Environmental Science and Pollution Research (2022) 29:83169–83190
https://doi.org/10.1007/s11356-022-21709-6

RESEARCH ARTICLE

Effect of agricultural activities on surface water quality from páramo ecosystems

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Received: 5 April 2022 / Accepted: 23 June 2022 / Published online: 28 June 2022

Abstract

Páramos are high mountain ecosystems strategic for water provision in South America. Currently, páramos are under threat due to agricultural intensification that impairs surface water sources. This research analyzed the effect of agriculture (spring onion—*Allium fistulosum*, potato—*Solanum tuberosum*, and livestock farming) on water quality in páramo ecosystems. A Hydrographic Unit upstream of the Jordan river catchment (Colombia) was selected and monitored in two different rainfall regimes, following the paired catchments and upstream-downstream approaches to compare water quality from natural and anthropic areas. Twenty-two parameters related to agricultural activities were analyzed (nutrients, salts, organic matter, sediments, and pathogens). The studied agricultural activities increased loads of surface water in quality in nitrates (0.02 to 2.56 mg $N\text{-}NO_3$/L), potassium (0.13 to 1.24 mg K/L), and *Escherichia coli* (63 to 2718 FCU/100 mL), generating risks on the human health and promoting eutrophication. Total nitrogen and organic matter in the rainy season were higher than dry. BOD_5, COD, turbidity, and *E. coli* were above international standards for direct human consumption. However, water could be used for irrigation, livestock watering, and aquatic life ambient freshwater. The results show that a small land-use change of almost 15% from natural páramo vegetation to agricultural uses in these ecosystems impairs water quality, limiting its uses, and the need to harmonize small-scale livelihoods in the páramo with the sustainability of ecosystem service provision.

Keywords Páramo · Hydrological services · Agriculture · Water quality · Water uses

Introduction

Mountain regions are fundamental from different perspectives for their inhabitants and people in the lowlands who benefit from their environmental services, including water regulation and supply (Schild and Sharma 2011; Wester et al. 2019). It is estimated that half of the global population depends on water collected, stored, and purified in mountain areas (Grêt-Regamey et al. 2012). Paradoxically, mountain ecosystems are increasingly threatened due to rapid global development, climate change (Grêt-Regamey et al. 2012; Hock et al. 2019; Wester et al. 2019), and land-use change, primarily related to the expansion and agriculture intensification (Dhakal and Kattel 2019; Shahgedanova et al. 2021).

Páramos are high-mountain ecosystems located in the Andean range, between the limit of the high forest and perpetual snows, and are strategic ecosystems for the provision of hydrological services. In Colombia, páramos are located in the three ranges and the Sierra Nevada de Santa Marta and provide water to around 17 million people (Pinilla et al. 2016). Despite recognizing their importance, páramo conservation is complex because stakeholders with different social, cultural, and economic realities converged in these lands (Díaz Ramos et al. 2020), including traditional small-scale farmers.

Globally, agriculture is considered the most pressing activity over water resources for its high demand and contribution to surface and groundwater pollution. In some regions, agriculture pollution is even higher than industrial and urban sources (Evans et al. 2019; FAO and IWMI 2018). The causes of agricultural pollution include excessive agrochemical use, inadequate postharvest and animal waste management, and conventional irrigation systems

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Responsible Editor: Xianliang Yi

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(Moss 2008; Zia et al. 2013). These practices cause the release of nutrients, salts, pesticides, organic matter, sediments, pathogens, heavy metals, and other emerging contaminants that, through different processes, such as runoff, erosion, atmospheric deposition, and leaching, reach water bodies compromising their quality (FAO and IWMI 2018). Despite this situation, water pollution from agriculture has not received enough attention (Evans et al. 2019; Patterson et al. 2013), mainly due to its diffuse nature, characterized by the random location of discharges, and complex transport mechanisms that increase the challenge for water resource management (Giri and Qiu 2016; Ongley et al. 2010; Ouyang et al. 2017a).

In high-mountain ecosystems, impacts from agriculture on water quality are critical. These ecosystems are considered among the most fragile ecosystems on earth, characterized by low recuperation rates after anthropic perturbations (Bierman-Lytle 2015). In addition, due to the peculiar environmental conditions, these areas have particular dynamics that govern the transport and fate of agricultural contaminants, which must be addressed to understand better the complex relationship between land use and water quality (Melland et al. 2018; Ouyang et al. 2017b; Yu et al. 2016).

In diverse geographical contexts, water quality monitoring in agricultural catchments has been crucial to identifying inadequate uses, causes, and pollution sources, assessing the fulfillment of regulations, validating or calibrating models, monitoring tendencies, and evaluating conservation practices' effectiveness. However, in developing countries, the lack of strategies for water quality monitoring in high-mountain regions is evident and a constraint to facing the challenges of science-based sustainable development (Riveros-Iregui et al. 2018; Shahgedanova et al. 2021).

In the case of Andean páramos, studies have been carried out in Ecuador to analyze the effect of tillage and burning (Poulenard et al. 2001) and extensive livestock (van Colen et al. 2018) on water quality, finding direct relationships between these agricultural activities and loss of soil and nutrient runoff. On the other hand, in a páramo from Venezuela with crops and fallow land, it was established that soil loss could be significantly reduced if conservation agriculture was adopted (Sarmiento 2000). In Colombia, two studies concluded that crops in páramo catchments deteriorate water quality due to the high concentrations of nitrogen and phosphorus in runoff (Otero et al. 2011; Ruiz et al. 2017). Other studies in Colombia have addressed water quality deterioration in Lago de Tota catchment, a páramo that provides water to several settlements. These investigations found negative impacts associated with pesticides (Mojica and Guerrero 2013; Barrera et al. and excess of nutrients (Abella and Martínez 2012; Aranguren-Riaño et al. 2018; Benavides Sierra et al. 2020). In addition, it has been demonstrated that different land uses in páramo (e.g., agriculture and carbon mining) could compromise water quality for direct human consumption and recreation (González-Martínez et al. 2019).

Even though these works evidence land-use effects on water quality in páramos, they only considered a few parameters for assessing the contribution of agriculture to surface water quality degradation in páramos and typically ignore their influence on ecosystem services. Furthermore, previous studies in páramos usually overlook the effect of the rainfall regime on the analysis of diffuse pollution from agriculture. To fulfill these gaps, we conducted an exploratory study in a páramo ecosystem from the Eastern range in Colombia, where agricultural activities are present. The objectives of our study were (i) to analyze whether different agricultural contaminants (nutrients, organic matter, sediments, and pathogens) affect water quality and could compromise its use for different purposes such as human consumption, irrigation, livestock watering, and aquatic life ambient freshwater, and (ii) to assess the influence of the rainfall regime on the water quality of surface sources. Results from this study facilitate decision-making around solutions to harmonize agricultural activities of traditional small-scale farmers from the páramo with the preservation of hydrological services from this strategic ecosystem.

Methods

Water quality monitoring approach

Two methodological approaches for water quality monitoring were adopted: (i) upstream-downstream and (ii) paired catchments. These approaches allowed an exploratory analysis of the effect of land use on the water quality attribute of the water supply hydrological service provided by the páramo ecosystem. The Environmental Protection Agency from the United States (USEPA) recommends these approaches for non-point water pollution monitoring (Dressing and Meals 2005). They have been used by different authors in the study of the relationship between land-use and water quality in high-mountain regions, including páramo ecosystems (Abella and Martínez 2012; Carney et al. 1993; Chittoor Viswanathan et al. 2016; González-Martínez et al. 2019; Mojica and Guerrero 2013; Restrepo and Syvitski 2006; Ruiz et al. 2017; Taniwaki et al. 2019).

The upstream-downstream approach allowed analyzing the evolution of water quality along the water channel. For this, monitoring points are located upstream and downstream of the areas where land-use changes are located or where best management practices are implemented. Thus, this allows attributing changes in water quality to specific causes, as long as land uses and management practices are identified inside and outside the area of interest (USDA-NRCS 2003).

However, this approach requires considering some catchment characteristics such as geology, or soil type, which could be different in the high, medium, and low sections, which could condition the differences evidenced between the monitoring points (Cammeraat 2014; Dressing and Meals 2005;). Under the traditional paired-catchment approach (Clausen and Spooner 1993), at least two catchments are studied (study and control) during two monitoring periods (calibration and treatment), in which water quality data are collected simultaneously in both catchments to assess the performance of management practices over water quality. However, our study only addressed the calibration period aiming for an exploratory comparison of water quality in catchments with and without anthropic intervention. Other authors have used this adaptation of the traditional approach to analyze the effect of different land uses on water quality in other geographical contexts (Elledge and Thornton 2017; Hopmans and Bren 2007; Jokela and Casler 2011; Stallard 2011; Taniwaki et al. 2017; Wang et al. 2017; Wilson et al. 2015).

Study area

The study was developed in the Jordan river micro-catchment in the Berlin Páramo, part of the Santurbán complex, in Colombia's Eastern range. Land uses were spring onion (*Allium fistulosum*) and potato (*Solanum tuberosum*) crops; conifers, grasslands, and pastures with the presence of shrubs and stubble; and extensive livestock farming for family subsistence (Suárez et al. 2008). The study area was a 207-ha hydrographic unit (HU), located upstream of the Jordan river in Tona municipality in Santander (Fig. 1).

