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Physical and chemical properties of the groundwater of the Santo Domingo-Salinas ranges, South Central Pyrenees

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ABSTRACT
The Santo Domingo-Salinas ranges represent a unique Natural Area in the south-central Pyrenees, and they were declarationas a Protected Landscape in 2015. Available biological and geological knowledge is extensive but lacks of information on groundwater quality. In this work we provide new hydrogeological results and integrate them with previously available hydrogeological data. To do so, we have: (i) compiled existing hydrogeological information, (ii) exhaustively developed an inventory of water points, (iii) sampled, analyzed and interpreted the hydrochemical facies detected, and (iv) developed a preliminary conceptual model for the hydrogeological functioning of the area. These information has been integrated in an map that displays the chemical analyses of the two new campaigns (Stiff diagrams), the flow rates and the three aquifer systems defined. This new information improves and synthetizes the knowledge of the hidrogeology of the Santo Domingo-Salinas ranges Protected Landscape and it will help in its future management and planning.

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1. Introduction

The westernmost corner of the External Sierras in the South-Central Pyrenees (Spain) was declared as a Protected Landscape by the Aragonian Government in 2015 (Decree 52/2015, BOA 72, 11767-96). The Santo Domingo-Salinas ranges are characterized by some remarkable conditions:

- *Climate*; these ranges represent the transition between Mediterranean and Atlantic weather conditions. The former dominates the region and the latter is confined to the north slope of the range, where snow may last some weeks during winter time in the highest elevations (between 1000 and 1500 m).
- *Geology*; the Santo Domingo-Salinas ranges represent the south-westernmost termination of the Pyrenean sole thrust separating the Pyrenean fold and thrust belt in the North from the Ebro foreland basin to the South. The complex evolution of the Pyrenean orogeny, especially during Eocene-Miocene times, has produced outstanding geological structures in the area such as large-scale conical geometries, folded thrusts and down-plunging folds, among others (Pueyo et al., 2020).
- *Geomorphology*; the Santo Domingo-Salinas ranges is a rough mountain terrain characterized by dominant E-W morphostructural alignments that are crossed by a deeply incised drainage network. The morphology is mostly governed by lithological and structural factors. The highest reliefs at the Sierra de Santo Domingo y Salinas ranges (>1500 m) represent the morphological expression of the Pyrenean sole thrust and its associated structures. A second, lesser relief is conditioned by conglomerates accumulated in the apex of a major Miocene alluvial fan (e.g. 1300 m, Puig Moné). The horizontal sedimentary series dominate the southern part of the area, where the fluvial network is more dendritic (Teixell et al., 1992a, 1992b). Fluvial terraces are absent throughout the area but glacis and slope deposits can be identified in some locations.
- *Hydrology and hydrogeology*; the area drains into three of the most important river basins of the Aragonian Pyrenees. Thus, the Asabón river drains most of the northern slope of the Santo Domingo-Salinas ranges into the Gállego basin, whereas the northwestern part of the area is drained into the Aragón basin through the Onsella river. Most of the southern slope of the sierras drains into the Arbas basin through the Arba de Luesia river and its tributaries, Arba de Biel and Farasdués rivers. Rivers in the area are characterized by modest flows and are very hierarchical and irregular due

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to the low capacity of regulation of their basins, typical of pre-Pyrenean rivers. In spite of this, water resources are abundant in the ranges; despite the presence of many streams, ravines and springs, hydrological information on the area is very scarce (Sánchez-Moreno, 2012).

- *Flora and fauna*; well preserved and autochthonous Scots pine (*Pinus sylvestris*), beech (*Fagus sylvatica*) and Valencian oak (*Quercus faginea*) forests thrive in the highest elevations and in the north slope of the ranges. Evergreen oak (*Quercus ilex*) forest with shrubs (*Buxus sempervirens, Arbutus unedo*, *Prunus spinosa*, *Genista scorpius*) dominate in the southern slope of the ranges. Poplars (*Populus alba, P. Nigra and P. tremula*) and willows (*Salix, Sp.*) grow along riverbanks. Alpine meadows are found in the highest altitudes. Reforested pine forest (*Pinus nigra*) represents 22% of total forest body. Among other relevant fauna occurrences (*Sus scrofa*, *Capreolus capreolus*, *Cervus elaphus* etc.), the population of necrophagous raptors stands out (*Gyps fulvus, Neophron percnopterus*, *Aegypius monachus* and few *Gypaetus barbatus*).
- *Socio-economic factors*; the area is characterized by low population density that ranges between 0.65 and 3.2 hb/km^2. Local communities make public use of the forest in most part of the territory, where sustainable use of resources (agriculture and livestock, forest management, hunting and mushroom reserves, cultural and outdoor activities) is promoted by local administrators.

These combination of features make the Santo Domingo-Salinas ranges a unique Natural Area with a high degree of environmental preservation, as was initially recognized by the European Union as a Site of Community Importance (SCI) in the European Commission Habitats Directive (92/43/EEC). The ES2410064-Santo Domingo and Caballera ranges together with ES2430063-Onsella River SCI's cover more than 70% of the protected landscape. The area was also identified as a Special Protection Area (SPA) of Wild Birds, (SPA ES0000287). These especial preservation areas are enclosed in the Natura 2000 Network promoted by the European Union for the protection of biodiversity and habitats.

In order to better improve the hydrogeological knowledge on the Protected Landscape, we have gathered all information on groundwater characteristics that is available from public repositories. Apart from controlling and managing surface waters quantity and quality, the Ebro Water Authority (*Confederación Hidrográfica del Ebro*-CHE) developed an initial inventory of groundwater points that consisted of 26 springs, nine wells and a basic survey on the groundwater system of the ranges. Additional information on the main aquifers of the area and their hydrogeological functioning was provided for the area in the framework of the ES091MSBT033 report produced by the CHE for the wider Santo Domingo-Guara region. We have had also access to some supplementary hydrogeological reports linked to the geological maps from the MAGNA Program, Sheets Uncastillo (208) and Agüero, (209) carried out by the IGME, where a more complete inventory of groundwater points (Garrido-Schneider, 1995; Garrido-Schneider & Azcón, 1994) and a hydrogeological study of the right bank of the Gállego river (Garrido-Schneider, 2004) are available. All in all, the existing information is scarce and has led to a simplistic and generic hydrogeological interpretation of the Santo Domingo-Salinas ranges. In addition to gathering previous information, we have made an exhaustive update of the inventory of water points in the area by undertaking two new field campaigns were new samples were taken and the physical–chemical parameters of the groundwater were also measured. All these results are shown in the map introduced in this paper with the aim of synthetizing the hydrogeological information and helping in the management plan of the protected landscape.

2. Map specifications

The map presented in this paper uses the ETRS_1989_TM30 projected coordinated systems (Royal decree 1071/2007, BOE 207 35986/89, ED50 was formerly used in IGME maps), so that it fits the requirements of the Directive 2007/2/EC of the European Union (March 2007) for establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). It also fulfills the Mapping Standards of Aragon (Spain; http://idearagon.aragon.es/).

