Geoarchaeology

WILEY

Geoarchaeology An International Journal

RESEARCH ARTICLE OPEN ACCESS

I'll Be Dammed: Efficiency and Cost-Analysis of a Rehabilitated Prehispanic Dam in the Andes

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Received: 13 April 2026 | **Revised:** 12 June 2026 | **Accepted:** 16 June 2026

Scientific Editor: Dr. Marta Lorenzon

Funding: Rotary Foundation, Grant/Award Number: GG2350435; Gerda Henkel Foundation, Grant/Award Number: AZ 25/BE/23; Harte Family Fund; Mountain Institute- Peru

Keywords: ancient technology | climate change adaptation | hydraulic archaeology | traditional ecological knowledge | water security

ABSTRACT

Within archaeology there is a growing shift away from the purely aesthetic towards making the past relevant to present and future needs and demands. The *Past Water Futures* project charts the impact of ancient dam rehabilitation on climate change-induced water scarcity in the North Central Andes. The rehabilitation of late period (AD 750–1532) Prehispanic dams is a novel approach to assuage increasing water shortage among the rural communities of the Andean highlands. Nevertheless, until now, we lacked data on the real-time impact of these modern conservation and rehabilitation projects. Here we present preliminary results, including volume capacity, potential demand, hydrological and hydraulic analysis and a reservoir filling log of the Prehispanic Weetacocha 'Lake of Flowers' Dam, which was rehabilitated in late 2024. Weetacocha belongs to the rural community of Racratumanka, District of Pamparomás, Province of Huaylas, Ancash Region, Peru. Importantly, we analyse the cost per m^3 unit of water recovered through the rehabilitation of the Weetacocha Dam, proving that the restoration of water dams can provide a viable, cost-effective, community-led, sustainable alternative to modern micro-dam construction in the Central Andes and potentially further afield.

1 | Introduction

There has been a longstanding interest in the archaeology of water and hydraulic management in the Andes (e.g., Kosok 1965; Lane 2014; Steward 1955), an awareness that has persisted up to the present-day (e.g., Caramanica et al. 2020; Chacaltana-Cortez and Ventura 2024; Fairley 2003; Farrington 1980; Grana et al. 2024; Lane 2017; Ortloff 2010; Quesada 2006; Zuccarelli Freire et al. 2021, among many others). Of even greater import has been the move since the 1970s towards rehabilitation of ancient hydraulic systems in the region. Initially pioneered by the likes of Ann Kendall (2005) and Clark Erickson (2006), this has blossomed more recently into NGO and state-driven programmes of rehabilitation including the *waru-waru* (raised field systems) of the Titicaca Basin (PIWA 1994; World Monument Fund 2025), to the ubiquitous terraces (Aguirre Morales Prouvé 2024; Willems et al. 2021), as well as the *amunas* (infiltration canals) and canals (Hoefsloot et al. 2024; Liang 2023), among others along the coast such as the Nazca *puquios* (Olmo 2023).

In this respect, modern climate change is driving curiosity away from the aesthetic value of hydraulic heritage towards its potential in addressing modern problems such as decreased rainfall and agricultural yields, compounded by rural out-migration. Archaeology and heritage management are increasingly addressing these issues in the Andes, especially its rural hinterland, and worldwide (Kaptijn 2018). A key factor to successful rehabilitation projects is the all-important issue of community engagement, in the knowledge that community governance is dynamic and priorities can change through time.

The *Past Water Futures* project is one such community-centred rehabilitation project dedicated to ameliorating water scarcity through the restoration of Prehispanic dams in the Central Andes (Lane et al. 2025b. Here we present the rehabilitation of the Weetacocha Dam located in the District of Pamparomás, Province of Huaylas, Ancash Region (Figure 1). This rehabilitation project proposed the preservation and restoration of the dam's stone wall to reestablish its capacity to hold water, providing a sustainable storage source of this critical resource in the upper reaches of the Cordillera Negra mountain range for the target community of Racratumanka and potentially ancillary communities (population of 600+ people). The project has been a success (Berrocal Flores and Sialer Carrillo 2024; Lane et al. 2025b), with the water recovered serving to supply both Racratumanka and, periodically, the neighbouring community of Catorce Incas. This dam rehabilitation also provided us an opportunity to identify elements that permitted research into the chronology, construction and operation of the dam during the Prehispanic period.

Further research undertaken together with the Peruvian National Institute of Agricultural Innovation (INIA) provided critical data on a variety of hydraulic aspects pertaining to the present-day functioning of the rehabilitated dam itself, including hydrological supply and demand, a maximum flood design flow, and a reservoir-dam filling log. Additionally, we carried out a cost per m^3 of the dam compared against similar-sized modern grey infrastructure micro-dam and reservoir projects in the region. Throughout, our results demonstrated that ancient micro-dam rehabilitation is an economical and sustainable alternative to modern micro-dam construction.

Finally, work on the Weetacocha Dam was undertaken in close collaboration with the community of Racratumanka. This involved a series of workshops culminating in an intercommunity workshop during the official inauguration of the Weetacocha Dam (August 2025) involving the community of Racratumanka, other invited communities and NGO's. This also provided an important opportunity to assess the immediate impact of the dam's rehabilitation as well as the potential challenges and opportunities afforded by the rehabilitation of Prehispanic micro-dams in the Andes. The results of these endeavours are presented below.

1.1 | Archaeological, Historical and Present-Day Context of Dam Building in the Andes

Although we are yet unsure when the Weetacocha Dam was built, a single Middle Horizon (AD 600–1000) ceramic fragment found inside the core of the dam wall suggests a potential

