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 link 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.

1. INTRODUCTION

1.1. Andean ecosystem degradation and water resources

The tropical Andes deliver 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 are unsuccessful efforts of local authorities to replicate a positive experience from Cajamarca, Peru, where degraded lands were restored mostly using *Pinus patula* (~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 characterised 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; Garzon, 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).

1.2. 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 to 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 0º 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}, 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 minimises 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 to 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 regionalise 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 generalisation 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.

2. METHODOLOGY

2.1. 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 (Célleri et al., 2010; Buytaert et al., 2014). The collaborative nature of iMHEA allows for (i) standardising 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 km^2, are located between 0º and 17º South and cover an elevation range from 2682 to 4840 m altitude. Sites are rural with no urbanisation 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.

2.2. 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 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 2 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; Célleri et al., 2007). Table II shows the different monitoring periods of the catchments.

2.3. Data analysis

A preliminary survey of catchment physical features was done before selection and to consider their influence on the hydrological response. Contour lines at 40 m vertical resolution were available for the characterisation 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 Busscher, 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 normalised between 0 (non-seasonal) and 1 (extremely seasonal). Correlations between the 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 to their probability of occurrence, information about when or for how long such flows happen is absent. Therefore, the average duration of hydrographs above or below a threshold help 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 visualisation purposes highlighting representative effects of land use change on catchment regulation that are consistently observed in the complete analysis periods.

3. RESULTS

3.1. 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 (2000) and Célleri et al. (2007). In the case of the páramo in Piura, this is characterised 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, DAYP0<0.30), which means that precipitation is well distributed throughout the year with high intensity events occurring approximately every three 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, DAYP0<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, DAYP0>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, DAYP0<0.26, PVAR<1.61), yet seasonality is larger and precipitation during dry months (*JJA*) 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~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 runoff ratios (RR) 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.

3.2. The impacts of land use change

3.2.1. 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 5. QVAR is high in both the natural and cultivated puna, yet larger when the páramo is intervened. Additionally, DLQ75 and DHQ25 are about 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.

3.2.2. 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 4 times lower, whilst low flows are even 7 times lower (up to 10 times in the jalca). This results consistently in a much lower water yield under afforestation compared to their neighbouring natural catchments. Corrected discharges differ by 250 mm year^{-1} (RR: 0.43 vs 0.20) in the páramo, in 386 mm year^{-1} (RR: 0.60 vs 0.19) in the jalca, and up to in 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.

3.2.3. 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 to 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 recognisable 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 100 l s^{-1} km^{-2}, quickly dropping to low flows below 1 l s^{-1} km^{-2} in a time span of a few days. This flow magnitude variation is even more critical considering the high seasonality of precipitation in the puna highlands. For example, in HMT_01 the ratio Qmax/Qmin reached up to 46250 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 6 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 rocketing flow to high peaks and plummeting again to almost completely dry baseflows.

4. DISCUSSION

4.1. 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.

4.2. 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 due to 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 (Diaz 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 to ancient terraces (Harden, 2006; Inbar and Llerena, 2004).

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 Diaz 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 g cm^{-3} to 0.64 g cm^{-3} in Ecuadorian wet páramo, while Diaz and Paz (2002) found increases from 0.20 g cm^{-3} to 0.41 g cm^{-3} under low- (<0.1 head ha^{-1}) and to 0.86 g cm^{-3} under high- (>0.5 head ha^{-1}) livestock density in Colombian wet páramo. These authors have also reported diminished soil hydraulic conductivities, for example, changing from 61 mm h^{-1} and 73 mm h^{-1} to 15 mm h^{-1} 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) recognised that the effects of grazing compared to 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.

5. 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 characterise 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 to 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 affect other processes such as nutrient fluxes or water quality, and interact with subsurface hydrological drivers. The latest efforts of iMHEA aim to address some of these issues, such as characterising erosion controls and sediment transport, monitoring key water quality components for downstream users, and tracing subsurface and groundwater flow pathways.

6. 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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Figure Captions:

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.

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.

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.

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.

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.