The available hydrogeological maps produced by the IGME and CHE were ruled out as background map since they display insufficient scale or very little detail (usually 1:200,000 scale). On the contrary, and due to the consistency between the lithology and the chronostratigraphy (no major lateral changes in the sedimentary facies are recognized in this sector), the MAGNA geological (1:50,000 scale) maps are more informative as a background layer and display much more detail in some key detritic and carbonatic formations that have a limited thickness but play a determinant role in the hydrogeological interpretation. Therefore, portions from MAGNA maps #208 (Uncastillo) and #209 (Agüero) (García-Sansegundo et al., 2009; Teixell et al., 2009 respectively) were used as background. The digital version used in this paper also benefits from the harmonization carried out under the GEODE Program in the Pyrenees (Robador et al., 2011, 2019). Additional improvements are derived from Sánchez-Moreno (2012) and Sánchez-Moreno et al. (2015) works. In this paper, the map scale is 1:25,000. In addition, the map has been enhanced with supplementary information on the hydrographic network, the digital terrain model, topography and the protected landscape boundaries (http://iber.chebro.es/geoportal/, http://ign.es/web/ign/portal, and https://idearagon.aragon.es/). Finally, the three main defined hydrogeology systems have been also drawn together with a qualitative estimation of the permeability derived from the geological formations in the region (Garrido-Schneider & Azcón, 1994, 1995).

The Stiff diagrams were calculated and generated with Easy-Quim_5.0 (free software of the Hydrogeology Group from the Polytechnic University of Catalonia), and have been represented with the Surfer v.15 software (Golden Software LLC). These diagrams are also displayed in the map for a quick comprehension of the compositional and spatial distribution of the groundwater hydrochemistry throughout the region. In addition, different water points (spring, well and borehole) were located in the map; their flowrates were measured in the field during the summer campaign, and are represented in the map with a blue spring symbol proportional to the flow range.

3. General setting

The Santo Domingo-Salinas ranges (Figures 1 and 2) are located across the Huesca and Zaragoza provinces (Northern Spain). The study area covers a surface of about 230 km^2. It is bordered to the north by the villages of Longás and Salinas de Jaca, to the east by the Gállego river valley, to the south by the townships of Luesia and Agüero, and to the west by the mountain pass between Luesia and Longás (Lurientes/San Marzal area). Elevation decreases from north to south, with a maximum altitude of 1524 m a.s.l. at the Peña de Santo Domingo summit and a lowermost point of about 700 m a.s.l. in the southernmost sector of the map. In the central area, South of the range backbone, there are still outstanding reliefs (1303 m a.s.l.) such as the Puig Moné (Figure 3).

In the southwestern sector of the range, the 'Arba de Luesia' and 'Arba de Biel' rivers run north–south until their coalescence to the Arba river, a first-order tributary of the Ebro river with a mean annual flow of 12.85 m^3/s in 2018 (CHE). The ravines on the northern slope drain their waters towards the Onsella river (mean annual flow 1.99 m^3/s in 2018, CHE). This river runs from east to west before entering the Aragón river. In the eastern sector, the Asabón river (mean annual flow 0.902 m^3/s in 2018-CHE) rises in Villalangua and flows eastwards through the northern slope of the range to the Peña Reservoir. Besides these main rivers, there are many torrents and ravines, numerous springs, waterfalls and river ponds.

The climate is continental-mediterranean with a certain Atlantic influence in this part of the westernmost Pyrenean foothills. The surroundings of Santo Domingo-Salinas ranges are quite humid, with an

Figure 1. Aerial picture of the hermitage of the Santo Domingo range. North is to the right.

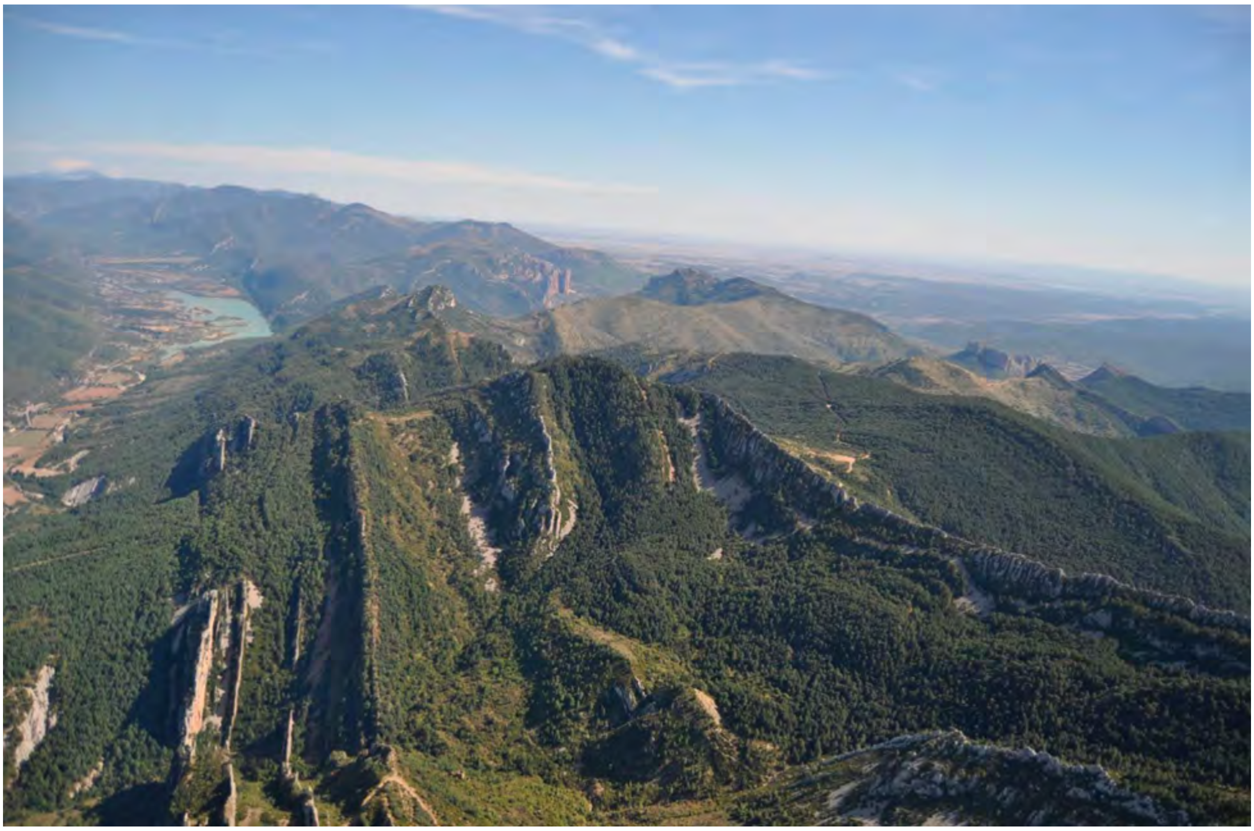

Figure 2. Aerial picture of the Salinas range and La Peña reservoir in the background. North is to the left.

average rainfall of around 900 mm per year in the northern slope of the area that decreases towards the Ebro valley in the South. Precipitation falls mainly during the winter-spring season, and are always scarcer over the summer. The average annual temperature of the area ranges between around 8°C in the higher elevations to 11°C in the valleys. The winters are cold, with frequent frosts, and the summers display an average temperature of around 20–22°C (Ibarra, 2007).

