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Geodiversity of Las Loras UNESCO Global Geopark: Hydrogeological Significance of Groundwater and Landscape Interaction and Conceptual Model of Functioning

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Abstract: Las Loras UNESCO Global Geopark (UGGp) is geologically diverse, particularly in relation to water-derived features: springs, karst springs, travertine buildings, waterfalls, caves. In this work, the interactions between geology, geomorphology, structures and hydrogeology are analyzed. As a result of this study, a first conceptual model of the hydrogeological functioning at Las Loras UGGp is presented. The most plausible hypothesis is that the system is formed by two superimposed aquifer systems, separated by an aquitard formed by Lower Cretaceous material. The deep lower aquifer formed by the Jurassic limestones only outcrops on the northern and southern edges of the Geopark and in a small arched band to the south of Aguilar de Campoo. It forms a basement subject to intense deformation. The upper aquifer system, formed by outcropping materials from the Upper Cretaceous, is a free aquifer. It is formed by a multilayered aquifer system that is highly compartmentalized, constituting individual moorland and lora units acting as a separate recharge–discharge system. This model explains the base level of the permanent rivers and the abundant springs, important components of the water cycle and representing a contribution to the rich geological heritage of the location.

Keywords: geodiversity; geosites; springs; Las Loras UNESCO Global Geopark (UGGp); hydrogeology; Ubierna Fault

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1. Introduction and Objectives

Geodiversity is a complex concept describing a spectrum of geological (together with some other natural) phenomena in a given area [1]. Gray (2004) [2] defines it as 'the natural range of diversity of geological (rocks, minerals and fossils), geomorphological (landforms and processes) and soil features, including their relationships, properties, interpretations and systems'. The base concept of geodiversity is the graphic presentation of a variety of geological elements that form the surface of planet Earth [3] and provides the foundation for the biota on which human societies depend. The United Nations included geodiversity in the 2030 Sustainable Development Goals (SDGs) Agenda [4], and International Geodiversity

Day was officially proclaimed by UNESCO in 2021, with the first celebrated on 6 October 2022 [5].

This paper describes a Geopark of relatively recent creation (2017), the Las Loras UNESCO Global Geopark (UGGp from here on). The approach presented considers the analysis of four of the components of the abiotic natural environment: (a) sedimentology; (b) structure; (c) geomorphology and (d) hydrogeology and the relationships between them. The role of both groundwater and surface water in shaping the landscape emphasizes the exceptional hydrogeological features of this UGGp, alongside other karstic areas in the Dolomites [6] (Testa et al., 2019) and Homolje region of Eastern Serbia [7] (Miljković et al., 2018).

The objective of this work is to establish the elements of the geological diversity of Las Loras UGGp that express the interaction between stratigraphy, sedimentology, geomorphology, structures and hydrogeology. It also provides a preliminary assessment of the hydrogeological processes that have led to that diversity. Most of the studied sites are recognized as existing geosites inventoried by the Las Loras UGGp. This study will identify the outstanding natural features, underpin further projects and provide the fundamentals for preservation management [6]. The scientific, cultural and educational importance of natural springs are highlighted. Some of the studied sites will be proposed as new geosites (Place of Geological Interest (PGI) according to Spanish legislation, Law 42/2007) [8,9], and their value in terms of science, education and tourism–recreation, as well as the risks of degradation, will be presented.

2. Materials and Methods

The Ubierna fault divides Las Loras UGGp into two well-differentiated sectors, or types of folded relief. The first, between the Ebro river and the Ubierna fault, is the Burgalesa Platform, characterized by the presence of calcareous moors made up of carbonate outcrops of extensive surface, and affected by a slight deformation presenting as horizontal or sub-horizontal platforms. The second, between the Ubierna Fault and the frontal thrust of the Cenozoic materials of the Duero basin, is the so-called Folded Band, characterized by the presence of frequent folds recognized as hanging synclines that are called “Loras” (Figure 1).

