A concerted research effort to advance the hydrological understanding of tropical páramos

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RESEARCH ARTICLE

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A concerted research effort to advance the hydrological understanding of tropical páramos

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Abstract

Páramos, a neotropical alpine grassland-peatland 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 from the high mountains down to the Pacific, Caribbean, and Amazon regions. Páramos are also widely recognized as a biodiversity and climate change hot spots, yet they are threatened by anthropogenic activities and environmental changes. Despite their importance for water security and carbon storage, and their vulnerability to human activities, only three decades ago, páramos were severely understudied. Increasing awareness of the need for hydrological evidence to guide sustainable management of páramos prompted action for generating data and for filling long-standing knowledge gaps. This has led to a remarkably successful increase in scientific knowledge, induced by a strong interaction between the scientific, policy, and (local) management communities. A combination of well-established and innovative approaches has been applied to data collection, processing, and analysis. In this review, we provide a short overview of the historical development of research and state of knowledge of the hydrometeorology, flux dynamics, anthropogenic impacts, and the influence of extreme events in páramos. We then present emerging technologies for hydrology and water resources research and management applied to páramos. 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 páramos. We conclude that this co-evolution of science and policy was able to successfully cover different spatial and temporal scales. Lastly, we outline future research directions to showcase how sustainable long-term data collection can foster the responsible conservation of páramos water towers.

KEYWORDS

advances-hydrology, science-policy, tropical-páramos

1 | INTRODUCTION

Páramos play an important role in regional and global cycles of water, carbon, and nutrients, having a direct impact on people's livelihoods in Latin America. The páramos are a collection of perennially humid,

[Correction added on 30 September 2020 after first online publication: ORCID for co-authors Ochoa-Tocachi, Zogheib and Buytaert has been added in this version.]

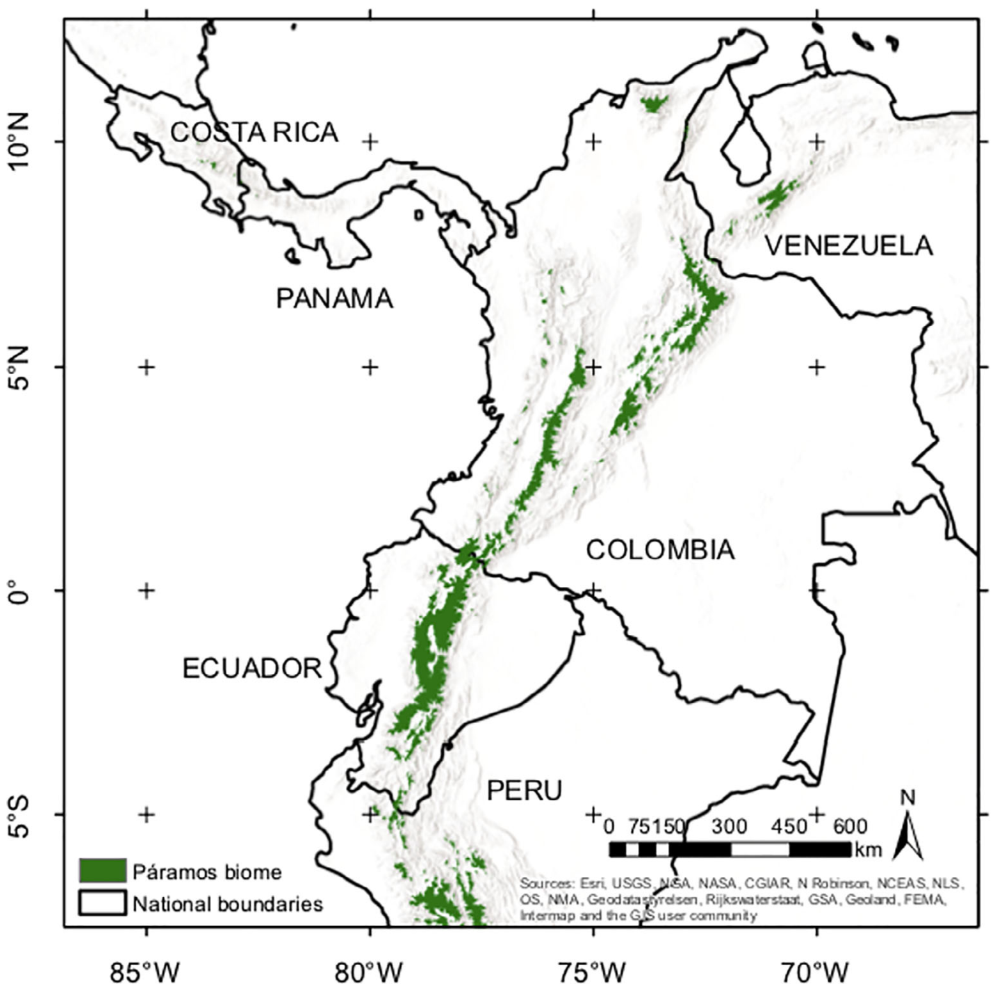

FIGURE 1 Extent of the páramos biome in the northern Andes and Central America

neotropical alpine ecosystems identified as hot spots for climate change (Bradley, Vuille, Diaz, & Vergara, 2006; Castaño Uribe, 2002; Dangles et al., 2017) (Figures 1 and 2). Densely populated areas in the tropical Andes (e.g., Bogotá, Quito, Cuenca and Lima), mostly depend on surface and shallow subsurface water sources for human consumption, industrial uses and hydropower generation (Buytaert et al., 2006). Surface water sources are particularly susceptible to the potential impact of changes in land-use and land cover which could lead to lower water availability and quality (Ochoa-Tocachi et al., 2016; Tovar, Seijmonsbergen, & Duivenvoorden, 2013). Implementing watershed interventions to improve ecosystem services became more widespread. However, often these catchment interventions have not been assessed well, sometimes resulting in negative hydrologic impacts at local and regional scales (Buytaert, Iñiguez, & Bièvre, 2007; Ochoa-Tocachi, Buytaert, & De Bièvre, 2016), trade-offs with other ecosystem services (Bonnesoeur et al., 2019), and severe ecosystem and biodiversity degradation (Hofstede, Groenendijk, Coppus, Fehse, & Sevink, 2002). These negative impacts highlighted the need for a concerted effort to improve our hydrometeorological understanding of the páramos. Likewise to avoid putting at risk the natural resources, socio-economic and human development of vulnerable populations, critical points for achieving the Sustainable Development Goals (SDG).

In the last decades, research efforts on understanding the ecohydrology and meteorology of páramos at various spatial–temporal scales has increased substantially. These efforts have overcome several challenges to understand the highly variable processes that are involved. Local catchment heterogeneity, large variability of hydrologic conditions, and extensive data-scarcity have historically been the main limitation to further advance hydrological and meteorological knowledge across the tropics and in Latin America (Bendix, 2000; Célleri & Feyen, 2009; Correa et al., 2018; Riveros-Iregui, Covino, & González-Pinzón, 2018). The body of literature also suggested Central American páramos research lagging behind the much more organized efforts in the northern Andes. Also, the complex topographical setting of the volcanic Cordillera in Central America and the Andean mountains generally complicate groundwater abstraction. These challenges are exacerbated by the effects of environmental and human-induced changes that have already prompted a fast rate of changes in the páramos hydrology (Buytaert, Célleri, et al., 2006; Buytaert, Cuesta-Camacho, & Tobón, 2011).

