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Research article

Assessing the potential of nature-based solutions as sustainable land and water management strategies in the high tropical Andean páramo ecosystem

Kalina Fonseca [a,b,*], Juan S. Acero Triana [c], Miguel Ramírez [d], William Martínez [d], Mercy Ilbay [b], Edgar Espitia-Sarmiento [a], Lutz Breuer [a,e]

[a] *Centre for International Development and Environmental Research, Justus Liebig University Giessen, Senckenbergstrasse 3, 35390, Giessen, Germany*
[b] *Water Resources Management Group, Technical University of Cotopaxi, Av. Simón Rodríguez s/n Barrio El Ejido Sector San Felipe, 050104, Latacunga, Ecuador*
[c] *Department of Environmental Sciences, University of California Riverside, 900 University Ave, Riverside, CA, 92521, USA*
[d] *Department of Geography, Universidad Nacional de Colombia, Bogotá D.C., Colombia*
[e] *Institute for Landscape Ecology and Resources Management (ILR), Research Centre for BioSystems, Land Use and Nutrition (iFZ), Justus Liebig University Giessen, Heinrich-Buff-Ring 26, 35390, Giessen, Germany*

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ABSTRACT

Nature-based solutions (NbS) are gaining attention as viable strategies for restoring water-rich ecosystems such as the páramo. However, the lack of evidence on their effectiveness, coupled with a limited understanding of their political, economic, social, technological, environmental, and legal (PESTEL) context, hinders their widespread adoption. To address this gap, we propose a multi-method framework that (i) captures PESTEL factors influencing the implementation of passive ecological restoration in páramo ecosystems as a measure of NbS and (ii) assesses its associated environmental impacts. Our approach integrates a scoping review with remote sensing techniques, water quality assessment, and correlation analyses. Focusing on the Upper Pita and Upper Cutuchi River Basins-key water sources for Andean communities in Ecuador, we reveal that the deterioration of their páramo ecosystems in the 20th century was mainly due to camelid grazing and pine timber production. In response to these threats, bottom-up management efforts starting in 1999, guided by various PESTEL factors, promoted policies, regulations, social agreements, and financial support for achieving passive ecological restoration between 2010 and 2017 in the Upper Pita River Basin. As a result, the conservation of 73.4% of natural páramo with excellent water quality in 2022. By contrast, top-down management in the Upper Cutuchi River Basin was ineffective because national strategies failed to tackle the local environmental challenges posed by the PESTEL factors. Hence, only 31.6% of the natural páramo remained with *poor* water quality by 2022. Our study is the first to demonstrate that passive ecological restoration benefits these ecosystems, while its absence results in significant changes that require additional restoration strategies.

1. Introduction

The high mountain landscape of the northern Andes region in South America is dominated by a unique tropical montane tundra ecosystem known as páramo, characterized by a high water retention capacity (Buytaert et al., 2006; Castanier, 2015; Christmann and Oliveras, 2020; Patiño et al., 2021). The páramo encompasses the high tropical Andes at elevations ranging from 3000 to 5000 m above sea level (m.a.s.l.) and plays a vital role in water supply for Andean communities, including those in large cities such as Quito (Ecuador) and Bogotá (Colombia) (Buytaert et al., 2006; Mosquera et al., 2023). The main river basins supplying these local communities have headwaters in this ecosystem, which provide high-quality drinking and irrigation water for the downstream population (Ávila and Gallo, 2021; Mulligan et al., 2010).

Despite the importance of páramo ecosystems in providing water ecosystem services to Andean communities, their intensive exploitation has become widespread in the northern Andes, posing a growing threat to water security (Buytaert et al., 2006; Gude, 2017; Mulligan et al., 2010). The natural páramo vegetation (i.e., tussock-forming grasses,

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[*] Corresponding author. Centre for International Development and Environmental Research, Justus Liebig University Giessen, Senckenbergstrasse 3, 35390 Giessen, Germany.
E-mail address: kalina.fonseca@utc.edu.ec (K. Fonseca).

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Abbreviations

CWQI	Canadian Water Quality Index
DEM	Digital Elevation Model
NbS	Nature-Based Solutions
LULC	Land Use and Land Cover
NGO	Non-governmental organization
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
PCC	Pearson Correlation Coefficient
SDGs	Sustainable Development Goals
UCutuchiRB	Upper Cutuchi River Basin
UPitaRB	Upper Pita River Basin

xerophytic shrubs, cushion-forming plants, and giant caulescent rosettes), which acts as giant sponges steadily supplying water, has been converted, often by burning into agricultural, forestry, grazing, mining, and urban systems (Castelo-Cabay et al., 2022; Giles et al., 2018). Transforming the vegetation cover and altering the hydro-physical properties of soil can significantly impact the hydrological performance of páramo ecosystems, affecting both the quality and quantity of water they provide (Patiño et al., 2021).

A crucial measure to reduce the impact of land use and land cover (LULC) changes on the water resources and to conserve the remnants of natural páramo vegetation is implementing sustainable management strategies (Buytaert et al., 2006; García et al., 2019; Mosquera et al., 2023; Rey-Romero et al., 2022). Many sustainable development agendas highlight nature-based solutions (NbS) among the available strategies because of the benefits of working with nature (Hanson et al., 2020; Possantti and Marques, 2022; Sowińska-Świerkosz and García, 2022). Cost-effectiveness, adaptation to local environmental issues, and contribution to achieving multiple Sustainable Development Goals (SDGs) are among the main advantages of NbS (Keesstra et al., 2018; Sowińska-Świerkosz and García, 2022).

In particular, in the headwaters of crucial Andean river basins, NbS initiatives, such as passive ecological restoration, are drawing the attention of the decision-makers to sustain drinking water sources (Brauman et al., 2019; Castanier, 2015). Passive ecological restoration is particularly well-suited for headwater streams, as it can restore their water quality by eliminating disturbances and favoring natural vegetation recovery (Buytaert et al., 2007; Taniwaki et al., 2019; Trujillo--Miranda et al., 2018). Nonetheless, conclusive results demonstrating that passive ecological restoration impacts on páramo ecosystems' environmental health are lacking. Similarly, the macro-environment surrounding the management of passive ecological restoration, including the political, economic, social, technological, environmental, and legal (PESTEL) context (Den Heijer and Coppens, 2023; Fonseca et al., 2022), remains largely unknown.

Recognizing the benefits of passive ecological restoration to reduce land degradation and improve water quality in the PESTEL context of páramo ecosystems requires an integrated assessment from different perspectives using multiple data sources. In this study, we propose a novel multi-method framework to i) capture PESTEL factors favoring (or constraining) the implementation of passive ecological restoration and ii) quantify its potential environmental impacts in páramo areas. It combines scoping review with remote sensing techniques, water quality assessment, and correlation analysis to address the following research questions: (1) What PESTEL factors favor (or constrain) the implementation of passive ecological restoration in the páramo ecosystems? (2) How do spatiotemporal changes in LULC and water quality differ between páramo areas with and without passive ecological restoration? (3) How does combining PESTEL analysis with environmental impact assessment of passive ecological restoration contribute to decision-making for sustainable land and water management in páramo areas? In this study, we selected the Upper Pita River (UPitaRB) and the Upper Cutuchi River Basins (UCutuchiRB) in Ecuador to illustrate the role of the páramos in the northern Andes of South America for drinking and irrigation water supply. By analyzing local passive ecological restoration efforts to maintain water ecosystem services, we provide decision-makers with strategies to improve páramo management.

2. Materials and methods

2.1. Study basins

The UPitaRB and UCutuchiRB are located in the Andean range within Ecuador's páramo ecosystems and along the protected areas of the Cotopaxi National Park and the El Boliche National Recreation Area, respectively, shown in Fig. 1. The UPitaRB covers 197 km^2 and is located ~20 km from Quito between the northeast side of the Cotopaxi volcano and the southwest side of the Sincholagua volcano (Fig. 1a). UPitaRB's elevations range from 3280 to 5800 m.a.s.l. with a mean slope of 16%. The UCutuchiRB covers 233 km^2, and it is situated ~23 km from Latacunga across the inter-Andean valley (2980–5800 m.a.s.l.; mean slope of 14%) to the west of the Cotopaxi volcano (Fig. 1b). According to the Köppen-Geiger classification, the climate in the basins is warm temperate (Cfb) (Kottek et al., 2006), with temperatures ranging from 6 to 12 °C (INAMHI, 2017). The mean annual precipitation in the UPitaRB varies between 1064 and 1406 mm, while in UCutuchiRB, between 662 and 1406 mm (1968–2014) (Ilbay-Yupa et al., 2021). A sandy-loamy soil is predominant in both basins. Specifically, 80% of UPitaRB's soils are classified as andisols (middle and upper parts), 10% entisols, and 10% mollisols (lower part). In the UCutuchiRB, andisols represent 40% of the basin's area, while the remaining 60% are equally covered by mollisols and inceptisols (MAG, 2019).