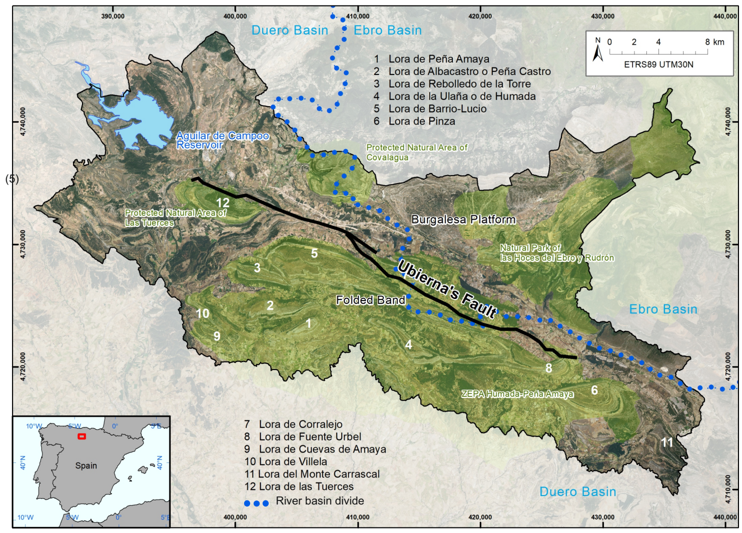

Figure 1. Location of the Las Loras UGGp in Spain, in the division of the hydrographic basins of the Duero and the Ebro. Green zones represent Protected Areas under the Spanish Legislation: Protected Natural Area of Covalagua, Protected Natural Area of Las Tuerces, Natural Park of Las Hoces del Ebro y Rudrón, and ZEPA (Zona de Especial Protección para las Aves, in Spanish, SCI) Humada Peña Amaya. Background image from Iberpix-IGN.

The moorlands are high mountains below the tree line. The loras is a local name to design geological elements of the Mesozoic age that characterize the landscape as culminating forms, and are characterized by a reduced extension compared with the moorlands and an altitude slightly upper than the moorlands. Both elements, moorlands and loras, conform the landscape of Las Loras UGGp.

2.1. Description of the Study Area and the Available Information

The Las Loras UGGp is located in the north of Spain (Figure 1); also, in the north of the autonomous community of Castilla y León (Spain), occupying part of the NE of the province of Palencia and NW of Burgos. The Las Loras UGGp includes 16 municipalities in the provinces of Palencia (Aguilar de Campoo, Pomar de Valdivia, Alar del Rey, Santibáñez de Ecla and Berzosilla) and Burgos (Valle de Valdelucio, Basconcillos del Tozo, Sargentes de la Lora, Rebolledo de La Torre, Villadiego, Sotresgudo, Humada, Urbel del Castillo, Montorio, Huérmeces and Valle de Sedano). Aguilar de Campoo is where one of the official headquarters of the Geopark is located. It is a sparsely populated area (13,076 inhabitants), which represents a density of somewhat less than 7 inhabitants/km^2. Most urban centers are widely scattered, rarely exceeding 500 inhabitants.

Agriculture provides the economic background of the region and includes sheep pastoralism and wheat cultivation. Other important industries include the biscuit factory in Aguilar de Campoo, the oil field of Ayoluengo (active between 1967 and 2017), the extractive forest industry, the production of wind energy and the tourist activity currently concentrated in the areas of the Palentina Mountain (Aguilar de Campoo) and the Ebro Canyons (Orbaneja del Castillo and Sedano).

2.1.1. Regional Geological Context

The Geopark has a mountain relief, with the lowest elevation in the Ebro River valley, to the north at 610 m asl and highest of 1377 m at Peña Amaya [10]. Las Loras UGGp straddles the Basque-Cantabrian Basin in the north (Figure 2), bordering the Asturian Massif (located to the NW) and the Duero Cenozoic Basin in the south. The study area is a rectangle bounded in the SW by the coordinate 42.53°, −4.41°, and in the NE 42.88°, −3.75°, covering 950.76 km^2 [11]. Out of the current borders of the Las Loras UGGP, there are important elements that must also be taken into account in this work because geologically, they are part of the same unit: Covanera, Tubilla del Agua and Pozo Azul.