Scientific and public awareness of the importance of studying the hydrology of páramos gained momentum around the turn of the century, as a result of several seminal research papers and policy publications (e.g., Hofstede, 1995; Kapelle & Uffelen, 2005; Mena, Medina, & Hofstede, 2001; Podwojewski, Poulenard, Zambrana, & Hofstede,

FIGURE 2 Typical landscapes of the Andean páramos

2002). These publications triggered a rapidly increasing community of research and practice around the hydrology, ecology, and climatology of páramos, featuring a variety of innovative techniques, intensive monitoring, and model-based regionalization approaches to improve understanding of hydrological processes and the effect of external pressures. In such emerging research, field-experimental based studies started assessing previously ignored variables such as precipitation structure (Orellana-Alvear, Célleri, Rollenbeck, & Bendix, 2017; Padrón, Wilcox, Crespo, & Célleri, 2015) and clarifying less known processes such as interception (Ochoa-Sánchez, Crespo, & Célleri, 2018), evapotranspiration (Carrillo-Rojas, Silva, Rollenbeck, Célleri, & Bendix, 2019; Córdova, Carrillo-Rojas, Crespo, Wilcox, & Célleri, 2015; Ramón-Reinozo, Ballari, Cabrera, Crespo, & Carrillo-Rojas, 2019), and carbon and nutrient concentrations in soil and vegetation (Minaya, Corzo, van der Kwast, & Mynett, 2016; Peña-Quemba, Rubiano-Sanabria, & Riveros-Iregui,- 2016; Pesántez, Mosquera, Crespo, Breuer, & Windhorst, 2018; Riveros-Iregui et al., 2018). For example, the use of conservative and bio-reactive tracers enlightened hydrological process understanding and allowed tracking and quantifying fluxes, storage and mixing, and assisted in defining the spatial–temporal dynamics of runoff sources and flow pathways (Correa et al., 2017; Esquivel-Hernández et al., 2018; Minaya, Camacho Suarez, Wenninger, & Mynett, 2016; Mosquera et al., 2016; Riveros-Iregui et al., 2018). Hydrologic model applications reproduced more accurately the observed streamflows, year-round and in drought and flood conditions (Avilés, Célleri, Paredes, & Solera, 2015; Avilés, Célleri, Solera, & Paredes, 2016; Mora, Campozano, Cisneros, Wyseure, & Willems, 2014; Muñoz, Orellana-Alvear, Willems, & Célleri, 2018). In addition, researchers started to evaluate data uncertainties related to the location and technical properties of equipment in the increasingly denser monitoring networks (Guallpa, 2013; Muñoz, Célleri, & Feyen, 2016; Sucozhañay & Célleri, 2018). As a result, the evaluation of land-use and climate change scenarios and their impact on the hydrological system became more feasible and helped decision-makers to predict potential economic benefits for several service providers (Bremer et al., 2019; Flores-López, Galaitsi, Escobar, & Purkey, 2016; Kroeger et al., 2019).

Therefore, this paper attempts to summarize the historical efforts and recent concerted research dynamics that have advanced the hydrological understanding of tropical páramos in the last decades with a regional focus on Latin America. However, considerable knowledge gaps still exist, and we outline research directions that have potential to support sustainable development of páramos ecosystems.

1.1 | Historical development of research in páramos

As of July 2020, 1129, scientific publications containing the word "páramo" in their title, abstract or keywords have been published focused on Latin America according to Scopus-Elsevier's database of abstracts and citations (Figure 3). The first publications reported on research were conducted in the Colombian páramos, between 1831 and 1848. In 1,831, Boussingault analysed the composition of a new mineral found at 3,800 m a.s.l. in Páramo Rico, near Pamplona and other authors analysed the acidic mineral water near the Purace volcano in Páramo de Ruiz. In the 20th century, 246 scientific documents were published, and a continuous growth started in 1967. As a result, some seminal publications paved the way to build knowledge about the functioning of páramos ecosystems. From an ecological perspective, Cuatrecasas (1934), Monasterio (1980), Cleef (1981), and Luteyn (1999) established a baseline on Andean páramos vegetation diversity. From a hydrological lens, Junk (1993) characterized páramos wetlands, Hofstede (1995) analysed the effect of human practices on soil covered by grasslands and Sarmiento (2000) quantified the water balance components in the Venezuelan páramos.

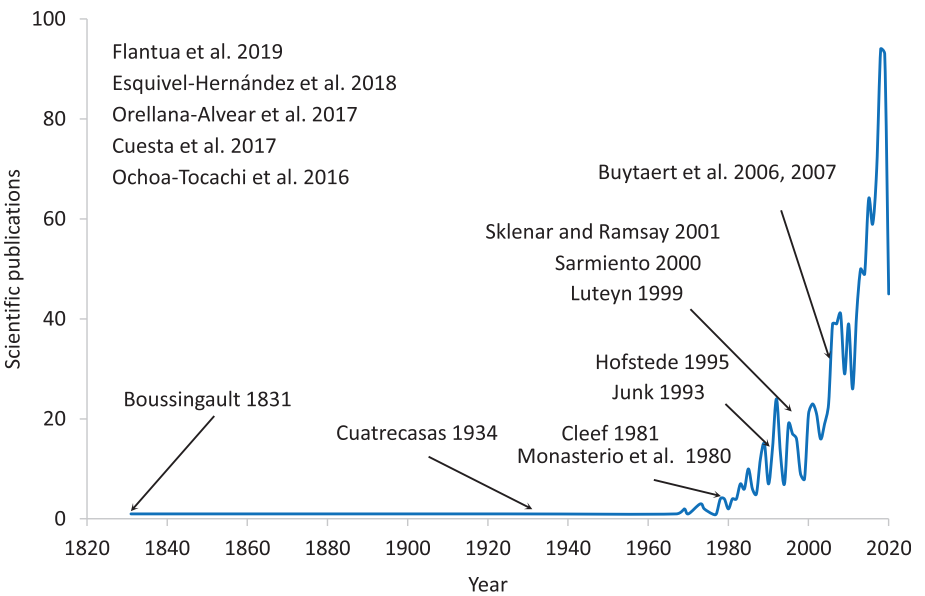

FIGURE 3 Historical development of scientific publications of páramos

The increasing level of interdisciplinary research, international cooperation and collaborative networks has resulted in 880 publications after 2000. This positions páramos as a highly studied and globally referenced biome for the rapid research progress that has been achieved. Among those publications, some benchmark papers highlighted milestones for research development in different disciplines. For example, key papers in ecology are that of Sklenar and Ramsay (2001), where they investigated the diversity of zonal páramos vegetation in Ecuador. The book "Páramos de Costa Rica" by Kapelle and Uffelen (2005) presented most of the geomorphology, ecology and paleoclimate research from Central America. Cuesta et al. in 2017 analysed the latitudinal and altitudinal patterns of vegetation communities along the Andean region. More recently, in 2019, Flantua et al. evaluated how climate fluctuations in combination with topography influenced habitat connectivity over thousands of years. Key papers in hydrology are those of Buytaert, Célleri, et al. (2006); Buytaert, Iñiguez, and Bièvre (2007) where the authors assessed (a) the effect of land-use change on the hydrological system and (b) the afforestation and cultivation impacts on the water yield. These papers used, for the first-time, information from paired catchments. Following this research line, Ochoa-Tocachi et al. in 2016 established guidelines for regionalizing land-use impacts on streamflow generation using a network of paired catchments in the tropical Andes.