The Pita and Cutuchi Rivers are a crucial source of drinking and irrigation water for Quito, the country's second-largest city (~2.8 million inhabitants), and for Latacunga, a relevant agroindustrial city (Aguilera et al., 2004; Castanier, 2015; SNAP, 2015; Zapata et al., 2021). In the UPitaRB, water is allocated to irrigation (53.8%), human consumption (25%), pisciculture (21%), and ponds (0.2%). Similarly, in the UCutuchiRB, water rights are predominantly concessioned to irrigation (87.5%), industrial supply (10.8%), human consumption (1.2%), and recreational use, pisciculture, and bottled water companies (0.5%) (SENAGUA, 2021). UPitaRB and UCutuchiRB are part of the fourth (9.65%) and sixth (7.30%) Ecuadorian provinces (i.e., Pichincha and Cotopaxi), which have the largest páramo areas (mainly shrubs and herbaceous vegetation) of all provinces (García et al., 2019). Despite their importance to the national territory, the limited spatial scope of passive ecological restoration has led to uneven protection of these ecosystems, with páramo areas continuing to be transformed into other LULC, jeopardizing water security in the Andean cities (Castanier, 2015; Zapata et al., 2021).

2.2. Multi-method framework

The designed framework consists of (a) a PESTEL analysis to create a timeline of PESTEL factors influencing passive ecological restoration through a scoping review and b) an integration of remote sensing techniques, water quality assessment, and correlation analysis to characterize spatiotemporal changes of LULC and water quality in the study area (Fig. 2).

2.2.1. PESTEL analysis

A scoping review was conducted from August 2022 to April 2023 following the methodology by Levac et al. (2010) to identify, select, and summarize relevant studies on passive ecological restoration in the páramo areas based on the analysis of PESTEL factors (Den Heijer and Coppens, 2023; Fonseca et al., 2022). This approach allows the

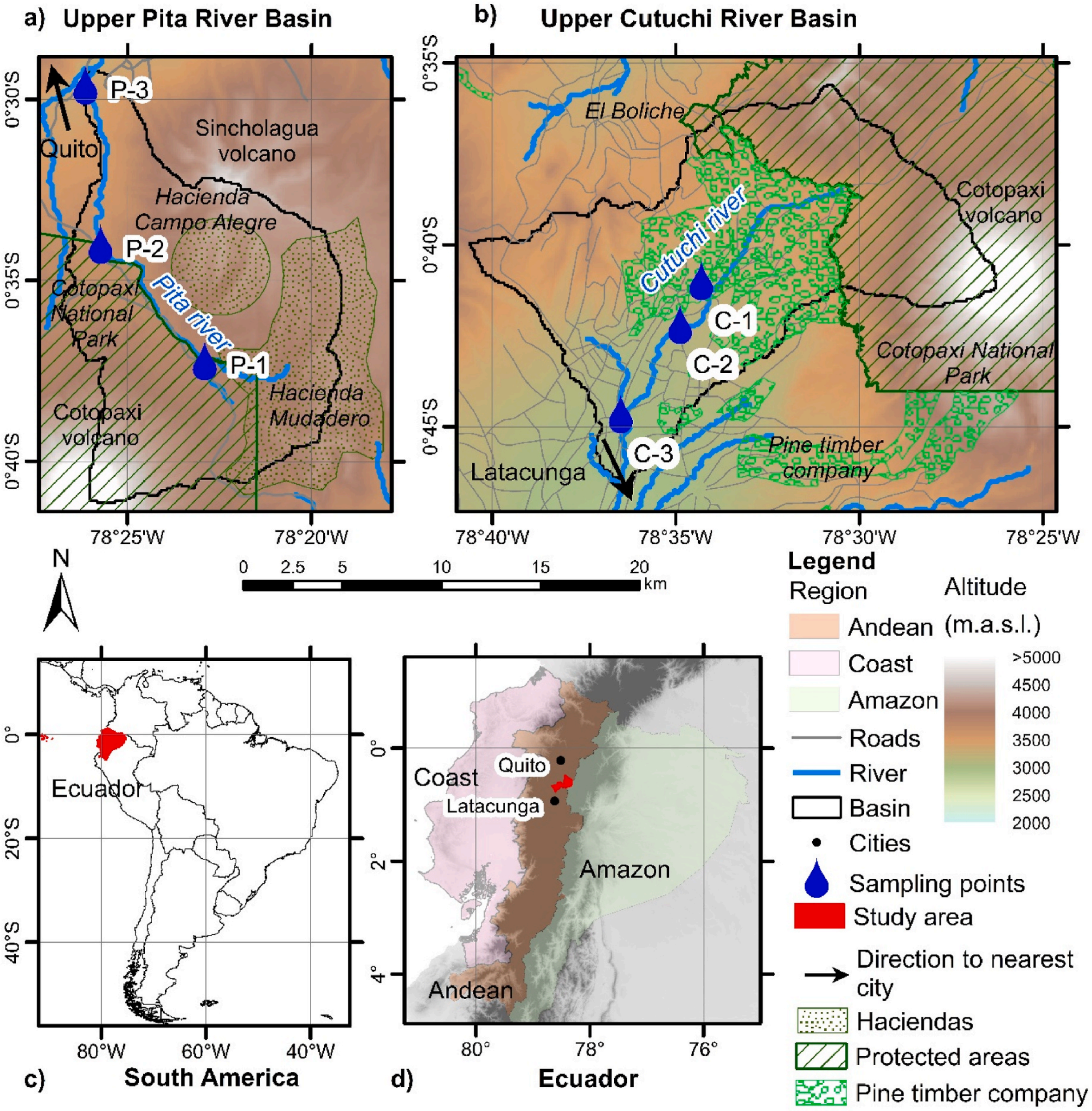


Fig. 1. Topography, hydrography, and protected areas of the (a) Upper Pita and (b) Upper Cutuchi River Basins, located in (c) South America and (d) Ecuador.

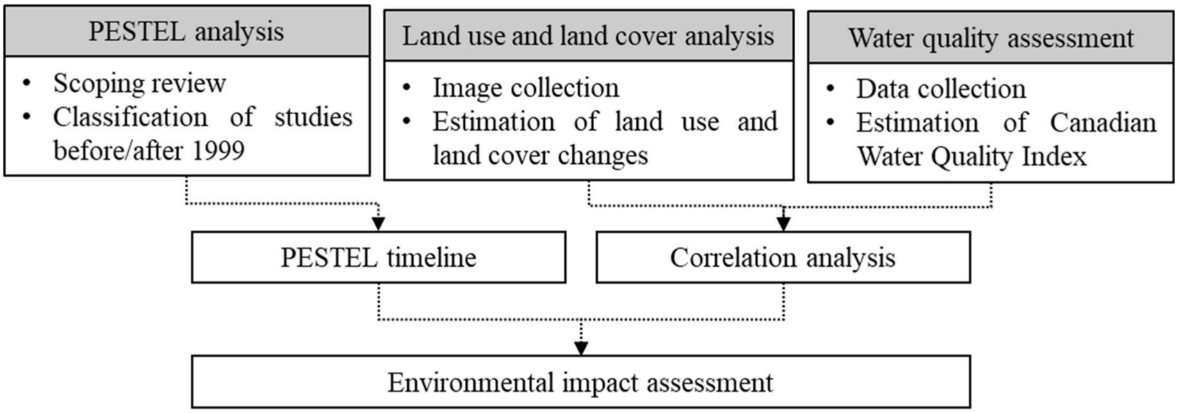


Fig. 2. Multi-method framework to capture the PESTEL factors involved in passive ecological restoration and quantify its potential environmental impacts.

incorporation of formal and grey literature to assess the size and scope of available literature on a specific topic and identify key trends and research gaps (O`Brien et al., 2016). We utilized widely recognized scientific databases, including ScienceDirect, Web of Science, Google Scholar, SpringerLink, and the Integrated System of Ecuadorian University Libraries. The studies on PESTEL factors were identified to address the research question: (1) What PESTEL factors favor (or constrain) the implementation of passive ecological restoration in the páramo ecosystems? The literature search consisted of keyword combination searches that associate PESTEL factors in each of the study basins with keywords such as LULC changes, NbS, basin management, sustainable land and water management strategies, sustainable land and water management initiatives, páramo transformation, passive ecological restoration, water quality, and land degradation. The selected studies met the following inclusion criteria proposed by the authors: a) peer-reviewed textbooks and book chapters, b) grey literature from non-governmental organizations (NGOs), consulting companies, and government agencies, and c) national and local laws, regulations, and policies.

