

Improving water quantity and quality in a mountain hard-rock watershed (La Vera, Spain) through Ancestral Nature-Based Solution for Managed Aquifer Recharge

Antonio González-Ramón

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Nuria Naranjo-Fernández

n.naranjo@igme.es

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Thomas Zakaluk

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Almudena de la Losa-Román

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Blas Ramos

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Carlos Marín-Lechado

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Héctor Aguilera

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Ana Fernández-Ayuso

Universidad Autónoma de Madrid

Jorge Jódar

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Fernando Gázquez-Sánchez

University of Almería

Sergio Martos-Rosillo

Instituto Geológico y Minero de España, Consejo Superior de Investigaciones Científicas (IGME-CSIC)

Research Article

Keywords: Managed Aquifer Recharge (MAR), Nature-based Solutions, hard-rock aquifer, water-rock interaction, stable isotopes, mountain hydrogeology

Posted Date: October 12th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10878205/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Nature-based Solutions (NbS), applied to water resources management, are increasingly promoted as sustainable strategies to address water scarcity and climate-change impacts. The restoration of ancestral aquifer recharge channel systems could be one of the most powerful and low-cost water-management tools. Recent studies have demonstrated that infiltration channels known as *pesqueras* contribute substantially to groundwater resources in Sierra de Gredos (western Spain). However, their role on groundwater quality and chemistry within the weathered granitic hillslope aquifer have yet remained unexplored.

This study aims to characterize how the restored *pesqueras* network functions as hydrogeological and hydrochemical NbS, based on hydrochemical and isotopic monitoring.

Two sampling campaigns were conducted in spring and autumn under contrasting hydrological conditions and included groundwater, stream-water, and recharge-channel samples. Major ions, dissolved silica, electrical conductivity, pH, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were used to identify recharge pathways, groundwater evolution and water-rock interaction processes.

The results demonstrate that restored *pesqueras* not only increase groundwater recharge but also promote natural hydrogeochemical conditioning of infiltrated waters during subsurface transit. Water-rock interactions within the weathered granitic aquifer increase groundwater mineralization from extremely dilute surface-water conditions, producing water of improved suitability for human consumption while preserving high-elevation recharge isotopic signatures that confirm recharge transfer through the aquifer to the discharge zones. Groundwater hydrochemical and isotopic signatures independently support and validate previous conceptual and hydrological models of recharge.

These findings show that ancestral recharge channels function as a multi-benefit NbS, simultaneously increasing groundwater storage, improving water quality and sustaining water supplies for mountain communities. The study highlights how the restoration of hydrological infrastructures based on traditional ecological knowledge can provide scientifically validated, low-energy and climate-resilient water-management solutions.

1. Introduction

Nature-based Solutions (NbS) are increasingly recognized as sustainable approaches for improving water security while simultaneously enhancing ecosystem services, climate resilience and environmental sustainability (Lalonde et al., 2024). NbS strategies are also expected to address increasing pressures on water resources arising from climate change, urban expansion, and overall population growth (WWAP, 2018). Similar practices have been implemented for centuries through traditional systems such as the *acequias de careo* in Sierra Nevada (southern Spain) and the *amunas* and *cochas* in the Peruvian Andes (Ochoa-Tocachi et al., 2019; Martos-Rosillo et al., 2019). These systems were developed through the observation, understanding, and adaptation of natural processes by local

communities. In the context of water resources management, their application aimed to enhance groundwater recharge, regulate streamflow, and improve both water availability and its distribution throughout the hydrological year (Jódar et al, 2022). These ancestral systems can be considered early forms of NbS because they intentionally exploit natural hydrological processes to increase groundwater storage, regulate streamflow and support human water supply without external energy inputs. The long-term functioning of *acequias de careo* and *amunas* demonstrates the effectiveness of combining hydrological processes with traditional ecological knowledge. Consequently, the recovery, preservation, and adaptation of ancestral water-management systems have gained increasing attention as strategies to enhance groundwater storage, mitigate the impacts of drought periods, and increase the resilience of local communities to water scarcity (Somers et al., 2018; Ochoa-Tocachi et al., 2019; Hoefsloot et al., 2024; Zakaluk et al., 2024).

Most studies assessing water-related NbS have focused on their capacity to enhance groundwater recharge, increase water availability, and regulate streamflow (Lalonde et al., 2024). In contrast, much less attention has been devoted to another potentially valuable ecosystem service provided by these systems: the improvement of water quality through natural hydrogeological and hydrogeochemical processes that occur during subsurface percolation and groundwater flow. As recharge water infiltrates through soils, weathered materials, and fractured bedrock, aquifers may function not only as natural storage reservoirs but also as hydrogeochemical treatment systems, where water-rock interactions alter groundwater chemistry and may enhance its suitability for human consumption. Understanding these processes is essential for assessing the full range of benefits delivered by water-related NbS.

Hydrochemical and isotopic techniques provide powerful means of investigating these processes, as they allow the identification of recharge pathways, groundwater evolution, mixing processes and water-rock interactions. Nevertheless, their application to ancestral managed aquifer recharge systems remains limited, especially in mountain hard-rock settings. One of the few documented examples is the *acequias de careo* system in Sierra Nevada (southern Spain), where infiltrated waters retained distinct isotopic signatures and experienced measurable hydrochemical evolution during subsurface transport (Barberá et al., 2018). These findings suggest that ancestral managed aquifer recharge systems may provide ecosystem benefits beyond groundwater storage, including water quality improvement through natural subsurface processes. However, evidence from similar systems around the world is still missing. This knowledge gap is particularly relevant in mountain hard-rock watersheds, where surface waters typically exhibit low mineralization and where geochemical processes occurring during groundwater flow may substantially alter water composition. Consequently, determining whether ancestral managed aquifer recharge systems can simultaneously enhance both groundwater quantity and quality is essential for evaluating their potential as multi-benefit NbS.

A representative example is provided by the *pesqueras* system of Aldeanueva de la Vera (Cáceres, western Spain), consisting in an extensive network of unlined infiltration channels, historically used to enhance groundwater recharge in weathered granitic hillslope aquifers. During recent decades, rural depopulation and agricultural abandonment have resulted in the gradual deterioration of this

infrastructure. Inspired by successful restoration of the *acequias de careo* in the Sierra Nevada, the Ocho Caños Irrigation Community (i.e., local water users) undertook the recovery of several ancestral *pesqueras* within the San Gregorio watershed. Recent hydrological studies indicate that the restored system accounts for approximately 58% of the total annual groundwater recharge, equivalent to nearly 2 hm³/yr (Aguilera et al., 2026; Naranjo-Fernández et al., 2025). Nevertheless, while its contribution to groundwater recharge has been quantified, its effects on groundwater quality and on the hydrogeological processes governing aquifer functioning remain largely unknown.

Understanding groundwater hydrochemical evolution is particularly important in granitic catchments, where water composition is largely controlled by water-rock interactions within thick weathered profiles. Silicate weathering reactions involving primary minerals such as plagioclase, K-feldspar, and biotite govern the progressive acquisition of dissolved constituents by groundwater. These processes release characteristic solutes, including Na⁺, K⁺, Ca²⁺, Mg²⁺, HCO₃⁻, and dissolved silica, while simultaneously promoting the formation of secondary clay minerals such as kaolinite (Lasaga, 1984). Consequently, artificially enhanced recharge through the focused infiltration of low-mineralized stream waters may influence groundwater residence times, reaction kinetics, mineralization patterns, and hydrochemical facies evolution along hillslope flow paths. Complementarily, stable isotopes of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and deuterium excess (d-excess) constitute robust conservative tracers for identifying recharge sources, assessing stream water-groundwater connectivity, estimating recharge elevations, and detecting evaporation processes (Celle-Jeanton et al., 2001; Barberá et al., 2018, Morales-Sotaminga et al., 2023).

We hypothesize that this ancestral NbS produces measurable improvements in groundwater quality for water supply through the natural hydrogeological and hydrogeochemical processes associated with enhanced recharge and subsurface flow. Specifically, we propose that groundwater affected by *pesquera* induced recharge retains the isotopic signature of infiltrated stream water while undergoing hydrochemical evolution that improves the quality of spring water used for supply in Aldeanueva de la Vera (Fig. 1). Under this framework, the aquifer operates not only as a natural water storage reservoir but also as a hydrogeochemical conditioning system.

This study investigates the hydrochemical and isotopic response of a shallow granitic hillslope aquifer to managed recharge through restored *pesquera* channels in the San Gregorio watershed. Building on previous water-balance assessments, the study aims to: (i) characterize the spatial and seasonal variability of major-ion chemistry and hydrochemical facies in surface water and groundwater; (ii) identify the dominant water-rock interactions controlling groundwater mineralization along hillslope flow paths; (iii) evaluate the suitability of $\delta^{18}\text{O}$, $\delta^2\text{H}$, and d-excess as tracers of induced recharge and groundwater mixing; (iv) refine the conceptual hydrogeological model by identifying the hydrochemical and isotopic signatures of individual *pesquera* channels in downstream spring systems, and (v) assess to what extent this ancestral NbS enhances both groundwater quantity and water quality for drinking water supply in small mountain communities.

By integrating hydrochemical and isotopic evidence, this study advances understanding of the hydrogeological and hydrogeochemical functioning of a restored ancestral recharge system and evaluates its capacity to enhance water quality through natural subsurface processes. The findings provide scientific support for the restoration and conservation of traditional managed recharge systems as low-energy, climate-resilient water-management strategies.

2. Study Area

The study was conducted in the San Gregorio watershed (12.71 km²), located in the municipality of Aldeanueva de la Vera (Cáceres, western Spain), on the southern slopes of the Sierra de Gredos, within the Spanish Central System (Fig. 1).

In the study zone, elevation ranges from 515 to 1,812 m above the level (a.s.l.), generating a pronounced topographic gradient. The climate is Mediterranean with Atlantic influence and is characterized by wet winters and dry summers (Peel et al., 2007). For the period 1950–2022, mean precipitation (P), air temperature (T_{air}) and potential evapotranspiration (PET; Hargreaves and Samani, 1985) were 1,386 mm/yr, 12.3°C and 1076 mm/yr, respectively (Peral et al., 2017). As shown in Fig. 2, these climatic variables exhibit a clear seasonal pattern.

The watershed is predominantly underlain by Variscan granites (Fig. 3), with minor schist outcrops and localized alluvial deposits. Weathering processes have produced an extensive regolith that occupies approximately 44% of the watershed surface. At higher elevations, weathered materials are mainly associated with glacial and periglacial deposits, whereas lower hillslopes are characterized by kaolinitic weathered granite mantles. These unconsolidated materials overlie low-permeability fresh granite and locally reach thicknesses close to 10 m, constituting the principal groundwater reservoir within the watershed (Martín-Loeches, 1995; Gómez et al., 2006; Contreras-López et al., 2008).

Groundwater circulation occurs mainly within shallow hillslope aquifers developed in the weathered granite layer. Recharge originates from direct rainfall infiltration and seasonal snowmelt at higher elevations, generating a thin saturated zone that develops along the contact between the weathered mantle and the underlying granitic bedrock. Groundwater flows downgradient from upland natural recharge areas and to lower elevation discharge zones, emerging through numerous springs distributed throughout the watershed. A total of 215 springs have been inventoried, with individual discharges typically ranging between 0.1 and 10 L/s. Due to the steep topography and the discontinuous nature of the weathered layer, groundwater commonly emerges through springs and subsequently reinfilters downstream, creating a flow system that ultimately contributes to streamflow (Martín-Loeches et al., 2020; Aguilera et al., 2026).

A distinctive feature of the watershed is the presence of traditional unlined infiltration channels (*pesqueras*). These channels divert water from streams and springs and distribute it along hillslopes, enhancing focused infiltration into permeable weathered granitic materials and thereby increasing groundwater recharge. Previous investigations identified approximately 70 km of *pesqueras* within the

watershed and documented the rehabilitation of 12.1 km of ancestral channels through community-based restoration initiatives (Aguilera et al., 2026).

Hydrological monitoring of four representative recharge channels (Cardos, Lanchas, Poyos and Toriles) has shown that channel flows vary seasonally, with peak discharges commonly reaching 40 L/s in Cardos and Poyos, while the perennial Lanchas channel can exceed 200 L/s during wet periods. At the watershed outlet, streamflow frequently exceeds 1,000 L/s during the wet season and may surpass 2,000 L/s after intense precipitation events, whereas summer baseflow commonly declines below 50 L/s (Aguilera et al., 2026).

