



Efficiency analysis of irrigation ditches over different land uses in the Andean region of Ecuador: implication for nature-based water management strategies

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Abstract

Human pressures and global change are threatening water resources. Circumstances vary in each location; therefore, finding solutions that address local issues helps achieve comprehensive water management strategies. In the Andean basins, the pre-Inca cultures used nature-based water management techniques to deal with the dry seasons. This knowledge and these techniques have been recognized as a strategy to increase water security. Additionally, they have been unconsciously applied to improve hydrological conditions in areas affected by extreme land-use changes. Water sowing and harvesting techniques have been used to manage territories dedicated to livestock and agriculture. This research evaluates three traditional infiltration ditch systems on two types of land use (páramo and cultivated pastures) in the Andean region of Azuay (Ecuador). The objective was to establish the potential for better management of water resources in dry seasons. Eosin-traced water diverted through channels or ditches, infiltrated into the soil, was retained for an average of 31 days in the páramo soil and from 90 to 111 days in the cultivated pasture soil. Controlled water infiltration contributes to effective water management by retaining water in the soil for extended periods. We conclude that nature-based systems perform better on soils with higher water retention capacity. These techniques are suitable for managing water in areas where land changes have reduced water storage potential.

Keywords Andean basin · Water management · Nature-based solutions · Sustainability

Introduction

Climate change affects water resources by altering hydrological cycles, runoff patterns, soil moisture levels, evapotranspiration rates, and water demand (Wagner et al. 2023). Overexploitation of the agricultural sector accelerates land use changes, fostering a cycle of resource depletion and alteration of vegetation cover, leading to a decrease in water availability (Lutz-Ley et al. 2021). In the Andes Cordillera, agriculture has been the main productive activity for hundreds of years. However, most of these areas have been

affected by human activities, leading to a loss of water storage potential due to soil compaction and/or sediment entrainment. A significant effect is the shift towards pastureland cultivated for livestock activities (Walker and Salt 2006; Schlink et al. 2010; Satgé et al. 2019). Additionally, water resources within the Andes Cordillera are highly susceptible to global climate variations, which have led to an increase in drought events (Campozano et al. 2020). As a result, water stress in drainage basins has intensified, putting the security for supplying at risk. Consequently, producers face challenges in managing their activities sustainably, especially following extreme events such as prolonged drought (Haigh et al. 2021).

For decades, water management issues have been addressed through human-made “grey” infrastructure solutions, often neglecting natural areas and overlooking the advantages of nature-based solutions -NbS- for resource sustainability, resilience, and community well-being (Carrós-Martínez et al. 2020). NbS emerges as a key approach

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in contemporary environmental management practices (Pugliese et al. 2022). NbS work in harmony with ecological systems to address societal challenges while promoting human well-being and biodiversity (Thaler et al. 2023; Turkelboom et al. 2021). As defined by the International Union for the Conservation of Nature (IUCN), NbS include “actions to safeguard, sustainably manage, and rejuvenate natural or modified ecosystems, addressing societal challenges in an effective and adaptive manner” (Cohen-Shacham et al. 2016). The benefits of these kind of practices are extensive, encompassing the enhancement of biodiversity, habitat creation, flood risk mitigation, runoff modulation, and water quality improvement (Keesstra et al. 2018). Historically, NbS have played a crucial role in providing adaptive responses to climatic changes and delivering essential ecosystem services (Chausson et al. 2020), particularly for increasing water security (Martos-Rosillo et al., 2020).

On the latter point, NbS offer a promising alternative, particularly for Latin America, where investment in water optimization has increased. However, more profitable and optimized systems are needed. Despite this progress, information regarding the effectiveness of these systems and the associated hydrological processes is scarce (Somers et al. 2018; Grainger et al. 2019). Therefore, additional efforts are needed to understand the hydrological role of ancestral techniques across different soil types, with the aim of optimizing water management strategies in combination with modern approaches.

A common NbS practice in mountainous regions worldwide involves diverting water from rivers to permeable or semi-permeable areas through channels, allowing it to infiltrate the slopes. Many techniques developed by pre-Inca civilizations, and later continued during the Inca period, share similarities with the “careos” diversion channels built in Southern Spain by the Arabs (Pulido-Bosch & Sbih, 1995). For instance, snowmelt flows in the Spanish Sierra Nevada mountain range are retained and infiltrated on the slope by ditches, these are channels dug into the ground without covering. This promotes water infiltration into the subsoil and increases the recharge of aquifers, leveraging the natural terrain’s capacity to store and regulate water (Martos-Rosillo et al., 2020; Jódar et al. 2022). Water Sowing and Harvesting (WS&H) systems have been expanding in the mountain regions of South America, where diverse ecosystems and land uses have enabled ditches to have diverse purposes, though these application remain underexplored.

In Ecuador, ancestral knowledge about NbS such as WS&H techniques still exists, specifically in rural areas (Stohtert 1995; Delgado Espinoza 2017), mainly focused on maintaining moisture in soils with naturally low level of water storage capacity. The most studied evidence is found in the region of the Pacific Coast, although these ancient

techniques were also developed in the Andes Mountains. In the coastal zone, structures such as “*albarrada*” and artisanal dikes are designed to store water and recharge aquifers, providing resources that can be used in times of low rainfall (Carrión-Mero et al. 2021). *Albarradas* are infiltration basins or lagoons located on the coastal plain of Santa Elena, Manabí and Guayas provinces in Ecuador, and are estimated to be approximately 3800 years old (Marcos and Álvarez 2016; Cassin and Ochoa-Tocachi 2021). These natural solutions for intra-annual water regulation have served as alternatives to the construction of dams and conveyance pipelines to supply downstream users (Oyonarte et al. 2022).