More recently, the development of advanced technology also helped in collecting more fine resolution data. For example, the access to more specialized equipment allowed setting-up Eddy-covariance flux towers and radars in the high tropical páramos in 2014. The RADARNET-SUR, the first weather radar network installed in páramos was used to detect the low frequency of heavy rain and to confirm the spatial variations of precipitation across páramos sites (Orellana-Alvear et al., 2017). Knowledge about the importance of the páramos biome was recognized much earlier in the Andes than in Central America, leading to more structured research efforts compared to Central America. However, emerging studies in geomorphology, ecology and hydrology in Central America (Chai et al., 2020; Esquivel-Hernández et al., 2018; Quesada-Román, Ballesteros-Cánovas, Guillet, Madrigal-González, & Stoffel, 2020) paved the way for future research and complemented the regional perspective of this study.

2 | CURRENT STATE OF KNOWLEDGE

2.1 | The páramos biome

The páramos constitute a tropical alpine biome located most extensively in the Northern Andes (between 11°N and 8°S) and to a lesser extent in parts of Central America (Figure 1) and dominated by grasslands, rosettes, and bushes. They occur above the tropical montane forest biome (□3,000 m a.s.l.) and below the cryosphere (□5,000 m a.s.l.) (Josse et al., 2009; Luteyn, 1999). However, their delineation is not always clear because of deforestation and increasing encroachment of the lower páramos for agricultural purposes (López Sandoval & Valdez, 2015; Tovar, Arnillas, Cuesta, & Buytaert, 2013) and ongoing induced glacier retreat caused by global-warming (Morueta-Holme et al., 2015). Páramos occupy an area of approximately 35,000 km^2 (Hofstede et al., 2002), with the largest extents occurring in Colombia and Ecuador and smaller disconnected patches in Venezuela (Páramos de Mérida) and Costa Rica (Cerro Chirripó and Kamuk). The southern limit of páramos is known as the *Jalca* (Sánchez-Vega & Dillon, 2006; Tovar, Duivenvoorden, Sánchez-Vega, & Seijmonsbergen, 2012), a transitional vegetation toward a drier alpine biome (*Puna*) of the central and south Peruvian Andes (Cuesta et al., 2017; Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016). Although ecosystems with very similar biogeographical and hydrometeorological characteristics to páramos occur as far south as Bolivia (Páramo Yungeño) (Jørgensen, Nee, & Beck, 2014), we focus here on the páramos biome of the Northern Andes and Central America only.

One key characteristic of páramos is the high level of fragmentation. Páramos have been a very dynamic landscape in the past where changes in isolation and connectivity were mostly defined by the complex topography (Flantua, O'Dea, Onstein, Giraldo, & Hooghiemstra, 2019). Glacial and interglacial periods raised and lowered, respectively, the upper forest line leading to changes in connectivity that have directly impacted the region's flora (Flantua & Hooghiemstra, 2018; van der Hammen, 1982; Hooghiemstra & Van der Hammen, 2004 and Quesada-Román, Campos, Alcalá-Reygosa, & Granados-Bolaños, 2020 for a Costa Rican reconstruction of the forest and snow line). These changes are one of the main drivers for the high levels of endemism and species diversification, making páramos the fastest evolved biome among biodiversity hotspots (Madriñán, Cortés, & Richardson, 2013).

The vegetation of páramos (Figure 2) is dominated by tussock grasses (*Calamagrostis*, *Stipa and Festuca sp.*) with scarce forest patches (e.g., *Polylepis sp.*), 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 & Oxley, 1997). The total number of plant species recorded in páramos is 3,595 distributed among 540 genera of which 14 are endemic (Sklenar & Balslev, 2005). Páramos have the highest number of plant species among tropical alpine flora (Sklenar, Hedberg, & Cleef, 2014) and are fundamental part of the habitats of emblematic wildlife species such as the Andean condor (*Vultur gryphus*) and the spectacled bear (*Tremarctus ornatus*).

2.2 | Hydrometeorology of páramos

Research outlining the current state of knowledge of hydrometeorological variables and fluxes, with precipitation, interception, temperature, and evapotranspiration components, as well as the role of soils and vegetation in the hydrological response of páramos is presented below. Precipitation in páramos is known for its remarkable spatial–temporal variability (Buytaert, Célleri, Willems, De Bièvre, & Wyseure, 2006; Célleri, Willems, Buytaert, & Feyen, 2007) caused by the interaction between various synoptic climate processes and the complex topography. The mean annual precipitation calculated from the global precipitation product CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) between 2000 and 2014 ranges between 150 and 4,090 mm yr^{-1} (Figure 4a). The highest mean maximum precipitation values are reported in Costa Rica and the lowest minimum in Perú (Table 1). Páramos are usually referred to as humid ecosystems (Buytaert et al., 2006; Padrón et al., 2015). Rainfall ranges between 1,000 and 2,000 mm yr^{-1} with values exceeding 3,000 mm yr^{-1} in some páramos on the Amazonian slopes of the Andes. However in a few drier páramos, rainfall can be well below 500 mm yr^{-1}, such as those of Chimborazo in Ecuador (Clapperton, 1990; Saberi et al., 2018). 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 themselves dampen the airflow on a large-scale, enabling local hydrothermal gradients to control extreme precipitation anomalies (Pineda & Willems, 2018).

The predominance of low-intensity rainfall and frequent fog, causes in parts of the Andes exceptionally high interception rates. For example, tussock grass in páramos of Zhurucay in southern Ecuador intercept between 10 and 100% of total rainfall, with a maximum storage capacity of 2 mm (Ochoa-Sánchez et al. (2018). Similarly, fog and drizzle can represent between 7 and 28% (120–212 mm yr^{-1}) of annual rainfall, as measured in the Colombian páramos (Cárdenas, Tobón, and Buytaert (2017). Using TRMM-3b43 (Tropical Rainfall Measuring Mission) and MODIS (Moderate Resolution Imaging Spectroradiometer) precipitation indices were estimated for the páramos (courtesy of Arciniegas-Esparza) (Figure 4b–d). The southern páramos present a prolonged dry season (high values of seasonal precipitation index, SPI), with the highest indexes of evaporation (EI) and aridity (AL), 50 and 100% respectively, higher than their northern counterparts (Table 1). Mid-ranges of EI were observed for most of the region with minima in Ecuador and Colombia. In addition, low aridity (AI) was observed in the central and northern páramos. Compared to rainfall, temperature across the year is much more homogeneous in páramos. Mean annual air temperatures range from around 10°C in the lower limit of the páramos to close to 0° on their upper fringes bordering the cryosphere (Buytaert, Célleri, et al., 2006). The low latitude of páramos limits annual seasonal temperature variability. In contrast, daily temperature variations can be extreme and are a direct result of the high altitude and Equatorial position, which gives páramos one of the world's highest influx of shortwave radiation (Buytaert, Célleri, et al., 2006).

