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Cryospheric headwater genesis discrimination and social perception under megadrought and climate change scenarios: the Putaendo Valley case, Chile

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The Putaendo watershed (Central Andes, Chile), notable for its pre-colonial history and as the first independent Chilean town (1817), also exhibits special hydrological features. It is one of the few areas in the Andes Cordillera where the inhabitants rely almost entirely on periglacial water sources. Since 2010, the region has also experienced a severe megadrought, drastically altering the water supply and straining the livelihoods of pastoralists and peasants to the limit. However, despite the significant decrease in precipitation recorded during the megadrought, water continued to flow from the headwaters to the Putaendo River. To elucidate the mechanisms behind this water persistence, we quantified the individual contributions of different water sources (snow, rock glaciers, and groundwater) within this basin through the analysis of stable water isotopes and major ions. The region's simple winter precipitation regime, another crucial hydrological characteristic, further facilitates the clear discrimination and quantification of meltwater inputs distinct from precipitation using physicochemical tracers. Additionally, to comprehensively understand public knowledge regarding water origin, the impact of the megadrought and climate change, and the potential development of mega-mining projects (as this is the last basin without this activity in the Chilean Central Andes), we conducted a social perception analysis using a cross-sectional descriptive survey with non-probabilistic causal sampling. Upstream of the Chacrillas dam's, where there is minimal human intervention, the river in this arid water cycle exhibited a marked predominance of water contributions from rock glaciers (56.1%), followed by groundwater (32.7%) and snow (11.2%). The inhabitants of the territory domonstrates a remarkable awareness and prior knowledge, with 45.5% of respondents identifying rock glaciers as the main source of water during dry years.

There was also a clear negative public opinion regarding the developing of mega-mining projects in the valley (84.1%). Integrating these perceptions of water scarcity's social complexities with an advanced understanding of water source contribution provides crucial information for regional water security management.

KEYWORDS

stable isotopes, water sources, rock glaciers, Central Andes, social perception, Putaendo Valley, climate change

1 Introduction

Chile is one of the most vulnerable countries to climate change (Arriagada et al., 2018). Alarming changes have already been observed in central Chile, with significant increases in temperature and decreases in precipitation, which have impacted the territory's water security (Carrasco et al., 2008; Falvey and Garreaud, 2009; Boisier et al., 2016; Garreaud et al., 2020). A widespread meteorological drought has severely affected the hydrological cycle of the Central Andes of Chile and Argentina (31–35°S) from 2010 to 2022 and has been referred to as the "Megadrought" (Garreaud, 2015; Garreaud et al., 2017; Garreaud et al., 2020; Muñoz et al., 2020; CR2, 2024). This event has occurred during the warmest decade of the last 100 years and seems to be unmatched by any drought in the last millennium (Morales et al., 2020). Additionally, long-term projections do not offer a more optimistic outlook for this Andean region as a higher frequency of droughts is expected in the coming decades (Bradley et al., 2004; Stocker et al., 2013; Rivera et al., 2020).

The inhabitants of the Central Andes depend on the precipitation originating from westerlies, whose genesis lies in the Pacific Ocean moisture source. The origin of the precipitation system that recharges the Central Andes of Argentina and Chile is relatively simple, with precipitation occurring during the austral winter and dry, sunny conditions prevailing in summer. As these winds travel from the ocean's interior, they gather moisture through evaporation, forming clouds that are carried inland. As they move across the mainland, these clouds release their moisture, replenishing rivers, glaciers, groundwater, wetlands, lagoons, lakes, and aquifers. These westward storms gradually release moisture as they ascend the Andean massif, where temperatures decrease due to tropospheric cooling at higher altitudes. Winter precipitation, primarily in the form of rain, in coastal areas, the Coastal Cordillera, and the central plain of Chile plays a crucial role in supporting evapotranspiration, meeting domestic water demand, and partially recharging aquifers. Upon reaching the morphotectonic units of the Cordillera Principal (Chile and Argentina) and Cordillera Frontal (Argentina), these storms help form and sustain glacial and periglacial environments, slowing the release of water stored in the solid form. This hydrological process influences the recharge of aquifers, wetlands, glaciers, rock glaciers, and snow, which together constitute the so-called "water towers" and modulate water availability for downstream populations (Viviroli et al., 2007).

Differences in landscape features—based on geology, topography, and snow and ice melting conditions—result in distinct air and sediment contact times for each water source, leading to different chemical characteristics in terms of ionic composition and stable isotopes (Crespo et al., 2020a; Crespo et al., 2020b).

The Chilean Central Andes, the country's most densely populated territory, faces considerable water resource stress due to the convergence of intensive agricultural, forestry, and mining activities, leading to substantial overexploitation (Taucare et al., 2024; Alvarez-Garretón et al., 2023; Fuentes et al., 2021; Webb et al., 2020; Aitken et al., 2016). This situation has resulted in severe water scarcity and has led to various hydro-social conflicts, driven by legally supported unequal access to water (Budds, 2004; Martin et al., 2013; Webb et al., 2020; Fragkou et al., 2023). The Putaendo River basin is one of the sub-basins in the region that is most vulnerable to drought events; however, its main water sources remain largely unknown. The effects of the megadrought event in the Putaendo River basin can be observed based on the variation in the rainfall anomaly index presented in Figure 1.

Previous work has focused on the Aconcagua River basin, of which the Putaendo River is a tributary (Crespo S. A. et al., 2020). In that study, we used a Bayesian model incorporating physicochemical and stable isotope data to approximate, characterize, and discriminate the contributions of various water sources: snow, glaciers, rock glaciers, and groundwater. Water isotope $\delta^{18}O$ and electrical conductivity were identified as the key parameters for the differentiation of each water source in principal component analyses as they explained most of the variability. During dry cycles, 76% of the Aconcagua River basin's summer water supply comes from sources other than snow (which accounts for the remaining 24%); this supply is crucial for crop irrigation, industrial, and domestic water demands. Breaking down the composition, the water supply was 34% from glacial origin, 23% from the periglacial sources, and 19% from groundwater. These results are consistent with those of previous studies (also in dry cycles) by Janke et al. (2017) and Rodriguez et al. (2016). Janke et al. (2017) estimated between 50% and 90% water input from glacial and periglacial environments for the Aconcagua River. Rodriguez et al. (2016) analyzed the Juncal River basin, a tributary of the Aconcagua River, and estimated that 80% of water is from sources other than precipitation (glacial, periglacial, and groundwater).

Building on this research, the present paper expands the water source assessment to the Putaendo territory and complements the hydrological and hydrochemical investigations with a social analysis.