Since passive ecological restoration plans began in the study area in 1999, studies conducted before this year were classified as development pathways of land and water management. While studies after 1999 were viewed as an adaptation of passive ecological restoration to páramo ecosystems, with significant implementation years being 2010, 2017, and 2022. Overall, data from 48 studies were extracted and presented in a timeline view to capture the PESTEL factors favoring and constraining the implementation of passive ecological restoration in páramo ecosystems.

2.2.2. *Remote sensing assessment*

The compilation of primary data was necessary to assess the spatiotemporal LULC changes across the UPitaRB and UCutuchiRB due to the lack of national high-resolution LULC datasets. Using Google Earth Engine, as suggested by Floreano and De Moraes (2021) and Gorelick et al. (2017), we performed image collection, estimated spectral indices, and conducted supervised classification using a random forest classifier. For the image collection, we combined annual medians of Level-2 Landsat 30-m multispectral imagery (TM5 for 1999, ETM+7 for 2001–2013, and OLI8 for 2013–2022) and a 30-m Digital Elevation Model (DEM) from February 2000 of the Shuttle Radar Topography Mission (SRTM) (Yang et al., 2011). The Level 2 Landsat imagery passed through a pre-processing step to eliminate atmospheric effects and, thus, reduce the probability of LULC misclassification in cloud-prone areas (Kuhn et al., 2019). Subsequently, these data layers were used to estimate seven spectral indices that served as predictor variables of LULC and discriminate between vegetation and developed areas: Normalized Difference Vegetation Index (NDVI) (Maxwell and Sylvester, 2012), Structure Intensive Pigment Index (SIPI) (Kobayashi et al., 2020), Photosynthetic Vigour Ratio (PVR) (Warren and Metternicht, 2005), Visible Atmospherically Resistant Index Green (VARIGreen) (Kobayashi et al., 2020), Green Atmospherically Resistant Vegetation Index (GARI) (Sonobe et al., 2018), Normalized Difference Built-up Index (NDBI), and Normalized Difference Water Index (NDWI) (Ashok et al., 2021).

Using a random forest classifier trained on labeled data from approximately 100 sampling points per land cover type, we generated LULC maps for 1999, 2010, 2017, and 2022 (key years related to passive ecological efforts). Random Forest algorithm was used to classify LULC due to the effective handling of large multi-temporal remote sensing datasets and high resistance to noise and overfitting (Acharki, 2022; Andrade et al., 2021; Hasan et al., 2023). The labeled data was identified by visual interpretation of medium-resolution Landsat and ESRI mosaics following the CORINE land cover classification (IDEAM, 2010) considering seven classes: (1) artificial surfaces, (2) forests (e.g., pine), (3) glacier and perpetual snow, (4) open spaces with little or no vegetation (including bare rocks, sparse vegetation and burned areas), (5) pastures, (6) shrub and herbaceous vegetation (categorized as natural páramo), and (7) temporary crops (e.g., potato, corn, beans). The accuracy of the LULC classification used the precision and kappa metrics, according to Foody (2020), at 30% of the sampling points for each class (Hastie et al., 2009). The LULC classification performed satisfactorily during calibration (precision = 87% and Kappa index≥0.85) and validation (precision = 69% and Kappa index≥0.63) according to the Random Forest algorithm. The resulting LULC maps were further refined using a majority filter (Kim, 1996) to remove isolated pixels. To identify spatiotemporal LULC changes, we used a change matrix upon four standardized categories (i.e., deforestation, pine plantation, crops, and converted) following the guidelines of IDEAM et al. (2010) and considering changes in spatial units of at least 4000 m^2.

2.2.3. *Water quality assessment*

We calculated the Canadian Water Quality Index (CWQI) to compare water quality for drinking and irrigation sources between the study basins, chosen for its flexibility in the type and number of water quality parameters, the period of application, and the waterbodies (CCME, 2017; Hurley et al., 2012). The CWQI (Eq (1)) is calculated as the complement of the square root of the sum of squares of the scope (F_1), frequency (F_2), and amplitude (F_3) of the water samples' exceedance from given standards (Hurley et al., 2012; Kaur et al., 2023).

$$\mathrm{CWQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \tag{Eq 1}$$

F_1 represents the number of parameters not meeting the water quality standards, while F_2 represents the number of times the water quality standards are not met. On the other hand, F_3 represents the deviation of the non-compliant parameters from their corresponding water quality standards (Ahmed et al., 2020; Kaur et al., 2023). CWQI varies between 0 and 100, with the latter indicating the best water quality (Marselina et al., 2022).

The acceptable standards for the quality of drinking and irrigation water sources used for calculating the CWQI are derived from national regulations (MAE, 2002; 2015), except total phosphorus (for both uses), nitrate-nitrogen, and turbidity for irrigation that followed international regulations (FAO, 1994; U.S. EPA, 1988; 2012) (Table 1).

The CWQI model requires a minimum of four water quality parameters but does not specify which ones. Additionally, the parameters used can vary by region, depending on local conditions, water use purposes, and quality issues (CCME, 2017; Uddin et al., 2021). Our water quality database incorporated seven physical, chemical, and microbiological parameters (Table 1) based on data availability in the study area, their relevance to drinking and irrigation water sources, and frequent parameters incorporated in water quality indices, as recommended by Uddin et al. (2021). These parameters include dissolved oxygen (DO), fecal coliform (FC), nitrate-nitrogen ($NO_3 - N$), pH, total dissolved solids (TDS), total phosphorus (TP), and turbidity (TURB) (Table 1). The water quality database includes data collected between 3000 and 5000 m.a.s.l. in the high tropical Andes from studies funded by governmental agencies, universities, and NGOs, was considered for the water quality database (Acosta, 2018; Amores, 2019; CODERECO, 2002; Quishpe, 2018; Rojas, 2020). In addition, a fieldwork campaign took place in

Table 1
Acceptable drinking and irrigation water quality standards.

Parameter	Unit	Drinking Water	Irrigation water
Dissolved oxygen (DO)	mg/L	≥6	≥3
Fecal coliform (FC)	NMP/100 mL	≤1000	≤1000
Nitrate-Nitrogen ($NO_3 - N$)	mg/L	≤10	≤10
pH	–	6–9	6–9
Total dissolved solids (TDS)	mg/L	≤500	≤2000
Total phosphorus (TP)	mg/L	≤0.1	≤2
Turbidity (TURB)	NTU	≤100	≤2

2022, in which the collection and preservation of additional samples complied with Ecuadorian technical standards for drinking water (INEN, 2013a, 2013b), Unified Text of the Secondary Legislation of the Ecuadorian Ministry of Environment (MAE, 2015), and section 1060 of the Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF; 2017, Apha and Wef; 2005; 2017).

The water quality database for UPitaRB and UCutuchiRB included 441 and 320 water samples, respectively, representing seven selected quality parameters at three sampling points in 2001, 2010, 2017, and 2022 (Fig. 1a and b). In UCutuchiRB, water quality data is scarcer than in UPitaRB, with only one data point available from 2001. This year was the starting point for analyzing passive ecological restoration initiatives in both basins from a water quality perspective.