Actual evapotranspiration (ETa), can account for 51% of total annual rainfall (Carrillo-Rojas et al. (2019), with values of 646 mm yr^{-1}

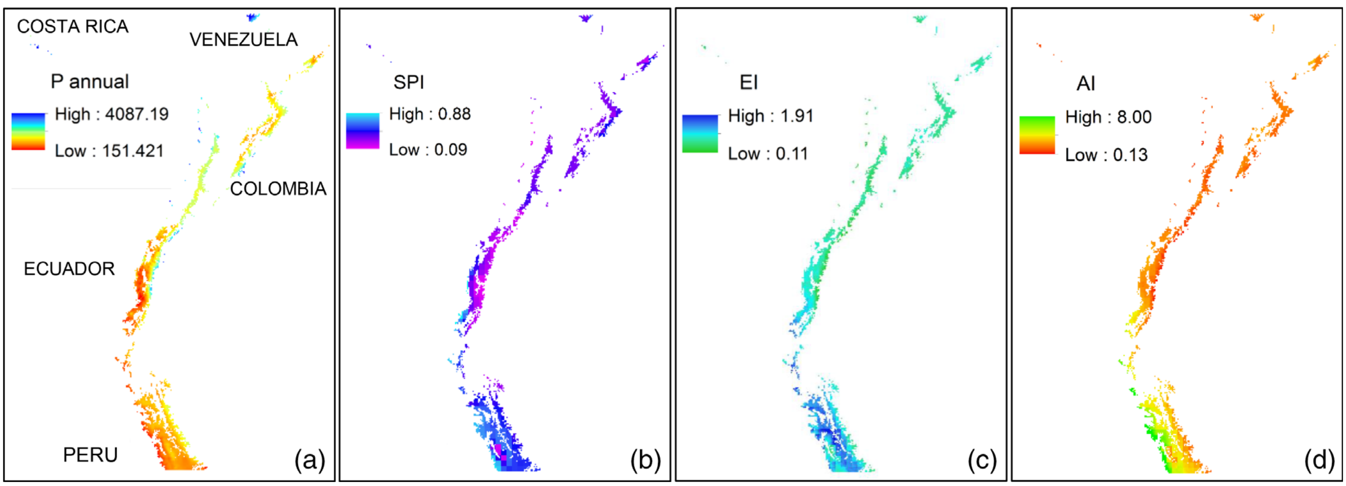

FIGURE 4 Annual precipitation and indexes: Seasonal Precipitation Index (SPI), Aridity Index (AI) and Evaporative Index (EI) for the páramos region

TABLE 1 Annual precipitation and indexes: Seasonal Precipitation Index (SPI), Aridity Index (AI) and Evaporative Index (EI) calculated for each country

	Annual precipitation (mm)			SPI index (–)			Evaporative index (–)			Aridity index (–)		
Country	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
Costa Rica	3,992	3,230	2,794	0.40	0.36	0.30	0.43	0.39	0.37	0.55	0.51	0.48
Venezuela	2,399	1,319	608	0.48	0.31	0.19	1.02	0.69	0.47	1.63	1.11	0.65
Ecuador	3,236	987	151	0.88	0.30	0.12	1.57	0.78	0.12	2.68	1.16	0.13
Colombia	4,087	1,640	798	0.50	0.30	0.10	0.93	0.55	0.11	1.44	0.84	0.14
Perú	1,783	901	213	0.79	0.49	0.15	1.91	1.15	0.36	7.99	2.26	0.60

(Buytaert, Iñiguez, & Bièvre, 2007) and 723 mm yr^{-1} (Córdova et al., 2015). However, when data are limited, errors can be as high as 30% (Carrillo-Rojas, Silva, Córdova, Célleri, & Bendix, 2016; Córdova et al., 2015). Using an Eddy-covariance tower, one of the highest in the world, evapotranspiration for páramos was measured, reporting values of around 620 mm yr^{-1} in southern Ecuador (Carrillo-Rojas et al., 2019; Ochoa-Sánchez, Crespo, Carrillo-Rojas, Marín, & Célleri, 2020; Ochoa-Sánchez, Crespo, Carrillo-Rojas, Sucozhañay, & Célleri, 2019). At the same site, net radiation was reported as the primary control of ETa (Ochoa-Sánchez et al., 2020); while meteorological observations highlighted the role of radiation and air humidity variation in the control of the hydrological system (Carrillo-Rojas et al., 2019; Ochoa-Sánchez et al., 2020). Furthermore, Buytaert and Beven (2011) emphasized the importance of non-stationary hydrological processes such as changing evapotranspiration, infiltration, and routing due to vegetation growth.

The hydrological response of páramos is strongly related to their soil conditions. Buytaert, Wyseure, De Bièvre, and Deckers (2005) revealed that the probability of water stress occurrence in wet páramos soils is reduced due to their hydraulic conductivity, which prevents soil moisture to drop below 60 vol%. Páramos soils are therefore important regulators of runoff production (Harden, 2006). The most organic-rich soils, primarily located at the foot of the hillslopes and at the bottom of the valleys, are commonly covered by cushion plants and often at saturated conditions (Buytaert et al., 2005). 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 páramos. During rainier periods, the contributing area expands, thus increasing the connectivity with lateral flow from hillslopes and thus its contribution to the channel network. In drier conditions, only the deep soil horizons from the hillslopes seem 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 Andean páramos catchments is the presence of underlying impermeable bedrock that minimizes deep infiltration and greatly limits the groundwater contributions (Buytaert, Iñiguez, & Bièvre, 2007). Nevertheless, some regions also present deep permeable soils, sustain important aquifers (Buytaert, Iñiguez, et al., 2006; Favier et al., 2008), and prove the influence of shallow groundwater on stream generation, especially when soil moisture decreases (Correa et al., 2017, 2018; Favier et al., 2008). Central American páramos were characterized by shallower soils with high organic matter content (Kapelle & Uffelen, 2005) and likely varying runoff generation mechanisms compared to the previously mentioned Andean páramos.

Runoff ratios (ratio between annual precipitation and annual discharge) in páramos have been reported at between 0.50 and 0.70 in natural wet páramos (Buytaert, Iñiguez, & Bièvre, 2007; Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016), reaching values as high as 0.9 at event scale (Correa et al., 2016). Páramos water yield increases with the extent and amount of wetlands, likely because of saturation excess flow (Mosquera, Lazo, Célleri, Wilcox, & Crespo, 2015). 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 hydrological response (Buytaert & Beven, 2011).