In the Andean regions, communities tackle water security challenges by developing communal irrigation and supply systems (Hinojosa et al. 2017). This organizational approach requires alternatives to enhance resource management, based on the ancestral knowledge of the community’s environment. One of the most remarkable initiatives is the integration of the páramo ecosystem, highlighting its regulatory role in the hydrological cycle and its multiple advantages, including water storage, regulation, and sustenance; climate regulation, biological, economic, and cultural significance. However, a major challenge for these communities is addressing land-use changes driven by the development of productive activities while simultaneously ensuring the responsible management of water resources.

The páramo is jointly with puna, Andean forests, inter-Andean valleys, and mountainous deserts, one of the five distinct landscape units found in the tropical Andes region based on altitude and average temperature (Cuesta et al. 2009). This unique ecosystem spans across the Andean region of western Venezuela, Colombia, Ecuador, and northern Peru (Young et al. 2017), extending above the native forest (ranging from 3000 to 3500 m a.s.l.) and situated below the permanent snow line of snow-capped mountains (typically between 4500 and 5000 m a.s.l.). Páramo is characterized by typical patterns of a high mountain tropical climate (Viviroli et al. 2007). Annual precipitation volumes reaching up to 3000 mm, although exhibiting significant spatio-temporal variability (Padrón et al. 2015), and the average annual temperature remains relatively constant, though it is marked by significant diurnal temperature variations, from 0 to 20 °C (Buytaert et al. 2006; Córdova et al. 2015).

Therefore, multi-analysis approaches need to be applied to better understand the nature-based water management strategies affecting available groundwater resources in the Andean region with a dual perspective: (1) increase knowledge to find suitable locations for groundwater exploration, its true potential, and correct use (Ponnusamy et al. 2022), and (2) contribute to a sustainable management of water resources, which is essential to cover needs in areas with seasons where droughts affect the population (Grönwall and

Oduro-Kwarteng 2018). Understanding the advantages of the WS&H system provides insights for implementing similar techniques at the basin scale to achieve water security and sustainability in areas with anthropogenically induced water stress (UNESCO 2018).

The objective of this research is to characterize the hydrological processes in various soil types within the Andean region of Azuay, Ecuador (Fig. 1), with the aim of evaluating the potential of nature-based techniques implemented in the region for better management of water resources during dry seasons. To do this, dye tracer tests and one-year flow records were conducted to estimate the residence time of

water in the subsurface of two types of land-use: páramo and cultivated pastures (grassland), from infiltration zones to discharge areas, under different hydro-meteorological conditions. The results obtained contribute to the knowledge of techniques integrated into traditional infrastructure, improving the management of water resources in the Andean region. This is essential in areas where changes in land use, driven by livestock activities, generate excessive demand for water.

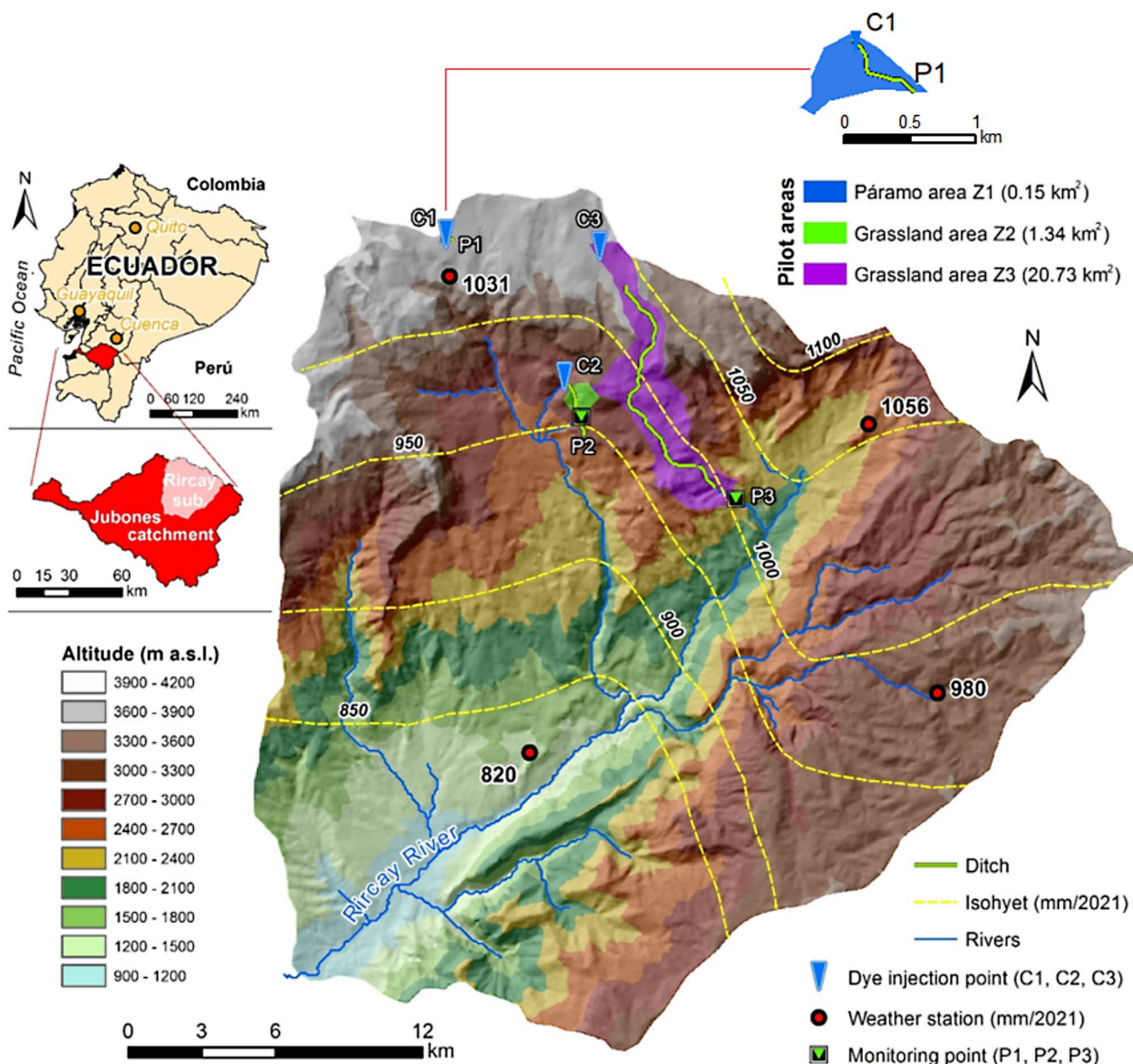


Fig. 1 Geographical location and general settings of the study area and pilot ditches in the Jubones basin, in the Andean Cordillera (Ecuador), including the spatial distribution of mean annual rainfall for the monitoring period 2018–2023

