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Local ecological knowledge for water management: a feasible solution through ecosystem services in high-Andean mountains

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Introduction: Mountain ecosystems are particularly sensitive to the impacts of climate change, which, in turn, affect the wellbeing of local populations. In this context, the sustainable use of ecosystem services is crucial to supporting the social and economic welfare of Andean communities in South America. The development of local ecological knowledge has facilitated both environmental adaptation and strengthened environmental awareness. Particularly, the *qocha*, an ancestral water-related agricultural technology, provides hydro-social value, and represents a local climate-change adaptation measure, however their ecosystem services valuation has not been integrally performed. Thus, we aimed to map and assess the perceived services associated with Yuyuchaqocha, a small reservoir managed by a high-Andean community characterized by pronounced economic poverty.

Methods: The methodology included semi-structured interviews with key informants, participatory mapping, and field observation. The participatory process involved the community, municipal, and technical stakeholders operating within the study area. The economic valuation was done by contingent valuation, market prices, and travel cost methods.

Results: The results revealed that local inhabitants recognized 10 ecosystem services (five provisioning services and five cultural services), primarily concentrated along its shores. The total local perceived value of these services was estimated at USD 10,104.97, benefiting the rural communities of Huanupampa and Totos. Among the cultural services, those related to community organization, species conservation, and the *pagapu* celebration had the highest economic values.

Discussions: Disseminating the results at various organizational levels would foster the integration of the local worldview into management plans, contributing to their legitimacy and sustainability, and promoting the involvement of institutions engaged in the intervention of mountain water socio-ecosystems. In this regard, integrating local ecological knowledge with ecosystem services valuation can be replicated or adapted in other regions.

KEYWORDS

Andean mountains, economic valuation, ecosystem services, local communities, nature-based solutions, water management

1 Introduction

Current changes in climate patterns are negatively affecting water security, particularly among indigenous populations in high-mountain regions (Calvin et al., 2023). These territories, typically situated above 3,000 m.a.s.l., encompass ecosystems that play key roles in water regulation and storage (e.g., wetlands and glaciers). The degradation of these ecosystems contributes to the decline in the quantity, quality, and availability of water resources (Drenkhan and Castro-Salvador, 2023; Garcia et al., 2025; Vuille et al., 2018). As a result, a historical interdependence has emerged between the ecological and social vulnerabilities of these populations (Calvin et al., 2023), prompting high mountain communities to develop adaptive strategies (Cepeda Arias et al., 2024). Within this context, water security is understood as a combination of physical, financial, and social measures, rather than being limited to infrastructure availability (Muñoz et al., 2025). Consequently, it is essential to implement integrated analytical and management approaches that are tailored to the specific characteristics of these regions (Cepeda Arias et al., 2024).

The socio-hydrological approach acknowledges community participation, ancestral knowledge, and local expertise as key factors that guarantee achieving sustainable outcomes (Herrera-Franco et al., 2021). This perspective is particularly relevant in contexts of climatic, economic, and social crises that affect vulnerable populations, such as those inhabiting the Peruvian Andes (Lane et al., 2025). Within these communities, local ecological knowledge (LEK) has emerged and evolved as a set of techniques and knowledge transmitted across generations and preserved as part of the community's cultural heritage, enabling adaptation to particular environmental conditions (Boafo et al., 2016). These traditional technologies, developed over centuries, have demonstrated remarkable adaptive capacity and resilience to climate change (Seemann, 2018). Consequently, their revaluation and integrated use with contemporary management strategies and scientific knowledge have yielded tangible improvements in the quality of life of local populations. In the South American Andean region, several successful cases have been reported involving the integration of LEK derived from ancestral practices related to traditional water management, collective governance, the adaptive capacity of small-scale farming, the use of native vegetation, sustainable soil management, aquifer recharge, ecosystem conservation and restoration, and rainwater harvesting, among others (Chávez Velásquez et al., 2024; Christmann et al., 2025; Guerrero Quispe, 2015; Hualpa et al., 2025; Rodríguez-Díaz et al., 2025). Conversely, there are documented cases in which the institutionalization of water-use rights by governmental authorities has led to the exclusion of indigenous peoples (Seemann, 2018). This dilemma underscores the need to rethink conservation, adaptation, and water resource management strategies by incorporating approaches grounded in traditional technologies and inclusive governance processes that actively involve local communities (Cavadia, 2025).

In recent years, the ecosystem services (ES) approach has aimed to quantitatively estimate and effectively communicate the intrinsic benefits that ecosystems provide to people through their ecological functions (Lei et al., 2026; Zhang et al., 2025; Christmann et al., 2025). An ES provides goods and services to human populations, and its economic value can be estimated based on both supply (i.e., ecological processes and characteristics) and demand (i.e., attributes of the beneficiary populations within a given territory; Schägner et al., 2013). Accordingly, the environmental valuation of these services (Ecosystem Service Valuation, ESV) can be defined as the estimation of the economic value that individuals in a specific area would be willing to pay to improve the quality or quantity of an environmental good or service available to them (Motta, 1997). This conceptual framework also incorporates the social, cultural, and intangible values assigned to the local resources through the integration of LEK (Bhatt et al., 2024). Although methodological limitations arise from the qualitative nature of these components, the inclusion of LEK enhances understanding of local socio-cultural relationships in resource management practices (Saylor et al., 2017). Therefore, its application remains highly useful for decision-making, even with the bias related to the anthropocentric perspective of assigning economic value to the benefits received (De Lucia, 2018; Muradian and Gómez-Baggethun, 2021; Schröter et al., 2014). For this reason, ESV studies provide a basis for designing public policies aimed at the preservation and conservation of ecosystem goods and services (Silveira et al., 2013; Supplementary Table S1). To address that, complementary approaches have been developed for a better understanding of the classification and relationships among ES [e.g., The Economics of Ecosystems and Biodiversity (TEEB), the Millennium Ecosystem Assessment (MEA), and the Common International Classification of Ecosystem Services (CICES); Costanza et al., 2017; De Groot et al., 2002]. Among these approaches, the CICIES approach groups ES according to their contributions to human wellbeing (i.e., provisioning ES, regulating and maintenance ES, and cultural ES), and allows for translation between the other ES approaches (Haines-Young, 2023).

It is important to emphasize that anthropogenic dynamics and social needs shape ES provision, whereas ecosystem functions themselves operate independently of these interactions (Spangenberg et al., 2014). Accordingly, the identification and valuation of ES benefits are regarded as dynamic constructs that evolve over time and vary across communities (Madrigal-Martínez and Miralles i García, 2019; Renard et al., 2015; Zhang et al., 2013). Thus, the choice of quantification method for ESV has become increasingly important for water resource assessment, particularly in basins that include arid zones (Shi et al., 2025). In these areas, climate change adaptation practices grounded in ancestral and local knowledge are closely associated with water management, agricultural and livestock production, ecosystem care, and climate prediction (MINCUL, 2019). Therefore, the proper identification and integration of relevant information are essential for conducting successful environmental and economic assessments that highlight the value and importance of water resources, thereby promoting their preservation and conservation (Toldo Moreira et al., 2024). Local ecological knowledge (LEK) plays a key role in maintaining and sustaining biomes that provide ES to local populations (Gadgil et al., 2001; Millennium Ecosystem Assessment, 2005). It also enables a deeper understanding of how local communities perceive, value, and manage these services (Madrigal-Martínez et al., 2023). In this context, assessing the value of water body biomes using LEK can significantly contribute to the sustainable management of high Andean basins, thereby strengthening water security. The *q'ochas*, water dams, and water reservoirs form part of the traditional "wet" hydraulic architecture designed to capture, retain, and infiltrate rainwater and surface runoff (Foster et al., 2020; Lane, 2009). Constructed and maintained on the local communal know-how and labor, these systems are integral components of broader hydraulic networks that serve multiple productive purposes, primarily agriculture and livestock (Lane, 2009, 2021).

