Chapter 9
Ecohydrological Gradient in Neotropical Montane Ecosystems: From Tropical Montane Forests to Glacier

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9.1 Introduction

Neotropical montane ecosystems are diverse and complex, ranging from glaciers, on top of highest mountains (above 4500 masl), with no vegetation at all, to páramo ecosystems with short vegetation (between 3000 and 4500 masl), mostly herbaceous and shrubs, and to montane forest with larger tree size and abundant epiphytes hanging from tree branches and attached to tree trunks (Tobón et al. 2010). Climate conditions affect these ecosystems in a different manner, which determines their soils (e.g. weathering, physical and chemical composition), vegetation and functioning, notably, the ecohydrological one (Tobón 2022a; Aparecido et al. 2018; Beck et al. 2008; Beck et al. 2008; Bruijnzeel and Lu 2001). Although Neotropical montane ecosystems are well known for their specific climate conditions, only until the last decades they are recognized by their importance as ecosystem service provider, mainly of fresh water and the large carbon storage in soils (Tobón 2022b; Bruijnzeel and Lu 2001). Albeit several hydrological and climate studies have been carried out in Neotropical regions (Tobón 2022a; Aparecido et al. 2018; Beck et al. 2008; Bendix et al. 2008; Wilcke et al. 2008), they concentrated on a specific individual ecosystem, but almost non comprised all ecosystems in the gradient of tropical montane forest to glaciers, where this gradient is characterized by changes on

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vegetation and environmental variables connected to the altitudinal decrease in precipitation and temperature, and the increase on air humidity and fog frequency. This environmental stratification may control plant diversity, ecosystem dynamics and functioning, with their partial contribution to water supply.

Retreat of tropical glaciers, through ice ablation and snowmelt, is one the most common processes occurring worldwide in the last decades (Veettil and Kamp 2019; Rabatel et al. 2013, 2018; Vuille et al. 2018; Buytaert et al. 2017; Zemp et al. 2015; Poveda and Pineda 2009; Ceballos et al. 2006), as these are very sensitive to global warming (Veettil and Kamp 2019; Chevallier et al. 2011; Thompson et al. 2011; Ruiz et al. 2008), consequently, most of them have already disappeared or are disappearing (Vuille et al. 2018), with an apparent consequence on water yield and water supply reduction, especially from tropical mountains where downwards ecosystems are dry (Veettil and Kamp 2019; Mark et al. 2017; Marulanda Aguirre et al. 2016; Rabatel et al. 2013; Kaser et al. 2010; Vuille et al. 2018; Bradley et al. 2006). However, in some tropical mountains, as those in Colombia, glaciers are not the main source of water for downstream population, as downwards ecosystems like paramos and montane forests also provide water for people living in the Andes (Tobón 2009, 2022a). Nevertheless glacier melt could affect in different ways downstream ecosystems, as paramos and montane forests (Rabatel et al. 2017), but this is still unknown.

Gradients in the Neotropics are found for several physical and ecological variables, which provide a spectrum of landscapes and biomes that may comprise worldwide tendencies. Most outstanding ones are: (i) the climate conditions (Tobón and Cárdenas 2023; Aparecido et al. 2018; Bendix et al. 2008; Martin et al. 2007), where rainfall varies from 750 to 3500 mm y^{-1} (Tobón and Cárdenas 2023; Bendix et al. 2008; Bruijnzeel and Lu 2001; Cavelier et al. 1996), and in several sites this increases through horizontal precipitation and fog inputs (Tobón 2009, 2022c; Bruijnzeel and Lu 2001), (ii) soils and their hydraulic and physical properties (Tobón 2022b; Wilcke et al. 2008a, b) and (iii) vegetation, with a general tendency to decrease in tree height and density with altitude, ranging from an average of 15 m height trees in tropical montane (Crausbay and Martin 2016; Prada and Stevenson 2016; Apaza-Quevedo et al. 2015; Martin et al. 2007), to around 1 meter height and herbaceous vegetation in paramos (Peyre et al. 2022, 2015).

Last but not the least are the ecohydrological gradients in these tropical montane ecosystems, where changes in environmental conditions controls some processes as evapotranspiration, rainfall interception (Tobón 2022d), and thus, water yield from these ecosystems (Aparecido et al. 2018; Morán-Tejeda et al. 2018; Marulanda Aguirre et al. 2016; Kaser et al. 2010; Wilcke et al. 2008a, b; Bradley et al. 2006). Nowadays, it is well known that disappearance of tropical glaciers may generate water scarcity, or at least considerably decrease the amount of water flowing from existent glaciers (Veettil and Kamp 2019; Morán-Tejeda et al. 2018; Buytaert et al. 2017; Marulanda Aguirre et al. 2016; Kaser et al. 2010; Vergara et al. 2007; Bradley et al. 2006). Adding to this, paramos and montane forest are widely known as large water yield Neotropical ecosystems (Tobón 2022a; Aparecido et al. 2018; Buytaert et al. 2011; Célleri and Feyen 2009). However, up to now, there are no ecohydrological studies that comprise these Neotropical ecosystems in a single one, which allows the understanding of the total ecohydrological contribution of these Neotropical montane ecosystems to total water yield.

Accordingly, in this study, we analyse the specific climatic and ecohydrological conditions of the three main Neotropical montane ecosystems in Colombia: glaciers, paramos and montane forests, and disclose the key parameters that control the ecohydrological functioning of these Neotropical montane ecosystems. Collected data from an entire elevational gradient at Río Claro basin within Los Nevados Natural Park (Colombia) allowed us for a comprehensive description of altitudinal climate and ecohydrological gradient and provides evidence of the role of climate, soils and vegetation drivers on ecosystem ecohydrological functioning, their specific role in Neotropical montane water cycle and ecosystem water yield.

9.2 Methodology

9.2.1 Study Sites

This study includes three ecosystems located above 2700 masl.: (i) tropical montane forest, also called cloud forest (Bruijnzeel 2004), (ii) paramos and (iii) glacier ice caps, in the uppermost headwaters of the Rio Claro basin (Fig. 9.1), which flows

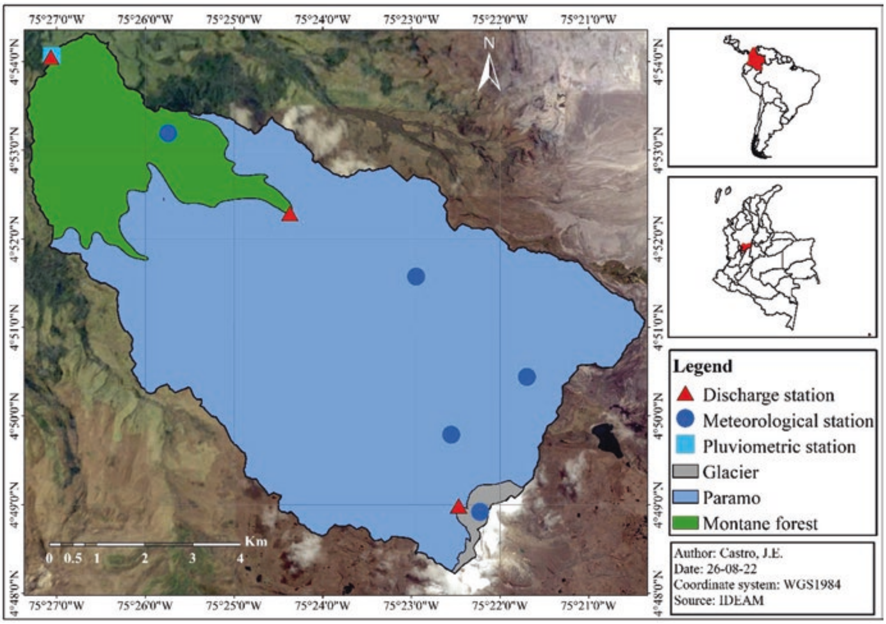

Fig. 9.1 Gradient of Neotropical ecosystems in Claro river basin of Colombia: glacier, paramo and montane forest areas and meteorological and hydrological stations are indicated