2.2.4. *Correlation analysis*

Pearson's correlation coefficient was applied to linearly associate spatiotemporal variations of LULC with water quality parameters (Li et al., 2008) and to evaluate the possible impacts of LULC changes on water quality in the UPitaRB and UCutuchiRB. Correlation analyses (Eq (2)) were conducted using average values of each water quality parameter (441 and 320 water samples for UPitaRB and UCutuchiRB, respectively) for the period 2001 to 2022, and each LULC class between 1999 and 2022 as follows.

$$\mathrm{PCC} = \frac{\sum (\mathrm{LULC}_i - \overline{\mathrm{LULC}})(\mathrm{WQP}_i - \overline{\mathrm{WQP}})}{\sigma_{\mathrm{LULC}}\,\sigma_{\mathrm{WQP}}} \qquad \text{(Eq 2)}$$

With Pearson's correlation coefficient (PCC), LULC_i and WQP_i the *i*th observation of LULC and water quality parameters, respectively. $\overline{\mathrm{LULC}}$ and $\overline{\mathrm{WQP}}$ are the mean observations, and σ represents the standard deviation (Herzog et al., 2019; Prion and Haerling, 2014). Correlations were considered statistically significant with $\mathrm{PCC} \geq 0.8$ and $p < 0.05$. The statistical analysis was performed using the R programming language.

3. Results

3.1. *Development pathways of land and water management in the 20th century*

Exploration of PESTEL factors over the period 1900–1999 revealed their influence on both land use changes in the páramo areas of UPitaRB and UCutuchiRB and the introduction of sustainable land and water management strategies, including passive ecological restoration as shown in Table 2. Predominantly political, economic, legal, and social factors led to the conversion of substantial páramo areas into large farms (estates known as haciendas) and later into a combination of large and small farms due to the 1964 agrarian reform in Ecuador (Coral et al., 2021; Goodwin, 2017; Solo De Zaldívar, 2015). Although a more equitable land distribution was expected with the agrarian reform, disparities between the landowners and peasant communities prevailed due to the landowners' strategies to sidestep the reform by dividing and transferring their lands to fictitious buyers (i.e., frontmen, usually relatives) (Coral et al., 2021; Solo De Zaldívar, 2015).

On the other hand, economic, social, and technological factors drove the introduction in the haciendas of non-native species, such as California pine trees in UCutuchiRB (1928; Table 2) and alpacas in UPitaRB (1985; Table 2), to develop the lumber and wool industry, respectively (Buytaert et al., 2007; MAE, 2007; Metcalf et al., 2014). Thus, the Mudadero and Campo Alegre haciendas covered UPitaRB, while forestry haciendas (pine timber company) occupied UCutuchiRB (Fig. 1a and b) (Coronel, 2019; MAE, 2007). In addition, peasant communities established small farms in these páramo areas, lacking the resources for the large-scale infrastructure (Keese, 1998; Partridge, 2016). Simultaneously, water and electricity infrastructures for Quito were developed across UPitaRB between the 1920s and 1970s (Carrion et al., 1997; González-Zeas et al., 2022); 2019 (Table 2). UCutuchiRB, meanwhile, focused on the development of irrigation and transport infrastructure (1970–1986) for the nascent timber industry in Latacunga, which began in 1978 on 16 km^2 of páramo land and the mining industry that took off after the discovery of registered gravel and stone deposits as early as 1983 (Table 2) (Aglomerados Cotopaxi, 2021; Allou et al., 1987; Martínez, 2006). At the same time, drinking water and electricity infrastructures for Latacunga were developed in other páramo areas in the southwest of the city (Ibarra, 2018).

Table 2

Relevant historical events associated with PESTEL factors affecting páramo areas over the 20th century. P: Political, Ec: Economic, S: Social, T: Technological, En: Environmental, L: Legal; blue = UPitaRB, grey = UCutuchiRB; white = both basins.

Year	PESTEL factor	Relevant historical events
1900	P	Large farms known as haciendas have been expanding in the páramo since colonial times
	S	Hacienda peasants work in precarious conditions
1922	T	Quito's hydropower plant in development
1928	T	California pine trees are introduced in high-altitude ecosystems
1964	L	Agrarian reform is enacted to redistribute land among peasant communities
	S	Landowners divide lands between relatives to sidestep the agrarian reform
1970	Ec	Peasants cannot afford the increasing land prices after the agrarian reform
	P	Area disparities in land redistribution
	Ec	Haciendas encompass páramo areas despite the agrarian reform
	Ec	Some new landowners intensify agriculture and livestock farming
	Ec	Peasant landowners cannot afford large-scale farming infrastructure
	T	Road network upgrading project begins
	S	Andean urbanization peaks, demanding more water from páramo
	T	Latacunga's utility infrastructure is modernized, excluding the basin
	T	Modernize and intensify agriculture and livestock farming
1973	L	Forestry haciendas (pine timber company) excluded from protected areas
1975	En	Cotopaxi National Park (334 km^2) is founded as a protected area
1977	T	Quito's water infrastructure in development
1978	T	A large pine tree lumber company begins activities on 16 km^2
1979	En	Boliche Recreation Area (3.9 km^2) is founded as a protected area
1983	T	Some gravel and rock deposits are unexpectedly discovered
1985	En	Alpaca population increases in the highlands
	Ec	Development of the wool industry
1986	T	Salcedo-Ambato canal is being constructed to irrigate 70 km^2 in Latacunga
	En	Water impairment by fecal coliform is reported
1990	P	Management strategies of the Ecuadorian Institute of Water Resources fail due to water disputes among stakeholders
1997	L	National Ecuadorian Institute of Water Resources is dissolved, and some functions are replaced by the National Water Resources Council creation
1998	L	The new constitution considers the protection of natural resources
1999	L	The newly created Environment Ministry approves the environmental management law
	Ec	Environmental investment is significantly constrained by a deep economic crisis
	En	Páramo areas are threatened by degradation agricultural expansion, livestock, and tourism
	En	Water impairment by pathogenic bacteria and total suspended solids is reported

During 1960–1980, the urbanization of Andean cities reached its peak, as well as the demand for food and irrigation water, which led to the intensification and modernization of agriculture and livestock farming in both basins (Alvarez and Sanchez, 2018; Cornejo and Wilkie, 2010; Rudel and Richards, 1990; Solo De Zaldívar, 2015). To counteract these anthropogenic pressures in the páramo areas associated with economic, social, and technological development and to promote tourism, the creation of protected areas was proposed as one of the early sustainable management strategies. With the prior agreement to exclude UCutuchiRB forestry haciendas from the protected areas, Cotopaxi National Park and the El Boliche National Recreation Area were founded in 1975 and 1979, respectively, to achieve ecological restoration objectives at the national level guided by a top-down management approach (from the National government) (MAE, 2007; SNAP, 2015).

Moreover, the National Ecuadorian Institute of Water Resources (INERHI) strategies failed to resolve water user conflicts and disputes within public institutions. Consequently, INERHI was dissolved, irrigation development competencies were decentralized to the Regional Development Corporations in 1994, and water resources management was transferred to the National Water Resources Council (CNRH) (Hoogesteger et al., 2016; Warner et al., 2014).

Despite the establishment of protected areas for sustainable land and water management in UPitaRB and UCutuchiRB, the continued degradation of páramo areas and their water quality (Allou et al., 1987; Brauman et al., 2019) prompted a reconsideration of new strategies for the páramo. Thus, several legislative initiatives were launched at the national level to safeguard ecosystems and promote the sustainable use of land and water resources (Asamblea Nacional Constituyente, 1998; Congreso Nacional, 1999; Warner et al., 2014). These initiatives could have been more effective if the environmental investment had not been significantly constrained by a deep economic crisis that led to the dollarization of the country's economy in 1999 (Joslin and Jepson, 2018) (Table 2).

3.2. Conditions favoring passive ecological restoration in Upper Pita river basin in the 21st century

3.2.1. PESTEL factor analysis in UPitaRB

Since 1999, passive ecological restoration of páramo areas in the UPitaRB has been promoted by several PESTEL factors to protect Quito's drinking water resources (Kauffman, 2014; Wiegant, 2022) (Table 3). The leading promoters at the political and economic levels were Quito's water and electricity utility companies and the Quito Water Fund, which had legal support at the local governance scale (bottom-up management) (Coronel, 2019; Kang et al., 2023).

In particular, the Water Fund created as an endowment fund in 2000, has been supported by donations from public, private, and non-profit organizations, including The Nature Conservancy, to invest in restoration projects in basins supplying water to Quito (Brauman et al., 2019; Coronel, 2019). However, the implementation of sustainable strategies did not occur until 2010, not meeting the expectations of the Water Utility Company, the largest donor of the Water Fund, which aimed to increase safe drinking water access by that time (Table 3) (Joslin and Jepson, 2018; Molina-Vera et al., 2018).