4. Geological setting

The Santo Domingo-Salinas ranges represent the relief caused by the outcrop of the South Pyrenean basal thrust (Arenas, 1993; Millán, 2006; Nichols, 1987 Pueyo, 2000; Puigdefàbregas, 1975; Turner, 1988). As part of the External Sierras structural unit, the Santo Domingo-Salinas ranges represent the southernmost limit of the mountain range, separating the fold-and-thrust belt (Pyrenees) to the North from its undeformed foreland in the South (Ebro basin) (Figure 4).

The oldest materials crop out at the core of the NW-SE oriented anticline (called Santo Domingo) that is associated with the South Pyrenean basal thrust (Figure 4). They are gypsum and clays belonging to the so-called Keuper facies, and dolostones belonging to the overlying Muschelkalk facies, both Triassic in age. These lagoon deposits display very low permeabilities, except for the highly conductive Muschelkalk dolostones. Atop of the Triassic materials, the marine transitional and bioclastic Upper Cretaceous limestones (≈ 70–85 M.a., <50 m in thickness, permeable) are found. Just above, the Garum facies (usually red sandstones) represent the Cretaceous-Tertiary boundary (approx. 50 m in thickness). Conformably above the Garum facies, the shallow platform limestones of the Guara Formation are found (Silva-Casal, 2017; Silva-Casal et al., 2019). This formation ranges in age from 49 to 40 Ma, shows a maximum thickness of 150 in the area, and constitutes the most prominent relief at both sides of the core of the Santo Domingo anticline. Above the Guara Formation, and usually forming topographic depressions due to their friability, the marls of the Arguis Formation (≈35–40 Ma, 300 m in thick) crop out. They represent a marine platform environment with some interbedded shallowing sequences made up of reef and siliciclastic deposits whose permeable is larger than that of the surrounding marls. Continental sedimentation begun right after deposition of the Arguis Formation, and is represented (from bottom to top) by the thin (50 m) Yeste-Arrés transitional sandstone, the Campodarbe Formation (made up by more than 4500 m of alluvial sandstones and clays) and the Uncastillo Formation (made up by 1000 m of mainly conglomerates and sandstones). This latter formation represents the youngest materials found in the area, and witnessed the exhumation and subsequent erosion of the highest reliefs of the Pyrenees during the Miocene. Accurate dating of most of

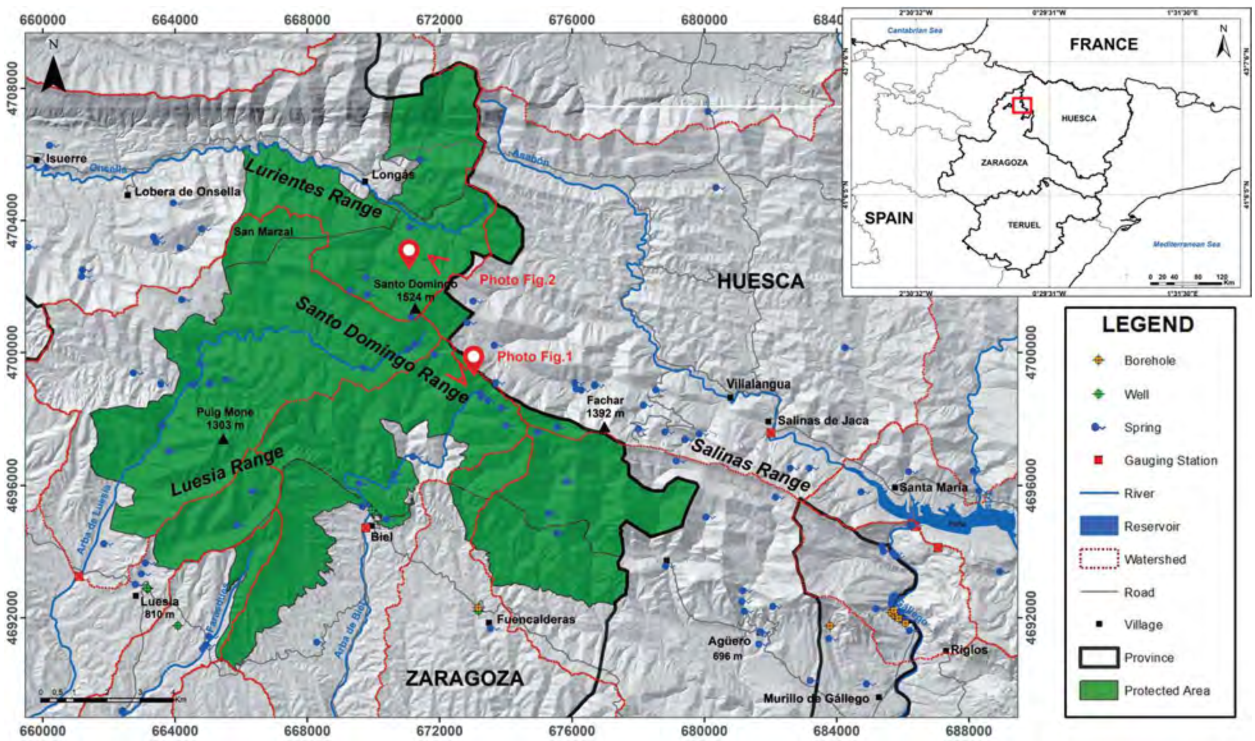

Figure 3. Map of the Santo Domingo-Salinas range Protected Area (see inset for location within the Aragón Autonomous Region), with the locations of rivers, villages, water points and the views depicted Figures 1 and 2.

these sequences have been carried out during the last years by means of magnetostratigraphic studies (Upper Cretaceous-Garum, Pueyo et al., 2016; Guara Formation, Rodríguez-Pintó et al., 2012; Silva-Casal et al., 2019; Arguis Formation, Costa et al., 2010; Pueyo et al., 2002; Campodarbe Formation, Oliva-Urcia et al., 2016; and Uncastillo Formation, Oliva-Urcia et al., 2019).

The main structural feature in the area is the aforementioned Santo Domingo anticline (Arenas et al., 2001; Calvin et al., 2017; Mallada, 1881; Millán et al., 1995, 2000; Oliva-Urcia et al., 2012; Puigdefàbregas, 1975; Teixell & García Sansegundo, 1995), which displays a prominent conical closure to the west in the San Marzal pericline (Millán et al., 1992; Nichols, 1987; Pueyo et al., 2017). To the east, the anticline reaches the Gállego River becoming a thrust fault and shows an eastwards down-plunge. This outstanding structure can be tracked along-strike the Pyrenean front for more than 30 km and affects more than 6 km of stratigraphic pile. The fold axis of the Santo Domingo anticline is horizontal throughout most of its length but in its westernmost part, where it strongly down-plunges to the west in San Marzal area in response to the pinning effect caused by the disappearance of the regional detachment level constituted by the Keuper facies (Pueyo et al., 2020).

Towards the east (sector of Riglos pinnacles in the Gállego river), the Santo Domingo anticline no longer displays the apparently simple geometry of its central sector. There, a set of Eocene and Cretaceous limestones, along with relicts of Jurassic limestones, appear south of the anticline. These outcrops attests to the complex imbricate system of thrust sheets (Upper Eocene) that developed prior to the completion of the folding (Oligocene-Miocene) of the Santo Domingo anticline (Oliva-Urcia et al., 2019).