There is currently an increase in the dissemination of ancestral technologies, both from international cooperation and government entities. This has led to the qochas in Peru being incorporated into public policies related to actions addressing climate change (Carrasco-Torrontegui et al., 2021), however their ES valuation has not been integrally performed. This nature-based solution has been highlighted by its value in the hydro-social cycle representing a local climate-change adaptation measure (Petzold et al., 2020; Postigo, 2021). Therefore, this research aimed to assess the economic and environmental value of the cultural and provisioning ecosystem services associated with a traditional water dam, as expressed through traditional ecological knowledge in a high Andean environment. Our approach was based on the perspectives of local communities as direct beneficiaries, as well as other key stakeholders, including academic institutions, political and administrative actors, and non-governmental organizations (NGOs). To achieve this, interviews were conducted and participatory "talking maps" were developed with stakeholders involved in the management of the traditional water dam built in the Yuyuchaqocha *q'ocha*, in the southern high Andean region of Peru. Based on this primary information, both cultural and provisioning ES were identified and economically valued. The research sought to address the following questions: (1) What are the characteristics of the communal organization responsible for the implementation, operation, and maintenance of the traditional water dam? (2) What ES are recognized by the beneficiary residents? and (3) What is the environmental and economic value of the identified ES? These findings allowed us to discuss (i) changes in ES and communal organization related to the implementation of the traditional water dam based on local ecological knowledge; (ii) its relationship with local water security; and (iii) the limitations and future directions for research.

2 Materials and methods

A methodology similar to that described by Gandarillas et al. (2016) was employed in this study to identify the primary ecosystem services perceived by the inhabitants of the Totos district regarding the presence of a *qocha*, based on LEK, and to collect the information necessary for its analysis and valuation. The research activities included field visits to the Yuyuchaqocha *qocha* and its beneficiary areas, interviews with local government officials and local experts, and participatory workshops with the principal beneficiaries. During the desk phase, Geographic Information System (GIS) tools and environmental economic valuation methods were employed to process and analyze the collected data.

2.1 Study area

The study area encompassed the Yuyuchaqocha lagoon (13°32′43.8″ S, 74°29′19.5″ W) and the surrounding zones benefiting from its waters in the district of Totos, Cangallo Province, Ayacucho Region in Peru (Figure 1). Situated at the headwaters of the basin (4,380 m.a.s.l.), this water body forms part of the Pampas River basin. Motorable road access (≈27.5 km) facilitates community-based monitoring and maintenance activities. The area is characteristic of the Andean *puna* ecosystem, with minimum temperatures reaching approximately −3 °C during June–August and average annual precipitation ranging from 600 to 800 mm (Castro et al., 2021).

The area is characterized by tall natural grasses and vegetation adapted to cold, dry climates, typical of high Andean grasslands (e.g., *Stipa ichu*, *Rumex peruvianus*). It hosts a diversity of native fauna and serves as a vital water source for South American camelids, such as llamas and alpacas, which are raised according to ancestral communal practices. Livestock farming, focused primarily on alpaca fiber production, is the main economic activity in the study area, with 36% of the economically active population engaged in this sector at the provincial level. Subsistence agriculture and livestock rearing, including the cultivation of fodder and pastures, are also practiced (Municipalidad Provincial de Cangallo, 2016). From 2017 to 2024, the district of Totos had an average inequality-adjusted Human Development Index of 0.35 (Programa de las Naciones Unidas para el Desarrollo, 2025). By 2018, it ranked 41st regionally in terms of total monetary poverty (INEI, 2018b), a situation linked to the underdeveloped productive system and low indices of formal employment. These conditions place Ayacucho as the second poorest region nationally. Furthermore, the population faces restricted access to health and education services, coupled with deficient infrastructure. The community's social dynamics revolve around rural communal life and its traditional cultural expressions (Municipalidad Provincial de Cangallo, 2016).

2.2 Ecosystem services (ES) selection

This study aimed to identify recognition patterns and quantify the use of ecosystem services (ES) derived from ancestral ecological knowledge among local residents. To this end, cultural and provisioning ES were selected as indicators of local perceptions regarding human needs fulfilled through ecosystem functioning (Kaltenborn et al., 2020). Regulating ES were excluded from the analysis due to the greater complexity of their perception by the local population. Cultural and provisioning ES were defined according to the Common International Classification of Ecosystem Services (CICES; Haines-Young, 2023; Supplementary Table S2). Adopting a participatory approach, primary information was collected directly from the social actors involved, and the results were validated with local decision-makers (Madrigal-Martínez et al., 2023).