Site description

This study focuses on the sub-basin of the Rircay River, in the southern Andes of Ecuador (Fig. 1), where ancestral practices for the management of water resources have been identified. This territory occupies an area of 830 km² within the Jubones river basin, with maximum elevations reaching over 4000 m a.s.l. Water is used mainly for grazing activities (Valladares and Boelens 2019). The climate is characteristic of the Andes Cordillera in Ecuador. Rainfall is influenced by anomalous events related to phenomena such as the Southern Oscillation (ENSO), called El Niño phenomenon, with more intense rains (Tobar and Wyseure 2018). The distribution of annual precipitation is irregular (Fig. 1) and occurs mainly from December to May, representing between 66 and 91% of yearly rainfall, with maximum values from mid-February to April (Haigh et al. 2021). The mean annual temperature is 14.5 °C.

Geologically, the substrate supporting the monitored areas primarily comprises Quaternary volcanic igneous rocks, including tuffs, rhyolitic, and andesitic agglomerates. Above these materials, there are outcrops of detrital sedimentary rocks, consisting of fine- to medium-grained sandstones, rich in feldspars and quartz (approximately 80% composition), and varying in thickness from 50 to 180 m. These rocks also contain a cementing matrix of silts and clays. In addition, lower percentages (about 30%) of shales

and siltstones in shades of gray and light brown have been identified (Ávila 2020).

To ensure that water reaches the entire pasture territory, an adaptation of pre-Inca system has been used that improves infiltration into the soil and keeps the grasslands in optimal condition, especially during dry periods (Grainger et al. 2019). Water is managed through a series of diversions, channels, and irrigation ditches, built over centuries, allowing cattle pastures to be retain moisture consistently. The process begins by capturing water from rivers or streams in the páramo during the rainy season using stone intakes built into the riverbed. This diverted water is then conveyed through routing channels to areas with high infiltration capacity (Fig. 2). The primary objective of infiltrating this water is to increase and sustain spring flows during dry seasons, as it can remain stored in the subsoil for several days. However, if these channels are not properly sealed, water diverted from the river may quickly infiltrate near the intake and return to the channel as surface flow, failing to contribute to infiltration areas further downstream (Emerton 2014). Repairing the diversion channels, waterproofing the initial section, and reinforcing the channel walls enhance flow in the channels directing water to infiltration slopes, thereby optimizing the intervention's efficiency (Cassin and Ochoa-Tocachi 2021).

Three zones with these kinds of practices have been identified in the Rircay River sub-basin (Z1, Z2 and Z3 in Fig. 1), each one with different characteristics such as

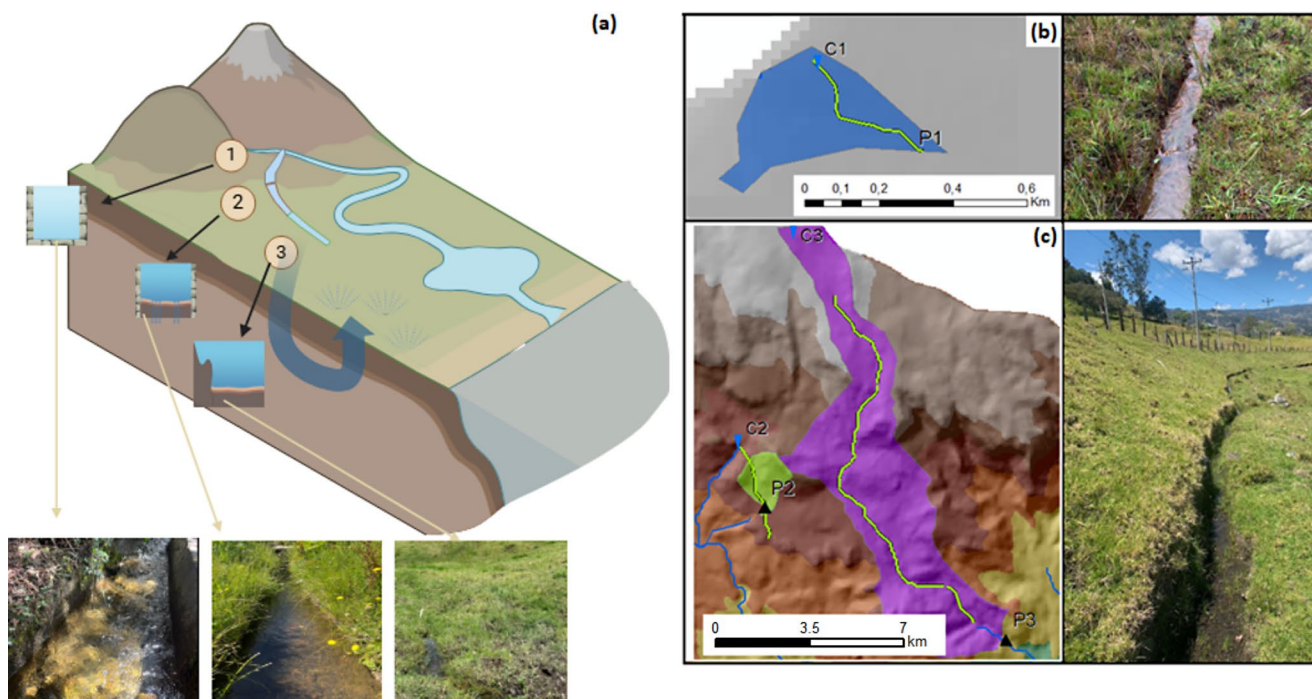


Fig. 2 (a) Conceptual linear scheme of the pre-Incan system of water infiltration improvement in the Andean region. System characteristics: routing channels (1), infiltration channels (2), infiltration slopes (3).

