A concerted research effort to advance the hydrological understanding of Tropical Páramos

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Abstract

The páramos, a neotropical alpine grassland-peatland dominated biome of the northern Andes and Central America, play an essential role in regional and global cycles of water, carbon, and nutrients. They act as water towers, delivering water and ecosystem services mainly from the continental water divide at the Andean highland down to the Pacific and Amazon regions. The anthropogenic influence in form of the climate crisis exerts enormous pressures on these identified "hotspot" ecosystems and increases the vulnerability of nearby populations undermining the socio-economic and human development. Further, increasing pressures reduce the resilience to face climate shocks, and dramatically alters the hydro-climatic regime and shifts the páramos from long-term carbon sinks towards carbon sources. Despite their importance and vulnerability, only three decades ago, páramos, were globally among the least studied ecosystems. However, researchers have since identified them as ideal targets for solving water scarcity issues and to offset carbon emissions. Increasing awareness of the need for hydrological evidence to guide sustainable management of the páramos prompted action for generating data and to fill long-standing knowledge gaps. This has led to a remarkably successful community-research-policy effort to generate this knowledge. The combination of well-established and innovative approaches was used to data collection, processing and knowledge extraction. In this review, we provide a short overview of the state of knowledge of the hydrometeorology, flux dynamics, anthropogenic and the influence of extreme events in the regional páramos. Then, we present emerging technologies for hydrology and water resources research and management applied to páramos. Lastly, we discuss how converging science and policy efforts have leveraged traditional and new observational techniques to generate an evidence base that can support the sustainable management of the páramos. We conclude that this co-evolution of science policy was able to cover different spatial and temporal scales. Finally, we outline future research directions to showcase how sustainable long-term data collection can be sustained for the responsible development of páramo water towers.

Introduction

The páramos (Figure 1) play an important role in regional and global cycles of water, carbon, and nutrients, which has led numerous researchers to focus their efforts on understanding their eco-hydrology and meteorology at various spatial-temporal scales. The páramos are a collection of perennially humid, neotropical alpine ecosystems identified as hot spots for climate change (Bradley et al., 2006; Castaño Uribe, 2002; Dangles et al., 2017). These ecosystems are characterized by a mountainous topography, low temperature and highly developed soils with large water-holding capacities (Buytaert et al., 2006b). Land cover in the páramos is dominated by short vegetation grasslands with scarce patches of woodlands (e.g., *Polylepis sp.*) and intermittent wetlands and ponds (Figure 2). Their hydrology is undergoing fast rates of environmental and human-induced changes (Buytaert et al., 2006b, 2011).These changes together with local catchment heterogeneity, large variability of hydrologic conditions and extensive data-scarcity, has historically complicated the conceptualization of high variable involved processes (Bendix, 2000; Célleri and Feyen, 2009; Correa et al., 2018; Riveros-Iregui et al., 2018). Therefore Riveros-Iregui et al., (2018), call for prompt hydrological assessments across Latin America. The complex topographical setting of the Andean mountains and the generally impermeable nature of the underlying geology complicate groundwater abstraction. Therefore, the tropical Andean region were high density cities are located (e.g., Bogota, Quito, Cuenca and Lima), mostly depends on surface and shallow subsurface water sources (Buytaert et al., 2006b; Correa et al., 2017). Previous led to concern about the potential impact of changes in land use and land cover on the hydrologic response of river basins, and the consequences for water availability and quality (Ochoa-Tocachi et al., 2016a; Tovar et al., 2013b). For instance, several catchment interventions have not been suitably assessed, resulting in negative hydrologic impacts at local to regional scale (Buytaert et al., 2007a; Ochoa-Tocachi et al., 2016b), and severe ecosystem and biodiversity degradation (Hofstede et al., 2002). This, at the cost of risking nature as a subject of rights and the socio-economic and human development of a vulnerable population, critical points described in the Sustainable Development Goals (SDGs). Scientific and public awareness of these impacts started to gain momentum around the turn of the century, as a result of some seminal research papers and policy publications (e.g., Hofstede, 1995; Mena et al., 2001; Podwojewski et al., 2002). This has triggered a rapidly increasing community of research and practice around paramos hydrology, which has applied a variety of innovative techniques, intensive monitoring and model-based regionalization to improve understanding of hydrological processes and the effect of external pressures. In the newest research, field-experimental based studies started assessing previously ignored variables such as precipitation structure (Orellana-Alvear et al., 2017; Padron et al., 2015) and clarifying less known processes such as interception (Ochoa-Sanchez et al., 2018), evapotranspiration (Carrillo-Rojas et al., 2019; Cordova et al., 2015; Ramon-Reinozo et al., 2019), carbon and nutrient concentrations in soil and vegetation (Minaya et al., 2016c; Pena-Quemba et al., 2016; Pesantez et al., 2018; Riveros-Iregui et al., 2018). The use of conservative and bio-reactive tracers opened a new dimension and allowed tracking fluxes, storage and mixing, and assisted in defining the spatial-temporal dynamics of runoff sources and flow pathways (Correa et al., 2017; Esquivel-Hernandez et al., 2018; Minaya et al., 2016b; Mosquera et al., 2016a; Riveros-Iregui et al., 2018). Hydrologic model applications start reproducing more accurately the observed streamflow, year-round and in extreme (droughts and floods) conditions (Aviles et al., 2015, 2016; Mora et al., 2014; Munoz et al., 2018b). In addition, researchers even started to evaluate data uncertainties related to the location and technical properties of equipment in the increasingly denser monitoring networks (Guallpa, 2013; Munoz et al., 2016; Sucozhanay and Celleri, 2018). Researchers have evaluated land-use change scenarios and their impact on the hydrological system to help decision-makers construct sustainable strategies and predict potential economic benefits for service providers (Bremer et al., 2019; Flores-Lopez et al., 2016; Kroeger et al., 2019). Figure 1. Figure 2.