1.1 Study area

The Putaendo Valley is located in the Valparaíso Region (Central Chile), in the northeastern area of the Aconcagua River basin, and constitutes one of the headwaters of this river. The

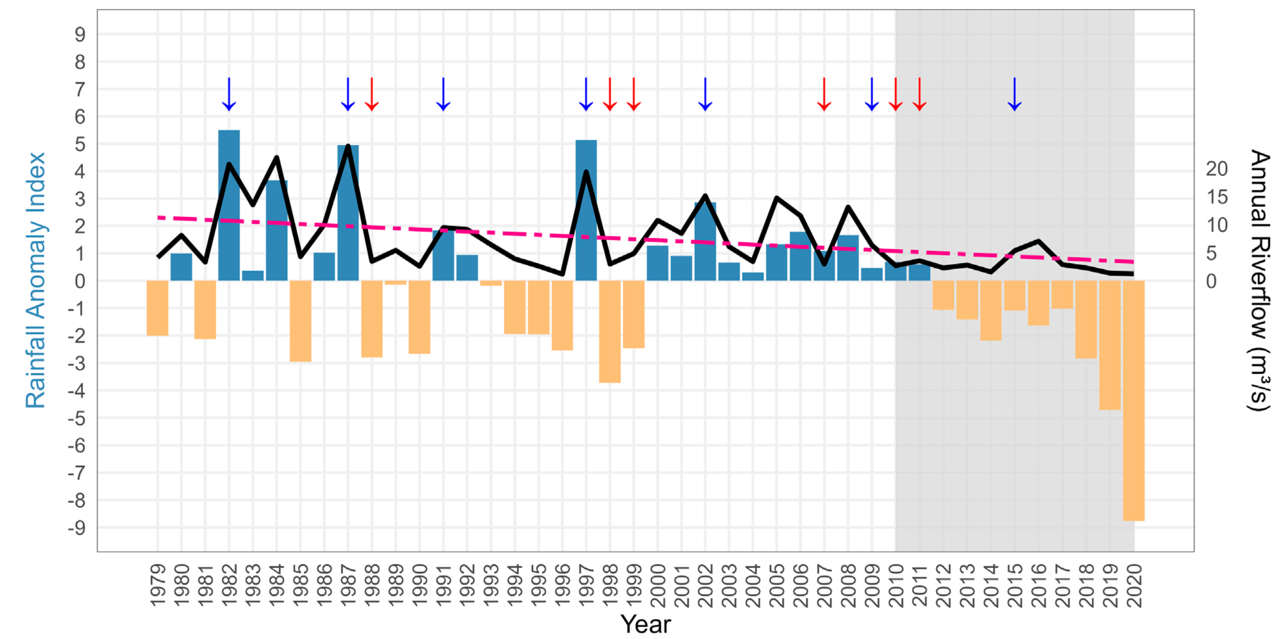

FIGURE 1
Flow response of the Putaendo river to drought and wet conditions. The Rainfall Anomaly Index (RAI) [calculated according to Hänsel et al, (2016)] is represented by blue (positive) or orange (negative) bars, and the average annual flow is indicated by the black line. The upper arrows mark the Niña (red) and Niño (blue) years (NOAA/National Weather Service, 2019). The dotted purple line marks the trend of decreasing average flow, and the gray shading marks the megadrought period. Hydrological data source: Alvarez-Garreton et al. (2018) and available data at the DGA website (DGA, 2019).

lithology of the study area (Figure 2) is dominated by volcanic rocks ranging from early Cretaceous (Pelambres Formation) to middle Miocene (Farellones Formation), including dacitic–rhyolitic tuffs, andesites, and basalts, with intercalations of sandstone and conglomerate (Rivano et al., 1993; Rivano, 1996). The recent sedimentary sequences in the valleys consist of alluvial, fluvial, and glacial sediments, which originated from erosional processes (post Pliocene) in the Principal Cordillera. Moreover, this region is affected by a NS-oriented brittle deformation zone known as the Pocuro Fault Zone (PFZ; Rivano et al., 1993).

This rock glacier-fed watershed presents a unique combination of characteristics: a simple precipitation regime dominated by Pacific winter snowfall, followed by sunny and dry summers (Garreaud et al., 2009), along with long-term human settlement patterns. These climatic conditions play a crucial role in distinguishing physicochemical water tracers.

As a historically significant population center within a major river watershed, it has relied on melt water from rock glaciers to sustain water availability during dry cycles. This makes it one of the few Andean watersheds—and the only one in the Central Andes—where such a combination of factors allows for the quantitative assessment of the socio-hydrological significance of rock glacier-derived water resources.

The aim of the study was to quantify potential sources of water supply to the main tributaries of the Putaendo River and complement these results with a social perception survey that was conducted in the territory. This study offers an interdisciplinary approach by integrating scientific data on water contributions from various sources with an analysis of the social perceptions of the territory. The study's results inform decision-making for future activities in the basin as it is the last basin in the central Chilean Andes without large-scale mining operations. Additionally, it provides valuable insights into social perceptions of water origins, the impacts of the megadrought, climate change, and the potential consequences of extractive activities. This research enhances the understanding of the strengths and weaknesses within the framework of territorial water security in Andean basins. Given the scarcity of such approaches, this study is particularly important in a context where the role of water contributions from the periglacial environment is increasingly questioned.

2 Methodology

2.1 Skin temperature

Skin temperature (ST) data determine the amount of net longwave radiation emitted from the Earth's surface and are, therefore, critical variables for studying environmental processes over land such as climate variability, land cover/use change, cryosphere, Earth's energy balance, and urban heat (Westermann et al., 2012; Hulley et al., 2014; Hulley and Nickeson, 2020). The only way to measure ST with high temporal resolution and extensive spatial coverage across the Earth is through satellite observations (Hall et al., 2013). Satellite-based thermal infrared data are directly linked to the ST using the radiative transfer equation.