In 2010, passive ecological restoration efforts began in the páramo areas of UPitaRB, focusing on reducing alpaca grazing. The Water Utility Company started with the Mudadero hacienda acquisition (73.89 km^2), which occupied 37% of the páramo area. Then, agreements were reached with landowners to reduce the camelid population by approximately 10,000 alpacas and other anthropogenic pressures (Table 3) (Castanier, 2015; FONAG, 2019).

Since 2011, the Water Fund has been allowed to allocate up to 30% of its annual income to contributions (Kang et al., 2023), yet passive ecological restoration projects did not expand until 2017 (Table 3). Nonetheless, this year, political, economic, and social factors enabled the Water Fund to purchase 27.2 km^2 of the Campo Alegre hacienda with the Electricity Utility Company support, turning an additional 13% of UPitaRB's páramo into passive ecological restoration after the relocation of 900 alpacas (Coronel, 2019; FONAG, 2019). In 2022, 50% of the 196 km^2 of páramo in the UPitaRB were subject to passive ecological restoration by eliminating disturbance factors and allowing for páramo natural vegetation recovery. The passive ecological restoration of páramo in UPitaRB by bottom-up management has effectively mitigated widespread land and water degradation, influenced by a complex interplay of PESTEL factors since the 20th century.

Table 3
Historical events associated with passive ecological restoration in páramo areas across UPitaRB in the 21st century. P: Political, Ec: Economic, S: Social, T: Technological, En: Environmental, L: Legal.

Year	PESTEL factor	UPitaRB
1999	P	Policymakers propose a water fund financed by the public, private sectors, and NGOs
	L	Public institutions can donate to independent water funds
2000	P	Water Fund is created by a municipal ordinance
	Ec	Water Utility Company and The Nature Conservancy become the first Water Fund donors
	P	Water Fund promotes management strategies in Quito's water-supplying basins
2001	T	Water Utility Company aims to increase high-quality water coverage by 2010
2002	Ec	Water Fund can only invest using its profits, which are limited
2003	Ec	Several beverage companies utilizing water from the páramo of the UPitaRB contribute to the Water Fund
2005–2009	P	Water Fund management strategies do not fulfill Water Utility Company expectations
2010	P	Water Utility Company purchases 74 km^2 of the UPitaRB without financial support from the Water Fund
2011–2013	S	Landowners agree to relocate 10,000 alpacas
	Ec	Water Fund is allowed to invest up to 30% of its annual income in contributions
	En	Alpaca grazing is reduced by 37% of the basin
	P	Water Fund restoration priorities deep the differences with Water Utility Company
2017–2020	P	Water Fund purchases 27 km^2 of the UPitaRB with Electricity Utility Company support
	En	Alpaca grazing is reduced by 13% of the basin
	S	Landowners agree to relocate 900 alpacas
	Ec	Water Utility Company reduces operative costs by improving water quality upstream
2022	En	50% of the upper basin undergoes passive ecological restoration

3.2.2. LULC changes in UPitaRB

The LULC maps and changes for 1999, 2010, 2017, and 2022, corresponding to the key years associated with passive ecological restoration of páramo areas in the UPitaRB, are shown in Fig. 3. In the UPitaRB, the main LULC class in 1999 identified was natural páramo, covering 79.3% (Fig. 3e), despite a few patches of temporary crops, forests, and pastures due to anthropogenic activities (Fig. 3a). In addition, open areas with little or no vegetation were observed, including bare rocks, sparse vegetation and burned areas associated with natural and human factors, respectively (Fig. 3a). Between 1999 and 2010, significant changes occurred in the LULC of the basin. The natural páramo decreased to 72.7% and increased open spaces with little or no vegetation to 7.1%, temporary crops to 5.9%, forests to 3.0%, and pastures to 0.5% (Fig. 3b and e). Natural páramo areas in Cotopaxi National Park, haciendas, and the lower part of the basin, as depicted in Fig. 3b and e, were primarily transformed into these four specified LULC.

LULC changes from 2010 to 2017 showed an increase to 81.8% of natural páramo and a decrease to 3.0 % of open spaces with little or no vegetation, 1.6% of temporary crops, and 0.7% of forests (Fig. 3b, c, and e). Comparing natural páramo between 2010 and 2017, it increased by 9.1%, mainly in the areas under passive ecological restoration (establishment of haciendas) (Fig. 3c). Moreover, pastures increased by 1.8% in the lower part of the basin, which did not evidence this strategy (Fig. 3c). In the last analysis period (2017–2022), the natural páramo

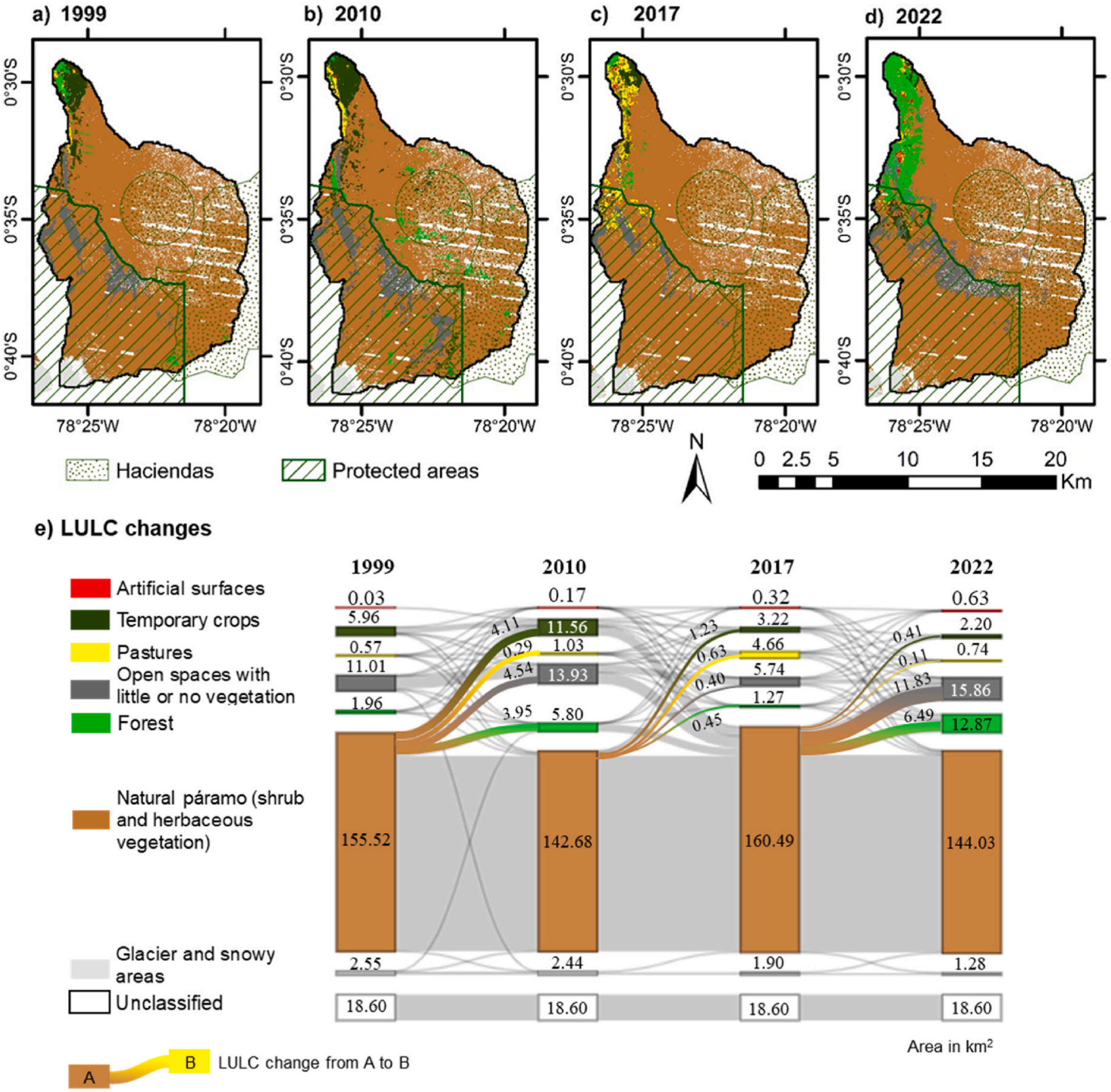
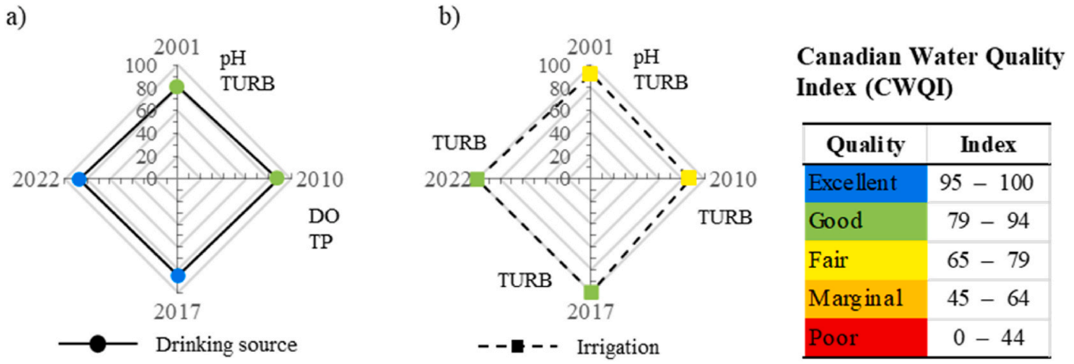


