observed between a natural puna (HUA_01) and its pair under low-density grazing (HUA_02) (Figure 6). The FDC profiles are similar, with only a slightly steeper FDC slope (R2FDC: -2.22) under low-density livestock grazing compared with the natural catchment (R2FDC: -2.06). Flow magnitudes are different by 28% on average, which is mainly expressed in the low flows (up to 50%). Also here, the flashier response of the grazed catchment is only recognizable in the high-resolution time series. The corrected discharge is slightly more affected, differing in 178 mm year^{-1} (RR: 0.70 vs 0.56).

However, the vast majority of puna highlands are overgrazed and exhibit visibly flashy hydrological responses similar to those of PIU_07 and HMT catchments (Figure 6). During rainfall events, flows are considerably unstable, with frequent peaks above $1001 \text{ s}^{-1} \text{ km}^{-2}$, quickly dropping to low flows below $11 \text{ s}^{-1} \text{ km}^{-2}$ in a time span of a few days. This flow

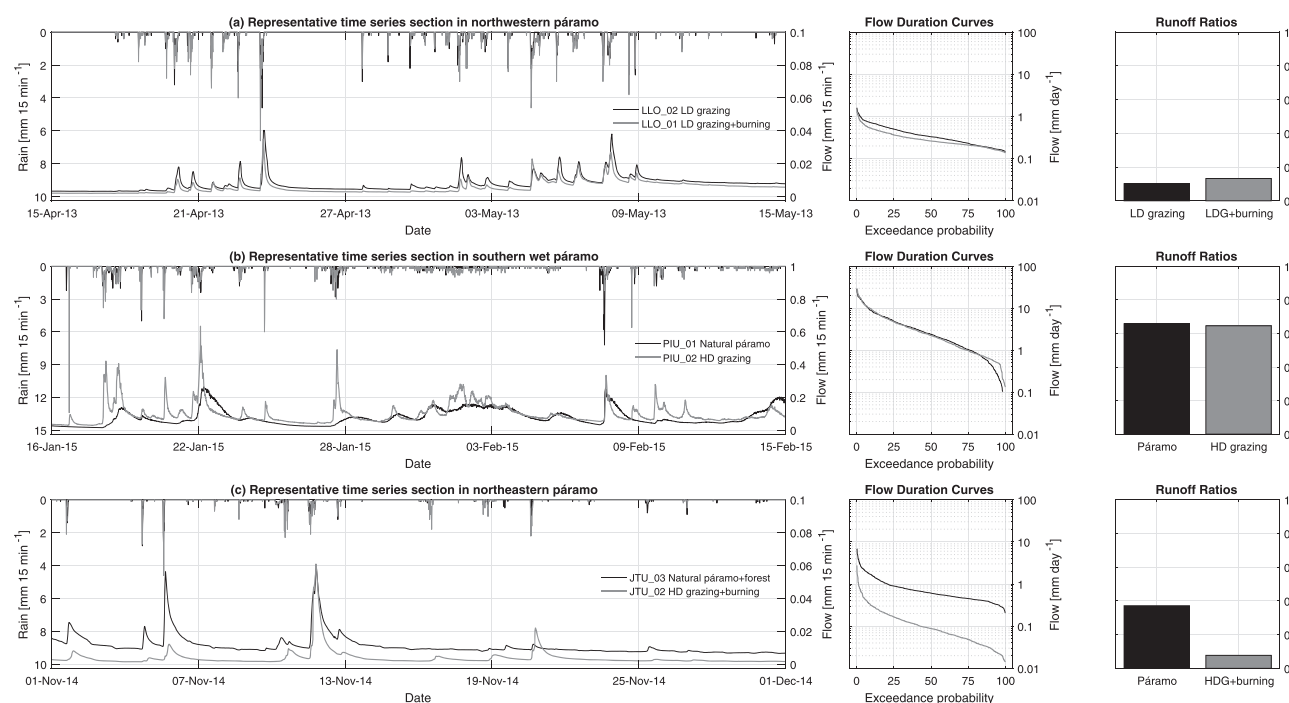


Figure 5. Impact of livestock grazing on the hydrological response of páramo under (a) low and (b) high animal density and (c) with respect to a neighbouring catchment with forest cover. The black lines represent the reference natural catchments and the grey lines their pairs. The high-resolution 30-day time series sections present comparable precipitation events and their correspondent streamflow responses. The flow duration curves and annual water yield are aggregated over the complete catchment monitored periods