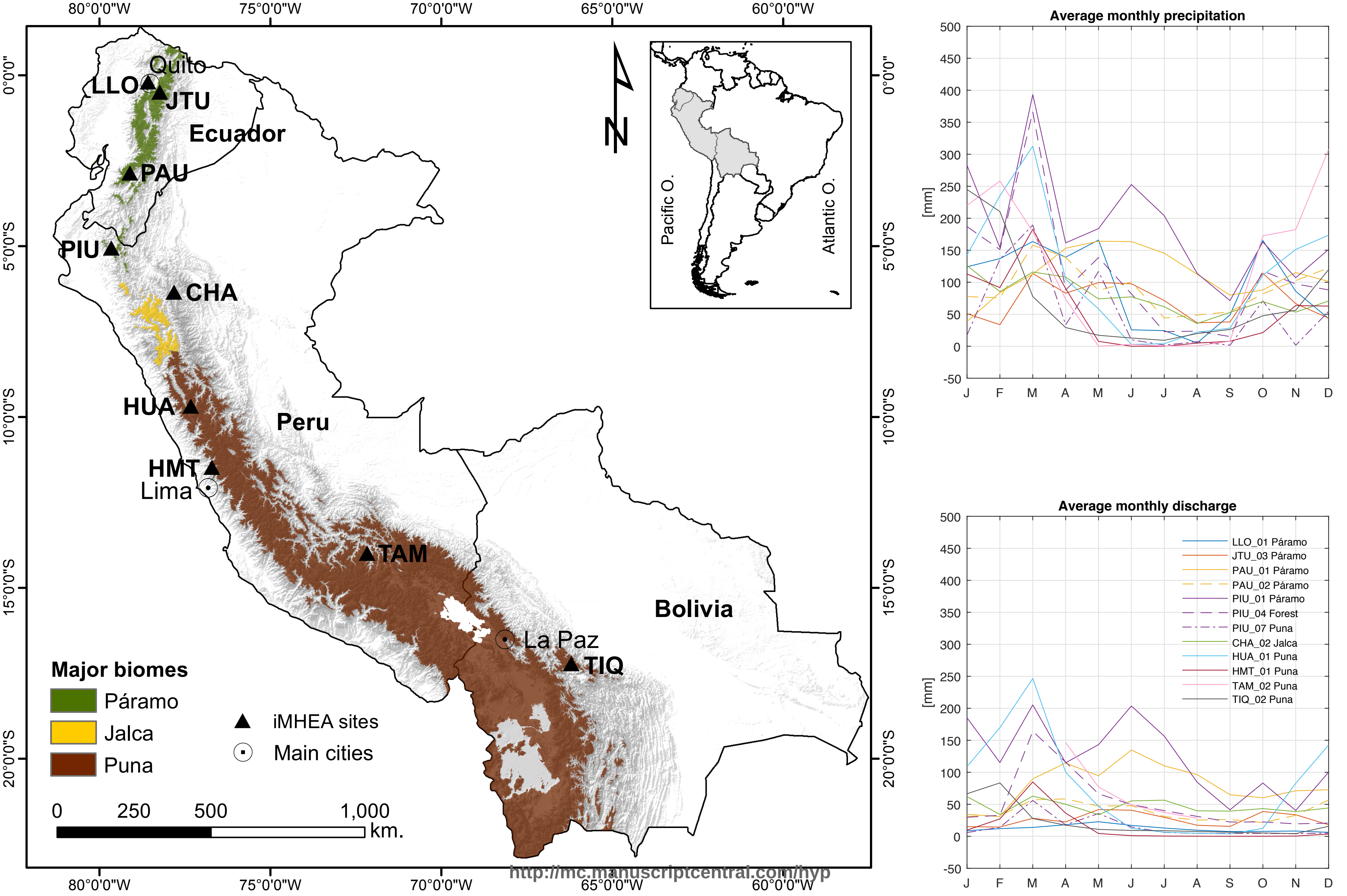
Figure 6: Impact of livestock grazing on the hydrological response of puna under (a) low and (b) high animal density, and (c) with respect to a neighbouring forest. The black lines represent the reference natural catchments and the grey lines their pairs. The high-resolution 30-day time series sections 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.

Table Captions:

Table I: Major physiographic properties of the studied catchments.