Two sub-hydrographic units (SHU) were limited to fulfill the requirements of the paired-catchment approach (Clausen

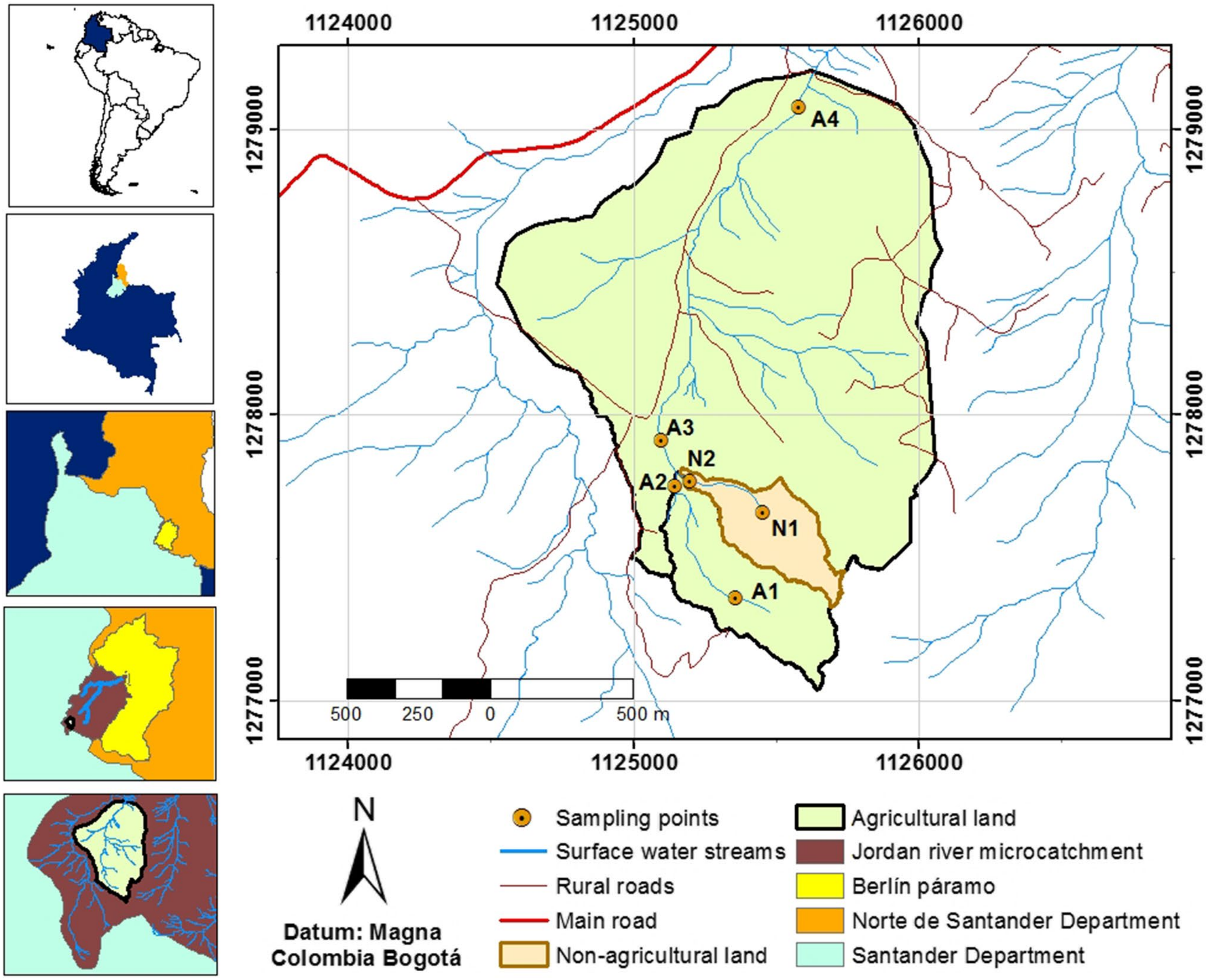

Fig. 1 Location of the study area

and Spooner 1993), upstream of the HU, with similar physical and hydroclimatic characteristics but with different land uses (Table 1). Although both SHUs had natural páramo vegetation, the anthropic SHU had almost 15% of its area represented by agricultural land cover (i.e., spring onion and potato crops and pastures for cattle farming). In contrast, the natural SHU only had about 2% of its area with pastures for cattle farming (Celis Vargas 2021). The areas of the SHUs were anthropic 19 ha and natural 11 ha.

Rainfall in the study area was bimodal, with two rainy seasons (March to May and September to November) and two dry seasons (June to August and December to February). Annual rainfall in the study area during the year of this research (2020) was 1089 mm (GPH et al. 2021). Figure 2 shows the monthly variation in the HU from August 2019 to December 2020. Some months of 2019 are included in the graph to show rainfall in the months before the dry season sampling campaign.

Table 1 Characteristics of the sub-hydrographic units

Land cover[1]	Area (%)[a]	
	A-SHU	N-SHU
Discontinuous urban fabric	0.139	0.005
Allium fistulosum	2.098	0.000
Solanum tuberosum	0.872	0.000
Pastures on abandoned land	11.937	2.091
Mixed forest	20.152	20.956
Coniferous plantation	0.426	1.403
Natural grassland without shrubs	43.317	58.769
Natural grassland with shrubs	18.849	13.983
Bare rock	1.220	1.835
Sparsely vegetated areas	0.990	0.957

A-SHU anthropic sub-hydrographic unit, *N-SHU* natural sub-hydrographic unit

[a]Source: Celis Vargas (2021)

Water quality monitoring

Six sampling points were selected following qualitative criteria (Nguyen et al. 2019), such as site representativeness, proximity to potential pollution sources, convenience for sampling, and acceptance from local stakeholders to allow access for monitoring. The general characteristics of sampling points are shown in Table 2 and Supplement 1. Sampling points identified with the letter N were located in the N-SHU, while sampling points identified with the letter A were located in the main HU, which flows through an area with anthropic activity (agriculture and extensive cattle farming) (see Fig. 1).

Each SUH included the start and outlet as a sampling point to allow an analysis under the paired-catchment approach. Sampling points A3 and A4 were included to allow for the analysis under the upstream-downstream approach.

Two monitoring campaigns were carried out, one in the dry season (February 21, 24, and 27 of 2020) and the other in the rainy season (November 2, 5, and 10 of 2020). Composite samples were taken simultaneously at the six points for 6 h during the first campaign. Flow water measurement and water quality parameters (pH, electrical conductivity, and temperature) were measured in situ every 30 min. Three in situ oxygen measurements were taken at each sampling point for each sampling day. Monitoring was carried out by 12 people previously trained by the research staff.

Access restrictions in the study area due to the COVID-19 pandemic forced the second monitoring campaign to work with a three-person team and collect point samples during different day periods at each sampling point. Although this was a change on the initially defined protocol, it was considered that this change would not impact sample representativeness since

Fig. 2 Monthly rainfall in the study area during the research (GPH et al. 2021)

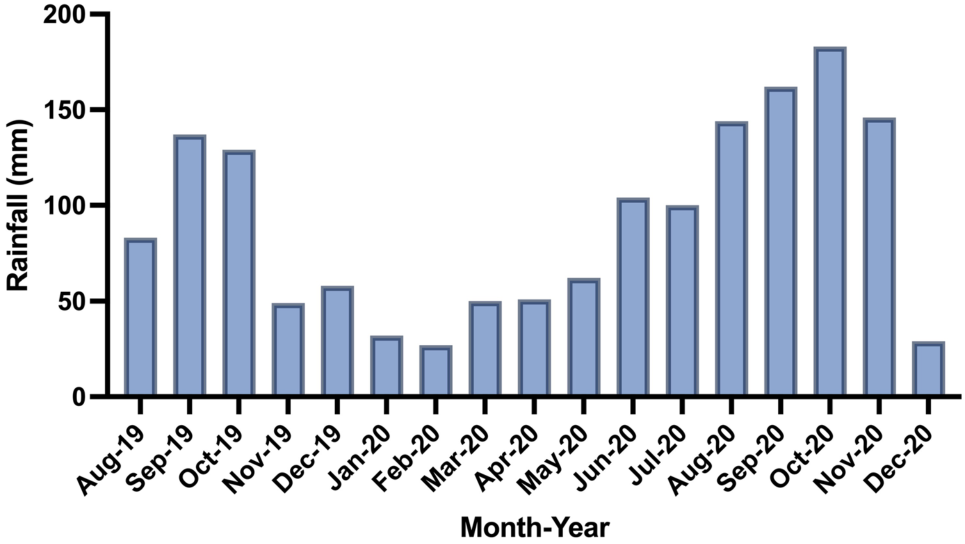

Table 2 General characteristics of sampling points

Water source	Code[a]	Location	Altitude (meters above sea level)
Tributary (natural páramo land cover)	N1	Start of tributary	3500
	N2	Outlet of the natural sub-hydrographic unit	3422
Main stream (crops, cattle farming, and natural páramo cover)	A1	Start of the main stream	3508
	A2	Outlet of the main stream	3419
	A3	Downstream junction of tributary and main stream	3418
	A4	Outlet of the hydrographic unit	3384

[a] Letter N stands for "Natural" as those sampling points are in the non-agricultural area, whereas letter A stands for "Anthropic" meaning those sampling points are in the agriculture-influenced area

the HU lacked continuous wastewater discharges (Madrid and Zayas 2007). In addition, the in situ analysis results in the first campaign resulted in negligible variations at each sampling point throughout the monitoring (Supplement 2).

Sample collection, storage, and transport followed Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WEF 2017). The analyzed water quality parameters were selected considering the primary contaminants related to agricultural activities (Evans et al. 2019; FAO and IWMI 2018). Table 3 shows methods for the analysis of each parameter in this research. A multiparameter meter SevenGo Duo and an oximeter Seven2Go from Mettler Toledo® were used for in situ analysis. Due to the topography in the study area and the narrow channels, flow measurements were carried out with the volumetric method at each sampling point, except for A4, where the magnitude of the flow and channel section did not allow using this method. At this point, the velocity-area method was adopted, using a magnetic flow meter FH950 de Hach®. *E. coli* analyses only were included in the first campaign due to access restrictions to the University laboratory during the pandemic.