down through the three ecosystems and originates in the snowfields of the Conejeras glacier, as part of the Nevado Santa Isabel, located on the West flank of the Central Cordillera of Colombia, as part of the Nevados National Park (Fig. 9.1). The Santa Isabel glacier has been retreating since the nineteenth century, with an intensification of deglaciation since the middle of the twentieth century, and as a result, the glacier is now a set of separated ice fragments instead of a continuous ice mass, as it was two decades ago (IDEAM 2012). One of the fragments, located at the northeast sector of the glacier, is the Conejeras glacier, which is studied here, as being part of the Rio Claro basin, and whose elevation ranges between 4700 and 4895 m. In 2006, at the glacier terminus, hydro-meteorological stations were installed in order to measure weather conditions, glacier contribution to runoff and rainfall. Automatic weather and hydrological stations were also installed in the paramo and montane forest, following an altitudinal gradient (Fig. 9.1). The total area of the basin with studied gradient of ecosystems comprises an area of 71,5619 km^2, (0,8559 km^2 correspond to glacier, 51,0487 km^2 to paramo and 19,6573 to montane forest) (Fig. 9.1).

The part of the Claro river basin studied here comprises ecosystems located at altitudinal gradient between 2700 and 4895 m and, from highest to lowest part included in this study, presents a succession of typical Andean ecosystems: glacier and periglacial (4300–4894), paramo biome (3200–4300 m) and montane tropical forest ecosystem (2700–3200 m). The first step was to determine the basin area, and separately for each ecosystem considered in this study. Therefore, a detail high-resolution watershed area for the entire Claro river was created using cartography on a 1:25.000 scale, from where the specific delimitation of the basin was made and ecosystem areas were separated (Fig. 9.1).

9.2.2 Collected Data

Meteorological and hydrological data used in the present work have been collected by the Institute for Hydrological, Meteorological and Environmental Studies of Colombia (IDEAM) and Universidad Nacional de Colombia. Data on meteorological and hydrological variables, as precipitation, temperature and air humidity were collected through a network of automatic weather stations, located at different altitudes within the Rio Claro basin, from 2010 until 2021 (Fig. 9.1, Table 9.1). These data were collected on an hourly basis, from where daily, seasonally and yearly data were calculated. From meteorological data, actual evapotranspiration (ETa) was calculated for the paramo and montane ecosystems by using the Penman-Monteith (PM) equation and parameters values deduced for the paramo and montane forest vegetation (Tobón and Castro 2023). There are no lysimeter measurements of evaporation/sublimation ($Ls = 2.834 \times 10^6$ J kg^{-1}) available for the studied glacier, therefore this was calculated from the latent heat of sublimation for snow/ice at zero degrees (Armstrong and Brun 2008; Wagnon et al. 1999). Data on stream discharge

Table 9.1 Meteorological and hydrological stations to measure weather conditions and stream discharge gradients in Neotropical basin (Río Claro), between 2010 and 2021

Ecosystem	Station type	Location	Altitude (m)	Average annual rainfall (mm)	Average annual temperature (°C)	Average annual relative humidity (%)
Glacier	Meteorological (MMA)	4° 48′ 59″ N 75°22′ 25″ W	4759	754.2 ± 36.6	0.10 ± 2.7	95.6 ± 9.1
Glacier	Meteorological (Conejeras)	4°48′59.16″N 75°22′28.02″W	4699	887.2 ± 40.8	1.09 ± 1.5	94.9 ± 8.6
Paramo	Meteorological (Sendero Laguna Verde)	4°50′26.4″N 75°21′41.76″W	4325	978.9 ± 209.2	3.8 ± 2.6	88.6 ± 12.0
Paramo	Meteorological (Conejeras)	4°49′47.4″N 75°22′33″W	4304	1211.10 ± 204.4	3.4 ± 1.9	ND
Paramo	Meteorological (PNN Los Nevados)	4°51′34.5″N 75°22′56.7″W	3637	972.3 ± 424.2	7.8 ± 2.5	84.9 ± 12.5
Montane forest	Meteorological (San Antonio)	4°53′11.46″N 75°25′44.52″W	3052	1406.8 ± 475,7	10.5 ± 3.0	92.9 ± 7.9
Montane forest	Pluviometric (Río Claro)	4°54′3,18″N 75°27′3,96″W	2714	1387.30 ± ND	ND	ND
Glacier[a]	Discharge (Conejeras)	4°48′59,16″N 75°22′28,02″W	4699			
Paramo[a]	Discharge (Sietecuerales)	4°51′34″N 75°22′56″W	3450			
Montane forest[a]	Discharge (Río Claro)	4°54′3.18″N 75°27′3.96″W	2714			

[a]Stations to measure discharge only

were collected at three elevations along the Claro river within the basin, by installing Parshall gauges in the main stream of Claro river, equipped with OTT Hydromet equipment (OTT Hydromet Co.) to measure the water level (Table 9.1) each minute, and average data was recorded every 15 minutes since 2010 until 2021. Data was converted to a water volume (m^3 s^{-1}) and water depth (mm) through in situ calibration by volumetric discharge measurements and the construction of a flow rate curve for each station.

In this study we concentrated on analysing the measured discharge from each studied ecosystem, which is, the amount of water flowing down from the three different ecosystems in this Neotropical gradient: glacier, paramo and montane forest, and compare the water outputs with inputs in each ecosystem. This was done by calculating the different hydrological indices (Table 9.2) to characterize streamflow responses of individual ecosystem to rainfall events.