Current state of knowledge

The paramos biome

The paramos form a tropical alpine grassland biome located mostly in the Northern Andes (between 11degN and 8degS) and parts of Central America (Figure 1), above the tropical mountain forest biomes (3000 m a.s.l.) and below the cryosphere (5000 m a.s.l.) (Josse et al., 2009; Luteyn, 1999). Their delineation is not always clear because of deforestation and increasing encroachment of the lower paramos for agricultural purposes (Lopez Sandoval and Valdez, 2015; Tovar et al., 2013a) and ongoing influence of global-warming that induced glacier retreat (Morueta-Holme et al., 2015). R. G. M. Hofstede et al., (2003) estimated that the paramos occupy an area of around 35000 km^2 of the tropical Andes. Geographically, the largest extent of paramos occurs in Colombia and Ecuador and smaller, disconnected patches exist in the Andes of Venezuela (Paramos de Merida) and Costa Rica (Cerro Chirripo). The southern limit of the paramos is known as the Jalca grasslands (Sanchez-Vega and Dillon, 2006; Tovar et al., 2012), a transition vegetation to the Puna biome of the central and south Peruvian Andes (Cuesta et al., 2017; Ochoa-Tocachi et al., 2016a). However, ecosystems with very similar biogeographical and hydrometeorological characteristics occur as far south as Bolivia, where they are known as the Paramo Yungeno (Jorgensen et al., 2014). The paramos are highly fragmented because of the complex topography of the Northern Andes and underwent in the past changes in isolation and connectivity (Flantua and Hooghiemstra, 2018). Glacial and interglacial periods raised and lowered respectively the upper forest line leading to changes in connectivity that have directly impacted the flora of the region (Flantua and Hooghiemstra, 2018; van der Hammen, 1982; Hooghiemstra and Van der Hammen, 2004). These changes are one of the main drivers of the high levels of endemism and species diversification making the paramos the fastest evolved biome among biodiversity hotspots (Madrinan et al., 2013). The vegetation of the paramos (Figure 2) is dominated by tussock grasses (*Calamagrostis, Stipa and Festuca sp.*) with scarce forest patches (e.g., *Polylepis sp.*) with transitions to acaulescent rosettes (e.g., *Werneria nubigena, Hypochaeris sessiliflora*) and cushions plants (e.g., *Azorella sp., Plantago rigida*) at higher elevations (Luteyn, 1999; Ramsay and Oxley, 1997). The total number of plant species recorded in the paramos is 3595 distributed among 540 genera of which 14 are endemic (Sklenar and Balslev, 2005). The paramos have the highest number of plant species among tropical alpine flora (Sklenař et al., 2014) and are fundamental part of the habitats of emblematic species such as the Andean condor (*Vultur gryphus*) and the spectacled bear (*Tremarctus ornatus*).

The hydrology and meteorology of páramos

Precipitation at the páramo is known for its remarkably spatial-temporal variability (Buytaert et al., 2006d; Celleri et al., 2007) caused by the interaction between various synoptic climate processes and the complex topography. The mean annual precipitation between 2000 and 2014 calculated from the global precipitation product CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) varies between 150 and 4090 mm yr^{-1} (Figure 3A) with mean maximum values reported in Costa Rica and minimum in Perú (Table 1). They are usually referred to as "wet" ecosystems (Buytaert et al., 2006a; Padrón et al., 2015)even though rainfall can be well below 500 mm yr^{-1} in some of the drier páramos, such as those of Chimborazo in Ecuador (Clapperton, 1990; Saberi et al., 2018). However, rainfall regimes between 1000 and 2000 mm yr^{-1} are more common, with values exceeding 3000 mm yr^{-1} in some páramos on the Amazonian slopes of the Andes. The analysis of rainfall extremes, evidenced that the southern component of tropical airflow is important for the distribution of wet convection, leading to a high intensity of precipitation in the Andean mountains. The mountains at the other hand, dampen the airflow on a large-scale, enabling local hygrothermal gradients to control extreme precipitation anomalies (Pineda and Willems, 2018). Compared to rainfall, the temperature range of the páramos is much more homogeneous, since this is one of the distinctive characteristics of their biogeographical niche (Tovar et al., 2013a). Average temperatures range around 10ºC in the sub-páramos to close to 0º on the upper fringes of the super-páramos, which borders the cryosphere (Buytaert et al., 2006b). The low latitude of páramos limits seasonal temperature variability, which is predominantly induced by the seasonality of precipitation and related cloud cover. Contrastingly, day-night temperature variations can be extreme and are a direct result of the high altitude and Equatorial position, which gives the páramos among the world's highest influx of shortwave radiation (Buytaert et al., 2006b). From the actual evapotranspiration (ETa), 51% of the total annual rainfall according to Carrillo-Rojas et al. (2019), only the component of interception loss can be considered important at the páramos. Despite the predominance of low-intensity rainfall and frequent fog, the vegetation can lead to exceptionally high interception rates. For instance, Ochoa-Sanchez et al. (2018) reported interception values by tussock grass in paramos between 10% to 100% of total rainfall, with a maximum storage capacity of 2 mm. Cardenas et al. (2017) estimated that inputs from fog and drizzle can represent between 7% and 28% (120 and 212 mm yr^{-1}) of the rainfall in Colombian paramos. In areas covered by fog, horizontal precipitation, and cloud water, interception amounts between 10% to 35% of the total precipitation have been reported for forested catchments (Bruijnzeel, 2004; Pryet et al., 2012), although Bonnesoeur et al. (2019) indicate that values between 2% and 8% may be more common. Actual evapotranspiration (ETa) shows values of 646 mm yr^{-1} (Buytaert et al., 2007a) and 723 mm yr^{-1} (Cordova et al., 2015). However, when data are limited errors are thought to be as high as 30% (Carrillo-Rojas et al., 2016; Cordova et al., 2015). Carrillo-Rojas et al. (2019) improved evapotranspiration estimates for paramos using Eddy-covariance, reporting a value of 635+-9 mm $yr^{-1}$for their study site in southern Ecuador. The same authors reported water deficit during specific periods and highlighted the role of air humidity variation in the control of the hydrological system. Furthermore, Wouter Buytaert & Beven, (2011) emphasized the importance of non-stationary hydrological processes such as changing evapotranspiration, infiltration and routing due to vegetation growth. In Figure 3B to 3D, indexes derived from TRMM-3b43 (Tropical Rainfall Measuring Mission) and MODIS (Moderate Resolution Imaging Spectroradiometer) were presented for the study region (Arciniega-Esparza et al., 2020 (in prep)). For the Seasonal Precipitation Index (SPI), high values represent a longer dry season compared to a rainy season and low values the absence of precipitation seasonality. The southern paramos therefore present a prolonged dry season, with the highest indexes of evaporation (EI) and aridity (AL), 50% and 100% respectively, higher than the subsequent ones (Table 1). Mid-ranges of EI were observed for most of the region with minimums in Ecuador and Colombia. In addition, low tendencies of aridity (AI) in the central and northern paramos can be observed. The high altitudinal position of the paramos compared to the elevation of most human settlements and cities makes them convenient "natural water towers" (Messerli et al., 2004) from which water can be sourced by gravity. The hydrological response of paramos is strongly related to their soil conditions and extent of wetlands (Mosquera et al., 2015). W. Buytaert et al. (2005) revealed that the probability of water stress occurrence in wet paramo soils is reduced due to their hydraulic conductivity, which prevents soil moisture to drop below 60 vol%. Paramos' soils are therefore important regulators of runoff production (Harden, 2006). The most organic-rich soils primarily located at the foot of the hillslopes and in the bottom of the valley are commonly covered by cushion plants and present nearly saturated conditions (Buytaert et al., 2005) while the more freely draining soils are situated on the hillslopes under a cover of tussock grass. The rainfall-runoff response is mainly controlled by the variable extent of the saturated zone in the valley bottom (Correa et al., 2017). Water from valley soils compose around 40% of the runoff in a headwater catchment in the Ecuadorian paramos. During rainier periods, the contributing area expands, thus increasing the connectivity with lateral flow from hillslopes and therefore its contribution to the channel network. In drier conditions, only the deep soil horizons from the hillslopes seems to be hydrologically connected (Correa et al., 2017) and water from these horizons drains via the riparian area into streams (Crespo et al., 2011). A particular characteristic of most of the studied high Andean catchments is the presence of underlying impermeable bedrock that minimizes deep infiltration and greatly limit the groundwater contributions (Buytaert et al., 2007a). Nevertheless, some regions also present deep permeable soils, sustain important aquifers (Buytaert et al., 2006a; Favier et al., 2008) and proof the influence of shallow groundwater on stream generation especially when soil moisture decreases (Correa et al., 2017, 2018; Favier et al., 2008). Runoff ratios (ratio between annual precipitation and annual discharge) between 0.50 and 0.70 have been reported in natural wet paramos (Buytaert et al., 2007a; Ochoa-Tocachi et al., 2016a) reaching even values of 0.9 during rainfall-runoff events (Correa et al., 2016). The water yield increases with the amount of wetland, likely because of saturation excess flow (Mosquera et al., 2015). Additionally, Buytaert & Beven (2011) highlighted the importance of threshold-triggered hydrological processes, such as disconnected water storages within the catchment microtopography. In addition, threshold-driven hydrological processes, such as disconnected water storage within the microtopography of the catchment, play a crucial role in the runoff generation and catchment response (Buytaert and Beven, 2011). Figure 3 Table 1