2.3 | Human impacts on the hydrology of páramos

The high altitudinal position of páramos compared to the elevation of most human settlements and cities makes them convenient "natural water towers" (Messerli, Viviroli, & Weingartner, 2004) from which water can be sourced by gravity. But the páramos themselves have been used for thousands of years for different human activities. Since the 20th century, páramos have been facing unprecedented anthropogenic pressures (Molina, Vanacker, Brisson, Mora, & Balthazar, 2015; Roa-García, Brown, Schreier, & Lavkulich, 2011; White, 2013). There is increasing evidence that intensive and extensive livestock (Molina et al., 2007), cultivation and land management practices negatively affect páramos' local biodiversity, their functional capacity (Erwin, 2009), and water yield (Buytaert, Iñiguez, & Bièvre, 2007). Scientific and public awareness put in evidence the lack of knowledge about the potential impact of rural development and ecosystem degradation on the hydrology of páramos (Célleri & Feyen, 2009).

Research on the impacts of anthropogenic intervention on the hydrological services of páramos (Buytaert, Célleri, Bièvre, & Iñiguez, 2007) have focused on comparing páramos natural vegetation with three main land-use types: cultivated lands, livestock grazed areas and forest plantations, including anthropic introduction of fire and sometimes land degradation (Poulenard, Podwojewski, Janeau, & Collinet, 2001). Despite the protection in National Parks of Central American páramos and limited human intervention (Quesada-Román, Campos, et al., 2020; Veas-Ayala et al., 2018) these systems are still severely understudied compared to the Andean counterparts. Croplands tend to reduce catchment's regulation capacity (□40% reduction) (Célleri & Feyen, 2009; Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016), increase peak discharge (□20%), reduce base flow (□50%) (Buytaert, Iñiguez, et al., 2006; Buytaert, Iñiguez, & Bièvre, 2007), and reduce soil storage capacity (up to 26% reduction) (Sarmiento, 2000). Cultivated areas also reduce the soil field capacity (e.g., from 100 to 83%) and wilting point (e.g., from 83 to 63%) (Díaz & Paz, 2002), and increase evapotranspiration rates up to 66% (Sarmiento, 2000).

Livestock grazing tends to increase soil density and reduce porosity, with often negative impacts on soil structure. For example, an increase of soil bulk density of up to 0.2 g cm^3 under extensive grazing, and of 0.7 g cm^3 under intensive grazing conditions compared to undisturbed páramos soils, has been reported in Popayán Colombia (Díaz & Paz, 2002). Water yield reduction, as a result of increasing evaporation, is typically less than 15% (Crespo et al., 2010), and this is usually associated with an increase in streamflow flashiness and a decrease in catchment's hydrological regulation capacity (Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016).

The introduction of exotic species for afforestation has been a common practice in the Andean páramos (Bonnesoeur et al., 2019). Pine trees, in particular, have been used to improve land productivity (Farley, Kelly, & Hofstede, 2004). However, this practice affects the hydrological response of páramos ecosystems. Pairwise catchment experiments in southern Ecuador showed that base flow reduced up to 66% (Buytaert, Célleri, et al., 2007; Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016) and water yield decreased between 42 and 50% (Crespo et al., 2010; Ochoa-Tocachi, Buytaert, De Bièvre, Célleri, et al., 2016) in afforested grasslands in comparison to native grasslands. These changes in hydrological responses are a consequence of higher interception in the canopy and higher evapotranspiration of the exotic trees. Burning, another common practice in the páramos, increases soil erosion, runoff, and reduces the rainfall-runoff response time (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 to the direct exposure of dark soils to sunshine (Buytaert et al., 2002). Nevertheless, a recent study concluded that soil and water conservation programs might be able to use burning to achieve adequate long-term vegetation cover in disturbed páramos (Bremer et al., 2019).

2.4 | Climate change impacts on páramos

Climate change is affecting the páramos in various ways; however, assessing these impacts is complicated by remarkably high uncertainties. Although there is good agreement between climate models on atmospheric warming, the increased temperatures are expected to be stronger at high altitude (Pepin et al., 2015). Precipitation and subsequent discharge variations are much more variable with differences up to 50% between CMIP3 model simulations and observed values in the Andes (Buytaert & De Bièvre, 2012). González-Zeas et al. (2019) compared results from a Regional Climate Model (RCM) with observed data in Ecuador and found an over prediction of precipitation by the RCM.

Despite these uncertainties, some regional patterns can be detected. Whereas part of the Bolivian Altiplano is likely to experience a reduction in precipitation, the northern Andes are likely to experience a future increase in precipitation (Buytaert & De Bièvre, 2012). Veas-Ayala et al. (2018) projected a significant temperature increase of a minimum of 2°C by the end of the century even under optimistic emission scenarios for the Costa Rican páramos at Chirripó National Park. The same study reported rainfall decreasing by 5% for the pessimistic emission scenario until 2099 with associated likely reduced runoff of major river systems originating in the Chirripó páramos.

An additional course of uncertainty is the El Niño Southern Oscillation (ENSO), which is an imbalance of sea-surface temperatures (SST) and ensuing air pressure in the tropical Pacific (National Oceanic and Atmospheric Administration; NOAA, 2019) with severe impacts on Andean and Central America weather patterns. The intensity and duration of ENSO increased substantially in the last decades, indicating a possible link to anthropogenic-induced climatic changes that occurred during the same period (Zheng, Hui, Xie, Cai, & Long, 2019).

Changes in climate will propagate through the terrestrial water cycle, thus affecting directly its hydrology. Most of the northern Andean region is expected to experience an increase in precipitation under future climate projections (Buytaert & De Bièvre, 2012). However, the increase in evapotranspiration as a result of warming is likely to compensate for the increase in precipitation, resulting in a net reduction in runoff.

Climatic changes will lead to changes in vegetation and soils, which may propagate to the water cycle. Ecological niche models have been used to model and project the distribution of Andean biomes and species under future climate scenarios in the tropical Andes (Tovar, Arnillas, et al., 2013; Vázquez-Patiño, Campozano, Mendoza, & Samaniego, 2020). Results project a median loss of páramos extent of 31.4% by 2039 under emissions scenario A1B, mainly due to a lack of available space for upslope migration (Tovar, Arnillas, et al., 2013). For species, approximately 50% of tropical Andean plants and birds are projected to experience reductions of up to 45% in their climatic niche, defined as the optimal set of climatic conditions for survival, with 10% of species potentially becoming extinct (Ramirez-Villegas et al., 2014).

Despite these advances, estimating climate change on mountain regions remains inherently challenging. First, the low number of weather stations – which restricts sound spatial–temporal data – makes it difficult to quantify a clear baseline and the resulting changes in hydrological processes caused by climate change influences. Second, the highly variable topography results in steep and sudden changes in local weather patterns which are hard to represent in available global climate models (GCMs) (Buytaert et al., 2010). Given the limited data and simplifications of the climate processes in GCMs, downscaling results from global or regional climate models is highly uncertain. This limits the possibility of concluding a more detailed analysis of expected climatic changes in the páramos.