Table 9.2 Hydrological indices to evaluate streamflow responses to rainfall events

Index	Equation	Description
Runoff ratio	$Wy = \frac{Q}{P}$	It is the ratio between the total discharge (Q) and precipitation (P), both in mm (Chang 2013)
Runoff coefficient (%)	$\mathrm{Rc} = \frac{\mathrm{Qr}}{P} \times 100$	It is the ratio between stormflow or fast runoff (Qr) and precipitation (P) in mm. This coefficient indicates how fast an ecosystem responds to rainfall events (Singh and Eng 2017)
Base flow index (%)	$\mathrm{BFI} = \frac{\mathrm{Qb}}{\mathrm{Qt}} \times 100$	It is the ratio of daily base flow discharge (Qb) and the daily total discharge (Qt) in mm (Stoelzle et al. 2020)
R-B flashiness index	$R - Bi = \frac{\sum_{i=1}^{n} \lvert q_i - q_{i-1} \rvert}{\sum_{i=1}^{n} q_i}$	It provides a meaningful characterization of the way a given basin converts rainfall into streamflow (Baker et al. 2004)
Water regulation index (%)	$\mathrm{IRH} = \frac{\Sigma Q_{Q<50}}{\Sigma Q}$	This is the volume of water below the 50th percentile (Q50) in the flow duration curve divided by total volume (Qt) (IDEAM 2014)
1st quartile of the distribution of de FDC	$Q25 = \frac{\sum_{i=1}^{Q25} q_i}{N_{q<Q25}}$	It is the average of discharge occurring during 25% of the time from the Flow Duration Curve (FDC), and it describes the mean discharge with less probability of exceedance
3rd quartile of the distribution of the FDC	$Q75 = \frac{\sum_{i=1}^{Q75} q_i}{N_{q<Q75}}$	It is the average of discharge occurring under 75% of the time from the FDC

9.2.3 Data Analysis

For a better understanding of gradient distribution of discharge, measured rainfall at the different sites was spatialized separately for the glacier, paramo and montane forest. This was carried out through Invers Distance Weight (IDW method), which is a deterministic method based on the assumption that the depth of rainfall at unmeasured sites is equal to the distance weighted average of data points occurring within a neighbourhood of measured sites (Albert et al. 2014; Di Piazza et al. 2011). Thus, through this method, the total rainfall for every point at each ecosystem was calculated using Eq. (9.2) $z(x) = \sum_{i=1}^{N} w_i z_i$

Where $z(x)$ is the estimated value of rainfall for the total area at issue, w_i is the weight expressed as function of distance. The function of distance is determined by the Eq. (9.3):

$$w_i = \frac{\frac{1}{d_{ik}}}{\sum_i^n \frac{1}{d_{ik}}}.$$

Where d_{ik} is the distance of every point (station) to the centroid of the zone or catchment, and n is the number of stations. From the annual amounts of precipitation and discharge measurements made at each gauge station (Table 9.1), annual and average water yield was calculated as the relationship between annual discharge and annual rainfall, from which standardized water yield ($m^3\ ha^{-1}\ year^{-1}$) was deduced, using the area occupied by each ecosystem in the studied basin. Discharge measurements also allowed for the calculations of daily discharge ($mm\ d^{-1}$) and average daily streamflow ($m^3\ s^{-1}$). To determine the hydrological gradient as the responses of individual ecosystems to rainfall events, two approaches were followed: (1) the separation of streamflow flowing down from each ecosystem and (2) the hydrological response analysis through hydrological indices (Table 9.2). Streamflow separation was carried out for individual events, as the direct response of ecosystem to rainfall events or stormflow and delay fluxes of water or base flow. To this purpose, a specific technique was carried out by means of *Recursive Digital Filter technique* proposed by Lyne and Hollick (1979): $\mathrm{Qb} = \propto q_{t-1} + \frac{(1+\propto)}{2}(Q_t - Q_{t-1})$,

Where Qb is the filtered quick response at kth sampling instant, $qt - 1$ is the filtered quick response at the previous instant ($t - 1$), α is a filer parameter (dimensionless), Q_t is the original streamflow and Q_{t-1} is the total discharge at the previous instant ($t - 1$).

As glacier melting seems to be the most important process worldwide, mainly in the tropics (Cepeda Arias et al. 2022; de Vries et al. 2022; Thompson et al. 2021; Xin et al. 2021; Braun et al. 2019; da Rocha et al. 2019; Dussaillant et al. 2019; Seehaus et al. 2019; Veettil and Kamp 2019; Morán-Tejeda et al. 2018; Wu et al. 2015; Zhang et al. 2011; Fujita et al. 2006), therefore a relationship between discharge from the glacier and air temperature was searched by means of regression analysis. The regression model (Eq. 5) estimated the daily discharge (dependent variable, y) in function of temperature (independent variable, x).

$$y = \beta o + \sum_{i}^{N} a_i X_i \,,$$

where a_i is the ith regression model parameter and X_i is the daily temperature.

9.3 Results

Climate in the entire gradient is normally inter-tropical and it is mainly characterized by small fluctuations in inter-annual temperatures but large daily temperature fluctuations. In studied gradient, rainfall displays a bimodal regime during the year due to the influence of the intertropical convergence zone (ITCZ) and the mountainous terrain of the region, with two seasons with higher rainfall (March to June and October to December) and two with lower rainfall amounts (December to early March and July to early September). The climate gradient in these Neotropical montane ecosystems is characterized by a gradual decrease in temperature as altitude increases, which is related to the adiabatic process undergone by air masses, which tend to expand and decrease in temperature with altitude, which in turn controls cloud formation and thus precipitation, partly determining the water entering and the supply from these ecosystems (Tobón and Cárdenas 2023). In addition, there is a low thermal oscillation on an annual scale, but a considerable wide range on a daily scale (Tobón and Cárdenas 2023), with sudden changes in meteorological conditions, which are determined by the presence of low clouds or fog, which cover these ecosystems and temporarily modify the atmospheric weather conditions. Average values for annual rainfall, air temperature and relative humidity of air are presented in Table 9.1 for the studied ecosystems.

In the studied Neotropical gradient, rainfall presents a large spatial variability between individual events, despite the fact that all rain gauges were located with the same exposure within the studied basin (towards the west side). Moreover, there were statistically significant differences ($p < 0.05$) in annual rainfall inputs to the three ecosystems located at different altitudes, showing a decrease on total annual rainfall as altitude increases (Table 9.3). In table 3 we present the average, maximum and minimum values of annual rainfall, and the rainiest day during the studied period, and for the entire gradient ecosystems. For all ecosystems, during the study period, 2013 was the wettest year and 2015 the year with the lowest precipitation. Similarly, most of the events were of low intensity and magnitude (most with rainfall between 0.2 and 0.8 mm being the lowest in the glacier and paramo ecosystems, respectively). Completely dry days, with no precipitation events are uncommon in the entire gradient, but dry days (with rainfall lower than 0.8 mm) normally occur between December to March and August to September, among which, January is on average the month with the highest number of dry days, followed by February.

Table 9.3 Maximum, minimum, and mean values for rainfall, temperature, relative air humidity and evaporation/evapotranspiration occurring at the Neotropical gradient of ecosystems in Colombia

Variable	Glacier	Paramo	Montane forest
Maximum annual rainfall (mm)	1157.3 (2011)	1583.8 (2011)	2064.4 (2011)
Mean annual rainfall (mm)	870.2 ± 43	1296 ± 106	1580 ± 206
Minimum annual rainfall (mm)	750.3 (2015)	948.9 (2015)	1387.3 (2015)
Rainiest day (mm day^{-1})	9.8 (2014)	58.5 (2010)	58.4 (2010)
Maximum daily temperature °C	11.3 (12:00 hours)	21.7 (13:00 hours)	24.9 (14:00 hours)
Mean daily temperature °C	0.33 ± 1.6	5.4 ± 3.1	10.58 ± 2.98
Minimum daily temperature °C	−9.3 – at night time	−2.6 – at night time	2.3 at night time
Maximum relative humidity (%)	100 (at least once a day)	100 (at least once a day)	100 (at last once a day)
Mean relative humidity (%)	94.8 ± 10.4	85.1 ± 11.7	92.93 ± 7.40
Minimum relative humidity (%)	60 (13:00 hours)	50 (15:00 hours)	40 (15:00 hours)
Maximum annual evaporation/ evapotranspiration (mm)	245.6 (2015)	443.3 (2015)	789.1 (2015)
Mean annual evaporation/ evapotranspiration (mm)	170.6 ± 21.5	378.6 ± 41.2	567.7 ± 72.3
Minimum annual evaporation/ evapotranspiration (mm)	148.7 (2011)	315.4 (2011)	498.7 (2011)