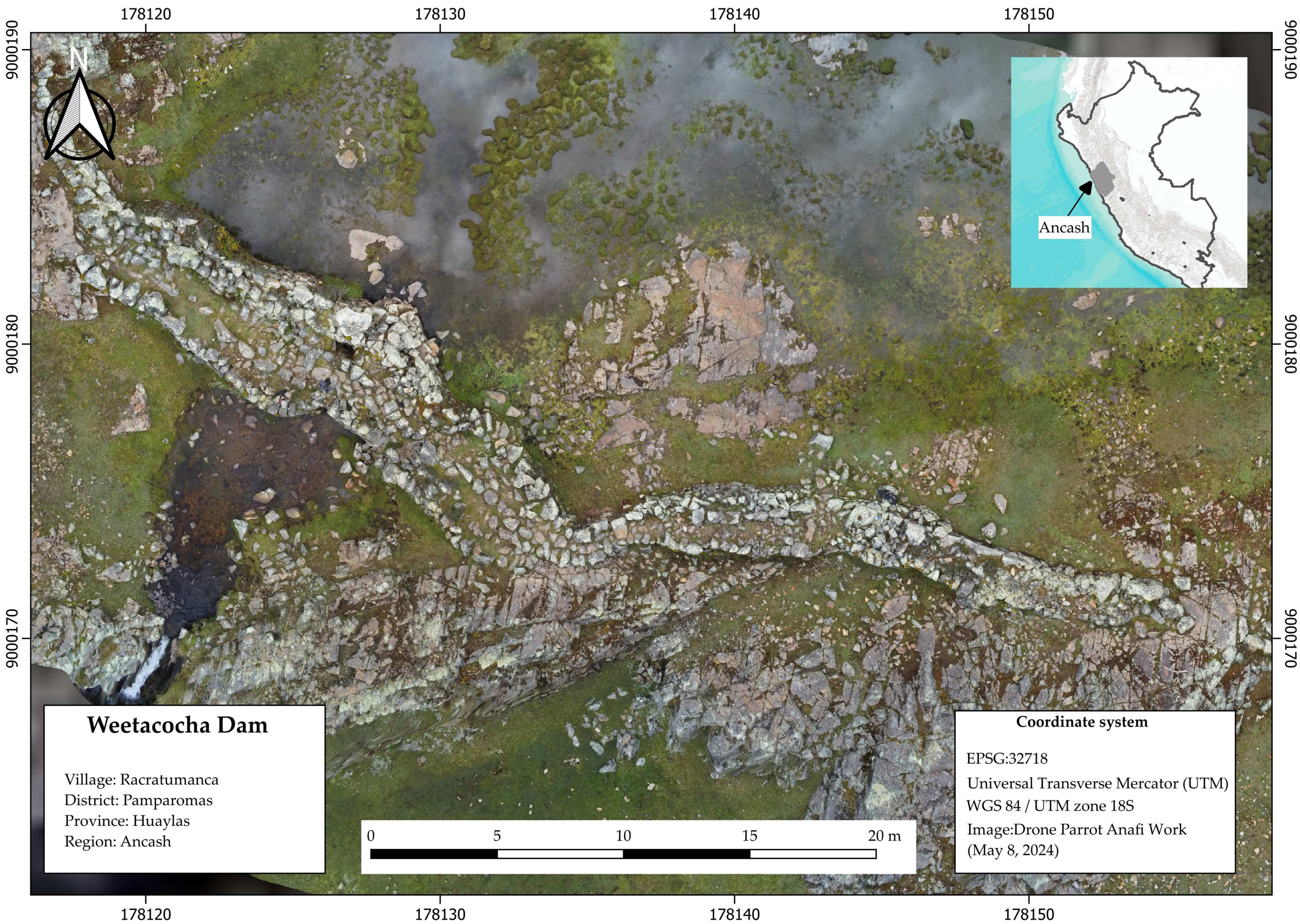

FIGURE 1 | Map showing location of Weetacocha Dam with image of the dam in its pre-restoration state.

terminus post quem for the structure's construction. If this is indeed the case, then it is possible that the original construction of the dam might have been due to climate stress in the Andes associated with the Medieval Climate Anomaly (MCA). In South America, this event likely commenced during the eighth to ninth century AD and lasted until the mid-fourteenth century (Lüning et al. 2019). It is possible that this climate event, bringing with it higher temperatures and less general precipitation in the Andean highlands, led to the disappearance of most of the remaining glacier cover in the Cordillera Negra. The gradual disappearance of glacier cover and associated meltwater could have been the necessary trigger for a precipitate investment in hydraulic technology (Williams 2002) during this period. Construction continued intensifying during the Late Intermediate Period (AD 1000–1400) and Late Horizon (AD 1400–1532).

This increased investment in hydraulic technology led to a rise in population (Arkush et al. 2024; Kramer and Boone 2002) associated with agro-pastoralist intensification and specialisation (Grant and Lane 2018). A higher population, in turn, likely exacerbated control over resources in many Andean areas (Arkush 2008; Covey 2008). While Prehispanic hydraulic engineering works demonstrate the importance given to agro-pastoralist economic development (Ertsen and van der Spek 2009), it also provides insights into the political structure of groups and polities at the time (e.g., Lane 2009; Netherly 1984; Steward 1955). All the while, not forgetting the religious and sacred dimensions linked to water among Prehispanic cultures (Glowacki and Malpass 2003; Gose 1993; Lane et al. 2018).

Although the expansion of the Inca Empire ushered in some sort of *pax incaica* (*sensu* Métraux 1969), which allowed local populations to prosper, it is possible that the over-exploitation of highland resources might have eventually triggered a collapse, with evidence for a certain amount of over-pasturing and deforestation present (Denevan 1992; Schiferl et al. 2023). Nevertheless, of much greater magnitude was the impact of European colonisation post-1532, seeing off in many regions indigenous adaptations to the Andes (Frogley et al. 2025; Marsh and Rademaker 2025). Given the catastrophic impact of European diseases on the indigenous population (Cook 1998) known as the 'Great Dying', it is no wonder that land and the technologies sustaining their use were also abandoned wholesale (Koch et al. 2019). It is against this background that most of the Prehispanic Andean micro-dams were themselves abandoned.

In the area where the Weetacocha Dam is located, this situation of neglect and abject destitution persisted well into the nineteenth (Raimondi 1874, 305) and through to the twentieth century (Moreno Rodríguez 1966). Starting in the 1970s, there was across the Andes a progressive move towards building water dams, even though the very first of these date to the 1870s (Alvarado Ancieta 2007, 49). Since the 1970s, the number of dams and micro-dams in the Peruvian Andes has increased apace, with over 750 registered modern dams in place by 2015 (World Bank 2017). Many more have been built since then as Peru adapts to climate change-induced water scarcity (Ministerio del Ambiente 2021).

Indeed, at present, the Andes and Peru are suffering ever greater hydric stress, exacerbated by changes in climate patterns (Bocinsky and Kohler 2014; Koren et al. 2021; Vesco et al. 2021; Zhang et al. 2007), including population shifts and an unprecedented demographic growth, particularly on the coast (Kahl 2006; McCool et al. 2022; Reinhard and Vaughn 2008; Weitzel and Codding 2022). Coastal pressure for scarce water resources is one of the prime reasons behind dam construction in the Andean highlands, as water is siphoned off to the coast, where hydraulic engineering storage projects have historically served to guarantee water resources for use over time (especially during the Andean dry season). Water destined for the coast is principally focused on mono-agricultural production (Carlstein 1982). This has been augmented over time by ever-increasing household and industrial demands (OECD 2021).

At present, water scarcity significantly hinders the sustainable development of communities in arid and semi-arid areas (Shams et al. 2025). Additionally, more than 90% of agricultural water use is consumptive, accounting for 70% of total global withdrawals (Salman 2016). In response to this, rainwater harvesting (RWH) is a critical strategy for water resource conservation, especially in mountainous areas experiencing increased hydric stress (Asmoay et al. 2025; Hamdan and Sawires 2013; Ibrahim et al. 2023; Moon et al. 2012; Napoli et al. 2014; Sazakli et al. 2007; Vohland and Barry 2009). RWH consists of the collection, storage and management of water from precipitation for later agricultural and population use activities (Kadam et al. 2012; Napoli et al. 2014).

RWH provides ecosystem services (ES) such as reduction of surface runoff, prevention of soil erosion, increased soil moisture retention, and mitigation of flooding in the lower areas of the hydrographic unit (Ammar et al. 2016; Singh et al. 2009). For RWH to be effective within an area, it must be evaluated, planned, and systematised, with an emphasis on watersheds with variable and uncertain rainfall (Dhakate et al. 2013; Rockstrom 2000). The rehabilitation of the Prehispanic Weetacocha micro-dam fits these criteria.

1.2 | Rehabilitation Strategy of Prehispanic Micro-Dams

As mentioned previously, the rehabilitation of ancient hydraulic infrastructure has a long pedigree in Peru (e.g., Erickson 1998; Herrera 2019). In this regard, the move towards rehabilitating Prehispanic micro-dams in the Andes, specifically in the Cordillera Negra of the Ancash Region, is based on over 25 years of archaeological research (e.g., Lane 2006, 2017, 2021), and social engagement with communities in the area. Additionally, a recent digital survey of the region has revealed the immense scale of Prehispanic micro-dam construction, with over 200 structures detected in the Cordillera Negra alone (Pey et al. 2025). This represents valuable *installed capacity* that can be recovered for use by modern-day rural communities in the region.

The *Past Water Futures* project has successfully rehabilitated two Prehispanic micro-dams in the Pamparomás District of the Cordillera Negra (Lane et al. 2025a; 2025b), with a third and fourth dam in the works. All these interventions are rooted in a participatory action research (PAR) approach involving the collection of quantitative and qualitative data through secondary sources, workshops, focus groups, and discussions with local communities, provincial authorities, and national agencies. The project directly tackles water insecurity among the rural communities of the Andes.

Indigenous communities require immediate solutions to persistent problems. None more so than reliable access to water. The rehabilitation of Prehispanic micro-dams confronts this problem head-on by providing a community-rooted solution to water accessibility while preserving this valuable tangible and associated intangible heritage for generations to come. Community buy-in on the project is therefore key. Our role then is to provide research and conservation expertise towards rehabilitation and thereby bring this scarce resource to the point of geographical need. In no way do we dictate subsequent uses of this water. In this regard, the *recovered ecology* does not necessarily mimic past ecological use of the landscape, given that modern concerns and interests are substantially different to Prehispanic ones.