Fig. 3. LULC changes in UPitaRB between 1999 and 2022. Unclassified = Areas of persistent cloud cover located near snow-capped mountains.

remained stable at 73.4% by 2022; however, open spaces with little or no vegetation increased to 8.1% and forest to 6.6 % in the areas outside this strategy (Fig. 3d and e).

3.2.3. *Water quality changes in UPitaRB*

The spatial and temporal variations of physical, chemical, and microbiological water quality parameters and the CWQI for 2001, 2010, 2017, and 2022 are detailed in Fig. 4. Between 2001 and 2010, the



Quality	Index
Excellent	95 – 100
Good	79 – 94
Fair	65 – 79
Marginal	45 – 64
Poor	0 – 44

Fig. 4. The lowest CWQI values in 2001, 2010, 2017, and 2022 and associated water quality parameters (see Table 1 for acronyms) that do not comply with water quality standards for a) drinking water and b) irrigation water in UPitaRB.

lowest water quality in UPitaRB was observed at the low and medium sampling points (Fig. 1a) due to elevated values of pH, TURB, TP, and low DO exceeded the water quality standards specified in Table 1. The CWQI categorizes these ranges as *good* for drinking water sources and *fair* for irrigation (Fig. 4).

In 2017–2022, with 50% under passive ecological restoration, the CWQI for drinking water indicated *excellent* quality for both years in all sampling points. Nonetheless, high levels of turbidity, caused the irrigation water to fall short of the highest water quality standards in all sampling points (Fig. 4).

3.2.4. Impacts of LULC changes on water quality in UpitaRB

For our study period (1999–2022), the correlation analyses by applying the average values of each water quality parameter and each individual LULC class in Table 4 indicates that temporary crops could be the main land use class to predict high levels of fecal coliform (FC) (PCC $= 0.97$; $p < 0.05$), total phosphorus (TP) (PCC $= 0.96$; $p < 0.05$), turbidity (TURB) (PCC $= 0.98$; $p < 0.05$) and low level of dissolved oxygen (DO) (PCC $= -0.99$; $p < 0.05$) in UPitaRB.

Moreover, there is a lack of strong correlation between the natural páramo class and impacts on water quality parameters, as shown in Table 4.

3.3. Conditions constraining passive ecological restoration in Upper Cutuchi River Basin in the 21st century

3.3.1. PESTEL factor analysis in UCutuchiRB

Between 2001 and 2022, the PESTEL analysis revealed that the top-down approach to sustainable land and water management in UCutuchiRB did not succeed in the ecological restoration of páramo areas (Table 5). Instead, there was a páramo loss despite the protected areas established, such as the Cotopaxi National Park and the El Boliche National Recreation Area. At the political level, the Cotopaxi Regional Development Corporation launched an integrated basin management plan in 2001 that combined passive ecological restoration of páramo areas and sustainable farming with conventional methods to improve the water quality of the Cutuchi River (CODERECO, 2002; Zapata et al., 2021). This initiative had to be managed by the National Water Resources Council (CNRH) due to its role in enforcing legal standards for water use (Hoogesteger et al., 2016). Although the CNRH was dissolved and replaced by a single governmental water authority in 2007 (Warner et al., 2014), economic resources have not yet been allocated, and environmental improvements have yet to be observed (Zapata et al., 2021). Then, in 2014, another strategy was proposed, according to Castillo (2022), a creation of the Cutuchi sub-river basin council to facilitate the formulation and implementation of water management plans and water fund mechanisms by the Organizational Code of Territorial Organization (COOTAD) and the Ecuadorian water law (Asamblea Nacional, 2010, 2014). Nevertheless, a legal loophole impeded the council from being recognized, restricting its access to state funds (Asamblea Nacional, 2014).

In 2022, as a consequence of poor land and water management, 233 km^2 of páramo in the UCutuchiRB continues to be used for pine timber production (40% of páramo areas by 2021) (Aglomerados Cotopaxi, 2021), stone and gravel mining (La Hora, 2018), agricultural activities (Solo De Zaldívar, 2015), and high levels of water pollution (Zapata et al., 2021).

Table 5
Historical events associated with passive ecological restoration initiatives in páramo areas across UCutuchiRB in the 21st century. P: Political, Ec: Economic, S: Social, T: Technological, En: Environmental, L: Legal.

Year	PESTEL factor	UCutuchiRB
2001	P	Regional Development Corporation proposes an integrated basin management plan managed by the National Water Resources Council
2002	Ec	No evidence of an executed budget for any basin management plan
2004	T	The largest pine tree lumber company owns 33% (77 km^2) of the basin area
2014	L	A subbasin council is created by Ecuadorian law
	P	Subbasin council creation promotes management plans and water fund mechanisms
2015	L	Non-approval of the state budget to the subbasin Council as the government prioritizes larger demarcation
2021	Ec	Ecuador's largest pine timber company owns ~40% (95 km^2) of the basin
	En	Alarming levels of contamination of the Cutuchi River and lack of management strategies
2022	P	Subbasin council lacks recognition due to a legal loophole in Ecuadorian law

3.3.2. LULC changes in CutuchiRB

From 1999 to 2022, natural páramo coverage of UCutuchiRB was substantially lower than in UPitaRB. It started at 38.9% in 1999, then decreased to 31.6% in 2022 (Fig. 5e). During this period, there has been a total decrease of 7.3% (17.0 km^2) of natural páramo and an increase of 12.4% (28.8 km^2) of non-native pine forest (Fig. 5a–d, and e). Thus, the pine forests covered 19.2% of the basin in 1999 and reached 31.6% in 2022, covering a similar area as the páramo (Fig. 5a–d, and e).

Páramo losses occurred in the upper UCutuchiRB, with increased pine forests and pastures in the upper and middle basin areas, including Cotopaxi National Park, a pine timber company, and El Boliche National Recreational Area (Fig. 5a–d). Fig. 5e shows that the natural páramo was converted primarily to pine forest, followed by temporary crops and pastures (major changes between 1999 and 2010).

3.3.3. Water quality changes in UCutuchiRB

UCutuchiRB's sampling points (Fig. 1b) showed low DO and pH, along with high levels of FC, TDS, TP, and TURB that do not meet drinking water or irrigation water quality standards of Table 1. Consequently, between 2001 and 2022, UCutuchiRB experienced a decrease in CWQI from *fair* to *poor* for drinking water and from *fair* to *marginal* for irrigation water (Fig. 6).

Table 4
Correlation analysis using Pearson's correlation coefficient (PCC) between water quality parameters and percent changes in LULC in UPitaRB; significant levels in grey with $*p \leq 0.05$, $**p \leq 0.01$. For abbreviations of water quality parameters see Table 1.

