



Real Value vs. Willingness to Pay: An Environmental-Economic Assessment of Water Provisioning Services in High-Andean Ecosystems Under Data-Scarce Conditions

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ABSTRACT

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High-Andean páramo watersheds provide critical water resources for rural communities; however, limited hydrometric data and low tariff structures constrain effective and equitable water management. This study proposes and applies an integrated framework to estimate the economic value of water (EVW) provision services in the Quinllunga Water Protection Area (APHQ), Ecuador, under data-scarce conditions. The approach combines a simplified water balance with economic and social valuation components. Water supply was estimated using satellite-based hydroclimatic datasets, while water demand was derived from authorized government allocations adjusted for conveyance losses. For the 2013-2023 period, total water supply reached 3.43 million m³/year, whereas total water demand reached 3.18 million m³/year. However, considering the effective available supply after evapotranspiration (1.44 million m³/year), the water stress index (WSI) reached 2.22, indicating significant pressure under maximum allocation scenarios. Economic valuation was disaggregated into four components. The water capture value (V_c) was estimated at 0.699 USD/m³, restoration value V_p at 0.005 USD/m³, domestic water use value V_{A-D} at 0.002 USD/m³, and agro-livestock water use value V_{A-A} at 0.188 USD/m³. Household surveys (n = 85) reported willingness to pay (WTP) values of 0.066 USD/m³ for domestic water use, 0.006 USD/m³ for agro-livestock use, 0.029 USD/m³ for páramo conservation, and 0.017 USD/m³ for ecological restoration. Results revealed clear differences between economic valuation and WTP, reflecting the gap between the economic importance of water services and the limited payment capacity of rural households. Irrigation-dependent agriculture represented the main driver of water demand, whereas conservation and restoration showed relatively low economic costs compared to their hydrological benefits. These findings support the implementation of integrated water governance strategies, differentiated tariff structures, and payment for ecosystem services (PES) mechanisms adapted to high-Andean socio-ecological conditions.

1. INTRODUCTION

The páramos are high-Andean ecosystems located between 3,000 and 4,500 meters above sea level [1, 2]. They play a crucial role in hydrological regulation, ensuring the provision of multiple ecosystem services [3, 4]. Among these, water supply for domestic, agricultural, and livestock use stands out as essential for community well-being and resilience [5]. This function is particularly relevant in territories historically inhabited by Indigenous, peasant, and mestizo communities, whose livelihoods depend both on agricultural land use and direct access to water sources [6].

In this context, water not only has environmental and productive value but also structures the social organization of páramo inhabitants. Water boards are a clear example, as they constitute community-based organizations responsible for managing the distribution and maintenance of water supply systems [7]. These entities, widely present in countries such as Ecuador, Peru, Colombia, and Bolivia, are a cornerstone in guaranteeing the human right to water in rural territories [8]. However, they face technical, financial, and legal challenges that threaten their sustainability [8].

Adding to this, the accelerated degradation of páramos driven by agricultural expansion, habitat fragmentation, and

the effects of climate change poses an additional threat [9]. To address this issue, the Ecuadorian State has implemented conservation instruments such as Water Protection Areas (APHs), a legal and technical mechanism designed to ensure sustainable water provision and management within the framework of the Organic Environmental Code (COA), with the participation of Decentralized Autonomous Governments (GADs) and local communities [2].

Nevertheless, legal instruments alone are insufficient without quantitative evidence demonstrating the real contribution of these ecosystems to human well-being. In this regard, Environmental Economic Valuation (EEV) is a key tool to make the importance of páramos visible in monetary terms [10, 11]. Applying this technique to quantify water provision is particularly useful, as it allows the economic valuation of the benefits associated with water supply [10].

However, the application of EEV faces significant limitations in high-mountain territories, where hydrometeorological monitoring infrastructure is scarce, and field data collection is technically and logistically challenging [12]. In response, alternative methodologies have emerged for data-scarce regions, such as the use of remote sensing, which enables the estimation of meteorological variables for water supply calculations an essential input for assigning an economic value to water [13, 14].

Despite these technological advances, the literature on the economic valuation of water supply services (EVWSS) in high-Andean ecosystems remains limited and fragmented, lacking standardized protocols that facilitate comparisons across studies [14, 15]. This methodological fragmentation represents a barrier to the operationalization of payment for ecosystem services (PES) schemes, highlighting the need for integrative approaches [10, 14, 15].

Under this perspective, the objective of this research is to estimate the economic value of water (EVW), conceived as an

integrative concept that encompasses four distinct valuation dimensions: water capture, restoration, domestic use, and agricultural use [16]. Each of these dimensions is derived from specific methodologies and approaches, and therefore they are not aggregated into a single value but rather analyzed in a complementary way. Subsequently, the results are contrasted with willingness to pay (WTP), understood as the subjective economic valuation expressed by users [17, 18]. To support this comparative exercise, a conceptual model was developed, articulating biophysical and socioeconomic variables within an integrated framework.

This comparison constitutes the basis for developing strategies for water conservation and compensation. The model is applied to the Quinllunga Water Protection Area (APHQ), located in Bolívar Province, Ecuador, a strategic territory due to its importance in supplying water to rural communities and, at the same time, its vulnerability to pressures derived from agricultural expansion, habitat fragmentation, and the impacts of climate change [19]. This makes it an ideal case to generate transferable evidence for other high-Andean ecosystems.

2. MATERIALS AND METHODS

2.1 Case study

The APHQ is located in the rural parish of San Simón, part of the Guaranda canton in Bolívar Province, within Ecuador's Andean region [6, 19]. In the Ecuadorian political-administrative system, parishes (urban and rural) constitute the basic division of cantons, which in turn form the provinces. The APHQ was officially declared a protected area in 2021 and comprises 558.56 ha of páramo ecosystems situated between 3,500 and 4,200 m.a.s.l. [19].

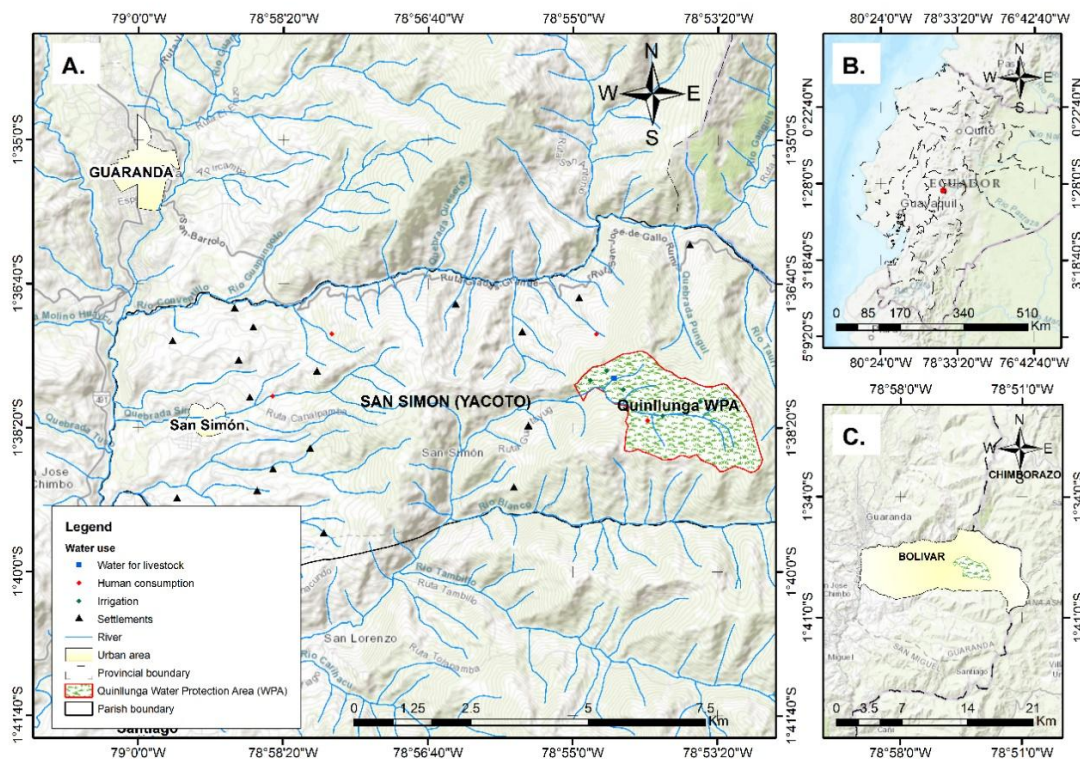


Figure 1. Geographical location of the study area. (A) map of San Simón parish (Yacoto); (B) location of the Quinllunga Water Protection Area (APHQ) within Bolívar Province; and (C) study area in the national context of Ecuador

The vegetation cover of the study area is mainly composed of grasslands (*pajonales*), with the presence of shrublands characteristic of the Andean páramo ecosystem [19]. Figure 1 shows the geographical location of the APHQ at different spatial scales. In Figure 1(A), the San Simón parish is presented, with the perimeter boundaries and the identification of main drainage networks, human settlements, and authorized water users (domestic, irrigation, and livestock watering). In Figure 1(B), the APHQ is represented within Bolívar Province. Finally, in Figure 1(C), the study area is located within Ecuador, highlighting its strategic position in the central Andean region.

2.2 Study design

This study was developed with a quantitative, descriptive, and applied approach, oriented toward the Economic Valuation of Water Supply Services (EVWSS) in páramo ecosystems. The design integrates biophysical and

socioeconomic variables under a socio-hydrological analysis framework, with the purpose of generating useful evidence for decision-making in territories characterized by high socio-environmental vulnerability and limited hydrometeorological information. In this context, water valuation is proposed as a strategic tool to promote sustainable management and water compensation mechanisms.