In this contribution, the ST estimation was based on MODIS satellite platforms (Terra and Aqua). Both platforms include thermal products (MOD21A1D and MYD21A1D), with a daily temporal and

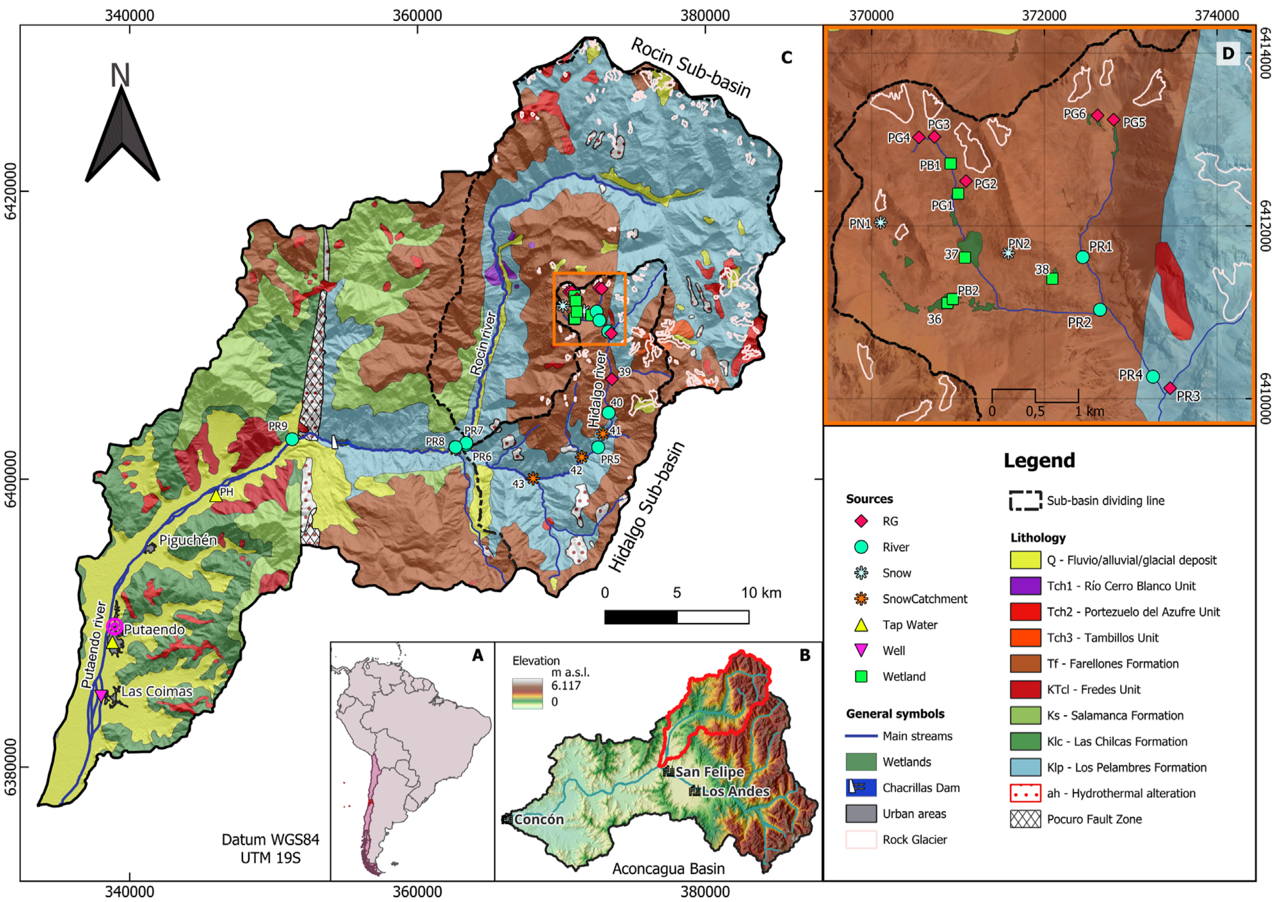

FIGURE 2
Approximation maps of the study area. Panel **(A)** highlights the Valparaíso Region within the limits of Chile; **(B)** Aconcagua River basin DEM highlighting the Putaendo River basin; **(C)** Putaendo River basin with the geology of the area (based on the study by Rivano et al., 1993), sampling sites, and rock glacier bodies obtained from the National Glacier Inventory (IPG, 2022); **(D)** Hidalgo River headwater (zoomed-in view).

spatial resolution of 1 km^2 and an uncertainty of ±1°C (Hulley and Nickeson, 2020), from February 2000 to October 2023 (Figure 3).

2.2 Snow cover area

To identify the snow cover area (SCA) in the Putaendo catchment, we used daily data from the MOD10A1 and MYD10A1 products at a 500-m resolution from February 2000 to October 2023 (Riggs et al., 2019). The basis of snow classification is the normalized difference snow index (NDSI) (Fugazza et al., 2021) (Figure 3).

2.3 Total precipitation

The total precipitation parameter from ERA5 is the accumulated liquid and frozen water that falls to the Earth's surface generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS) (Hersbach et al., 2020). ERA5 is the fifth-generation ECMWF reanalysis for the global climate and weather, covering the period from the 20th century to the present. For the reanalysis, the accumulation period is set to daily intervals. It is the depth the water (mm) that would result if it were evenly spread over the grid box (31 km). The major issue with ERA5 is the overestimation when the automatic weather station (AWS) registers zero accumulation. To determine the confidence of the ERA5 reanalysis data, the dataset was compared against the daily cumulative rainfall records of the Resguardo los Patos AWS from the Dirección General de Aguas of Chile (https://climatologia.meteochile.gob.cl/application/informacion/fichaDeEstacion/320068). We calculated the root mean square error (RMSE) and the average absolute difference (AAD). Overall, ERA5 overestimates the AWS records (AAD) by 0.64 mm d^{-1}. A scatterplot between AWS and ERA5 records showed a linear fit (R^2 = 0.54, p-value<0.05) and an RMSE equal to ±0.89 mm d^{-1}. ERA5 captures 48% of the zero-accumulation registered from AWS. In the remaining cases (52%), when AWS registered zero-accumulation, ERA5 showed accumulation between 0.0006 mm d^{-1} and 5 mm d^{-1} (Figure 3).

2.4 Spatial sampling

To analyze variations in surface temperature, SCA, and total precipitation variables across the catchment, our observations were grouped into three zones, namely, lower, middle, and upper catchment. The lower catchment includes sites between 526 and 1,513 m a.s.l. (Figure 3a), the middle catchment ranges from 1,514 to 2,993 m a.s.l. (Figure 3b), and the upper catchment consists of sites above 2,993 m a.s.l. (Figure 3c).

2.5 Sampling and hydrochemical analysis

A total of 33 water samples were collected during January 2021. Samples were taken from nine sites, as summarized in Figure 2. Our sampling focused on the main Putaendo River tributaries, rock glaciers, snow, snow catchments, and groundwater (Supplementary Table S1).