9.3.1 Temperature

Annual average temperature for the different sites in studied Neotropical gradient is presented in Table 9.1. Differences among sites within the same ecosystem were not significant ($p \geq 0.05$); however, annual average values were significantly different among ecosystems ($p < 0.05$), but also in the maximum and minimum values registered at each one (Table 9.3). Except for the glacier, in studied Neotropical ecosystems, temperature decreases at a rate of 0.89 °C at each 100 m of altitude, and the greatest amplitude of diurnal variation of temperature was observed in the paramo (a difference of 18.9 °C in the same day), as compared with the other two biomes (Table 9.3). Maximum, minimum and annual average values of daily temperature at the studied gradient of ecosystems are presented in Table 9.3. During the studied period and for the entire gradient, the warmer years were 2015 and 2016, respectively, in which the number of warm nights (temperatures above 5 °C) increased considerably compared to the overall average, which appeared to be related to the ENSO phenomena occurring between 2015 and 2016 (IDEAM 2016). In general, in the entire gradient, the maximum extreme temperature values occurred in January and eventually, in September. In contrast, the coldest ones were 2011 and 2019, but lowest temperature tended to occur annually between December and February. For the glacier, negative temperatures are normal throughout the year, but almost not for the montane forest (Table 9.3). As a general tendency, in the studied Neotropical gradient, there is a daily tendency of having low temperatures between 00:00 and 5:00 hours, which increases during early mornings, reaching a maximum around 12:00 hours for the glacier, 13:00 hours for the paramo and around 14:00 hours in the montane forest (Table 9.3).

9.3.2 Relative Air Humidity

Relative air humidity in studied Neotropical ecosystems does not have a gradient in any direction: lowest relative air humidity in time was registered in the glacier and the highest, through the time, occurred in the paramo; moreover, some very high air humidity, close to saturation (above 98%) was common at all ecosystems, and almost every day (Table 9.3). This variable has a negative asymmetric distribution or negative bias, which indicates that there is a greater possibility of finding values above the mean (87.8 ± 9.4%) in studied ecosystems. Predominantly, increases in air humidity in this Neotropical gradient of ecosystems were related to the presence of rain, fog or both, reaching saturation conditions in most cases and exhibiting stability conditions for several hours, independently of diurnal or nocturnal hours. Nonetheless, the stability was longer during the night and early morning. Air humidity ranged from 60% to 100% in the glacier, from 50% to 100% in the paramo and between 60% and 100% in montane forest. The averages of maximum, mean and minimum annual values are presented in Table 9.3. The largest range of variation of relative humidity in a single day was 61%, occurring in the paramo and the lowest was 5%, occurring both, in the paramo and montane forest, mainly between April and July and in November of each year, except at the end of 2015 and first months of 2016, when air humidity was the lowest, which could be related to the effects of the ENSO phenomenon (2015) on the national territory (IDEAM 2016). Although

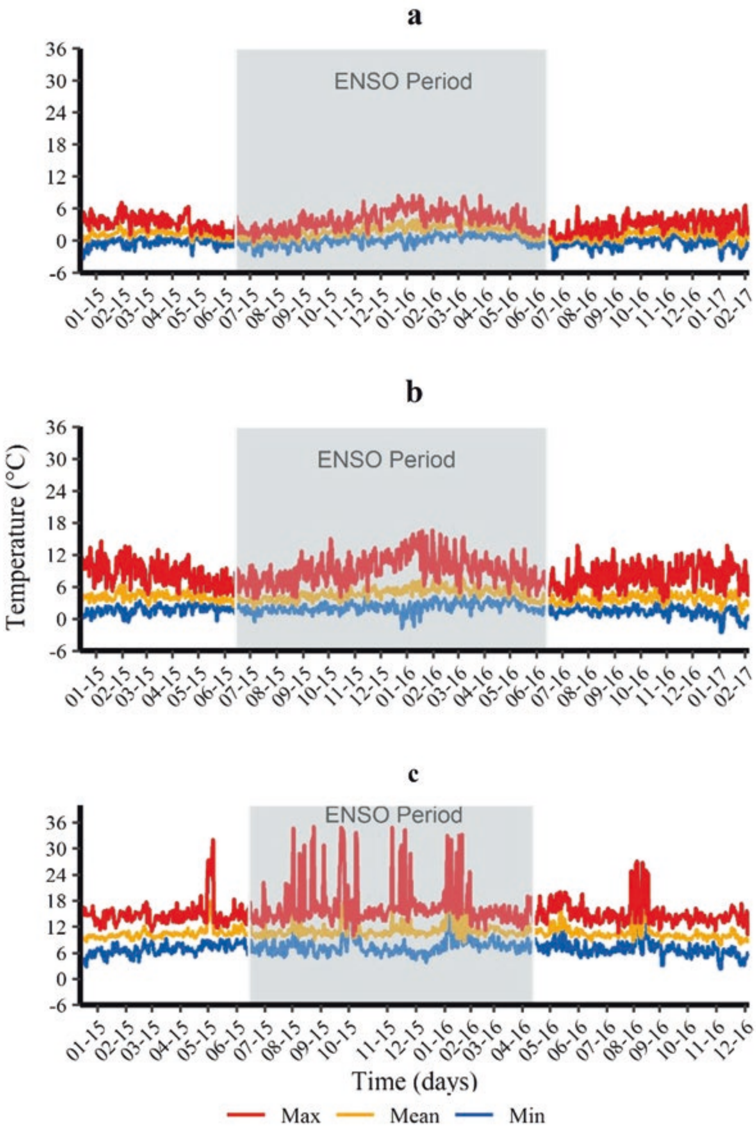

Fig. 9.2 Temporal behaviour of maximum, minimum and average values of temperature in studied gradient of Neotropical ecosystems in Colombia ((**a**) glacier, (**b**) paramo, (**c**) montane forest), during the ENSO phenomena occurring from 2015 to 2016