5. Methodology

Aiming to improve the hydrochemistry information on the characteristics and distribution of the water drained from the aquifers of the Santo Domingo-Salinas ranges, two field campaigns were carried out. An initial campaign in winter, with three field trips (13–14 December 2016, 22–24 February and 15–16 March 2017), was followed by a second one in summer (22–28 July 2017). In these campaigns, the inventory of water points was updated and completed, and water samples and 'in situ' measurements of physical–chemical parameters were also taken (Figure 5). In order to review and update the water points database, the information collected from the CHE and the IGME was previously studied, and it was completed with additional fountains and springs found during the development of this work and also reported by the local forest rangers (Luesia and Ayerbe headquarters). In total, information from 179 water points was compiled, nine of them being boreholes and eight wells. The total number of water points falling within the boundaries of our study area reaches 78 springs. From them, 58 (none of them wells or boreholes) were sampled and studied with

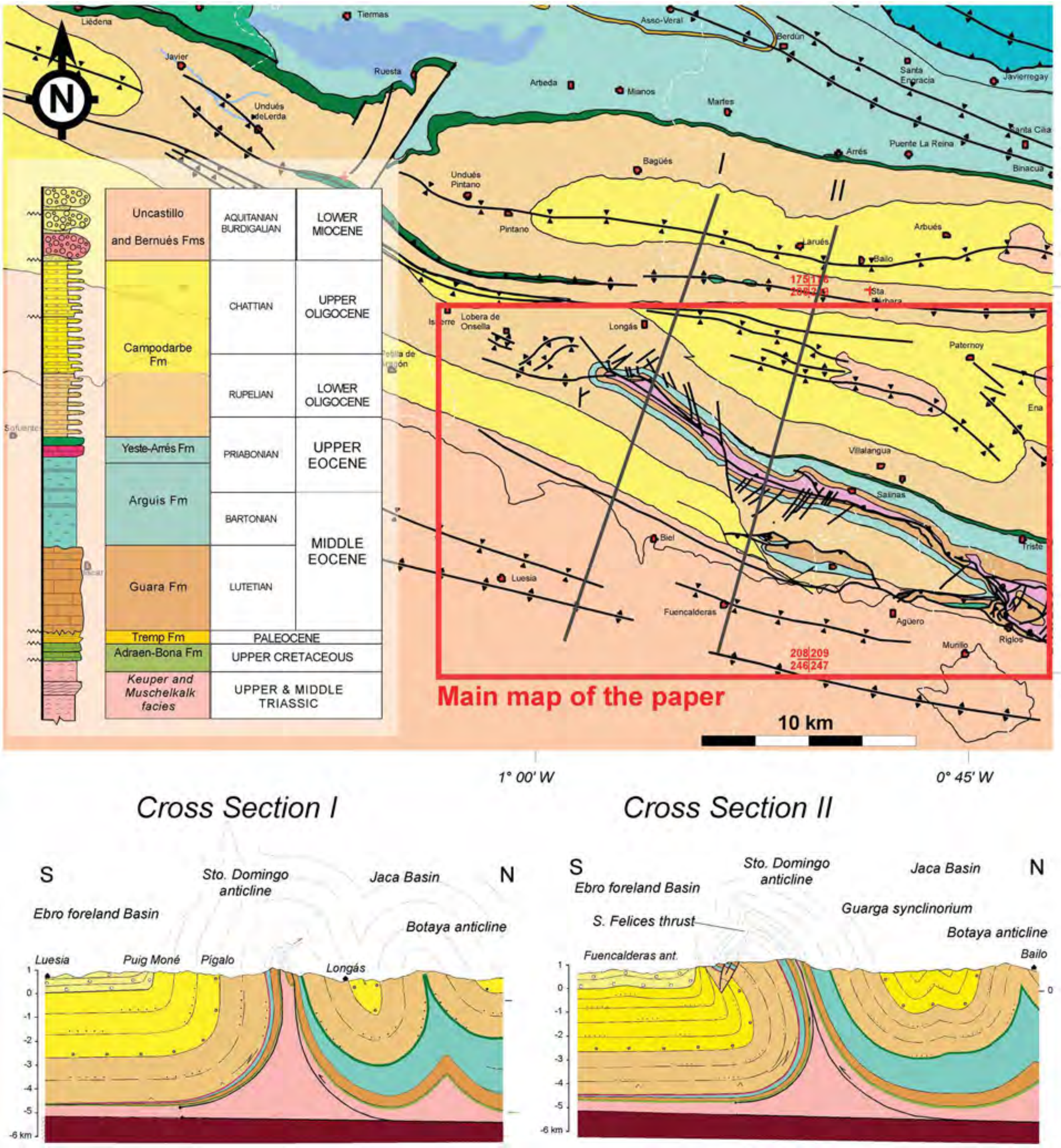

Figure 4. Geological map of the Western External Sierras (Oliva-Urcia et al., 2012). A simplified stratigraphic column and two cross-sections (Millán et al., 1995) are also shown together with the position of the main map of this paper.

physical measurements and chemical analysis. In addition, the flowrate of these springs were also measured.

Electrical conductivity (EC), temperature (T°) and pH measurements were taken during our campaigns using portable meters (CRISON pH25/CH35). These devices were calibrated before measuring in the field every day. The alkalinity (ALK) was determined in the field by volumetric titration (0.1 N H_2SO_4) (HACH AL-AP). The air temperature was measured with a digital thermometer. All this information is synthesized in Table 1. Water samples for standard chemical analyses of main elements were analyzed at the IGME Water Laboratory in Tres Cantos (Madrid) using mainly spectrometric techniques. Spectrophotometry (ALLIANCE Integral Plus) for SO_4, NO_3, SiO_2, HCO_3 and Cl and AAS (flame operation, VARIAN FS-220) for Na, K, Mg, Ca and Fe (García-Gil et al., 2018; Sánchez-España et al., 2005).

The chemical analyses were represented in the Piper and Stiff diagrams. The Piper (1953) diagram consists of two triangles with a rhombus that collects information from both triangles. Cations are represented in the lower-left triangle whereas anions are represented in the lower-right triangle. The data are converted from mg/l to meq/l and transformed into percentages. These diagrams are very useful and allow for representing numerous analyses at a glance.

Figure 5. Fountains and springs sampling.

Besides, they help identifying geochemical similarities since different waters types are grouped in specific regions of the diagram (Custodio & Llamas, 1983). The Stiff diagrams (Stiff, 1951) represent the milliequivalents per liter (meq/l) concentrations of main anions (right) and cations (left) in parallel rays. Then, a polygon is generated connecting those values and the resulting shape promptly illustrates the water type, allowing for rapid, inter-site comparisons.

6. Results

The physical and chemical analyses performed in this work are summarized in Table 1. The main map of the paper represents also an overview of the physical and chemical results obtained in this work. Regarding the chemical composition, the Piper (Figure 6) and Stiff diagrams (Main Map) witness a relative spatial chemical homogeneity and highlights dominant calcium and/or magnesium bicarbonated water types. This is consistent with the predominance of carbonate rocks in the Santo Domingo-Salinas ranges. To a minor extend, calcium sulfated and sodium chloride waters are also observed at the core of the anticline, were Triassic evaporites crop out (Calvin et al., 2017 and references therein).