Nevertheless, the recent micro-dam restoration projects are demonstrating that Prehispanic hydraulic systems often outperform their modern counterparts. This is due to a number of factors, including, (i) their adaptation to the local geomorphology; (ii) they are built with durable, locally available materials (stone, clay, compacted earth); (iii) stone and clay systems last for centuries, require minimal energy input, and use locally available materials for maintenance and repair; (iv) as stone and clay gravity dams they are less vulnerable to catastrophic failure; (v) once rehabilitated, they are maintained through community governance; (vi) They are compatible with traditional ecological knowledge (TEK) and local knowhow; and (vii) rehabilitation of old dams costs on average a 10% of what a new-build costs. Furthermore, the rehabilitation and adoption of Prehispanic dams by their parent communities strengthens these people's ancestral links with their landscapes and heritage.

2 | Materials and Methods

2.1 | Local Context

The present-day District of Pamparomás has a population of approximately 8,476 people, of whom around 30% live in monetary poverty (INEI 2018). The population's main mother tongue is Quechua (81.65%), and 96.10% of the population has completed their basic schooling, with around 80.05% of people engaged in agricultural activities (INEI 2017). The agricultural area of the Pamparomás District covers approximately 9172 hectares, of which 38.9% of production is destined for sale, and the rest is set aside for self-consumption. The main cultivated crops are potatoes (39.6%) and avocados (17.8%), and around 68.66% of the area is irrigated (MIDAGRI 2025b). The Weetacocha Dam is located within the jurisdiction of the community of Racratumanka (Figure 2), a small rural village of *c.* 600 inhabitants that practices the agriculture local to the area.

The Weetacocha Dam is one of a series of high-altitude dams along the Sisuran micro-valley, which runs *c.* 6 km downslope from its headwaters to where it joins the Uchpacancha River, known historically as the Río Grande (Anon 1774). The Sisuran is the main water stream supplying the community of Racratumanka's lands. It is a potentially water-rich area, given it can garner water from a series of dammed lakes (e.g., Yanacocha Macho, Yanacocha Hembra, Huancacocha, Iscaycocha, Huaytacocha, Sacracocha and Weetacocha). Of these two, Yanacocha Macho and Huancacocha have been recently re-dammed, with the original Prehispanic dam having been destroyed. The other five still retain their Prehispanic character, with Huaytacocha and Sacracocha even maintaining a limited pool of water. The Weetacocha Dam was selected for rehabilitation as it was the Prehispanic dam nearest to Racratumanka.

All the dams are located above 4100 m in the *puna* tundra grassland ecozone (4100-5100 m) with an underlying geology composed of Volcanic Calipuy, a basalt and andesite composite (Hollister and Sirvas 1978; Lisenia et al. 2010) with low porosity (Torres Yupanqui and Poterico Huamayalli 2017, 102–103). It allows for water to settle into lakes while filtering through seismic and geological cracks to replenish underground aquifers. Nowadays, the water from the top of the valley flows through a mostly widowed herding landscape before reaching the present-day cultivated zone within the *kichwa* (2100–3100) and *suni* (3100–4100) ecozones. In the *suni* ecozone are vestiges of abandoned terraces possibly originally Prehispanic in nature, although the local villagers claim that some of these had been cultivated as recently as 50 years ago.

Given this context, the rehabilitation of the Weetacocha Dam was primarily undertaken to heighten water security for the community of Racratumanka, especially in the face of ongoing climate change. In particular, the villagers wanted to use the water to irrigate 25–30 ha of abandoned land and terraces in the nearby Trancauran area [77°57′1.89“W 9°2′45.70“S] located *c.* 3.25 km from Weetacocha at *c.* 3600 m. This would mean on average *c.* 0.5 ha. for each registered community member (there are currently 56 registered community members). This new cultivation area in the *suni* ecozone would be used to grow potato (*Solanum tuberosum*) and *olluco* (*Ullucus tuberosus*) for local consumption.

2.2 | Rehabilitation of the Weetacocha Dam

Rehabilitation of the Weetacocha stone, clay and gravel gravity dam followed a tried-and-tested archaeological conservation methodology, previously developed by the project team for the Ricococha Alta Dam rehabilitation in the Pamparomás District (Lane, Branch, and Handleyet al. 2025b). This process of rehabilitation involved an intricate series of interrelated steps with the final aim of strengthening the walls through a carefully curated conservation methodology that also replaced the wall core with new material. The rehabilitation actions included the following:

1. Manual cleaning of the site, including vegetation and undergrowth.
2. Drawn and photographic documentation of the dam, before and during works.
3. Cataloguing of wall sections and stones to facilitate reinsertion should they be removed.
4. Cleaning out of the core, removal of loose stones and material.
5. Re-assembling and repositioning of the stone units in accordance with the coded plans and photographs of the

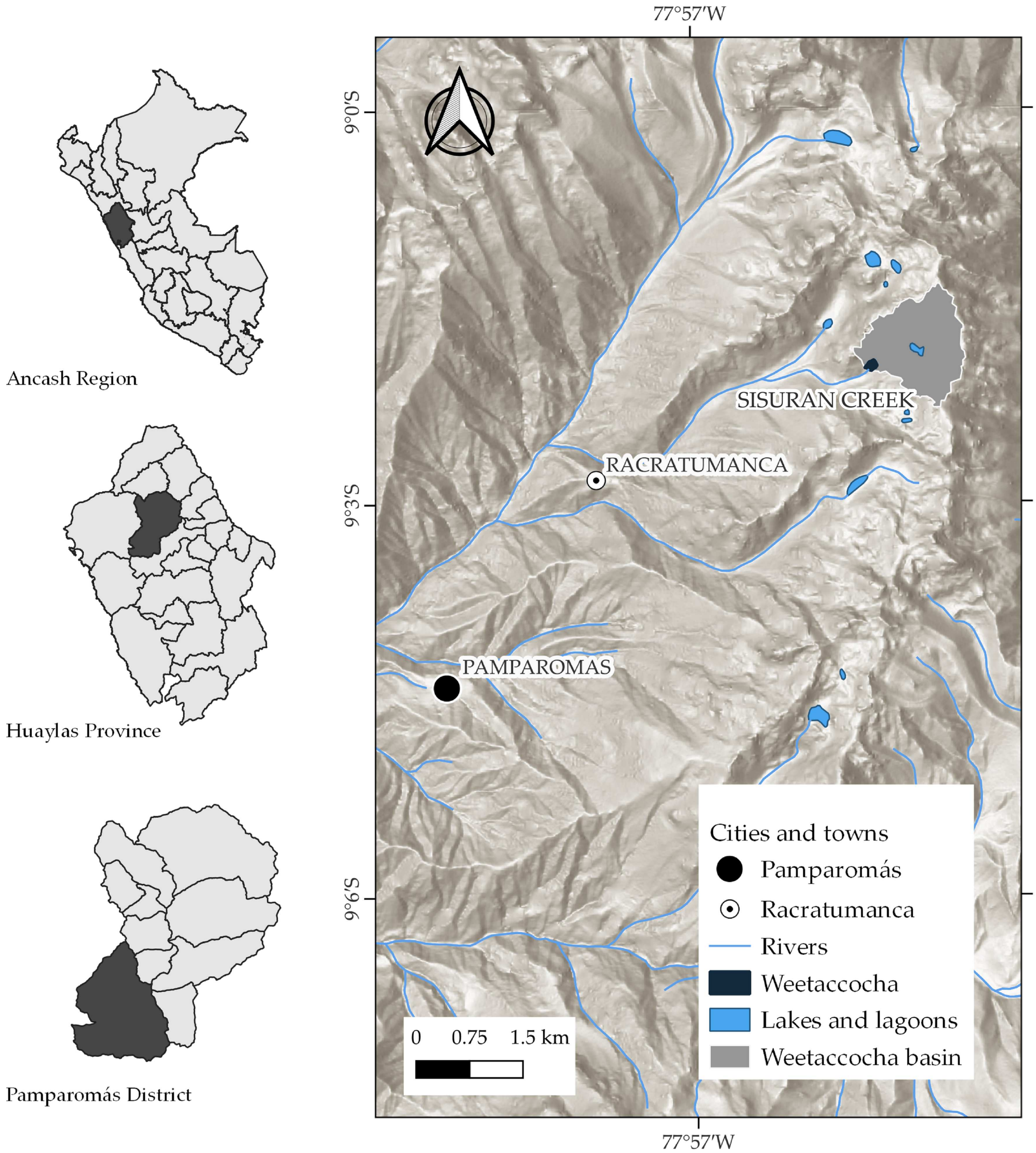

FIGURE 2 | Location of the community of Racratumanka in relationship to Pamparomás and the Weetacocha Dam watershed (shaded in grey).

walls. This was undertaken at the same time as the stabilisation of the structure's fill.