Figure 2 presents the conceptual model for EVWSS in the APHQ. At the top, the input variables are represented: biophysical, economic, and social. Biophysical parameters include climatic data obtained from remote sensing (precipitation and evapotranspiration) and physical data (area, runoff, slope, and vegetation cover). Together, these elements characterize the water supply capacity of high-Andean páramo ecosystems [4, 20]. Socioeconomic inputs include concessioned flows and agricultural and livestock production data, representing water demand. Social inputs consider the number of beneficiaries and perceptions obtained through surveys.

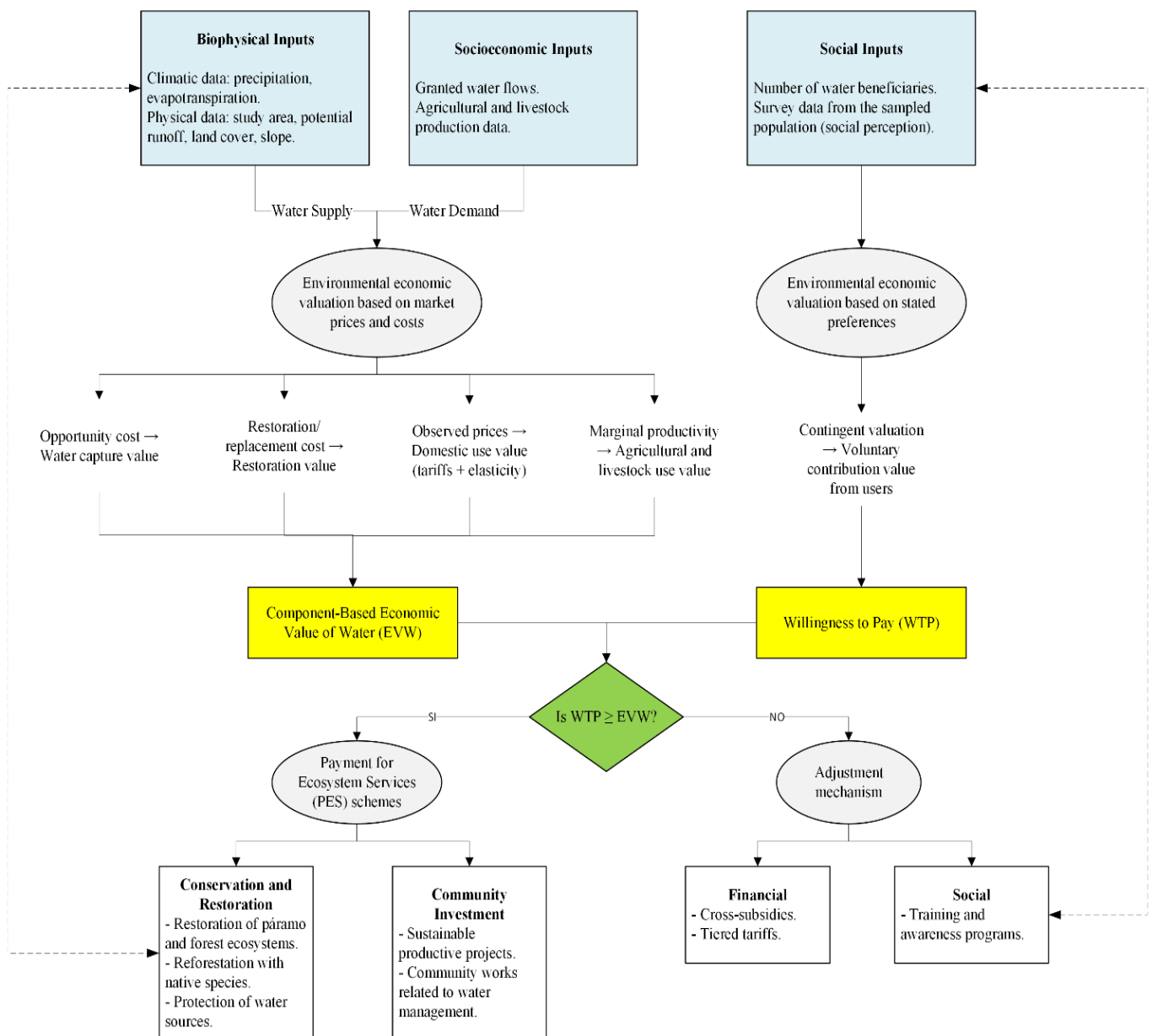


Figure 2. Conceptual model of the economic valuation of water services in the Quinllunga Water Protection Area (APHQ)
Note: It integrates market-based and stated-preference methods, comparing EEV and WTP to define PES schemes or adjustments, with feedback loops.

The model is based on the application of two methodologies (represented by ovals). The first corresponds to economic valuation based on market prices and costs, which integrates four complementary approaches: the opportunity cost of land use to estimate the water capture value; the restoration or replacement cost, reflecting the investment required to maintain water provision; observed market prices, applied to calculate domestic use value; and marginal productivity, which links water to agricultural and livestock production [14, 15]. Together, these approaches provide a comprehensive estimate of the EVW. The second methodology corresponds to stated-preference valuation, implemented through the contingent valuation method, which estimates users' WTP for conserving the water-providing ecosystem.

Subsequently, the model jointly compares EVW and WTP, which constitutes the decision-making core of the scheme (represented by a diamond). These values are not independent; their integrated analysis allows the evaluation of the financial and social sustainability of compensation schemes.

When WTP is equal to or greater than EVW, the situation suggests favorable conditions for the implementation of PES schemes [21]. In this scenario, the resources obtained can be allocated to both community investment and the implementation of conservation actions, which in turn strengthen water supply and reduce future restoration costs [17, 22]. In this way, a sustainability cycle is consolidated, in which social valuation and environmental management actions reinforce each other positively.

In contrast, when WTP is lower than EVW, the model identifies a critical condition, as the social valuation does not cover the real value of water provision, revealing a potential risk for the ecosystem. In this case, financial adjustment mechanisms are activated, such as cross-subsidies and tiered tariffs, which allow for a more equitable redistribution of users' contributions. At the same time, social strategies of education and awareness are implemented to transform community perceptions regarding the value of water, with the aim of increasing WTP in the medium term and reducing the gap with EVW.

In summary, the integrated comparison of EVW and WTP not only allows for assessing the financial feasibility of water compensation schemes but also for anticipating critical scenarios and proposing adjustment mechanisms that strengthen the sustainability of páramo ecosystems.

2.3 Methodological procedure

2.3.1 Estimation of water supply and demand

(1) Water supply

The estimation of water supply was based on satellite inputs processed in Google Earth Engine (GEE), using Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for precipitation and the Global Land Data Assimilation System Version 2 (GLDAS-2) for evapotranspiration [17, 23]. The use of these sources is crucial in areas with limited meteorological instrumentation. Based on annual averages of precipitation, evaporation, and transpiration for the 2013-2023 period, a representative hydrological characterization was constructed, prioritizing interannual consistency, although with the limitation of not capturing seasonal variability or extreme events. Therefore, the hydrological results should be interpreted as a first-order annual approximation rather than as a seasonal water balance [5].

The main components of the hydrological cycle were calculated sequentially: total supply (OT), available supply (Od), net infiltration (R), and surface runoff (ESC_S). It was assumed that water supply comes exclusively from direct precipitation, consistent with the dynamics of high-Andean páramos, where lateral contributions are minimal and hydrological regulation depends primarily on vegetation cover [4, 20].

The OT corresponds to the volume of water generated by precipitation over the study area, calculated as follows:

$$OT = 0.001 \bar{P} A + O_e \quad (1)$$

where, OT is the total supply ($m^3/year$); \bar{P} is the mean annual precipitation ($mm/year$); A is the area of the APHQ (m^2); O_e is the external water contribution ($m^3/year$), assumed to be null in this study; and 0.001 is a conversion factor to standardize units (mm to m) [15].

Subsequently, Od was estimated, representing the water volume remaining after evapotranspiration losses:

$$Od = OT - (0.001 ET A) \quad (2)$$

where, Od is the available supply ($m^3/year$) and ET is evapotranspiration ($mm/year$) [15].

The R , defined as the volume of water that percolates and contributes to groundwater recharge, was estimated from the water surplus ($\bar{P} - ET$), converted to volume using the study area, and adjusted by a recharge coefficient:

$$R = 0.001 (\bar{P} - ET) A C_r \quad (3)$$

where, C_r is 0.25, a value within the range reported for páramo ecosystems (0.20-0.50), which are characterized by organic soils, high water retention capacity, and dominant vegetation cover [20].

Finally, surface runoff ESC_S was calculated as the difference between available supply and infiltrated volume:

$$ESC_S = Od - R \quad (4)$$

where, ESC_S is surface runoff ($m^3/year$) [24].

(2) Water demand

Total water demand (DT) was represented by social demand (Q^s), which includes sectoral demand and conveyance losses [17, 25].

$$DT = Q^s \quad (5)$$

where, DT is total water demand ($m^3/year$) and Q^s is social demand ($m^3/year$).

Social demand Q^s was obtained as follows:

$$Q^s = \sum q_j + f_i \quad (6)$$

where, q_j is the volume of water demanded by sector j ($m^3/year$), and f_i is the conveyance loss volume ($m^3/year$), equivalent to 10% of the total sectoral demand ($\sum q_j$). The sectors considered include domestic, agricultural (irrigation), and livestock water use [15].