LULC	Water quality parameter						
	DO	FC	NO$_3$-N	pH	TDS	TP	TURB
Artificial surfaces	0.68	−0.69	−0.31	−0.91	−0.067	−0.77	−0.58
Forests	0.17	−0.40	−0.15	−0.50	0.24	−0.25	−0.07
Glacier and snowy areas	−0.82	0.80	0.45	0.98	0.26	0.89	0.75
Open spaces with little or no vegetation	−0.28	−0.03	0.02	0.01	0.39	0.25	0.36
Pastures	0.44	−0.09	0.10	−0.35	−0.17	−0.48	−0.46
Natural páramo (Shrub and/or herbaceous vegetation)	0.42	−0.21	−0.39	−0.05	−0.72	−0.32	−0.52
Temporary crops	−0.99*	0.97*	0.85	0.90	0.79	0.96*	0.98*

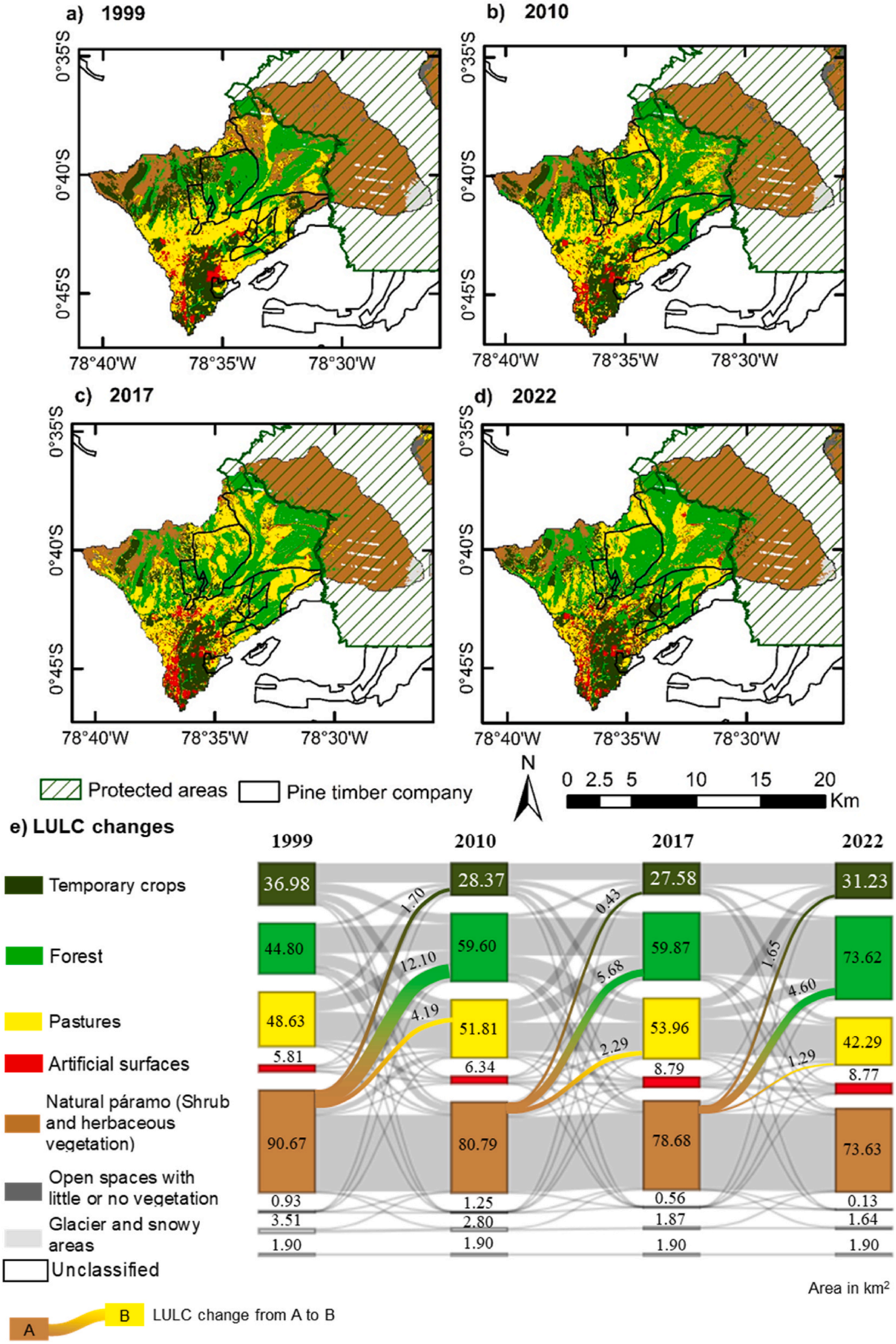


Fig. 5. LULC changes in UCutuchiRB between 1999 and 2022. Unclassified = Areas of persistent cloud cover located near snow-capped mountains.

3.3.4. Impacts of LULC changes on water quality in UCutuchiRB

Correlation analyses by applying the average values of each water quality parameter and each individual LULC class for the study period shows in Table 6 that the forests class (pine forest) was significantly correlated to total phosphorus TP (PCC = 0.99; $p < 0.01$) and open spaces with little or no vegetation was positively related to TDS (PCC = 0.99; $p < 0.01$).

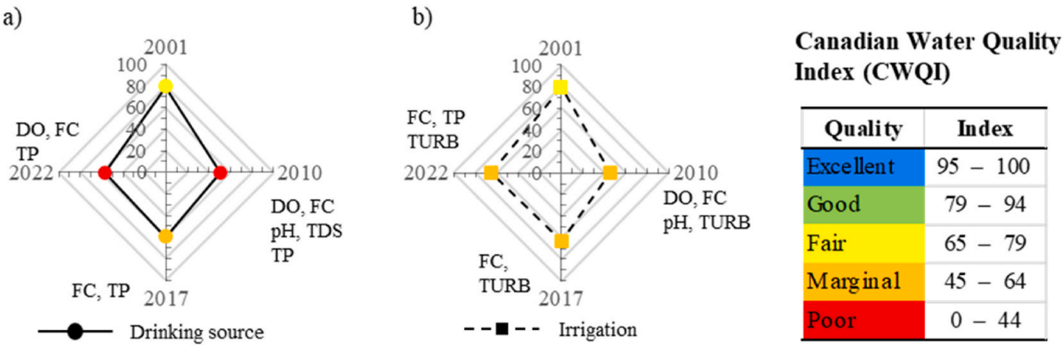


Fig. 6. The lowest CWQI values in the years 2001, 2010, 2017, and 2022 and associated water quality parameters (see Table 1 for acronyms) that do not comply with water quality standards for a) drinking water and b) irrigation water in UCutuchiRB.

Table 6
Correlation analysis using Pearson's correlation coefficient (PCC) between water quality parameters and percent changes in LULC in UCutuchiRB; $*p \leq 0.05$; $**p \leq 0.01$. For abbreviations of water quality parameters see Table 1.

LULC	Water quality parameters						
	DO	FC	NO_3-N	pH	TDS	TP	TURB
Artificial surfaces	0.99	0.90	0.12	0.94	−0.68	0.32	−0.54
Forests (pine)	0.39	0.70	0.98	−0.02	−0.91	0.99**	0.63
Glacier and snowy areas	−0.95	−0.99	−0.49	−0.74	0.91	−0.66	0.18
Open spaces with little or no vegetation	−0.74	−0.93	−0.81	−0.40	0.99**	−0.91	−0.24
Pastures	−0.28	−0.61	−0.99	0.13	0.86	−0.99	−0.71
Natural páramao (Shrub and/or herbaceous vegetation)	−0.52	−0.80	−0.94	−0.13	0.96	−0.99	−0.50
Temporary crops	0.30	0.62	0.99	−0.12	−0.87	0.99	0.70

4. Discussion

Passive ecological restoration as a NbS measure in water-rich ecosystems affected by anthropogenic pressures, such as páramo, requires a clear understanding of these ecosystems as complex biophysical arrangements that interact with PESTEL contexts to influence NbS performance.

Several studies indicate that since the 20th century, initiatives for sustainable land and water management, including passive ecological restoration, have been introduced at both national and local levels as strategies to reduce land degradation in páramo ecosystems and ensure water supply for Andean communities.

4.1. National-level strategies failing passive ecological restoration

The creation of protected areas (Echavarria, 2002; Joslin and Jepson, 2018), river basin management approach (Hoogesteger et al., 2016; Warner et al., 2014), and NbS such as passive ecological restoration (Brauman et al., 2019; Castanier, 2015; Wiegant, 2022), have been launched as this level across several páramos. However, our PESTEL analysis and corroborating studies demonstrate that many of these efforts have not been achieved due to their linkage to top-down management (national-level strategies) that do not fit local needs. For instance, protected areas managed face difficulties in addressing the complex transformations in páramo areas due to the national government's lack of active management and control over the territory, as well as limited financial resources (Echavarria, 2002; Joslin and Jepson, 2018). Similarly, river basin management initiatives, like those experienced in UCutuchiRB, as noted by Warner et al. (2014), have been largely ineffective in Ecuador because without the government's attaching political significance to this management scale, it is almost doomed to fail from the beginning. Regarding water-related ecological restoration efforts in Ecuador, research by Wiegant (2022) and Wiegant et al. (2020) shows that short-term electoral cycles and the desire to meet short-term political interests conflict with long-term restoration timelines.