6. Consolidation and stabilisation of the core through insertion of a clay, sand and soil mix (2 parts clay; 1 part sand; 0.5 parts soil) in between the inner and outer walls of the dam. Each layer was laid down and compounded to generate greater stability, making it capable of supporting considerable live and dead loads.
7. Installation of a modern metal and concrete control gate and sluice, concealed within the stonework. This is the only modern feature within the dam and was accepted by the Peruvian Ministry of Culture as a viable alternative to the old stone sluice.
8. Further consolidation included: compaction of the core crest; placement of flagstone-type stones along the crest; assembly and replacement of the spillway located on the dam crest; and installation of geomembrane, geotextile and a cutoff wall along the water side of the dam wall.
9. Note: reversibility was key to the placement of the control gate, sluice, geomembrane, geotextile and a cutoff wall, in case a better solution to impermeability becomes available in future.

The key component of these micro-dam rehabilitation projects was community engagement and buy-in. This was achieved with the community of Racratumanka, who provided their labour and know-how concerning stone and clay constructions, for instance,

TABLE 1 | Dimensions and parameters of the Weetacocha Dam.

Parameter	Value	Unit
Reservoir		
Storage volume	23,352.0	m^3
Maximum extraordinary water level	4301.6	m.a.s.l
Maximum operating water level	4301.4	m.a.s.l
Dam		
Dam crest level	4301.8	m.a.s.l
Maximum height	1.9	m
Maximum length	57.0	m
Crest width	4.0	m
Overflow spillway		
Spillway level	4301.4	m.a.s.l
Spillway length	8.6	m
Spillway width	8.0	m
Bottom structures		
Bottom intake level	4299.7	m.a.s.l
Water outlet level	4299.4	m.a.s.l
Diameter of the discharge pipe	200.0	mm

irrigation canals. The project team supported the work with critical restoration, engineering and archaeological knowledge. The parameters and dimensions of the dam in its restored state are presented below (Table 1), as is a schematic of the rehabilitated structure (Figure 3).

FIGURE 3 | The dam of Weetacocha before rehabilitation (May 2024).

2.3 | Reservoir/Dam Filling Log

Following the rehabilitation of the Weetacocha Dam, the structure, it's dimensions and efficiency were monitored in collaboration with the National Institute of Agricultural Innovation (INIA) of the Peruvian Government towards assessing how successful the project had been. This provided important data which quantifiably validates the Prehispanic micro-dam rehabilitation. To this end, a weather station (Davis Vantage Pro 2) (9°01'59.8'S 77°55'39.1'W) was installed adjacent to the crest of the dam, and a water level monitoring station (HOBO® U20L Water Level Logger; Models: U20L-04 and U20L-01) in the 'filling chamber'. The Water Level Loggers were installed inside a vertical PVC pipe Ø 4" - PN 10 with holes drilled from the base and a threaded cap, allowing communication with the water in the chamber and ensuring that it could not be tampered with by outsiders. Both monitoring stations recorded data on an hourly basis.

2.4 | Hydrological and Hydraulic Analysis

2.4.1 | CUBHIC Methodology for Water Balance

To analyse the water balance of the reservoir, the CUBHIC 2.0 (Quantification of Hydrological Benefits of Interventions in Watersheds) methodology developed by Ochoa-Tocachi et al. (2022a) was used for permeable micro-reservoirs (also known as *qochas*). According to the proposed methodology, the water balance in the *qocha* is given by the equation below. For further details of the calculation, refer to Ochoa-Tocachi et al. (2022b).

$$\Delta V_{(\mathrm{t})} = V_{\mathrm{q_0}(t)} + V_{\mathrm{gw}(t)} + V_{\mathrm{P}(t)} + V_{\mathrm{in}(t)} - V_{\mathrm{ET}(t)} - V_{\mathrm{S}(t)} - V_{\mathrm{wd}(t)} - V_{\mathrm{out}(t)},$$

where t is the time step, $\Delta V_{(t)}$ thec hange in storage volume during time step t (m^3), $V_{\mathrm{q_0}(t)}$ the surface runoff inflow during time step t (m^3), $V_{\mathrm{gw}(t)}$ the groundwater inflow during time step t (m^3), $V_{\mathrm{P}(t)}$ the direct precipitation volume during time step t (m^3), $V_{\mathrm{in}(t)}$ the additional inflow during time step t (m^3), $V_{\mathrm{ET}(t)}$ the evaporation loss during time step t (m^3), $V_{\mathrm{S}(t)}$ the Seepage loss during time step t (m^3), $V_{\mathrm{wd}(t)}$ the direct water abstraction volume during time step t (m^3), $V_{\mathrm{out}(t)}$ the surface spill/discharge volume during time step t (m^3).

Inputs for the CUBHIC model were constructed based on geospatial information, literature and field measures. The contributing watershed under study was delimited in QGIS 3.22.14 using a 12.5-m resolution Digital Elevation Model (DEM) from the ALOS PALSAR Radiometric Terrain Corrected (RTC) product (scene ID: ALPSRP261557000; ASF DAAC 2014). Land cover classifications were used according to the classification carried out by the MapBiomas project (2025) (i.e., grasslands, rocky outcrops, scrubland, wetlands), and crop coefficients (Kc) based on Buytaert et al. (2006) and Pereira et al. (2024). Additional characterisation parameters were considered according to Ochoa-Tocachi et al. (2022a). The characteristics of the *qocha* were obtained from field measurements (i.e., dam height, maximum volume, flood area). For climate conditions, a representative year was selected based on the available historical information. Daily precipitation and temperature values were extracted from the gridded products RAIN4PE (Fernandez-Palomino et al. 2021) and PISCO-t (Huerta et al. 2018), respectively. To identify the representative year, the Empirical Cumulative Distribution Functions (ECDF) (Shyamprasad et al. 2010) were analysed, with the representative year being the one whose ECDF was closest to that of the entire analysis period according to the Kolmogorov-Smirnov (K-S) test. Data extraction and subsequent processing of the gridded datasets were performed using the terra package (Hijmans et al. 2026) for R 4.5.2.

2.4.2 | *Water Demand Estimation*

To estimate water demand, a model was constructed in CROPWAT 8.0 that integrated associated pasture production. For the crop module, the crop coefficients (Kc) recommended by Pereira et al. (2024) for semi-natural high mountain meadows and grasslands for grazing and hay, freezing winter, and no killing frost were considered. The planting of pastures in early November, with average cutting periods of 90 days, was calculated. The climate information corresponded to the daily precipitation for the representative year and the historical monthly average temperatures. Considering loamy soils, we applied supplemental irrigation to field capacity after reaching a critical decrease of 60% in the water content of the soil available to the plant.