Human impacts on the hydrology of the paramos

Since the 20th century, the paramos have been facing unprecedented anthropogenic pressures (Molina et al., 2015; Roa-Garcia et al., 2011; White, 2013). There is increasing evidence that anthropogenic activities such as intensive and extensive livestock (Molina et al., 2007), cultivation and land management practices affect negatively the paramos' local biodiversity, their functional capacity (Erwin, 2009) and total water yield (Buytaert et al., 2007a). Scientific and public awareness raised concerning the lack of knowledge about the potential impact of rural development and ecosystem degradation on the hydrology of paramos (Celleri and Feyen, 2009). Research focused in anthropogenic intervention impacts on hydrological services of paramos (Buytaert et al., 2007b), explored the shift from endemic land cover to cultivation lands, livestock and forest plantations, anthropic introduction of fire and degradation (Poulenard et al., 2001). Cultivation tends to reduce the catchment regulation capacity (40% reduction) (Celleri and Feyen, 2009; Ochoa-Tocachi et al., 2016a) increases peak discharge (20%), reduces base flow (50%) (Buytaert et al., 2006a, 2007a) and reduces the soil storage capacity (up to 26% reduction) (Sarmiento, 2000). Cultivation also reduces the soil field capacity (from 100% to 83%) and wilting point (from 83% to 63%) (Diaz and Paz, 2002), and the increase of evapotranspiration rates (up to 66%) (Sarmiento, 2000). Livestock density tends to increase, with often negative impacts on the soil structure. Diaz & Paz, (2002) report an increase of the soil bulk density up to 0.2 g cm^3 under extensive and 0.7 g cm^3 under intensive conditions compared to undisturbed paramo soils in Popayan Colombia. Water yield reduction as a result of increasing evaporation is typically less than 15% (Crespo et al., 2010), but this tends to be accompanied by an increase in streamflow flashiness and a decrease in hydrological regulation capacity (Ochoa-Tocachi et al., 2016a, 2016a). The introduction of exotic species as a forestation strategy has been a common practice in the Andean paramos. Pine trees in particular have been used as a strategy to improve the inhabitants' income (Farley et al., 2004) but may affect the hydrological response of paramo ecosystems. Pairwise catchment experiments in southern Ecuador showed that base flow reduced up to 66% (Buytaert et al., 2007b; Ochoa-Tocachi et al., 2016a), water yield decreases between 42% to 50% (Crespo et al., 2010; Ochoa-Tocachi et al., 2016a) as consequence of interception in the canopy and higher evapotranspiration. Burning, another common practice increases the soil erosion, the amount of runoff, reduces the rainfall-runoff time response (Molina et al., 2007), as well as the saturated soil hydraulic conductivity (Poulenard et al., 2001). Drying and hydrophobicity up to 40% have been reported due the direct exposure of dark soils to sunshine (Buytaert et al., 2002). However, a recent study shows that programs aimed at the conservation of hydrological services and soil maintenance do not necessarily need to exclude burning to assure adequate long-term vegetation cover in disturbed paramos (Bremer et al., 2019).