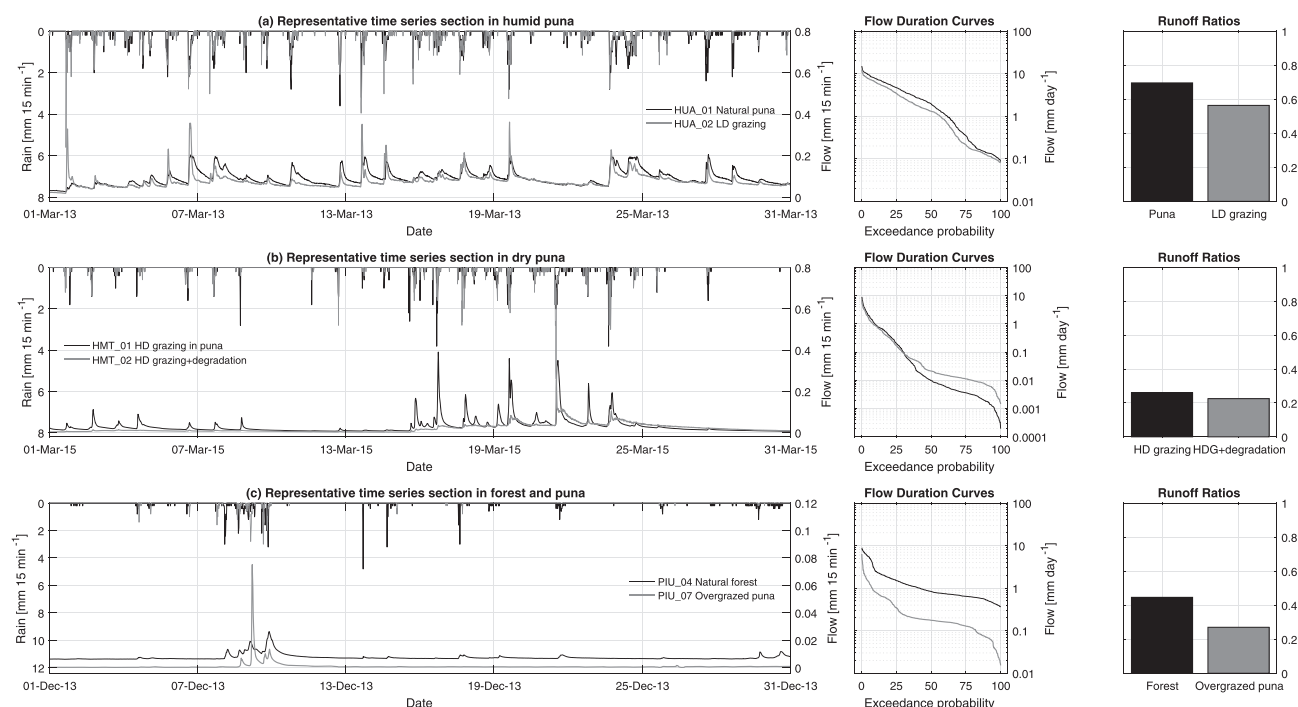


Figure 6. Impact of livestock grazing on the hydrological response of puna under (a) low and (b) high animal density and (c) with respect to a neighbouring forest. The black lines represent the reference natural catchments and the grey lines their pairs. The high-resolution 30-day time series sections present comparable precipitation events and their correspondent streamflow responses. The flow duration curves and annual water yield are aggregated over the complete catchment monitored periods

magnitude variation is even more critical considering the high seasonality of precipitation in the puna highlands. For example, in HMT_01, the ratio Q_{max}/Q_{min} reached up to 46 250 during the monitored period, and its FDC is very steep ($R2FDC: -3.33$). Although the flow regime of HMT_02 appears stable during the time series section shown, field observations suggest that water from rainfall events does not easily infiltrate in the soil and is evaporated from the surface before reaching the catchment stream. The water yield in these overgrazed punas is considerably low, at 173 mm year^{-1} ($RR=0.27$) in PIU_07, 168 mm year^{-1} ($RR=0.26$) in HMT_01 and 138 mm year^{-1} ($RR=0.23$) in HMT_02.