The value of q_j was obtained from the sum of the maximum authorized flows of existing concessions in the APHQ for

domestic and agricultural use (Table 1). Although in practice users do not always consume the maximum authorized flow, this value was used to avoid underestimation in intensive-use scenarios. This approach may lead to a conservative overestimation of demand; however, it allows the identification of potential stress scenarios under maximum allocation conditions. Accordingly, the estimated water stress should be understood as an upper-bound condition rather than as actual year-round water use [25].

In the absence of direct and continuous hydrometric records on the volumes effectively used by each activity, officially authorized flows were adopted from the outset as the main methodological criterion. This approach provides an institutionally verifiable and traceable reference, particularly in a context of limited real-consumption data. Since the unit EVW is calculated by dividing the net benefit generated by each use by the water volume considered, the result is sensitive to the flow used as the denominator. Therefore, the use of

authorized flows provides a conservative and institutionally consistent estimate, without weakening the economic valuation of water; rather, it strengthens comparability among uses and coherence with the official water-demand framework applied in this study [26, 27].

This hydrological framework provides the basis for linking water availability with sectoral demand and subsequent economic valuation.

2.3.2 Population and sample

The population consisted of 724 families benefiting from water resources in the APHQ. This figure corresponds to the total number of users officially registered through administrative authorizations granted to boards, associations, and individuals. Table 1 details the authorizations, disaggregated by user, source, type of use, concessioned flow, and number of beneficiary families.

Table 1. Authorizations for water use, concessioned flows, and number of beneficiary families

No.	Authorized User	Source	Use	Flow (L/s)	Beneficiaries
1	Chela Chela Sergio, Common Representative	Quinlluga Stream	Domestic Livestock watering	0.03 0.03	1
2	Tualombo Mullo Juan Rodrigo et al.	Quinllunga River	Irrigation	15.00	1
3	Allauca Juan Isidro	Quinlluga Stream	Irrigation	15.00	2
4	Provisional Water Board of the Suro Potrero Community	Spring N° 6	Irrigation Livestock watering Domestic	2.25 0.07 0.08	12
5	Pre-Board for Irrigation Waters of Gradas, Gradas Chico, Pachagron, and others	Sacha River River	Irrigation	30.00	524
6	Administrative Board of Potable Water and Sewerage of Cachisagua	Quinllunga Spring	Domestic	2.26	146
7	Association of Independent Agricultural Workers Shulala Santa Teresa	Diablo Sacha River	Domestic Irrigation	0.10 5.00	11
8	Water Board of the Shulala Community	Quinlluga Stream	Irrigation	7.00	27
				Total, Irrigation	89.25
				Total, Livestock watering	0.10
				Total, Domestic	2.46
				Total, Beneficiaries	724

From this population, a representative sample of 85 families was calculated using the finite population formula:

$$n = \frac{NZ^2pq}{e^2(N-1) + Z^2pq} \quad (7)$$

where, n is the sample size; N is the total population (724); Z is the statistical value for a 95% confidence level (1.96); p is the expected success proportion (0.5); $q = 1 - p$; and e is the allowed sampling error ($\pm 10\%$). The calculation was made under the assumption of homogeneity in perceptions within each user group, a methodological criterion commonly applied in similar socio-environmental assessments [14].

A structured questionnaire was applied to this sample, divided into four sections: (1) socio-demographic data (gender, age, ethnicity, main economic activity, income); (2) productive activities and resource use (cultivated area, number of livestock, dairy production, agricultural yields, and related expenses); (3) perceptions regarding the importance of páramo conservation; and (4) WTP for access to drinking water, irrigation water, and conservation (Appendix A2). This instrument provided the socioeconomic variables required for

subsequent analyses.

2.3.3 Environmental Economic Valuation based on market prices and costs

This procedure is based on observed prices and the estimation of costs associated with the provision or replacement of water resources, following the scheme developed in the Tempisque River Basin, Costa Rica [15], and adapted to the conditions of the APHQ through four complementary approaches:

- *Water Capture Value (V_c)*

The V_c was estimated using an opportunity cost approach. Agriculture is the dominant activity (50.7%), followed by livestock (23.9%), reflecting the dependence of local livelihoods on land use. Agricultural production is small-scale, with an average cultivated area of 0.88 ha/household, mainly potato (0.43 ha) and maize (0.58 ha). Irrigated yields were 16000 kg/ha (potato) and 8697 kg/ha (maize), with market prices of 0.30 USD/kg and 0.38 USD/kg, respectively. The average agricultural investment was 227.59 USD/household/year (Table 2).

Table 2. Water supply and demand parameters in the Quinllunga Water Protection Area (APHQ)

Variable	Value	Unit
Water Availability		
\bar{P}	613.46	mm/year
E	267.21	mm/year
T	89.13	mm/year
ET	356.34	mm/year
A	5585600	m ²
A	558.56	ha
O_e	0	m ³ /year
OT	3426562	m ³ /year
Od	1436190	m ³ /year
R	359047.5	m ³ /year
ESC_s	1077142	m ³ /year
Water Demand		
Q^s	3184817.48	m ³ /year
$q_{domestic}$	77673.17	m ³ /year
$q_{livestock}$	3122.06	m ³ /year
$q_{irrigation}$	2814493.39	m ³ /year
$\sum q_j$	2895288.62	m ³ /year
f_i	289528.86	m ³ /year
DT	3184817.48	m ³ /year

Livestock systems are based on 1.79 ha of pasture per household, with an annual investment of 450 USD/head. Dairy production averaged 10.98 L/day per household at 0.5 USD/L, generating 2,003.85 USD/household/year. Livestock production costs were estimated at 1,890 USD/household/year, after scaling the unit cost by the average number of livestock heads per household. The opportunity cost of land use B_i was estimated by integrating agricultural and livestock net benefits, weighted by their respective areas. A social perception coefficient was incorporated based on survey results, where 94 % of respondents recognized the importance of the páramo ecosystem.

The V_c was estimated under the opportunity cost approach, understood as the EVW relative to the most profitable alternative land use. In the páramo, this value reflects the ecosystem's capacity to intercept, infiltrate, and regulate hydrological flows. It was calculated as follows:

$$V_c = \frac{\alpha_i B_i A}{O_{c_i}} \quad (8)$$

where, V_c is the capture value (USD/m³); α_i represents the relative importance of the páramo in terms of water quantity and quality (dimensionless, $0 \leq \alpha \leq 1$); B_i is the opportunity cost of the activity competing with the páramo for land use (USD/ha/year); A is the study area (ha) and O_{c_i} is the amount of water captured (m³/year) [10, 14].

The α_i parameter was obtained from survey data regarding users' willingness to contribute financially to páramo conservation. B_i was calculated considering agricultural (maize, potato) and livestock activities. O_{c_i} was defined as ESC_s , representing the volume of water directly captured from intakes and community distribution systems.

- *Restoration Value (V_p)*

The V_p was calculated as the equivalent cost of investments required to guarantee water supply through ecological recovery actions such as reforestation. It was estimated as follows:

$$V_p = \frac{\delta_{ij} C_{ij} A r_i}{O_{c_{i^*}}} \quad (9)$$

where, V_p is the restoration value (USD/m³); δ_{ij} is the fraction of the cost of action j specifically allocated to páramo restoration in relation to water (dimensionless); C_{ij} is the cost of action j to restore páramo i (USD/ha/year); $A r_i$ is the area to be restored (ha); and $O_{c_{i^*}}$ is the amount of water captured (m³/year) [10, 14].

C_{ij} was obtained from the Technical Management Plan of the APHQ, which details the planned restoration budget for the area. $A r$ corresponds to the degraded surface identified by the presence of grassland burning and erosion processes. δ_{ij} was defined based on Latin American literature showing that restoration generates multiple benefits (water, biodiversity, carbon), with the hydrological component typically representing between 60% and 80% of total costs [21, 28]. $O_{c_{i^*}}$ was defined as Od , as restoration actions benefit both surface runoff and infiltration.

In this context, the EVW from V_p was estimated using a cost-based approach linking restoration efforts with hydrological service provision. The restoration area $A r_i$ was estimated at 56.1 ha, while the restoration cost C_{ij} was set at 200 USD/ha/year. A hydrological fraction coefficient $\delta_{ij} = 0.7$ was incorporated to represent the proportion of restoration benefits associated with water provision services. Water availability O_{c_i} was approximated by Od , representing the hydrological contribution of restored areas, estimated at 1,436,190 m³/year.

- *Use Value: Domestic (V_{A-D}) and Agricultural-Livestock (V_{A-A}).*

Domestic Use: The V_{A-D} was estimated using a Cobb-Douglas isoelastic demand function, incorporating empirical parameters of consumption, prices, and elasticity. This formulation ensures internal consistency in the estimation of consumer surplus, where price, quantity, and elasticity parameters are coherently linked [17, 21].

$$k_1 = Q_1 P_1^{-\varepsilon} \quad (10)$$

where, Q_1 is the water volume (m³/month); P_1 is the current financial tariff for water supply services (USD/m³); k_1 is the empirical proportionality factor (dimensionless); and ε is the price elasticity of demand (dimensionless).

Domestic water demand Q_1 was obtained from authorized water use, yielding 77673.17 m³/year (6,472.76 m³/month) for 170 households. The tariff P_1 was derived from a fixed fee of 3 USD/month per household, equivalent to 0.079 USD/m³. A price elasticity of demand (ε) of 0.30 was assumed, based on empirical evidence from the rural Andean region of La Libertad, Peru [11].