Data analysis

Two-way ANOVA was applied to water quality data to identify statistically significant differences in the values of each parameter between the sampling points and if the rainfall regime had a significant effect on these values. For this, first, assumptions for the ANOVA test were checked. Normality was checked through normality analysis of residuals using the Anderson-Darling test. The homogeneity of variance was verified using the Bartlett test. Data from total nitrogen (N), ammoniacal nitrogen, organic nitrogen, electrical conductivity, total alkalinity, chemical oxygen demand (COD), dissolved oxygen, oxygen saturation, total suspended solids, and total solids fulfilled the normality assumption and homogeneity of variance (Supplement 3). Nitrates, nitrites, total phosphorus, soluble reactive phosphorus, total hardness, total potassium, biological oxygen demand (BOD_5), turbidity, pH, *E. coli*, and temperature were not normal. Thus, the non-parametric Friedman test was applied since it is considered equivalent to the two-way ANOVA (Núñez Colín 2018; Pereira et al. 2015). Given that *E. coli* only was measured in the first campaign, the variation between sampling points for this parameter was tested through Kruskal-Wallis, equivalent to non-parametric one-way ANOVA (Núñez Colín 2018).

The statistical analysis was carried out using the trial version of Minitab V19® with a significance level of 0.05. Charts were prepared to show results for the parameters with a statistically significant spatial or temporal variation to visualize water quality behavior along the channel.

Finally, to explore the effects of land use on the water quality attribute of the water supply hydrological service, results obtained for the sampling points in the area with anthropic influence were compared to water quality standards for (i) human consumption, (ii) irrigation, (iii) livestock watering, and (iv) aquatic life ambient freshwater. Reference values include measurements in the natural SHU, water use standards for different countries (i.e., Colombia, Ecuador, Peru, Venezuela, and USA) (Ministerio del Ambiente 2015; Ministerio de la Protección Social and Ministerio de Ambiente 2007; Presidencia de la República 1984, 1995, 2017; USEPA 1986, 2018, no date), water quality guidelines for different purposes from literature search (AAFC 2000; Ayers and Westcot 1985; Bauder et al. 2011; Oklahoma State University Extension 2016; WHO 2017a, 2017b), and results from other research in high-mountain Andean ecosystems without anthropic influence (Benavides Sierra et al. 2020; Cerón-Vivas et al. 2019; Ramírez and Plata-Díaz 2008; Ramírez et al. 2018; Tenorio et al. 2018;Vázquez et al. 2020; Vimos-Lojano et al. 2020).

Results and Discussion

Impact of agricultural contaminants to surface water quality

The impact of anthropic uses such as spring onion crops, potato crops, and livestock farming over water quality parameters grouped

Table 3 Methods used for water quality analysis

Agricultural contaminant	Parameter	Method
Nutrients	Total nitrogen	It was calculated from the determination of other nitrogen forms
	Nitrates	Molecular absorption spectrophotometry (Rodier et al. 2016)
	Nitrites	SM 4500-NO_2^- B
	Ammoniacal nitrogen	SM 4500-NH_3 B, C
	Kjeldahl nitrogen[a]	SM 4500-N_{org} C; SM 4500-NH_3 B, C
	Organic nitrogen	It was calculated from the difference between Kjeldahl Nitrogen and Ammoniacal nitrogen.
	Total phosphorus	SM 4500-P B, E
	Soluble reactive phosphorus	SM 4500-P E
Salts	Electrical conductivity[b]	SM 2510
	Total hardness	SM 2340 C
	Total alkalinity	SM 2320 B
	Total potassium	SM 3030 F; SM 3111 B
Organic matter	Biological oxygen demand $(BOD)_5$	SM 4210 B; SM 4500 O H
	Chemical oxygen demand (COD)	SM 5220 C
	Dissolved oxygen[b]	SM 4500 O G
	Oxygen saturation	SM 4500 O G
Sediments	Turbidity	SM 2130 B
	Total suspended solids	SM 2540 D
	Total solids	SM 2540 B
Pathogens	*Escherichia coli*	ISO 9308-I: 2014 (ISO 2014)
N/A	pH[b]	SM 4500 H^+ B
	Temperature[b]	SM 2550 B

SM Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WEF 2017)

[a] The results of this parameter are not presented because its determination was made to calculate the concentration of organic nitrogen and total nitrogen

[b] In situ measurements

in five categories (nutrients, salts, organic matter, sediments, and pathogens) was assessed. The assessment involved spatial and temporal variation (rainfall regime). Likewise, results were compared with water quality standards for different purposes. Table 4 shows the results of each water quality parameter at the different sampling points and rainfall regimes. Table 5 shows that spatial variation was statistically significant ($p < 0.05$) for most analyzed parameters, except for ammoniacal nitrogen, organic nitrogen, total phosphorus, and BOD_5. The identified variations can be linked in the case of some parameters to the agricultural activity in the HU and could compromise the water supply service in the studied area. Regarding the parameters that showed statistically significant differences ($p < 0.05$) between rainfall regimes, the season in which the most critical behavior occurred is analyzed. Water quality standards for different purposes are shown in Table 6.

Nutrients

Inadequate irrigation and excessive use of fertilizers are among the most important causes of water quality degradation from agriculture. These practices favor nutrient loss from the soil and their introduction to surface and groundwater (Li et al. 2019). The nutrient surplus in water sources promotes eutrophication, associated with the accelerated growth of algae and aquatic plants. The decomposition of these organisms contributes to a decrease in dissolved oxygen, from which other aquatic life forms are dependent. In addition, some algae produce toxins and bacteria dangerous for people, thus being a risk related to the consumption or contact with water (FAO and IWMI 2018). On the other hand, high nitrate concentrations generate toxicity conditions in water for human consumption (Powlson et al. 2008; Townsend et al. 2003; WHO 2017a) and livestock watering (AAFC 2000).

As shown in Table 4, ammoniacal nitrogen (N-NH_3) and nitrites (N-NO_2^-) had low concentrations (< 0.4 mgN/L) along the water channel, in both the natural and anthropic SHUs. Similar values have been reported for other headwaters in the Santurbán Páramo (Ramírez and Plata-Díaz 2008) and first-order tributaries in high-mountain Andean ecosystems with preserved riparian vegetation (Ramírez et al. 2018). Organic nitrogen also had low concentrations at the different sampling

Table 4 Flows and physicochemical and microbiological surface water qualities according to rainfall regimes

Parameter[a]	Units	Dry season ($n = 3$)						Rainy season ($n = 3$)					
		N1	N2	A1	A2	A3	A4	N1	N2	A1	A2	A3	A4
Flow	L/s	0.61 ± 0.02	2.15 ± 0.06	1.37 ± 0.08	1.49 ± 0.81	4.20 ± 0.91	23.70 ± 4.75	0.58 ± 0.06	2.28 ± 0.15	3.19 ± 0.06	3.93 ± 0.34	7.17 ± 0.95	48.45 ± 8.40
Total nitrogen	mg N/L	0.32 ± 0.14	0.44 ± 0.05	0.28 ± 0.20	1.71 ± 0.38	1.07 ± 0.20	2.87 ± 0.24	0.92 ± 0.27	0.90 ± 0.42	0.57 ± 0.09	1.92 ± 0.25	1.34 ± 0.15	3.25 ± 0.34
Nitrates	mg N-NO_3^-/L	0.02 ± 0.01	0.20 ± 0.02	0.00 ± 0.00	1.40 ± 0.27	0.58 ± 0.20	2.56 ± 0.11	0.02 ± 0.02	0.19 ± 0.02	0.01 ± 0.01	1.01 ± 0.05	0.63 ± 0.02	2.53 ± 0.31
Nitrites	mg N-NO_2^-/L	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.000	0.001 ± 0.001	0.003 ± 0.009	0.003 ± 0.004	0.004 ± 0.006	0.004 ± 0.006	0.004 ± 0.006	0.003 ± 0.006	0.003 ± 0.006
Ammoniacal nitrogen	mg N-NH_3/L	0.15 ± 0.13	0.19 ± 0.09	0.26 ± 0.23	0.26 ± 0.09	0.38 ± 0.46	0.21 ± 0.12	0.13 ± 0.08	0.11 ± 0.20	0.32 ± 0.03	0.07 ± 0.13	0.07 ± 0.06	0.25 ± 0.18
Organic nitrogen	mg N/L	0.15 ± 0.13	0.06 ± 0.10	0.02 ± 0.03	0.05 ± 0.09	0.11 ± 0.19	0.10 ± 0.16	0.76 ± 0.23	0.59 ± 0.32	0.24 ± 0.09	0.84 ± 0.36	0.64 ± 0.09	0.46 ± 0.27
Total phosphorous	mg P/L	0.03 ± 0.00	0.04 ± 0.00	0.02 ± 0.00	0.04 ± 0.02	0.05 ± 0.01	0.03 ± 0.01	0.05 ± 0.03	0.02 ± 0.01	0.02 ± 0.00	0.04 ± 0.03	0.03 ± 0.02	0.03 ± 0.01
Soluble reactive phosphorus	mg P/L	0.02 ± 0.01	0.02 ± 0.00	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.00	0.01 ± 0.01	0.03 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.01 ± 0.00
Electrical conductivity	µS/cm	30.76 ± 3.34	37.19 ± 4.20	28.96 ± 2.94	48.19 ± 6.65	41.68 ± 6.75	57.82 ± 4.38	41.54 ± 3.04	41.57 ± 3.07	32.86 ± 4.18	42.33 ± 2.73	45.68 ± 4.82	68.41 ± 15.85
Total hardness	mg $CaCO_3$/L	10.3 ± 0.8	10.0 ± 1.0	10.1 ± 0.2	13.2 ± 1.0	12.0 ± 0.5	18.8 ± 0.8	14.3 ± 1.6	15.1 ± 3.5	12.4 ± 2.1	13.8 ± 1.6	15.4 ± 4.1	20.5 ± 0.8
Total alkalinity	mg $CaCO_3$/L	16.3 ± 0.4	15.8 ± 0.3	16.1 ± 0.6	15.7 ± 1.4	15.0 ± 0.6	16.2 ± 0.6	16.1 ± 1.1	16.2 ± 0.3	14.2 ± 0.4	14.2 ± 0.3	15.2 ± 1.0	15.5 ± 0.9
Total potassium	mg K/L	0.40 ± 0.13	0.30 ± 0.01	0.27 ± 0.12	0.55 ± 0.13	0.43 ± 0.02	1.01 ± 0.04	0.32 ± 0.01	0.31 ± 0.09	0.13 ± 0.11	0.28 ± 0.25	0.38 ± 0.06	1.24 ± 0.06
BOD_5	mg O_2/L	1.67 ± 0.25	1.23 ± 0.59	1.70 ± 0.00	1.80 ± 0.17	1.90 ± 0.00	1.50 ± 0.35	2.93 ± 1.10	3.23 ± 1.07	2.87 ± 1.10	3.03 ± 0.93	2.80 ± 0.79	3.10 ± 0.78
COD	mg O_2/L	4.00 ± 1.60	5.33 ± 4.41	3.75 ± 1.20	5.07 ± 1.67	10.67 ± 2.44	6.13 ± 2.57	6.27 ± 2.66	7.20 ± 1.74	6.27 ± 3.35	9.20 ± 1.74	8.27 ± 2.54	9.07 ± 1.40
Dissolved oxygen	mg O_2/L	6.44 ± 0.28	6.94 ± 0.12	7.35 ± 0.16	7.01 ± 0.07	6.86 ± 0.14	7.07 ± 0.18	7.00 ± 0.29	6.78 ± 0.10	7.22 ± 0.08	7.03 ± 0.20	6.77 ± 0.21	6.30 ± 0.21
Oxygen saturation	%	91.97 ± 0.87	96.62 ± 1.71	98.32 ± 1.64	97.27 ± 0.90	98.23 ± 0.84	102.00 ± 4.18	94.64 ± 3.61	92.97 ± 0.75	97.33 ± 0.95	95.93 ± 1.35	93.03 ± 1.53	90.63 ± 3.44
Turbidity	NTU	1.89 ± 1.07	3.14 ± 2.17	1.08 ± 0.40	2.93 ± 2.53	10.83 ± 2.90	6.67 ± 2.83	4.05 ± 2.63	0.89 ± 0.27	0.84 ± 0.24	2.78 ± 1.25	2.50 ± 0.62	5.00 ± 2.35