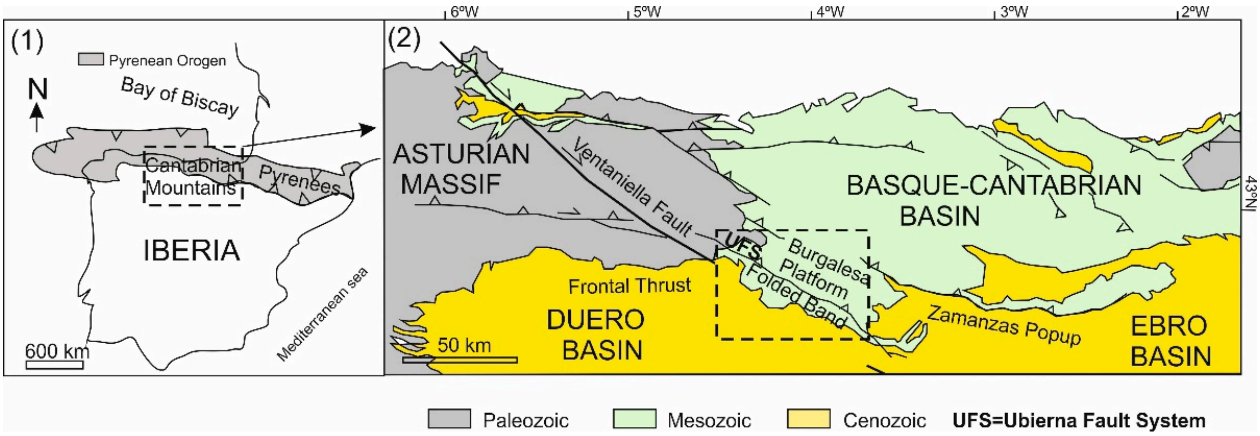

Figure 2. Geological context of Las Loras UGGp in Spain (modified from [12]). (**1**) Location map of the study area in the southern portion of the Pyrenean Orogen; (**2**) Major units and faults. UFS: Ubierna Fault System.

2.1.2. Lithology and Geology

The Ayoluengo-1 borehole (X = 3°53′37.94′′ W/Y = 42°45′21.07′′ N/Z = 1022 m asl) [13] is 2397 m deep, reaching the Keuper facies of the Upper Trías at 2375 m and is essential to understanding the structure and stratigraphy of the sedimentary sequence.

The geology of Las Loras UGGp is formed predominantly by sedimentary materials (Figure 3) with an almost complete record from the Upper Triassic to the Paleogene [13–18]. The oldest are represented by the red clays and gypsum of the Keuper facies. The outcrop of this unit is associated with the main faults and thrusts (Villela, Ubierna faults, Becerril de Carpio thrust and frontal thrust of the Duero Cenozoic basin), where it has acted as a detachment layer due to its plasticity. Overlying the Keuper, the Infralías (Rhetian), the Lías and the Dogger Formations appear in stratigraphic sequence. These marine sediments form carniolas, dolomitic limestone on platforms, and limestone-marly rhythmites on the slopes. Upper Jurassic (Malm) and Lower Cretaceous (Berrasiense–Albian) continental detrital and carbonate units (Purbeck, Weald and Utrillas facies) continue the stratigraphic sequence followed by alternating limestone and loamy formations of the Upper Cretaceous (Cenomanian–Maastrichtian). Quaternary fluvial incision and deposition cover the consolidated rocks.