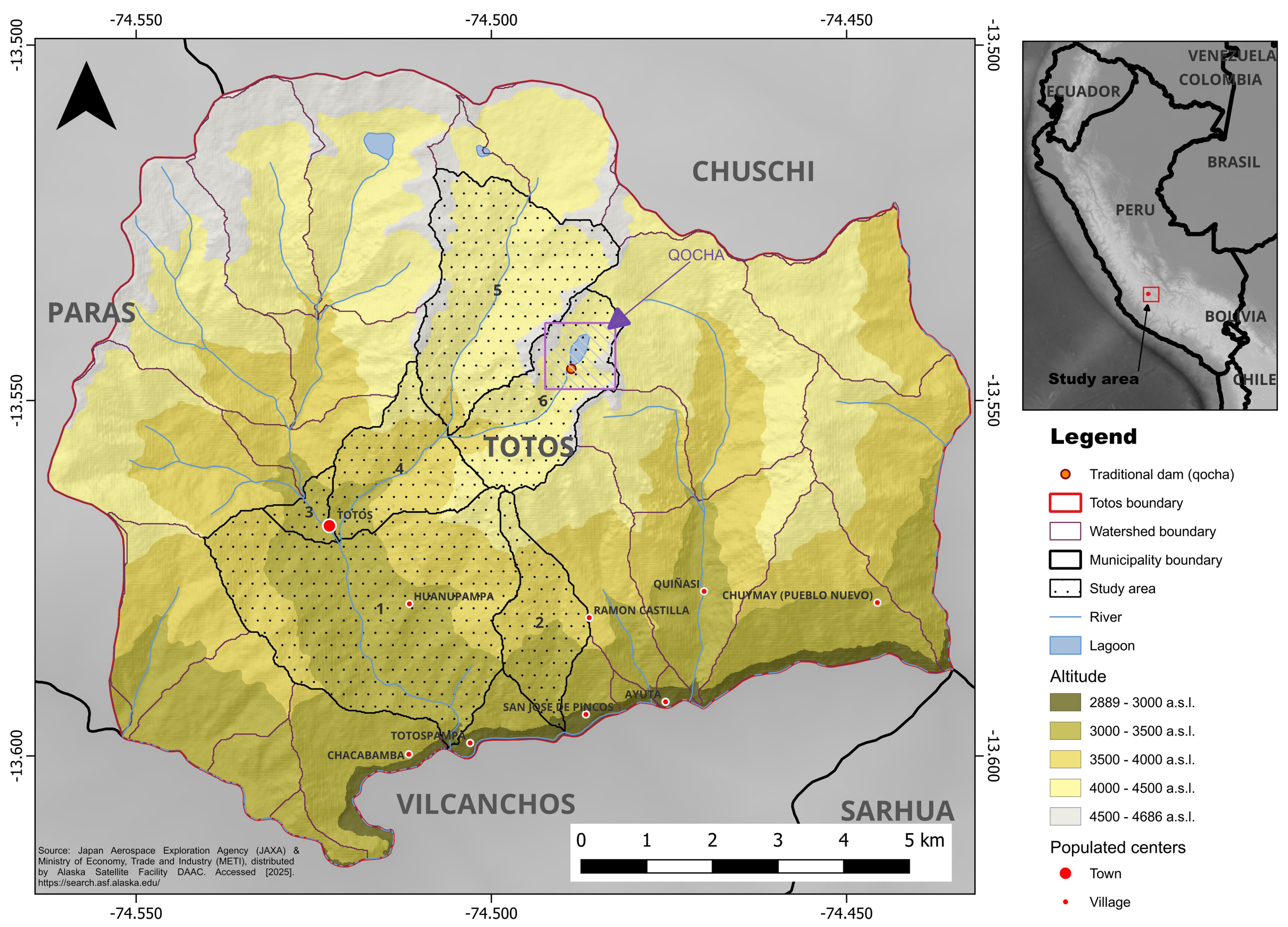

FIGURE 1
Study area with elevation and watershed distribution **(left)**, Peru with Mapzen Global Terrain **(top right)**. Source: Japan Aerospace Exploration Agency (JAXA) & Ministry of Economy, Trade and Industry (METI), distributed by Alaska Satellite Facility DAAC. Accessed [2025] https://search.asf.alaska.edu/ © 2026 ASF. Licensed under Creative Commons Attribution-ShareAlike 2.0 license (CC BY-SA 2.0).

2.3 Primary data collection

Primary data collection was conducted through interviews and the development of talking maps, based on the approaches described by Karnad (2022) and Gnecco et al. (2024). To ensure participants' full understanding, all interactions were conducted in the local language, and oral informed consent was obtained regarding the study's objectives, the audio recording of the sessions, and the preservation of anonymity for residents not holding public office.

To plan the intervention, a preparation stage was carried out from September 2024 to March 2025. In that stage, a site visit was conducted to identify the main characteristics of the traditional reservoir and to define the scope of the study. The intervention area falls under the jurisdiction of the Water Resources Council of the Pampas Interregional Basin, a decentralized body of the Peruvian National Water Authority (ANA, 2025). Then, an engaging phase was carried out from April to June 2025 in which the key actors to be involved in the consultation process were identified and raised awareness about the aim of the study. To emphasize the multi-participatory nature of traditional ecological knowledge, three groups associated with the technology under study were included: community actors, municipal actors, and technical actors operating within the study area (Supplementary Table S3). The technical actors were defined based on the list of non-governmental organizations (NGOs) involved in environmental and agricultural activities in the Ayacucho region (APCI, 2025), as well as the San Cristóbal de Huamanga National University, which offers academic programs related to agricultural production and rural development, and the Water Resources Council of the Pampas Interregional Basin.

The next stage of primary-data collection was carried out in two phases. The first phase included eight semi structured interviews and the creation of two participatory maps. Interviews had an average duration of 45 min conducted between July and September 2025. Each participant was interviewed separately. The participants were asked about their organization's vision for collaborative actions with local communities, their stance on the revaluation and application of ancestral knowledge for implementing climate change adaptation measures, their previous and planned interventions, and the limitations they face when operating within the study area. Interviews with non-governmental organizations (NGOs) were performed online via Google Meet, while for the other stakeholders were in person. One representative from each institution participated in the interviews. Regarding the creation of the participatory maps in August 2025, 10 participants (80% men and 20% women—aged 30–60 years) took part, including representatives and authorities from the villages of Totos, Huanupampa, and Ramón Castilla. The methodological script applied was structured around the previously defined list of cultural and provisioning ecosystem services (Supplementary Table S2). Following the introduction of the research team, the workshop objectives, and an explanation of the participatory map methodology, participants were asked to identify and draw the ES they perceived. The entire first phase was conducted in Spanish after confirming participants' full comprehension.

Based on the analysis of the gathered information of the first phase, we carried out a second phase (September 2025) to clear up the varying responses obtained and to validate the results. In this case, we developed participatory maps with community members and authorities of the Huanupampa village, who were previously identified as the direct beneficiaries of the traditional water dam under study. The participation was coordinated by the community president, resulting in an average attendance of 50 people (60% men and 40% women), all of whom were adults aged 30–60 years. The methodological script applied was similar to first phase, and the participants were randomly divided in two groups. The validation phase was conducted in both Spanish and Quechua, the native language of the area.

2.4 Ecosystem service valuation methods

To identify the ecosystem services, their associated benefits, and to estimate their economic value within the study area, the modified ecosystem services cascade model approach was applied (Supplementary Figure S1; De Groot et al., 2011). The economic valuation methods were defined based on the frameworks proposed by Toldo Moreira et al. (2024) and Brander et al. (2025), as well as the availability of primary information (Supplementary Table S4). The primary information about market prices, frequencies of consumption, dates of celebrations, participants of each activity, etc. were provided by local residents and technical actors through the participatory-maps construction and semi structured surveys in the primary data collection. The mapping of ES at the micro-basin scale was performed using QGIS version 3.42.2. All monetary values were initially recorded in the local currency (Peruvian sol) and subsequently converted to U.S. dollars at an exchange rate of US$1.00 = S/3.55.

2.4.1 Contingent valuation

This method aims to estimate the value stakeholders are willing to assume, expressed as willingness to pay (WTP) or willingness to accept (WTA), in response to changes in an environmental resource. Respondents' willingness is analyzed within a hypothetical market whose conditions closely resemble real-world scenarios (Motta, 1997). For its application to the benefits associated with species conservation, it was assumed that the contingent value would be borne by the Peruvian State, particularly through workshops aimed at fostering collective environmental awareness. Accordingly, reference information was obtained from public investment projects carried out in areas with similar characteristics within the Pampas River basin (MEF, 2022). The analysis also incorporated components related to good ecosystem management practices.