(b) Infiltration ditch in páramo land (Z1). (c) Infiltration ditches in cultivated pastures zones (Z2 and Z3)

surface, land use, or infiltration infrastructures, although the native land uses and the intervened uses consider for pasture differ between each other (Figs. 1 and 2). Areas of each site were estimated considering the drainage point of the contributing basin where a monitoring device was installed. After selecting the gauging points, the directions and flow accumulation were defined to assess the contributing area. The characteristics of each study zone are shown in Table 1. Water diversion begins through routing channels, which lead to the infiltration channel systems. From there, water infiltrates into the hillside through small infiltration and irrigation ditches distributed along the slope.

The monitored zone in páramo (Z1 in Figs. 1 and 2) was analyzed in detail since it does not have a system that contains channels and subsequent infiltration ditches, but only one ditch to collect and storage runoff water. The implementation of ditches in páramo soils often drains water from wetlands instead of diverting it for later infiltration. Nevertheless, this example offers valuable insights into the true implications of used water recharge systems across different land uses. A detailed understanding of these dynamics is essential to assess the effectiveness and impact of various water management practices in maintaining the ecological balance and hydrological functions of ecosystems. Páramo soils are generally moist, acidic, rich in humus, and dark brown, with low nutrient levels and slow decomposition, which contribute to surface organic matter accumulation. These young, poorly developed soils (often formed with volcanic ash) have thin profiles (<50 cm), although deeper profiles can be found in active volcanic areas (Favier et al. 2008). Soil horizons are similar across elevations, resulting in lower diversity compared to forested high and mid-Andean regions (Patiño et al. 2021).

In the Rircay sub-basin, natural grasses make up a large portion of the páramo vegetation, particularly the pajonales (*Stipa ichu*). In addition, herbaceous plants are commonly found in more humid areas, including rabbit's foot (*Geranium sp.*), sigse (*Cortaderia sp.*), and horned deer (*Halenia weddelliana*). Shrub vegetation is also abundant, with species like *Diplostephium ericoides*, which is uniquely found in Ecuador's high mountain páramo regions. However, land-use changes for cattle ranching have led to a shift from native vegetation to planted grasses, mainly ryegrass (*Lolium*) and bluegrass (*Poa annua*), known for their adaptability, rapid growth, and high biomass yield for livestock.

In this context, nature-based solutions help maintain cultivated pastures, particularly during the dry season (Grainger et al. 2019).

On the other hand, in pilot sites Z2 and Z3 (Figs. 1 and 2) cattle pasture zones were selected since the shrub vegetation and forest plantations are only small areas found in the middle of the cultivated pasture. In Z3, however, the upper part of the intervention area still contains a portion of páramo ecosystem, which may influence specific hydrological behavior. Although there are marked differences in area and slope between these zones, they were chosen because they are functional systems that enable control and evaluation of the process. The process of recharge management practice through infiltration ditches is implemented through the hillside. Thus, water is infiltrated through the soil, eventually surfacing at a downstream outcrop point, depending on the topography and drainage conditions of each site. In the study area, the páramo has a flat topography, with small canals. At lower elevations (outside Z1), on the slopes, there are cultivated areas with more relevant canals. This method aims to enhance water recharge and improve the hydrological balance in these managed agricultural landscapes.

Materials and methods

In this work, flow-rate was monitored at each of the 3 sites and tracer tests were carried out in infiltration ditches to verify the storage time into the soil.

Flow measurements

Runoff water measurements were conducted from February 2020 to January 2021 at each pilot site, where local communities have implemented water sowing and harvesting systems. Measurements were taken at the ends of the channels (referred as P1, P2, and P3 in Figs. 1 and 2), with the páramo channel featuring a rectangular cross-section and the pasture channels having a trapezoidal cross-section. The objective was to assess the initial implications of implementing these water management practices.

Regular monthly flow measurements were conducted by using the salt-dilution method, resulting in high efficiency due to the channel conditions, which facilitate complete mixing of the salt. The solution used was a mixture of common

Table 1 Characteristics of the zones with infiltration ditches selected in this study for sowing and harvesting water

Study zone	Area (km ²)	Type of vegetation cover / land use	Annual precipitation (mm)	Mean slope (%)	Altitudinal range (m asl)
Z1. Páramo	0.15	Páramo	1030–1056	9	3840–4000
Z2. Cultivated pastures	1.34	Pastures for livestock	977–1003	42	3124–2334
Z3. Cultivated pastures	20.73	Pastures for livestock	1003–1030	13	3747–2248

Table 2 Characteristics for tracer testing used in this research

	C1	C2	C3
Injected mass (kg)	0.85	1	1
Injection time (h)	7:40	11:30	14:00
Injection level (m a.s.l.)	3829	2880	3726
Monitoring level (m a.s.l.)	3804	2716	2161
Distance (m) ^a	422	1797	11,699
Vegetation cover type injection point	Páramo	Pastures	Páramo
Vegetation cover type monitoring point	Páramo	Pastures	Pastures
Soil depth	<20 cm	15–35 cm	(<15–30 cm)
Detection	Yes	Yes	Yes

^a Straight line distance from injection point to monitoring point

salt (NaCl) with water at a ratio of 250 g in 5 L. The equipment used for flow-rate measurements was a WTW model 3110 (precision of 5%), which stores continuous data later converted into water flow by integrating the electrical conductivity record. In addition, daily-step records of water level variations were recorded during the monitoring period by using HOBO U20L-02 water level sensors. The information was stored in a data logger to be later processed and analyzed in order to calculate the respective rating curve. The fit values (R^2) for the flow rate curve that relates water level to flow-rate was 0.96 for point P1, 0.98 for P2, and 0.91 for P3.