For isotopic analysis, the water samples were collected in 50-mL plastic tubes (Falcon, Corning, NY, United States), and for physicochemical analysis, they were collected in 1-L plastic bottles (frozen until laboratory analysis); both were sealed with thermoplastic cohesive (Parafilm, Neenah, WI, United States) to prevent evaporation. *In situ* electrical conductivity and temperature were measured using automatic temperature-compensated conductimeters (Hanna Instruments). A PWT HI98308 (range: 0.0–99.9 µS cm^{-1}, resolution: 0.1 µS cm^{-1}) was used to measure electrical conductivity below 100 µS cm^{-1}, and a DiST® HI98303 (range: 0.0 to 1999 µS cm^{-1}, resolution: 1 µS cm^{-1}) was used for values above this threshold. The isotopic determination was performed at the Laboratorio de Análisis Isotópicos of the Andrés Bello University (LAI-UNAB), Viña del Mar (Chile), using a "Los Gatos Research" LGR OA-ICOS laser absorption spectrometer, with analytical uncertainty for $\delta^{18}O$ and $\delta^{2}H$ less than 0.1‰ and 0.8‰ VSMOW, respectively (Supplementary Table S1). Physicochemical analysis was conducted at LAI-UNAB, where sulfate, magnesium, potassium, and chloride concentrations were measured using the iris Visible HI801 spectrophotometer (340–900 nm). This method provided accuracies of ±5 mg/L ±3% for sulfate, ±3 mg/L ±3% for magnesium, ±2 mg/L ±7% for potassium, and ±0.5 mg/L ±5% for chloride. Bicarbonates and calcium were determined by titration using sulfuric acid (0.01639 N). Sodium and pH were measured using an ISE multiparameter (Hanna HI98191) with detection limits of 0.23 mg/L for sodium and an accuracy of ±0.01 pH.

2.6 Water ionic and stable isotope composition statistical analysis

Principal component analysis (PCA, FactoMineR 2.8 package; Lê et al., 2008) was performed on the physicochemical data to identify water sources. The correlation between the first PCA dimension and electrical conductivity was tested using a Spearman test as data normality was not verified. Generalized linear mixed-effects models (nlme package v3.1-162; Pinheiro et al., 2021) and multi-model inference (MuMIn package v 1.48.4; Barton, 2024) were used to determine the significance of the variables most strongly correlated with the two main axes of variation identified in the principal component analysis (Table 1). All statistical analyses were performed using R software in the R Studio environment (R Core Team, 2023). To quantify the contribution of the different water sources, the hydrochemical data were included in a Bayesian model (package simmr v 0.5.1.215; Govan and Parnell, 2023), where each value was combined with 100,000 pseudo-replicates. This model analyzes the contribution of different water sources (snow, rock glaciers, and groundwater) using two tracers, namely, $\delta^{18}O$ and electrical conductivity. Based on Gaussian parsimony, it estimates mean contributions with 95% credible intervals, indicating a 95% probability that the true value falls within this range. Thus, the selected water sources represent the main contributors. Due to the lack of boreholes in the mountainous areas, groundwater samples were collected from APR ("Agua Potable Rural") boreholes in Las Coimas (Figure 2). To enhance statistical representativeness, both fresh snow and snow catchment samples were classified as "snow."

2.7 Social perception survey

We conducted a cross-sectional descriptive survey with non-probabilistic causal sampling to characterize social perceptions of the impact of the megadrought, climate change, mega-mining activity, and the natural water supply from different water sources. As detailed in Section 3.3, the survey included 16 multiple-choice and open-ended questions and was conducted among 88 residents of the Putaendo Valley (Supplementary Table S2). The responses were analyzed and presented as percentages, accompanied by figures for improved visualization. The results are interpreted in relation to the hydrological information collected and the relevant literature on the topic. The territorial survey had the approval of the PUCV Bioethics and Biosafety Committee, code BIOPUCV-H 438–2021.

3 Results and discussion

3.1 Precipitation analysis

During the sampling, there was an absence of liquid and solid precipitation events throughout the basin, according to ERA5, SCA reanalysis data, and fieldwork observation. The last precipitation events recorded prior to sampling occurred between 17 December 2020 and 31 December 2020, particularly in the upper watershed (Figure 3c). By 6 January 2021, the precipitated snow had mostly melted as a result of average temperatures above 20°C.

3.2 Water source supply: discrimination and quantification

The following section presents the differentiation of water sources along the upper and lower zones of the Putaendo River basin. In the upper sub-basin, represented by the Hidalgo River at the PR1 sampling point (Figure 2; 3,404 m a.s.l.), streamflow composition was dominated by contributions from rock glaciers (63.0%), followed by groundwater (16.5%) and snowmelt (20.5%). In contrast, the PR2 sampling point—located in a sub-basin to the west of PR1 (Figure 2)—showed a markedly different composition, with snow accounting for 88.0% of streamflow and much lower contributions from rock glaciers (6.1%) and groundwater (5.9%).

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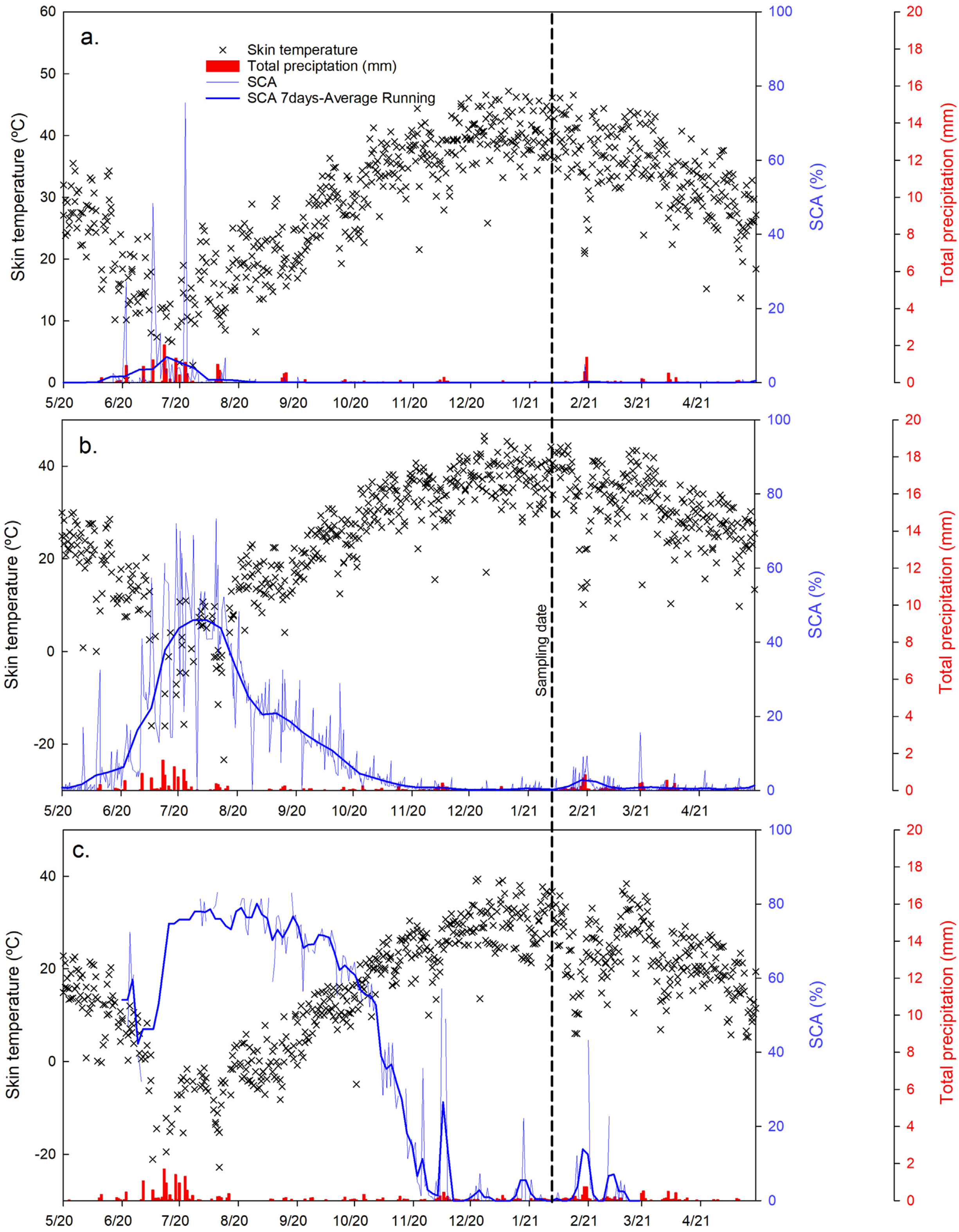