Climate change impacts on paramos

Climate change is very likely to have an impact on the paramos and their ecosystem services. Global warming effects on temperature are generally well quantified with agreement amongst models on the direction of change. This is due to both a higher air moisture content resulting from increased evapotranspiration and the intensification of the Hadley circulation in tropical regions. Both processes are expected to lead to increased temperatures at high altitude (Bradley et al., 2009). However, precipitation and subsequent discharge variations are much more variable with differences up to 50% between various Intergovernmental Panel on Climate Change (IPCC) models from the currently observed values in the Andes (Buytaert and De Bievre, 2012). For instance, Gonzalez-Zeas et al. (2019) compared results from a Regional Climate Model (RCM) with observed data in a catchment that provides 30% of the water needs of Quito, the capital of Ecuador. They found considerable disagreement between both data sources with an over prediction of precipitation by the RCM. In addition, major spatial differences exist, in spite of all the uncertainties across climate projections. Whereas part of the Bolivian Altiplano is likely to experience a reduction of 10% precipitation, areas of the Peruvian Andes will potentially be subjected to increases up to 60% (Buytaert and De Bievre, 2012). Exacerbating the underlying climate is the El Nino Southern Oscillation (ENSO), an imbalance of sea-surface temperatures (SST) and ensuing air pressure in the tropical Pacific (NOAA, 2019). This phenomenon has severe impacts over global and, Andean and Central America weather. El Nino events, where SST anomalies are positive, lead to increased drought risks across the Bolivian Altiplano combined with intense precipitation over northern Peru and Ecuador. Conversely, during a La Nina, where SST anomalies are negative, an intensification of precipitation is observed causing major flooding in certain areas of the tropical Andes (Zola and Bengtsson, 2006). (Mendoza et al., 2019) proposed intra- and inter-annual scale climate teleconnections with Trans Nino Index (TNI), North Athlantic Oscillation (NAO) and the Caribbean Index (CAR). Additionally, the altitudinal factor plays an important role, when the westerly winds dominate, dry conditions occur especially at high altitude, while the opposite when the easterly winds dominate. In this case all the moisture from the eastern Pacific Ocean is transferred to the mountain range. ENSO occurs naturally and is not a consequence of climate change. However, the intensity and duration of ENSO events has increased substantially in the last decades, indicating a possible link to anthropogenic-induced climatic changes that occurred in the same period. These changes will propagate through the terrestrial water cycle, thus affecting directly its hydrology. Studies have quantified these changes, Wouter Buytaert & De Bievre (2012) showed that most of the northern Andean region is expected to experience an increase in precipitation. However, the increase in evapotranspiration as a result of warming is likely to compensate the increase in precipitation, resulting in a net reduction in effective precipitation and water availability. Climatic changes will affect ecosystems more broadly through changes in vegetation and soils, which may propagate to the water cycle. In mountain regions, climate change is likely to induce shifts in the distribution of ecosystems and biomes. Logistic regressions coupled with Global climate models (GCM) and Climate Networks (CN) have been used to simulate climate patterns in future scenarios and to estimate the extent of such future changes for the tropical Andes ((Tovar et al., 2013a; Vazquez-Patino et al., 2020). Tovar, Arnillas, et al. (2013) estimated that the paramos may lose 30% of their current areas due to a lack of room for upslope migration, necessary in the face of warmer temperatures at higher elevations. Additionally, species distribution is also at risk (Ramirez-Villegas et al., 2014). More than 50% of species considered could experience reductions in quantities up to 45% with 10% potentially extinct. However, despite these advances, estimating changes in mountainous areas remains inherently difficult, making the downscaling of global or regional coarse resolution models highly uncertain as the highly variable topography results in steep and sudden changes in local weather patterns which are difficult to represent in available GCMs (Buytaert et al., 2010). Moreover, simplifications of climate processes and errors in input data exacerbate the problem. As we subsequently discuss, new tools such as citizen science and participatory monitoring, provided agreed-upon data quality and reliability standards, can help bridge some of those hydrometeorological information gaps. In the midst of a highly unpredictable future, water and land decision-makers will have to resort to various methods of incorporating uncertainty in increasing resilience in the face of climate shocks, from scenario analysis in designing infrastructure to implementing measures to control growth on the demand side.

New observational techniques

Tracers hydrology and flux exchange in paramos

Knowledge about the spatial distribution of water sources and temporal dynamics of water and material fluxes and release mechanisms is needed to represent a holistic response of catchment behavior. Such knowledge can be gained using tracers in conjunction with independently measured hydrometric data (Buttle, 1994; Inamdar et al., 2013). Hydrochemical tracers to identify and quantify contributions of geographic sources, time-domain tracers, such as water stable isotopes to study the fate of water and water age dynamics, and "smart" bio-reactive tracers, like resazurin (Raz), to assess Carbon Dioxide (CO2) dynamics have been successfully applied in the paramo ecosystem (Correa et al., 2017, 2018; Esquivel-Hernandez et al., 2018; Mosquera et al., 2016b; Riveros-Iregui et al., 2018). Correa et al. (2017, 2018, 2019) used a multi-method approach and a large number of natural tracers to analyze the runoff composition at multiple spatial temporal scales. Their findings highlighted the paramount role of soils from different geographic locations to compose the runoff and draw attention into the evident contributions of the freshwater and shallow-groundwater sources, including a quantification of water contributions from the different compartments. These studies additionally pinpointed the variable stream water age, the spatial variability and diverse evolution of hydrological processes under different hydrometeorological conditions. Other researchers used water stable isotopes to evaluate the effect of land use change on rainfall-runoff response (Roa-Garcia et al., 2011), quantify runoff generation (Minaya, Camacho Suarez, et al., 2016), and determine the isotopic composition of high mountain lakes (Esquivel-Hernandez et al., 2018). Additionally, mean transit times were evaluated in order to understand catchment dynamics (Mosquera et al., 2016b; Munoz-Villers and McDonnell, 2012; Roa-Garcia and Weiler, 2010) and quantify stream water ages (53–264 days) (Mosquera et al., 2016b). Artificial tracers were as well applied in an experimental based 4 days -high resolution sampling campaign in the Colombian paramos. This with the aim to assess the land use impact on the dynamics of dissolved CO2 and potential for CO2 evasion (Riveros-Iregui et al., 2018). The bio-reactive RAZ -which is reduced to resorufin (Rru) via aerobic cellular respiration (Gonzalez-Pinzon et al., 2014)- was injected together with chloride into sites with different land cover. Results suggested that most of the outgassing in wetland systems occurs near the stream wetland interface, where the potential CO2-enriched water flowing out of the wetland mixes in a turbulent form. A high density of carbon-rich peatlands was mapped in the high elevation mountains of the Ecuadorian paramos by (Hribljan et al., 2017) improving sustainable management for national and global carbon accounting. Pena-Quemba et al. (2016), using the portable soil respiration chamber technique in their field experiment revealed that the agricultural management and land use changes were the main drivers of soil-atmosphere exchange of CO2 in the paramo of Guerrero (Colombia). The authors additionally stated that the easy decomposition of organic matter in paramo soils turns them into carbon sinks. Soil respiration is a key factor in the heat balance, the concentration of atmospheric carbon and global ecological changes (Jassal et al., 2007; Veenendaal et al., 2004). Small changes in soil respiration as a potential effect of global warming can determine the shift point where an ecosystem acts as a source or sink for CO2 (Jassal et al., 2007). A recent study revealed that paramos are carbon sources (Carrillo-Rojas et al., 2019). Processes of CO_2 emission (100+-30 gr m^{-2} yearly) show that this ecosystem are more susceptible to lose the carbon fixed in the soil (especially dry periods) due to the effects of climate change and vegetation alterations. (Carrillo-Rojas et al., 2019).This would have far-reaching implications for water storage and dynamics, biodiversity and ecosystem services management.