Dye tracer tests

A multi-tracer test was conducted at each pilot site (1) assess the hydrological connections between water diversions through ditches and sampling points; and (2) quantify the residence time of water into the soil layers. Three losing ditches (C1, C2, and C3 in Figs. 1 and 2) were selected for dye tracer injection at the point where the main channel deviates into the infiltration ditch network. Water samples were then collected downstream at the flow-rate monitoring points (P1, P2, and P3 in Figs. 1 and 2). Eosin (CAS: 548-24-3) was used as the tracer due to its wide use in hydrological applications (Goldscheider et al. 2008). Tracer injections were performed on the same day (March 7, 2020) during the wet season, but at different times (Table 2). Water samples were collected weekly at the monitoring points (Fig. 2; Table 2). Additionally, electrical conductivity and temperature of water were recorded also weekly using a WTW 3110 probe.

At each monitoring point, 41 water samples were collected using amber glass bottles to minimize photodegradation and microbial activity that could affect the concentration of the tracer dye. The samples were carefully stored in the dark and then analyzed using a FL 6500 Fluorescence Spectrophotometer from PERKIN ELMER. The laboratory

Table 3 Results obtained from the tracer test

Sampling Point	P1 (Z1)	P2 (Z2)	P3 (Z3)
First detection time (days)	31	91	111
Time to peak concentration (days)	154	155	160
Peak concentration ($\mu\text{g/L}$)	3.6	5.2	5.8
Tracer recovery (%)	2.7	16.9	16
Higher flow velocity (m/h)	0.6	0.8	4.4
Modal flow velocity (m/h)	0.1	0.5	3.1
Discharge flow rate (L/s) ^a	Mean	1.4	22.5
	Maximum	9.5	76.6
	Minimum	0.6	9.5
	CV	0.9	0.7

^a series comprising 345 data

responsible for these analyses was situated at the Center for Research, Innovation, and Technology Transfer of the Catholic University of Cuenca.

Results

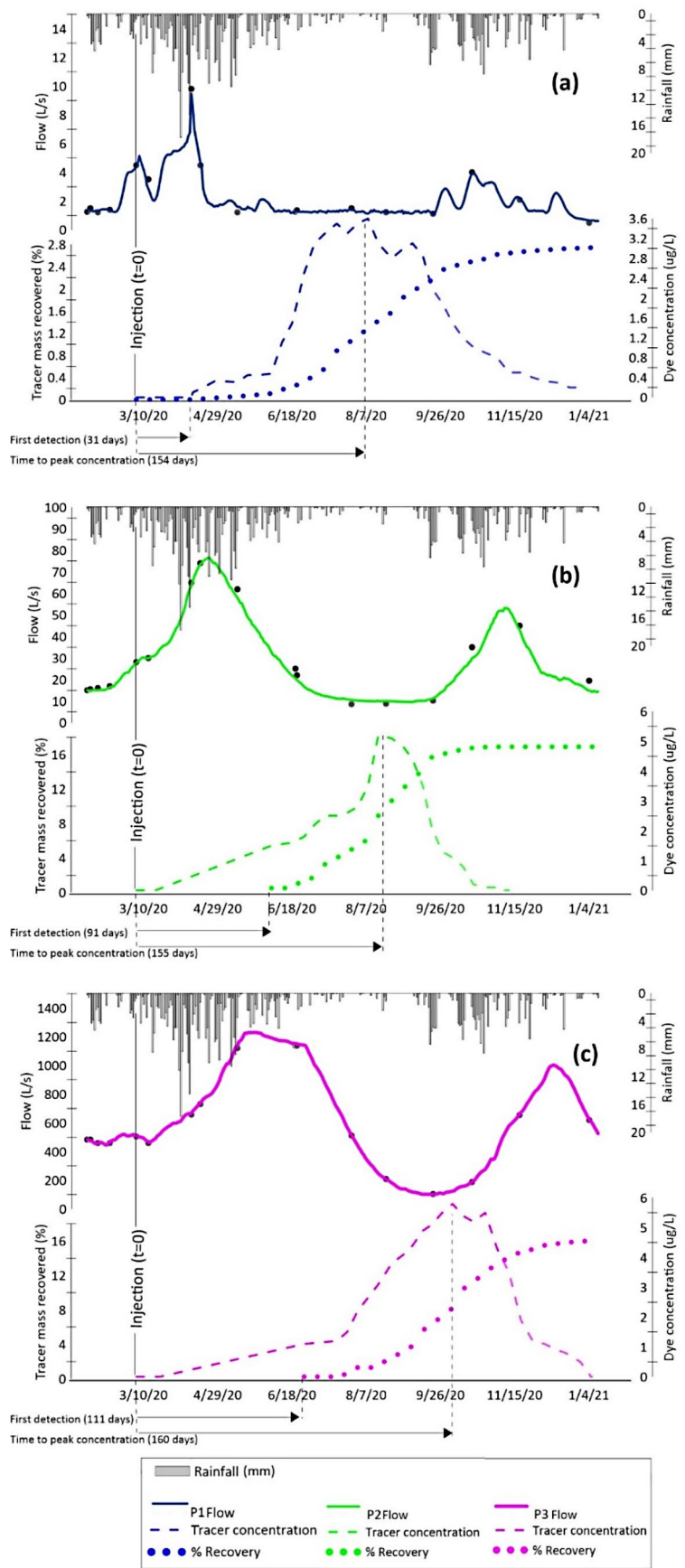
Comparative analysis of flow-rate from monitoring points P1, P2, and P3

Table 3 shows the maximum, minimum, and average flow values for each of the pilot sites, in addition to the detection times and the concentration peak of the tracer in each site. Figure 3 displays the daily evolution of the flows at the monitoring points in the cultivated pastures and páramo sites for the control period. The hydrodynamic response at each collector point of the two areas with cultivated pasture land-use shows maximum flow values of 76.6 L/s (P2) and 1230.1 L/s (P3). For the last one, which has a greater intervention through channels and infiltration ditches, a lag is observed in the maximum flow compared with the monitoring points P1 and P2. In addition, a minimum flow value of 101.7 L/s is maintained throughout the dry season in P3.