Lastly, contrasting the hydrological response of overgrazed grasslands (JTU_02 and PIU_07) with nearby conserved catchments under partial forest cover (JTU_03 and PIU_04) shows average and high flow magnitudes up to six times lower and low flows up to 14 times lower (Figures 5 and 6). Although QVAR and DLQ75 are larger in the affected grasslands than in their counterparts, R2FDC is very low in all cases (> -1.12) and DHQ25 is shorter. An extraordinary regulation capacity of the natural catchments is observed at the high-resolution time series, reducing and delaying peak flows when rainfall occurs and sustaining large baseflows in the absence of precipitation. In contrast, the overgrazed catchments rapidly react to rainfall events pushing flow

to high peaks and plummeting again to almost completely dry baseflows.

DISCUSSION

The natural hydrological regime

All catchments share the predominance of low precipitation intensities that is characteristic for high Andean regions (Buytaert *et al.*, 2006a; Padrón *et al.*, 2015). Mean intensities for a 1-h interval are between 0.5 to 2 mm h^{-1} . This is below the infiltration capacity of the soils, which typically ranges between 10 and 20 mm h^{-1} with maxima up to 70 mm h^{-1} in páramo (Buytaert *et al.*, 2005; Crespo *et al.*, 2011; Carlos *et al.*, 2014). The occurrence of low intensities has been further confirmed by a recent study using an LPM disdrometer in a páramo catchment of southwestern Ecuador where 50% of annual rainfall occurs at intensities lower than 2 mm h^{-1} (Padrón *et al.*, 2015).

As a result, the natural hydrological regime is generally a baseflow-dominated response, with the conspicuous absence of sharp peaks in the extreme high and low ends of the FDCs (Figure 2). This has also been observed by Buytaert *et al.* (2006a) and Crespo *et al.* (2011) for wet páramo regions in southern Ecuador. However, when such peaks are present in the section of high flows, they

might represent the occasions when saturated overland flow occurs (Buytaert *et al.*, 2007). Seasonality is clearly an important driver of the hydrological regime in puna, which contrasts strongly with the more perennially wet páramo regimes that sustain higher flows during the shorter periods without precipitation.

Although natural RRs range from 0.30 to 0.72, Padrón *et al.* (2015) argued that tipping-bucket rain gauges underestimate real rainfall by about 15% when precipitation occurs as very low-intensity events, which may result in an overestimation of the RR. Nevertheless, the overall results contrast with the local mislead idea that punas are naturally less efficient than páramo catchments in terms of water yield, while our results show that the perceived smaller runoff production is mostly a result of their lower precipitation input and higher seasonality. Further insights of seasonality effects are indicated by duration indices in Table II. In natural catchments, DLQ75 and DHQ25 are the lowest in jalca and largest in puna, contrasting with the buffered behaviour of páramo catchments.

From our results, it is clear that, apart from the precipitation regime, diverse factors, such as vegetation types, soils, geology and topography, increase the heterogeneity of catchment hydrological responses. For instance, the particularly low water yield of JTU and LLO ($RR < 0.37$) might be related to subsurface and groundwater preferential flow paths probably enhanced by important soil infiltration in their deeper soil profiles (Buytaert *et al.*, 2006a). These results may support previous investigations of groundwater flow in the wet páramos of northern Ecuador (Favier *et al.*, 2008), although this is not common in the other studied catchments and requires more specific investigation.

The impacts of land use change

The impact of cultivation on the catchments' hydrological regulation capacity tends to be larger than on water yield. The increase in the steepness of FDCs in both cultivated páramo and puna are consistent to the loss in regulation of around 40% reported by Buytaert *et al.* (2007) and Crespo *et al.* (2010). Buytaert *et al.* (2004, 2005, 2007) have attributed this effect to a shift from base to peak flows because of the increase in hydraulic conductivity of the soils under cultivation and especially the introduction of artificial drains and mechanisms that enhance drainage in cultivated catchments. Additionally, soil exposure to radiation and drying effects of wind is known to induce hydrophobicity (Buytaert *et al.*, 2002). Other studies on cultivated plots in Venezuelan dry páramos (Sarmiento, 2000) and Colombian wet páramos (Díaz and Paz, 2002, as cited by Célleri, 2010) reported reductions in the water storage

capacity of soils and important evapotranspiration rates controlling the water balance.