Recent hydrological analyses demonstrated that the rehabilitated *pesqueras* constitute an additional recharge mechanism within the watershed. The four monitored channels infiltrated 2.23 hm³ during the 2023–2024 hydrological year and 1.77 hm³ during 2024–2025, corresponding to an average recharge volume close to 2 hm³/yr. Water-balance simulations estimated total groundwater recharge of 3.7 hm³ and 3.1 hm³ for the respective hydrological years, indicating that recharge induced by *pesqueras* accounted for approximately 58% of the annual groundwater recharge. Among the monitored channels, the Lanchas *pesquera* provided the largest contribution, accounting for more than half of the total infiltrated volume (Aguilera et al., 2026).

The coexistence of natural diffuse recharge and concentrated infiltration through *pesqueras* creates a unique hydrogeological setting in which groundwater evolution, water–rock interactions, and stream water-groundwater mixing can be investigated. The infiltration of low-mineralized stream water through weathered granitic materials is expected to modify groundwater residence times, geochemical evolution pathways, and mixing dynamics along hillslope flowpaths within the hard-rock aquifer. Given the substantial contribution of induced recharge to the groundwater budget, this system provides an exceptional opportunity to identify and quantify the hydrochemical and isotopic signatures associated with an ancestral nature-based managed aquifer recharge system.

3. Materials and Methods

Two field sampling campaigns were conducted during contrasting hydrological periods: spring, when stream and spring discharges typically reach their annual maxima, and autumn, when hydrological conditions are generally drier. The first campaign was carried out from 12 to 14 May and included 45 sampling locations. A second campaign was conducted from 28 and 31 October, covering 35 locations, as several sampled in spring had become dry by then. During both campaigns, *in situ* measurements of electrical conductivity (EC), pH, and water temperature (T) were obtained. A portable electrical conductivity (EC) and temperature probe (WTW® 340i) and a pH-meter (WTW® 315i) were used to measure field parameters. The accuracy was $\pm 0.5\%$ for EC and ± 0.03 units for pH. Water samples intended for major ion analysis were stored in 250 mL polyethylene bottles, while samples for isotopic analysis were collected in 5 mL glass vials. All samples were filtered prior to storage. Samples were transported to the laboratory in coolers and maintained at an appropriate temperature throughout

transport. Major anions and cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , F^- , Cl^- , SO_4^{2-} , NO_3^- ; Hereafter the corresponding ionic charge is omitted) were analyzed by ion chromatography at the Department of Geology, University of Jaén, using a Professional IC 850 equipped with a Metrohm 919 IC Autosampler Plus, with typical analytical precision of ± 0.01 mg/L.

The stable isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) of spring and *pesqueras* waters was determined at the Stable Isotope Laboratory of the University of Almería (Spain) using a Picarro L2140-i cavity ring-down spectroscopy (CRDS) analyzer (Steig et al., 2014). Isotopic measurements were calibrated to the Vienna Standard Mean Ocean Water (V-SMOW) reference scale through repeated analyses of laboratory standards performed before and after each analytical sequence of 12–15 samples. Three in-house reference waters, previously calibrated against the international standards V-SMOW, Standard Light Antarctic Precipitation (SLAP), and Greenland Ice Sheet Precipitation (GISP), were used to normalize the analytical results. The isotopic compositions are expressed in delta notation (‰) relative to V-SMOW. Long-term analytical precision (1σ) was ± 0.1 ‰ for $\delta^{18}\text{O}$, ± 0.3 ‰ for $\delta^2\text{H}$, based on measurements of an internal standard ($n = 22$) every 5–6 samples.

In addition, the same sampling protocol was applied to several traditional water diversion channels (*pesqueras*) used to enhance water infiltration. These included the *pesqueras* Los Cardos, Las Lanchas, and Los Toriles, located along the main San Gregorio stream, as well as Los Poyos, situated on the Yedrón stream, a secondary tributary draining the left side of the watershed. Water from the main river was also sampled at the watershed outlet, adjacent to the urban area of Aldeanueva de la Vera.

4. Results

The analyzed waters exhibit sodium-calcium or calcium-sodium bicarbonate-chloride facies in the headwaters of the watershed during the wettest period, with an evolution toward sodium bicarbonate-rich waters at lower elevations and during drier periods (Fig. 4). EC values are low (Fig. 5a and Tables 1 and 2), with a mean of $35.2 \mu\text{S}/\text{cm}$ (range: 10.6 – $199.2 \mu\text{S}/\text{cm}$), but significant differences are observed between rivers and springs samples ($10.62 \mu\text{S}/\text{cm}$ and $38.27 \mu\text{S}/\text{cm}$, respectively; Tables 1 and 2). Significant differences are observed between waters sampled in the upper and middle parts of the watershed, where EC values do not exceed $35 \mu\text{S}/\text{cm}$, and springs in the lower area around the urban center of Aldeanueva de la Vera, where EC values increase notably (Fig. 5a). Differences between the wet and dry period samplings campaigns are very subtle in the upper watershed, where salinity remains virtually unchanged. In the middle zone, EC values are noticeably lower during the wet period; this does not occur in the lower watershed, where EC remains high in both periods. Groundwater T ranges between 10 and 18.8°C , with a mean of 13.6°C . As expected, the highest values occur at lower elevations, with waters sampled in May showing a lower T than those sampled in October (warmer) (Fig. 5b).

Groundwater is generally acidic, whereas surface water tends toward neutral pH values. Values range from 4.5 to 7.4 , with a mean of 5.6 , also show noticeable differences between May samples (more acidic) and October samples, although no strong correlation with altitude is observed (Fig. 5c and

Table 2). SO_4 and Cl concentrations are very low, averaging 1.6 and 2.5 mg/L, respectively, with ranges between 0–4.5 mg/L for SO_4 and 1.6–8.1 mg/L for Cl. Both parameters show a wider range in October samples (Fig. 4). These two parameters are the only ones for which there are no significant differences between surface water and groundwater (Tables 1 and 2 and Fig. 4). Similarly, HCO_3 and NO_3 concentrations are very low, with mean values of 11 and 4.6 mg/L, respectively, although maxima of 68.3 and 32.8 mg/L are reached in the lower watershed near the urban center. Finally, cation concentrations are also very low, averaging 2.9, 2.2, 1.1, and 0.5 mg/L for Na^+ , Ca^{2+} , K^+ , and Mg^{2+} , respectively, with peak values likewise occurring in the lower watershed (Table 1).

Table 1
Summary statistics for physicochemical and isotopic parameters measured in surface water of the Garganta de San Gregorio watershed.

Parameter	Unit	Max	Min	AM	Q25	Q50	Q75	DC*
pH		6.98	6.12	6.54	6.34	6.58	6.68	3.79
T	°C	15.10	10.00	11.97	11.05	11.70	12.50	12.25
Cond	$\mu\text{S}/\text{cm}$	60.90	10.62	21.82	14.10	16.10	21.95	69.39
Na^+	mg/L	2.72	0.56	1.90	1.69	1.96	2.16	26.32
K^+	mg/L	0.42	0.00	0.16	0.07	0.12	0.24	82.92
Mg^{2+}	mg/L	0.47	0.06	0.19	0.16	0.18	0.21	45.59
Ca^{2+}	mg/L	1.48	0.35	0.72	0.49	0.79	0.85	39.12
Cl^-	mg/L	2.76	1.61	2.08	1.62	2.16	2.51	22.39
SO_4^-	mg/L	1.82	0.00	1.37	1.13	1.14	1.81	37.17
NO_3^-	mg/L	5.02	0.00	2.95	1.33	4.24	4.75	67.26
HCO_3^-	mg/L	12.20	1.38	4.96	3.16	3.62	6.10	60.61
SiO_2^-	mg/L	4.29	2.53	3.46	3.13	3.54	3.70	13.33
$\delta^{18}\text{O}$	‰	-6.57	-7.80	-7.24	-7.34	-7.22	-7.12	-4.19
$\delta^2\text{H}$	‰	-40.43	-49.10	-44.74	-45.60	-44.82	-43.54	-4.79
d-excess	‰	14.0	12.1	13.2	12.6	13.3	13.65	4.59
*DC – Deviation Coefficient								

Table 2

Summary statistics for physicochemical and isotopic parameters measured in groundwater of the Garganta de San Gregorio watershed.

Parameter	Unit	Max	Min	AM	Q25	Q50	Q75	DC*
pH		7.42	4.45	5.41	5.02	5.42	5.63	10.16
T	°C	18.80	10.40	13.92	12.00	13.80	15.10	14.90
Cond	µS/cm	199.20	12.90	38.27	18.90	22.00	40.00	95.10
Na ⁺	mg/L	11.13	1.36	3.16	2.00	2.44	3.36	59.29
K ⁺	mg/L	16.04	0.00	1.34	0.20	0.36	1.36	202.19
Mg ²⁺	mg/L	3.97	0.10	0.58	0.16	0.22	0.45	136.40
Ca ²⁺	mg/L	15.84	0.24	2.52	0.67	0.96	2.15	135.88
Cl ⁻	mg/L	8.10	1.60	2.56	1.62	2.55	2.79	46.17
SO ₄ ⁻	mg/L	3.17	0.00	1.60	1.14	1.80	1.81	32.82
NO ₃ ⁻	mg/L	32.80	0.00	4.92	1.35	4.28	6.12	116.92
HCO ₃ ⁻	mg/L	68.25	2.59	12.44	3.73	6.10	13.61	116.58
SiO ₂ ⁻	mg/L	9.90	1.15	4.44	3.81	4.41	5.06	31.75
δ ¹⁸ O	‰	-5.82	-8.29	-6.86	-7.21	-6.86	-6.53	-7.47
δ ² H	‰	-36.31	-50.95	-42.16	-44.81	-41.87	-39.95	-7.76
d-excess	‰	16.2	9.9	12.7	12.10	12.70	13.30	8.50
*DC – Deviation Coefficient								

4.1. Oxygen and hydrogen stable isotopes

δ¹⁸O values have a mean of -6.9‰, and range from -8.3 to -5.8‰. For δ²H, the mean is -42.2‰, with a range between -51 and -36.3‰, although significant differences are observed between the May and October 2025 campaigns. In May, mean δ¹⁸O and δ²H values were -7.0‰ and -43.3‰, respectively, with ranges between -8.0 to -5.8‰ and between -51 to -36.3‰. Samples collected in October show slightly heavier mean values of -6.9‰ for δ¹⁸O and -41.8‰ for δ²H, with ranges of -8.3 to -6‰ and -50.1 to -37‰, respectively. October samples are also shifted above the May samples in the δ²H–δ¹⁸O plot (Fig. 6). In this figure, local groundwater lines (LGWL) have been plotted using sampled springs that are unaffected by irrigation channels (*pesqueras*), either because they are located upstream or situated on a different slope from the two rivers where water is diverted for infiltration. The May line lies below the October line, but has a steeper slope (2.99 versus 1.33). Samples from the Yedrón River and the

Garganta de San Gregorio at the watershed outlet are clearly shifted toward heavier isotopic values in the October campaign. Samples collected at the *pesquera* intakes show the same shift.

5. Discussion

5.1. Physicochemical water-rock interactions

At most sampling points, except for those located around the urban center of Aldeanueva de la Vera, mineralization can be explained by evaporative concentration of dissolved salts in precipitation (Fig. 4). This is clearly reflected in the anions, including Cl , SO_4 , and to a lesser extent HCO_3 , which exhibit very low concentrations, generally below 3 mg/L, in most samples (Tables 1 and 2 and Fig. 4). Strong correlations are observed among these anions, particularly between Cl^- and SO_4^{2-} (Table 3). However, cation chemistry is particularly informative. The correlation among Na^+ , K^+ , Ca^{2+} , and Mg^{2+} is very high (Table 2) with $R^2 > 0.88$, suggesting a common origin for all of them. At higher elevations, Na^+ concentrations exceed those of Ca^{2+} (Figs. 4 and 7), although both remain very low, suggesting an atmospheric origin (Custodio and Llamas, 1976). Downstream, values for all cations increase significantly below 800 m a.s.l. due to lithological inputs resulting from the weathering of feldspars, plagioclase, and micas within the granitic bedrock by infiltrating water. The bedrock consists mainly of granodiorites in the upper and middle parts of the watershed, and leucogranites in the lower areas (Fig. 3). These granitoids are composed of K-feldspar, plagioclase, biotite, and quartz and are covered by a weathered granitic layer, except in the highest parts of the watershed, where weathered granitic hillslope aquifer is virtually absent. The weathering of these minerals through hydrolysis in acidic waters releases Na^+ , K^+ , Ca^{2+} , HCO_3^- , and SiO_2 , generating phyllosilicates as secondary products such as kaolinite, montmorillonite, and illite, which—along with quartz—make up the weathered granitic layer. The relationship between these ions and elevation indicates that groundwater becomes increasingly enriched in Na^+ and K^+ below 1000 m a.s.l., where springs influenced by water infiltrated through the Los Cardos and Los Poyos channels (*pesqueras*) emerge. At lower elevations, springs influenced by infiltration through the Los Toriles and, especially, the Las Lanchas channel also emerge, with Las Lanchas contributing the largest infiltrated volume (Fig. 7a). In contrast, Ca^{2+} and Mg^{2+} only increase below 800 m a.s.l. (Fig. 7b). This could be attributed to the presence of more calcic plagioclase (anorthite) in the leucogranites outcropping in the lower watershed, whereas in the granodiorites of the upper and middle sections, the dominant feldspars may supply more sodium and potassium. Mg^{2+} is released through the weathering of biotite, but its concentration is substantially lower than that of Ca^{2+} , showing only a slight increase in the lower watershed. The weathering of these minerals does not yield Cl^- or SO_4^{2-} ; consequently, their negative correlation with elevation is much weaker ($R^2 < -0.43$ in Table 2) than that of the cations ($R^2 > -0.45$). By contrast, it does release HCO_3^- , which displays an inverse correlation similar to that of the cations ($R^2 = -0.53$).