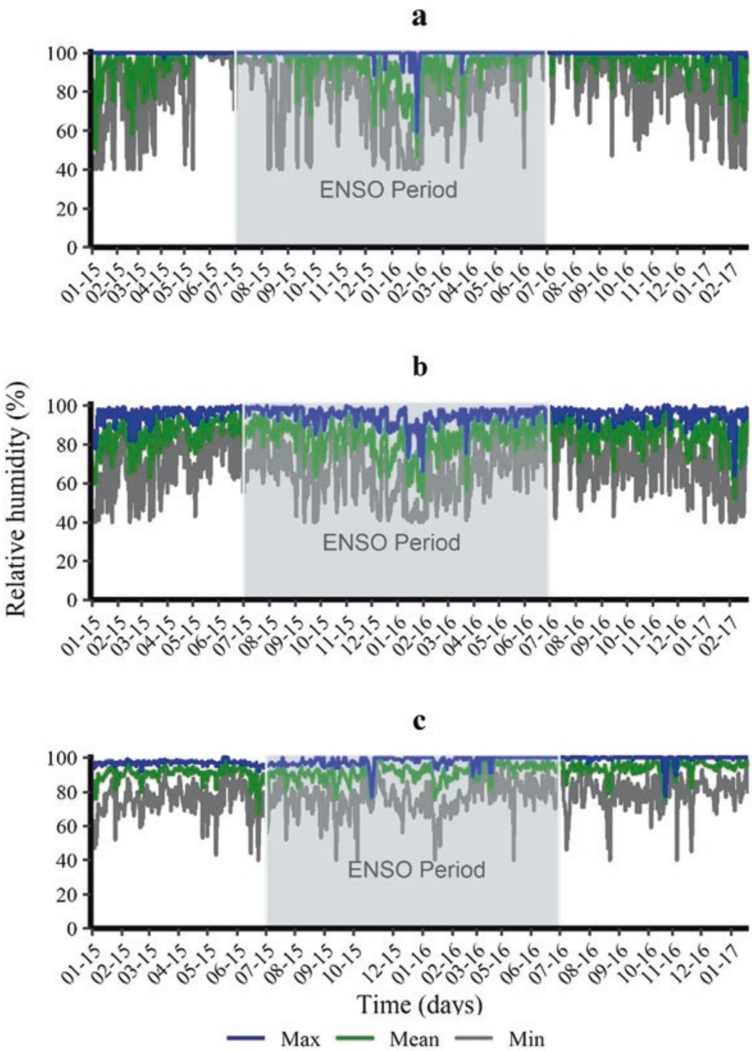

Fig. 9.3 Temporal dynamics of maximum, minimum and average values of relative air humidity in a gradient of Neotropical ecosystems in Colombia ((**a**) glacier, (**b**) paramo, (**c**) montane forest), during the ENSO phenomena occurring from 2015 to 2016

temperature showed a seasonal behaviour, with the highest temperature normally between December to March, for the three ecosystems studied here, the ENSO phenomenon introduces a noise, which considerably increases on air temperature (Fig. 9.2), and decreases slightly on relative air humidity (Fig. 9.3) between August 2015 and April 2016, with maximum temperatures in December (2015) and March (2016) in the three ecosystems. Minimum temperatures and air humidity values also increased on the average, resulting in less frequent negative temperatures mainly in the paramo.

9.3.3 Evaporation and Evapotranspiration

In Table 9.3, we present the annual average, maximum and minimum values of evaporation (sublimation) calculated for the icecap of Conejeras, according to Armstrong and Brun 2008; Wagnon et al. 1999) and field measurements of radiation. Values for evapotranspiration calculated for the paramo and montane forest are shown in Table 9.1. Statistically significant differences ($p < 0.05$) were found for average values encountered in the three ecosystems. Moreover, results indicate that there is a gradient on water losses through evaporation/evapotranspiration in studied ecosystems, where montane forest presents the largest water losses through evapotranspiration and the glacier the lowest by calculated sublimation.

9.3.4 Streamflow

Found values of streamflow responses of each ecosystem to rainfall events, as water yield, baseflow and stormflow. Runoff ratio and coefficient and discharge indices are shown in Table 9.4. The hydrological response of the glacier is significantly different from the other two ecosystems ($p < 0.05$), given that its streamflow generation was constantly above total entering rainfall (larger than 100% rainfall inputs), which is indicated by the Runoff coefficient (Table 9.4), while in the paramo, the value for this parameter is less than 4% (Table 9.4), implying that about 96% of total rainfall infiltrates in the soil. This different behaviour is also evidenced in the Base Flow index, which shows that the lowest value was found for the glacier, as compared with the other two ecosystems (Table 9.4). During the study period, the largest annual water yield per hectare was observed from the glacier, as compared with the other two ecosystems in studied gradient (Table 9.4). However, it is important to

Table 9.4 Average values of streamflow parameters and indices found for the biomes studied in a gradient of Neotropical montane ecosystems in Colombia

Hydrological response index	Glacier	Paramo	BAA
Water yield (m^3 ha^{-1} $year^{-1}$)	29,624.3	4905.4	5050.6
Base flow water yield (m^3 ha^{-1} $year^{-1}$)	9883.0	4467.2	4177.8
Stormflow water yield (m^3 ha^{-1} $year^{-1}$)	20,055.6	438.2	872.8
Mean daily discharge (mm d^{-1})	8.66 ± 6.5	1.46 ± 0.2	2.56 ± 1.2
Mean daily streamflow (m^3 s^{-1})	0.02 ± 0.02	0.28 ± 0.04	1.87 ± 1.1
Runoff ratio	1.2	0.8	0.5
Runoff coefficient (%)	215.6	3.4	15.4
Base flow index (%)	36.0	96.0	86.8
R-B Flashiness Index	0.3	0.03	0.1
Water regulation index, IRH (%)	30.7	96.5	85.2
Q25 (mm d^{-1})	12.29 ± 5.6	1.67 ± 0.2	4.03 ± 1.7
Q75 (mm d^{-1})	8.73 ± 6.5	1.51 ± 0.2	2.82 ± 1.3

understand from Fig. 9.1 that the actual area of this glacier is less than 15 ha, which renders a very low value for total water yield. Moreover, most of this water yield flowed out of the glacier as a stormflow, during rainfall events (Table 9.4). In contrast, most of the total water yield from the paramo and montane forest ecosystems flowed out as base flow.

According to the results for the R-b Flashiness index, there was large variation in the daily discharge among studied ecosystems, where values range between 0.3 and 0.03. Largest values indicate high variation of discharge amounts, while low ones are an expression of stability in the discharge regimes, and values close to 0 indicate the permanence of stable discharges (e.g. paramo biome). To illustrate these dynamics, we deduced a flow duration curve for the three ecosystems (Fig. 9.4). Differences among ecosystems are evident from the 10% of the total daily flow distribution (decile). Despite the flow duration curve bringing similar quantities on the first decile (10%) for studied ecosystems, it does not mean the same moment of occurrence. It is worth noting that the glacier protrudes a shape of "false" high-water regulation, as the daily discharge values remained higher during more than 60% of the time, whereas the rest of the time, it descends to the lower values of discharges, meaning nothing but that base flow or the permanent flow is highly contrasting with the flows with low probability of exceedance. It is important to stress that in the glacier, the base flow belongs exclusively to the ice and snow melting, since there is no evidence for soil presence under the ice. In contrast, paramo and montane forest present a constant slope throughout their daily discharge distribution, but the last presents a greater slope and a lower magnitude of daily discharges (Fig. 9.4).