Table 4 (continued)

Parameter[a]	Units	Dry season (n = 3)						Rainy season (n = 3)					
		N1	N2	A1	A2	A3	A4	N1	N2	A1	A2	A3	A4
Total suspended solids	mg/L	4.3 ± 3.3	8.0 ± 7.9	2.3 ± 1.3	7.5 ± 5.3	24.2 ± 9.4	11.4 ± 5.2	11.8 ± 8.1	1.9 ± 0.4	2.9 ± 2.8	13.1 ± 10.2	8.2 ± 4.2	9.1 ± 1.7
Total solids	mg/L	46 ± 7	55 ± 10	35 ± 2	64 ± 12	78 ± 7	89 ± 12	54 ± 8	48 ± 2	42 ± 4	59 ± 11	52 ± 2	72 ± 6
E. coli	FCU/100 mL	677 ± 563	300 ± 67	63 ± 52	2718 ± 867	2095 ± 2276	398 ± 318	-	-	-	-	-	-
pH	-	7.36 ± 0.27	7.37 ± 0.09	7.80 ± 0.19	7.46 ± 0.11	7.32 ± 0.08	7.37 ± 0.06	7.51 ± 0.14	7.28 ± 0.52	7.74 ± 0.10	7.62 ± 0.08	7.46 ± 0.16	7.27 ± 0.04
Temperature	°C	12.8 ± 1.4	12.0 ± 0.2	10.1 ± 0.4	12.0 ± 0.2	13.3 ± 1.2	14.4 ± 1.6	10.5 ± 0.3	11.4 ± 0.3	10.1 ± 0.1	11.2 ± 0.6	11.5 ± 0.6	13.6 ± 0.2

[a]Values are related to average ± standard deviation

n number of data at each sampling point, *N1* start of tributary in the natural sub-hydrographic unit, *N2* outlet of the natural sub-hydrographic unit, *A1* start of the main stream, *A2* outlet of the main stream, *A3* downstream junction of tributary and main stream, *A4* outlet of the hydrographic unit

Table 5 Analysis of variance results for surface water physicochemical and microbiological parameters (significance level of 0.05)

Parameter	*P* value		Statistical test
	Factor 1	Factor 2	
Total nitrogen	0.000	0.000	Two-way ANOVA
Nitrates	0.000	0.285	Friedman
Nitrites	0.013	0.008	Friedman
Ammoniacal nitrogen	0.695	0.206	Two-way ANOVA
Organic nitrogen	0.078	0.000	Two-way ANOVA
Total phosphorous	0.071	0.317	Friedman
Soluble reactive phosphorus	0.001	0.134	Friedman
Electrical conductivity	0.000	0.035	Two-way ANOVA
Total hardness	0.002	0.000	Friedman
Total alkalinity	0.027	0.021	Two-way ANOVA
Total potassium	0.000	0.317	Friedman
BDO_5	0.678	0.000	Friedman
COD	0.037	0.029	Two-way ANOVA
Dissolved oxygen	0.000	0.123	Two-way ANOVA
Oxygen saturation	0.025	0.000	Two-way ANOVA
Turbidity	0.003	0.157	Friedman
Total suspended solids	0.010	0.374	Two-way ANOVA
Total solids	0.000	0.019	Two-way ANOVA
pH	0.003	0.346	Friedman
E. coli	0.023	-	Kruskal-Wallis
Temperature	0.000	0.001	Friedman

Factor 1: sampling point (i.e., spatial variation); factor 2: rainfall regime (i.e., temporal variation)

points (< 0.9 mgN/L), with lower values compared to those reported in a headwater tributary in Lago de Tota (Boyacá — Colombia) (Benavides Sierra et al. 2020). The low content of these nitrogen forms could be considered the absence of direct wastewater discharges to the source (Aguilar et al. 2021; Sardiñas Peña and Pérez Cabrera 2004) and does not represent a risk for the water uses considered in this study.

Figure 3a-c show the variation of total nitrogen, nitrates, and organic nitrogen in surface water according to the rainfall regime. The most noticeable changes were identified for nitrates, which had low concentrations at both starts of the SUHs and outlet of the natural SHU (< 0.3 mg $N\text{-}NO_3^-$/L), in agreement with reports from similar ecosystems without human activities (Cerón-Vivas et al. 2019; Ramírez and Plata-Díaz 2008; Ramírez et al. 2018. However, the input of nitrates from diffuse sources along the channel path was evident in our anthropic HU. In most agricultural land, ammonia is rapidly converted into nitrate, increasing nutrient mobility through the soil matrix (Norton and Ouyang 2019). In the study area, the loss of nitrates could increase with an inefficient use of inorganic and organic fertilizers (i.e., application rate higher than soil adsorption and crop assimilation rates).

Table 6 Water quality reference values for different purposes

Parameter	Units	Human consumption		Irrigation		Livestock watering		Aquatic life ambient freshwater			
		Standard	Reference	Standard	Reference	Standard	Reference	Standard	Reference	Literature[a]	Reference
Total nitrogen	mg N/L	–	–	–	–	–	–	–	–	0.91	Ramírez et al. (2018)
Nitrates	mg $N\text{-}NO_3^-/L$	< 10	USEPA (2018); WHO (2017a)	< 5.0	Ayers and Westcot (1985); Ministerio del Ambiente (2015)	< 100	AAFC (2000); Oklahoma State University Extension (2016); Presidencia de la República (1984)	< 2.9	Ministerio del Ambiente (2015; Presidencia de la República (2017)	0.023–0.290	Cerón-Vivas et al. (2019); Ramírez and Plata-Díaz (2008); Ramírez et al. (2018)
Nitrites	mg $N\text{-}NO_2^-/L$	< 0.9	WHO (2017a)	< 0.15	Ministerio del Ambiente (2015)	< 10	AAFC (2000); Oklahoma State University Extension (2016); Presidencia de la República (1984)	< 0.06	Ministerio del Ambiente (2015)	0.0018	Ramírez et al. (2018)
Ammoniacal nitrogen	mg $N\text{-}NH_3/L$	< 23.3	USEPA (2018)	–	–	–	–	< 1.8	Ministerio del Ambiente (2015); Presidencia de la República (2017)	0.009–0.086	Benavides Sierra et al. (2020); Ramírez and Plata-Díaz (2008)
Organic nitrogen	mg N/L	–	–	–	–	–	–	–	–	9.238	Benavides Sierra et al. (2020)
Total phosphorous	mg P/L	< 0.1	–	–	–	–	–	< 0.05	Presidencia de la República (2017)	0.08–0.17	Benavides Sierra et al. 2020; Ramírez et al. (2018)
Soluble reactive phosphorus	mg P/L	–	–	–	–	–	–	–	–	0.023–0.026	Ramírez and Plata-Díaz (2008)

Table 6 (continued)