Some chemical characteristics are better understood considering the geological background of the different water points. The chemical analyses of groundwater allow us to differentiate four main types of water in the Mesozoic and Cenozoic limestone formations: (a) calcium bicarbonate drained by limestones from the Cretaceous-Eocene aquifer, (b) calcium-magnesium bicarbonate drained by limestones and dolomites from Muschelkalk facies (Triassic), (c) calcium sulfate and (d) sodium chloride, both related to siltstones and evaporites found within the Keuper facies (Triassic). The largest flows are always measured at the foothills of the northern slope; this is the case of the Ibon de Nofuentes (point #50), with 15 l/s, and the Fayar spring (#87), where 20 l/s were gauged during the summer period (Garrido-Schneider & Azcón, 1994).

On the other hand, the continental Tertiary hydrogeological system is located in a series of detritic (siltstones and sandstones) Oligo-Miocene rocks in age. There, the type of water is mostly calcium-magnesium bicarbonate type, with a maximum measured flow of 0.3 l/s during summer periods. Similarly, in the Plio-Quaternary hydrogeological system, the springs are numerous, ephemeral during the summer period, and draining mainly calcium-magnesium bicarbonate waters. The maximum flow measured during the summer period is 1 l/s.

7. Preliminary analysis of the groundwater systems

The information and results obtained in this work support the preliminary interpretation on the three main hydrogeological units proposed by Garrido-Schneider (1995), and provide novel information on the characteristics, boundaries and functioning of these three hydrogeological units. According to orographic criteria, structural and sedimentological characteristics, field observations, and chemical analysis of groundwater, the three distinctive hydrogeological systems can be defined as follows:

(1) Santo Domingo-Salinas hydrogeological system is composed of Mesozoic and Tertiary limestone formations: (a) Muschelkalk limestones and

Table 1. Physico-chemical parameters and chemical analysis of the water samples taken in the field trip in winter (blue) and summer (red.)

No.	FEATURE NAME	Date	Flow (l/s)	pH	EC (µS/cm)	Tª water (°C)	Tª (°C)	ALK. HCO_3^- (mg/l)	HCO_3 meq/l	SO_4 meq/l	Cl meq/l	NO_3-meq/l	Na meq/l	K meq/l	Ca meq/l	Mg meq/l	EC Lab. (µS/cm)	Ph Lab.
76	SAN FELICES-1	12/13/2016	0.5	6.82	492	9.8	7.7	260	2.87	0.18	0.19	0.30	0.21	0.01	2.80	0.66	349	7.23
		7/24/2017		7.53	471	25.7	22.2	238	2.97	0.13	0.18	0.12	0.29	0.01	3.10	0.08	457	7.66
10	ALISOVA SPRING	12/13/ 2016	0.03	6.96	558	13.05	9	298	4.20	0.28	0.19	0.04	0.37	0.02	4.00	0.50	469	7.16
		7/24/2017	0.005	6.9	581	14.05	21.5	290	3.77	0.23	0.17	0.01	0.50	0.02	3.25	0.58	560	7.68
86	ASNOS SPRING	12/13/2016	0.39	6.92	414	11.55	4.6	235	3.44	0.12	0.09	0.01	0.12	0.00	2.95	0.74	348	7.34
		7/24/2017	0.01	7.18	464	15.65	22.1	219	3.31	0.10	0.08	0.01	0.22	0.00	3.10	0.08	450	7.65
71	ARRIELLO SPRING	12/13/2016	≈ 3	7.17	421	11.85		245	2.82	0.11	0.07	0.04	0.09	0.01	2.45	0.66	304	7.29
		7/24/2017	0.33	6.9	467	13.1	22.5	228	3.10	0.10	0.08	0.04	0.15	0.01	3.25	0.08	455	7.53
7	CHINCHÓN SPRING	12/13/2016	0.2	6.92	520	12.25	5.7	260	3.20	0.52	0.41	0.01	0.69	0.01	2.55	0.91	409	7.29
		7/24/2017	0.023	6.91	546	15.75		201	2.84	1.20	0.42	0.00	0.79	0.02	2.60	1.24	530	7.75
6	POMPILLO SPRING	12/13/2016	0.05	6.94	525	11.35	10.6	350	3.87	0.11	0.10	0.01	0.49	0.02	3.00	0.83	405	7.43
		7/24/2017	0.008	7.43	577	14.75	20.4	294	3.20	0.10	0.12	0.01	1.04	0.02	2.05	0.33	468	7.56
9	POYO SPRING	12/13/2016	0.02	7.7	443	9.85		243	2.66	0.24	0.17	0.01	0.12	0.01	2.45	0.66	303	7.74
		7/24/2017	0.023	7.56	475	13.4	19.1	244	2.70	0.22	0.15	0.00	0.17	0.01	2.60	0.41	418	7.65
8	L'ARTICA SPRING	12/13/2016	0.02	7.33	532	6.85	4.7	294	3.36	0.34	0.25	0.01	0.13	0.01	3.55	0.50	395	7.62
		7/24/2017	0.007	7.45	557	19.9	20	248	2.97	0.32	0.25	0.00	0.19	0.01	3.25	0.25	408	7.44
70	FORMAYOR-2	12/13/2016	1	7.08	439	11.05	6.9	256	2.79	0.17	0.11	0.02	0.12	0.00	2.60	0.50	309	7.29
		7/24/2017	0.96	7.16	448	14.65	17.9	240	4.56	0.12	0.09	0.01	0.15	0.01	4.45	0.33	438	7.44
61	GOYA SPRING	12/13/2016	0.66	7.02	486	12.95		255	2.79	0.33	0.12	0.16	0.21	0.01	3.00	0.33	339	7.27
		7/24/2017	0.38	6.88	469	12.15	17.5	240	2.92	0.19	0.11	0.08	0.24	0.01	2.95	0.08	456	7.52
74	CELESTINO SPRING	12/14/2016	0.66	7.21	385	11.5		230	2.93	0.10	0.08	0.02	0.09	0.00	2.60	0.58	315	7.33
		7/24/2017	0.35	7.16	438	15.4	18.5	236	2.59	0.08	0.06	0.01	0.14	0.01	2.65	0.08	403	7.57
36	BOJ SPRING	12/14/2016	0.5	7.14	497	11.05		263	3.79	0.18	0.35	0.02	0.52	0.03	2.80	1.16	423	7.28
		7/28/2017	0.3	7.03	536	10.35	30.2	283	5.34	0.12	0.26	0.01	0.60	0.04	4.40	0.91	525	7.43
12	LAS CASAS	12/14/2016	0.014	6.99	674	11.85	5.6	274	2.61	0.44	0.65	0.95	0.13	0.05	4.05	0.66	450	7.15
		7/28/2017	0.01	6.97	656	14.45	26.2	272	3.95	0.34	0.49	0.71	0.17	0.04	5.00	0.58	632	7.32
11	HUERTALO SPRING	12/14/2016	≈ 3	7.49	390	9.5	5	216	3.15	0.15	0.24	0.02	0.34	0.01	2.40	0.99	344	7.54
		7/28/2017		6.93	535	13.3	24.5	272	4.92	0.11	0.37	0.01	0.60	0.01	3.95	0.66	537	7.44
35	TRECE MEDIOS	12/14/2016	0.03	7.11	483	11.1		253	3.10	0.28	0.33	0.01	0.49	0.02	2.60	0.74	382	7.32
		7/28/2017	0.05	7.01	530	11.85	28.2	234	4.41	0.50	0.53	0.01	0.87	0.02	3.80	0.83	518	7.45
1	PINO SPRING	12/14/2016	0.04	7.21	387	7.05		230	3.49	0.15	0.08	0.01	0.06	0.00	3.30	0.58	368	7.33
		7/28/2017	0.03	7.14	447	11.55	24.1	?	3.80	0.13	0.07	0.00	0.08	0.01	3.60	0.17	438	7.54
47	BERROS SPRING	12/14/2016	≈ 3	7.34	393	11.2	5	227	3.23	0.28	0.08	0.04	0.10	0.01	2.85	0.83	362	7.48
		7/28/2017	≈ 3	7.31	427	11.2	20.4	252	4.25	0.36	0.08	0.03	0.15	0.01	3.80	0.83	435	7.64
2	YESO SPRING	12/14/2016	≈ 4	7.88	1154	11.4	6.4	199	1.70	10.42	0.25	0.03	0.35	0.03	10.40	2.31	1008	7.49
		7/28/2017	≈ 3	7.73	1215	13	25.4	217	2.84	11.22	0.49	0.02	0.59	0.04	11.60	2.31	1084	7.52
3	SANTO DOMINGO SPRING	12/14/2016	0.03	7.78	328	6.85	3.2	209	3.34	0.08	0.04	0.02	0.05	0.02	2.15	1.40	340	7.82
		7/28/2017		7.7	362	11.85	15.9	213	3.84	0.06	0.03	0.01	0.07	0.01	2.50	1.24	363	7.73
4	LISAN SPRING	12/14/2016	0.5	7.22	486	10.2		255	3.08	0.84	0.07	0.02	0.11	0.01	3.15	0.91	406	7.45
		7/28/2017		7.14	519	10.7	17.9	252	4.51	0.82	0.07	0.01	0.20	0.01	4.60	0.91	502	7.46
5	MARIGUARILLA SPRING	12/14/2016	0.03	7.11	607	9.95	7.4	294	5.61	1.23	0.22	0.02	0.44	0.03	4.95	1.65	596	7.28
		7/28/2017	0.03	6.94	628	12.05	18.1	288	5.08	1.27	0.23	0.01	0.58	0.04	4.50	1.57	590	7.51
44	BCO. DE CALISTRO	2/22/2017	0.041	7.27	1450	10.35		264	6.00	0.25	0.08	0.00	0.15	0.03	5.40	0.91	488	7.14
166	ARBA DE BIEL-2	2/22/2017		7.28	595	7.2		290	6.10	1.05	0.08	0.00	0.15	0.05	4.85	2.56	592	7.40
		7/24/2017	≈ 0.03	7.99	387	11.95	15.6	180	2.52	0.53	0.13	0.00	0.24	0.02	1.90	0.99	370	7.82
45	ARBA SPRING	2/22/2017	0.01	7.21	614	7.5		254	6.10	1.37	0.09	0.00	0.12	0.04	5.45	1.82	577	7.23