2.4.2 Market price

This method was applied to benefits with established exchange markets, where the economic value corresponds to the remuneration received by the respondents (Gandarillas et al., 2016). For grazing areas, the meat and wool markets were considered, based on local yields and market prices. Accordingly, the average values per animal unit reported by the Peruvian Ministry of Agricultural Development and Irrigation (MIDAGRI, 2025) were used. Regarding water use, both irrigation and human consumption were included. The irrigation module for the benefited irrigated areas was estimated using climatic data from CLIMWAT 2.0 and the CROPWAT 8.0 model, applied to the region's main crops. The economic compensation value for surface water used in agriculture was set at US$0.169 per 1,000 m^3 (DS No. 013-2023-MIDAGRI, 2023). Regarding water for human consumption, the total population and the number of beneficiary households (INEI, 2018a) were considered, as well as a per capita water consumption of 80 L $person^{-1}$ day^{-1} in rural areas, assuming the presence of a conventional sewerage system with flush toilets (MVCS, 2016), and incorporating the local maintenance cost of the drinking water service, according to locally collected information. Finally, for local species use such as *Nostoc sphaericum*, harvested volumes by residents and their sale prices in local markets were estimated.

2.4.3 Travel cost

The travel costs incurred by respondents to reach the study site are primarily associated with recreational activities in natural areas. Therefore, it is necessary to identify the demand population, the distance to the site of interest, and the related expenses according to local data. This method captures only the direct and indirect use values associated with visits to the study site (Motta, 1997). To estimate the costs associated with travel time to the *qocha*, which is usually on foot, the potential costs equivalent to the time invested in the activity were considered. For activities involving adult residents, local wage rates were used to estimate man-hour costs based on locally collected information. For student transportation, the state investment per student (MINEDU, 2024) and the number of instructional hours per school year (RV No. 148-2023-MINEDU, 2023) were considered. Regarding cultural activities carried out in areas surrounding the *qocha*, the frequency and duration, the participating population, the average time spent on travel and performance, and the acquisition of complementary amenities (e.g., musical bands) were identified.

3 Results

3.1 Specification of traditional dam system boundaries and conditions

The Yuyuchaqocha Lagoon covers approximately 10.2 ha (as measured from satellite imagery, May 2014). Fed by a 90.44-ha catchment area, it is surrounded by communal livestock-grazing lands comprising natural pastures and rocky outcrop areas (Figure 2A). At the lagoon's outlet, the Huanupampa community, with support from the NGO Huñuq Mayu Association for Andean Amazonian Development (AAAD–HM), constructed a dam featuring a clay core and stone walls (Figure 2B). This intervention enabled a storage capacity of approximately 142,800 m^3. The NGO provided incentives, including tools, technical assistance, and technical training sessions related to the dam's construction, operation, maintenance, and the sustainable use of stored water.

The seasonality of rainfall, evaporation, and infiltration processes determines variations in water levels, influencing the proliferation of macroalgae collected and consumed by local residents (e.g., *Nostoc sphaericum*), the availability of flooded grazing areas, the development of macrophytes, and the presence of wildlife [e.g., bird species such as the Puna Duck (*Spatula puna*), Huachua (*Oressochen melanopterus*), and Yanahuico (*Plegadis ridgwayi*); and mammals such as the Taruca (*Hippocamelus antisensis*) and Vicuña (*Vicugna vicugna*)], as shown in Figure 2C. Local livestock, comprising cattle, sheep, and South American camelids (i.e., alpacas and llamas), as well as wildlife, graze on the vegetation of the seasonal wetlands and use the stored water for drinking. The macrophyte "islands" in the *qocha's* central areas serve as nesting and feeding sites for wild birds. The permeability of the dam and the reservoir bottom allows infiltration and downstream water outflow; therefore, water catchments were constructed for human consumption (Figures 2D, E) and irrigation purposes (Figure 2F).

In April 2025, the Huanupampa community (Figure 2E) organized and revived the celebration of the *pagapu*, inspired by the continued observance of this ritual among the inhabitants of the village of Totos. The ceremony was held as an expression of gratitude to local deities, such as *Apu* (the spirit of the mountains) and *Mama Cocha* (the spirit of the lagoon), for maintaining the water flow into the *qocha* and to petition for sustained water levels during the dry season. The ritual involved the offering of symbolic items such as coca leaves, fruits, tubers, liquor, bread, sweets, and tobacco, presented at a rocky site regarded as sacred within the local worldview (Figure 2C). Following the ritual, the community gathered in a festive atmosphere, complete with traditional dances and a performance by a local orchestra. Municipal authorities from the Totos district were invited to participate, and the event was scheduled to take place annually in April.