The effects may intensify when cultivated lands are abandoned after some crop cycles becoming susceptible to degradation processes. The rainfall-runoff response in catchments with degraded soils is also often quicker and higher than in natural ecosystems, although the difference is highly variable. For example, using simulated rainfall plots with different vegetation cover in wet páramo, Molina *et al.* (2007) reported surface runoff between 4% and 100%, with an average of 47%, which is much higher than in arable land or natural ecosystems. There are no reports of paired catchment experiments in degraded lands in this region, but long-term discharge records in other degraded areas give evidence of a baseflow increase following large-scale rehabilitation (Beck *et al.*, 2013). Furthermore, field observations report a substantial increase in sediment production affecting water quality that is generally rare in natural Andean grasslands (Crespo *et al.*, 2010).

Planting of exotic tree species for this area such as pine affects considerably the soil water retention, water yield and hydrological response. The severe reduction in discharges after pine afforestation in natural Andean grasslands is attributed to the higher water evapotranspiration of trees and interception in the canopy. This is coherent with other studies that report regions under moderate to high rainfall patterns (see e.g. a thorough review of comparable studies cited in Farley *et al.* (2005) and Buytaert *et al.* (2007)). The particular magnitude of these impacts in each biome may depend on the local precipitation amounts and higher potential evapotranspiration favouring for larger water consumption (Table II). However, the similar trends in the observed effects across biomes clearly reflect the expected response of Andean grasslands under intensive afforestation interventions (e.g. 1000 stems ha^{-1} , Buytaert *et al.*, 2007).

Similarly, the buffered discharge response of all afforested catchments shown in Figure 4 is consistent with the absence of peak flows reported by Crespo *et al.* (2010, 2011). Such a difference with respect to more rapidly responding natural catchments is likely produced by an enhanced soil infiltration caused by tree roots. Additionally, according to Crespo *et al.* (2010), soil water content is lower in pine plantations near the root zone, which produces an accelerated organic material decomposition altering the normal catchment regulation feature. Furthermore, low flows may reduce in up to 66% (Buytaert *et al.*, 2007), but the way in which water moves through the ecosystem remains unchanged (Crespo *et al.*, 2011). The possible potential for flooding control of pine plantations is still under debate (Célleri, 2010).

We are not aware of specific studies about the effects of eucalyptus plantations on Andean hydrology, but similar

effects can be expected. In a global assessment, Farley *et al.* (2005) found that eucalypts caused more severe impacts than other tree species in afforested grasslands and especially on low flows. Similarly, Inbar and Llerena (2000) indicated that a 10-year-old afforested puna in central Peru generated more surface runoff and sediment yield than any other vegetated area in their studies. Additionally, the apparent role in preventing soil erosion is lower compared with ancient terraces (Inbar and Llerena, 2004; Harden, 2006).

Although the impacts of afforestation in natural catchments are mostly negative, the improvement in soil infiltration could be tailored extensively and leveraged to recover degraded lands by identifying zones with potential to control and avoid strong erosive processes. The general agreement is that dry-season flow in forested catchments depends on a 'trade-off' between soil infiltration enhanced by forest roots and soil water storage consumed by vegetation (Beck *et al.*, 2013).

The impacts of grazing depend on the animal density as much as on the catchment physiographic and soil characteristics. The flashy response of grazed catchments observed in the high-resolution time series is mainly attributed to an aggressive soil compaction as reported by Díaz and Paz (2002); Quichimbo (2008), and Crespo *et al.* (2010), affecting hydrological regulation. As cited by Célleri (2010), Quichimbo (2008) observed an increase in soil bulk density from 0.40 to 0.64 g cm⁻³ in Ecuadorian wet páramo, while Díaz and Paz (2002) found increases from 0.20 to 0.41 g cm⁻³ under low-livestock density (<0.1 head ha⁻¹) and to 0.86 g cm⁻³ under high-livestock density (>0.5 head ha⁻¹) in Colombian wet páramo. These authors have also reported diminished soil hydraulic conductivities, for example, changing from 61 and 73 mm h⁻¹ to 15 and 18 mm h⁻¹ under overgrazing.