FIGURE 3
2020/2021 seasonal trend of skin temperature, snow cover area (SCA), and total precipitation in the lower **(a)**, middle **(b)**, and upper **(c)** basins.

TABLE 1 Mean, standard deviation (SD), and p-values for $\delta^{18}O$ and electric conductivity (EC) composition for water sources compared with rock glaciers. Akaike weights were w = 0.99 and R^2 = 0.82 and w = 1 and R^2 = 0.67 for $\delta^{18}O$ and electric conductivity, respectively.

Water source	Mean $\delta^{18}O$‰	SD $\delta^{18}O$	p-value	EC µS cm^{-1}	SD EC	p-Value
Rock glacier	−14.23	0.23	<0.001***	172.71	39.19	<0.001***
Groundwater	+1.28	0.65	**0.0807.**	+253.95	106.80	**0.0342***
Snow	+2.13	0.36	**<0.001*** **	−79.88	57.68	0.2175

Note: The significant codes are as follows: 0; "***" 0.001; "**" 0.01; "*" 0.05; "." 0.1. The significant variables are marked in bold.

A more detailed analysis of the PR2 sub-basin reveals the presence of several wetlands that drain into the stream. These wetlands are primarily sustained by snowmelt (PB2, 37, and 38), although during summer, some wetlands located near the head of rock glaciers may also receive inputs from these cryospheric features, as indicated by the isotopic composition of the PG1 and PB1 samples. For the PG1 wetland, water composition consisted of 59.0% rock glacier melt, 29.0% snowmelt, and 12.0% groundwater. A similar distribution was observed at PB1, with 59.8% rock glacier contribution, 28.1% snowmelt, and 12.1% groundwater (Table 2). Downstream, at the PR4 sample point, the Hidalgo River demonstrates the combined influence of the PR1 and PR2 tributaries, exhibiting a pronounced impact from snowmelt. The water composition is as follows: 22.8% of rock glacier water, 62.2% of snowmelt, and 15% of groundwater. However, the substantial water input of the PR3 tributary with a sub-basin that comprises 11 rock glaciers (IPG, 2022) alters the composition of the Hidalgo River's water sources downstream at the PR5 sample point (2,993 m a.s.l.). At that middle sample point (PR5), the river is composed of 45.2% rock glacier water, 38.1% snowmelt, and 16.7% groundwater.

In the final downstream section of the Hidalgo River (PR6, 1,520 m a.s.l.), prior to the confluence with the Rocín River (PR7, 1,519 m a.s.l.), the numerous snow catchments draining into the Hidalgo River between PR5 and PR6 have exerted a considerable influence on the water source composition, with the snowmelt contribution increasing to 50.1% and the rock glacier contribution decreasing to 28.2%. This is in close proximity to the groundwater contribution, which stands at 21.7%.

The water journey composition traceability of the Hidalgo River revealed the initial rock glacier dominance at the upper catchment (PR1), which was subsequently drained by different tributary streams, resulting in a shift toward a snowmelt-dominated river at the downstream section PR6 (1,530 m a.s.l.). At that altitude, the Rocín River (PR7) merges with the Hidalgo River. With 104 rock glaciers spanning 11.21 km^2 (IPG, 2022), the Rocín River (PR7) exhibits a pronounced dominance of rock glaciers, as evidenced by a 73.3% contribution of rock glacier-derived water to its composition. This is in the contrast with the 8.6% contribution from snowmelt and 18.1% from groundwater to the river's water composition. At PR8, the confluence of the Rocín and Hidalgo rivers (1,511 m a.s.l.) results in a mixed water composition reflecting contributions from both rivers. At PR8, before the Chacrillas dam, the river shows 56.1% of its water originating from rock glaciers, 11.2% from snow, and 32.7% from groundwater. Even though the groundwater composition logically increased its contribution as the water composition decreased in altitude, there was a notable increase in groundwater composition at the next sampling point PR9 (1,197 m a.s.l.). The large groundwater proportion reaching 53.5% at PR9 was an unexpected result, followed by 30.8% of RG and 15.7% of snow. This may indicate a groundwater recharge due to the Chacrillas dam, located just upstream of the PR9 sampling point. However, despite the dam effect, the limited evaporative process observed at PR9 compared to PR8 (Figure 4), along with the fact that the groundwater contribution remained too high to be fully explained by this first hypothesis, led us to consider another hypothesis. By overlapping geological maps and analyzing the chloride concentration in the waters (Figure 5D), we revealed that this remarkable groundwater contribution increase could also be due to the water input from the Pocuro Fault Zone (PFZ) (trellis symbology dotted red points; Figure 2). In this area, the high density of interconnected fractures in the PFZ—particularly the oblique basement faults crossing the main N–S trending trace—allows groundwater drainage from the Cordillera Principal, contributing to the recharge of adjacent alluvial aquifers in the Central Depression (Taucare Toro et al., 2020). This generates a topographic shift and seems to accumulate water in its deep pores before its water drains to the Putaendo River at the PR9 location.