Once k_1 was estimated, its evolution over time was projected using the following expression:

$$k_t = k_1 (1 + r)^{t-1} \quad (11)$$

where, r is the annual population growth rate. Population growth was incorporated assuming proportional scaling between population and water demand, with $r = 0.0019$ (0.19% per year), estimated from census data (4,194 inhabitants in 2010 and 4,288 in 2022).

The projected demand function was then expressed as:

$$Q_2 = k_t P_2^{-\varepsilon} \quad (12)$$

where, Q_2 is projected water consumption (m³/month) and P_2

corresponds to the current fixed tariff (USD/m³).

The domestic use value V_{A-D} was estimated as the consumer surplus associated with an increase in water availability [10, 14], expressed as:

$$V_{A-D} = \frac{P_1 \left(Q_2^{\frac{1}{\varepsilon}+1} - Q_1^{\frac{1}{\varepsilon}+1} \right)}{Q_1^{\frac{1}{\varepsilon}(\frac{1}{\varepsilon}+1)}} - P_2(Q_2 - Q_1) \quad (13)$$

where, V_{A-D} is the domestic use value (USD/m³), normalized per unit of water.

Agricultural-Livestock Use (V_{A-A}): The agricultural-livestock value was estimated by integrating agricultural (p^{ag}) and livestock (p^{pec}) components.

Agricultural use

This study integrates primary and secondary data to estimate the economic value of agricultural water use. Primary data included cultivated area per household (0.88 ha), crop distribution (potato: 0.43 ha; maize: 0.58 ha), agricultural investment (227.59 USD/household/year), irrigated yields ($Q_k^{irrigated}$ = 16000 for potato and 8,697 kg/ha for maize), and market prices (p_k = 0.30 and 0.38 USD/kg). Secondary data included total irrigation volume $V_{irrigation}$ = 2814493.39 m³/year) and the number of households with irrigation access (578).

The total agricultural area $A_{agriculture}$ was estimated from the average cultivated area per number of households with irrigation access, while crop areas (A_k) were derived from household proportions and interpreted as annual cultivated areas due to rotation and mixed cropping. Irrigation water availability per unit area V_i was obtained by distributing $V_{irrigation}$ over $A_{agriculture}$.

Marginal water productivity q_k was estimated from the difference between irrigated and rainfed yields ($Q_k^{irrigated} - Q_k^{rainfed}$). The EVW per crop P_k^{ag} was calculated by combining q_k with net returns ($p_k - c_k$), where c_k was derived from agricultural investment expressed per hectare and converted to a unit basis. The aggregated agricultural water value p^{ag} was estimated as a production-weighted average using total production Q_k .

For the agricultural component, the marginal productivity method was applied, comparing crop yields under irrigated versus rainfed conditions:

$$q_k = \frac{Q_{irrig}^k - Q_{rainfed}^k}{V_i} \quad (14)$$

where, q_k is marginal water efficiency (kg/m³); Q_{irrig}^k is the yield of crop k under irrigation (kg/ha); $Q_{rainfed}^k$ is yield under dry conditions (kg/ha); and V_i is the irrigation water volume (m³/ha). It is assumed that productivity gains originate primarily from irrigation water [14, 15].

The EVW for each crop was then obtained as:

$$P_k^{ag} = (p_k - c_k)q_k \quad (15)$$

where, P_k^{ag} is the agricultural water cost for crop k (USD/m³); p_k is product price (USD/kg); and c_k is production cost under irrigation (USD/kg).

The average market prices were p_k ($papa$) = 0.30 USD/kg

and p_k ($maiz$) = 0.38 USD/kg [29]. The c_k was obtained from survey data based on total production costs, cultivated area, and yields.

The overall agricultural water value was calculated as a weighted average of the crops analyzed:

$$p^{ag} = \frac{\sum_{i=1}^n P_k^{ag} Q_i}{\sum_{i=1}^n Q_i} \quad (16)$$

where, p^{ag} is the weighted average agricultural water value (USD/m³); Q_i is total crop production (kg); and n is the number of crops considered.

Livestock use

The livestock water value p^{pec} was estimated using household-level data and species-specific water consumption coefficients. The average livestock composition per household included dairy cows (n_{dairy} = 1.8, $n_{dry cows}$ = 0.8, $n_{bulls/steers}$ = 0.9 and $n_{heifers}$ = 0.7). Daily water consumption coefficients C_j were defined as 0.06, 0.04, 0.05, and 0.035 m³/day/animal, respectively. The number of livestock beneficiary households N_{pec} was obtained from official water use authorizations, along with the total allocated volume for livestock watering V_c^{pec} .

The annual livestock water consumption was calculated as [30]:

$$V^{pec} = \sum(C_j N_j) 365 \quad (17)$$

where, V^{pec} is the annual volume consumed per species j (m³/year); C_i is the average daily water consumption per animal of species j (m³/day); and N_j is the number of animals of species j . The total livestock water consumption V^{pec} was obtained by aggregating all species [15].

Gross income I_{gross} was estimated based on milk production, with an average yield of 10.98 L/day per household and a market price of 0.5 USD/L [29, 31], equivalent to 2,003.85 USD/household/year. Annual production costs C_{pec} were obtained from survey data and estimated at 450 USD/head/year, scaled according to the average number of livestock units per household.

The unit value of water for livestock use was then obtained as:

$$p^{pec} = \frac{I_{gross} - C_{pec}}{V^{pec}} \quad (18)$$

where, p^{pec} is the unit value of livestock water (USD/m³); I_{gross} is gross income (USD/year); and C_{pec} is the annual livestock production cost (USD/year); and V^{pec} is total livestock water consumption (m³/year).

For aggregation purposes, the combined agricultural-livestock water value was calculated as a weighted average:

$$V_{A-A} = \frac{(p^{ag} V_c^{agr}) + (p^{pec} V_c^{pec})}{V_c^{agr} + V_c^{pec}} \quad (19)$$

where, V_c^{agr} and V_c^{pec} correspond to the concessioned irrigation and livestock water volumes, respectively.

• EVW

The EVW comprises four main components: V_C , V_P , (V_{A-D}) y (V_{A-A}). These components were not aggregated into a single

total value; instead, they were analyzed separately as component-based economic values to avoid mixing ecosystem-scale and household-scale functions. This disaggregation is essential, as it makes it possible to quantify and highlight the multiple contributions of water resources in páramo ecosystems, acknowledging both their ecological function and their social and productive relevance [32].

2.3.4 Environmental Economic Valuation based on stated preferences

WTP values obtained from the survey were converted into volumetric units (USD/m³) to ensure comparability with the economic water values estimated in the study. A weighted average WTP per household (USD/household/month) was calculated by assigning midpoint values to each payment range and weighting them according to the percentage distribution of responses.

For domestic water use, the average monthly consumption per household was estimated by dividing the total domestic water use ($Q_1 = 6,472.76$ m³/month) by the number of beneficiary households (170). The volumetric WTP (USD/m³) was then obtained by dividing the weighted average household payment by this average water consumption.

For agro-livestock use, water volumes were estimated using officially allocated water from water use authorizations. The total irrigation volume was $V_c^{agr} = 2,814,493.39$ m³/year, and the livestock watering volume was $V_c^{pec} = 3,122.06$ m³/year. These were aggregated to obtain a total agro-livestock allocation of 2,817,615.45 m³/year. The number of beneficiary households was defined based on irrigation users (578), assuming that agricultural and livestock activities are integrated within the same user systems, thereby avoiding double counting. The average monthly water volume per household was calculated by dividing the total annual allocation by the number of households and by 12 months. This value was used to express WTP in volumetric terms (USD/m³) for agro-livestock use.

For páramo conservation and restoration, water availability was defined based on the total annual water supply within the system. Two indicators were considered: the captured water volume ($OC_i = 1,077,142$ m³/year) and the hydrological offer derived from the water balance ($Od = 1,436,190$ m³/year). These volumes were distributed across all beneficiary households ($N = 724$) and converted to a monthly basis to obtain average values per household. The resulting estimates were used as reference volumes to express ecosystem-related WTP values (USD/m³) for conservation and restoration. This distinction allows differentiating between direct water capture and broader hydrological regulation services provided by the páramo ecosystem. WTP values were converted into volumetric units (USD/m³) by normalizing weighted household payments using average water consumption per household.

2.3.5 Comparison between willingness to pay and component-based economic value of water

The comparison between WTP and EVW was conducted by converting both metrics to the same unit of analysis (USD/month/household). To standardize the EVW, the unit value of water (USD/m³) was multiplied by the estimated monthly concessioned consumption volume per family.

This comparison made it possible to identify financing gaps: when $WTP \geq EVW$, households would have the capacity to cover the economic cost of water, making a community-based

compensation scheme viable. Conversely, when $WTP < EVW$, the need arises to implement adjustment mechanisms such as cross-subsidies, differentiated tariffs, or complementary public investment to ensure both economic sustainability and equity in water management. This condition is interpreted as an indicator of financial feasibility rather than a strict decision rule.

2.3.6 Multivariate statistical analysis

A Factorial Analysis of Mixed Data (FAMD) was applied to explore the relationships between WTP and socioeconomic, productive, and perception variables at the household level. This multivariate technique allows the simultaneous analysis of quantitative and qualitative variables.