90	RALLA DE LAS PESETAS	7/25/2017	0																
87	FAYAR SPRING	2/22/2017	2.3	7.13	451	8.9		218	5.02	0.27	0.10	0.00	0.14	0.02	4.55	0.74	433	7.16
		7/25/2017	0.6	7.09	455	9.45	16.8	230	2.74	0.28	0.09	0.01	0.16	0.01	2.50	0.58	435	7.73
167	O RINCÓN DE SOLER	2/22/2017	0.4	7.11	724	10.5		320	6.75	1.42	0.32	0.01	0.61	0.03	5.75	2.31	675	6.92
		7/25/2017		7.15	724	15.7	22.9	312	6.07	1.69	0.33	0.01	0.78	0.02	5.10	2.31	665	7.62
89	SAN MIGUEL DE LISO	2/22/2017		7.35	701	10.8		351	7.74	0.71	0.14	0.01	0.39	0.76	5.70	1.90	658	7.06
		7/25/2017		6.95	660	14.6	23.7	330	7.05	0.59	0.11	0.03	0.41	0.41	5.45	1.74	616	7.25
88	O ACHOCETA SPRING	2/22/2017	0.6	7.35	695	9.4			7.67	0.71	0.23	0.00	0.48	0.06	5.65	2.40	646	7.08
		7/25/2017	0.004	7.66	803	14.6	22.2	375	5.25	0.96	0.58	0.00	1.10	0.04	3.25	2.48	629	7.36
83	FUENCALDERAS	7/25/2017	0.031	6.78	706	14.95	21.6	322	6.89	0.45	0.39	0.26	0.75	0.13	5.80	1.40	632	7.27
92	JUANES SPRING	2/23/2017	6	7.11	547	9.4		239	5.48	1.15	0.17	0.00	0.27	0.03	4.60	1.57	519	7.06
		7/26/2017	1	7.12	601	13.75	25.6	270	4.25	0.97	0.28	0.00	0.51	0.02	3.50	1.57	545	7.58
51	PUIG DEL PANO	2/23/2017	5	8.22	410	8.25		220	4.26	0.31	0.06	0.01	0.14	0.03	3.00	1.32	381	7.44
		7/26/2017																
50	IBON DE NOFUENTES	2/23/2017	45	7.27	491	8.9		254	5.43	0.27	0.07	0.00	0.12	0.03	3.95	1.74	461	7.14
		7/26/2017	15	6.93	492	10.15	17.4	240	4.30	0.29	0.08	0.00	0.20	0.02	2.95	1.57	440	7.39
169	JULIANIN SPRING	2/23/2017	0.1	8.09	591	9.5		275	5.25	1.12	0.18	0.00	0.48	0.05	3.65	2.40	531	7.29
		7/26/2017																
93	BUICHO SPRING	2/23/2017	≈ 5	7.44	459	10.5		233	5.28	0.23	0.08	0.01	0.16	0.02	4.25	0.99	440	7.37
		7/26/2017	≈ 1	7.77	492	12.55	22.5	254	3.82	0.28	0.10	0.03	0.39	0.01	3.15	0.74	411	7.54
106	RATA SPRING	2/24/2017	≈ 2	7.8	564	11.35		233	4.66	1.57	0.37	0.00	0.38	0.04	4.35	1.74	521	7.47
		7/27/2017	≈ 2	8.03	850	13.8			3.87	2.79	3.75	0.00	4.45	0.08	4.30	2.15	944	8.01
109	SALADA SPRING	7/27/2017	2	6.54	≈199.900	14.3	≈ 30	105	14.10	242.77	6645.67	0.00	6599.35	80.69	51.00	114.05	632000	6.76
110	BASA SPRING	2/24/2017	1.5	8.08	501	9.75		186	3.77	1.15	0.39	0.00	0.40	0.03	3.40	1.65	449	7.73
		7/26/2017	≈ 1	8.23	461	16.55		170	3.00	1.11	0.38	0.01	0.49	0.02	2.80	1.40	418	7.84
111	FUENFRÍA SPRING	2/24/2017	1.5	8.06	418	5.95		177	3.49	0.77	0.11	0.00	0.12	0.02	3.35	0.91	377	7.81
		7/26/2017	0.005	7.76	490	11.75	18	163	2.46	2.26	0.09	0.00	0.13	0.02	3.60	0.91	446	7.62
112	BAÑOS SPRING	3/15/2017	7	7.9	522	11.35		186	3.61	1.30	0.48	0.00	0.60	0.04	3.15	1.74	456	7.68
131	KM 257	3/15/2017	0.25	7.34	484	9.85		269	5.15	0.30	0.05	0.00	0.09	0.00	4.45	1.16	442	7.42
132	ANTES KM 257	3/15/2017	0.3	8.05	384	9.35		188	3.64	0.89	0.09	0.00	0.35	0.04	2.70	1.82	392	8.06
172	CARCAVILLA SPRING	3/15/2017	25	7.71	971	14.25		198	4.25	3.30	2.54	0.02	3.23	0.06	5.05	2.23	803	7.78
		7/23/2017	≈ 15	7.4	923	15.8		219	2.89	3.21	2.63	0.03	3.12	0.06	3.75	2.23	790	7.83
173	TRAVERTINO DE CARCAVILLA	3/15/2017	≈ 50	7.48	1019	14.5			4.38	3.57	2.88	0.02	3.58	0.07	5.15	2.40	870	7.55
		7/23/2017																
130	CARCAVILLA	3/15/2017	1	7.96	1350	11.9		222	4.13	11.21	0.28	0.00	0.71	0.04	12.40	3.64	1498	7.49
127	P.K. 254.700	3/15/2017	2.5	7.98	1299	9.25		168	3.11	12.13	0.13	0.00	0.35	0.05	11.00	3.72	1409	7.78
		7/27/2017	0.05	8.08	328	17.6		188	2.85	0.38	0.08	0.01	0.16	0.01	2.05	1.24	346	7.97
118	SAN FELICES	3/16/2017	0.25	6.78	794	12.4		264	5.74	0.89	0.17	0.00	0.47	0.01	4.3	2.23	540	7.32
		7/22/2017	0.1	6.84	626	13.85		281	4.07	0.94	0.17	0.00	0.52	0.02	2.75	2.15	594	7.54
115	AGÜERO SPRING	3/16/2017	0.6	7.3	567	13.35		206	4.30	0.48	0.13	0.00	0.24	0.01	3.95	1.07	408	7.42
		7/22/2017	≈ 0.3	6.95	421	17.85		180	2.80	0.47	0.13	0.00	0.26	0.02	2.55	0.74	405	7.63
113	VIEJA SPRING	3/16/2017	0.22	6.98	798	12.85		286	2.70	0.31	0.16	0.05	0.27	0.12	1.50	1.57	294	7.78
		7/23/2017	0.014	6.9	650	16.95		302	6.07	0.50	0.26	0.26	0.49	0.47	4.35	2.15	632	7.55
174	PALOMAS SPRING	3/16/2017		7.36	912	13.65		348	7.48	0.32	0.29	0.00	0.55	0.01	4.95	2.64	605	7.50
		7/23/2017	0.0007	7.43	681	20.75												
162	BUICIOS SPRING	7/22/2017	0.02	7.53	465	30.5		200	2.77	0.38	0.05	0.00	0.14	0.02	1.80	1.40	395	7.88
114	CALENTURAS SPRING	3/16/2017	0.03	7.19	702	10.9		264	2.23	0.13	0.09	0.01	0.49	0.01	1.30	0.99	224	7.77
		7/22/2017	0.01	6.91	547	14.3		272	4.48	0.23	0.16	0.04	1.11	0.03	2.35	1.24	466	7.65
128	LOS IBONES	3/16/2017	≈ 2	6.97	653	12.75			5.38	0.59	0.10	0.00	0.33	0.01	4.15	1.74	476	7.39
		7/23/2017																
175	GARUM-GÁLLEGO	3/16/2017	0.5	7.27	590	13.7		239	5.08	0.14	0.07	0.00	0.12	0.01	3.80	1.40	421	7.56