Albite hydrolysis yields kaolinite, dissolved sodium (Na⁺), bicarbonate (HCO₃⁻), and silicic acid (H₄SiO₄), proceeding according to the following reaction:

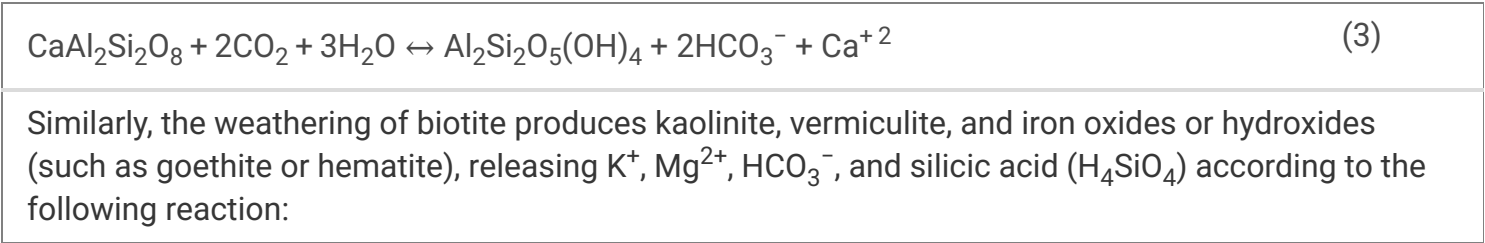
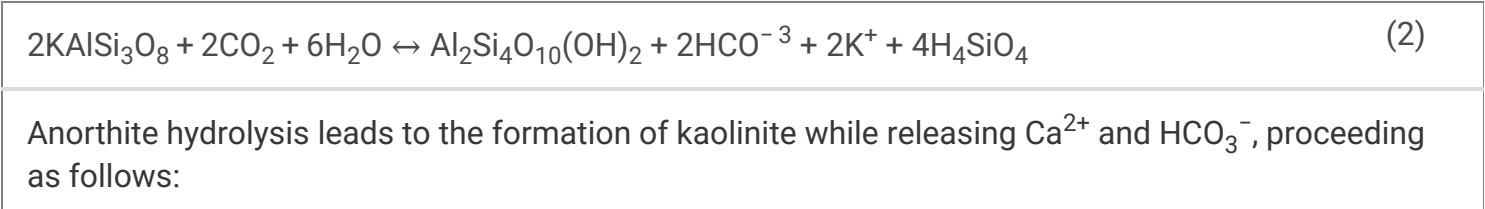
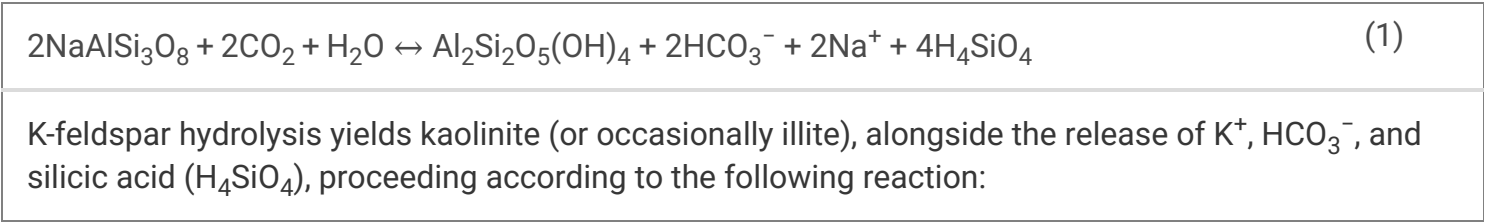
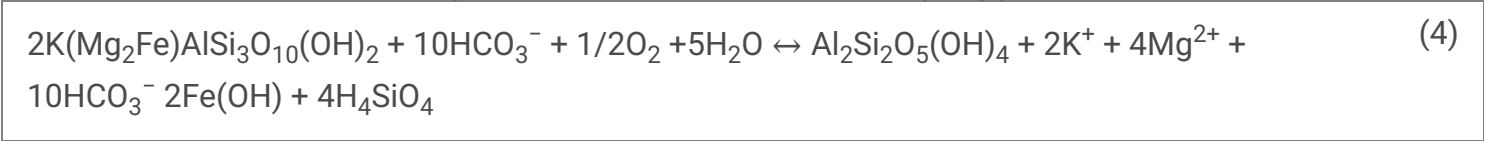


Table 3
Correlation matrix between selected physico-chemical and isotopic parameters measured in the samples and the elevation of the sampling points.



In the Principal Component Analysis (PCA) shown in Fig. 8, all physico-chemical and isotopic variables measured at the sampling points (observations) across both campaigns were considered, including the elevation of each sampling location. For the May campaign, factors 1 and 2 (i.e., F1 and F2) account for over 82% of the total variance, with F1 contributing 70% and F2 12% (Fig. 8a). F1 represents total mineralization, carrying similar weight across chemical variables and EC, except for silica, which is more strongly influenced by F2. F2 explains the relationship with elevation—positive in the case of pH and d-excess, and negative for δ¹⁸O, δ²H, SiO₂, and T. The water samples evolve toward greater mineralization, higher T, and heavier isotopic values (purple arrow in Fig. 8a), strongly influenced by F2. The influence of F1 becomes more evident at certain points downstream of the irrigation/infiltration channels (yellow envelope in Fig. 8a), suggesting that artificially induced surface water infiltration into the weathered granitic layer affects the hydrochemistry of those springs, as well as that of waters emerging around the village at lower elevations. Surface water sampled at the watershed outlet (S. Gregorio) exhibits variances similar to that of springs at higher elevations, although the data points are slightly shifted along the F1 axis, which could reflect the contribution of groundwater that has circulated through the weathered granitic layer.

For the October campaign, factors F1 and F2 account for more than 75% of the variance (Fig. 8b), behaving similarly to the May campaign, but with F2 carrying greater weight (F1 = 60% and F2 = 15%). Water evolution follows a similar pattern, albeit with fewer data points since some springs had dried up. The overall trend mirrors that observed in May but is even more pronounced due to waters with longer residence times in the weathered granitic layer. These waters also shift the surface water sampled at the watershed outlet (S. Gregorio) toward a position similar to that of the springs around the village and those located at mid-watershed elevations, clearly reflecting the impact of artificially recharged water.

The plot relating cation contents (Fig. 9) provides deeper insight into the evolution of water from the headwaters of the watershed to its outlet at Garganta de San Gregorio and allows an evaluation of the influence of artificially infiltrated water. The plot illustrates a higher Na + K content relative to Ca + Mg in both groundwater and surface water in the headwaters and middle watershed, where water is diverted for infiltration via *pesqueras*. Conversely, in the lower part of the watershed (orange envelope in Fig. 9a), below 800 m a.s.l., data points display a higher Ca + Mg content relative to Na + K, showing a similar evolution in both the May and October campaigns. Differences between the two campaigns are observed in the headwaters and middle zone of the watershed. In the May campaign, the water evolves along two distinct pathways: one linear trend incorporating all ions in equal proportions, and another evolutionary trend in which Na + K is incorporated to a greater extent than Ca + Mg, with subsequent enrichment in Ca^{2+} and Mg^{2+} downstream of the *pesqueras*. This evolution is similar to that observed in the October samples. In general, Ca^{2+} in plagioclases dissolves more readily than in Na^+ and K^+ ones (Lasaga, 1984), implying that waters with shorter residence times in the aquifer can more easily incorporate Ca^{2+} than Na^+ , which could explain the linear evolution between these ions during the wet period. For this reason, waters from the dry period, having longer contact with the rock, can preferentially incorporate Na^+ and K^+ rather than Ca^{2+} and Mg^{2+} , likely due to the higher abundance of K-feldspar and sodium plagioclase in the upper watershed. October samples represent waters with longer residence times, as do waters infiltrated into the weathered granitic layer via *pesqueras* (yellow envelope in Fig. 9b). Further downstream, springs are associated with the leucogranite outcropping in that area, where the dominant plagioclase appears to be anorthite; this ultimately causes the groundwater facies to transition from sodium-calcium to calcium-sodium, as shown in Fig. 9a.

5.2. Stable oxygen and hydrogen isotopes

The relationship between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in both groundwater and surface water samples collected during both campaigns is consistent with the Western Mediterranean Local Meteoric Water Line (WMMWL) (Celle-Jeanton et al., 2001). However, given the location of the study area, it is more likely that precipitation originated from Atlantic air masses and that the isotopic composition of the associated precipitation was subsequently modified by local isotopic fractionation processes. Given the high temperatures prevailing from late spring to late autumn, the elevated d-excess values observed in meteoric waters are likely influenced by regional moisture recycling, a process associated with non-equilibrium (kinetic) isotopic fractionation that appears to have been more pronounced during the

October sampling campaign. In addition, d-excess increases with elevation (Fig. 10), reaching values of approximately 14–15‰ at higher elevations and decreasing to around 10–12‰ at lower elevations. This pattern further supports the occurrence of sub-cloud evaporation processes affecting precipitation and, consequently, the isotopic composition of meteoric water.

The N-S orientation of the watershed allows the spatial distribution of $\delta^{18}\text{O}$ values to be examined in a diagram relating them to the X coordinate (Fig. 11a). In this way, it is possible to distinguish both the altitudinal distribution—owing to the high correlation between isotopes and elevation (Table 3)—and the longitudinal distribution. Thus, two sub-watersheds can be clearly differentiated, in which intentional surface water infiltration into the hillslope aquifer is carried out via unlined channels (*pesqueras*). This plot allows to distinguish the influence of recharged waters from different *pesqueras* on the isotopic composition of downstream springs, using distinct envelopes for each channel, with the exception of Los Toriles, whose influence is very minor due to its short length, low diverted flow and flow interruption due to sediment clogging, and proximity to the riverbed. The relationships between sampling point elevation and $\delta^{18}\text{O}$ are shown in Figs. 11b and 11c, which separate the two aforementioned sub-watersheds; these figures depict the inferred recharge elevation ranges for points potentially affected by the *pesqueras*. This allows for an evaluation of the impact of recharged waters on springs exhibiting lighter isotopic values than expected in the absence of this intentional recharge.

Since a specific local rainfall isotopic dataset for the La Vera sector (Gredos mountain range) is not available, a $\delta^{18}\text{O}$ –altitude relationship was adopted based on available regional evidence for Spain and the Iberian Peninsula. Studies from the Spanish precipitation isotope network (REVIP) demonstrate that the spatial distribution of $\delta^{18}\text{O}$ can be reasonably reproduced using regression models that incorporate elevation alongside other geographic factors such as latitude, as well as analysis of long-term series indicating a pattern of increasingly negative values with increasing altitude. Consequently, a conservative gradient of $-2 \pm 0.5\text{‰/km}$ was applied to represent the altitudinal effect on the southern slope of Gredos, incorporating an uncertainty band to account for meteorological and seasonal variability documented in Iberian precipitation (blue lines in Figs. 11b and 11c). The inferred gradient for unaffected groundwater is 1.64‰/km , slightly higher than that reported by Barberá et al. (2018) on the southern slope of Sierra Nevada (southern Iberian Peninsula), which was $1.2\text{--}1.3\text{‰/km}$ with a precipitation gradient of 2.7‰/km . In any case, these values do not differ significantly from those obtained in this watershed.