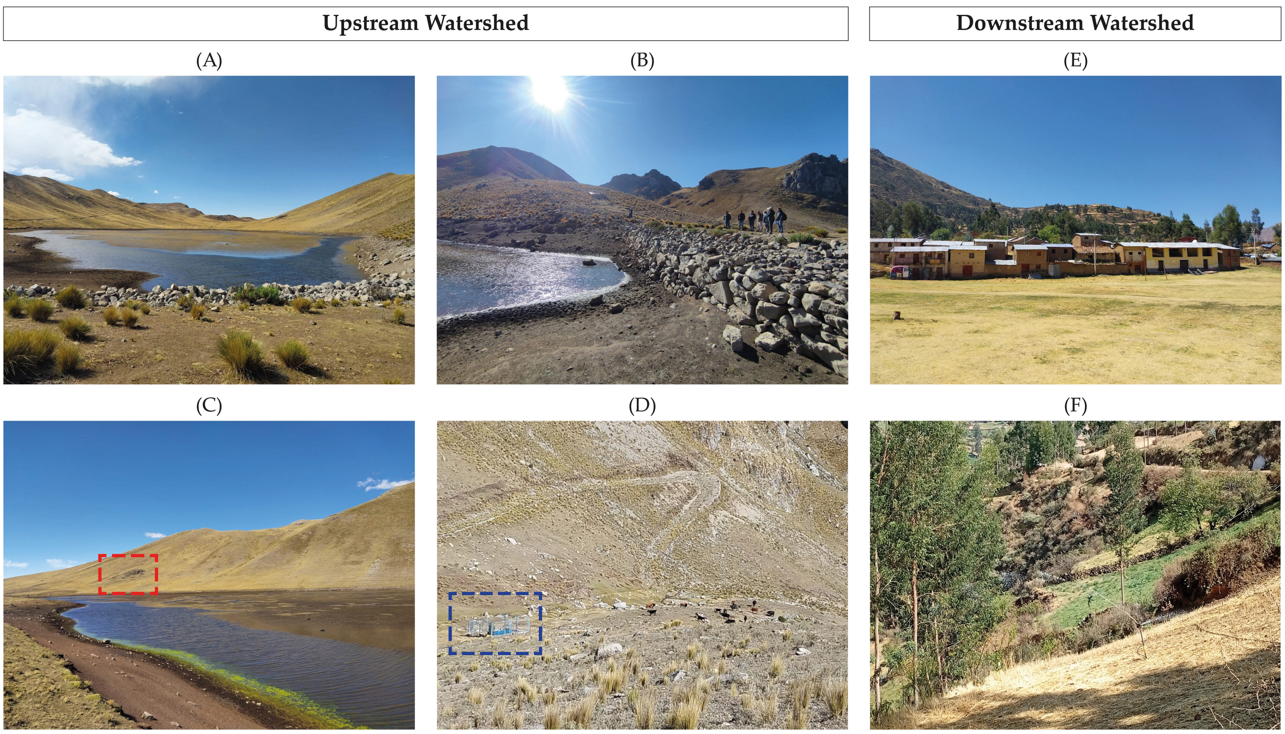

FIGURE 2
Views of the study area between August and September: **(A)** Yuyuchaqocha viewed from the traditional water dam; **(B)** inner face view of the dam; **(C)** middle section view facing the qocha inlet, showing the site of religious importance for the Yakur Fiesta (red) and the presence of algae along the shores; **(D)** water catchment view for human consumption downstream of the dam (blue) and grazing areas surrounding the *qocha*; **(E)** Huanupampa village; and **(F)** irrigation areas of the Huanupampa community.

3.2 Identification and mapping of ecosystem services

Ten ecosystem services associated with the *qocha* were identified by the beneficiary population (Figure 3). Of these, five were provisioning ES, three related to biomass, and two to water; and five were classified as cultural services, linked to community experience and physical interaction (one), representativeness and intellectual enrichment (two), symbolism and spirituality (one), and conservation (one). The identified ES were primarily associated with the biophysical (nine) and geophysical (one) characteristics of Hydrographic Unit 6 (Yuyuchaqocha micro-basin), mainly concentrated along the *qocha's* shoreline. Other hydrographic units were involved in supporting ecosystem processes or benefiting from the ES through their biomes.

3.3 Perceived ecosystem benefits

Table 1 presents a detailed description of the 10 ecosystem benefits perceived by the local population, their quantification methods, and the economic and environmental valuation methods. Based on that, Table 2 presents the estimated values for these ecosystem benefits perceived. Their use is primarily concentrated in the community of Huanupampa, except for the benefits associated with recreational visits (3.1.1.1) and educational visits (3.2.1.1), as shown in Figure 4. Five benefits were identified as seasonal, indicating dependence on wet and dry periods, as well as the timing of festive celebrations.

3.4 Economic value of ecosystem services

A total monetary value of \$10,104.97 was estimated for the ES perceived by the local population in relation to Yuyuchaqocha, equivalent to $\$990.68 \cdot ha^{-1}$ of the *qocha* (Table 3). The detailed calculations are provided in Supplementary Table S5. Noteworthy findings include the active participation of upper secondary school students in educational visits to the *qocha*, the strong communal organization responsible for its maintenance using traditional methods, and the heightened environmental awareness within the Huanupampa community regarding the conservation of ecosystems influenced by the *qocha*. Water use for irrigation extends to agricultural areas near the village of Huanupampa

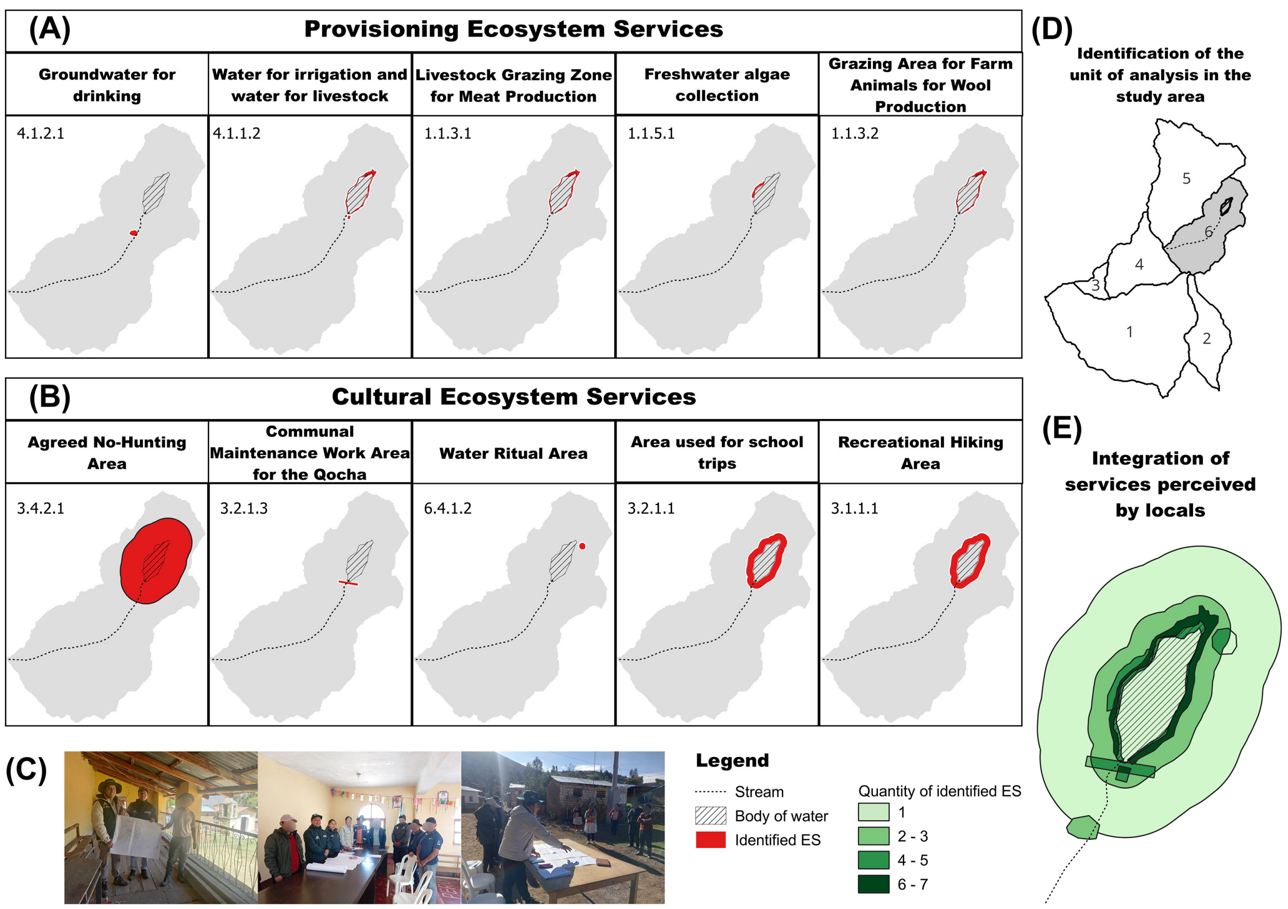

FIGURE 3
Mapping of the identified ecosystem services. **(A)** Provisioning Ecosystem Services. **(B)** Cultural Ecosystem Services. **(C)** Photographs from the participatory process (faces of non-author participants have been blurred for privacy). **(D)** Identification of the unit of analysis in the study area. **(E)** Integration of ecosystem services perceived by locals.

TABLE 1 Detailed description of the identified environmental benefits, their quantification methods, and the economic and environmental valuation methods.