Due to the ineffective implementation of land and water management strategies identified, large areas of Ecuador's páramo continue to be used and expanded primarily for extensive cattle ranching, large-scale agriculture, mineral extraction, and afforestation (Brück et al., 2023; Mosquera et al., 2023; Thompson et al., 2021). We observed that the natural páramo areas in the UCutuchiRB in 2022 covered only 31.6%, in contrast to the UPitaRB, which maintained 73.4% natural páramo. Similar results for natural páramo remnants (~30%) in central and southern Ecuador were obtained by García et al. (2019, 2020), where large-scale agriculture, cattle ranching, and forestry are present despite the establishment of protected areas.

The intensive páramo exploitation poses a significant threat to water security, given that even minor changes cause impacts on water quality. Rey-Romero et al. (2022) found that a small change of 15% from natural páramo to agricultural land use impairs water quality for drinking water sources through increased turbidity and fecal coliform levels. These findings align with the ecological conditions in the UCutuchiRB, where the water quality for drinking and irrigation is *poor* and *marginal*, respectively, both inside and outside protected areas (Acosta, 2018; Quishpe, 2018; Rojas, 2020; Zapata et al., 2021). In UCutuchiRB, the pine plantations cover significant areas of páramo areas, which our study identifies as the main class to predict high levels of total phosphorus and total dissolved solids in the basin. The presence of high concentrations of phosphates in the basins can be related to fertilizer management practices such as urea or superphosphate application (Lebron et al., 2012; Shah et al., 2022). In addition, livestock, mining, and urban systems adjacent to water courses have an impact on the input of materials to rivers and, therefore, also influence water quality (Cheng et al., 2022; Stenfert Kroese et al., 2020). Thus, Zapata et al. (2021) and Rojas (2020), based on a review of technical documents, found low concentrations of dissolved oxygen and high levels of fecal coliform, total dissolved solids, and turbidity in UCutuchiRB for drinking and irrigation water uses, respectively, in line with our results.

4.2. Local-level strategies promoting passive ecological restoration

In contrast, páramos like the UPitaRB implemented partially passive ecological restoration through bottom-up management (local-level strategies) to sustain mainly Quito's drinking water (Brauman et al., 2019; Castanier, 2015; Coronel, 2019; Kauffman, 2014). Thus, at the political, social, and economic level, páramo headwater management and financial support directly relied on local utility companies, private and public water users, NGOs, and a Water Fund (Bremer et al., 2016; Coronel, 2019). At the economic and environmental level, given the limited financial resources and the fragility of the páramos, choosing passive ecological restoration was a key strategy. This strategy is much more cost-effective and requires less time than active restoration (Trujillo-Miranda et al., 2018).

Passive ecological restoration is especially effective for headwater streams to support high water quality conditions often found in these streams, typically situated in isolated areas away from populated areas (Haigh and Křeček, 1991; Taniwaki et al., 2019; Trujillo-Miranda et al., 2018). Furthermore, passive ecological restoration supports the achievement of several SDGs by promoting sustainable and efficient use of natural resources (target 12.2; SDG 12) (Groll, 2017), restoring aquatic ecosystems (target 6.6; SDG 6) (Kauffman, 2014), promoting the conservation of mountain ecosystems (target 15.4; SDGs 15) (Brauman et al., 2019), and reducing land degradation (target 15.3; SDG 15) (Muller et al., 2016). Additionally, it supports access to adequate, safe, and affordable basic services, focuses on impoverished neighborhoods (target 11.1; SDGs 11) (Castanier, 2015), and enhances local community livelihoods (target 1.4 SDG 1) (Coronel, 2019).

As a result of implementing passive ecological restoration in 50% of the basin, the UPitaRB maintained 73.4% natural páramo, *excellent* water quality for drinking water sources, and *good* water quality for irrigation sources until 2022. Equivalent results were obtained by García et al. (2020), who identified a páramo coverage of 74% in Cajas National Park and excellent water quality, where the implementation of strategies follows the UPitaRB management approach (Ministerio del Ambiente, 2018). In terms of investing in passive ecological restoration, Brauman et al. (2019) anticipate a positive financial return over the next twenty years for Water Utility Company in Quito. This projection is based on savings in water treatment costs resulting from reduced levels of nutrients, bacteria, turbidity, and sediments in the source water. Although there is no strong correlation between the impact of natural páramo on water quality parameters in UPitaRB in our study, this does not necessarily mean that the restoration has failed. Muller et al. (2016) recommend understanding the effects of passive ecological restoration on water quality by recognizing the complex nature of water quality as a dynamic watershed-scale process. Furthermore, passive ecological recovery takes time, even under optimal conditions, so relying solely on natural recovery processes is often seen as too slow and uncertain to meet the timelines and performance expectations of decision-makers (Zahawi et al., 2014).

Ongoing efforts to sustain aquatic ecosystem health are vital for long-term sustainability, and any interruption in these endeavors jeopardizes the progress made so far (Wang et al., 2016). Castillejo et al. (2018) found that the areas of the Pita River Basin with passive ecological restoration exhibited higher water quality compared to those without such interventions. The latter areas displayed lower water quality characterized by high levels of total phosphorus, high turbidity, and low dissolved oxygen levels associated with more populated zones. Although our findings suggest that temporary crops primarily negatively affect water quality parameters in UPitaRB forests, and open spaces with little or no vegetation could also contribute to this impact. For instance, open spaces with little or no vegetation (including bare rocks, sparse vegetation, and burned areas) could affect turbidity levels identified in UPitaRB and have been reported in similar studies by Carrillo and Díaz-Villanueva (2021) and Chen and Chang (2023). Moreover, with the surge in afforestation in the UPitaRB, future research should prioritize the identification of tree species driving forest change. *Pinus radiata* and *Pinus patula* plantations are prevalent in páramo ecosystems. However, Mosquera et al. (2023) recommend investigating the impacts of other exotic (*Cupressus* and *Eucalyptus*) and native (*Polylepis*) plantations on water resources. This information can be valuable in understanding the direct impact of plantations on ecosystem water quality and can compel the adoption of sustainable management strategies.

5. Conclusions

Passive ecological restoration through bottom-up management in páramo ecosystems emerges as an effective NbS to mitigate widespread land and water degradation, shaped by a complex interplay of PESTEL factors since the 20th century. Over seven years (2010–2017), bottom-up management facilitated the recovery of up to 9.1% of the natural páramo while sustaining the capacity of headwater to provide safe drinking and irrigation water. Although our study did not reveal a strong correlation between restoration and water quality parameters, this does not necessarily indicate that restoration efforts have failed. Rather, it suggests the need for further investigation into potential influencing factors.

Conversely, top-down management, characterized by national-level strategies, lacks the legal, economic, and political interconnections necessary for successful passive ecological restoration in páramo ecosystems. Based on this management, several Ecuadorian páramos have lost up to 30% of their natural páramo vegetation, coinciding with an expansion of pine plantations and elevated total phosphorus levels in the basins. Additionally, agricultural and mining activities also contribute to the deterioration of water source quality. Given the severe degradation of páramo ecosystems, passive ecological restoration alone may not suffice to mitigate environmental impacts. Therefore, exploring alternative NbS or conventional methods, or their combination, is advisable to enhance the restoration process.

By integrating diverse data sources and methodologies, our findings provide valuable insights for decision-makers. However, challenges related to limited data availability underscore the need for future research to obtain continuous, representative, and accurate datasets to ensure the validity of our results. In particular, long-term monitoring programs are needed to assess surface water quality and conduct spatial analyses of LULC in páramos.

CRediT authorship contribution statement

Kalina Fonseca: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Juan S. Acero Triana:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Conceptualization. **Miguel Ramírez:** Methodology, Formal analysis, Data curation, Conceptualization. **William Martínez:** Methodology, Formal analysis, Data curation, Conceptualization. **Mercy Ilbay:** Methodology, Formal analysis, Data curation, Conceptualization. **Edgar Espitia-Sarmiento:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Lutz Breuer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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