6. Discussion

6.1. Hydrochemical and isotopic processes

The low mineralization observed in the hydrochemical samples collected from the San Gregorio watershed reflects the low solubility of the granitic lithology and the short residence times of water within the hard-rock aquifers of the high-mountain hillslopes. However, the observed changes are sufficient to reveal a clear increase in electrical conductivity and higher concentrations of Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , and dissolved silica. Similar hydrochemical patterns have been reported for the Medel

infiltration channel (Sierra de Guadarrama, Spain), where spring waters exhibit conductivity values up to 650 $\mu\text{S}/\text{cm}$ higher than those of surface waters prior to infiltration (Baizán-Alcón et al., 2026).

The isotopic composition of surface water and groundwater is consistent with that of precipitation derived from Atlantic air masses (Gat, 1996), although it has been subsequently altered by local kinetic isotopic fractionation processes. The relationship between isotopic composition and elevation also shows isotopically lighter waters discharging from springs located at lower elevations, supporting their origin from waters infiltrated through the *pesqueras* at higher elevations (Springer et al., 2016). Similar isotopic responses have been observed in Sierra Nevada, where infiltrated waters retain high-elevation isotopic signatures during surface transport and subsequently emerge at lower-elevation springs (Barberá et al., 2018). In the San Gregorio watershed, isotopic evidence independently supports the conceptual recharge model derived from field sampling campaigns and, together with hydrochemical and hydrological observations, confirms the effectiveness of the traditional recharge structures locally known as *pesqueras* as a Nature-based Solution (NbS).

Hydrochemical evidence further supports the conceptual hydrological model proposed in previous studies, which indicated that the *pesqueras* account for approximately 58% of the total groundwater recharge in the watershed and contribute, on average, 2 hm^3 of infiltrated water annually (Aguilera et al., 2026; Naranjo-Fernández et al., 2025).

The results indicate that infiltration through the *pesqueras* enhances groundwater circulation and prolongs water-rock interaction times. Consequently, the restoration of this network of infiltration channels not only increases groundwater storage but also enhances water mineralization, thereby improving the quality of the meteoric water downstream of the recharge area, where it would otherwise exhibit a very low mineral content. The observed increase in dissolved ions reflects greater contact between infiltrated water and the granitic aquifer layer, revealing that the recharge process provides both quantitative and qualitative benefits. Similar effects have been documented in the ancestral *acequias de careo* of Sierra Nevada, where managed aquifer recharge significantly increases groundwater storage and modifies groundwater discharge patterns (Baizán-Alcón et al., 2026, Jódar et al., 2022; Morales-Sotaminga et al., 2023, Zakaluk et al., 2024). Likewise, studies of pre-Incan *amunas* in the Peruvian Andes have shown that intentionally infiltrated stream water can be stored within mountain aquifers and released months later as spring discharge, thereby sustaining water availability during dry periods (Ochoa-Tocachi et al., 2019).

6.2. Benefits and implications for water resources management

The recovery of the *pesqueras* network driven by the "Ocho Caños" Irrigation Community constitutes a successful example of community-led participatory restoration of ancestral NbS. Such practices foster a strong sense of shared responsibility and social cohesion among local users (Albarracín et al., 2021). Through this initiative, traditional community knowledge has been recovered while local water management has been optimized without relying on public administration, demonstrating that

participatory governance can be an effective tool for ensuring the long-term maintenance and success of traditional water infrastructure (Cabello et al., 2026).

Furthermore, groundwater storage capacity increases, and the induced infiltration processes enhance the quality of water that would otherwise exhibit very low mineral content. These processes can be replicated in other mountain areas with similar characteristics and represent an exemplary approach to resilience and adaptation to climate change.

Overall, this study shows that the hydrochemical and isotopic changes occurring in water infiltrating through the *pesqueras* result in moderate mineral enrichment while maintaining the concentrations of the analysed constituents within the guideline values recommended by the World Health Organization for drinking-water quality (WHO, 2026). This enrichment is driven by increased water residence time within the weathered granitic mantle. As water circulates through this layer, progressive mineral dissolution occurs, leading to enhanced concentrations of major ions and silica in the springs used for water supply. Consequently, these findings indicate that restoring the *pesqueras* network as a NbS can provide significant benefits not only in terms of water availability and spatial distribution, but also by preserving a suitable hydrochemical quality for drinking-water supply without compromising its suitability for human consumption.

Ultimately, the results of this study demonstrate that the restoration of *pesqueras* provides multiple simultaneous water-management benefits, such as increasing groundwater resource availability, improving water quality, and sustaining downstream spring discharge throughout the year. The integration of the hydrogeological and hydrochemical ecosystem services delivered by this NbS enhances its value and effectiveness as a low-cost climate-adaptation strategy for mountain communities facing increasing environmental pressures.

7. Conclusions

The restoration of the ancestral *pesqueras* network in the San Gregorio watershed functions as an NbS that provides multiple benefits, including increased groundwater storage, improved water quality, and the maintenance of spring discharge, particularly at downstream springs within the local population center. The hydrochemical and isotopic study of groundwater validates the existing hydrogeological model and provides new evidence that intentional recharge through the *pesqueras* increases groundwater residence times, resulting in greater water mineralization. The subsurface transit of water makes it more suitable for human consumption, as evidenced by the samples collected from downstream springs.

The restoration and rehabilitation of the *pesqueras* network carried out by the Ocho Caños Irrigation Community provides an example of an initiative that highlights the value of local community knowledge and demonstrates how such environmental knowledge can contribute to the development of more resilient water-management strategies. Finally, this study provides scientific validation of ancestral recharge systems that are based on and help preserve local ecological knowledge, offering a powerful,

low-cost, and highly adaptable approach that can be replicated in other mountainous areas underlain by granitic rocks and adapted to future climate change scenarios.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics, Consent to Participate, and Consent to Publish

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable

Funding

This work has been supported by INCHA project (PID2022–140092OB-I00 funded by MCIN/AEI/10.13039/501100011033 and co-financed by FEDER).

Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by AGR, SMR, FGS, BR,AFA,HA,JJ and TZ. The first draft of the manuscript was written by NNF,SMR and AGR all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

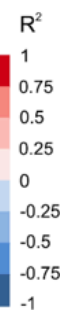
Data Availability

The data used in this study were obtained from publicly available sources and from field observations and analyses conducted by the authors. The data generated and analysed during the current study are available from the corresponding author upon reasonable request.

Table 3

Table 3 Correlation matrix between selected physico-chemical and isotopic parameters measured in the samples and the elevation of the sampling points.

		Temp	pH	Cond	Na	K	Ca	Mg	Cl	SO4	HCO3	NO3	SiO2	18O	2H	d-excess
Altitude	m(asl)	-0,75	-0,15	-0,57	-0,60	-0,45	-0,55	-0,53	-0,33	-0,43	-0,53	-0,30	-0,25	-0,93	-0,91	-0,59
Temp	°C		-0,02	0,57	0,65	0,49	0,63	0,62	0,23	0,50	0,66	0,27	0,30	0,85	0,87	-0,13
pH				0,19	0,13	0,16	0,11	0,12	-0,07	0,07	0,14	-0,02	-0,11	0,28	0,31	-0,42
Cond	uS/cm				0,89	0,92	0,87	0,90	0,43	0,56	0,88	0,42	0,21	0,59	0,61	-0,52
Na	mg/L					0,89	0,92	0,94	0,57	0,72	0,94	0,56	0,42	0,68	0,68	-0,41
K	mg/L						0,88	0,92	0,55	0,68	0,89	0,59	0,10	0,52	0,52	-0,49
Ca	mg/L							0,98	0,65	0,82	0,96	0,67	0,21	0,61	0,61	-0,48
Mg	mg/L								0,60	0,77	0,96	0,63	0,20	0,61	0,60	-0,45
Cl	mg/L									0,79	0,52	0,96	0,28	0,33	0,26	-0,41
SO4	mg/L										0,77	0,85	0,18	0,49	0,47	-0,45
HCO3	mg/L											0,57	0,25	0,61	0,62	-0,47
NO3	mg/L												0,14	0,33	0,27	-0,01
SiO2	mg/L													0,23	0,29	-0,82
18O	‰														0,98	-0,70



References

1. Aguilera H, Fernández-Ayuso A, Ramos B, Naranjo Fernández N, Zakaluk T, Marín-Lechado C, González-Ramón A, Jódar J, Huertas R, de la Losa A, Martín-Civantos JM, Martos-Rosillo S. (2026) Recovering ancestral infiltration channels (pesqueras) as managed aquifer recharge in weathered granite slopes: hydrological impact, community-led restoration and Nature-based Solution implications (La Vera, Sierra de Gredos, Spain). Groundwater for Sustainable Development. *Preprint*.
2. Albarracín M, Ramón G, González J, Iñiguez-Armijos C, Zakaluk T, Martos-Rosillo S. The Ecohydrological Approach in Water Sowing and Harvesting Systems: The Case of the Paltas Catacocha Ecohydrology Demonstration Site, Ecuador. *Ecohydrology & Hydrobiology*; 2021.
3. Barberá JA, Jódar J, Custodio E, González-Ramón A, Jiménez-Gavilán P, Vadillo I, Pedrera A, Martos-Rosillo S. Groundwater dynamics in a hydrologically-modified alpine watershed from an ancient managed recharge system (Sierra Nevada National Park, Southern Spain): Insights from hydrogeochemical and isotopic information. *Sci Total Environ*. 2018;640–1. <https://doi.org/10.1016/j.scitotenv.2018.05.305>.
4. Baizán Alcón N, Luque T, Talavera L, Rodríguez A, González Yélamos J, Fernández Ayuso A. (2026). Soluciones basadas en la naturaleza para la gestión del agua en la Sierra de Guadarrama: Estudio de la cacera de San Medel (Torrecaballeros, Segovia). *Geogaceta*, 79, 15–18. <https://doi.org/10.55407/geogaceta117197>
5. Cabello J, Casas JJ, Escudero-Clares M, Martín-Civantos JM, Martos-Rosillo S, Pacheco-Romero M, Salinas-Bonillo MJ. Acequias tradicionales de Sierra Nevada (España): una infraestructura socio-ecológica para la conservación de paisajes multifuncionales. *Ecosistemas*. 2026;35(1):3042. <https://doi.org/10.7818/ECOS.3042>.
6. Celle-Jeanton H, Travi Y, Blavoux B. Isotopic typology of the precipitation in the Western Mediterranean region at three different time scales. *Geophys Res Lett*. 2001;28(7):1215–8.

7. Contreras-López E, Sánchez-Carretero R, Junco-Aguado F. Mapa geológico y Memoria de la Hoja nº 599 (Jaraíz de la Vera). Mapa Geológico de España. Escala 1:50.000. Madrid: Instituto Geológico y Minero de España (IGME); 2008.
8. Custodio E, Llamas MR, editors. Hidrología subterránea [Groundwater hydrology]. Volume 2. Barcelona: Volumes Ediciones Omega; 1976. p. 2350.
9. Gat JR, ISOTOPES IN THE HYDROLOGIC CYCLE. OXYGEN AND HYDROGEN. *Annu Rev Earth Planet Sci.* 1996;24(1):225–62. <https://doi.org/10.1146/annurev.earth.24.1.225>.
10. Gómez P, Turrero MJ, Garralón A, Peña J, Buil B, De la Cruz B, Sánchez L. Hydrogeochemical characteristics of deep groundwaters of the Hesperian Massif (Spain). *J Iber Geol.* 2006;32(1):113–31.
11. Hargreaves GH, Samani ZA. Reference Crop Evapotranspiration from Temperature. *Appl Eng Agric.* 1985;1(2):96–9. <https://doi.org/10.13031/2013.26773>.
12. Hoefsloot FI, Martínez J, Pfeffer K. An emerging knowledge system for future water governance: sowing water for Lima. *Territory Politics Gov.* 2024;12(6):825–45. <https://doi.org/10.1080/21622671.2021.2023365>.
13. Jódar J, Zakaluk T, González-Ramón A, Ruiz-Constán A, Marín-Lechado C, Martín-Civantos JM, Custodio E, Urrutia J, Herrera C, Lambán LJ, Durán JJ, Martos-Rosillo S. Artificial recharge by means of careo channels versus natural aquifer recharge in a semi-arid, high-mountain watershed (Sierra Nevada, Spain). *Sci Total Environ.* 2022;825:153937. <https://doi.org/10.1016/j.scitotenv.2022.153937>.
14. Lalonde M, Drenkhan F, Rau P, Baiker JR, Buytaert W. Scientific evidence of the hydrological impacts of nature-based solutions at the catchment scale. *WIREs Water.* 2024;11(5):e1744. <https://doi.org/10.1002/wat2.1744>.
15. Lasaga AC. Chemical kinetics of water-rock interactions. *J Geophys research: solid earth.* 1984;89(B6):4009–25.
16. Martín-Loeches M. (1995). Hydrogeology of the igneous and metamorphic rocks in a sector of the Alberche River Watershed and its relationship with the groundwaters of the Madrid Watershed. PhD Thesis, University of Alcalá de Henares, Spain.
17. Martín-Loeches M, Pavón-García J, Molina-Navarro E, Martínez-Santos P, Almeida C, Reyes-López J, Sastre-Merlín A. Hydrogeochemistry of granitic mountain zones and the influence of adjacent sedimentary watersheds at their tectonic borders: the case of the Spanish Central System batholith. *Hydrogeol J.* 2020;28(7):2425–42. <https://doi.org/10.1007/s10040-020-02196-w>.
18. Martos-Rosillo S, Ruiz-Constán A, González-Ramón A, Mediavilla R, Martín-Civantos JM, Martínez-Moreno FJ, Durán JJ. The oldest managed aquifer recharge system in Europe: New insights from the Espino recharge channel (Sierra Nevada, southern Spain). *J Hydrol.* 2019;578:124047. <https://doi.org/10.1016/j.jhydrol.2019.124047>.
19. Morales-Sotaminga S, Fernández-Ayuso, Ramos B, Fornell JAB, González-Ramón A, Zakaluk T, Martos-Rosillo S. Caracterización hidrogeoquímica e isotópica de la cuenca de alta montaña del río