In the páramo soil (P1 in Table 3), the mean flow value was 1.4 L/s, which is lower than in the pasture soils due to the smaller extent of this zone. However, the páramo exhibited the highest coefficient of variation for discharge flow (Table 3), suggesting a possible effect of constructing infiltration channels in this type of ecosystem. The pristine soils of the páramo naturally possess high water retention capacity, which could be disrupted by such interventions. In this area, infiltration occurs directly through ditches, as there is no evidence of a water diversion system followed by infiltration channels. Introducing routing channels could unintentionally transform the system into a drainage network, compromising the natural infiltration process thereby reducing the water storage capacity.

The hydrodynamic response of the cultivated pasture soils shows inertial behavior in response to precipitation

Fig. 3 Hydrographs of water flows at the monitoring points and breakthrough curves (BTC) for Eosine at the three discharge points located after the water diversions in the research site: **(a)** water flow in P1, **(b)** water flow in P2, and, **(c)** water flow in P3 (See location in Fig. 2)



(Fig. 3b and c, and Table 3), with smaller variations between the mean and extreme flow values. This shows the influence of irrigation ditches on water infiltration and the overall response in these areas. The relationship between recorded rainfall and the amount of water produced is proportional to the catchment area where each evaluated system is located. In the most heavily intervened area (Fig. 3c), there is a delayed response to peak rainfall attributed to water behavior and retention times within the soil. In the smaller intervention zones (Fig. 3a and b), the flow peak aligns with the maximum recorded precipitation, showing no time lag.

Tracer test results

Tracer dyes were applied to evaluate water residence times in soils where ancestral sowing and water harvesting systems have been implemented. This approach aims to identify potential applications for water resource management and to develop a conceptual model for water storage to support its use in the dry season. Figure 3 presents the breakthrough curves (BTC) for the concentration of eosin detected in the water of each catchment. Weekly monitoring links water residence times in soils to infiltration enhancement processes. Eosine was detected in páramo soils 31 days after injection (Table 3), while first appearances occurred at 91 and 111 days at points P2 and P3, respectively, in the soils of cultivated pastures.

The highest tracer concentrations were recorded in August 2020 for sites P1 and P2, with values of 3.6 µg/L and 5.2 µg/L, respectively. For site P3, the peak concentration occurred in September 2020, reaching 5.8 µg/L. Following these peaks, tracer concentrations progressively decreased until they completely disappeared: in P1 and P2 by November and in P3 by December. The breakthrough curves (BTC) for P1 and P2 showed a continuous decline beginning in August, whereas the curve for P3 exhibited a delayed decline due to the longer travel distance. In P3, the concentration began decreasing steadily after September 14, with a slight increase before tapering off until December 13.

Tracer tests in various terrains (páramo and cultivated pasture) reveal significant variations in water velocity and recovery rates based on location. In the páramo (P1), the maximum water velocity was 0.6 m/h, and the recovery rate was low (2.7%), indicating higher water retention in the soil. In contrast, in the cultivated pasture areas (P2 and P3), velocities were higher (0.8 m/h and 4.4 m/h, respectively) with higher recovery rates (16.9% and 16%), suggesting more efficient water transport. These findings are crucial for understanding water behavior and management in different ecosystems.

Discussion

This research highlights the water retention capacity in the subsoil of the pastures used livestock, suggesting that ditches could serve as a practical solution for managing water resources in livestock districts. Implementing such systems could reduce water consumption from main channels while attenuating flow peaks caused by soil compaction, which decreases water retention capacity (Vanacker et al., 2022). Moreover, these applications could extend beyond water security to include flood prevention. A study conducted by Kato & Huang (2021) demonstrated how natural infrastructure can attenuate runoff from heavy rainfall events.

The results from the three pilot sites located in the Andes Cordillera (Ecuador) revealed variations in flow behavior, influenced by factors such as the size of the intervened area, soil type, vegetation cover, and the dimensions of the ditches used; these data are presented in Tables 1 and 2. Cross-sectional areas of the channels have not been included in this analysis, as the main objective was to understand water retention times through infiltration processes on the slope.

In the páramo zone, a distinct hydrodynamic response occurred possibly linked to the inherent potential storage capacity of the soil. According to Buytaert et al. (2007) and Anthelme and Peyre (2020) infiltration processes through irrigation ditches in pristine soils with natural storage characteristics may not generate significant benefits; in fact, they could potentially compromise the water storage capacity of moorlands. Various effects on different types of páramo ecosystems in South America have been determined by cattle ranching activities, as confirmed by Molinillo (2002). The primary impact is the change in vegetation cover, leading to a loss of water storage capacity (Buytaert et al. 2006; Marín et al. 2018; Patiño-Gutiérrez et al. 2024). Therefore, in these areas, the results clearly indicate that the practice of irrigation ditches is detrimental to the hydrological functioning of the ecosystem.

However, cultivated pasture areas exhibit flow regulation when irrigation ditches are implemented to enhance water infiltration, making the advantages of this practice clear. In the páramo zone, the soil's natural regulating capacity reduces the visibility of this effect. In cultivated pasture lands, the use of infiltration ditches improves the attenuation and prolongation of the hydrograph. This effect is most pronounced in Z3, which covers a larger area and more extensive implementation of these practices has been performed.