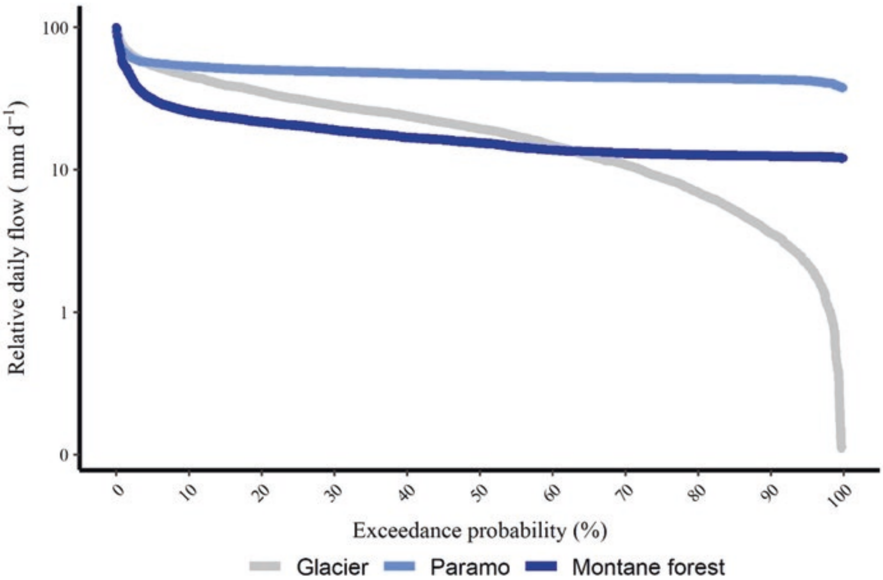

Fig. 9.4 Curves for the probability of exceedance of the daily water flow from the gradient of studied Neotropical montane ecosystems

Results of mean daily streamflow from each ecosystem indicate that the largest value is observed from the glacier, being four to six times larger than ones from montane forest and paramo, respectively (Table 9.4, Fig. 9.5), but the probability of exceeding this streamflow is lower from the glacier (16.4%) as compared from the other two ecosystems, which present a similar probability between them (39.7% and 34.2% from the paramo and montane forest, respectively). Noticeable, the glacier presents the highest amount of water by unit of area during the first and third quartile of the of the total distribution of the FDC (Q25 and Q75), as compared to the Paramo and the High Andean Forest ecosystems (Fig. 9.5), which is the result of snow and ice melting throughout the studied time, as indicated above. However, we

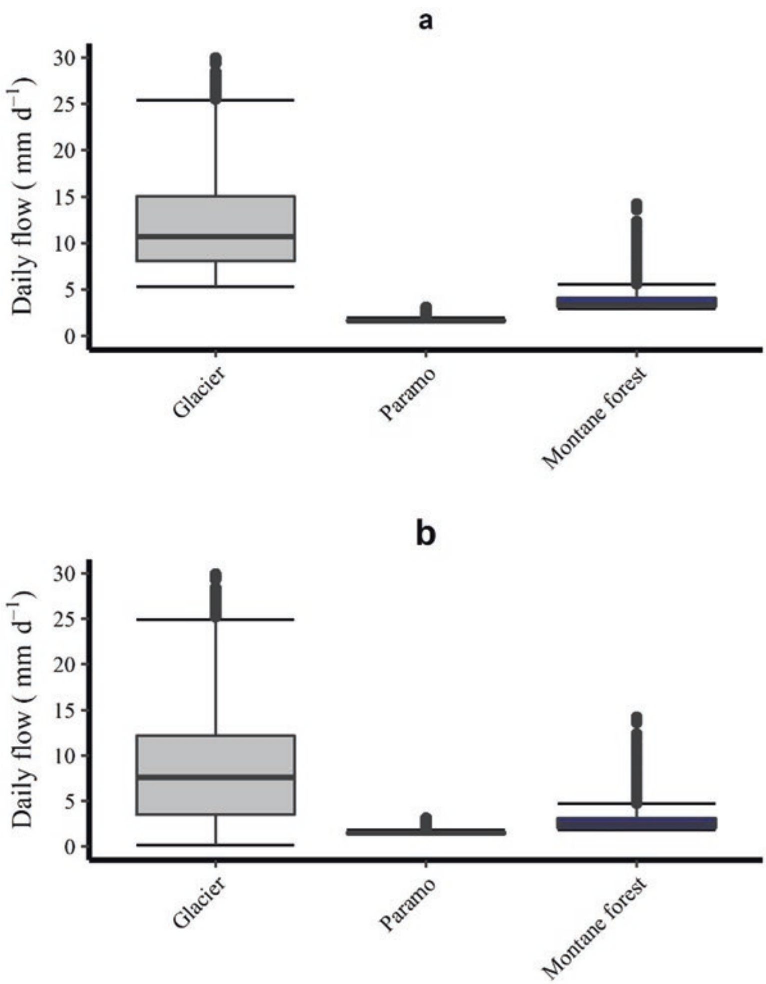

Fig. 9.5 Temporal behaviour of water flow from studied ecosystems located in an altitudinal gradient in the Neotropical environment. (**a**) Q1 (25%) and (**b**) Q3 (75%)

may take into account that some of past snow and ice coming to the glacier, accumulated on top of these mountains, which in fact acted as a regulation system for water yield today, when local environmental conditions are changing. Nevertheless, the distribution of this water yield presents low variation in the paramo, as it is illustrated in the small change in the interquartile range (Fig. 9.5), whereas the glacier changes meaningfully. The aforementioned brings a perception of stability of the discharges at the Paramo zone.

Figure 9.6 shows the temporal dynamics of daily discharge from studied gradient of ecosystems during the studied period. Daily discharge distribution from each ecosystem presented a large variability, the largest being the one from the glacier (Fig. 9.6). Average daily discharge from the glacier was about 0.02 ± 0.02 $m^3\ s^{-1,}$ with a range between 0.00013 $m^3\ s^{-1}$ and 0.1 $m^3\ s^{-1}$. The Paramo presented a mean discharge of 0.28 ± 0.04 $m^3\ s^{-1}$, with values ranging from 0.18 $m^3\ s^{-1}$ and 0.62 $m^3\ s^{-1}$, while mean daily discharge from the montane forest was 1.87 ± 1.08 $m^3\ s^{-1}$ with a range varying from 0.98 $m^3\ s^{-1}$ and 11.53 $m^3\ s^{-1}$ (Table 9.3). Discharge responses during the ENSO period (El Niño and La Niña South Oscillation) is highlighted in Fig. 9.6. According to the National Unity for the Disaster Risk Management (UNGRD), El Niño phenomenon was presented chiefly between July 2015 and July 2016 at Colombia, and La Niña between July 2010 and May 2011 (UNGRD 2016). During these events, discharge observed a distinctive behaviour through the gradient, as compared with average time conditions (Fig. 9.6). During El Niño time, there was clearly an increase in daily discharge from the glacier, with values 1.5 to 2.3 times higher than during times of average conditions. Moreover, the largest increase of discharge in studied gradient were observed from October 2010 until the half of 2011, with increments up to 2.3 times the average discharge, the largest being the one from the glacier (Table 9.3). It is important emphasize that one of the streamflow sources is the glacier melt, and during the augmentation of temperature that El Niño generates, and the evident response on discharge behaviour is evident from the glacier. Results from the regression analysis between air temperature and discharge from the glacier, as the result of ice and snow melting due to air temperature, indicated that there is a significant relationship between the discharges of the glacier and the temperature ($p < 0.05$) with a Pearson's coefficient of 0.34 (Table 9.5).