Remote sensing and new technologies

Remote sensing has been used in hydrology for estimating hydrometeorological states and fluxes (Kumar and Reshmidevi, 2013), such as precipitation, land surface temperature, near surface soil moisture, snow cover, water quality, landscape roughness, land use and vegetation cover. Schmugge et al. (2002) used primarily remote sensing technique to define evapotranspiration and snowmelt runoff. In the paramos, applications have been related mainly to precipitation detection, land use and vegetation cover mapping, and to evapotranspiration estimation. Improvements in the spatial-temporal estimation of precipitation were possible thanks to a number of methodologies, ranging from the identification of the best satellite products, model images (Ballari et al., 2018; Manz et al., 2017; Nerini et al., 2015; Ulloa et al., 2017, 2018) and use of dense and/or extensive rain gauges networks (Manz et al., 2016; Sucozhanay and Celleri, 2018), to the use of more sophisticated equipment such as radars and disdrometers (Orellana-Alvear et al., 2017; Padron et al., 2015). Precipitation forecasting and projections use statistical and dynamical downscaling applications (Campozano et al., 2016a; Ochoa et al., 2016) and forecasting of daily precipitation occurrence (Urdiales and Celleri, 2018). The RADARNET-SUR is the first weather radar network located in tropical high mountains. It was installed to complement an existing sparse rain gauge network (Bendix et al., 2016; Orellana-Alvear et al., 2017). The radar successfully detected the relatively low frequency of heavy rain (particles diameters between 1 and 2 mm) and confirmed the high occurrence of drizzle. Raindrop size spectra were characterized with the radar observations, confirming spatial variations across paramo sites. Particularly the use of satellite products in the high mountains showed that Integrated Multi-satellite Retrievals for GPM (IMERG) has a superior detection and quantitative rainfall intensity estimation ability than Multi-satellite Precipitation Analysis (TMPA) (Manz et al., 2017). The latter enabled to reveal the existence of different regimes (unimodal, bimodal, and three-modal) and helped to comprehend the precipitation and cloud dynamics and generation processes of precipitation (Campozano et al., 2016b). Regarding land use and vegetation cover, deforestation and landscape transformation was detected with the comparison of LANDSAT and ARDAS satellite images (Munoz-Guerrero, 2017). Those images helped to detect crop expansion, especially regarding to the conservation of forests and wetlands (Munoz et al., 2018a). The occurrence of wetlands was characterized in the Colombian paramos, with remote sensing derived data (Estupinan-Suarez et al., 2015). Lastly fires and their intra- and inter-annual variability, that affect the paramo, was also analyzed through Landsat and MODIS imagery (Borrelli et al., 2015). The energy-balance model METRIC with Landsat and MODIS-Terra imagery provided a robust first estimate of spatial-temporal changes of evapotranspiration (Carrillo-Rojas et al., 2016), which was further greatly improved measuring energy fluxes with an Eddy-covariance tower, one of the highest in the world (Carrillo-Rojas et al., 2019).

Citizen science and participatory monitoring networks

Long-term monitoring of water quantity and quality is often criticized for being unaffordable and challenging in low-income and remote regions (Rufino et al., 2018). Novel strategies allow the participation of new actors (e.g., actors with a non-research oriented profile) in scientific projects; their participation is usually referred to as citizen science. The inclusion of local stakeholders changes the traditional monitoring approach, from intensive-highly specialized in experimental sites to a polycentric and collaborative network with large spatial coverage and a wider range of data collector profiles (Buytaert et al., 2014, 2016). The second option involves the horizontal management of information and massive distribution of knowledge. The participation of stakeholders has proven to be an effective tool to reduce costs while providing hydrological data with sufficient quality (Weeser et al., 2018), and generating locally relevant knowledge to tackle the data scarcity in regions such as the tropical Andes (Ochoa-Tocachi et al., 2018). Regional monitoring networks such as the *Regional Initiative for Hydrological Monitoring of Andean Ecosystems* (iMHEA, Celleri et al., 2009; Ochoa-Tocachi et al., 2018) integrate locals (land and water users and government offices), academic institutions and other minor monitoring networks. iMHEA generates and analyses information about the impact of land use changes on the hydrological response of mountain catchments with high spatial and temporal resolution, yet short time series (Buytaert et al., 2016; Ochoa-Tocachi et al., 2016b, 2018). Particularly in paramos, the network studies watershed interventions and common land-use activities such as cultivation, grazing, and afforestation with exotic species, as well as connectivity pathways and effects of land use to downstream users (Ochoa-Tocachi et al., 2018). With this collaborative project the authors were able to detect regional patterns such as increases in variability of stream flow and decreases in the water yield of the catchments. Furthermore, decreases in the regulation capacity of the catchments (effect of livestock grazing) and impacts on the base flows (effect of afforestation with exotic species and crops) were evidenced (Ochoa-Tocachi et al., 2016b). With results such as the above mentioned, it is demonstrated that broad networks with scientific and non-scientific actors provide opportunities for data collection, generation of knowledge and support to water management policies (Buytaert et al., 2016).

Towards an integrated evidence base to support sustainable management of the paramos