Parameter	Units	Human consumption		Irrigation		Livestock watering		Aquatic life ambient freshwater			
		Standard	Reference	Standard	Reference	Standard	Reference	Standard	Reference	Literature[a]	Reference
Electrical conductivity	µS/cm	< 1000	Ministerio de la Protección Social and Ministerio de Ambiente (2007)	< 700	Ayers and Westcot (1985)	< 5000	Presidencia de la República (2017)	< 1000	Presidencia de la República (2017)	14–129	Benavides Sierra et al. (2020); Cerón-Vivas et al. (2019); Ramírez and Plata-Díaz 2008; Ramírez et al. (2018); Vázquez et al. (2020); Vimos-Lojano et al. (2020)
Total hardness	mg $CaCO_3$/L	< 300	Ministerio de la Protección Social and Ministerio de Ambiente (2007)	–	–	–	–	–	–	35.6	Ramírez et al. (2018)
Total alkalinity	mg $CaCO_3$/L	< 200	Ministerio de la Protección Social and Ministerio de Ambiente (2007)	–	–	< 500	AAFC (2000)	> 20	USEPA (1986, n.d.)	15.5–38.8	Ramírez et al. 2018; Cerón-Vivas et al. (2019)
Total potassium	µg K/L	–	–	–	–	–	–	–	–	4.7–8.5	Tenorio et al. (2018)
BOD_5	mg O_2/L	< 2.0	Ministerio del Ambiente (2015)	< 15	Presidencia de la República (2017)	< 15	Presidencia de la República (2017)	< 10	Presidencia de la República (2017)	0.4–2.16	Cerón-Vivas et al. (2019; Ramírez et al. (2018)
COD	mg O_2/L	< 4.0	Ministerio del Ambiente (2015)	< 40	Presidencia de la República (2017)	< 40	Presidencia de la República (2017)	< 40	Ministerio del Ambiente (2015)	–	–

Table 6 (continued)

Parameter	Units	Human consumption		Irrigation		Livestock watering		Aquatic life ambient freshwater			
		Standard	Reference	Standard	Reference	Standard	Reference	Standard	Reference	Literature[a]	Reference
Dissolved oxygen	mg O_2/L	> 4.0	Presidencia de la República (1995)	> 3.0	Ministerio del Ambiente (2015)	> 5.0	Presidencia de la República (2017)	> 5.0	Presidencia de la República (1984)	4.65–10.5	Benavides Sierra et al. (2020); Cerón-Vivas et al. (2019); Ramírez and Plata-Díaz (2008); Ramírez et al. (2018); Vázquez et al. (2020); Vimos-Lojano et al. (2020)
Oxygen saturation	%	> 50	Presidencia de la República (1995)	–	–	–	–	–	–	64.3–96.1	Vázquez et al. (2020)
Turbidity	UNT	< 1.0	WHO (2017b)	–	–	–	–	–	–	0.0–13.2	Cerón-Vivas et al. (2019; Ramírez et al. (2018); Vázquez et al. (2020); Vimos-Lojano et al. (2020)
Total suspended solids	mg/L	–	–	–	–	–	–	< 100	Presidencia de la República (2017)	0.9–13.0	Ramírez et al. (2018); Tenorio et al. (2018); Cerón-Vivas et al. (2019)
Total solids	mg/L	–	–	–	–	–	–	–	–	2.7–20	Cerón-Vivas et al. (2019)
E. coli	CFU/100 mL	0	Ministerio de la Protección Social and Ministerio de Ambiente (2007); USEPA (2018); WHO (2017a)	–	–	–	–	–	–	514	Ramírez et al. (2018)

Table 6 (continued)

Parameter	Units	Human consumption		Irrigation		Livestock watering		Aquatic life ambient freshwater			
		Standard	Reference	Standard	Reference	Standard	Reference	Standard	Reference	Literature[a]	Reference
pH	-	6.5–8.5	USEPA (2018)	6.5–8.4	Ayers and Westcot (1985); Bauder et al. (2011)	6.5–8.4	Presidencia de la República (2017)	6.5 – 9.0	Presidencia de la República (1984, 2017); Ministerio del Ambiente (2015)	5.5–8.1	Benavides Sierra et al. (2020); Cerón-Vivas et al. (2019); Ramírez and Plata-Díaz (2008); Ramírez et al. 2018; Tenorio et al. (2018); Vázquez et al. 2020; Vimos-Lojano et al. (2020)

[a] Values reported in the literature regarding high-mountain ecosystems without anthropic intervention

Along the main stream path in the anthropic SHU, a considerable increase in nitrate concentration up to 1.40 mg N-NO_3^-/L was observed at the outlet, despite the small size of the land under crops in this area. This concentration decreased around 50% in 130-m length due to dilution in the junction of this source with the natural SHU. However, on the path from this point to the main stream outlet (approximately 1.4 km), the concentration increased up to 2.56 mg N-NO_3^-/L. In the Colombian context, other authors found nitrate concentrations around 0.50 mg N-NO_3^-/L in the lowlands of a high-mountain catchment, which included a páramo area and 25.2% of croplands (Ruiz et al. 2017). On the other hand, a study on four tributaries to Lago de Tota reported concentrations between 2.3 and 5.6 mg N-NO_3^-/L in the dry season, ascribable to intensive agriculture, characterized by spring onion monoculture (Barrera et al. 2019), which could contribute to an increasing eutrophic condition (Aranguren-Riaño et al. 2018). These data suggest that the nitrate concentration obtained at the sampling point A4 was relatively high for the study area, considering the small drainage area (207 ha) and its headwater condition in the Jordan river catchment. Nitrates in water for human consumption have been associated with methemoglobin production in the blood. However, in this study, the nitrate concentration at all sampling points was below standard for human consumption (<10 mg N-NO_3^-/L) (USEPA 2018; WHO 2017a) and livestock watering (<100 mg N-NO_3^-/L) (AAFC 2000; Oklahoma State University Extension 2016; Presidencia de la República 1984).

Regarding irrigation, nitrates in water could benefit crops under fertirrigation schemes. However, high concentrations of this compound (> 5 mg N-NO_3^-/L) could force farmers to adjust the fertilizer doses to avoid damage to susceptible crops (Ayers and Westcot 1985; Ministerio del Ambiente 2015). Therefore, farmers downstream could be affected by the high input of nitrates from the HU. Furthermore, the nitrate concentration at the outlet of the HU was closed to the limit set in some countries for the preservation of aquatic life in lotic mountain sources (< 2.9 mg N-NO_3^-/L) (Ministerio del Ambiente 2015; Presidencia de la República 2017), which could endanger biodiversity in this páramo ecosystem.

The high concentrations of phosphorous (> 0.1 mg P/L) indicate potential pollution and demand specific treatment processes to use water for human consumption (Presidencia de la República 2017). In addition, levels higher than 0.05 mg P/L could favor eutrophication in lotic water bodies (USEPA 1986; n.d.). Phosphorous can be found in natural waters due to vegetable or animal waste mineralization from diffuse or point pollution sources related to agriculture or domestic activities (Aloe et al. 2014). In our study, total phosphorous had low concentrations at all sampling points with values between 0.02 and 0.05 mg P/L. The maximum values occurred both at the start and outlet of the anthropic SHU and outlet of the