Code	Ecosystem services	Identification	Benefit	Quantification of the benefit	Method for economic and environmental valuation
1.1.3.1	Animals reared for nutritional purposes	Livestock (cattle and South American camelids), raised for meat production, feed on plants growing along the shores and in the peatland throughout the year, rotating among different sites near the *qocha*.	Forage for livestock raised for meat (cattle and South American camelids) and milk production (cattle); see Figure 2A.	Average annual meat production (kg) from grazing in the area.	Market price
1.1.3.2	Fibers and other materials from reared animals for direct use or processing (excluding genetic materials)	Livestock (South American camelids) raised for wool production feed on plants growing along the shores and in the peatland throughout the year.	Forage for livestock raised for wool production; see Figure 2A.	Average annual wool production (kg) from grazing in the area.	Market price
1.1.5.1	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition	The aquatic plant *lluyo* grows along the shores and is consumed by local inhabitants during the flood season.	Edible algae (*lluyo*) consumed by local inhabitants, see Figure 2C.	Kilograms of *lluyo* collected by local inhabitants.	Market price
3.1.1.1	Elements of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions	Local inhabitants visit and walk around the *qocha* with their families during both dry and flood periods.	Recreational walks from nearby villages to the *qocha*, see Figures 2A, C.	Hours spent walking by local families in the area.	Travel cost
3.2.1.1	Elements of living systems that enable scientific investigation or the creation of traditional ecological knowledge, including the importance of between and within species genetic diversity	Students from Totos school visit the *qocha* to learn about water management and its importance for wildlife.	School excursion walks to observe the qocha, see Figures 2A, C.	Class hours devoted to the school excursion.	Travel cost
3.2.1.3	Elements of living systems that are resonant in terms of culture or heritage	The *qocha* is considered important by the Huanupampa community, which carries out annual communal work (*faenas*) for its conservation (see the dam maintenance area in Figure 2B).	Communal organization for maintenance using traditional methods, see Figure 2B.	Number of work hours contributed by local residents for *qocha* maintenance.	Travel cost
3.4.2.1	Elements or features of living systems whose contemporary existence or conservation is important to people, including the importance of between and within species genetic diversity.	The inhabitants of Huanupampa have stopped hunting wild animals (birds and mammals) in the *qocha*, as they consider them essential for preserving nature.	Conservation of species inhabiting the area, see Figures 2A, C.	State investment in environmental awareness generation.	Contingent valuation
4.1.1.2	Surface water used as a material (non-drinking purposes)	The inhabitants of Huanupampa use qocha water for livestock drinking and for irrigating their croplands.	Irrigation water and livestock drinking water, see Figure 2F.	Cubic meters paid to the State as an economic retribution for the irrigated area.	Market price
4.1.2.1	Ground (and subsurface) water for drinking	The inhabitants of Huanupampa believe that the formation of the *qocha* led to the emergence of springs suitable for drinking.	Water for human consumption, see Figures 2D, E.	Monthly payment for water consumption.	Market price
6.4.1.2	Elements of geophysical systems that have sacred or religious meaning	The inhabitants of Huanupampa make a symbolic payment to the water as an act of gratitude.	Water payment ceremony at a specific rocky area on the shore, see Figure 2C.	Hours dedicated to participation in the ceremony.	Travel cost

(108.24 ha) and along the Puncoruni stream (2.54 ha), with potatoes and maize being the main crops produced. In terms of domestic water consumption, a monthly fee of $0.28 per household was reported for service maintenance.

The ES with the highest value corresponded to the elements of living systems that are resonant in terms of culture or heritage (3.2.1.3), living system elements whose contemporary existence or conservation is vital to people (3.4.2.1), and geophysical system elements with sacred or religious significance (6.4.2.1), as shown in Figure 5. Thus, the highest environmental economic value of the identified benefits was concentrated on the Huanupampa village.

TABLE 2 Ecosystem services perceived by local residents.

Code	Benefit	Value of benefit
1.1.3.1	Feed for livestock raised for meat (cattle and camelids) and milk (cattle) production.	26.93 kg Llama's meat; 25.6 kg Alpaca's meat; 12.18 kg Sheep's meat; 128.61 kg Cow's meat
1.1.3.2	Feed for livestock raised for wool production.	1.61 kg Llama's wool; 1.74 kg Alpaca's wool; 1.34 kg Sheep's wool
1.1.5.1	Edible algae for local residents.	60 kg of yuyo
3.1.1.1	Recreational walks from nearby villages to the *qocha*.	725 h invested
3.2.1.1	School excursion walks to observe the *qocha*.	330 teaching hours
3.2.1.3	Communal organization for its maintenance using traditional methods.	1,280 working hours
3.4.2.1	Conservation of the species inhabiting the area.	289 aware people
4.1.1.2	Irrigation water and water for livestock.	607,783 m^3 of irrigation water
4.1.2.1	Water for human consumption.	8,438.8 m^3 of drinking water
6.4.1.2	Water payment ceremony held on a specific rocky area along the shore.	640 h invested

TABLE 3 Selection of benefit quantification variables and environmental economic valuation.

Code	Benefit	Environmental economic valuation
1.1.3.1	Feed for livestock raised for meat (cattle and camelids) and milk (cattle) production.	$ 135.19
1.1.3.2	Feed for livestock raised for wool production.	$ 22.04
1.1.5.1	Edible algae for local residents.	$ 67.61
3.1.1.1	Recreational walks from nearby villages to the *qocha*.	$ 1,531.69
3.2.1.1	School excursion walks to observe the *qocha*.	$ 533.92
3.2.1.3	Communal organization for its maintenance using traditional methods.	$ 2,704.23
3.4.2.1	Conservation of the species inhabiting the area.	$ 2,933.21
4.1.1.2	Irrigation water and water for livestock.	$ 102.72
4.1.2.1	Water for human consumption.	$ 327.89
6.4.1.2	Water payment ceremony held on a specific rocky area along the shore.	$ 1,746.48