Despite the spatial-temporal variability and complexity of the hydrological processes of paramos, as well as the logistical challenges imposed by the remote and barren environment, the above review shows great advances in hydrological knowledge of the paramos. This is exceptional for a remote mountain environment, and arguably unique in the Andes. We consider that this knowledge was gained as a result of the interdisciplinary participation of actors, combined with the use of well-established methods and technologies. This has led to the creation of an unwritten "common agenda", leading to a focusing of research activities and fostered convergence between seemingly independent research efforts. The acceleration of hydrological research in the late 1990s coincided with an increasing awareness of the ecological and societal value of the paramo highlands, notwithstanding paramos provided crucial ecosystem services long before this (Johansen et al., 2018). Indeed, especially in Ecuador and northern Peru, paramos have been inhabited for centuries and major centers of the Inca empire were located in or near the paramo border (Bendix et al., 2013). Ingenious hydraulic infrastructure drew water from the paramo headwaters and used the region for agricultural activities and livestock grazing in particular. Since the 1970, forestation with pine species became a widespread activity as an attempt to support the economic activity of paper production (Bonnesoeur et al., 2019). However, the most direct ecosystem service of the paramos has been water supply, especially for major Andean cities. Population growth and related increase in water demand put rising pressure on these resources as well as an augmenting awareness of their vulnerability among decision-makers. In 2000, the city of Quito in Ecuador, established one of South America's first and most successful water funds (FONAG), with the aim to protect and manage the city's water supply regions. As more than 90% of these regions are covered by paramos, initiatives like these drew political and scientific attention to the lack of scientific understanding of their hydrological functioning and the potential impact of changes in land use, as well as global climate change. Throughout its first decade, this focus was strengthened further by growing evidence of mountain environments as hotspots of biogeographical and human vulnerability to climate change (e.g., Myers et al., 2000; Viviroli et al., 2011). The issue of climate change not only stressed the need to better understand the paramo water cycle, but also its links to other processes such as the carbon cycle and biodiversity (Buytaert et al., 2011). These processes shaped a local and international research agenda which led to a step-change in scientific activity in the paramos. In addition, large scale initiatives on the science-policy interface connected and integrated these efforts. Among those efforts, the Global Environmental Facility funded Proyecto Paramo Andino, which ran from 2006 to 2012, which stood out because of its role in building a research community. In 2010, the project initiated the iMHEA regional network (Celleri et al., 2009; Ochoa-Tocachi et al., 2016b). Such initiatives created a strong connection between the scientific and operational communities. For example, many recent studies on the spatial-temporal variability of precipitation processes in the Andes are joint efforts between national meteorological offices and scientists (e.g., Manz et al., 2017; Nerini et al., 2015). This has led to an accelerated uptake of the use of satellite-based precipitation products in operational practice, and an optimization of the monitoring efforts between different research groups. Political decisions to make hydrometeorological datasets available for scientific use have further accelerated this evolution. The iMHEA started originally as a community of practice of scientists, government institutes, decision-makers and civil society representatives. All these actors aimed at understanding the high Andean water resources and address the critical data scarcity in the region (Celleri et al., 2009). The network grew until today and manages 27 flow gauging stations and 67 rain gauges in headwater catchments of the Andes of Ecuador, Peru, and Bolivia. The network is designed to complement institutional hydrometeorological monitoring, and to generate evidence on land management practices through a pairwise catchment design (Ochoa-Tocachi et al., 2018). In addition, to the scientific productivity the network is creating an institutional legacy as well. In Peru, the iMHEA methodology has been adopted by the National Drinking Water and Sanitation Regulation Agency (SUNASS) to evaluate the implementation of recent laws on ecosystem services. The mentioned methodology promotes the use of natural infrastructure for water security. The exceptional experience of linking evidence generation with in-situ water management have raised similar convergence between scientific and policy priorities in other disciplines. The growing awareness of the potentially dramatic impact of climate change on high mountain regions (e.g., Vuille et al., 2018) has triggered several concerted efforts to improve the predictive capacity of global climate models. This has promoted the development of more appropriate downscaling methods, the evaluation of the multiple impacts of climate change, and the development of better and more flexible adaptation strategies in the tropical Andes. A notable initiative in this regard was the Andean Climate Change Interamerican Observatory Network (ACCION), which ran from 2012-2014 (Vuille, 2015). Similarly, research on ecological processes and carbon recycling in paramos emerged in parallel to hydrological research (e.g., R. G. M. Hofstede, 1995; Podwojewski et al., 2002; Tonneijck et al., 2010). Interdisciplinary endeavors to link these processes are becoming increasingly common (e.g., Minaya, Corzo, Romero-Saltos, et al., 2016). The use of tracer hydrology has been especially instrumental in analyzing the biogeochemical cycles that underpin and connect these processes (e.g., Correa et al., 2017, 2018; Esquivel-Hernandez et al., 2018; Mosquera, Celleri, et al., 2016).

Enhancing hydrological understanding at local scale: field observatories densely monitored to understand the hydrological functioning of headwater catchments.

To demonstrate emerging research in the paramo, we present the great value of an experimental site established since 2010 by iDRHICA, University of Cuenca, Ecuador. This eco-hydrological observatory (7.5 km^2) is located the in southern Ecuadorian Andes (Fig. 4) in an altitudinal range between 3,505 and 3,900 m a.s.l. Two types of soils, Histosols (20%) and Andosols (80%) mainly covered by grassland and cushion plants respectively dominate the catchment. This observatory is densely monitored, hydro-meteorologically: a weather station, a spatially distributed network of tilting bucket rain gauges and a nested system of discharge stations. In addition, a laser disdrometer and an Eddy covariance flux tower have been placed at the study site. Water samples are collected for stable isotope, carbon, nutrient and element concentration analyses, periodically and during intensive campaigns in streams, precipitation and soils. Being an intensive and highly specialized research site, the findings built a strong ecohydrological knowledge, which can be synthesized as follow: Fog and drizzle common in the region (Buytaert et al., 2006c) accounted for an additional amount of 15% of precipitation (Padron et al., 2015). Interception losses represented a high percentage of precipitation and the canopy storage capacity of grassland was approximately 2 mm (Ochoa-Sanchez et al., 2018). The key role of air moisture variation in the control of the hydrological system was as well reported by Carrillo-Rojas et al. (2019). Streamflow showed to be dominated by water inflows from the riparian zone (mainly occupied by Histosols soils) year-round and the contribution from hillslopes (where primarily Andosols soils are located) was relevant during the wet season (Correa et al., 2017; Mosquera et al., 2016a). The age of water from the streams varies between 2-9 months (Mosquera et al., 2016b) and decreased when connectivity to the hillslopes existed (Correa et al., 2017). Rainfall-runoff event-based sampling showed slower connectivity with hillslopes in the lower in relation with the upper sub-catchments (Correa et al., 2018). The dynamic storage of the catchment increases with rainfall intensity, while the passive storage with larger wetlands extent. Less than 10% of passive storage is hydrologically active in the water balance (Lazo et al., 2019). The carbon source behavior of the paramo was evidenced by a net positive exchange of CO2 (Carrillo-Rojas et al., 2019). In a nearby comparable catchment, increasing of DOC concentrations while decreasing soil moisture were reported and land-use and land cover identified as key predictors of soil water DOC concentrations (Pesantez et al., 2018). Figure 4

Enhancing hydrological understanding at regional scale: integrating research towards a regional understanding and predictions in ungauged basins