9.4 Discussion

Most ecohydrological studies in the Neotropics, as well in other latitudes, were done in a specific ecosystem (Tobón 2022a; Tobón and Bruijnzeel 2021; Rodríguez-Morales et al. 2019; Aparecido et al. 2018; Buytaert et al. 2017; Tobón 2009; Beck et al. 2008; Bendix et al. 2008; Wilcke et al. 2008a, b, Bruijnzeel and Lu 2001), although some included different ecosystems in a given gradient (Buytaert et al. 2011; Beck et al. 2008; Martin et al. 2007; Bendix et al. 2004; Cavelier 1996), but not including the three uppermost ecosystems in the Neotropics. This study allowed us to reveal the ecohydrological role of each one of these ecosystems, thus

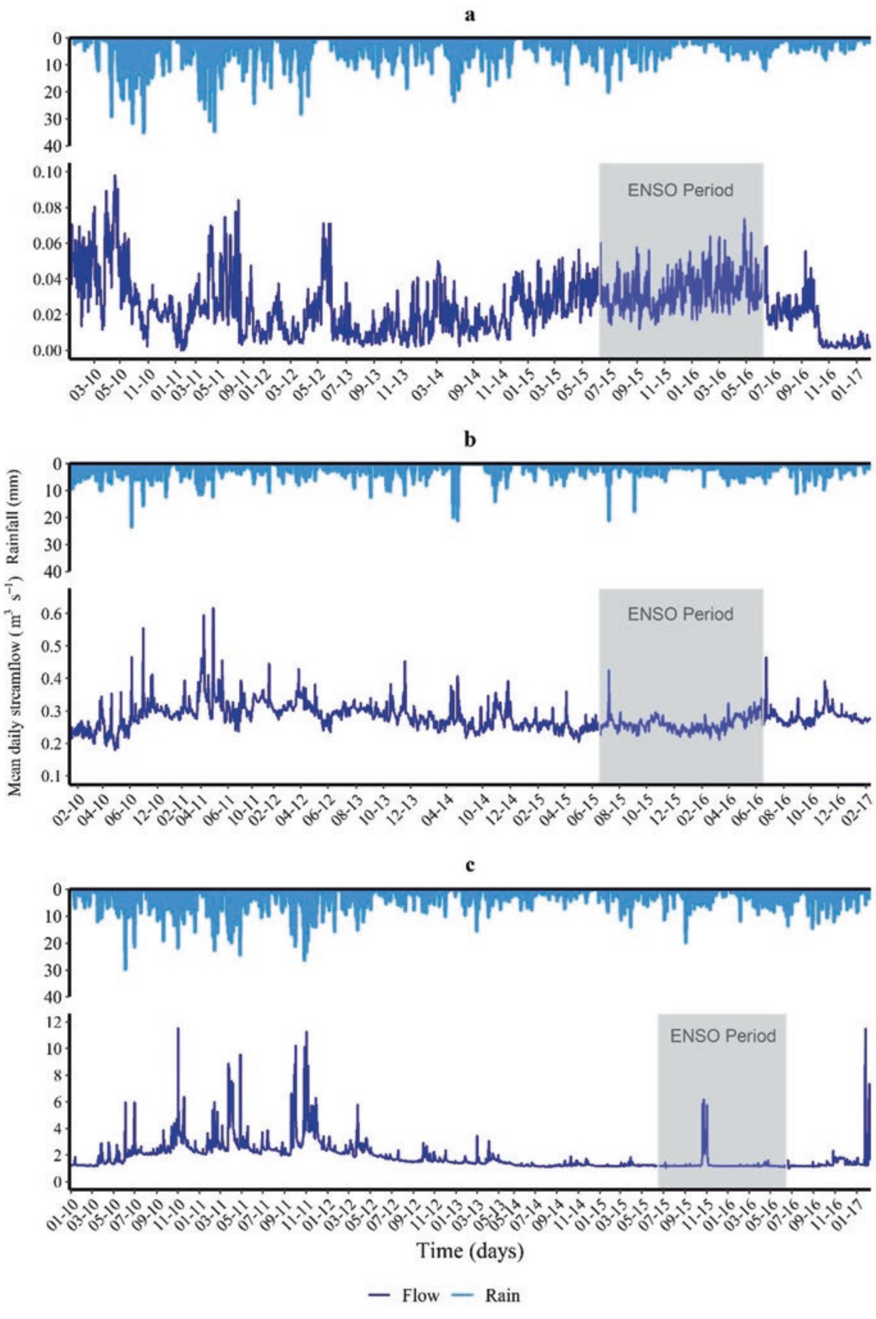

Fig. 9.6 Temporal dynamics of discharge from the Neotropical gradient of montane ecosystems, during the ENSO period, 2015–2016. Glacier (**a**), paramo (**b**) and montane forest (**c**)

Table 9.5 Results from the regression model analysis between air temperature and discharge from the glacier in the studied Neotropic gradient of ecosystems

Correlation coefficient	*t*	Degrees of freedom	*P* value	Confidence interval
0.34	14.79	1660	<2e-16	0.30–3.38

clarifying the real hydrological effects of glacier extinction on water yield, and the specific ecohydrological contribution of neighbouring ecosystems.

Based on measured weather variables, the studied ecosystems present a gradient on rainfall annual amounts and temperature conditions, both decreasing with altitude. This is similar to that described in other gradient analysis in the tropics (Sierra et al. 2015; Cavalcanti and Shimizu 2012; Buytaert et al. 2011; Poveda et al. 2011; Beck et al. 2008; Bendix et al. 2004; Cavelier 1996). Nonetheless, a clear shift on rainfall amounts occurs in studied altitudinal gradient, decreasing from the montane forest to the glacier, implying that the higher the ecosystem in the altitudinal gradient, the lower the inputs by rainfall and air temperature. Nevertheless, the fog and low clouds covering the ecosystems may contribute differently to inputs at each ecosystem according to their frequency and density (Berrones et al. 2022; Tobón 2022c; Cárdenas et al. 2017). Fog is a common feature in studied ecosystems; however, depending on its frequency, and therefore its contribution to total water inputs to the ecosystems, it seems to be higher in paramos than to other Neotropical montane ecosystems (Berrones et al. 2021, 2022; Tobón 2022c; Cárdenas et al. 2017), but there is no data available for fog inputs in Neotropical gradient, and existing studies for fog inputs to cloud forest (montane forest) may indicate the contrary (Aparecido et al. 2018; Tobón 2009; Bendix et al. 2004; Bruijnzeel and Lu 2001; Bruijnzeel and Veneklaas 1998). In any case, its contribution, as an extra water input to these ecosystems, is known worldwide (Tobón 2022a; Bruijnzeel et al. 2010; Bruijnzeel and Lu 2001).