The analysis was conducted using a dataset of 85 households. The variables included in the FAMD were: (i) WTP for domestic water use (DAP_dom), (ii) agro-livestock water use (DAP_agro), (iii) páramo conservation (DAP_cons), and (iv) restoration (DAP_rest), all expressed in USD/household/month; and (v) categorical variables including sex, ethnicity, income level, main economic activity, and perception of páramo importance. All categorical variables were treated as factors, while WTP variables were treated as continuous. The FAMD was performed using the FactoMineR package in R. The number of retained dimensions was determined based on eigenvalues and cumulative explained variance.

3. RESULTS AND DISCUSSION

3.1 Water supply and demand

The results presented in Table 2 show a water balance characterized by a total supply (OT) of 3.43 million m³/year, approximately 7-8% higher than the total demand (DT) of 3.18 million m³/year, initially suggesting a scenario of moderate pressure on water resources. However, when considering the available water supply after evapotranspiration losses ($Od = 1.44$ million m³/year), a different scenario emerges. The WSI, defined as the ratio between total demand and available supply DT/Od , reaches a value of 2.22, indicating that water demand exceeds available supply by a factor of more than two, reflecting significant water stress under maximum allocation scenarios. This behavior is consistent with findings from the Tempisque River Basin, where excessive agricultural use compromised surface water availability [15].

Similarly, in the APHQ, agricultural and livestock activities account for 97.3% of total demand, while domestic consumption represents less than 3%, a proportion comparable to that reported in high-Andean communities of Peru and Colombia [11, 33]. Regarding the distribution of water supply, surface runoff (ESC_s) reached 1.08 million m³/year (31.4%), while net infiltration (R) accounted for 0.36 million m³/year (10.5%), indicating that most of the water flows rapidly toward river channels instead of recharging aquifers.

This pattern is typical of Andean páramo ecosystems, where organic soils act as natural water reservoirs, but their regulation capacity decreases when agricultural practices such as potato cultivation and pasture expansion intensify, leading to soil compaction and reduced infiltration [34]. Consequently, although the mean annual precipitation ($\bar{P} = 613$ mm) ensures a constant input, anthropogenic pressure and growing demand are likely to generate recurrent water deficits under increasing

demand scenarios [4, 34, 35].

These results should be interpreted as upper-bound conditions, given that demand was estimated using maximum authorized flows, which may result in a conservative overestimation of water use.

3.2 Socioeconomic characterization of the surveyed population

Table 3. Social and agricultural indicators of the surveyed population

Variable	Category	Value	Unit
Sex	Male	55	%
	Female	45	%
Ethnicity	Indigenous	94	%
	Mestizo	6	%
Main economic activity	Agriculture	50.7	%
	Livestock	23.9	%
	Other	25.4	%
Income	< 470 USD (minimum wage)	66	%
	470 - 940 USD	10	%
	> 940 USD	24	%
	Investment	227.59	USD/year
Agriculture	Total area	0.88	ha/household
	Area (Potato)	0.43	ha/household
	Area (Maize)	0.58	ha/household
	Price (Potato)	0.30	USD/kg
	Price (Maize)	0.38	USD/kg
Crop yield	Potato (irrigated)	16000	kg/ha
	Potato (rainfed)	12800	kg/ha
	Maize (irrigated)	8697	kg/ha
	Maize (rainfed)	5218	kg/ha
	Potato	16.42	%
Agricultural diversification	Maize	22.39	%
	Potato and others (melloco, mashua, beans)	25.37	%
	Maize and others	7.46	%
	Potato and maize	19.4	%
	Not applicable	8.96	%
Livestock	Investment	450	USD/head/year
	Total area	1.79	ha/household
	Price (Milk)	0.5	USD/L
Yield	Dairy cows	3606.93	USD/year
	Milk	10.98	L/day
Livestock (average per household)	Dairy cows	1.8	unit
	Dry cows	0.8	unit
	Bulls/steers	0.9	unit
	Heifers	0.7	unit
Perception of páramo importance	Important	94	%
	Not important	6	%
Restoration	Degraded páramo	56.1	ha
	Ecological restoration	200	USD/ha/year

The results presented in Table 3 show that the surveyed population is composed of 55.29% men and 44.71% women, with a predominance of individuals who self-identify as Indigenous (94.12%). Regarding economic activity, agriculture constitutes the main source of livelihood (50.7%), followed by livestock production (23.9%) and other activities (25.4%). However, income derived from these activities is limited: two-thirds of households (66%) earn less than 470 USD per month, indicating a clear condition of economic vulnerability. This finding is consistent with studies in other Andean communities, where strong dependence on natural

resources and low income constrain the adoption of sustainable practices [2, 6].

On average, each family allocates 1.79 ha to pastures and 0.88 ha to agricultural crops. Moreover, annual investment in livestock (450 USD) is nearly double that invested in agriculture (227.59 USD), suggesting that livestock is perceived as a more stable source of income. Nevertheless, studies have shown that the expansion of pastures in páramo ecosystems reduces soil infiltration capacity, compromising the ecosystem's hydrological regulation function [12].

Agricultural production is concentrated in potato (0.43 ha per family) and maize (0.58 ha per family). The yields reflect a strong impact of irrigation: potato productivity increases by 25% (from 12800 to 16000 kg/ha) under irrigation, while maize productivity rises by 67% (from 5218 to 8697 kg/ha). These results confirm the usefulness of estimating the EVW based on the productivity gains associated with irrigation [36]. In livestock systems, each family owns on average 4.2 head of cattle, of which 1.8 are dairy cows producing approximately 10.98 L of milk per day.

Together, these data constitute key variables for the EEV of water, as they allow the quantification of the resource's contribution in terms of marginal productivity and differentiated benefits by use. At the same time, the information reveals significant pressure on both land and water, where low incomes, intensive production systems, and a high dependence on irrigation create a scenario of socio-environmental vulnerability. This duality, also reported in other páramo studies, underscores the need to implement water valuation schemes and PES mechanisms that help balance conservation and production [33, 37].

Component-Based EVW, the V_C was estimated at 0.699 USD/m³, based on a water capture efficiency coefficient ($\alpha_i = 0.94$) and an effective regulated water volume of 1,077,142 m³/year over 558.56 ha in the APHQ. The opportunity cost of competing land uses (B_i) reached 4,357.52 USD/ha/year, indicating economic pressure on páramo conservation. Agriculture shows the highest returns, particularly potato (4,541.38 USD/ha/year) and maize (3,064.26 USD/ha/year), exceeding livestock values (63.60 USD/ha/year). These results suggest that irrigation-dependent agriculture constitutes the principal economic driver of water use, a pattern widely reported in mountain systems where marginal water productivity strongly influences land-use decisions.

This value is higher than that reported for the Tempisque River Basin (approximately 0.65 USD/m³), a difference that can be explained by the greater water retention capacity of páramo soils and the strong productive dependence of local communities [15, 36].

From a management perspective, the relatively high V_C reflects the economic importance of water and the increasing pressure on water resources under current demand conditions. In páramo ecosystems, this pressure can lead to progressive agricultural encroachment and reduced hydrological regulation capacity, as soil structure and infiltration processes are altered [35, 38].

The V_p was estimated at 0.005 USD/m³, based on a cost allocation factor ($\delta_{ij} = 0.7$), a restoration cost of 200 USD/ha/year, and an intervention area of 56.10 ha, considering a water supply of $O_{c_i} = 1,436,190$ m³/year.

This value was considerably lower than the estimated water capture value, indicating that conserving existing páramo ecosystems is economically more efficient than restoring

already degraded areas. Nevertheless, investment in ecological restoration remains essential to recover infiltration processes, soil water retention, and hydrological regulation functions, consistent with findings reported for high-Andean ecosystems [39, 40].

From a management perspective, the relatively low V_p suggests that restoration actions could be financially feasible within local water governance schemes, particularly under PES approaches, where relatively small user contributions may help sustain long-term hydrological services. Integrating restoration strategies into watershed management may also contribute to reducing future pressures on water resources and mitigating ecosystem degradation under increasing anthropogenic and productive demands [9, 36].

The V_{A-D} was estimated at 0.002 USD/m³, based on a total domestic water consumption of 77,673.17 m³/year and a fixed tariff of 3 USD/month per household, as established by community water management organizations. Monthly domestic water demand ranged from 6,472.76 to 6,581.27 m³, reflecting slight population growth during the evaluated period. The estimated unit water price ($P_1 = 0.07879$ USD/m³) and the assumed demand elasticity ($\varepsilon = 0.3$) indicate relatively inelastic consumption behavior, which is characteristic of essential water services.

The domestic water value was substantially lower than the values estimated for productive uses, indicating a comparatively limited contribution to the overall economic valuation of water resources. This result reflects the predominantly social function of domestic water supply in rural mountain communities, where affordability and equitable access are prioritized over economic profitability. Although domestic demand represents a relatively small proportion of total water use, it remains fundamental for household well-being and local livelihoods. Therefore, water management strategies should ensure secure, continuous, and affordable domestic supply while simultaneously addressing the greater pressures associated with irrigation-dependent agricultural activities [22, 25].

The V_{A-A} was estimated at 0.188 USD/m³, based on a total water allocation of 2,817,615.45 m³/year, predominantly driven by agricultural use (2,814,493.39 m³/year), while livestock represents a marginal share (3,122.06 m³/year). In the agricultural sector, water use is concentrated in potato and maize production over 508.64 ha, involving 578 households with agricultural water permits. Irrigation significantly increases yields: potato from 12,800 to 16,000 kg/ha and maize from 5,218 to 8,697 kg/ha. The estimated marginal water productivity reached 0.5783 kg/m³ for potato and 0.6287 kg/m³ for maize, highlighting the strong dependence of local agricultural productivity on irrigation water availability.