(*Continued*)

Table 1. Continued.

No.	FEATURE NAME	Date	Flow (l/s)	pH	EC (µS/cm)	Tª water (°C)	Tª (°C)	ALK. HCO_3^- (mg/l)	HCO_3 meq/l	SO_4 meq/l	Cl meq/l	NO_3-meq/l	Na meq/l	K meq/l	Ca meq/l	Mg meq/l	EC Lab. (µS/cm)	Ph Lab.
126	PK 254.400 / CASCADA	3/16/2017	2	7.92	493	10.75		195	3.66	0.36	0.09	0.01	0.18	0.01	2.90	1.40	366	7.88
		7/27/2017	≈ 3	7.86	328	17.4	26.2	210	3.66	0.34	0.09	0.02	0.20	0.02	2.70	1.32	372	7.94
170	NICOLAS Y ANA SPRING	7/26/2017	0.2	7.03	771	12.85	25.1	323	6.03	1.40	0.43	0.06	1.15	0.04	4.85	2.15	660	7.29
178	DULCE SALINAS SPRING	7/27/2017	0.04	8.26	694	21.45	29.9	158	1.74	5.47	1.50	0.00	1.83	0.06	5.40	1.74	775	7.66
179	BCO. LA BOBA	7/27/2017	0.02	7.69	575	16.15		241	3.85	0.78	0.27	0.01	0.38	0.04	3.20	1.49	500	7.98

dolostones (high porosity and permeability by fracturing and dissolution) are bounded at the base by Muschelkalk siltstones and at the top by siltstones and evaporitic rocks (gypsum and halite) from the Keuper facies; (b) Upper Cretaceous limestones and calcarenites; and (c) Eocene limestones (Guara Formation). Both Cretaceous and Eocene rocks display high permeability, because of fractures and karstification, but low porosity. Interestingly, the Garum facies (siltstones and sandstones) are interbedded between the two limestone formations, but its small thickness appears to allow for an effective hydraulic contact between the Cretaceous and Eocene aquifers. The mudstones of the Arguis Formation constitute the upper and thick impermeable seal of the system.

The hydrogeological functioning of the system seems to be strongly conditioned by the structural control over the geomorphology of the system. The subvertical bedding of the aquifer formations are captured by the drainage network, which display an orthogonal arrangement with respect to the dominant tectonic grain at both slopes of the range. In this context, the low permeable formations above the aquifer act as a barrier for the hydraulic gradient and preclude the water recharge (precipitation) to follow the topographic gradient of the range. In addition, the significant fracturing pattern of the evaporites (Muschelkalk and Keuper) at the core of the anticline seems to promote the formation of preferential flow paths responsible for the occurrence of saline springs with significantly higher flows than those expected from these rock formations, as it is the case at the Yeso spring (point #2) and the Salada spring (point #109).

(1) The continental Tertiary hydrogeological system is located in a series of detritic (siltstones and sandstones) Oligo-Miocene outcrops that constitute a thick multilayer aquifer (from low to very low permeability) only present in the southern flank of the ranges. The high vertical anisotropy gives rise to numerous perched and small aquifers of free character draining above the hydrographic network after a short transit time in the aquifer. Part of the water infiltrates deeper forming a regional level of saturation towards the Ebro basin. These waters are characterized by a much longer residence time in the aquifer, which are sporadically captured by the few existing boreholes. Considering the chemical composition of these waters, most of springs in this system are related to perched aquifer drains.