From the glacier discharge measurements, we observed a daily streamflow cycle, which seems to be related with the ablation and accumulation dynamics presented in the Conejeras glacier (Morán-Tejeda et al. 2018). Nevertheless, these cycles were not observed at the other two measurement sites (Sietecuerales and Rio Claro stations), which implies that amounts of water added from the last mask the one from the glacier, given their larger magnitudes. Temporal dynamics of discharge from studied ecosystems normally responds to rainfall dynamics (Fig. 9.6), as it does in other ecosystems (Tobón and Castro 2023; López-Ramírez et al. 2020; Zhai et al. 2020; Guan et al. 2016; Penna et al. 2016; Crespo et al. 2011; Poveda et al. 2011). However, glaciers seem to have a differential hydrological functioning as ice and snow melting contribute considerably to the discharge (Veettil and Kamp 2019; Morán-Tejeda et al. 2018; Vuille et al. 2018; Buytaert et al. 2017; Mark et al. 2017; Chevallier et al. 2011; Marulanda Aguirre et al. 2016; Penna et al. 2016; Rabatel et al. 2013; Kaser et al. 2010; Bradley et al. 2006; Gutiérrez et al. 2006).

Although the glacier zone is capable of producing the highest quantity of water by unit of area both 25% and 75% of the time compared to the Paramo and montane forest, its very small area protrudes in a very low contribution to total streamflow in the studied gradient of ecosystems. Moreover, results here indicate that the discharge from the glacier is mostly related to snow and ice melting, according to the large values for mean daily discharge (8.66 mm d^{-1}), which is 4–5 times larger than the one in paramo and montane forest ecosystems, even during no rainfall events (Table 9.4), but also the large runoff ratio above the unit (Table 9.4), implying either a melting contribution or an extra water input to the basin. The last must not be the case, as rainfall inputs to the glacier are lower than to the other two ecosystems (Table 9.1). Moreover, a considerable discharge is flowing down from the glacier, even during the dry periods, a process that is more common in recent decades and has been widely explained by several authors, and is to be connected to ice and snow melting (Cepeda Arias et al. 2022; de Vries et al. 2022; Thompson et al. 2021; Xin et al. 2021; Braun et al. 2019; da Rocha et al. 2019; Dussaillant et al. 2019; Seehaus et al. 2019; Veettil and Kamp 2019; Morán-Tejeda et al. 2018; Wu et al. 2015; Chevallier et al. 2011; Zhang et al. 2011; Fujita et al. 2006). Moreover, ice and snow melting from the studied Conejeras glacier has been observed by different authors (de Vries et al. 2022; Braun et al. 2019; Morán-Tejeda et al. 2018; Johansen et al. 2018; Albert et al. 2014; Rabatel et al. 2013; Ceballos et al. 2006), which explains the high runoff ratio of 1.2 found from the glacier discharge, despite its very low mean daily streamflow, as compared with that from the paramo and montane forest (Table 9.4).

Results here show that the studied glacier is melting throughout the years, which explains its current large discharge as compared to rainfall annual inputs, indicating that if the trend continues as it is occurring now, this glacier will disappear soon (Morán-Tejeda et al. 2018; Rabatel et al. 2018; Vuille et al. 2018; Poveda and Pineda 2009; Ceballos et al. 2006), with important consequences for water supply to the local population, as concluded by several authors (Cepeda Arias et al. 2022; Veettil and Kamp 2019; Morán-Tejeda et al. 2018; Johansen et al. 2018; Vuille et al. 2018; Marulanda Aguirre et al. 2016; Chevallier et al. 2011; Vergara et al. 2007; Bradley et al. 2006; Gutiérrez et al. 2006), whose studies comprise the glaciers only, without considering the ecohydrological functioning of neighbouring ecosystems.

Contrary to those findings, after including the entire gradient of Neotropical montane ecosystems in an ecohydrological survey, this study demonstrates that disappearance of small glaciers, such as the Conejeras one, located in humid gradients (e.g. Claro river basin), the extinction of a glacier will not threaten the water supply, nor water availability for people downstream. The found low values for streamflow indices (Table 9.4) and the very small area of the glacier (0.8559 km^2) clearly indicates that in this gradient of ecosystems, paramos and montane forest are the main water source in the studied basin, mainly due to their large rainfall inputs and large exposed areas. Although runoff alterations are expected to occur once this glacier disappears (whose actual values are shown in Table 9.4), glacier streamflow magnitudes will be masked by downward ecosystems. However, this must not be the case, for a glacier located in dry environments, where downward ecosystems do not receive considerable precipitation, thus does not have an important contribution to streamflow, and people depend on glacier water, as happens in Peru and Chile (Escanilla-Minchel et al. 2020; Seehaus et al. 2019; Vuille et al. 2018; Baraer et al. 2012;

Gascoin et al. 2011; Vuille et al. 2018; Kaser et al. 2003) and other dry zones of the world (Frans et al. 2018; Carey et al. 2017; Sorg et al. 2012; Kaser et al. 2010; Tandong et al. 2007). Notably, in this gradient analysis, the water regulation capacity of each ecosystem becomes an important issue to study, as this capacity can be used as an indicator of the level of risk for water supply to people depending on water from Neotropical ecosystems.

Concerning the paramo ecosystem, the runoff ratio is 0.8, which implies that at least 20% of rainfall inputs is converted to evapotranspiration and deep water percolation. However, according to the results here, evapotranspiration from the paramo represents 29% of average rainfall inputs (Table 9.4), which suggest that there are extra water inputs to the paramo ecosystem. According to Tobón (2022c), annual fog inputs to this paramo range from 142 to 219 mm, which represent 18% of mean annual rainfall. Fog water inputs to the paramo ecosystem in Northern Andes are well documented (Berrones et al. 2021; Ochoa-Sánchez et al. 2018; Cárdenas et al. 2017; Tobón et al. 2008), with values up to 340 mm y^{-1}; however, larger numbers have been reported for montane forest (Bittencourt et al. 2019; Ramirez et al. 2017; Domínguez et al. 2017; Pryet et al. 2012; García-Santos and Bruijnzeel 2011; Rollenbeck et al. 2011; Tanaka et al. 2011; Holwerda et al. 2010; Gomez-Peralta et al. 2008; Villegas et al. 2008; Holder 2003).

Lastly, to highlight the hydrological attributes and as part of the flow duration curve within studied ecosystems, paramo stands out as the highest water regulation, as is indicated by the largest IRH value, which is closely followed by montane forest (see Table 9.4). This implies a homogeneity in discharge distribution, where the average volume of this discharge is similar to the total volume of water that these ecosystems generate. These results also indicate that the Glacier has a high heterogeneity in the distribution of its discharges, with large values depending either on temperature conditions or rainfall events.

9.5 Conclusion

The climate and ecohydrological gradient of Neotropical ecosystems in the Claro river basin was studied, which gives an insight into the partial contribution of each ecosystem to total water yield from the basin and ecohydrological functioning of Neotropical ecosystems. Temperature and rainfall decrease with increase in altitude, while relative air humidity did not present a clear trend. Rainfall–runoff responses from each ecosystem showed that although the actual contribution of glacier is relatively high, its net contribution is considerably low when considering the contribution of other ecosystems, such as the paramo and montane forest, which showed to be connected to rainfall amounts and exposed area of each ecosystem.

This study demonstrates that the extinction of small Neotropical glacier may not threaten the water supply to the local population. The specific humid conditions of ecosystems surrounding the studied glacier makes a great difference on the hydrological consequences of glacier retreat and its disappearance, as the contribution from those ecosystems to water yield is considerably larger than the one from the small glacier. This highlights the ecohydrological importance of paramos and montane forests for water supply to the local population, notably their large capacity for water regulation.

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