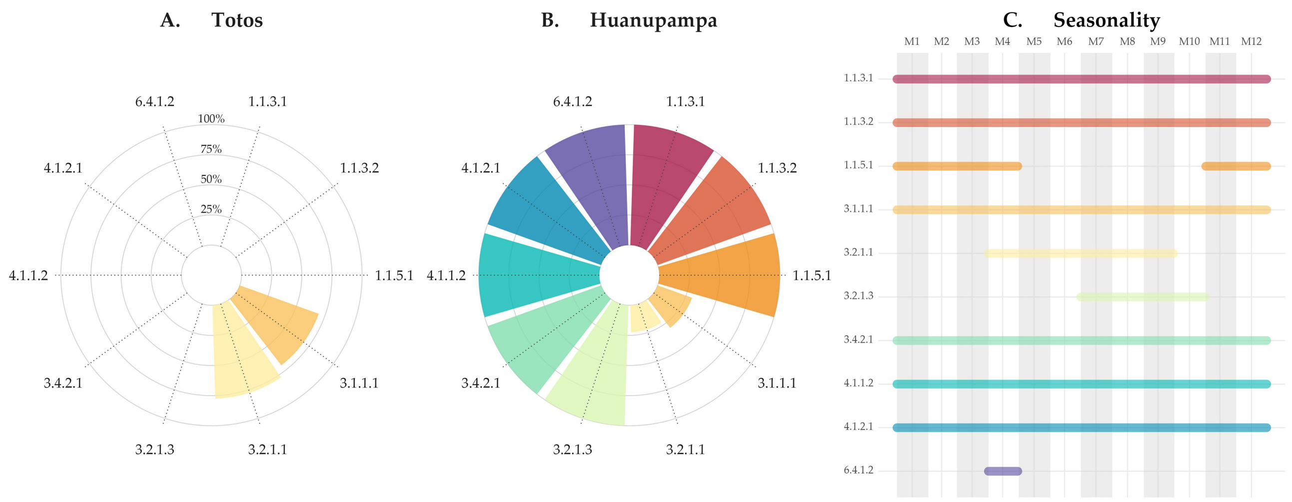

FIGURE 4
Percentage of perceived ecosystem benefits received by Totos village **(A)** and Huanupampa village **(B)**. Seasonality of the perceived benefits across the months of the year **(C)** (M1: January—M12: December).

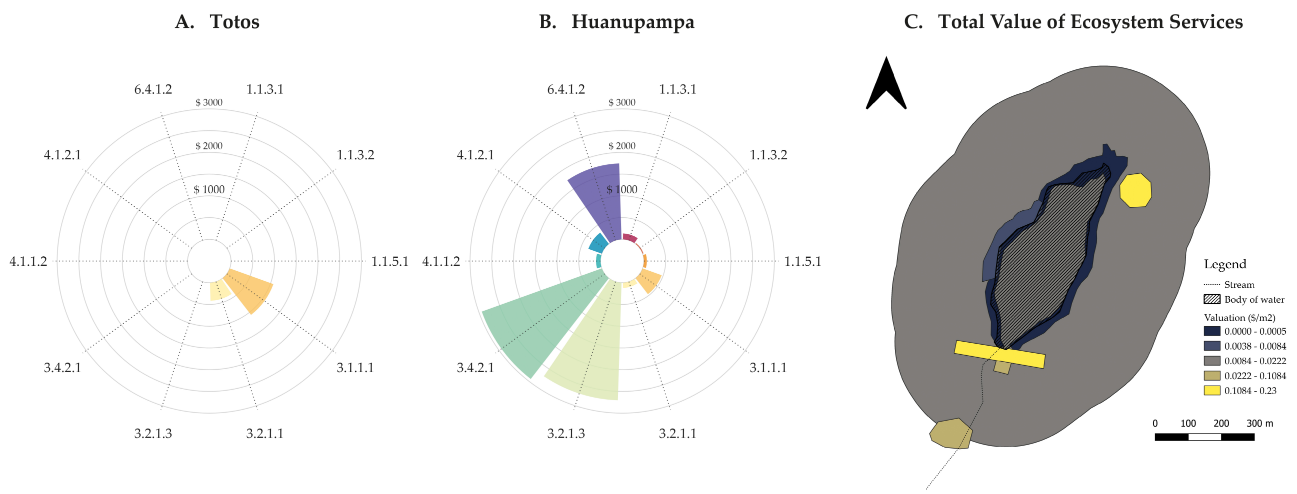

FIGURE 5
Environmental economic value of ecosystem services distributed by Totos village **(A)** and Huanupampa village **(B)**. Total value of ecosystem services **(C)**.

4 Discussion

4.1 Ecosystem services of the mountain water socio-ecosystem

Local inhabitants have perceived 10 ecosystem benefits associated with the traditional water dam implemented in Yuyuchaqocha. Previous research on anthropogenically influenced water ecosystems has reported similar categories of perceived benefits (Gandarillas et al., 2016; Madrigal-Martínez et al., 2023). Among these, freshwater provision services stand out as some of the most significant and easily recognized in mountain ecosystems (García-Llorente et al., 2020). In the socio-ecosystem under study, where the implementation of the traditional dam aimed to increase water availability for use, the benefits perceived by the population are strongly related to water management practices. Consistent with this, cultural benefits such as the *pagapu* ceremony are deeply intertwined with both water resources and the surrounding ecosystem (Esquivel, 2025). Furthermore, freshwater provision ES has been extended to areas near villages for use, where the adoption of technologies such as pressurized irrigation has reduced dependence on climatic variability (Hermans, 2006).

The perceived ES were valued at $990.68 per hectare of *qocha*, amounting to a total of $10,104.97 per year. Similarly, Baba and Hack (2019) estimated $1,895.04·ha^{-1} (€1,633·ha^{-1}) for nine ES identified by local communities in the agro-pastoral system of the Sakabansien dam in Benin (West Africa). Both reservoirs, classified as small dams (Yuyuchaqocha: 10.2 ha; Skabansi: 3.13 ha), are situated in regions affected by evident poverty conditions (The United Nations Development Programme, 2025). However, the characteristics of the influence area of the water body, the dam, and its flooded zone, as well as the socio-economic and productive features of the population, account for variations in value. In the case of Yuyuchaqocha, the influence area hosts low-density flora and fauna that are mainly dependent on rainfall. No productive activities, such as aquaculture, occur within the flooded area, and local production systems are primarily oriented toward self-consumption patterns. Furthermore, the low costs associated with using these benefits by low-income populations reduce the monetary value transferred to the service.

Among the ES previously reported for similar biomes (Costanza et al., 2014; De Groot et al., 2020; Madrigal-Martínez et al., 2022; Xie et al., 2017; Yaping, 1998) but not perceived by the population under study, aesthetic appreciation (6.2.1.4 CICES) and artistic inspiration (6.3.1.1 CICES) stand out. The perception of ES associated with recreation suggests an understanding of the beauty of the landscape. However, their absence among the services recognized by the population may be related to the *qocha's* distance from the villages (i.e., its remoteness and altitudinal difference limit its integration as part of the local landscape). Conversely, the need to hike to visit the site enables the use of the biome's scenic beauty as an ES linked to family recreation activity (3.1.1.1 CICES). Regarding artistic inspiration as an ES, the difficult access (approximately 4 h of travel) for painters and artisans to the *qocha* from the city of Huamanga (home to an art school), along with the lack of an established artistic tradition in the district (i.e., a mainly agricultural population), limits its recognition.

4.2 Local ecological knowledge as a driver of development

The inhabitants are aware of the intrinsic relationship between conserving the *qocha* and maintaining the benefits it provides. The presence of cultural ecosystem services related to the preservation and mysticism of the biome, together with the absence of ecosystem services linked to the hunting of wild animals, reflects this collective awareness. In this way, rural communities maintain sustainable management practices of their surroundings, even in areas with high levels of monetary poverty (≈50%) (INEI, 2018b,a). This is particularly relevant in rural communities with subsistence economies (Barrientos-Fuentes and Torrico-Albino, 2014), which are subject to the relative aging of their population (i.e., migration of younger inhabitants; Pinilla et al., 2008), where processes of economic valuation and the transmission of ancestral ecological knowledge may be diminished (Brandt et al., 2013).