2.4.3 | *Analysis of the Design Flow of Maximum Floods*

A frequently used, relatively simple and well-supported procedure for estimating maximum flows in micro-basins is the Rational Method (Kellagher 1981). It estimates the discharge based on the catchment area, upstream land cover and average rainfall intensity. However, a disadvantage of this method is that it does not include the effects of water bodies that mitigate flooding (Miller et al. 2023). Therefore, a likely solution to this situation is to incorporate the FARL index (Flood Attenuation by Reservoirs and Lakes), as detailed by the Institute of Hydrology (1999):

$$FARL = \prod_{i=1}^{n} \left(1 - \frac{r_i}{w_i}\right)^{0.2},$$

where r_i is the water surface area of the ith reservoir, w_i is the catchment area draining to the ith reservoir, and n is the total number of significant water bodies in the basin. Thus, according to Miller et al. (2023), the design flow for a micro-basin is estimated as follows:

$$Q_p = 0.278 \times C_R \times C_v \times i \times A \times FARL^{\theta},$$

where Q_p is the peak discharge ($m^3\ s^{-1}$), C_R the dimensionless routing coefficient, C_v the volumetric runoff coefficient, i the rainfall intensity (mm h^{-1}), and A is the basin area (km^2). Based on Miller et al. (2023), C_R was 1.3, representative C_v was calculated according land-cover distribution, and θ was 3.445 for mountain basins. The concentration time of the basin was calculated by Kirpich (1940) and used as the duration of the design rainfall. Considering a 50-year return period and the Intensity—Duration—Frequency (IDF) curves constructed by the National Service of Meteorology and Hydrology of Peru (https://idesep.senamhi.gob.pe/dhi-idf/), the design rainfall intensity was estimated. Consequently, Q_p allow us to evaluate the potential spillway performance by Francis (1871). The HCANALES 3.0 software was used, considering a broad-crested weir based on the dimensions of Weetacocha Dam listed in Table 1.

2.5 | Economic Analysis

The investment in new grey infrastructure, especially reservoirs and dams, is substantial within the Peruvian Andes (Carrasco Freitas 2025; MIDAGRI 2025a; World Bank 2017). Given climate change and the ever-increasing demand for water, this is hardly surprising. In a bid to rank the expense of dam rehabilitation versus new-builds, we calculated the cost per cubic metre (m^3) of water recovered from Weetacocha against recent reservoir projects from the Ancash region. Cost and storage capacity data for each project were obtained by querying the Peruvian government's investment database of the Ministry of Economy and Finance, General Directorate of Public Investment (https://ofi5.mef.gob.pe/inviertePub/ConsultaPublica/ConsultaAvanzada). The search included projects containing the keyword 'water harvesting' developed within the last 5 years.

3 | Results

3.1 | Reconstructed Weetacocha Dam

The monitoring of water levels in the dam after its restoration showed that the expected storage was achieved during the period October 2024–June 2025 (Figure 4). During the first-months of rainfall, the community residents kept the valve open, allowing the reservoir to function as a retention reservoir for precipitation events until early December 2024. By January 2025, the gate was closed almost completely, enabling the reservoir to fill and store water during the wet season. Finally, by the end of the rainy season (April 2025), with the valve completely closed, the slow decline in water level was likely associated with outflows due to crack porosity infiltration through the underlying andesite geology and evapotranspiration from the reservoir itself.

The water level in the dam showed three water-high points, representing three instances when water in the reservoir peaked. The data also shows that the dam was completely full in June 2025, during the middle of the Andean dry season. A site visit in late August 2025 showed that the dam was still full, even though water had been siphoned off for use by the communities of Racratumanka and Catorce Incas. A further visit by the villagers from Racratumanka in November 2025, prior to the 2025-2026 rainy season, also revealed a full dam, indicating the continued recharge of the basin from springs and dry season streams located further uphill in the direction of the

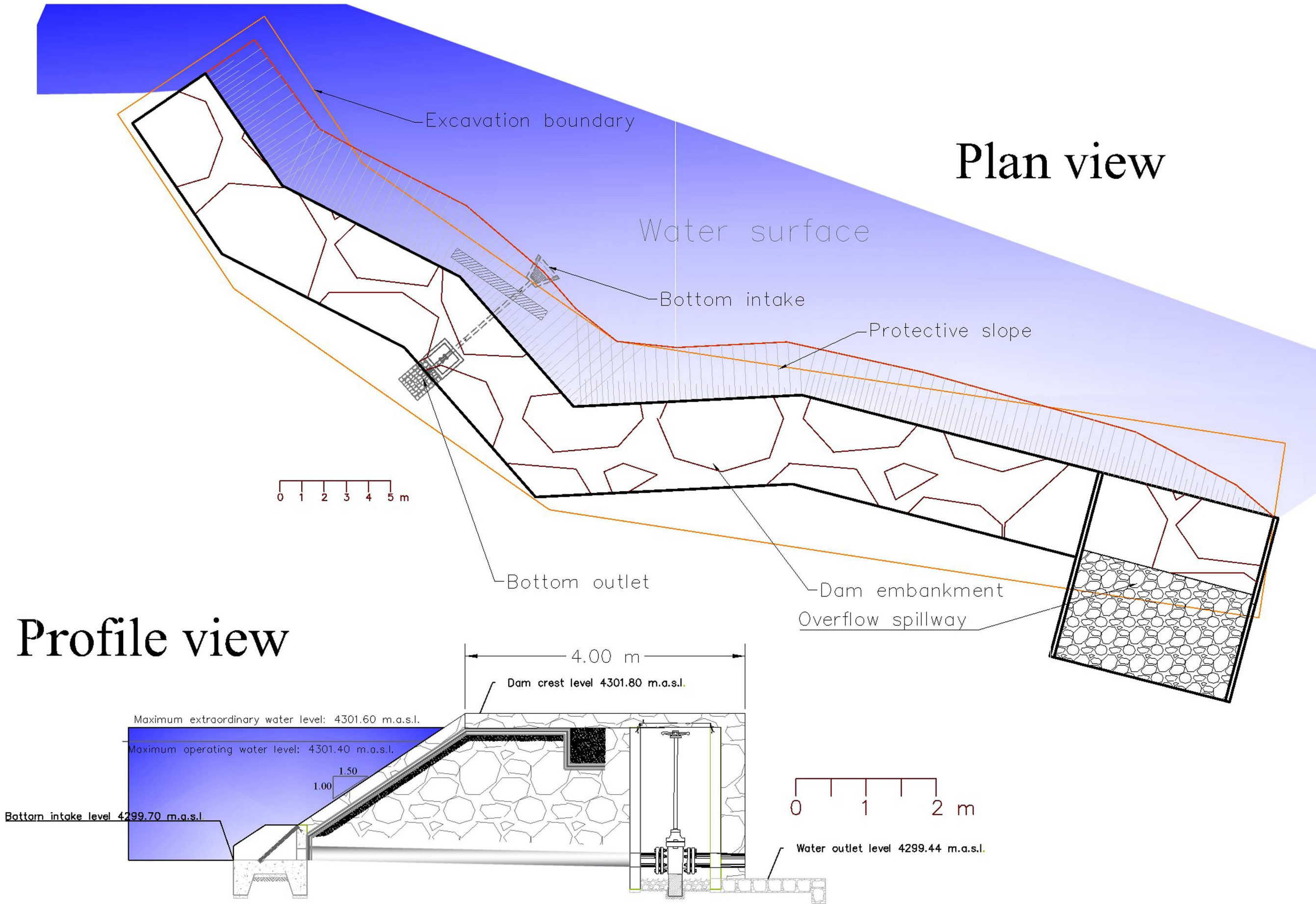

FIGURE 4 | Schematic of the Weetacocha Dam showing the main elements of its rehabilitation.

FIGURE 5 | The dam of Weetacocha rehabilitated (July 2025).

unrehabilitated Prehispanic dams of Huaytacocha and Iscaycocha. Rehabilitation of the whole system could greatly increase local water security.

3.2 | Hydrological and Hydraulic Feasibility

For the hydrological analysis, 1997 was selected as the representative year for precipitation, 2002 for maximum temperature, and 1982 for minimum temperature (Figure 5). Based on this, we estimated that in an average year, the reservoir could supply *c.* 10 ha of additional cultivated pasture (extrapolating from Figure 6). We suggest that the forage could be planted in November with the onset of the rainy season and subject to a period of summer fallow during the low water season (August–October). By this means, villagers can manage the re-growing seasonality of cultivated pasture and combine it with additional conservation techniques such as silage.

Regarding the spillway's performance, the design flow for a 50-year return period was calculated at 1.37 $m^3\ s^{-1}$, resulting in a water head of 0.24 m over the structure. This level remains well below the maximum potential head of 0.40 m, at which point the spillway would reach a discharge capacity of 2.93 $m^3\ s^{-1}$. This potential maximum discharge would be caused by an extraordinary rainfall event with a return period of ≈290 years. This confirms that the rehabilitated hydraulic design provides a significant safety margin, even under extreme weather events.