The greater presence of the dye tracer in Z3 could be related to the size of the area since there is a greater amount of infiltration ditches and a lower slope. Z2 and Z3 grassland areas have a delay of several days in the appearance of the tracer concentration directly related to the size of the

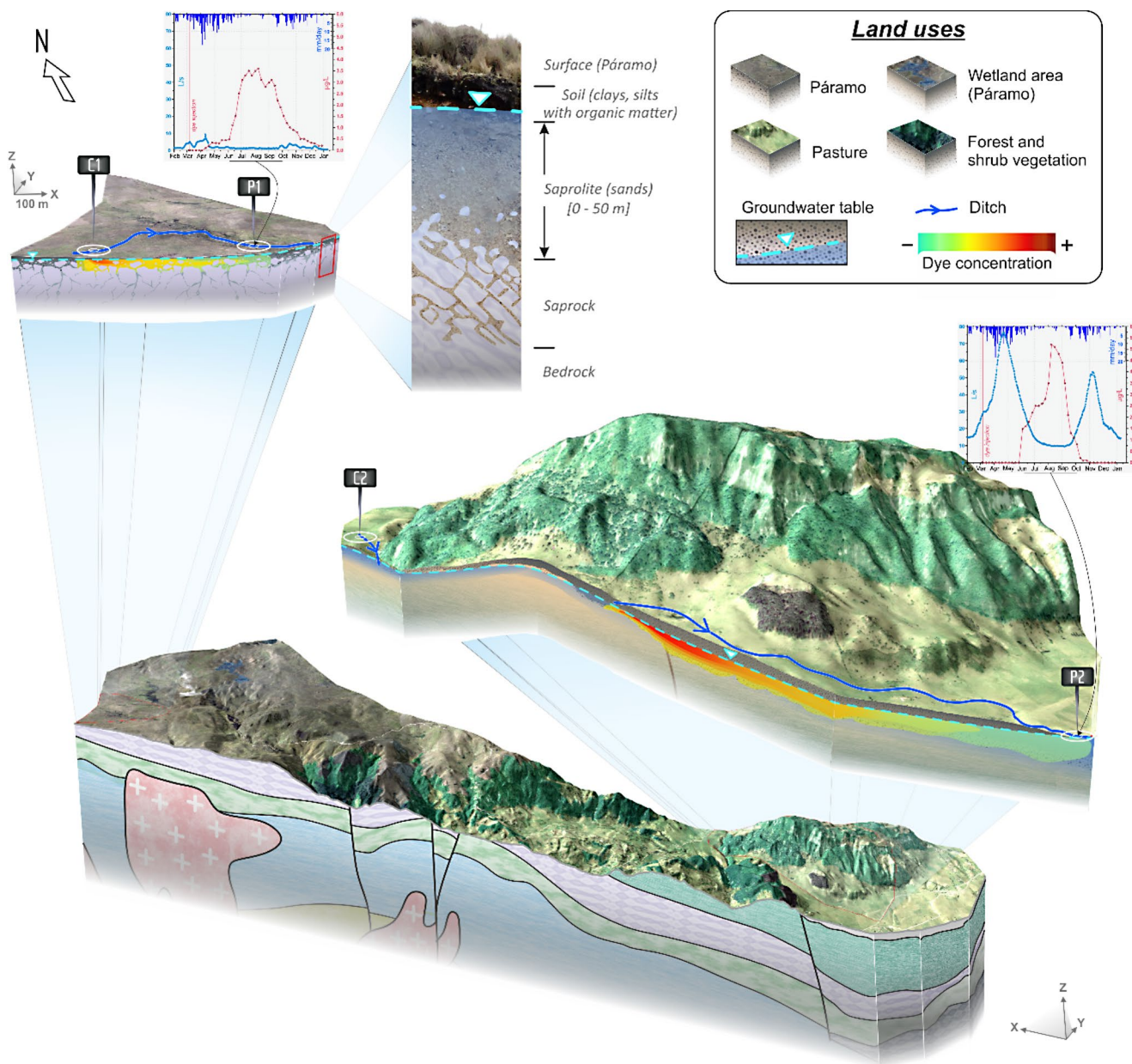


Fig. 4 Hydrological conceptual model for the recharge management practices (sowing and harvesting water) applied the study area, considering differences in land uses

considered extension. Between the two zones, the biggest difference is the average flow rates that directly relate to the size of the areas. Another fundamental difference is the flow peaks, with an earlier response in the smaller cultivated pasture area (Z2; Fig. 3).

Although the monitoring distance in the páramo ditch is the shortest, the flow velocity is also the lowest, indicating that water can be retained longer in these soils. For the second grassland ditch at monitoring point P3, the maximum flow velocity is the highest, suggesting less water retention in this type of soil, allowing for faster drainage. Additionally, these results may be attributed to hydrological

conditions, such as the greater accumulation of runoff water in the ditch.

A hydrological conceptual model developed in the framework of this work explains water flows through infiltration ditches in each pilot site (Fig. 4). In páramo soils, infiltration ditches are located in the most elevated parts of the mountain, where slopes are low, and drainage areas are small. The presence of these ditches (C1 - P1) primarily facilitates water flow toward specific location, but does not significantly enhance the natural characteristics of pristine soils. The implementation of ditches proves more beneficial in areas covered with grasses, particularly when larger sizes are

applied in regions with higher water pressure. In this case, water infiltration into the soil and subsequent recovery (C2 - P2) optimize water resource management by maintaining soil moisture and enabling water recapture. Initially, water is diverted through the primary irrigation ditches, where it infiltrates the soil. The soil absorbs moisture from the initial water diversion through the primary irrigation ditches, where it undergoes infiltration. Subsequently, water permeates through the ground to reach the drainage point, where it is recaptured (P2 in Fig. 4). Monitoring these ditches allows for the identification of optimal locations efforts, ensuring a reliable water supply for irrigating pastures in areas where it is most needed.

In Ecuador, ancestral knowledge on water management practices, such as those studied by Carrión et al. (2018) in a coastal aquifer, have proven to be valuable tools for the sustainable management of water resources (Carrión-Mero et al. 2021). Although such methodologies were successfully applied in that context, the present research focuses on an Andean region, where differences in altitude, morphology, soil type and land uses pose specific challenges. However, the ultimate goal remains the same: to store water for long periods to ensure its availability in dry seasons. Albarracín et al. (2021) analyzed the advantages of water sowing and harvesting practices in Andean watersheds in southern Ecuador, particularly in *cochas*, as small artificial water sources; validating the importance and efficiency of these systems to mitigate the effects of drought. They also emphasized the fundamental role of community practices in the recovery of these ancestral systems, which not only improve water quality, but also the water resilience of local communities.