Of the 10 ES identified in the *qocha*, this study showed that the locals perceive one ES linked to education (CICES 3.2.1.1), particularly benefiting children living in the villages of Huanupampa and Totos. The development of curiosity, appreciation, and care for nature depends on both the duration and degree of exposure to the environment (Schultz, 2000, 2002). In this regard, fostering children's and youth's immersion in nature, along with an understanding of its value and opportunities for direct and indirect interaction through recreation, helps cultivate early environmental awareness of protection (Chawla, 2006; Kellert, 2002; Wells, 2000). Thus, the presence of this service promotes the sustainability of the ES associated with species conservation in the area (CICES 3.4.2.1) by enabling the education of future generations in the care of nature. Complementarily, it fosters the understanding of the controlled use of species such as *Nostoc sphaericum*, which provides a valuable nutritional contribution (Méndez-Ancca et al., 2023) and is promoted by the state (Law No. 31825, 2023.

One of the main strengths of this research was the careful involvement of local stakeholders as a primary source of information, which increased the reliability of the results obtained and significantly reduced the likelihood of information inference. This approach has been employed by authors such as Evangelista et al. (2024) and Madrigal-Martínez et al. (2023) to identify local ecological knowledge (LEK), primarily related to the adoption of customs and practices inherent to rural environments. In our case, this approach enabled a comprehensive analysis of the ES associated with a *qocha*, an ancestral agricultural technology for climate change adaptation (Carrasco-Torrontegui et al., 2021) and conceived as a nature-based solution for sustainable water management (Morante-Carballo et al., 2024).

4.3 Andean worldview and the importance of ecosystem services

The environmental economic value of cultural ES can surpass that of provisioning services in rural mountain socio-ecosystems. In this context, involvement at the educational level, the continuity of communal work, and the persistence of cultural celebrations evidence that the need to transmit and preserve traditional knowledge is a concept well assimilated by the community. However, limited articulation with neighboring communities and local government bodies was documented. This represents a threat to the consolidation of strong governance and constrains the strengthening of the community's capacity for action (e.g., the implementation of complementary actions that reinforce non-perceived ecosystem services). Therefore, developing integrated policies aimed at strengthening social capital could enhance the implementation of resilient and equitable solutions for water security (Muñoz et al., 2025). Additionally, internal disconnection was observed, mainly associated with historical social conflicts and contrasting religious tendencies. On one hand, the armed conflict experienced in Peru during the late 20th century fostered intergenerational fragmentation through migratory processes (Ciurlizza Contreras et al., 2014), diminishing the active participation of younger generations in communal work and restricting their involvement to festive rituals and celebrations. On the other hand, the incompatibility between the religious beliefs of some parts of the population and traditional spiritual practices can limit participation and, consequently, the transmission of the local worldview.

This disconnection has opened the way for seeking structural improvements to the traditional water dam, maintaining an understanding of the benefits associated with the dam's presence, but becoming detached from the potential ecosystem benefits related to traditional practices (e.g., self-management capacity for maintenance, structural flexibility). This trend aligns with the dependence of rural mountain communities on provisioning ecosystem services (Madrigal-Martínez et al., 2023), the ease of perceiving such services in water ecosystems (Grizzetti et al., 2016), and the increasing pressures on water availability (CENEPRED, 2025). Hence, there is a pressing need to strengthen the technical capacities of mountain communities by merging traditional and modern technologies. This is particularly critical in the Andean context, where water resource management relies on integrated local environmental knowledge shaped by a worldview that balances the ecosystem and the community (Oshun et al., 2021).

4.4 Limitations

We identified several limitations that restricted our complete understanding of all the ES associated with the *qocha* as part of the LEK related to water management. First, the analysis was limited only to provisioning and cultural services. Their selection aimed to document the benefits directly recognized and desired by the community, as opposed to the indirect benefits essential for ecological subsistence, which are associated with regulating and supporting services (in the CICES classification, both categories are considered regulating services; Jones and Chikwama, 2021; Small et al., 2017). In this context, it was found that the low educational level of the residents (approximately 34.7% with completed secondary education) and the widespread use of Quechua as a mother tongue (approximately 92%; INEI, 2018a) could represent a communication barrier for conducting the workshops. To address this, a methodological script covering the key topics was prepared, and the support of a Quechua-speaking professional was included to facilitate open communication and bidirectional understanding. It is worth noting that the collective workshops fostered feedback among participants, enabling consensus-building and reducing subjectivity in the information provided. In this process, the use of talking maps facilitated the understanding of territorial dynamics (Evangelista et al., 2024), allowing for the synthesis and environmental economic valuation of ES. By emphasizing the use of primary data collection (i.e., interviews, workshops, and field visits), the study intentionally avoided the application of the benefit transfer method.

This study represents an initial effort to systematize and valorize the ecosystem services provided by a *qocha*, understood as local ecological knowledge for water management in the Andean region of Peru. In this regard, it is necessary to continue developing collaborative research that addresses this type of analysis in diverse contexts. Particular attention should be given to the study of cultural ES, due to the existing scientific information gap, and to the assessment of regulating ES through the integration of scientific knowledge (i.e., *in-situ* monitoring) and local knowledge (i.e., stakeholder perception and social value). This approach could facilitate the syncretism between traditional and modern technologies to enhance the impact of interventions. In addition, disseminating the results at various organizational levels (e.g., municipal and communal authorities, local communities, management actors, etc) would foster the integration of the local worldview into management plans, contributing to their legitimacy and sustainability, and promoting the involvement of institutions engaged in the intervention of mountain water socio-ecosystems.

5 Conclusion

This research constitutes the first study to develop an environmental economic valuation of local ecological knowledge (ancestral agricultural technology) related to water security in a high-Andean environment. Our findings indicate that the ecosystem services perceived by the local population amount to 10, with a total annual economic value of USD 10,104.97. This local ecological knowledge (*qocha*) has been demonstrated to provide multiple benefits, which the local community has quantified and monetized, considering its conservation necessary for achieving the sustainable development of their territory. Furthermore, future studies should focus on a holistic analysis of local ecological knowledge and its associated ecosystem services, taking into account the particular anthropogenic and environmental characteristics of each context.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

This study employed questionnaires and participatory mapping involving adult participants from high-Andean communities. The research was conducted under the technical supervision of the National Institute of Agricultural Innovation of Peru (INIA), which granted an institutional exemption from formal ethics committee approval (CARTA 00014-2026-MIDAGRI-INIA/DSEA). All participants provided verbal informed consent prior to participation, ensuring respect for local cultural identity and oral traditions. The study guaranteed participant anonymity and data protection in accordance with Peruvian Law No. 29733 and the principles of the Declaration of Helsinki.

Author contributions

RF-M: Writing – original draft, Methodology, Investigation, Conceptualization. RP-C: Methodology, Writing – original draft, Investigation, Conceptualization. TC-A: Writing – original draft, Investigation. SM-M: Methodology, Conceptualization, Writing – review & editing, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1738736/full#supplementary-material

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