The large body of data and knowledge generated in a few experimental highly monitored sites in the South American paramos provide a starting point to generalize findings to a larger area in which water resources are used and managed. To prove the usefulness of pooling data from monitored sites to make predictions in ungauged basins, we used data generated from the iMHEA network of paired, collocated catchments with contrasting land-use types, and tested how such a monitoring design can improve the detectability of land-use change signals and thus the prediction of land-use impacts in ungauged basins. The regionalization exercise related a set of hydrological indices to physical and climatic descriptors using multilinear regressions (Figure 5). The collocation of catchments is intended to increase the contrast of land-use and land-cover variables between pairs and, at the same time, minimize climatic and physical differences. This was tested by treating each catchment as ungauged while keeping its pair with similar descriptors but contrasting land use in the derivation of regional models. The regression results showed that regionalization using paired catchments enhances the detectability of land-use change impacts improving model performance and predictive capacity for 66% of the 50 indices tested (Ochoa-Tocachi et al., 2016b). For the runoff ratio, baseflow index, and slope of the flow duration curve, the mean absolute error reduced on average by 53% and the variance of the residuals by 79%. In contrast to previous research that found it difficult to isolate land-use signals in regionalization (e.g., Visessri & McIntyre, 2016) the collocation of catchments increased the contrast of land-use and land-cover variables between pairs, at the same time it minimized climatic and physical differences. In consequence, the robust regionalization results are attributed to the paired catchment network setup that covers diverse physiographic characteristics, contrasting land-use types, and degrees of conservation/alteration (Ochoa-Tocachi et al., 2016b). This demonstrates that such a design of monitoring network is a useful strategy to optimize data collection, provide commonly available geographical information, understand the major controls of hydrological response, and provide robust predictions in ungauged basins in data-scarce regions such as the tropical Andes, with potential application elsewhere. Figure 5

Concluding remarks

Hydrological understanding of the Latin American paramos improved dramatically over the last three decades, being the result of a good interaction between scientists, local and regional stakeholders. In addition, two tendencies are noticeable in the developed research structure, one regional with more non-scientific actors and decision-makers involved and a second in small densely monitored experimental sites where mostly-scientist and academics are involved. Furthermore, international cooperation initiatives succeeded in creating a community-based strong connection between the scientific and operational communities. Within these initiatives, multidisciplinary research projects used innovative approaches to collect and process information, and to generate knowledge at regional level. Others in experimental sites generated strong hydrological knowledge with great detail and high resolution. Ideally, this knowledge could be regionalized to non-monitored sites to massify the benefit. The progress of eco-hydrological and meteorological research in paramos, once one of the least studied regions in the world, is a regional and global reference. We are convinced that the rapid reaction and increased interaction of the scientific community and decision-makers have been responsible for the generation of long-needed information for robust understanding and management of water resources in the region. With the knowledge acquired, we encourage the research community, for example, to participate in projects that provide insights into the global change that occurs in these fragile ecosystems. Also, to complement the challenge of long-term data collection, incursion into modeling of future hydro-climatic scenarios is essential. Finally, we encourage the community to continue collaborating and establishing new international cooperation initiatives. All this to generate long-term management strategies and ensure the socio-economic development without compromising hydrological and ecosystem resources.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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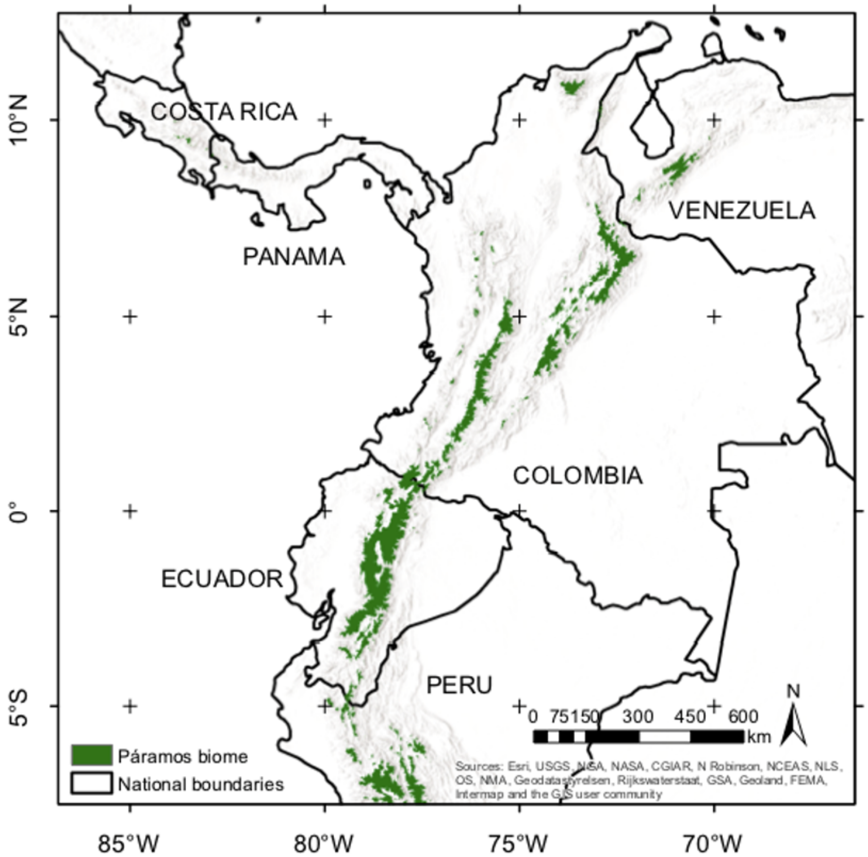
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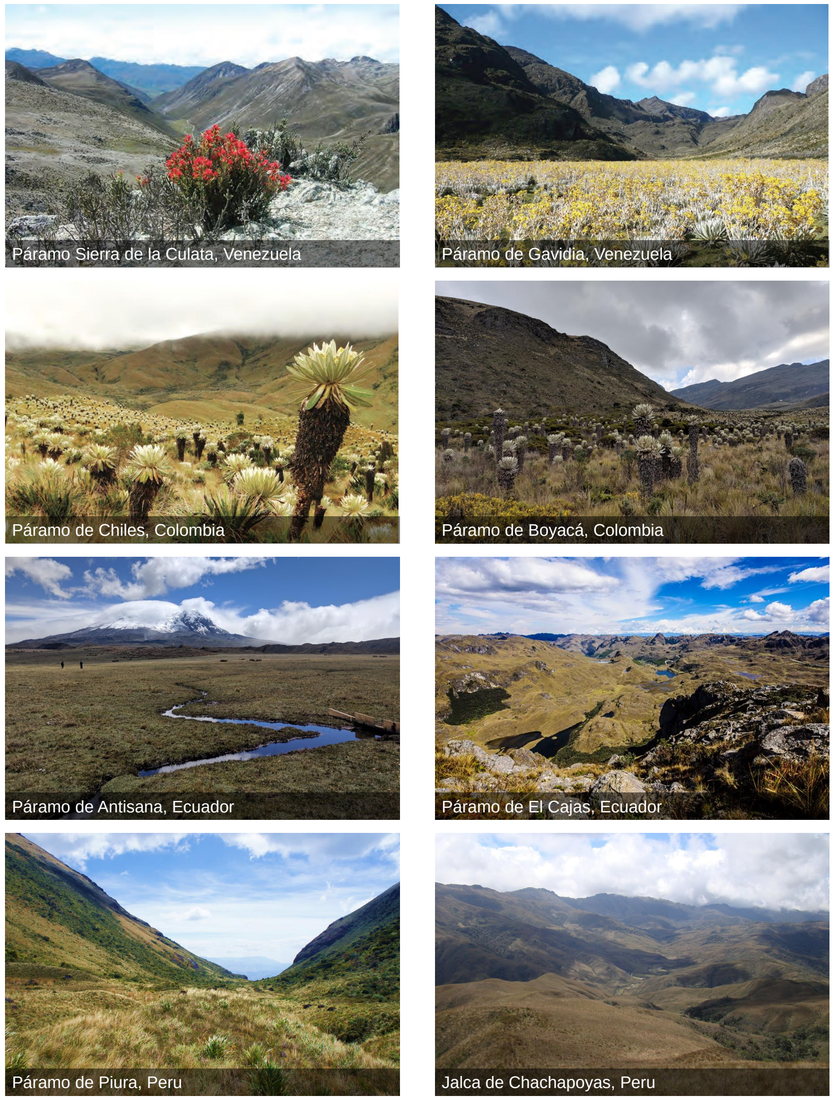
Páramos biome
National boundaries
Sources: Esri, USGS, NOAA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community