- Alhorí (Sierra Nevada, Sur de España). *Geogaceta*. 2023;73:15–8.
<https://doi.org/10.55407/geogaceta95514>.
20. Naranjo Fernández N, Fernández Ayuso A, Aguilera H, Marín Lechado C, González Ramón A, Zakaluk T, Martos Rosillo S. Evaluación de la recarga de agua subterránea en cuencas de montaña desarrolladas sobre rocas duras: caso de la garganta de San Gregorio, Aldeanueva de la Vera (Cáceres). *Geogaceta*. 2025;78:27–30. <https://doi.org/10.55407/geogaceta113419>.
21. Ochoa-Tocachi BF, Bardales JD, Antiporta J, Pérez K, Acosta L, Mao F, Zulkafli Z, Gil-Ríos J, Angulo O, Grainger S, et al. Potential contributions of pre-Inca infiltration infrastructure to Andean water security. *Nat Sustain*. 2019;2(7):584–93. <https://doi.org/10.1038/s41893-019-0307-1>.
22. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. *Hydrol Earth Syst Sci*. 2007;11(5):1633–44. <https://doi.org/10.5194/hess-11-1633-2007>.
23. Peral C, Navascués B, Ramos P. (2017). Serie de precipitación diaria en rejilla con fines climáticos. Nota Técnica No. 24. Agencia Estatal de Meteorología (AEMET).
24. Somers KA, McKenzie JM, Mark BG, Lagos P, Ng G-HC, Wickert AD, Yarlequé C, Baraer M, Gutierrez A, Condom T. (2018). Groundwater buffers decreasing glacier melt in the tropical Andes. *Geophys Res Lett*, 45(23), 12,974 – 12,984.
25. Springer AE, Boldt EM, Junghans KM. Local vs. Regional Groundwater Flow Delineation from Stable Isotopes at Western North America Springs. *Groundwater*. 2016;55(1):100–9.
<https://doi.org/10.1111/gwat.12442>.
26. Steig EJ, Gkinis V, Schauer AJ, Schoenemann SW, Samek K, Hoffnagle J, Dennis KJ, Tan SM. Calibrated High-Precision ^{17}O -Excess Measurements Using Cavity Ring-down Spectroscopy with Laser- Current-Tuned Cavity Resonance. *Atmos Meas Tech*. 2014;7. 10.5194/amt-7-2421-2014.
27. World Health Organization (WHO). (2022). *Guidelines for Drinking-water Quality*. Fourth Edition Incorporating the First and Second Addenda. Geneva: World Health Organization. 617 pp. ISBN 978-92-4-012122-5.
28. WWAP. Nature-Based Solutions for Water. United Nations World Water Development Report 2018. UNESCO World Water Assessment Programme; 2018.
29. Zakaluk T, Jódar J, González-Ramón A, Civantos JM, Lambán LJ, Martos-Rosillo S. Ancestral managed aquifer recharge systems and their impacts on the flow regime of a semi-arid alpine watershed (Sierra Nevada, Spain). *J Hydrology: Reg Stud*. 2024;54:101870.
<https://doi.org/10.1016/j.ejrh.2024.101870>.

Figures

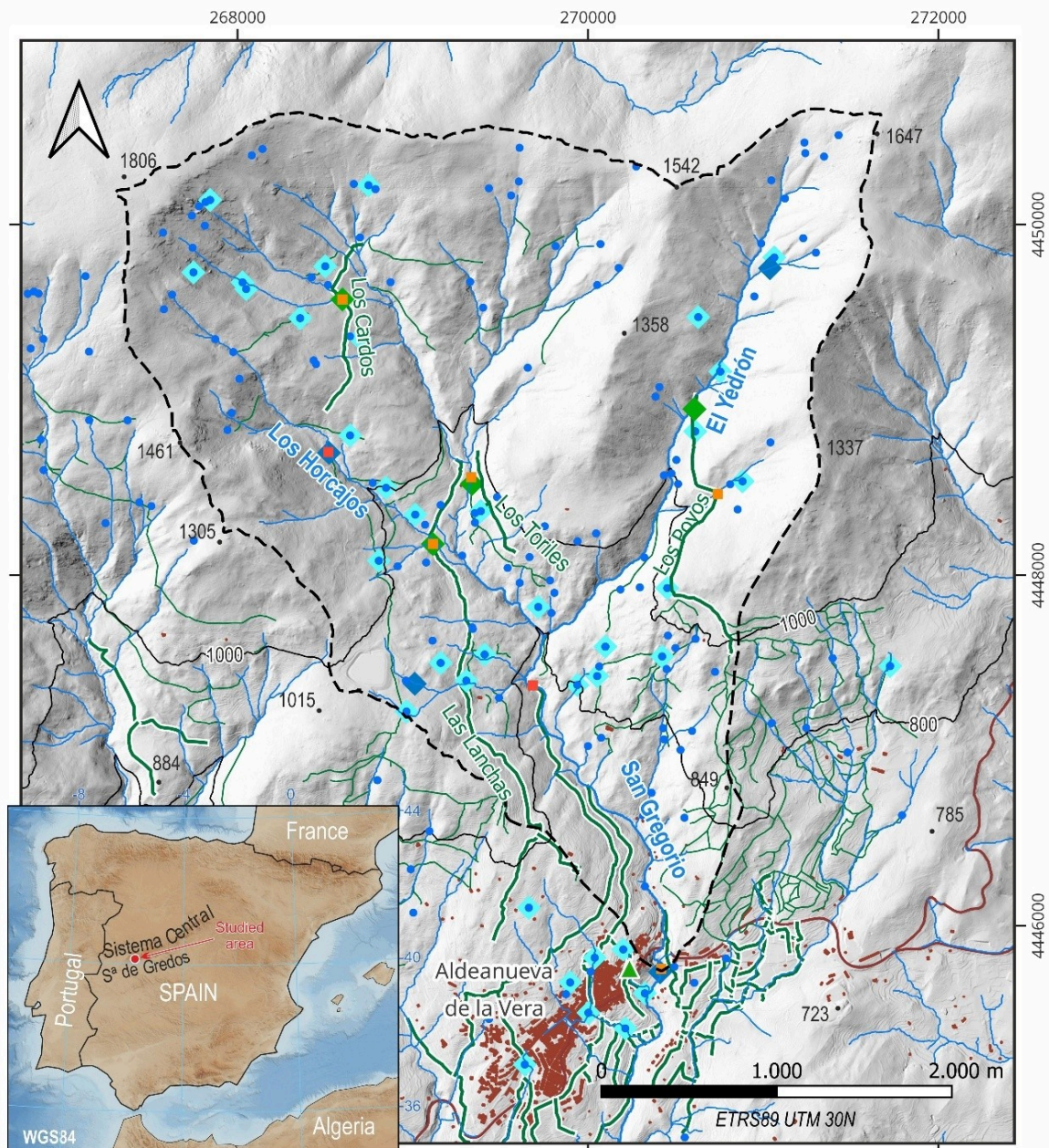


Figure 1

Location map of the study area.

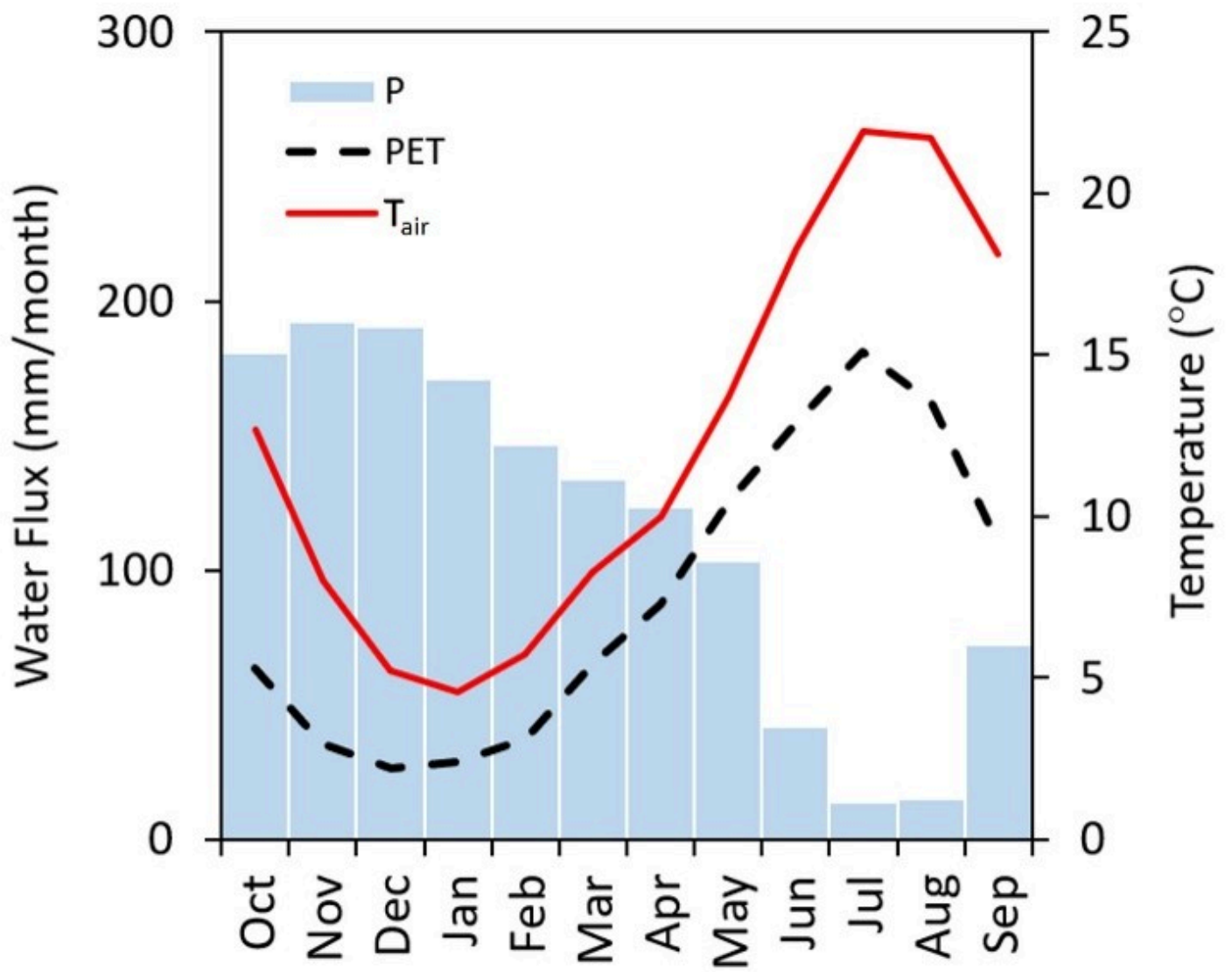


Figure 2

Seasonal variation in the water fluxes precipitation (P) and potential evapotranspiration (PET), together with air temperature (T_{air}), in the San Gregorio watershed.