3 | NOVEL OBSERVATIONAL TECHNIQUES AND APPROACHES APPLIED IN PÁRAMOS

3.1 | Tracer hydrology and flux exchange in páramos

Knowledge about the spatial distribution of water sources, the temporal dynamics of water and material fluxes, and release mechanisms is needed to represent a holistic response of catchment hydrological behaviour. Such knowledge can be gained using tracers in conjunction with independently measured hydrometric data (Buttle, 1994; Inamdar et al., 2013). A variety of tracers has been successfully applied in the páramos to improve our understanding of its hydrology. For example, by using hydrochemical tracers, Correa et al. (2017, 2018); Correa, Ochoa-Tocachi, and Birkel (2019) found the paramount role of soils from different geographical areas and shallow-groundwater contributions to runoff composition. Time-domain water stable isotopes have been used to determine the isotopic composition of high mountain lakes in Central American páramos (Esquivel-Hernández et al., 2018), to estimate mean transit times (Mosquera et al., 2016; Muñoz-Villers & McDonnell, 2012; Roa-García & Weiler, 2010) and quantify stream water ages (53–264 days) (Mosquera, Segura, et al., 2016). Most of these studies aimed to assess the evolution of hydrological processes under different hydro-meteorological conditions and quantify runoff generation (Minaya, Camacho Suarez, Wenninger, & Mynett, 2016),

Other tracers such as the "smart" bio-reactive tracers (e.g., resazurin [Raz]) have been used to assess carbon dioxide (CO_2) dynamics. Artificial tracers (bio-reactive RAZ in 4 days – high resolution) applied in the Colombian páramo wetlands showed that most of the CO_2 outgassing occurs near the stream wetland interface, where the potential CO_2-enriched water flowing out of the wetland mixes in a turbulent form (Riveros-Iregui et al., 2018). A high density of carbon-rich peatlands was mapped in the high elevation mountains of the Ecuadorian páramos (Hribljan et al., 2017) improving sustainable management for national and global carbon accounting. Carbon dioxide dynamics have also been assessed using portable soil respiration chambers in field experiments. Using this technique, agricultural management and land-use changes were identified as the main drivers of soil-atmosphere exchange of CO_2 in páramos of Guerrero (Colombia) (Peña-Quemba et al., 2016). The authors additionally stated that the easy decomposition of organic matter in páramos soils turns them into carbon sinks. Because soil respiration is a key factor in the heat balance, the concentration of atmospheric carbon and global ecological changes (Jassal et al., 2007; Veenendaal, Kolle, & Lloyd, 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 CO_2 (Jassal et al., 2007). A recent study revealed that páramos are carbon sources (Carrillo-Rojas et al., 2019) and that these ecosystems 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).

3.2 | Remote sensing and new technologies

Remote sensing has been used in hydrology for estimating hydrometeorological states and fluxes (Kumar & Reshmidevi, 2013). Particularly in páramos, those 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 the identification of the best satellite products, model images (Ballari, Giraldo, Campozano, & Samaniego, 2018; Manz et al., 2017; Nerini et al., 2015; Ulloa, Ballari, Campozano, & Samaniego, 2017; Ulloa, Samaniego, Campozano, & Ballari, 2018), the use of dense and/or extensive rain gauges networks (Manz et al., 2016; Sucozhañay & Célleri, 2018), and more sophisticated equipment such as radars and disdrometers (Orellana-Alvear et al., 2017; Padrón et al., 2015). Precipitation forecasting and projections use statistical and dynamical downscaling applications (Campozano, Tenelanda, Sánchez, Samaniego, & Feyen, 2016; Ochoa, Campozano, Sánchez, Gualán, & Samaniego, 2016) and forecasting of daily precipitation occurrence (Urdiales & Célleri, 2018). The RADARNET-SUR 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 páramos sites (Orellana-Alvear et al., 2017).

Particularly the use of satellite products in the high mountains showed that Integrated Multi-satellite Retrievals from GPM (IMERG) has a superior detection and better ability to estimate quantitative rainfall than Multi-satellite Precipitation Analysis (TMPA) (Manz et al., 2017). The latter revealed the existence of different regimes (unimodal, bimodal, and three-modal) in the páramos and helped to comprehend the precipitation and cloud dynamics, and generation processes of precipitation (Campozano, Célleri, Trachte, Bendix, & Samaniego, 2016). Changes in vegetation cover, a key element of the hydrological cycle, was detected with the comparison of LANDSAT and ARDAS satellite images for páramos of Nariño, Colombia (Muñoz-Guerrero, 2017). Those images helped to observe crop expansion and how this affected conservation and sustainability of páramos ecosystems (Muñoz, Pencue, Figueroa, & Guzmán, 2018). Landsat and MODIS sources were further used to assess fires that affect páramos, their intra- and inter-annual variability and resulting ecological impacts (Borrelli, Armenteras, Panagos, Modugno, & Schütt, 2015). The same imagery has also been used to robustly assess spatiotemporal evapotranspiration changes in the páramos, in combination with the energy-balance model METRIC (Carrillo-Rojas et al., 2016). Besides changes in land cover and land-use, satellite images have allowed the identification of páramo wetlands and their changes over time (Ospina, 2019).

3.3 | Citizen science and participatory monitoring

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). However, novel strategies developed in these regions, with the participation of new actors (e.g., actors with a non-research oriented profile) in scientific projects, have allowed effective monitoring. The inclusion of local stakeholders changes the traditional monitoring approach, from intensive-highly specialized in experimental sites to a polycentric and collaborative network with larger spatial coverage and a wider range of data collector profiles (Buytaert et al., 2014; Buytaert, Dewulf, De Bièvre, Clark, & Hannah, 2016). Known as citizen science, this participatory monitoring involves the horizontal management of information and massive distribution of knowledge. It has proven to be an effective tool to reduce costs while providing hydrological data with sufficient quality

(Weeser et al., 2018). Citizen science also generates locally relevant knowledge to tackle the data scarcity in regions such as the tropical Andes and generating locally relevant knowledge to tackle the data scarcity in regions such as the tropical Andes (Ochoa-Tocachi et al., 2018). No such efforts were to the best of our knowledge reported from Central American páramos.

Regional monitoring networks such as the *Regional Initiative for Hydrological Monitoring of Andean Ecosystems* (iMHEA, Célleri et al., 2009; Ochoa-Tocachi et al., 2018) integrate local users (land and water users and government offices), academic institutions and other minor monitoring networks along the tropical Andes, from Venezuela to Bolivia. 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., 2018; Ochoa-Tocachi, Buytaert, & De Bièvre, 2016). Particularly in páramos, 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 have been able to detect regional patterns such as increases in variability of stream flow and decreases in the water yield of the catchments (Ochoa-Tocachi, Buytaert, & De Bièvre, 2016). The emerging broad networks of scientific and non-scientific actors provide opportunities for data collection, generation of knowledge, and support for sustainable water management policies (Buytaert et al., 2016).

3.4 | Toward an integrated evidence base to support sustainable management of páramos

Despite the spatial–temporal variability and complexity of the hydrological processes in páramos, as well as the logistical challenges imposed by the remote and barren environment, the above review shows great advances in hydrological knowledge of páramos. This is exceptional for a remote mountain environment, and arguably unique in the Andes and Central America. 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 páramos highlands, notwithstanding páramos provided crucial ecosystem services long before this (Johansen et al., 2018). Indeed, especially in Ecuador and northern Peru, páramos have been inhabited for centuries and major centres of the Inca empire were located in or near páramos border (Bendix et al., 2013). Ingenious hydraulic infrastructure drew water from páramos 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 páramos 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. Despite that Central American páramos are mostly National Parks and completely protected areas with little to no land-use change impacts, their ecosystematic value particularly in terms of water resources remains speculative. In contrast, the city of Quito in Ecuador, established in 2000 the world's first and most successful water fund (FONAG), with the aim to protect and manage the city's water supply regions. As more than 90% of these regions are covered by páramos, 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 hot spots of biogeographical and human vulnerability to climate change (e.g., Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000; Viviroli et al., 2011). The issue of climate change not only stressed the need to better understand páramos water cycle, but also its links to other processes such as the carbon cycle and biodiversity (Buytaert et al., 2011).