Credits: Luis Llambí, Bernabé Torres, Adolfo Correa, Boris Ochoa-Tocachi, Alicia Correa, Bjoern Weeser, Paul Viñas.

Figure 2. Typical landscapes of the Andean páramos

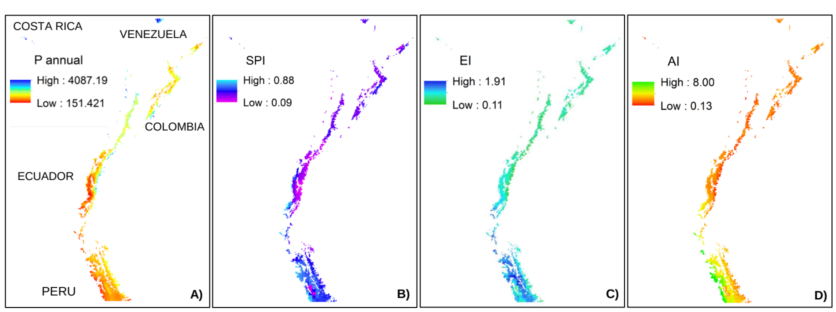


Figure 3. Annual precipitation and indexes: Seasonal Precipitation Index (SPI), Aridity Index (AI) and Evaporative Index (EI) for the páramo region.

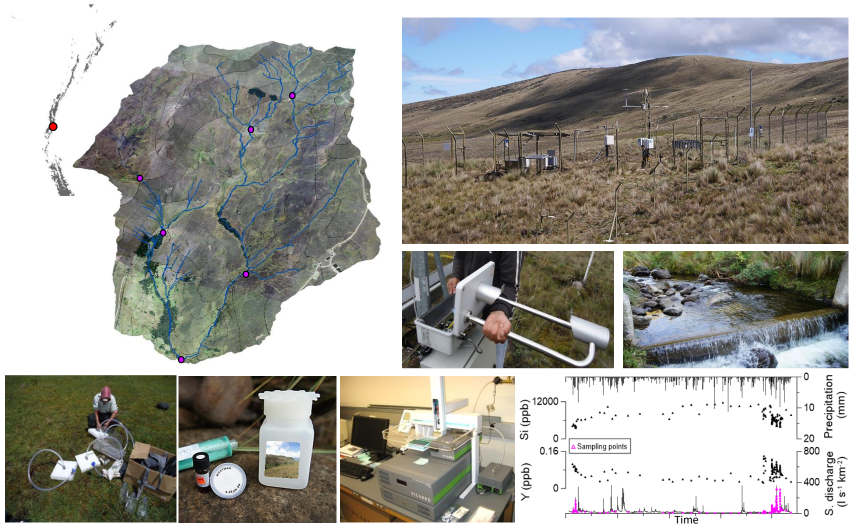


Figure 4. The eco-hydrological observatory located in southern Ecuador with sampling stream sites. Hydro-meteorological (upper right panel), water sample (lower panel) monitoring and lab scheme, and an example of high-resolution precipitation, discharge and element-concentration from water samples.
Photo credits: Alicia Correa and Galo Carrillo.

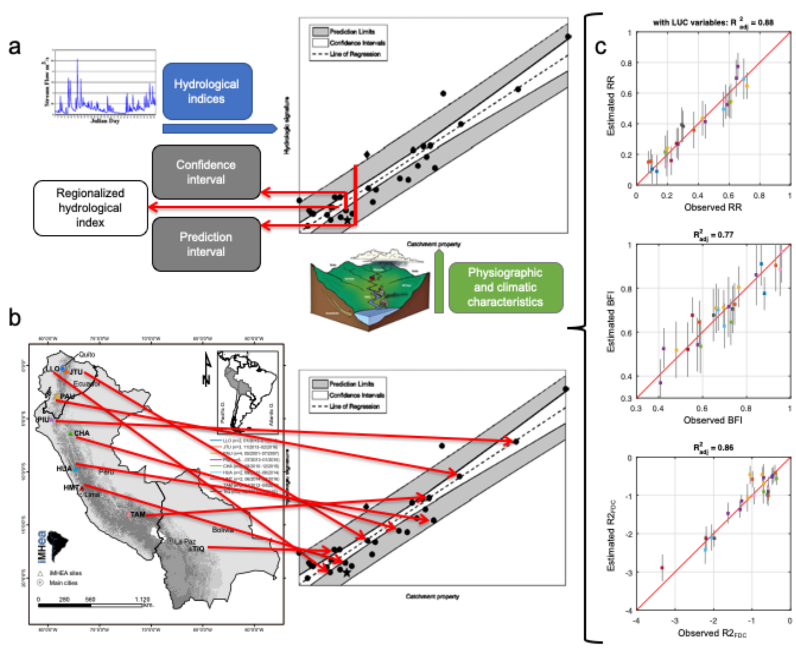


Figure 5. Regionalization of hydrological responses: (a) Regional relationships between catchments characteristics and streamflow signatures provide an option to make predictions in ungauged basins; (b) Pooling data from monitoring sites in the páramo and other similar biomes can support the development of statistically robust regional models; and (c) Examples of regionalized hydrological indices using data from the iMHEA network (Ochoa-Tocachi, Buytaert, & De Bièvre, 2016); from top to bottom: runoff ratio, baseflow index, and slope of the flow duration curve.

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