(2) The Plio-Quaternary hydrogeological system, represented by terraces, glacis and colluvium, constitutes small, isolated superficial, low thickness and

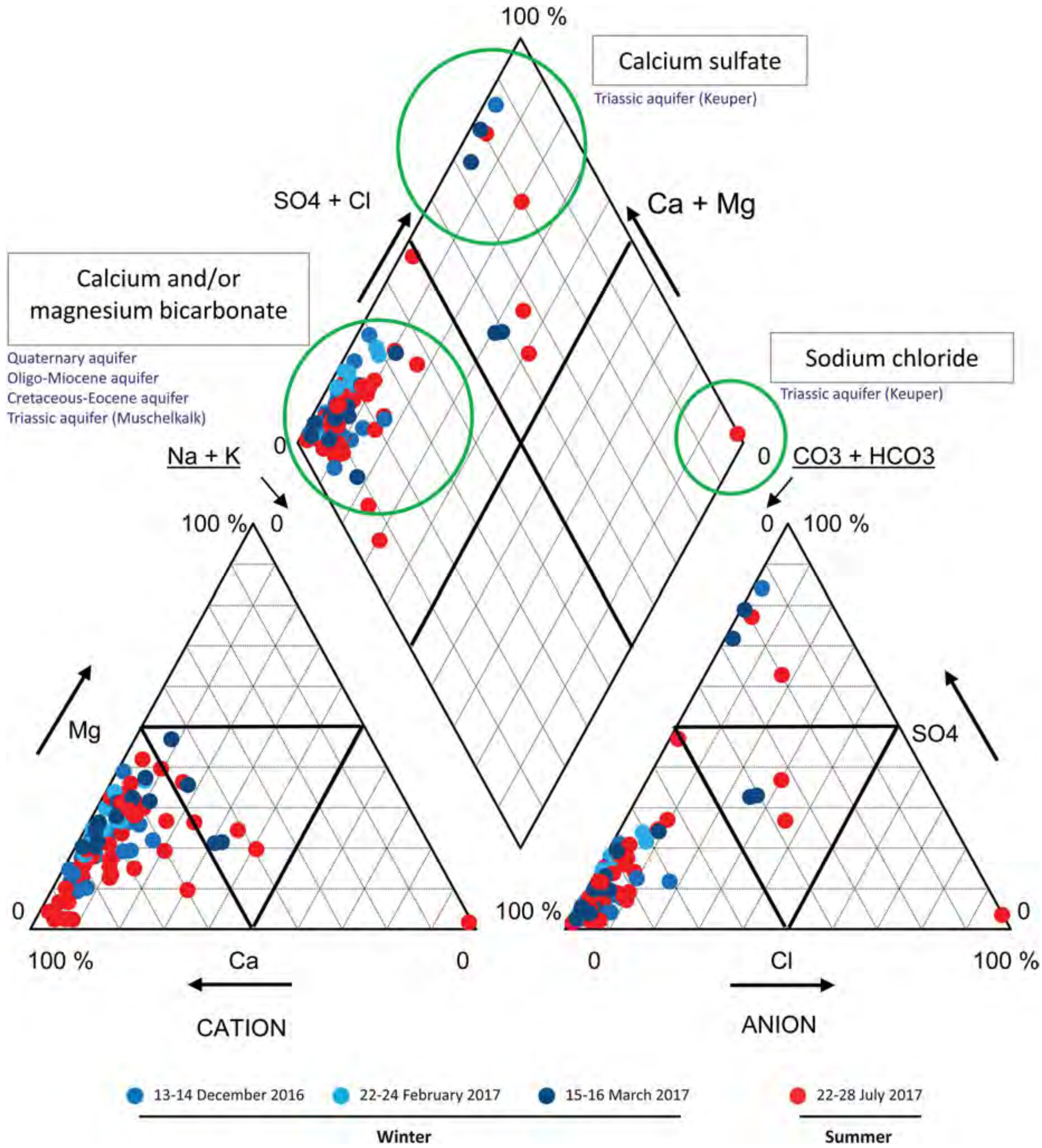

Figure 6. Piper diagram of the water sampled (winter and summer campaigns 2016-2017).

poor lateral continuity aquifers (medium-high permeability).

8. Conclusions

The physical and chemical studies conducted in this work were aimed at characterizing the hydrogeology of a region that has a high natural value but is mainly devoid of pre-existent information. A preliminary conceptual model of the hydrogeological functioning of the Santo Domingo-Salinas ranges and the hydrochemical characterization of their waters have been also established. Thus, three aquifer systems with independent hydrogeological functioning have been identified, based on the hydrogeological systems defined by Garrido-Schneider (1995). The most important one, the Santo Domingo-Salinas system, it is composed of Mesozoic and Tertiary limestones formations that crop out mainly in the northern slope. On the southern slope, these beds only crop out at high elevations, bordering and forming part of the backbone of the ranges. Discharges are much more important in the northern slope than in the southern one, in both cases constituting the base flow of the hydrographic network in the region. Four types of water were differentiated under the light of chemical analyses: calcium bicarbonate water drained by Cretaceous-Eocene formations, calcium-magnesium bicarbonate water drained by Muschelkalk facies (Triassic), and calcium sulfate and sodium chloride water drained by the Keuper facies (Triassic).

In order to improve our knowledge on the hydrogeological functioning of these systems, we recommend to follow the next steps: (a) to perform new field campaigns for physical–chemical analysis of groundwater in different periods; (b) to carry out flow measurement campaigns aiming to control the discharge of the main aquifers; (c) to interpret and represent the data, and to compare the hydrogeological functioning with studies in nearby areas (Oliván, 2013; Pérez-Bielsa, 2013) as well as with analogous methodologies (Sarkar & Shekhar, 2015; Singh et al., 2015). A vulnerability study of the groundwater should be considered as a following step, as it has been done in other areas at risk of being contaminated (Vidal Montes et al., 2016, 2017), provided that enough information is collected in the future. An interpretative map for the adequate management of land uses in this kind of environment will be useful and novel.

Beyond outreach purposes, the hydrogeological knowledge presented in this paper can provide very useful information to manage the demand of water resources in the near future. This is the case of the Uses and Management Master Plan (PRUG acronyms in Spanish) of the Natural Protected Landscape, which is currently in the preparation phase. The final agreed PRUG will establish the regulations for the natural heritage (including water resources) of the Santo Domingo and Salinas ranges. Within this frame, the updating of the water points inventory and the hydrogeological characterization here defined will be valuable to locate new and potential sources for water supply, livestock, agriculture or fire prevention and extinction. In addition, outstanding springs (Fuente del Yeso, Fuente Salada, Ibón de Nofuentes) are better characterized now.

Finally, one of the main goals of the Protected Landscape is to highlight remarkable natural values of the territory. The map, data and knowledge derived from this paper will be useful to articulate hiking and camping activities as well as to delineate cultural or natural trails in the area. Additionally, part of the water inventory may be included within the points of geological interest and geological footpaths (Sánchez-Moreno, 2012).

Software

Esri ArcGIS 10.2 was used for gathering and visualization physico-chemical parameters groundwater and the final map was compiled in ArcMap 10.2.2.

Data repository

The data shown in this paper (Table 1) will be integrated in available data bases to grant the FAIR principles including the public and interoperable access. http://info.igme.es/BDAguas/.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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