In Figure 4, the isotopic values of the tap water from Putaendo (HLM_072021) fall near the isotopic composition of groundwater (GW Coimas). This supports the finding that 79.4% of water originates from groundwater, as indicated by simmr results (Table 2, HLM_072021), and is consistent with the supposed source of the drinking water system (APR Las Coimas). This origin is further confirmed by the similar chloride concentration observed in the tap water sample (Figure 5D, HLM_072021) and the groundwater samples (Figure 5D, GW Coimas).

3.3 Social perception

Since mountain geographical imaginaries are crucial in the process of building local identity and influence the ways natural resources are managed (Matallo, 2013; Alduncе et al., 2021; Yager et al., 2021; Castro, 2023; Palmisano and Godfrid, 2025), we also carried out a social perception analysis in the Putaendo Valley territory. Local knowledge shapes understandings of communities and their natural environments, fostering locally grounded capacities to counteract extractive economic paradigms (Castro, 2023). In order to improve water management, it is crucial to analyze

TABLE 2 Water source contribution percentage for each sample.

ID	RG%	SD RG%	Snow%	SD snow%	GW%	SD GW%	DTS %
PR1	63.0	16.1	20.5	15.3	16.5	9.6	79.5
PR2	6.1	4.2	88.0	5.7	5.9	3.9	12.0
PR4	22.8	13.3	62.2	14.4	15.0	8.3	37.8
PR5	45.2	18.6	38.1	19.6	16.7	9.4	61.9
PR6	28.2	14.7	50.1	15.7	21.7	10.8	49.9
PR7	73.3	11.6	8.6	5.6	18.1	11.3	91.4
PR8	56.1	14.9	11.2	7.4	32.7	16.0	88.8
PR9	30.8	13.9	15.7	9.5	53.5	15.9	84.3
HLM_072021	8.8	7.4	11.8	6.4	79.4	10.6	88.2
PB2(36) spring	3.0	2.0	93.7	3.1	3.3	2.3	6.3
PB2 summer	9.2	6.4	83.6	7.7	7.2	4.6	16.4
37 spring	4.4	3.1	91.2	4.4	4.4	3.0	8.8
38 spring	4.7	3.3	90.6	4.6	4.7	3.2	9.4
PB1	59.8	19.4	28.1	20.1	12.1	7.4	71.9
PG1	59.0	19.5	29.0	20.3	12.0	7.4	71.0

RG, rock glacier; SD, standard deviation; GW, groundwater; DTS, % contribution of different water sources other than snow (RG + GW).

these different perceptions and collective imaginaries in light of the current data about their fundamental source of water supply.

As previously noted, a cross-sectional descriptive survey using non-probabilistic causal sampling was conducted among 88 residents of the Putaendo Valley. The survey included characterization questions covering a) age; b) gender; c) job; and d) place of residence. It also addressed the following topics: e) perception of the major origin of water during drought years; f) perception of the major origin of water during normal to rainy/snowy years; g) whether they were affected by the megadrought; h) how they were affected; i) perception of when the megadrought started; j) perception of the worst drought year; k) perceptions of the causes of water shortage; l) perception of the likelihood of future drought events; m) adaptive strategies; n) acceptance or rejection of mega-mining; o) perspective on the effects of mega-mining; p) knowledge of the existence of environmental movements in Putaendo and participation.

According to the results of the survey, the majority of the Putaendo Valley residents have severely suffered from the megadrought effects (90.9%) and expect more droughts in the future (88.6%). A multiple-choice question was used to determine social perceptions of how the megadrought affected them. The two most frequent responses pertained to the reduction in water availability for agricultural activities (less irrigation water, 49 responses) and shorter irrigation periods (46 responses). The third most selected option highlights the impact of the megadrought on crop loss (43 responses). The loss of livestock was less frequently mentioned, with only 25 responses. This high percentage of responses linked to irrigation and crops demonstrates the pivotal role of agricultural activities in the lives of the Putaendo inhabitants and the profound impact of the megadrought. Subsequently, the group of responses related to the impact of the megadrought on access to drinking water is particularly noteworthy. Thirty respondents indicated an increase in the cost of drinking water, while 24 respondents reported a decrease in the supply of water for human consumption for domestic and economic needs. The reduction in working hours (20 responses) and the decrease in sales (28 responses) also show how the megadrought is perceived as a catalyst for the deterioration of material livelihoods. Within the residual category “others,” four responses reffered to the economic impacts of the megadrought (loss of employment and investments), two to the loss of native vegetation, and two to the impact on subjective aspects, such as psychological damage and the deterioration of local peasant identity.

Perceptions regarding the underlying causes of water scarcity: nearly half of the respondents (48.9%) identified both climate change and excessive water extraction as key factors. A total of 39.8% of respondents selected climate change as a contributing factor, while 9.1% identified excessive extraction as the sole cause. It is noteworthy that some respondents also identified socio-political factors as contributors to water scarcity. These included concerns about the efficacy of water management practices and inequity of the water distribution, which were mentioned by five respondents.