The $p^{ag} = 0.188$ USD/m³) reflects the productivity gains associated with irrigation, supported by local market prices and relatively low production costs. In contrast, estimated livestock water consumption reached only 994.08 m³/year, yet the livestock water value based on physiological consumption $p_{estimated}^{pec}$ reached 1.49 USD/m³. This comparatively high unit value is influenced by the relatively low volumetric water consumption associated with livestock systems, which tends to increase unit economic values when applying marginal productivity approaches. Similar patterns have been reported in water economics studies, where elevated unit values emerge in systems characterized by limited water

inputs but stable economic outputs [25, 41].

However, when normalized using the officially authorized livestock water allocation ($V_c^{pec} = 3,122.06$ m³/year), the livestock water value decreased to $p^{pec} 0.474$ USD/m³, providing a more conservative estimate consistent with the institutional water allocation framework applied throughout this study. Therefore, these values reflect the relative economic productivity of water under specific local production conditions rather than absolute water scarcity or universal efficiency metrics, and should be interpreted as context-dependent indicators rather than directly transferable values [42].

Overall, the results highlight the multifunctional value of páramo water resources, where hydrological regulation, agricultural production, domestic supply, and ecological restoration are strongly interconnected within the socio-ecological dynamics of the APHQ. The estimated water values revealed marked contrasts among ecosystem functions and water uses. The $V_c = 0.699$ USD/m³) represented the highest economic contribution, emphasizing the strategic importance of páramo ecosystems in sustaining water availability and productive activities. In contrast, the $V_p = 0.005$ USD/m³ remained comparatively low, suggesting that ecosystem maintenance and recovery actions may be implemented at relatively low economic cost compared to the benefits generated through hydrological regulation [43, 44].

Regarding water use, the $V_{A-A} = 0.188$ USD/m³ reflected the strong dependence of local livelihoods on irrigation-dependent agricultural production, particularly potato and maize cultivation. By comparison, the domestic water value $V_{A-D} = 0.002$ USD/m³ was considerably lower, reflecting the social nature of rural water supply systems, where affordability and equitable access are prioritized over economic profitability [41, 45].

From an integrated management perspective, the combined valuation framework demonstrates that conserving and restoring páramo ecosystems is essential not only for ecological integrity but also for maintaining the hydrological services that support local economies and community well-being. Therefore, management strategies that integrate ecological restoration, sustainable agricultural practices, and community-based governance may contribute to strengthening hydrological resilience and reducing future pressures on high-Andean water systems. All input parameters and valuation results used in this analysis are presented in Table 3 and Table 4.

3.3 Willingness to pay

Table 5 summarizes the respondents' WTP and willingness to contribute through non-monetary actions across different scenarios. In the non-monetary dimension, 31.9% of respondents expressed willingness to adopt agroecological production, followed by 30.8% for sustainable livestock practices and 22% for silvopastoral systems. Community-based tourism received lower acceptance (13.2%), while only 2.2% declared that they were not willing to implement any changes. These findings indicate that the population prioritizes strategies directly linked to their existing agricultural and livestock base, as transitioning toward more sustainable productive practices appears more feasible than promoting external activities such as tourism [22, 46].

Table 4. Parameters and results of water economic valuation in the Quinllunga Water Protection Area (APHQ)

Variable	Value	Unit
Water Capture Value		
a_i	0.94	Dimensionless
B_i	4,357.52	USD/ha/year
$B_{agriculture}$	4,226.83	USD/ha/year
B_{maize}	3,064.26	USD/ha/year
B_{potato}	4,541.38	USD/ha/year
$B_{livestock}$	63.60	USD/ha/year
OC_i	1,077,142.00	m ³ /year
A	558.56	ha
V_c	0.699	USD/m³
Restoration Value		
δ_{ij}	0.7	Dimensionless
C_{ij}	200.00	USD/ha/year
Ar_i	56.10	ha
O_d	1,436,190.00	m ³ /year
V_p	0.005	USD/m³
Domestic Water Use Value		
Population (2010)	4,194.00	inhabitants
Population (2022)	4,288.00	inhabitants
$N_{domestic}$	170	households
r	0.00185	dimensionless
T	10	years
$q_{domestic}$	77,673.17	m ³ /year
Q_1	6,472.76	m ³ /month
Q_2	6,581.27	m ³ /month
Price	3.00	USD/month/household
P_1	0.07879	USD/m ³
ε	0.30	dimensionless
k_1	3,020.19	dimensionless
k_t	3,070.82	dimensionless
V_{A-D}	0.242	USD/month
V_{A-D}	0.002	USD/m³
Agro-Livestock Water Use Value		
V_c^{agr}	2,814,493.39	m ³ /year
V_c^{pec}	3,122.06	m ³ /year
V_{A-A}	0.188	USD/m³

Agricultural Use		
$V_{irrigation}$	2,814,493.39	m ³ /year
$N_{irrigation}$	578	households
$A_{agriculture}$	508.64	ha
$Q_k(potato)$	0.5783	kg/m ³
$Q_{irrigation(potato)}$	16,000.00	kg/ha
$Q_{rainfed(potato)}$	12,800.00	kg/ha
V_i	5,533.37	m ³ /ha
$Q_k(maize)$	0.6287	kg/m ³
$Q_{irrigated(maize)}$	8,697.00	kg/ha
$Q_{rainfed(maize)}$	5,218.00	kg/ha
$P_k^{ag}(potato)$	0.1641	USD/m ³
$p_k(potato)$	0.3000	USD/kg
$c_k(potato)$	0.0162	USD/kg
$P_k^{ag}(maize)$	0.2202	USD/m ³
$p_k(maize)$	0.3800	USD/kg
$c_k(maize)$	0.0297	USD/kg
$Q_i(potato)$	3,976,640.00	kg
$Q_i(maize)$	2,915,582.28	kg
p^{ag}	0.188	USD/m³
Livestock Use		
C_{dairy}	0.060	m ³ /day/animal
$C_{dry cows}$	0.040	m ³ /day/animal
$C_{bulls/steers}$	0.050	m ³ /day/animal
$C_{heifers}$	0.035	m ³ /day/animal
N_{dairy}	1.80	animals
$N_{dry cows}$	0.80	animals
$N_{bulls/steers}$	0.90	animals
$N_{heifers}$	0.70	animals
N_{pec}	13	households
V^{pec}	994.08	m ³ /year
C_{pec}	1,890.00	USD/year
I_{gross}	2,003.85	USD/year
$p_{physiological}^{pec}$	1.49	USD/m ³
V_c^{pec}	3,122.06	m ³ /year
p^{pec}	0.474	USD/m³

Table 5. Results of willingness to pay (WTP) and non-monetary contributions in the Quinllunga Water Protection Area (APHQ)

Scenario	Category	Result (%)	Midpoint	Weighted Value (USD/household/month)	WTP (USD/m ³)
Domestic water use	≤ 3 USD	68.66	1.5	1.03	0.039
	3–5 USD	14.93	4	0.60	0.105
	5–10 USD	4.48	7.5	0.34	0.197
	> 10 USD	4.48	12.5	0.56	0.328
	Not willing to pay	7.46	0	0	0.000
	Weighted average	-	-	-	2.52
Agro-livestock water use	≤ 3 USD	59.7	1.5	0.90	0.004
	3–5 USD	23.88	4	0.96	0.010
	5–10 USD	4.48	7.5	0.34	0.018
	> 10 USD	1.49	12.5	0.19	0.031
	Not willing to pay	10.45	0	0.00	0.000
	Weighted average	-	-	-	2.37
Páramo conservation	≤ 3 USD	37.30	1.5	0.56	0.012
	3–5 USD	38.81	4	1.55	0.032
	5–10 USD	4.48	7.5	0.34	0.060
	> 10 USD	8.96	12.5	1.12	0.101
	Not willing to pay	10.45	0	0.00	0.000
	Weighted average	-	-	-	3.57
Páramo restoration	≤ 3 USD	55.22	1.5	0.83	0.009
	3–5 USD	25.87	4	1.03	0.024
	5–10 USD	4.48	7.5	0.34	0.045
	> 10 USD	4.98	12.5	0.62	0.076
	Not willing to pay	9.45	0	0.00	0.000
	Weighted average	-	-	-	2.82

Regarding domestic water use, 68.66% of households would be willing to pay ≤ 3 USD/month, while only 8.96% would reach higher payment ranges (above 5 USD). A total of 7.46% of respondents stated that they would not be willing to pay. This pattern reflects both a strong dependence on the resource and a limited payment capacity—consistent with the fact that two-thirds of households report monthly incomes below 470 USD. Similar findings have been reported in high-Andean communities in Peru, where WTP for domestic water rarely exceeds 3 USD/month [11].

For irrigation water, 59.7% of respondents indicated a WTP ≤ 3 USD/month, and 23.88% would pay between 3-5 USD, while only 1.49% would pay more than 10 USD. In contrast, 10.5% declared unwillingness to pay. This result confirms the high vulnerability of the agricultural sector to increases in water costs [10, 41].

With respect to conservation, most contributions were concentrated in the lower ranges: 37.30% of households indicated WTP ≤ 3 USD, and 38.81% between 3 and 5 USD. Only 9% would contribute more than 10 USD, while 10.5% stated they would not contribute. For restoration, this trend was even more pronounced, with 55.22% willing to pay ≤ 3 USD and 25.87% between 3 and 5 USD. These results reveal the presence of strong social capital and a clear predisposition to participate in páramo conservation, although monetary amounts are limited by household income constraints. This pattern is likely driven not by a lack of environmental awareness but by income limitations [17].