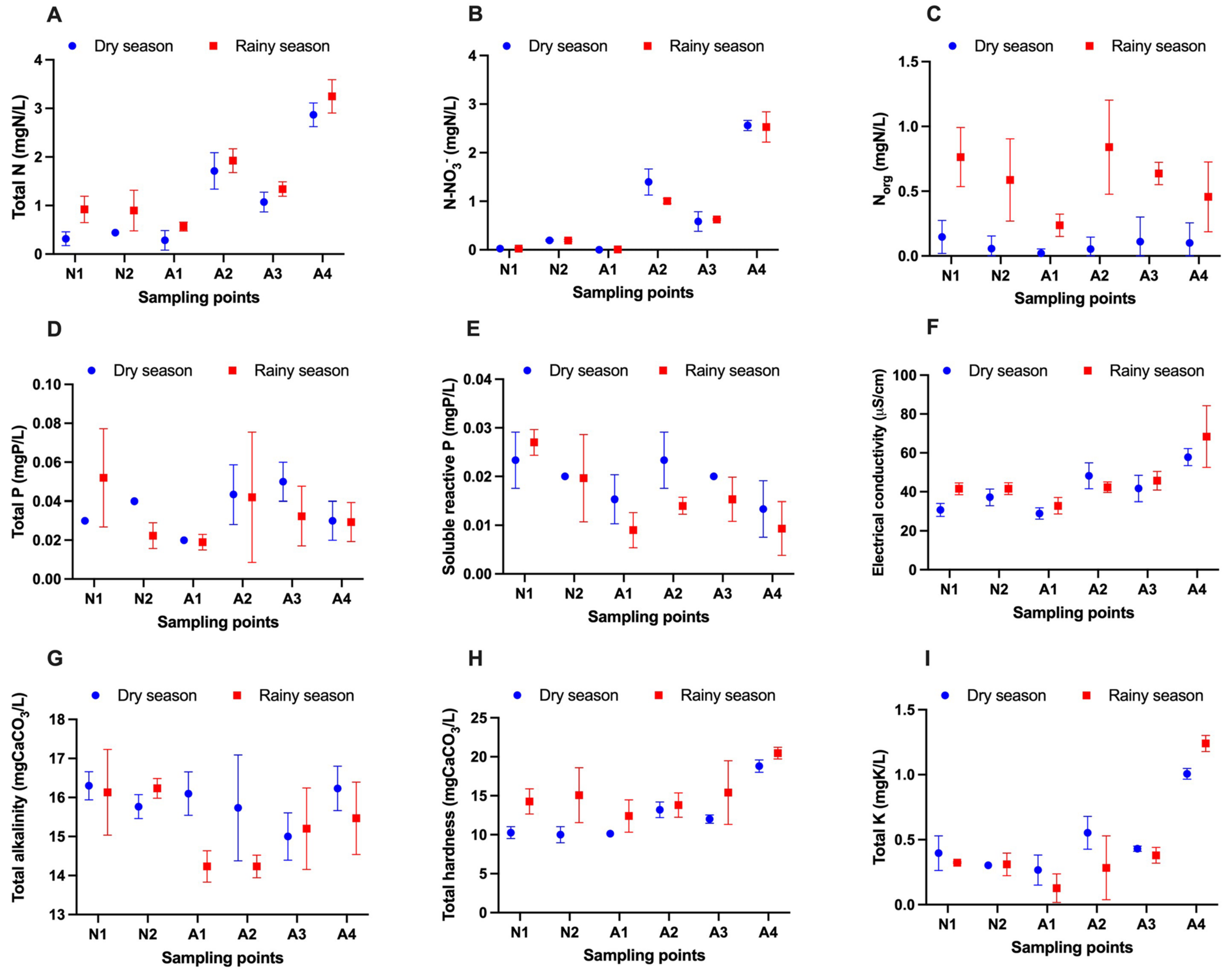

Fig. 3 Water quality parameters related to nutrients and salts according to rainfall regimes. Note: **a** total nitrogen, **b** nitrate-nitrogen, **c** organic nitrogen, **d** total phosphorus, **e** soluble reactive phosphorus, **f** electrical conductivity, **g** total alkalinity, **h** total hardness, **i** total potassium. Dots and squares in the graphs represent average values of the measured data at each sampling point, and error bars represent standard deviation. N1: start of the tributary of the natural sub-hydrographic unit; N2: outlet of the natural sub-hydrographic unit; A1: start of the main stream; A2: outlet of the main stream; A3: downstream junction of tributary and main stream; A4: outlet of the hydrographic unit

HU. The levels of soluble reactive phosphorus were similar to those reported in other páramo headwaters (Ramírez and Plata-Díaz 2008). Furthermore, the ratio between soluble reactive phosphorus and total phosphorus was relatively steady along the stream path (see Fig. 3d and e).

A study in an Andean high-mountain ecosystem without anthropic intervention reported 0.08 mg P/L (Ramírez et al. 2018). On the other hand, a study in a brook tributary to Lago de Tota found values between 0.07 and 0.43 mg P/L in the dry season. The higher values were in areas influenced by spring onion crops and livestock farming (Benavides Sierra et al. 2020). By comparing our results with these values, our UH had the potential to attenuate diffuse phosphorus pollution. In contrast to nitrate, highly soluble in water, inorganic phosphorus generally moves through the soil because it strongly adheres to particles and organic matter from the soil (FAO and IWMI 2018). In addition, besides the effect that land use has on the input of nitrogen and phosphorus to surface water, different environmental conditions in the catchment, such as the slope, could contribute to attenuating or increasing nutrient pollution sources. For instance, catchments with steep slopes produce high runoff velocity, reducing water contact time with soil and lowering nitrate solubilization (Otero et al. 2011; Zhang et al. 2017). Likewise, it has been found that high total phosphorus typically occurs in catchments with steep slopes since those favor phosphorus transport through erosion or runoff (WHO 2016; Zhuang et al. 2015). In our study area, croplands were in the lowlands of the UH, which could be a contributing factor to the high nitrate and low total phosphorus concentrations in the surface water.

Salts

Salinity refers to the total concentration of inorganic ions dissolved in water and, thus, is a characteristic of natural water sources (Williams and Sherwood 1994). The content of these ions could be expressed as the ionic activity of a solution, in terms of its capacity to transmit electric current (Cañedo-Argüelles et al. 2013) and with other water quality parameters such as alkalinity, hardness, and concentration of specific ions (FAO and IWMI 2018). The charge of salts in water associated with irrigation is one of the major impacts of agricultural activities over water sources around the world (Barnard et al. 2021), mainly due to the impairment of crop irrigation (Zaman et al. 2018) and lethal effects at higher concentrations for aquatic organisms (Delaune et al. 2021).

In our study, although there were statistically significant differences between sampling points, no land uses were observed that could generate considerable contributions of ions that would affect the salinity of surface water. The electrical conductivity at all sampling points had average values between 30 and 70 µS/cm (see Fig. 3f), which indicates low salinity (Zaman et al. 2018) and was below the maximum recommended values for human consumption (< 1000 µS/cm) (Ministerio de la Protección Social and Ministerio de Ambiente 2007), irrigation (< 700 µS/cm) (Ayers and Westcot 1985), livestock watering (< 5000 µS/cm), and aquatic life ambient freshwater (< 1000 µS/cm) (Presidencia de la República 2017). Since this parameter was in situ analyzed for 6 h at 30-min intervals during the monitoring campaign in the dry season, some peak values were observed (80–100 µS/cm). However, these values occurred in both the anthropic and natural SHUs. Thus, they could be related either to diffuse pollution sources from croplands or to the geological characteristics of the HUs, which could be important for this parameter (Cammeraat 2014; Cañedo-Argüelles et al. 2013). Other studies in Andean high-mountain ecosystems, including páramos, have reported values similar to those presented here for water sources with and without anthropic activities (Barrera et al. 2019; Benavides Sierra et al. 2020; Cerón-Vivas et al. 2019; Ramírez and Plata-Díaz 2008; Ramírez et al. 2018; Ruiz et al. 2017; Vázquez et al. 2020; Vimos-Lojano et al. 2020).

Specific ions such as sodium, sulfates, and chlorides, which are of particular interest for their harmful effects on soil structure and crop health (FAO and IWMI 2018), were not analyzed. However, results from total alkalinity and electrical conductivity indicate low salinity. High alkalinity waters favor the generation of insoluble compounds of magnesium and calcium, making sodium the primary ion in the solution (Bauder et al. 2011). From certain alkalinity levels (> 500 mg $CaCO_3$/L), the acceptability of water for livestock watering could be restrained due to the laxative effect (AAFC 2000). Regarding aquatic life ambient freshwater, typically, the standard is set at values higher than 20 mg $CaCO_3$/L. If natural waters have alkalinity below this level, the concentration of this parameter should not be under 25% of the characteristic value of the considered ecosystem (USEPA 1986, n.d.).

In the study area, low total alkalinity values were obtained, between 14.1 and 16.3 mg $CaCO_3$/L, at the different sampling points, including the two starts of the sources (Fig. 3g). Low total alkalinity could be a characteristic of high-mountain surface waters since similar values have been reported for these ecosystems in areas without anthropic influence (Cerón-Vivas et al. 2019; Ramírez et al. 2018). Even though total alkalinity results in this study fulfilled standards for water consumption, irrigation, livestock watering, and aquatic life ambient freshwater, they represent a low buffer capacity for pH variations. However, at all sampling points, pH levels were close to neutral conditions (7.3 to 7.8) and did not represent adverse effects for the water purposes considered in this research (Ayers and Westcot 1985; Bauder et al. 2011; Ministerio del Ambiente 2015; Presidencia de la República 1984, 2017; USEPA 2018).

In the case of total hardness (Fig. 3h), both streams had values between 10.00 and 20.47 mg $CaCO_3$/L, showing a slight increase related to anthropic activities, which could be associated with soil irrigation and runoff (Thorslund et al. 2021). These values suggest a soft-water and, given the low alkalinity and neutral pH (Figs 3g and 4a), are not a threat to pipe incrustation (WHO 2017a) and fulfill water consumption standards from Colombia (Ministerio de la Protección Social and Ministerio de Ambiente 2007). Similar results of total hardness were found in La Fucha stream (Cundinamarca, Colombia), which catchment includes páramo ecosystem with crops (Chavarro and Gélvez Bernal 2016), and also in other headwaters from Santurban páramo (Ramírez and Plata-Díaz 2008).

On the other hand, potassium (K) was similar to nitrate since it increased along the channel path in the anthropic HU (see Fig. 3i). A study from Ecuador found low-potassium concentrations (even below the detection limit) in páramo surface water sources without anthropic influence (Tenorio et al. 2018). In addition, high-potassium concentrations have been measured in the runoff from different agricultural lands (including grasslands and potato crops) in high-mountain ecosystems in Colombia (Suescún et al. 2017). Thus, an increase in potassium in our case study could be associated with inadequate fertilization practices and losses due to surface flow. Although its concentration does not represent substantial salinity alterations, its presence in water could favor eutrophication processes.