To optimize the management of these resources through ancestral practices, it is crucial to evaluate key aspects such as water retention time, the interconnection between wastewater systems and the capacity of flows to favor water retention. These findings are consistent with the results of Ochoa-Tocachi et al. (2019), who studied an ancestral system specifically designed to store water during dry periods. In that research, an average residence time of 45 days was estimated, a value comparable to the 31 days recorded at the páramo site in the present study. However, in areas dedicated to cattle grazing, a significantly longer time was required to observe these processes due to the greater extension of the areas and the fact the water had to travel distances.

The high porosity and low bulk density of páramo soils, along with local climatic conditions, provide excellent potential for water storage and minimizing surface runoff. Various authors (Cárdenas Aguedo 2016; Quichimbo et al. 2012) report that higher soil degradation correlates with higher suction rates, while preserved soils have lower suction rates. Soils with natural vegetation, like páramo, can

have suction rates of 0 KPa indicating high water retention curves. In contrast, cattle ranching results in faster increases in soil suction, indicating reduced water retention (Patiño et al. 2021).

The studies by Somers et al. (2018) and Lafevor & Ramos-Scharrón (2021), alongside the findings of Jódar et al. (2022), provide a comprehensive perspective on the role of trenching and irrigation channels in enhancing water infiltration and modulating hydrological dynamics across diverse environments. While the modest recharge increases (1.2–2.5%) observed in the Shullcas River Watershed, Peru, and subalpine catchments in Mexico highlight the potential of trenching to capture runoff during rainfall events, the results from the Bérchules basin, Spain, emphasize the critical influence of water origin on recharge efficiency. The significant recharge increment of 65% in the Spanish test site, driven by continuous snowmelt infiltration, underscores the potential for prolonged water availability in snow-fed systems.

Moreover, Barberá et al. (2018) demonstrated the ability of irrigation channels in the Sierra Nevada to significantly enhance aquifer recharge, exceeding natural levels. By using isotopic analysis, they observed reduced snowmelt peaks and increased base flows, which align with the capacity of unsaturated and disturbed soil zones to act as reservoirs under managed infiltration conditions. These findings reinforce the notion that engineered structures such as trenches and channels not only facilitate recharge but also contribute to peak flow attenuation, thus improving watershed hydrodynamics.

The analysis of the páramo hydrograph demands careful attention, particularly when comparing the three monitoring points across two different soil types. Several factors influence runoff processes in this environment, including antecedent moisture, field capacity and the concentration of organic matter, among others. In páramo ecosystems, sustained base flow with high-quality water is collected and stored, resulting in a sustained base flow that is gradually released (Flores-López et al. 2012, 2016). Understanding these hydrological dynamics is crucial for developing effective water management and conservation strategies in these sensitive ecosystems. By closely examining the hydrograph and runoff processes, we gain deeper insights into the unique hydrological functions of the páramo, enabling the creation of targeted approaches to preserve its ecological balance and ensure a reliable water supply.

Different studies have presented the effects of changes in land use on the amount of water within the Andean basins, such as Kim et al. (2013), Avilés et al. (2020) and, especially changes from native vegetation to cultivated pastures (Strauch et al. 2009); Taniwaki et al. 2017). Other studies, such as Mosquera et al. (2022) showed a superior presence

of wetlands and native vegetation when higher maximum and mean water flows values are observed than in regions where the vegetation cover has changed. The change in land use and vegetation cover changes the native rhizosphere, which is a determinant for soil response since it is the zone of water and nutrient flows and where biogeochemical processes become very active. Its greatest effect would be given for the surface horizons, while for the subsurface horizons, the depth would be a limiting factor for root development. This has led to the hydrophysical properties being affected to a lesser degree (Quichimbo et al. 2012). According to the data presented in this work, ditches favor subsurface water recharge, improving hydrophysical properties such as water retention; useful for management of the resource in areas where native vegetation cover has been lost, such as grasslands.

Therefore, the ancient techniques for water management showed in this research represent an improvement in the water regulation of the basin, especially in soils that have lost their natural capacity to store water for times of low water. With the analysis of the hydrographs, there is sufficient evidence to affirm that the intervention processes generate water retention in the soil with the potential to be used as a resource management technique and climate change mitigation.

Conclusions

Traditional water management techniques, such as irrigation ditches in the Andes Mountains' watersheds, have evolved to ensure sustainable water resource management. These methods promote water infiltration into the subsoil, ensuring a consistent supply for sub-basin users, particularly during dry seasons.

Flow measurement and dye tracer tests have demonstrated a clear correlation between water diversion through irrigation ditches and subsequent outflows after the infiltration processes. These tests reveal extended water retention times within the soil, ranging from 31 to 111 days, indicating the potential for water availability even during dry seasons. Interestingly, in páramo soils, the water harvesting process does not significantly enhance their hydrological response. However, tracer tests highlight extended water retention in this soil, underscoring their unique characteristics and interconnections within páramo soils, which possess distinct attributes related to water storage and subsurface flow transport.

The introduction of irrigation ditches yields two distinct outcomes. First, they significantly improve water retention in the subsoil and enhances the recharge of hillside aquifers, exceeding the levels achievable through natural recharge

alone. Second, it modifies basin hydrological dynamics by reducing peak runoff discharges and increasing subsurface flow, especially during low-rainfall periods.

High mountain watersheds in the Andes display deviations from expected hydrological patterns due to the impacts of global warming. Consequently, implementing similar water management systems using irrigation ditches in alpine basins worldwide could serve as an effective strategy for climate change adaptation, enhancing water security and resilience in these vulnerable environments.

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Data availability The data will be provided in a supplementary file.

Declarations

Competing interests The authors declare no competing interests.

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