3.3 | Cost Efficiency of Dam Rehabilitation

The cost and total storage of 24 recent water-harvesting projects were recovered from the Invierte. pe database (Table 2). The Weetacocha Dam restoration required an investment of USD 83,000.00 to recover 23,351.99 m^3 of water. This results in a Specific Investment Cost (SIC) of 3.55 USD m^3. Comparing against the other new builds, Weetacocha's SIC is well below

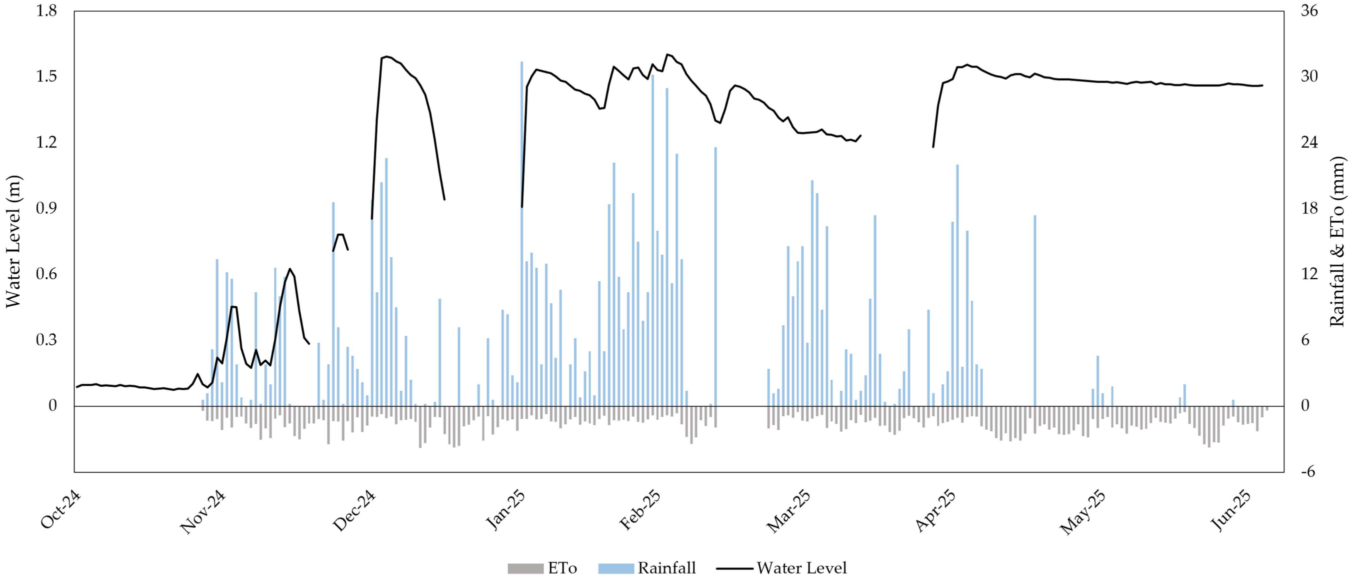

FIGURE 6 | Rainfall, potential evapotranspiration (ET0) and water level at the Weetacocha Dam (October 2024–June 2025). ET0 values are shown on the negative axis to represent outflows from the system.

TABLE 2 | Specific Investment Cost in USD per m^3 unit of water in new-build reservoirs in Ancash 2021–2025.

UIC	Province	District	Year of works	Investment (USD)	Water storage (m^3)	Specific investment (USD m^{-3})
2522521	Bolognesi	Huayllacayan	2021	43,385.9	42,766.5	1.0
2522527	Bolognesi	Huayllacayan	2021	45,017.4	106,471.2	0.4
2522533	Bolognesi	Huayllacayan	2021	48,013.9	54,153.4	0.9
2559685	Pallasca	Pampas	2022	54,758.9	35,796.4	1.5
2559703	Pallasca	Llapo	2022	51,464.6	8933.7	5.8
2568968	Pallasca	Llapo	2022	94,507.1	3667.6	25.8
				102,217.9	3639.9	28.1
2568971	Pallasca	Cabana	2022	76,623.6	13,359.2	5.7
				69,083.8	4554.2	15.2
				111,612.4	6153.6	18.1
2568973	Pallasca	Conchucos	2022	170,469.1	26,124.52	6.5
				121,806.4	7285.07	16.7
2568977	Pallasca	Lacabamba	2022	167,258.1	33,886.71	4.9
2568981	Pallasca	Pampas	2022	34,620.5	3162.2	10.9
				200,069.0	11,849.57	16.9
2569082	Huaraz	Independencia	2022	63,523.2	2236.629	28.4
2573703	Ocros	Congas/Vista Alegre	2023	129,445.6	48,600	2.7
2574763	Ocros	Congas	2023	714,098.0	82,911	8.6
2613864	Huari	Cajay	2023	324,226.0	24,330	13.3
2652165	Huari	Cajay	2024	224,191.4	197,057.24	1.1
2673415	Huaraz	Huanchay	2025	557,126.1	78,230	7.1
				601,577.7	59,250	10.2
				349,685.6	26,330	13.3
2686935	Antonio Raymondi	Mirgas	2025	11,4694.2	12,162.14	9.4

Abbreviation: UIC, unique investment code.

the regional average of 9 USD m^3 (Figure 7). Indeed, only six of the 24 new-build projects achieved a lower SIC than Weetacocha, while 12 were above the 9 USD m^3 average, some by a substantial margin. Just perusing this limited sample, on average, the SIC of the restored Weetacocha dam was *c.* 60% cheaper than that of a new build, underlining the cost-effectiveness of ancient dam rehabilitation (Figures 8 and 9).

4 | Discussion

Rehabilitation projects of ancient technology are fraught with problems. Crucially, there is a generalised sentiment, especially among many modern structural engineers, that the old is inherently obsolete. Unfortunately, this is an impression that all too often is shared by the rural communities of the Andes. The persistence of this attitude does much to undermine local Traditional Ecological Knowledge (*sensu*, Huntington 2000) and further invalidates communities that often ascribe to externally imposed negative cultural stereotyping that perceives them as backward, ignorant and indolent.

This could not be further from the truth and flies in the face of embedded millennian knowledge that constructed these features to last and to adapt to the landscape rather than the often one size fits all approach that is adopted by many modern micro-dam projects. A structural and hydrological study of the Weetacocha Dam has shown that the structure is substantially over-engineered, such that, '…the safety factors are greater than the minimum prescribed safety factors, which means that the established stability criteria are met' (Lapa Navarro and Munaytia Rojas 2024, 24). This is likely due to the inability of past populations to accurately calculate the hydrostatic force of the water against the dam wall.

In line with this, we demonstrated that the spillway would guarantee good functioning during extreme events of large return periods. This situation is consistent with paleo-hydraulic analyses worldwide, which show that ancient water engineering often incorporated additional security elements to ensure resilience against extreme events, even at the expense of efficiency under normal conditions (Ortloff 2023a). Thus, for Weetacocha, further safety features included a dam wall that was angled along its length four times to spread the water pressure of the hydrostatic force across smaller sections of the structure; and an over-sized emergency spillway designed to discharge over exposed bedrock, reducing the risk of erosion of the structure and downstream.