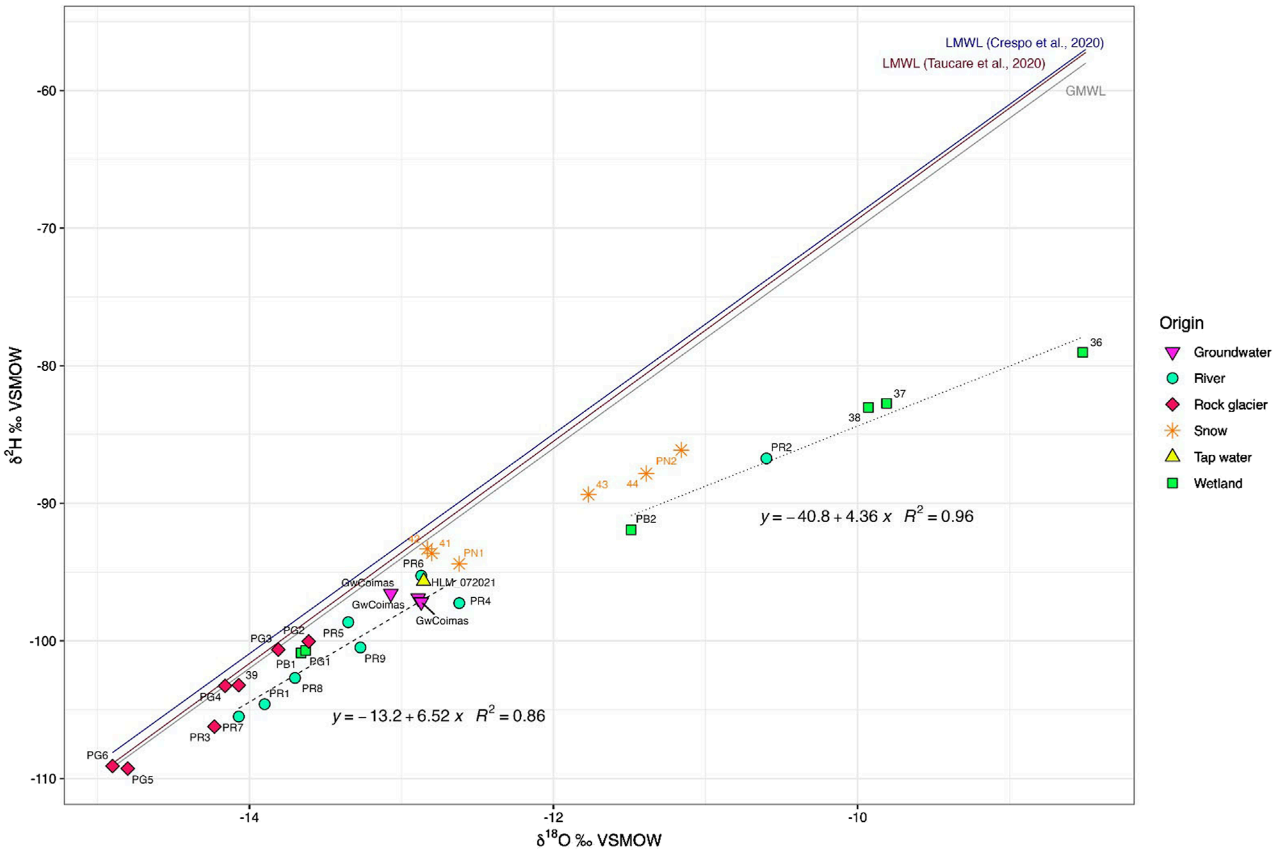

FIGURE 4
Stable isotope ($\delta^{18}O$ and $\delta^{2}H$) scatterplot of rivers and water sources. The gray line represents the Global Meteoric Water Line (GMWL) according to the equation of Craig (1961). The blue line represents the Local Meteoric Water Line (LMWL), constructed with data at 33 °S of Crespo S. A. et al. (2020), using the equation $\delta^{2}H = 7.9874 \times \delta^{18}O + 10.892$ ($R^2 = 0.9974$) and is close to the LMWL reported by Taucare Toro et al. (2020): $\delta^{2}H = 8.076 \times \delta^{18}O + 11.42$ ($R^2 = 0.97$) for the same latitude.

In light of these considerations, the responses regarding mega-mining in Putaendo warrant particular scrutiny. The notion of water appropriation by mega-mining and its potential impact on the local population—who perceive the possibility of resource exploitation and contamination that could affect agricultural and livestock production—has led to a resounding rejection of mega-mining projects in the valley (84.1%). Upon disaggregation of this value, it becomes evident that half of the respondents are in complete opposition to the activity, while the other half express rejection of this activity, specifically in the territory of Putaendo.

These perceptions describe a complex process of social problematization around water scarcity, its impacts on the population's way of living, and how activities, such as mega-mining, are perceived as exacerbating this situation. This complex awareness process is informed by prior knowledge, which has been accumulated through academic research and social mobilization (Fernández Navarro and y Ferrando Acuña, 2018; Cádiz-Véliz et al., 2023; Palmisano, 2020; Palmisano et al., 2022).

This is especially apparent in the depth of the local population's understanding of the origins of their water resources. In response to the question on the primary source of water supply during drought years, 45.5% of respondents identified rock glaciers as the main source. Rainfall and snow were each cited by 19.3% of participants, while 10.2% mentioned groundwater. Additionally, 4.5% identified the mountains, and 1.1% pointed to wetlands. Altogether, 61.4% of respondents recognized sources other than direct precipitation—namely, rock glaciers, groundwater, mountains, and wetlands—as their principal water supply. Since these sources are all part of the periglacial environment, such responses reflect a notable degree of prior knowledge.

This awareness becomes even more apparent when considering responses regarding normal to wet years: in these cases, the majority shifted their focus toward precipitation, with 45.5% identifying snow and 40.9% rain as the main sources. In contrast, only 4.5% mentioned rock glaciers and the cordillera, and just 2.3% cited groundwater (see Figure 6).

4 Conclusions and further work

The megadrought that affected the Putaendo Valley from 2010 to 2022 significantly deepened the already precarious subsistence conditions faced by the local population. This prolonged climatic stress triggered numerous social tensions and conflicts, particularly impacting farmers and ranchers whose livelihoods, income sources, and socio-economic stability were severely compromised.