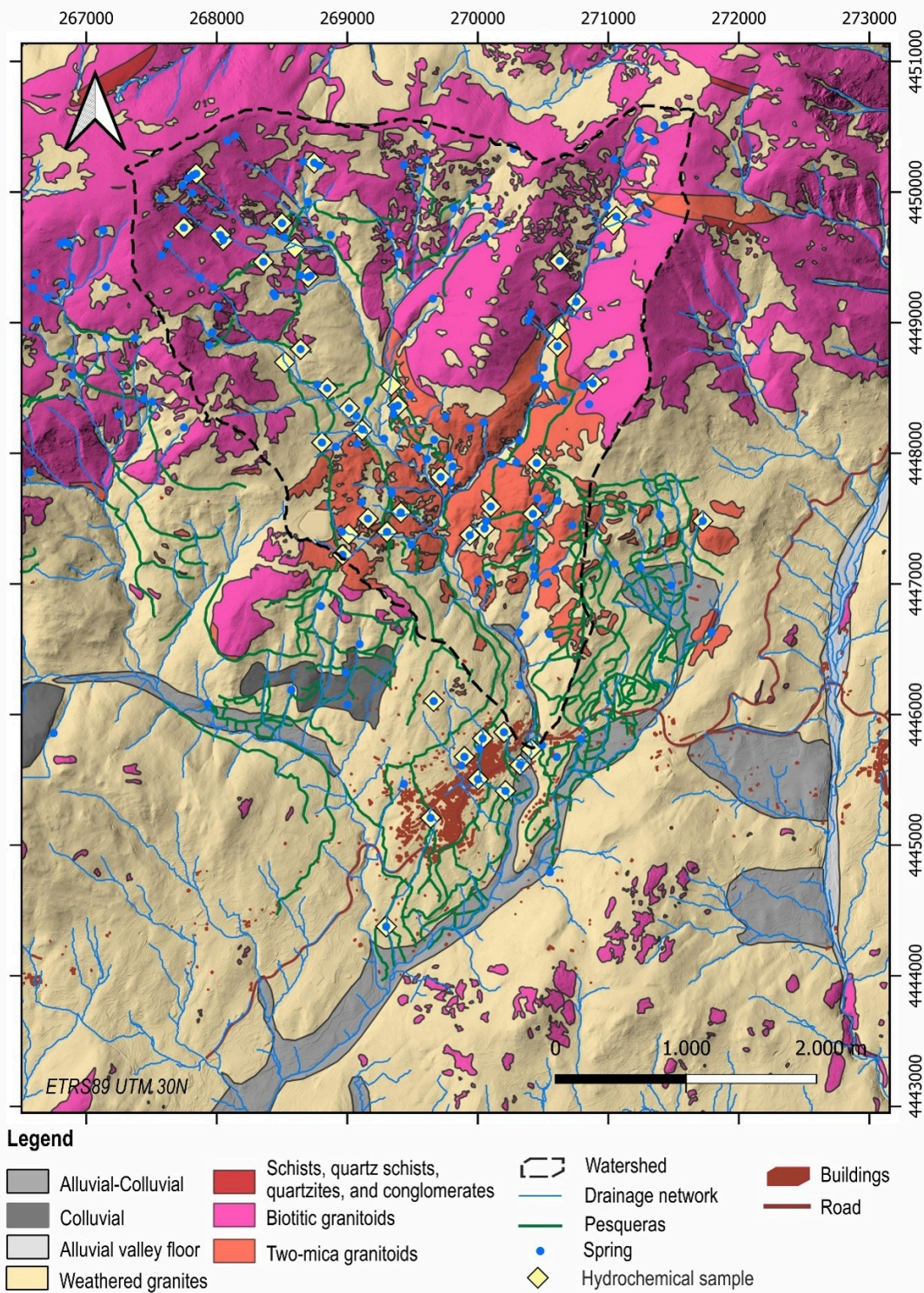


Figure 3

Hydrogeological map.

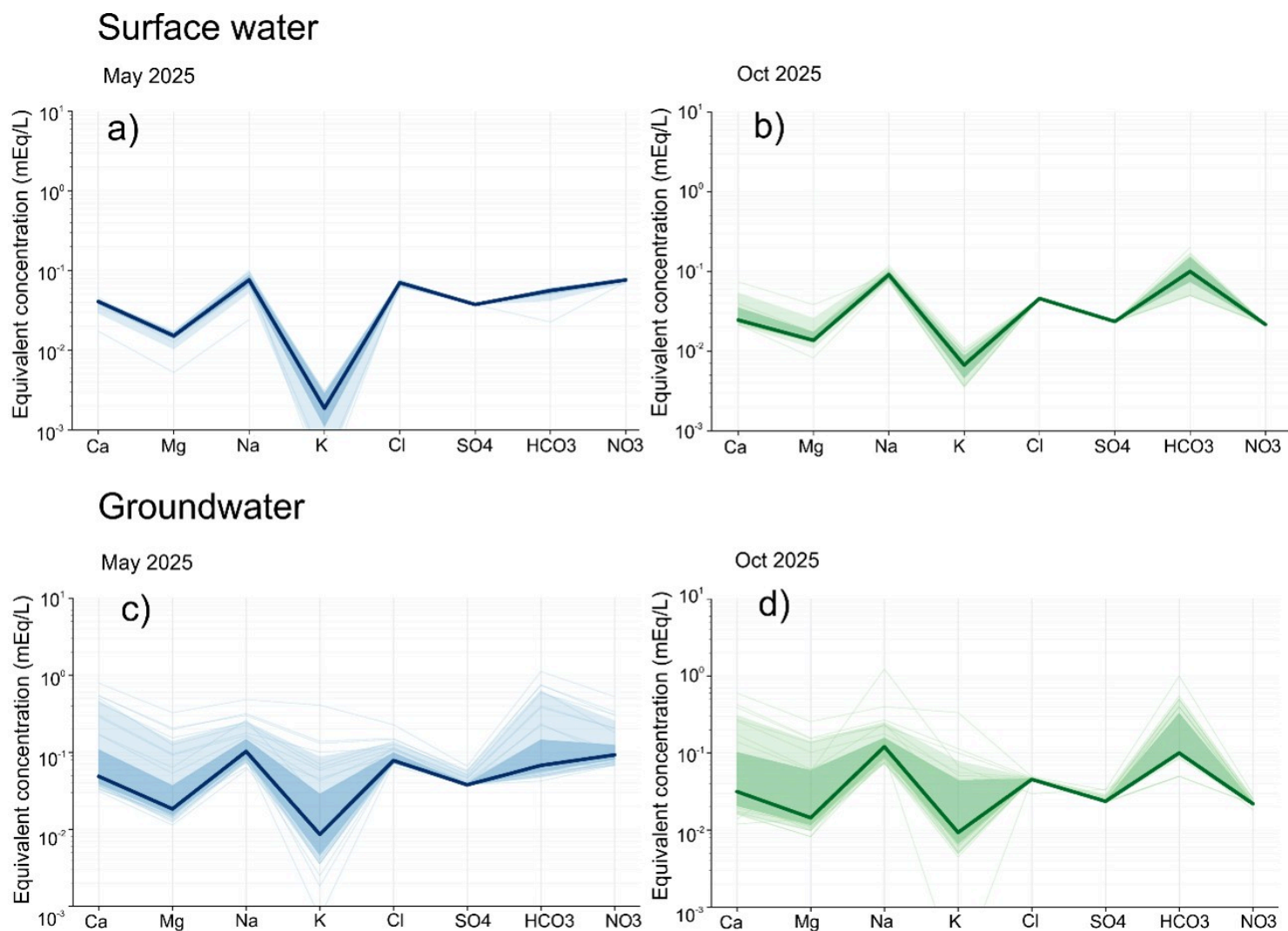


Figure 4

Schoeller-Berkaloff diagram for the analyzed samples. a) and c) Samples collected in May 2025; b) and d) samples collected in October 2025. The shaded areas indicate the 10th-90th and the 25th-75th percentile ranges, and the thick line represents the median.

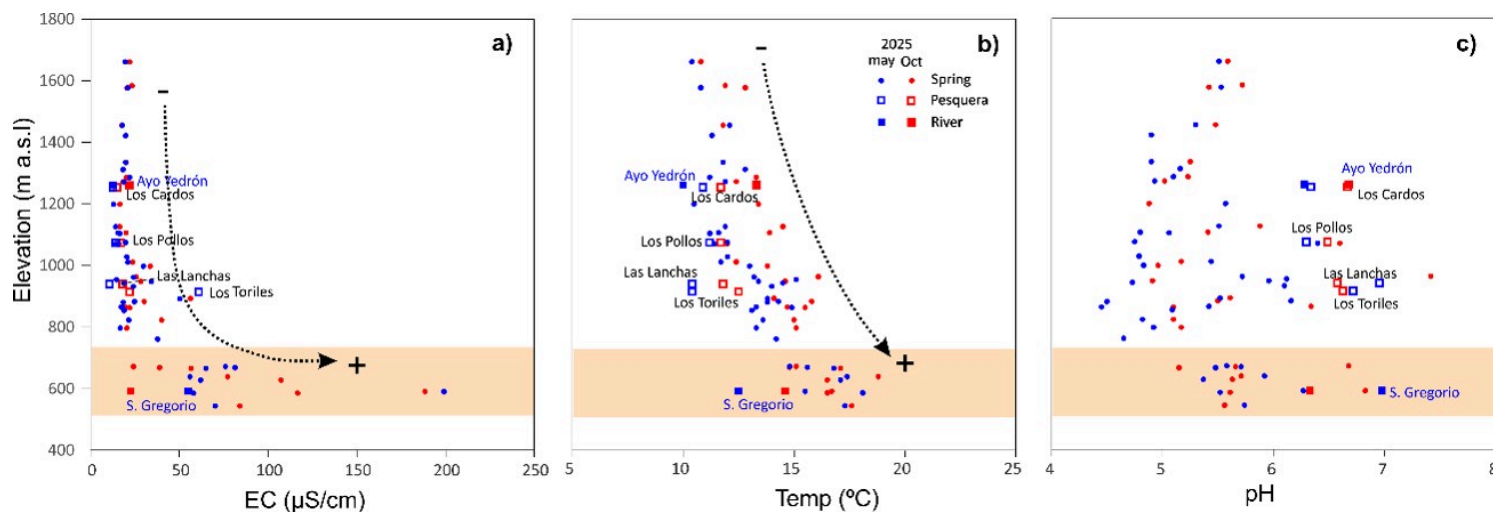


Figure 5

Relationships between EC (a), T (b), and pH (c) with elevation, for the two sampling campaigns. The orange band corresponds to the group of springs identified at elevations below 800 m a.s.l. around the urban center of Aldeanueva de la Vera. Filled rectangles indicate surface water values in the two main rivers (blue label), and open rectangles represent water diverted by the irrigation channels (*pesqueras*) (black label).