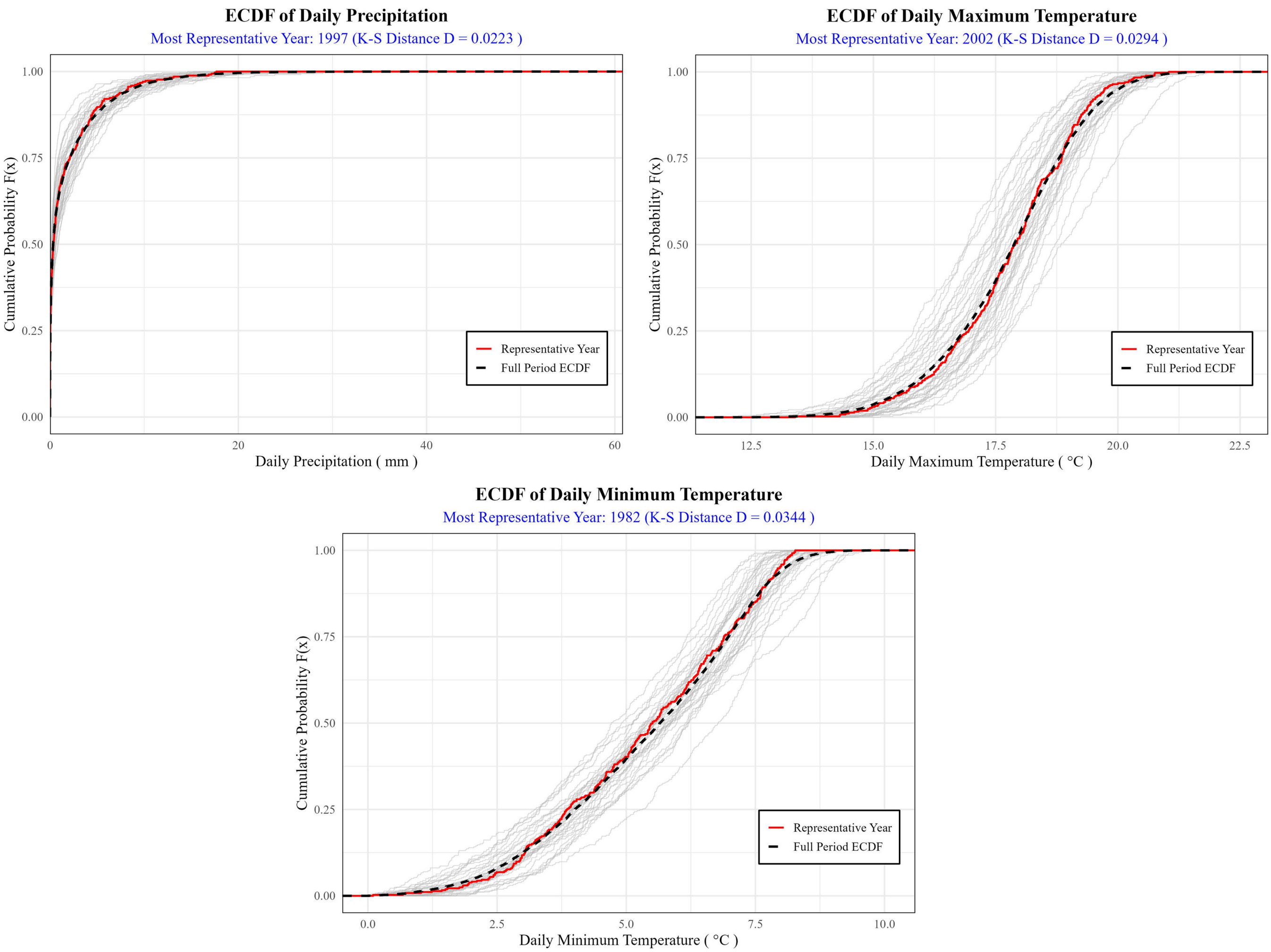

FIGURE 7 | Selection of representative year for climate variables using Empirical Cumulative Distribution Functions (ECDF) analysis. K-S, Kolmogorov–Smirnov test.

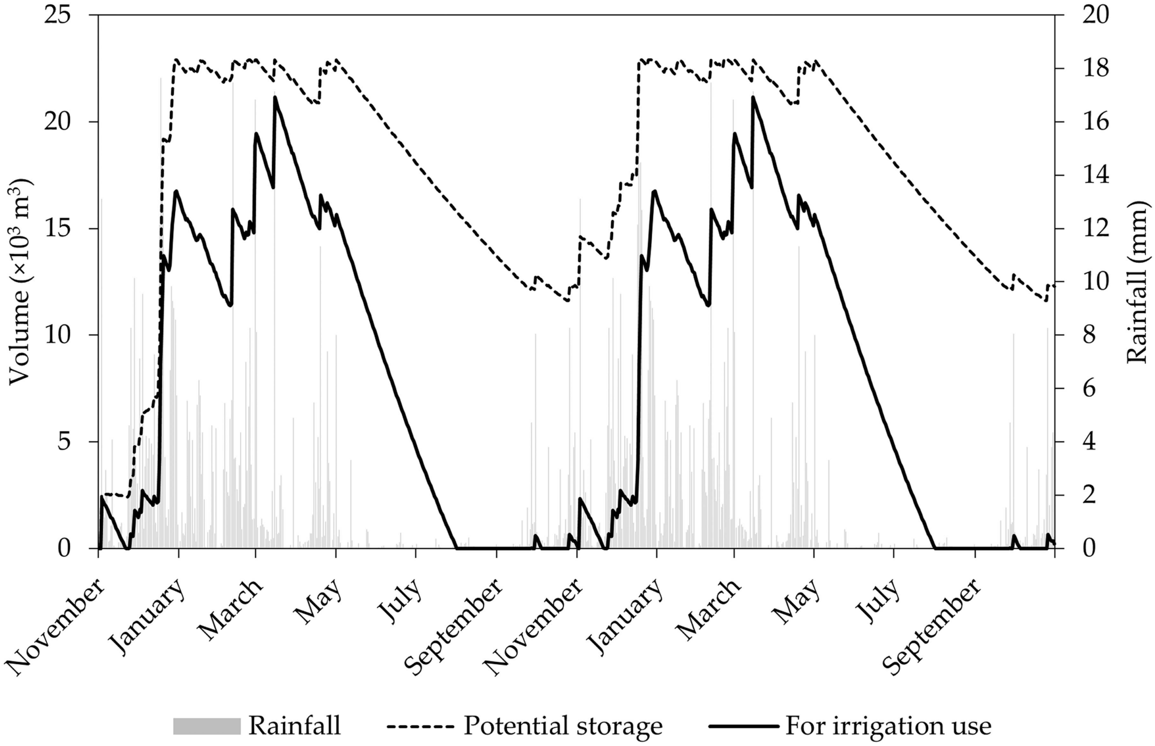

FIGURE 8 | Estimated reservoir performance for the representative year. The potential storage capacity and estimated projection after water use for supplementary irrigation of cultivated pasture areas are presented. Daily precipitation (mm) is shown in shaded areas.

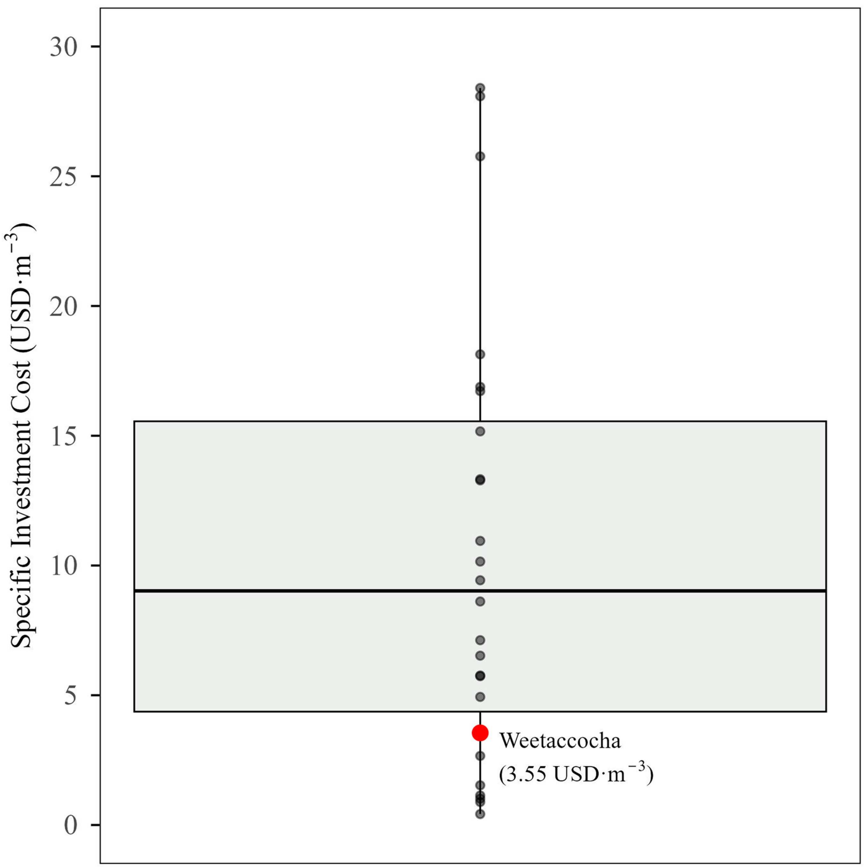

FIGURE 9 | Boxplot comparing the Specific Investment Cost (USD m^{-3}) of Weetacocha against the other 24 new-build reservoirs from Table 2.