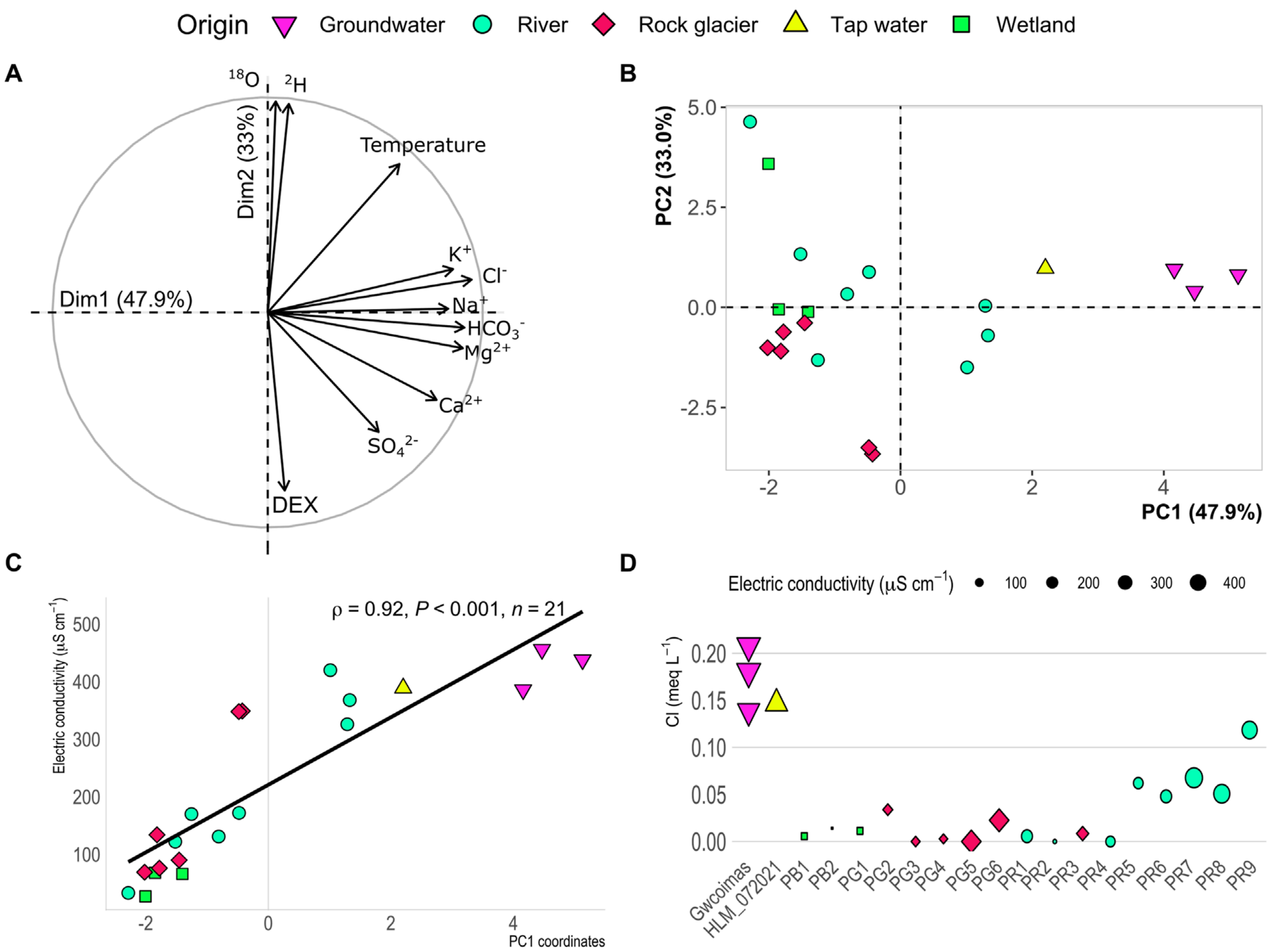

FIGURE 5
PCA and correlations. **(A)** Correlation circle of the PCA based on physicochemical features and water isotope signatures. **(B)** Individual plot along the two first dimensions of the PCA. **(C)** Spearman's correlation between electrical conductivity and coordinates along the first PCA dimension. **(D)** Link between chlorides, electrical conductivity, and the type of water source. Water source is shown in color, and size represented the electrical conductivity in μS cm^{-1}.

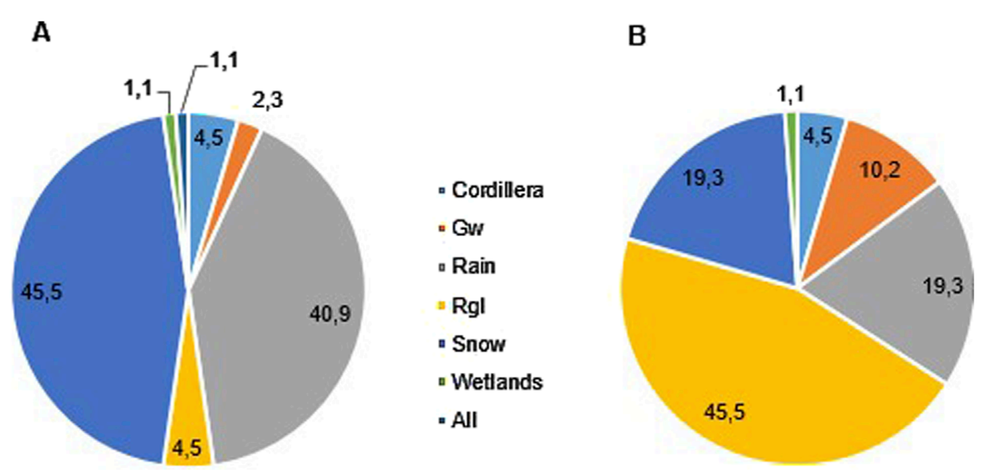

FIGURE 6
Social perception of the main water supply origin during normal to wet years **(A)** and during dry years **(B)**.

Despite the unprecedented succession of dry years during the megadrought period, the Putaendo River did not reach a critical depletion or dry up entirely. This hydrological resilience is largely attributed to sustained meltwater contributions from the periglacial environment. At the monitoring site PR8—located just upstream of human intervention at the Chacrillas Dam—56.1% of streamflow originates from rock glaciers and 32.7% from groundwater sources (Table 2). Notably, this scientific evidence is mirrored by local knowledge: 45.5% of surveyed residents identified rock glaciers as the primary water source during drought years, reflecting a significant level of hydrological awareness within the community. This convergence between empirical data and local knowledge highlights the value of incorporating community insights into water resource management and the formulation of mitigation strategies for extreme drought events. Such integrative approaches are increasingly vital in the context of projected regional climate change scenarios that forecast escalating water stress (Bozkurt et al., 2018). Future adaptation efforts should prioritize the protection of key water sources—such as the periglacial system and potential groundwater storage identified at the PFZ. To bolster these strategies, groundwater tracing techniques can be refined by applying ^{222}Rn mass balance methods, which would allow for more precise discrimination of groundwater contributions from the Chacrillas Dam and/or the PFZ (Ortega et al., 2015).

In the context of the ongoing dispute between the local community of Putaendo and mega-mining projects, as well as the broader regional and global climate crises, the dialectic relationship between the commune and water is a crucial factor. This relationship is characterized by the exercise of water power, whereby various strategies associated with water control, business, discourses, social actors, and state influence converge in the same space. By conceptualizing this space as a socio-ecological system where transformation arises from external factors linked to economic production and climate change, it generates a configuration and reconfiguration in the territories (Sanchis Ibor and Boelens, 2018) that can impact culture and symbolism in terms of the socio-historical change, which is a significant phenomenon in a rural locality such as Putaendo.

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

The studies involving humans were approved by the Pontifical Catholic University of Valparaíso Bioethics and Biosafety Committee, code BIOPUCV-H 438–2021. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, and Writing – review and editing. JR: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – review and editing, Resources, and Supervision. TP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, and Writing – review and editing. CL: Data curation, Formal analysis, Methodology, Validation, Visualization, and Writing – review and editing. AL: Formal analysis, Investigation, Methodology, Visualization, and Writing – review and editing. LM: Data curation, Formal analysis, Writing – review and editing, and Methodology. FF: Funding acquisition, Resources, Validation, Writing – review and editing, and Supervision. YV: Funding acquisition and Writing – review and editing.

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Conflict of interest

The authors declare that the research 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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The author(s) declare that Generative AI was used in the creation of this manuscript. To enhance the quality of the English language in the accepted manuscript, AI tools were employed for editing certain sections.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2025.1560106/full#supplementary-material

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