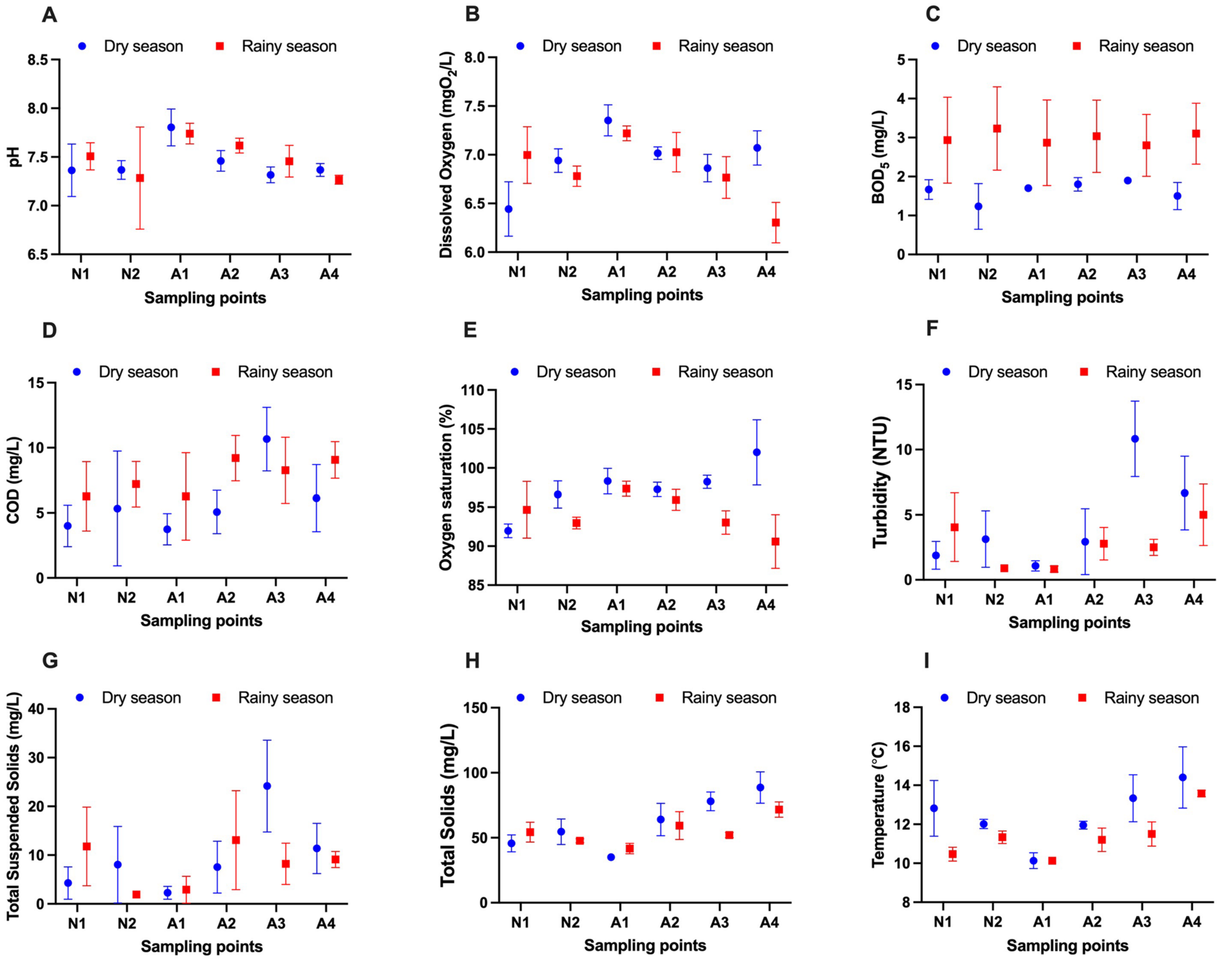

Fig. 4 pH, temperature, and water quality parameters related to organic matter and sediments according to rainfall regimes. Note: **a** pH, **b** dissolved oxygen, **c** BOD$_5$, **d** COD, **e** oxygen saturation, **f** turbidity, **g** total suspended solids, **h** total solids, **i** temperature. Dots and squares in the graphs represent average values of the measured data at each sampling point, and error bars represent standard deviation. N1: start of the tributary of the natural sub-hydrographic unit; N2: outlet of the natural sub-hydrographic unit; A1: start of the main stream; A2: outlet of the main stream; A3: downstream junction of tributary and main stream; A4: outlet of the hydrographic unit

Organic matter

In catchments with anthropic intervention, the primary water pollution sources related to organic matter are associated with animal food and excreta or inadequately managed postharvest waste (FAO and IWMI 2018). Organic matter pollution is generally assessed through dissolved oxygen, oxygen saturation, COD, and BOD$_5$. Results from this study suggest a negligible impact on water quality regarding these parameters (see Fig. 4b–e), possibly because of the absence of point discharges from domestic wastewater and the negligible livestock farming activity that was minimum and extensive, mainly milk production for self-consumption.

The BOD$_5$ concentration remained steady along the channel path, at all sampling points, under 2.0 mg/L for the dry season and 3.3 mg/L in the rainy season. These results are coherent with the average dissolved oxygen values at each sampling point, between 6.30 to 7.07 mg/L, and oxygen saturation higher than 90%. On the other hand, COD had variations along the path, possibly due to the leaching of non-biodegradable organic matter from cultivated soils in the anthropic area. However, in the path from A3 to A4, COD decreased in the dry season and remained relatively steady during the rainy season. This condition is associated with the capacity of the HU to attenuate organic matter pollution.

Regarding water uses, the parameters associated with organic matter fulfilled standards for irrigation, livestock watering, and aquatic life ambient freshwater. Still, they were above the established limits for human consumption in BOD_5 and COD (Ministerio del Ambiente 2015; Presidencia de la República 1984, 1995, 2017). In general, results from these parameters are consistent with values reported in the literature for other high-mountain Andean ecosystems without anthropic influence (Benavides Sierra et al. 2020; Cerón-Vivas et al. 2019; Ramírez and Plata-Díaz 2008; Ramírez et al. 2018; Ruiz et al. 2017; Vázquez et al. 2020; Vimos-Lojano et al. 2020), and are similar to average concentrations in Lago de Tota catchment in an area with spring onion crops (Abella and Martínez 2012). In addition, results from this study are different from those in Andean high-mountain ecosystems where livestock farming is intensive, and concentrations of BOD_5 and COD in surface water were 4.48 mg/L (Chavarro and Gélvez Bernal 2016) and around 40 mg/L (Coello et al. 2014), respectively.

Sediments

Agricultural activities increase soil erosion and sediment load to surface water sources due to the removal of the natural vegetal cover, which makes soils left bare and vulnerable to erosion. In addition, activities such as plowing, harvesting, and livestock keeping promote mineralization of organic matter in the soil and its compaction, reducing infiltration and increasing runoff, which intensifies erosion rates (FAO and IWMI 2018). No soil loss measurements were conducted in the study area. However, from the low values found in our study for turbidity, total solids, and total suspended solids at all sampling points, we could say that erosion rates were possibly low. Nonetheless, in most cases, turbidity exceeded the recommended limit for human consumption (<1 UNT) (WHO 2017b) (see Fig. 4f), except at N2 and A1, with turbidity lower than that limit in the rainy season. This condition at N2, which is the outlet of the natural SHU, shows lower erosion rates than the anthropic SHU. The increase in turbidity at A3 during the dry season could be related to cattle passing frequently observed around this sampling point during the monitoring campaigns.

Total suspended solids (TSS) at the different sampling points were between 1.9 and 24.2 mg/L and between 35 and 89 mg/L for total solids (TS). Figure 4 g and h show a steady behavior of the ratio between TSS and TS along the channel length and that the major fraction of TS was for dissolved solids. At all sampling points, TSS were below the reference limit for aquatic life ambient freshwater in high-mountain lotic ecosystems (< 100 mg/L) (Presidencia de la República 2017). Furthermore, both turbidity and concentration of solids were similar to values found in other research in similar ecosystems without anthropic influence (Cerón-Vivas et al. 2019; Ramírez et al. 2018; Vázquez et al. 2020; Vimos-Lojano et al. 2020).

Although a higher increase in TSS could be expected as the stream runs through agricultural land due to the lack of natural páramo vegetation and the high susceptibility to erosion, typical of páramo soils (Podwojewski and Poulenard 2000), the low slopes in the study area could prevent the transport of soil particles to surface waters (Durán Zuazo et al. 2004). Thus, this natural condition in the study area could attenuate water pollution due to sediments, consistent with the low total phosphorus inputs previously discussed.

Pathogens

E. coli in the surface water is an indicator of fecal pollution and is associated with the risk of pathogen exposure (Haack 2017). Typically, sources of this bacterium include runoff from agricultural areas where manure is used as fertilizer, direct fecal deposition, infiltration from septic systems, and discharges from wastewater treatment plants (Garzio-Hadzick et al. 2010). *E. coli* results obtained in the dry season suggest fecal contamination, especially at the outlet of the anthropic SHU and downstream the joint of the two SHUs, with concentrations between 2000 and 3000 CFU/100 mL (see Fig. 5).

Considering that livestock farming in the HU was scant, the generalized use of chicken manure as fertilizer for the potato and spring onion crops in the study area is possibly a relevant factor in the observed increase in *E. coli* concentration. In addition, both stream starts had average *E. coli* of 677 CFU/100 mL (N1) and 63 CFU/100 mL (A1). These results indicate that no sampling point fulfilled the *E. coli* standard for human consumption (0 CFU/100 mL) (WHO 2017b), becoming a public health risk.

The high *E. coli* concentration at N1 could be associated with the sporadic presence of livestock in areas adjacent to this point and sediment resuspension during sampling. Sediments in the channel bed could have high relative importance as bacterial habitats and source of fecal coliforms and *E. coli*. In some catchments, it has been found that they provide a higher pathogen load compared to runoff from nearby soils (Pachepsky and Shelton 2011).

Finally, Fig. 5 shows the attenuation capacity of the natural SHU, where the *E. coli* concentration almost halved in contrast to the substantial increase identified in the anthropic SHU. In the absence of human activity, the *E. coli* decay in the natural SHU could be linked to high radiation, low temperatures, and low nutrient availability (Nakhle et al. 2021). These results suggest that páramo ecosystems could have a crucial role in water purification regarding fecal pollution.