Additionally, our studies have clearly shown the positive impact of this dam rehabilitation project across different projected parameters including volume capacity, potential demand, hydrological and hydraulic analysis based on a reservoir filling log of the dam. For the study area, we estimated that *c*. 10 ha of land could be recovered for agriculture using the water storage from Weetacocha. These additional areas could be exploited through the growth of high yield pastures such as *Dactylis glomerata*, *Trifolium incarnatum*, *Trifolium repens*, *Hordeum vulgare* and *Vicia sativa* (Arias Arredondo et al. 2025; Ruiz 2022). These plants have a high resistance to low temperatures and drought and provide good nutritional content for livestock.

Alternatively, this water could be used to part irrigate the 25–30 ha. of abandoned fields and terraces in the Trancauran area located *c*. 3.25 km from Weetacocha at *c*. 3600 m and for potential use in potato (*Solanum tuberosum*) and *olluco* (*Ullucus tuberosus*) cultivation that the villagers desire. Furthermore, the use of drip-irrigation could substantially improve cultivation area and yield (Santini et al. 2025). Added to that, the economic analysis (cost per m^3 unit of 3.55 USD as opposed to a 9 USD average) proves that the recovery of the Weetacocha Dam is a viable cost-effective alternative to modern micro-dam construction in the Central Andes.

As previously mentioned, the key component to effective rehabilitation of these dams, and likely all such infrastructure, is community buy-in. Indeed, many other such infrastructure recovery programmes have often failed by being too top-down in their approach, eschewing local considerations and concerns, such as occurred with some of the raised field systems around Puna in southern Peru (Claverías et al. 2001, 15) or where local conditions have changed leading to their subsequent abandonment (Kendall and Drew 2019). In fact, caution should be taken when promoting rehabilitation projects given that not all projects of this type are needed or indeed sustainable (Plekhov et al. 2024). Andean societies have historically self-organised around the use of water supply, with distribution technologies forming the foundational elements (Ortloff 2023b). Thus, integrating historical knowledge with modern technologies should be approached as a horizontal exchange, evolving into an interdisciplinary framework that encompasses water resource management, climate variability, and socioeconomic sustainability (Bajpai et al. 2025).

In the case of the Weetacocha Dam, community engagement was done early and sustained throughout. In particular, an intercommunity workshop organised as part of the 2024 ICOMOS Culture-Nature Prize award (https://www.icomos.org/actualite/icomos-culture-nature-prize-2024-winners/) with the community of Racratumanka, custodians of the homologous dam and other Andean communities from the Cordillera Negra and the Nor Yauyos region of the central Peruvian Andes. The workshop was instrumental in setting the parameters for lobbying, and then, undertaking the rehabilitation of Prehispanic dams in their respective districts. A major factor behind support for dam rehabilitation by the different communities was the low-cost and quick turn-around—1 year—as opposed to that of modern grey infrastructure projects which can take substantially more.

Throughout, the conversations between the communities were extraordinarily frank, possibly because none of the communities present were near neighbours and thus were not competing for the same resources. Key topics of discussion included the methods employed in rehabilitating ancient technology, as well as the challenges being faced due to climate change and other external factors against the backdrop of the social and economic conditions prevailing in the Andes today (e.g., population growth, out-migration of community members, export agriculture and mining). Data on everything discussed was collected through recourse to map boards, unstructured interviews and questionnaires. The results of these are currently being analysed and will be the subject of future publications.

A mayor aim of this intercommunity workshop was to prepare the ground among the communities themselves for future projects rooted in the appreciation, rehabilitation and use of their Traditional Ecological Knowledge and technical knowhow, revaluing embedded rural indigenous expertise by positively positioning it alongside modern micro-dam projects. This topic has great potential for sustainable development, as evidenced by Flores-Marquez et al. (2026) regarding the ecosystem services provided by *qochas* built on local ecological knowledge within high Andean socio-environmental contexts. According to these authors, beyond the inherent provisioning (e.g., water supply, wildlife habitat renovation) and regulating services (e.g., erosion and water flow control), cultural ecosystem services emerge as the most significant for local populations, being deeply rooted in their customs and traditions. This cultural revaluation acts as a primary driver for sustainable development, as the community's willingness to maintain these water management practices persists despite prevailing socio-economic challenges and climate pressures, making *qochas* a highly promising adaptive measure.

5 | Conclusion

Rehabilitation works, and the Weetacocha dam project amply demonstrates this. Furthermore, the sheer number of Prehispanic micro-dams across the Cordillera Negra and further afield (Pey et al. 2025) attests to both the versatility and range of these structures. Indeed, the fact that they exist proves beyond doubt their past success. As such, the rehabilitation of the Weetacocha Dam re-establishes a proof-of-concept that was first mooted over a millennia ago. Critically, Andean communities see the benefits in re-establishing Prehispanic dams as a means towards combating incremental climate change and its adverse impact on water security. The only appreciable downside is that these older structures have less carrying capacity, but this is offset by their low-cost both in time and money.

Our research and close collaboration with the INIA were important in quantifying the actual impact of the dam itself on the watershed and wider landscape. Nevertheless, the parameters associated with infiltration and the consequent contribution to the water table downstream of the structure require more exhaustive measurements. To this end, long-term monitoring networks should be implemented, as the impacts on the hydrological cycle are usually expressed in timescales of more than 5 years of intervention, depending on local hydrogeological characteristics.

In the case of Weetacocha, more research should be undertaken across the twin basins in which it is located, especially the use of chemical tracers, to further assess the potential effect of the dam at the basin level, while evaluating environmental impacts through ecosystem services approaches. In relation to infiltration, it is possible to measure changes in the saturated hydraulic conductivity of the soil, so that the variations in the infiltration processes of these interventions can be assessed. Nevertheless, the preliminary data gathered here already shows the positive effects of ancient dam rehabilitation and promotes a hybrid approach to water scarcity in the Andes which sees the rehabilitation of ancient hydric *installed capacity* alongside the construction of new grey infrastructure where the former does not exist. Only by equally valuing both past and present solutions to water scarcity and management can we best tackle the transformative processes at play due to modern-day climate change.

Author Contributions

Kevin Lane: conceptualisation, methodology, validation, formal analysis, research, data curation, writing – original draft, writing – review and editing, visualisation, project administration. **Flores-Marquez, Ricardo:** conceptualisation, methodology, validation, formal analysis, research, data curation, writing – original draft, writing – review and editing, visualisation, project administration. **Puga-Calderon, Rodrigo J.:** conceptualisation, methodology, validation, formal analysis, research, data curation, writing – original draft, writing – review and editing, visualisation, project administration. **Gonzalez, Pedro:** methodology, validation, research, data curation, project administration. **Mario Advíncula:** methodology, research, project administration. **Alexander Herrera:** research, writing – review and editing.

Acknowledgements

The authors thank the community of Racratumanka and their wholehearted involved in this project, without their driving interest and ancestral knowledge this project would have been impossible. The *Weetacocha—Pamparomás Archaeological Research Project for Conservation and Enhancement* was co-financed by the *Rotary Club International* and the *Mountain Institute—Peru* through its Global Giving programme. The initial digital survey of the dam was undertaken through recourse to funds provided by the *Gerda Henkel Foundation* and the *Harte Family Fund* and the intracommunity workshop was run as part of the activities associated to this project having won the *UNESCO-ICOMOS Culture and Nature Prize* (2024). The participation of the Peruvian National Institute of Agricultural Innovation (INIA) was within the framework of the project: *Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali CUI 2487112*. Special thanks go to the community of Racratumanka for their generosity and for believing in this project.

Data Availability Statement

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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