The WTP results show differences across scenarios. For domestic water use, the weighted average reaches 2.52 USD/household/month (0.066 USD/m³), with most respondents willing to pay ≤ 3 USD, indicating limited payment capacity but general acceptance of tariffs. In the agro-livestock scenario, WTP decreases to 2.37 USD/month (0.006 USD/m³), reflecting a lower perceived value of water for productive uses despite its high demand, and a higher proportion of respondents unwilling to pay (10.45%).

In contrast, páramo conservation shows the highest WTP (3.57 USD/month; 0.029 USD/m³), with a more balanced distribution across payment ranges, suggesting greater recognition of ecosystem services. Similarly, páramo restoration reaches 2.82 USD/month (0.017 USD/m³), indicating moderate support for investment in ecosystem recovery actions. These results should be interpreted cautiously, as the comparison between WTP and EVW represents an indicator of feasibility rather than a strict decision rule.

These results show a mismatch between dependence and value: although agriculture dominates water use, conservation is valued more. This reflects recognition of ecosystem services

but limited ability to pay. Low WTP and 7-10% unwillingness to pay suggest that PES schemes must be affordable and community-based [17, 47].

3.4 Comparison between willingness to pay and economic value of water

The comparison between EVW and WTP reveals substantial differences among water uses and ecosystem functions within the APHQ (Table 6). These differences reflect the contrast between the estimated economic importance of hydrological services and the limited financial capacity of rural households, a pattern frequently reported in environmental valuation studies conducted in mountain socio-ecological systems [22, 45].

For $V_{A-D} = 0.002$ USD/m, the reported WTP for domestic water use reached approximately 0.066 USD/m³. Although the economic value associated with domestic water use was comparatively low, households expressed a relatively higher willingness to contribute financially to secure access to drinking water. This result reflects the essential social function of domestic water for household well-being, health, and daily subsistence, where perceived value is not necessarily linked to volumetric economic profitability but rather to the security and continuity of supply [48].

In contrast, the agro-livestock sector presented the highest productive dependence on water resources. The $V_{A-A} = 0.188$ USD/m³, largely driven by irrigation-dependent potato and maize production, while the reported agricultural WTP remained substantially lower (approximately 0.006 USD/m³). This marked difference indicates that although agricultural livelihoods strongly depend on water availability, the economic capacity of households to support higher water tariffs remains limited. Similar dynamics have been documented in rural Andean economies, where irrigation systems operate under socially subsidized community management schemes rather than under full economic cost-recovery approaches [48].

For ecosystem services, the $V_C = 0.699$ exceeded the reported conservation WTP (0.029 USD/m³). Likewise, the $V_p = 0.005$ USD/m³, remained lower than the reported restoration WTP (0.017 USD/m³). These results suggest that local communities recognize the importance of páramo conservation and restoration despite their economic limitations. In particular, the relatively low restoration value indicates that ecosystem maintenance and recovery actions could potentially be sustained through modest collective contributions under local governance arrangements [33, 48].

Table 6. Gaps between economic value of water (EVW) and willingness to pay across water use and conservation scenarios in the Quinllunga Water Protection Area (APHQ)

Component	Use / Function	Type of Value	Indicator	Value (USD/m ³)
Domestic water use	Consumption	Social (WTP)	WTP	0.066
		Economic	V_{A-D}	0.002
Agro-livestock water use	Production	Social (WTP)	WTP	0.006
		Economic	V_{A-A}	0.188
Páramo conservation	Ecosystem protection	Social (WTP)	WTP	0.029
	Ecosystem service	Economic	V_C	0.699
Páramo restoration	Ecosystem recovery	Social (WTP)	WTP	0.017
		Economic	V_p	0.005

Overall, the relationship between EVW and WTP varied considerably across water uses and ecosystem functions. While EVW reflects the estimated economic contribution of hydrological services to productive systems and ecosystem regulation, WTP primarily reflects socially perceived value constrained by household income levels. This explains why reported WTP values remain substantially lower than several estimated economic values despite the high dependence of local livelihoods on water resources [33, 48].

These differences should also be interpreted in light of the simplified water-supply and water-allocation framework used in the study. The estimates of water supply and demand provide a first-order annual approximation suitable for economic valuation under data-scarce conditions, but they should not be interpreted as a detailed seasonal water balance or as direct measurements of real-time water use [1, 20]. Likewise, the unit economic values obtained for domestic, agricultural, and livestock uses depend on the volume adopted as the denominator; therefore, they are not fixed attributes of water itself, but context-dependent indicators of the relationship between economic benefits, social uses, and allocated water volumes. In this sense, the results should not be read as absolute measures of overvaluation or undervaluation, but as comparative signals that help identify how water availability, water allocation, productive dependence, and household payment capacity interact in a data-scarce high-Andean context. This interpretation strengthens the usefulness of the valuation framework for water governance, as it allows economic values and WTP to be discussed jointly without reducing them to a single monetary criterion [22, 41, 49].

From a policy and governance perspective, these findings indicate that the financial sustainability of páramo conservation and water management cannot rely exclusively on contributions from rural households. Instead, integrated financing mechanisms such as cross-subsidies, differentiated tariffs, PES, and Water Funds may be necessary to distribute conservation and management costs among the broader set of beneficiaries of hydrological regulation services. Under this

framework, the comparison between EVW and WTP should be interpreted not as a strict economic decision criterion, but rather as an indicator of financial feasibility and social acceptability for the implementation of equitable and sustainable watershed management strategies [45].

3.5 Multivariate analysis of willingness to pay

To identify the structural factors explaining variability in the WTP for páramo conservation, a FAMD was applied. This technique allows for the simultaneous examination of categorical, ordinal, and continuous variables. The approach is particularly appropriate given the diversity of variables involved, including socioeconomic characteristics, water use patterns, and different levels of WTP.

The FAMD enabled the synthesis of productive, socioeconomic, and WTP-related information for households within a reduced two-dimensional space. The FAMD results are interpreted as descriptive patterns of household segmentation and should not be considered evidence of causal relationships [50]. Figure 3 presents the biplot, showing surveyed individuals (gray points) and variables (red arrows). The orientation of each arrow indicates the direction of association with the factorial axes, while its length represents the magnitude of contribution to the explained variability.

In the first factorial dimension (Dim1, 39.5%), a clear gradient can be observed between households with higher income levels (> 2 Basic Unified Remunerations - BUR), located on the right side of the plot and associated with higher production of milk, maize, and potato, as well as a greater WTP for domestic and agricultural water uses, compared to low-income households (< 1 BUR), positioned on the left side and characterized by lower production and limited payment capacity.

The second dimension (Dim2, 14.3%) mainly differentiates households with intermediate incomes (1-2 BUR), projected toward the lower part of the plane and linked to a higher WTP for ecosystem restoration, suggesting a distinct profile compared with both lower- and higher-income groups.

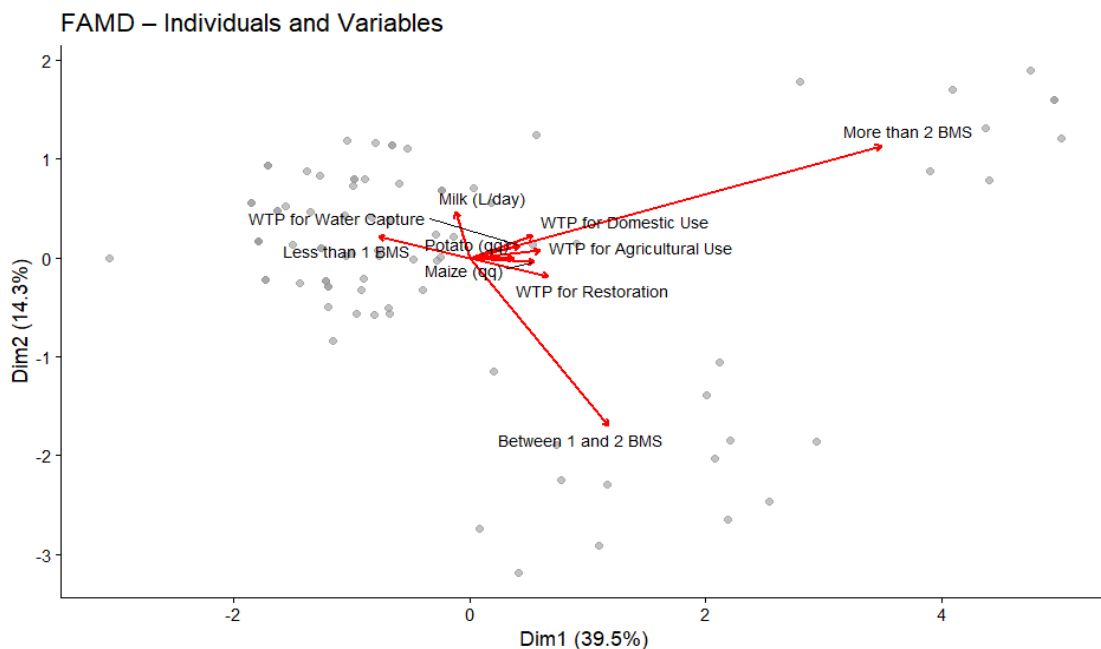


Figure 3. Factorial Analysis of Mixed Data (FAMD): Biplot of individuals and variables
 Note: The ten variables with the highest contribution to explained variance are highlighted in red.