Influence of rainfall regime on surface water quality

Since rainfall is the main driving force for runoff, it is closely related to the transport of contaminants to surface water. During rainfall-runoff events, the main pollutant

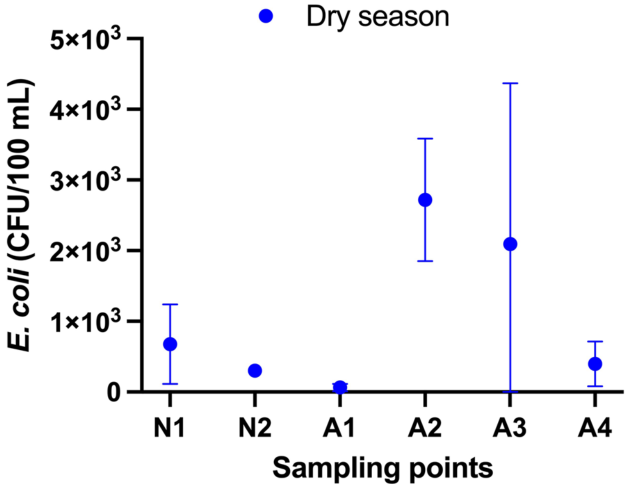

Fig. 5 *E. coli* concentration in water during the dry season. Note: Dots in the graph represent average values of the measured data at each sampling point, and error bars represent standard deviation. N1: start of the tributary of the natural sub-hydrographic unit; N2: outlet of the natural sub-hydrographic unit; A1: start of the main stream; A2: outlet of the main stream; A3: downstream junction of tributary and main stream; A4: outlet of the hydrographic unit

transport mechanisms from agricultural lands are dissolution in surface and subsurface runoff and adsorption by soil particles (He et al. 2014). Table 5 shows results from a variance analysis, where it is observed that the rainfall regime had a statistically significant influence ($p < 0.05$) on the behavior of some of the studied parameters. As shown in Table 4, in the rainy season, besides the decrease in water temperature at most of the sampling points compared with the dry season, lower levels were found for total alkalinity, oxygen saturation, and total solids, which could be associated with the dilution effect of flow increase.

In the case of nutrients, recognizing the temporal variation of their concentrations in water allows for identifying the periods with higher eutrophication risk, thus facilitating the selection of strategies to mitigate the environmental effects associated with nutrient losses (Xia et al. 2020). Different studies in high-mountain ecosystems have informed that the major nutrient losses from agricultural lands to surface water occur in the rainy season or during high-intensity rainfall events (Ramos et al. 2019; Ruiz et al. 2017; Suescún et al. 2017). However, some studies have found that high periods with high-intensity rains tend to decrease nitrate concentrations due to dilution (Barrera et al. 2019; He et al. 2014). Our study showed an increase in total nitrogen, nitrites, and organic nitrogen in the rainy season.

Raindrop splash promotes soil erosion (He et al. 2014). Other factors such as slope and land cover favor detachment of soil masses and sediments (Durán Zuazo et al. 2004). This condition could influence the increase of organic nitrogen in the rainy season, considering that in páramo soils, high nitrogen content has been reported (Minaya et al. 2016). In the case of nitrates, due to their high solubility in water, this compound generally reaches watercourses by leaching from agricultural soils and is subsurface transported (Carney et al. 1993). In this study, nitrates in surface water were similar in both rainfall regimes, which could be associated with the presence of permanent crops during the whole year (i.e., the farmers grow onion in different plots at different stages of growth to ensure continuous harvests all year round) and with irrigation practices that promote lixiviation in the dry season.

During the rainy season, a statistically significant increase in electrical conductivity and total hardness was observed, which is related to variations in the ionic activity of water. This increase in salinity could be associated with natural processes such as catchment weathering, which depends on geology and rainfall (Cañedo-Argüelles et al. 2013), and with a major wash of fertilizers from the soil due to the increase in surface runoff (Thorslund et al. 2021). At the same time, the higher inputs of organic matter to water evidenced the increase of BOD_5 and COD concentrations. Dissolved organic carbon concentrations in agricultural catchments generally exhibit high temporal variations due to the high fluctuations in the discharges (Graeber et al. 2012). In this study, the increase in the concentration of these parameters is possibly related to the generalized use of organic fertilizers, which surplus is dragged by surface runoff during the rainy season.

Final considerations and recommendations of water management for different purposes in Berlin páramo

Table 7 provides a synthesis of potential surface water uses from the study area, considering water quality and some recommendations for water management according to purpose (see Table 6). In general, even though affectations to water quality due to land use were observed in the anthropic hydrographic unit, according to the parameters and standards considered in this study, the hydrological service of water supply for crop irrigation, livestock watering, and aquatic life ambient freshwater was not compromised.

However, the surface water did not fulfill standards for human consumption in turbidity, BOD_5, COD, and *E. coli*. The concentration of the last three parameters could be associated with livestock grazing nearby surface waters and the local fertilization practices, including the use of chicken manure in potato and spring onion crops. These results indicate a health risk for local communities, typically taking water from surface sources and drinking it without treatment.

On the other hand, the inefficient use of fertilizers could represent a considerable input of nutrients to the surface water, evidenced by the high concentrations of nitrates and potassium downstream the catchment areas with anthropic

Table 7 Potential uses of the surface water from the study area considering water quality and some recommendations for water management according to purpose.

Water use	Water quality	Recommendations for water management
Human consumption	Unsuitable	The water requires treatment before consumption due to high levels of turbidity, BOD_5, COD, and *E. coli*.
Livestock watering	Suitable	Stablish areas for livestock grazing and watering to avoid livestock nearby water sources.
Crop irrigation	Suitable	Improve fertilization, irrigation, and nutrient management practices to reduce levels of nitrogen and potassium that could limit water use for crop irrigation or aquatic ecosystems conservation downstream of the headwaters of the hydrographic unit.
Aquatic life ambient freshwater	Suitable	

intervention. Although the nitrate concentration did not surpass water quality standards and regulations for different water uses, values close to recommended maximums for preserving aquatic life in high-mountain ecosystems were found at the outlet of the hydrographic unit. Furthermore, coming from a relatively small drainage area, this considerable load of nitrates could compromise water quality to irrigate susceptible crops downstream.

Our results highlight the importance of management practices with the potential to protect water quality, such as restricting livestock grazing nearby water sources and implementing improvements to current fertilization and irrigation practices to reduce losses of nitrogen, potassium, and organic matter and the transport of pathogens from agricultural lands to water sources (Kannan and Anandhi 2020; Tahat et al. 2020; Velasco-Muñoz et al. 2019). These strategies could reduce the negative impact on community health and contribute to preserving the Berlin Páramo biodiversity. In the context of páramo ecosystems, the financial compensations to local farmers through schemes such as payment for ecosystem services (Pissarra et al. 2021) could be a pivotal strategy to harmonize the livelihoods of traditional páramo communities with the preservation of the water supply ecosystem service.

Considering the relatively small size of the study area and its location at the headwaters of the Jordan River, more research is needed to evaluate the influence of human activities in a hydrological zone with a larger area. Furthermore, future research needs to address the analysis of pesticides in surface water. These are agricultural contaminants not covered here, which could compromise the potential uses of water for downstream communities and activities.

This study shows the need to set water quality continuous monitoring schemes that provide the information required for decision-making on the effect of anthropic activities such as agriculture in strategic mountain ecosystems such as páramos. Participatory public policy formulation, including rural communities and farmers, could include the improvement of small-scale agriculture and livestock farming, the delimitation of areas to develop productive activities, and the implementation of payment for ecosystem services schemes. Working around these issues will contribute to progress on the Sustainable Development Goals (SDGs) (UN 2015), in particular to SDG 2 “Zero Hunger” (Target 2.4), SDG 6 “Water and Sanitation for all” (Targets 6.3 and 6.6), and SDG 15 “Life on land” (Targets 15.4 and 15.9).

Conclusions

- This study found that current land uses in the Berlin Páramo, including potato and spring onion crops, and extensive livestock farming negatively affect the quality of surface water sources. This was evidenced by the significant increase ($p < 0.05$) in levels of nitrates (0.02 to 2.56 mg $N\text{-}NO_3$/L), potassium (0.13 to 1.24 mg K/L), and *E. coli* (63 to 2718 FCU/100 mL), which could compromise the water supply ecosystem service. These impacts are noticeable considering the inputs of nutrients and pathogens to the surface water in the anthropic SHU were only about 15% of its area is represented by agricultural land cover.
- The anthropic influence on water quality was significantly amplified ($p < 0.05$) during the rainy season, as indicated by higher levels of total nitrogen, BOD_5, and COD.
- Water from the studied area did not fulfill quality standards for direct human consumption on turbidity, *E. coli*, BOD_5, and COD.
- In the hydrographic unit, all the assessed parameters achieved quality standards for uses such as livestock watering, crop irrigation, and aquatic life ambient freshwater. However, the high nutrient load (nitrogen and potassium) could promote downstream eutrophication and represent a risk for lotic aquatic páramo ecosystems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-21709-6.

Acknowledgements The authors thank the families of the Berlín Páramo who allowed the development of this research and provided valuable information. Also, thanks are given to Universidad Industrial de Santander Universidad Industrial de Santander for funding the research projects (Program Santander Científico- 2018) identified through Grant 2438. We also thank Juan Durán, Jesús Torres, Jean Larrotta, Viviana Gómez, Juan Quintero, Luis Buitrago, Mayra Afanador, and Andrés Barón for their support in the fieldwork and/or laboratory analysis. Rey-Romero thanks MinCiencias for her PhD scholarship.

Author contribution All authors contributed to the study conception, methodological design, data collection, and analysis. The first draft of the manuscript was written by Daniela Cristina Rey-Romero, and all authors commented on previous versions of the manuscript. Daniela Cristina Rey-Romero, Isabel Domínguez, and Edgar Ricardo Oviedo-Ocaña read and approved the final manuscript.

Funding This study was funded by Universidad Industrial de Santander, through the Program Santander Científico (2018) - Grant 2438.

Data availability The data used and analyzed under this study are available from the corresponding author upon request.

Declarations

Ethics approval This study was approved by the Scientific Research Ethics Committee (CEINCI) of the Universidad Industrial de Santander (UIS).

Consent to participate The owners of the farms where the study was conducted gave their permission for its development through informed consent, which was approved by the Scientific Research Ethics Committee (CEINCI) of the Universidad Industrial de Santander (UIS).

Consent for publication Authors consent the publication of the manuscript.

Competing interests The authors declare no competing interests.

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