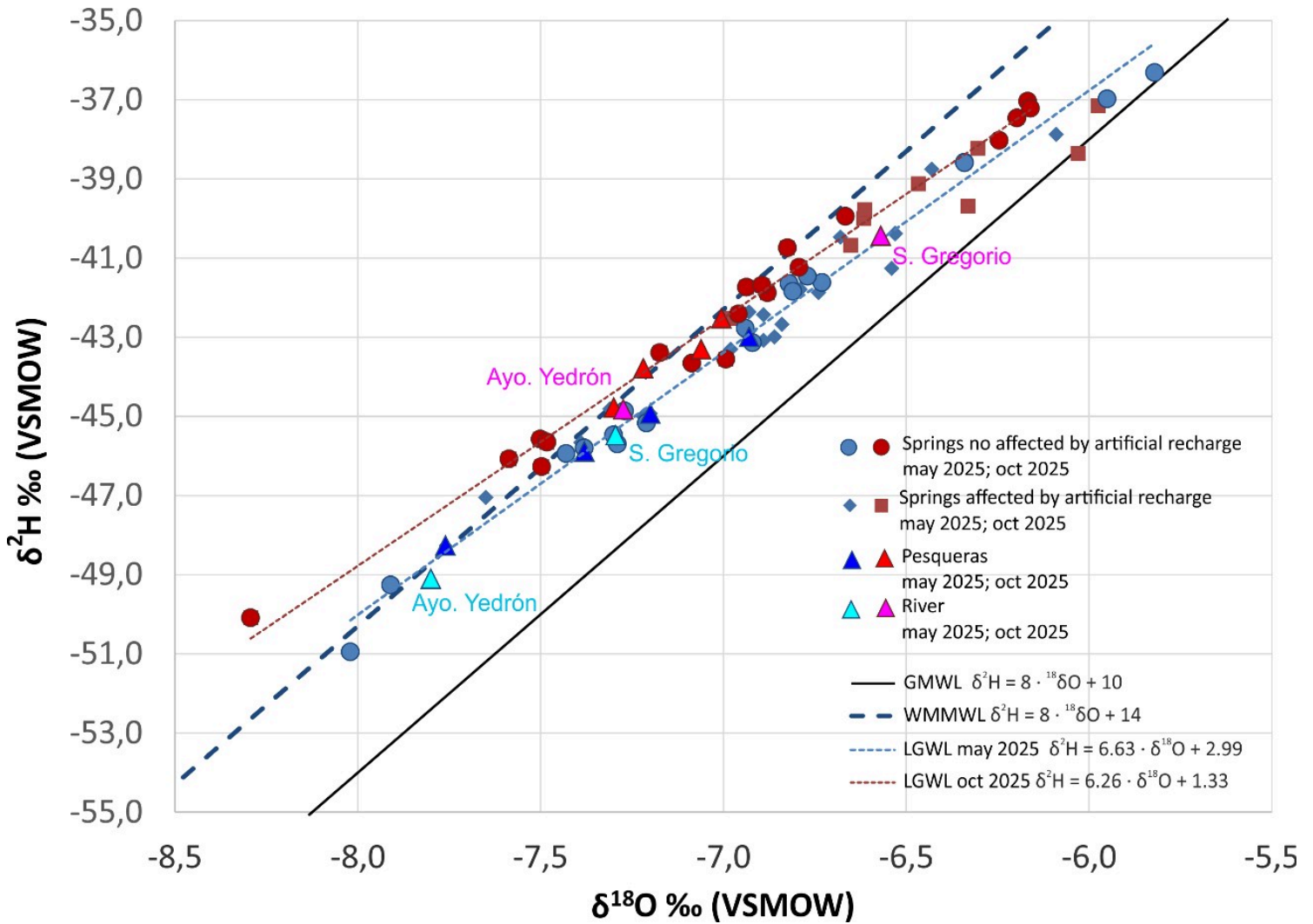


Figure 6

$\delta^2\text{H}$ vs $\delta^{18}\text{O}$ plot for all groundwater, river and *pesqueras* samples collected in May and October 2025. GMWL ($d = 10\text{‰}$), WMMWL ($d = 14\text{‰}$), LGWL for May ($d=2.99\text{‰}$) and October ($d=1.33\text{‰}$) of 2025; stand for Global, Western Mediterranean Meteoric, and Local Groundwater Water Line respectively.

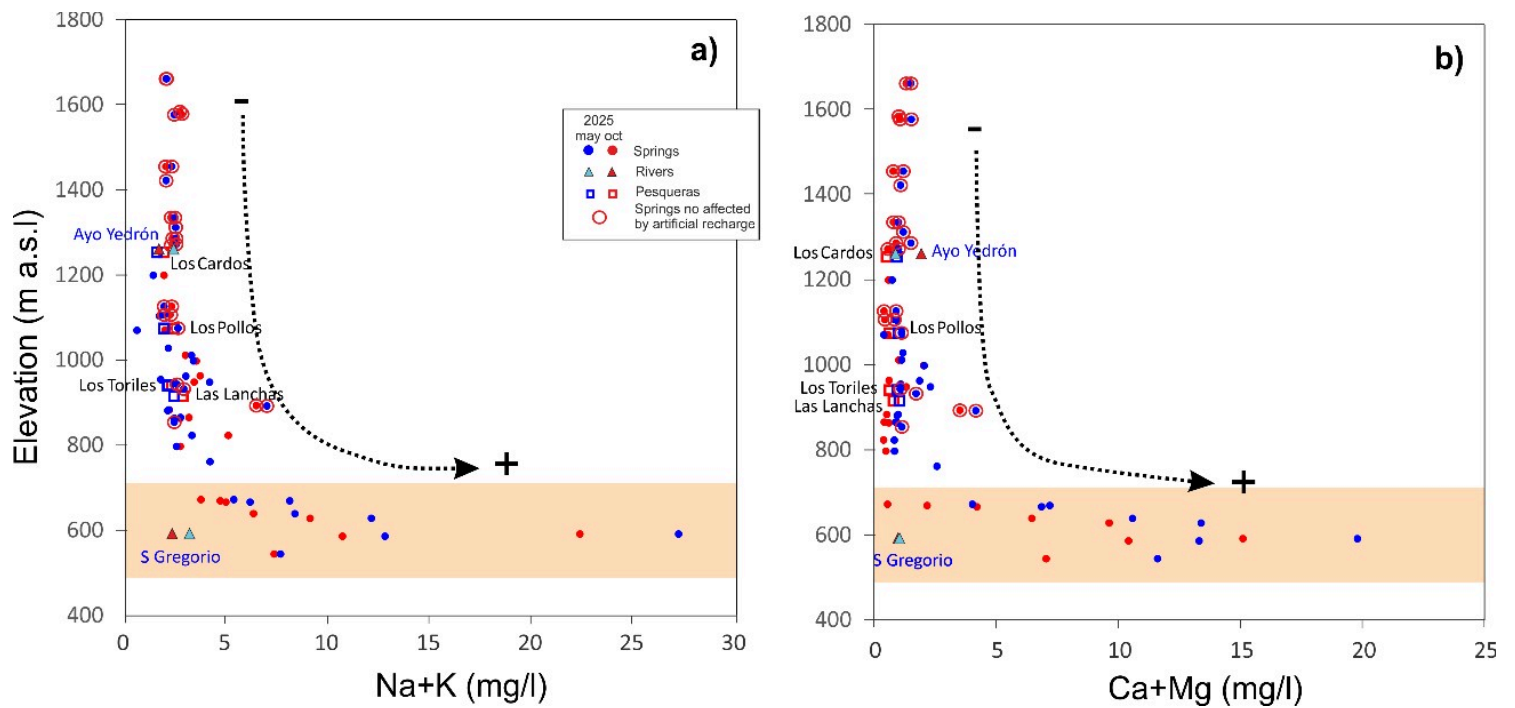


Figure 7

Altitudinal variation in Na+K (a) and Ca+Mg (b) content in groundwater and surface water. Samples corresponding to surface waters from the two main rivers, as well as intake points for channel diversion (*pesqueras*) and their subsequent infiltration into the weathered granitic layer, are indicated. Dotted arrows indicate the evolution of mineralization. The orange band corresponds to the group of springs identified at elevations below 800 m a.s.l. around the urban center of Aldeanueva de la Vera.

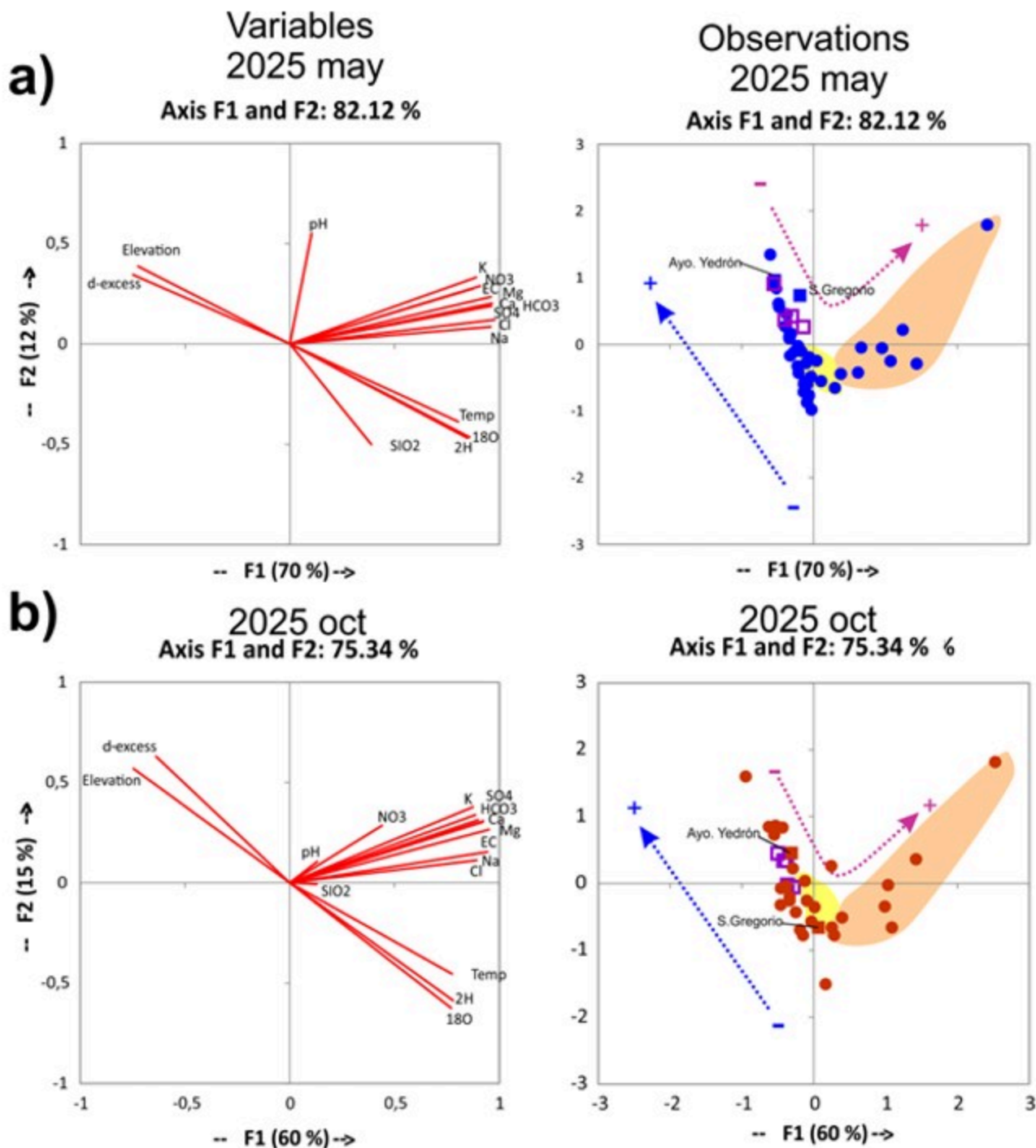


Figure 8

Principal Component Analysis including physico-chemical variables measured in groundwater and surface water and sampling-point elevation for samples collected in May 2025 (a) and October 2025 (b). The yellow envelope indicates points that could be affected by artificial recharge through the irrigation/infiltration channels (*pesqueras*), and the orange envelope indicates springs located below 800 m a.s.l.