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

Table III: Definition of the hydrological indices analysed in the study.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Average monthly discharge
LLO_01 Páramo
JTU_03 Páramo
PAU_01 Páramo
PAU_02 Páramo
PIU_01 Páramo
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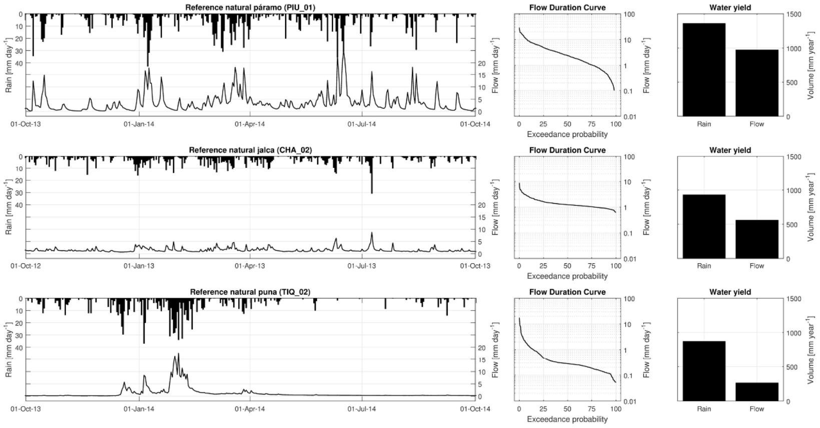
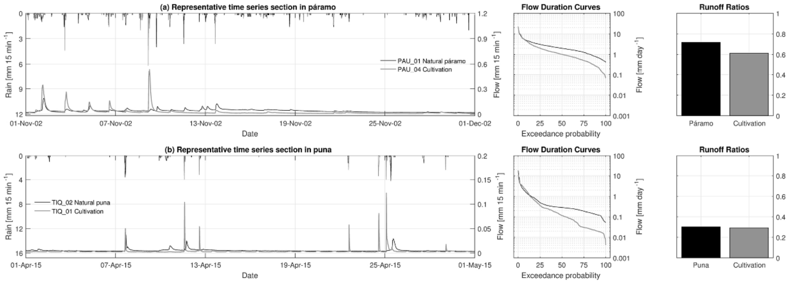
TIQ_02 Puna



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.

Figure 2

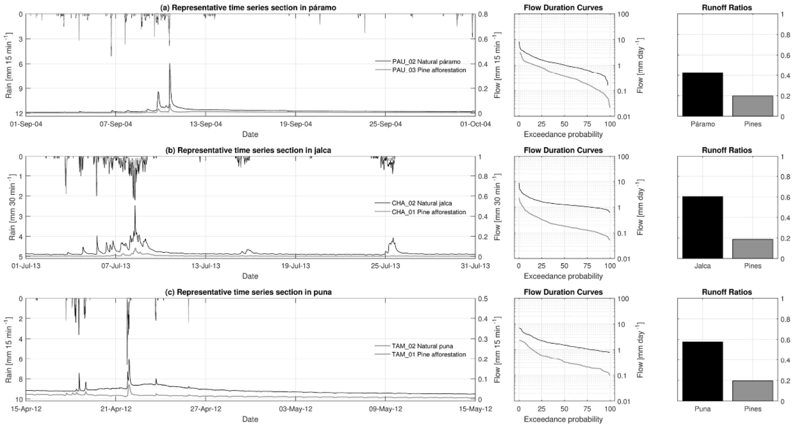
242x115mm (300 x 300 DPI)



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.

Figure 3

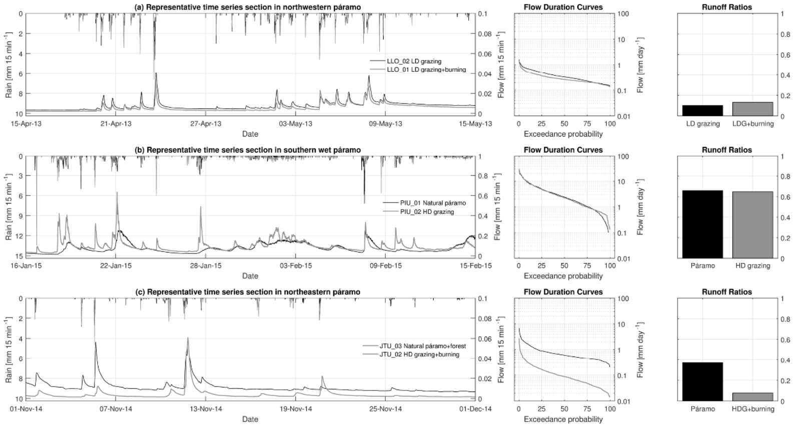
242x115mm (300 x 300 DPI)



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.