The dispersion of individuals in the biplot confirms the existence of three differentiated household groups based on their economic, productive, and environmental conditions:

1) Low-income households (< 1 BUR) show limitations in both income and production, resulting in low WTP and a need to be integrated into social support or in-kind compensation schemes such as community work (“mingas”) or participation in restoration activities.

2) Intermediate-income households (1-2 BUR) are characterized by moderate agricultural and livestock production and a higher WTP for environmental restoration, making them a key segment for promoting participatory reforestation programs.

3) High-income households (> 2 BUR) exhibit greater agricultural production and higher WTP for direct water uses (domestic and agricultural), positioning them as the group with the greatest financial capacity to support hydraulic infrastructure and community irrigation systems.

These findings confirm that socioeconomic status is the main structuring factor of WTP, aligning with previous studies that emphasize the close relationship between economic capacity and preferences for domestic or productive water uses. However, the results also reveal nuances in environmental valuation: while higher-income households prioritize water security for consumption and production, intermediate-income households display greater affinity with ecosystem restoration, which may reflect a resilience-oriented strategy in response to environmental degradation.

In practical terms, this differentiation of household profiles provides valuable evidence for designing fair and effective water governance strategies. Higher-income households can contribute financially to strengthen infrastructure, while intermediate-income households can serve as strategic allies in conservation and restoration efforts. Conversely, more vulnerable households require differentiated schemes, such as social tariffs or non-monetary compensation mechanisms.

Overall, the FAMD not only identified socioeconomic inequalities but also revealed divergent priorities regarding water use and conservation key insights for implementing PES mechanisms and community-based policies tailored to local territorial contexts.

4. CONCLUSIONS

The EEV proved to be an effective tool for highlighting the contribution of páramo ecosystems to water provision and hydrological regulation. The integration of satellite-based datasets (CHIRPS, GLDAS-2) with socioeconomic information enabled a consistent estimation of both water supply and demand, despite the limited availability of local data. However, given the use of annual averages and maximum concessioned flows, the results should be interpreted as context-dependent approximations rather than definitive estimates of hydrological and economic conditions. The comparison between EVW and WTP revealed significant gaps in both domestic and agricultural uses, confirming that current tariff schemes do not reflect the real EVW provision and therefore constrain the financial sustainability of community-managed water systems.

The multivariate analysis showed that both the capacity and willingness to contribute financially depend on household socio-productive profiles. Livestock production was associated with a higher unit economic value per cubic meter

of water, whereas agriculture concentrated the highest volumetric demand and represented the principal driver of water use in the APHQ. This asymmetry indicates that tariff and compensation schemes must balance economic efficiency with social equity and local livelihood dependence. Moreover, the observed willingness to adopt sustainable production practices and participate through non-monetary contributions represents an important form of social capital that could strengthen the implementation and long-term viability of future PES mechanisms.

The study also confirmed that conservation is economically more efficient than restoration, as reflected by the higher water capture value. Nevertheless, both actions remain essential for maintaining the hydrological regulation capacity of páramo ecosystems under increasing pressures associated with agricultural intensification and climate variability. It is therefore recommended to advance toward integrated and tiered PES schemes that incorporate the shared responsibility of downstream water users, including urban and productive sectors, while simultaneously strengthening hydrological monitoring systems to reduce uncertainty in water supply estimation. Together, these actions could reinforce the technical, institutional, and social foundations required for implementing integrated, equitable, and resilient water management strategies with potential applicability in other high-Andean socio-ecological systems.

This research successfully integrated biophysical and economic approaches within a data-scarce context; however, several limitations should be acknowledged. Although the use of maximum concessioned flows may lead to conservative upper-bound estimates of demand, applying arbitrary reduction scenarios without field-based evidence could introduce additional uncertainty. Future studies should therefore incorporate continuous or seasonal hydrometric monitoring, operational flow records, intake-level measurements, and, where possible, user-level water metering. These data would allow authorized volumes to be contrasted with effective water use and would support empirically calibrated sensitivity scenarios to assess changes in water stress indicators, unit economic values, and EVW-WTP gaps. Likewise, the harmonization of EVW and WTP under common volumetric units facilitated comparison among water uses and ecosystem services, although it may partially obscure intra-household heterogeneity and transaction costs associated with PES implementation. Finally, WTP was estimated using weighted averages derived from closed-ended survey scenarios, which limits the representation of dynamic preferences and temporal variability. Future research should therefore consider dichotomous choice models, mixed valuation approaches, or longitudinal analyses to improve the behavioral and temporal robustness of valuation estimates.

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APPENDIX

Appendix A1. Acronyms

Description	Acronym
Payment for Ecosystem Services	PES
Organic Environmental Code (Código Orgánico del Ambiente)	COA
Decentralized Autonomous Governments	GADs

Quinllunga Water Protection Area (Área de Protección Hídrica Quinllunga)	APHQ
Water Protection Areas	APH
Total water supply	OT
Available water supply	Od
Potential recharge	Ip
Net infiltration	R
Surface runoff	ESC _S
Social demand	Q _s
Total water demand	DT
Water capture value	VC
Water use value	V _A
Restoration value	V _P
Domestic water use value	V _{A-D}
Agricultural water use value	V _{A-ag}
Environmental Economic Valuation	EEV
Economic Valuation of the Water Provision Service	EVWPS
Component-Based Economic Value of Water	EVW
Willingness to Pay	WTP
Google Earth Engine	GEE
Global Land Data Assimilation System v2	GLDAS-2
Climate Hazards Group InfraRed Precipitation with Station data	CHIRPS
Contingent Valuation Method	CVM
Factorial Analysis of Mixed Data	FAMD

Appendix A2. Survey structure

The following survey has as its main objective: To collect community preferences to implement conservation measures of the páramo ecosystem and guarantee better access to water.

Instructions

The information you provide will only be used for research purposes.

Investigative Purposes

Mark a single answer with an (X) in each of the following questions

Informative Data

Sex	Man	Woman		
Ethnic Self-Identification	Mongrel	Indigenous	White	Other.....
Your Household's Main Economic Activity	Agriculture	Animal husbandry	Commerce	Other.....
Monthly Income	Less than \$460	\$470 to \$940	Over \$940	

Age

1. How many hectares of paddock do you have or lease?

- A Less than 1 hectare
- B Between 1 and 1.5 hectares
- C Between 1.5 to 2 hectares

- D More than 2 hectares
- E No

2. How much is your milk supply in a day?

- A Less than 5 litres
- B Between 5 and 10 liters
- C Between 10 and 15 liters
- D Between 15 and 20 liters
- E More than 20 litres
- F No

3. Indicate the number of cattle you have according to the table.

	0	1	2-3	4-5	>5
Producing cows					
Dry cows					
Bulls and bulls					
Vaconas					

4. How much money do you estimate you invest per head of cattle per year including feed, veterinary care, medicines and other necessary supplies?

- A Less than \$350
- B Between \$350 to \$550
- C Between \$550 to \$750
- D Over \$750
- E None

5. What is your estimate of expenditure on agricultural inputs, such as seeds, fertilizers, pesticides per crop?

- A Less than \$200
- B Between \$200 to \$350
- C Between \$350 to \$500
- D More than \$500
- E None

6. How many hectares of land do you have for the different agricultural activities?

- A Less than 1 hectare
- B Between 1 and 1.5 hectares
- C Between 1 and 2 hectares
- D More than 2 hectares
- E No

7. What products do you plant on your farms? (you can select more than one)?

- A Potato
- B Corn
- C Melloco
- D Mashua
- E Broad bean
- F Other

8. How many have you planted of each product mentioned in the previous question?

- A Potato
- B Corn

- C Melloco
- D Mashua
- E Broad bean
- F Other

9. How much do you get per year, with irrigation, of the product you plant the most?

- A Less than 200 quintals
- B Between 200 and 350 quintals
- C Between 350 and 500 quintals
- D More than 500 quintals
- E None

10. How much do you get per year, with irrigation, of the second product you plant the most?

- A Less than 200 quintals
- B Between 200 and 350 quintals
- C Between 350 and 500 quintals
- D More than 500 quintals
- E None

11. How much do you get per year, without irrigation (only with rain), of the product you plant the most?

- A Less than 200 quintals
- B Between 200 and 350 quintals
- C Between 350 and 500 quintals
- D More than 500 quintals
- E None

12. How much do you get per year, without irrigation (only with rain), of the second product you plant the most?

- A Less than 200 quintals
- B Between 200 and 350 quintals
- C Between 350 and 500 quintals
- D More than 500 quintals
- E None

13. Do you consider the páramo important to your life and that of your community?

- A Yes
- B No
- C I do not know

14. What activities would you be willing to carry out to protect the páramos without harming your economy and that of your family?

- A Silvopastoral systems
- B Agroecological production
- C Sustainable Livestock
- D Community-based tourism
- E Other, please specify
- F No

15. If you could count on safe and consistent drinking water year-round, how much would you be willing to pay per month to guarantee this service?

- A Less than \$3
- B Between \$3 to \$5
- C Between \$5 to \$10
- D Over \$10
- E None

16. If you ensure enough water for irrigation in dry seasons, how much would you be willing to pay monthly to maintain that access?

- A Less than \$3
- B Between \$3 to \$5
- C Between \$5 to \$10
- D Over \$10
- E None

17. To finance conservation activities for the páramo that regulates water, how much would you be willing to contribute each month?

- A Less than \$3
- B Between \$3 to \$5
- C Between \$5 to \$10
- D Over \$10
- E None

18. To fund páramo restoration activities, how much would you be willing to contribute each month?

- A Less than \$3
- B Between \$3 to \$5
- C Between \$5 to \$10
- D Over \$10
- E None