This development shaped a local and international research agenda which led to a step-change in scientific activity in páramos. In addition, large scale initiatives on the science-policy interface connected and integrated these efforts. Among those efforts, in the World Congress on Páramo (2002), the Paipa Declaration was signed, the Global Environmental Facility funded Proyecto Páramo 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 (Célleri et al., 2009; Ochoa-Tocachi, Buytaert, & De Bièvre, 2016). 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 and international 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 (Célleri 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 GCMs. 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 to 2014 (Vuille, 2015). Similarly, research on ecological processes and carbon recycling in páramos emerged in parallel to hydrological research (e.g., Hofstede, 1995; Podwojewski et al., 2002; Tonneijck et al., 2010). Interdisciplinary endeavours to link these processes are becoming increasingly common (e.g., Minaya et al., 2016). The use of tracer hydrology has been especially instrumental in analysing the biogeochemical cycles that underpin and connect these processes (e.g., Correa et al., 2017, 2018; Esquivel-Hernández et al., 2018; Mosquera, Célleri, et al., 2016).

Lastly, the interdisciplinary research of páramos has advanced beyond hydrology and ecology to encompass other sciences, particularly social sciences, that show quantitative evidence of the importance of páramos for water security. Socially relevant research has been generated to understand how people manage their landscapes, use their land and water, and produce and incorporate community and citizen science in their decision making (Buytaert et al., 2014). The link of the natural sciences with the social sciences for environmental conservation have also resulted in robust analyses. For example, hydro-socio-economic studies have started investigating the economic value of páramo conservation and restoration (Ochoa-Tocachi, 2019), whereas new theories for water governance have emerged from the polycentric nature of this ecosystem and the need to incorporate data from multiple actors and consider power balances between them (Zogheib et al., 2018).

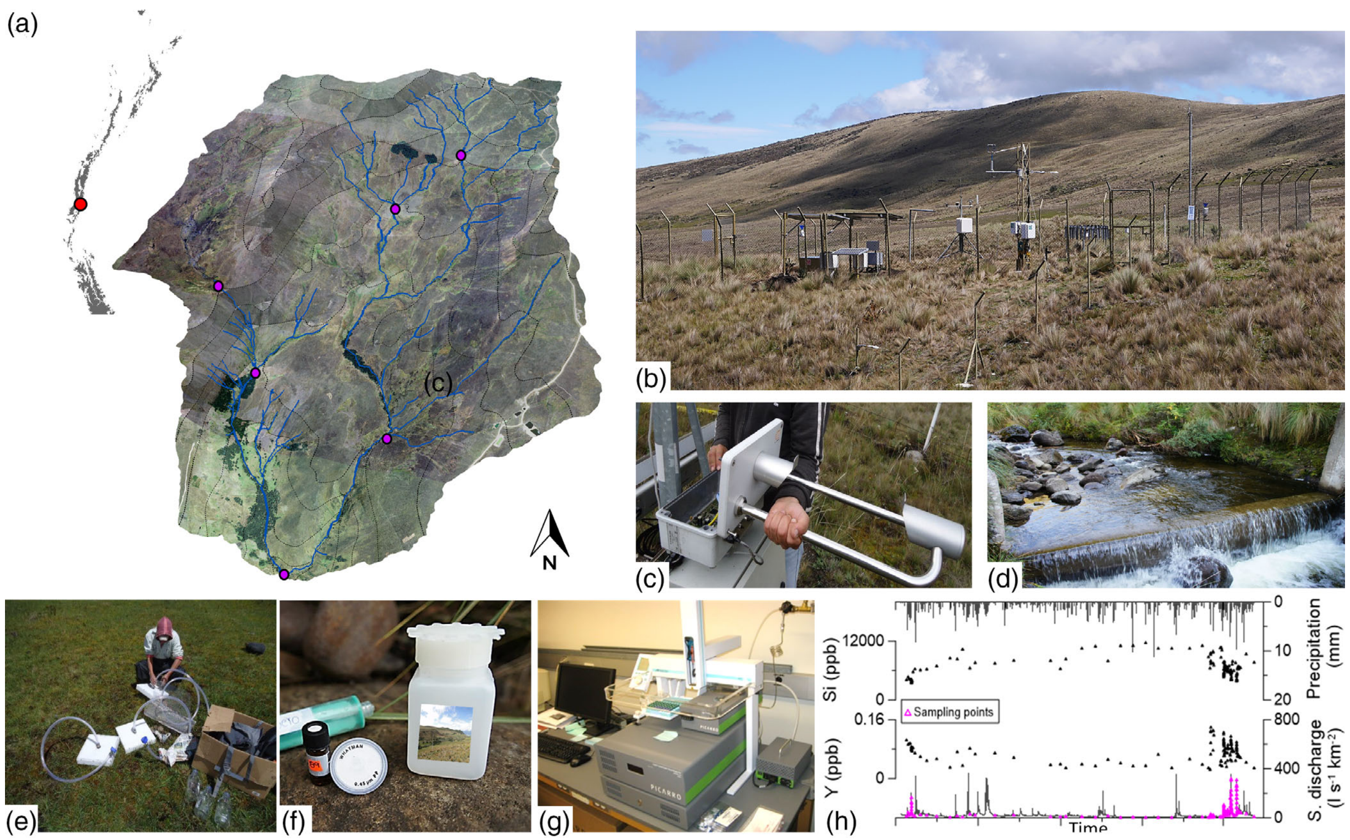

FIGURE 5 The Zhurucay eco-hydrological observatory located in southern Ecuador: (a) Catchment with sampling stream sites; (b) Hydro-meteorological monitoring equipment; (c) Disdrometer; (d) Weir at the catchment outlet; (e) Wick sampler installation materials; (f) 2-ml amber glass bottle, 100-ml polypropylene bottle and filter used for water sampling; (g) Picarro L1102-I analyser and (h) Example of high-resolution precipitation, discharge and element-concentration from water samples. Photo credits: Alicia Correa and Galo Carrillo

3.5 | Enhancing hydrological understanding at local scale: Densely monitored field observatories to understand the hydrological functioning of headwater catchments

One example of an integrated field observatory is the iDRHICA site established in 2010 by University of Cuenca, Ecuador. This eco-hydrological observatory (7.5 km^2) is located the in southern Ecuadorian Andes (Figure 5) 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 eco-hydrological knowledge, which can be summarized as follows:

Fog and drizzle common in the region (Buytaert, Célleri, et al., 2006) accounted for an additional amount of 15% of precipitation (Padrón et al., 2015). Interception losses represented a high percentage of precipitation and the canopy storage capacity of grassland was approximately 2 mm (Ochoa-Sánchez 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, Célleri, et al., 2016). Costa Rican páramos were also characterized by organic-rich and water-logged, but shallower soils compared to Andean sites (Kapelle & Uffelen, 2005). The age of water from the streams varies between 2 and 9 months (Mosquera, Segura, et al., 2016) 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, Mosquera, McDonnell, & Crespo, 2019). The carbon source behaviour of páramos was evidenced by a net positive exchange of CO_2 (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 (Pesántez et al., 2018). In comparison, Central American páramos are still severely understudied and research mostly focused on ecological inventories and paleoclimate studies (Kapelle & Uffelen, 2005). Only recently, Esquivel-Hernández et al. (2018, 2019) initiated more detailed hydrology research in Costa Rican páramos.