Figure 4

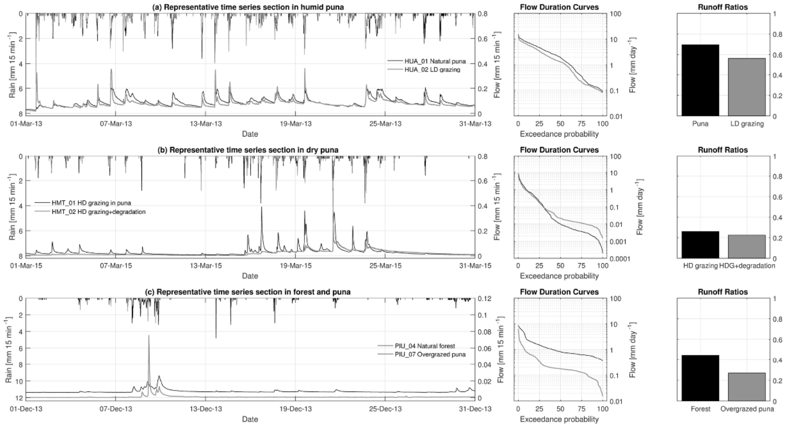
242x115mm (300 x 300 DPI)



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 5

242x115mm (300 x 300 DPI)



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.

Figure 6

242x115mm (300 x 300 DPI)

Table I: Major physiographic properties of the studied catchments.

Code Units	Ecosystem	Altitude [m]	Area [km^2]	Shape [1]	Slope [2]	Soils	Land–use [3]	Land–cover [4] [%]
				LLO Lloa				
LO_01	Páramo	3825–4700	1.79	SO	SU	Andosol	EG, B	TG(90), SH(10)
LO_02	Páramo	4088–4680	2.21	SO	U	Andosol, Histosol	EG, NF	TG(70), NF(10), WL(20)
				JTU Jatunhuaycu				
TU_01	Páramo	4075–4225	0.65	O	U	Andosol	IG	TG(100)
TU_02	Páramo	4085–4322	2.42	O	U	Andosol	IG	TG(100)
TU_03	Páramo	4144–4500	2.25	CO	U	Andosol, Histosol	N	TG(80), SH(20)
TU_04*	Páramo	3990–4530	16.05	SO	U	Andosol, Histosol	IG, N, R	TG(70), SH(10), WL(5), NR(15)
				PAU Paute				
AU_01	Páramo	3665–4100	2.63	CO	U	Andosol	N	TG(100)
AU_02	Páramo	2970–3810	1.00	O	SU	Andosol, Histosol	N, EG	TG(80), NF(20)
AU_03	Páramo	3245–3680	0.59	CO	SU	Andosol, Histosol	PF	TG(10), PF(90)
AU_04	Páramo	3560–3721	1.55	CO	U	Andosol	IG, CR	TG(70), CP(30)
				PIU Piura				
IU_01	Páramo	3112–3900	6.60	CO	U	Andosol, Histosol	N	TG(75), NF(15), L(10)
IU_02	Páramo	3245–3610	0.95	CO	SU	Andosol, Histosol	IG	TG(75), NR(15), L(10)
IU_03	Páramo	3425–3860	1.31	CO	SU	Andosol, Histosol	IG	TG(90), L(10)
IU_04	Forest	2682–3408	2.32	O	SU	Andosol, Cambisol	NF	G(20), NF(80)
IU_07	Dry puna	3110–3660	7.80	O	U	Andosol	IG	TG(45), SH(20), CP(35)
				CHA Chachapoyas				
HA_01	Jalca	2940–3200	0.95	O	U	Andosol, Inceptisol	PF	TG(20), PF(80)
HA_02	Jalca	3000–3450	1.63	O	U	Andosol, Inceptisol	N	TG(90), NF(10)
				HUA Huaraz				
UA_01	Humid puna	4280–4840	4.22	CO	U	Andosol, Histosol	N, EG	TG(60), NR(25), WL(15)
UA_02	Humid puna	4235–4725	2.38	O	U	Andosol, Histosol	EG	TG(55), NR(30), WL(15)
				HMT Huamantanga				
MT_01	Dry puna	4025–4542	2.09	O	U	Leptosol, Inceptisol	IG	G(75), NR(15), SH(10)
MT_02	Dry puna	3988–4532	1.69	O	SU	Leptosol, Inceptisol	IG	G(85), NR(10), SH(5)
				TAM Tambobamba				
AM_01	Humid puna	3835–4026	0.82	O	U	Leptosol, Inceptisol	IG, PF	G(80), PF(20)
AM_02	Humid puna	3650–4360	1.67	CO	SU	Leptosol, Inceptisol	N, NF	G(60), NF(40)
				TIQ Tiquipaya				
IQ_01	Humid puna	4140–4353	0.69	O	U	Leptosol, Inceptisol	IG, CR	G(70), NR(30)
IQ_02	Humid puna	4182–4489	1.73	SO	U	Leptosol, Inceptisol	N	TG(90), NR(5), WL(5)