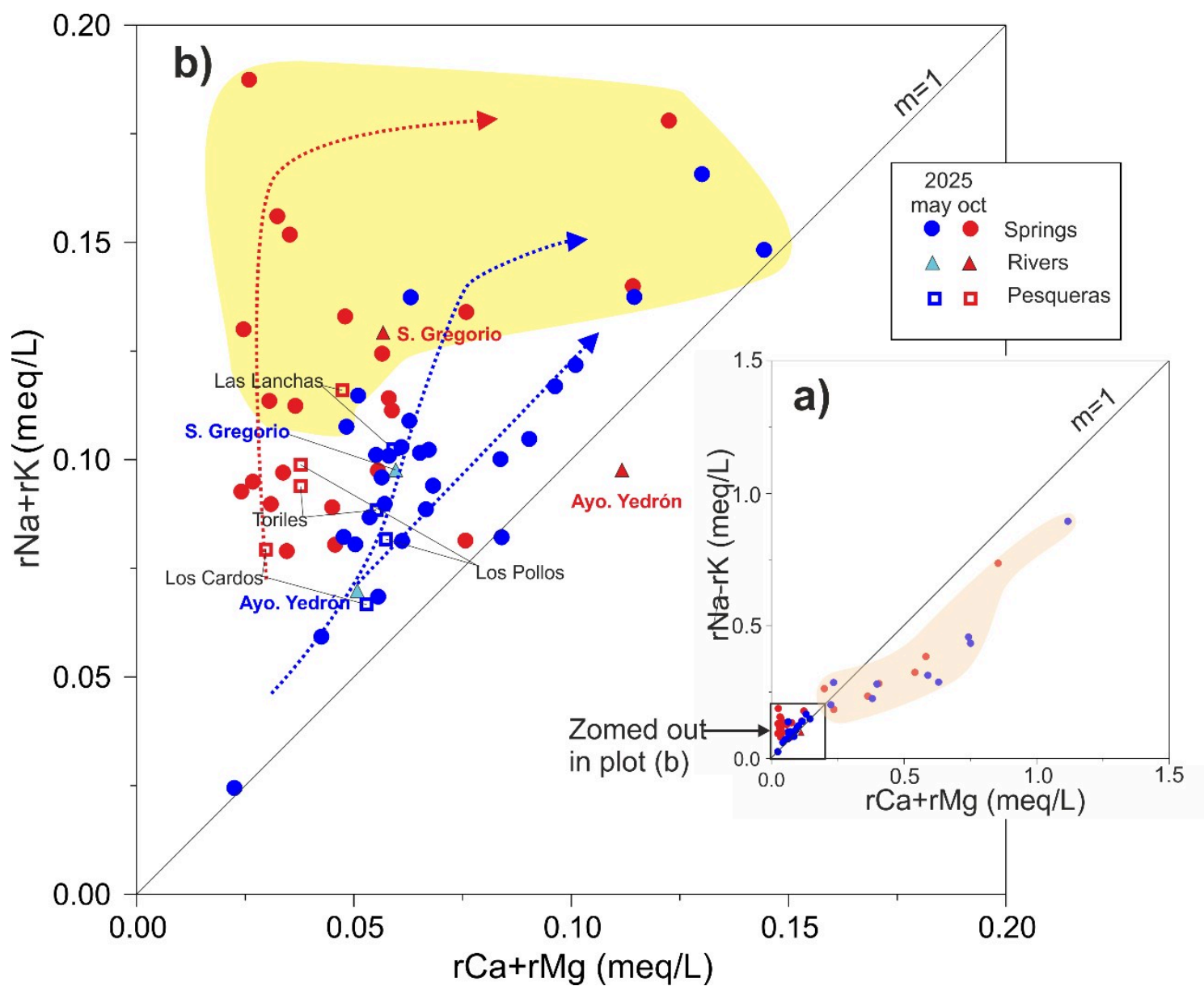


Figure 9

Relationship between $rNa+rK$ and $rCa+rMg$ for the entire watershed (a) and for the upper and middle watershed (b) in groundwater and surface water samples collected in May and October 2025. The yellow and orange band have the same meaning as in Fig. 8.

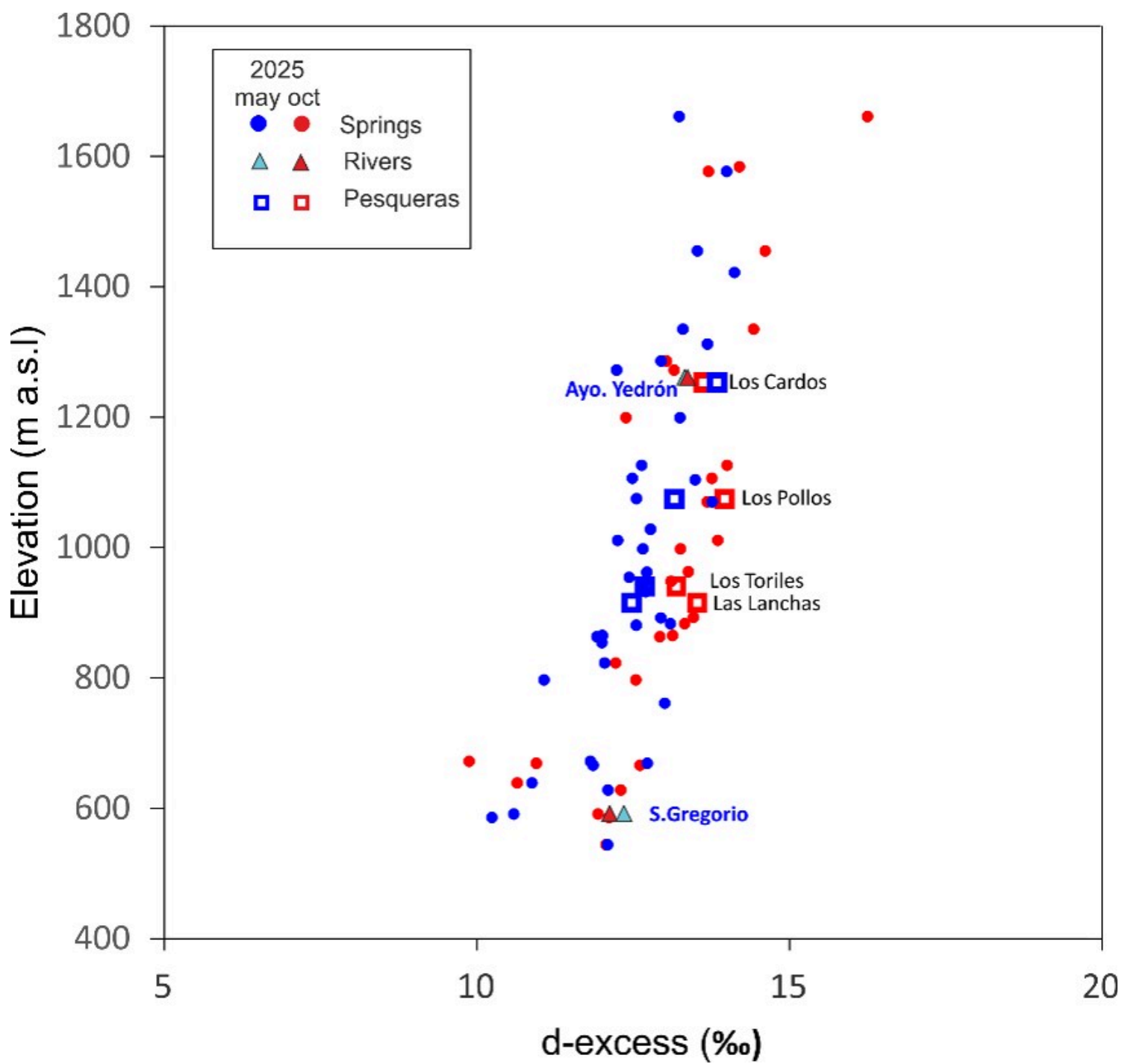


Figure 10

Relationship between d-excess and elevation for the sampling campaigns of May and October.

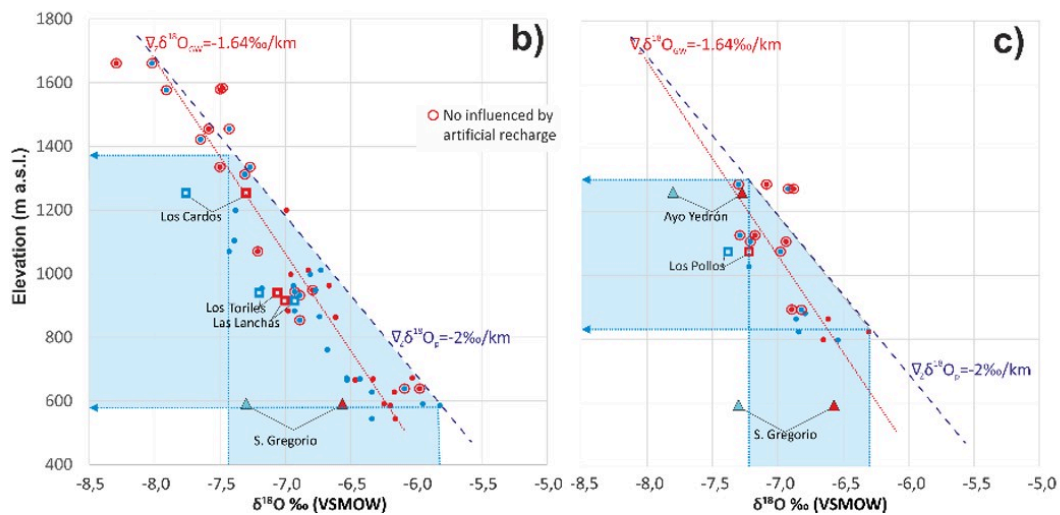
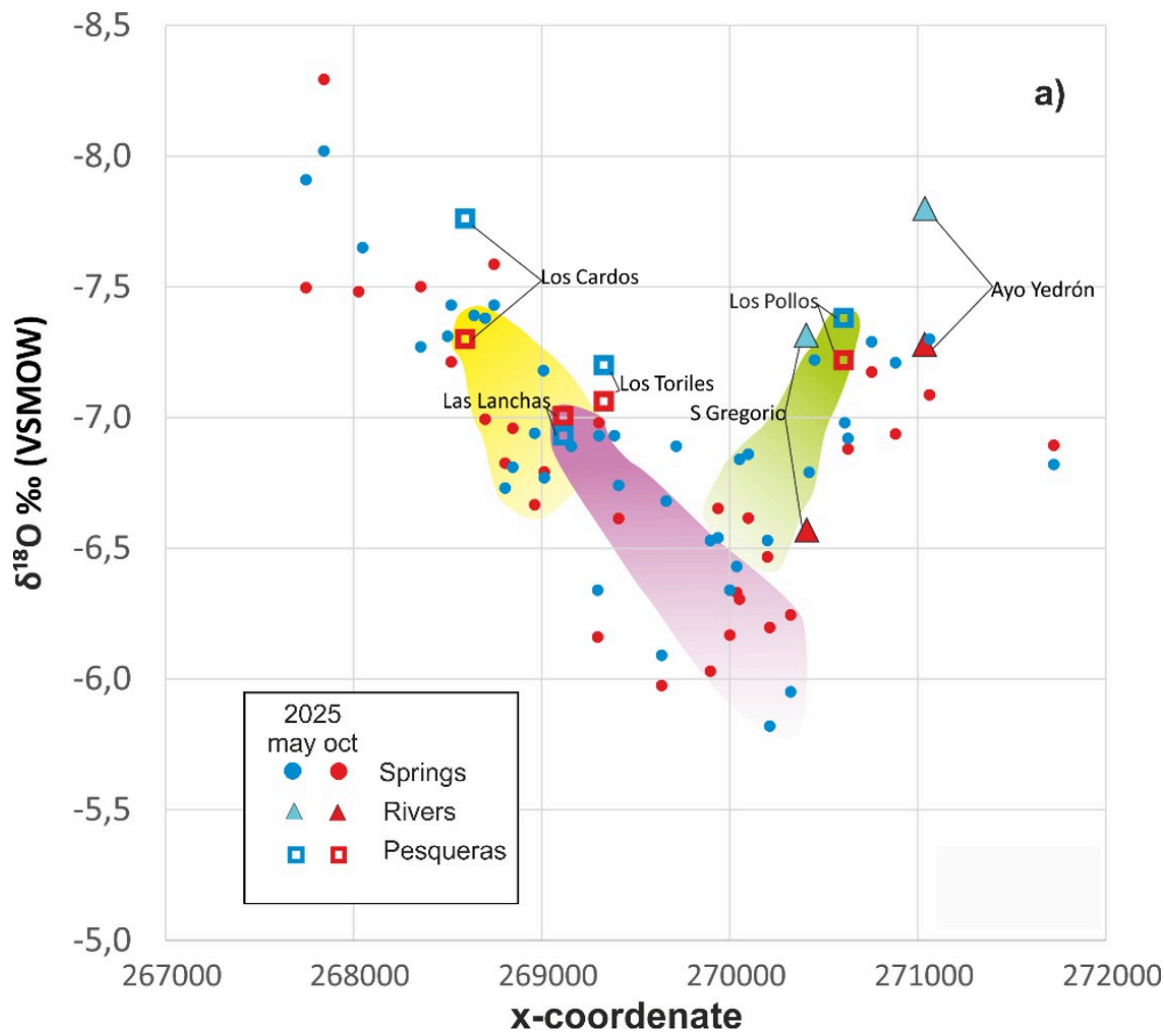


Figure 11

a) Distribution of $\delta^{18}\text{O}$ with respect to the X coordinate of water samples collected in the watershed, and in relation to altitude in the Garganta de San Gregorio sub-watershed. The envelopes of different colors indicate the influence of waters recharged from the distinct pesqueras. (b) and the Yedrón stream and sub-watershed (c). The red line represents the altitudinal isotopic line constructed using the isotopic composition of watershed sampling points unaffected by recharge induced by irrigation channels

(*pesqueras*). The dashed blue line corresponds to the altitudinal isotopic line for precipitation considered for the southern slope of the eastern Sierra de Gredos. The blue shaded area corresponds to the recharge elevation range of springs potentially influenced by irrigation channel recharge, derived from maximum and minimum values projected onto the blue line.