The difficulty of identifying changes in water yield and catchment regulation using aggregated indices and FDCs has happened in previous studies. Although Crespo *et al.* (2010) reported an increase in soil bulk density up to 0.99 g cm⁻³, water yield was around 15% lower and evapotranspiration 24% higher in grazed lands than in the natural wet páramo of southern Ecuador. Based on a comparison of FDCs, they reported that cattle grazing with annual burning did not seem to affect the hydrological response, mainly because of the low animal density, while water yield was considered to be reduced slightly. Later, Crespo *et al.* (2011) recognized that the effects of grazing compared with natural ecosystems are unnoticeable in the shape of FDCs.

Lastly, the highly seasonal and small precipitation volumes in the punas, their thinner soil profiles (Carlos *et al.*, 2014) and their steeper topography deepen the impacts of grazing even when animal density is low. This amplifies the reduction of vegetation cover and the loss of

organic soil, which results in a substantial detriment of catchments' hydrological regulation. Livestock grazing also affects water quality by increasing the suspended sediments and coliform concentrations (Roa-García and Brown, 2009). This is particularly relevant when water is used downstream, for instance, for human consumption with minimum treatment. Overall, livestock overgrazing, especially in puna, may be considered as the most impacting land use in the Andean grasslands.

CONCLUSIONS

Despite the importance of Andean ecosystems as major water sources, there is still a considerable lack of knowledge about their hydrology, which is exacerbated by the high spatial and temporal gradients and variability in their geographic and hydrometeorological conditions. The absence of long-term, high-resolution, good-quality monitoring data can be overcome by information generated from novel polycentric and participatory monitoring schemes, such as iMHEA. This paper aimed at the use of such data to characterize regionally the natural hydrological regime of Andean catchments and the impacts of land use on their responses.

The analysis reveals very diverse climatic characteristics generating a wide range of responses within natural catchments. The wet páramo and jalca of Ecuador and northern Peru are generally humid, perennially wet or low seasonal and present a highly buffered hydrological response. On the other hand, the drier puna highlands of southern Peru and Bolivia are highly seasonal, with greater rainfall variability controlling their hydrological behaviour. However, similar characteristics are associated with the three biomes under natural conditions: a baseflow-dominated response and a large water yield.

Correspondingly, the impacts of land use are highly diverse, and the magnitude of those changes should be considered together with the original and the replacement vegetation, soil properties and changes therein, as well as the governing climate pattern. We find regionally consistent trends in such impacts, which result most commonly in an increase of streamflow variability and a decrease in catchment regulation capacity and water yield, irrespective of the hydrological properties of the original biome. On the one hand, cultivation and afforestation with exotic species clearly affect the entire range of discharges, and low flows in particular. On the other hand, the impacts of livestock grazing depend on the animal density and catchment physiographic and soil characteristics. Although they may pass unnoticeable in the flow distribution overall, they have the largest impact on the catchment hydrological regulation, which is observable using high-resolution time series.

Although this paper focused on surface water availability, LUCC also affects other processes, such as nutrient fluxes or water quality, and interacts with subsurface hydrological drivers. The latest efforts of iMHEA aim to address some of these issues, such as characterizing erosion controls and sediment transport, monitoring key water quality components for downstream users and tracing subsurface and groundwater flow pathways.

AUTHOR CONTRIBUTIONS

BOT and WB led the writing and development of the paper. RC, PC, MV, CL, LA and MG contributed to the description and analysis of the case studies. BOT, WB, BDB, RC, PC and LA led the conception and design of the monitoring network. BOT, MV, MG, JG, PF, DO, PV, GR and SA set up the experimental catchments and collected and curated the data. BOT processed the data. All the authors contributed to the development of ideas and to the reflection process. We also acknowledge fieldwork support and input by Katya Pérez, Javier Antiporta, Juan Diego Bardales and Lesly Barriga from CONDESAN.

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