otes

1] SO: Stretched oval; O: Oval; CO: Circular to oval.

2] U: Uneven; SU: Strongly uneven; S: Steep; VS: Very steep.

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

4] 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.

able II: Water balance and hydrometeorological features of the studied catchments.

de its	Monitoring period	Rainfall [mm year^{-1}]	Discharge [mm year^{-1}]	ET$_0$ [mm year^{-1}]	SINDX [-]	DAYP0 [-]	PVAR [mm mm^{-1}]	RR [-]	QVAR [mm mm^{-1}]	R2FDC [-]	IRH [-]	DLQ75 [day]	DHQ25 [day]
LLO Lloa													
O_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
O_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													
U_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
U_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
U_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
U_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													
U_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
U_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
U_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
U_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													
U_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
U_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
U_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
U_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
U_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													
A_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
A_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													
A_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
A_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													
IT_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
IT_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													
M_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
M_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													
Q_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
Q_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

tes

eference catchments. Average monthly precipitation and discharge for these are plotted in Figure 1.

e Table III for the definitions of the analysed hydrological indices.

able III: Definition of the hydrological indices analysed in the study.

breviation	Reference formula	Units	Definition
			Indices related to meteorological features
0	$0.0023(T_{mean}+17.8)(T_{max}-T_{min})^{0.5}Ra$	[mm year^{-1}]	Reference evapotranspiration based on monthly temperature estimates only.
NDX	$(1/P_{year})(\Sigma\|P_{month}-P_{year}\|/12)(6/11)$	[-]	Seasonality index scaled between 0 (non-seasonal, all months with equal rainfall) to 1 (extremely seasonal, all annual ra occurring during one month).
YP0	$D_{P<RGres}/D_{total}$	[-]	Percentage of days with zero precipitation (i.e. not registered by the rain gauge resolution) with respect to the total numb days over the monitored period.
AR	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
	Q_{year}/P_{year}	[-]	Ratio between average discharge volume and average rainfall volume over the monitored period.
AR	σ_Q/Q_{mean}	[mm mm^{-1}]	Coefficient of variation in daily flows over the monitored period, standard deviation divided by mean.
FDC	$(\log_{10}(Q_{66})-\log_{10}(Q_{33}))/(0.66-0.33)$	[-]	Slope in the middle third of the flow duration curve in logarithmic scale.
H	$\Sigma(Q_{Q<Q50})/\Sigma(Q)$	[-]	Volume below the 50th flow percentile (Q50) in the flow duration curve divided by total volume.
Q75	$\Sigma(D_{Q<Q25})/N_{Q<Q25}$	[day]	Average duration of flows below the 25th flow percentile (Q75) over the monitored period.
Q25	$\Sigma(D_{Q>Q75})/N_{Q>Q75}$	[day]	Average duration of flows above the 75th flow percentile (Q25) over the monitored period.