3.6 | Enhancing hydrological understanding at regional scale: Integrating research toward 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 páramos provide a starting point to generalize findings to a larger area in which water resources are used and managed. Recently, a regional study by Esquivel-Hernández et al. (2019) compared the moisture origin of rainfall in Ecuadorian and Costa Rican páramos systems based on stable isotope data demonstrating the potential for regionalization. Further, to prove the usefulness of pooling data from monitored sites for streamflow predictions in ungauged basins, Ochoa-Tocachi, Buytaert, and De Bièvre (2016) used data from the iMHEA network of paired, collocated catchments with contrasting land-use types, to detect land-use change signals and thus the prediction of land-use impacts on the hydrological response of ungauged basins. The approach regionalizes a set of hydrological indices using multilinear regressions with physical and climate descriptors (Figure 6).

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, Buytaert, & De Bièvre, 2016), in contrast to previous research elsewhere in the world that found it difficult to isolate land-use signals in regionalization (e.g., Visessri & McIntyre, 2016). This demonstrates that a 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.

4 | CONCLUDING REMARKS

Hydrological understanding of the Latin American páramos improved dramatically over the last decades, being the result of increasing interaction between scientists, local and regional stakeholders. 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 amplify the benefit.

The progress of research in páramos, once one of the least studied regions in the world, is a regional and global reference due the fast development of research. With 880 scientific publications from 2001

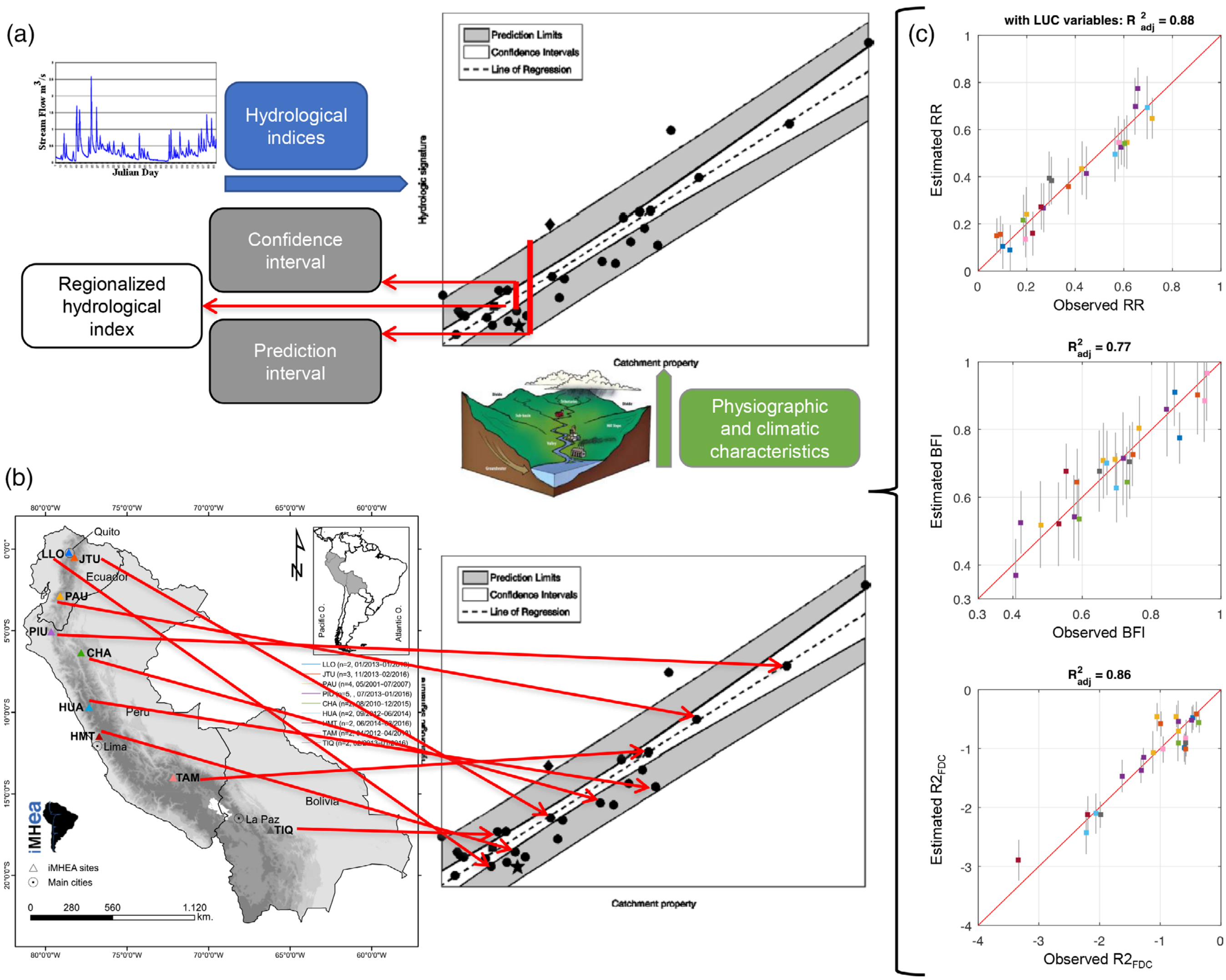

FIGURE 6 Regionalization of hydrological responses: (a) Regional relationships between catchments characteristics and streamflow signatures provide an option to make predictions in ungauged basins; (b) Pooling data from monitoring sites in the páramo and other similar biomes can support the development 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

to date a development of knowledge is evident. Increased investment in research, technology and specialized equipment has allowed the generation of long-needed information and research milestones for robust understanding and management of water resources in the region. However, the latter is strictly not the case for the Central American páramos, which are in comparison to Andean páramos still mostly understudied. Albeit smaller in spatial extent, they provide the same but unquantified water resources to downstream communities.

We therefore urgently encourage the research community to participate in projects that provide insights into the global change that occurs in these fragile ecosystems. Under the current context of climate change, it becomes important to analyse its impact on the interrelations and synergies of social biophysical and hydroclimatic conditions. We urge the scientific community to complement the challenge of long-term data collection, incursion into lumped and spatially distributed modelling to represent and transfer eco-hydrological processes knowledge to poorly monitored areas, as well as to consider the non-stationary nature of those processes. 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.

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DATA AVAILABILITY STATEMENT

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

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