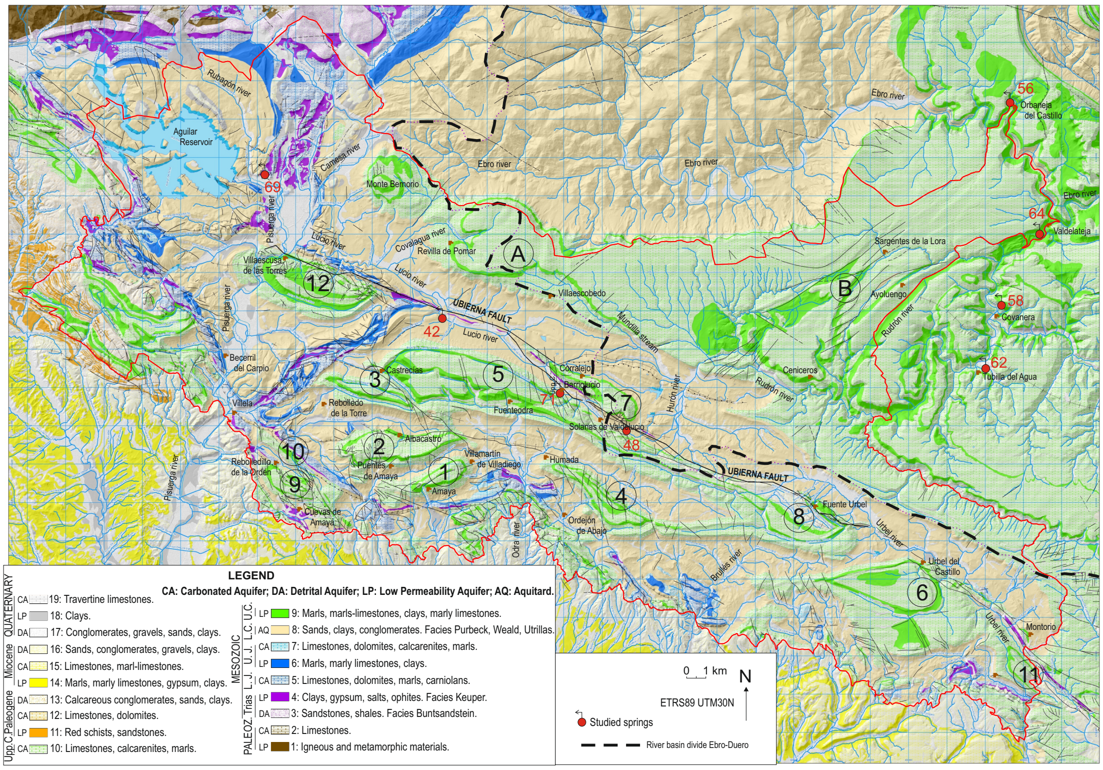

Figure 3. Hydrogeological map of Las Loras UGGp. Studied springs are in red: 69 = Peñalonga spring; 42 = Pisadera spring; 71 = Barriolucio waterfall; 48 = San Bol; 56 = Orbaneja waterfall; 58 = Pozo Azul (Covanera); 62 = Tubilla del Agua waterfall; 64 =Valdelateja. The hydrogeological sectors defined by the moorlands and the Loras have been differentiated and identified with numbers in circles. These sectors refer exclusively to the perched aquifers of the Upper Cretaceous: A = Moorland of Lora de Covalagua; B = Moorland of Lora de la Pata del Cid; 1 = Lora de Peña Amaya; 2 =Lora de Albacastro; 3 = Lora de Rebolledo de la Torre; 4 = Lora de Ulaña o de Humada; 5 = Lora de Barriolucio; 6 = Lora de Pinza; 7 = Lora de Corralejo; 8 = Lora de Fuente Urbel; 9 = Lora de Cuevas de Amaya; 10 = Lora de Villela; 11 = Lora de Monte Carrascal; 12 = Lora de las Tuerces (Tabla 2) Ayoluengo is the main village of the oil field. Ceniceros was a highlighted spring in the Moorland of la Pata del Cid. 58 = Pozo Azul (Covanera); 82 = Tubilla del Agua; 64 = Valdelateja are highlighted geosites which are being studied in order to be included into the Las Loras UGGp border.

2.1.3. Climatology

Average annual precipitation at Aguilar de Campoo (2009–2021) is 570 mm, while the temperature ranges between a maximum of 27.08 °C in July 2013 (Figure 4), and a minimum of −4.66 °C in December 2009; and the average annual temperature is 9–11 °C between 2009 and 2021.

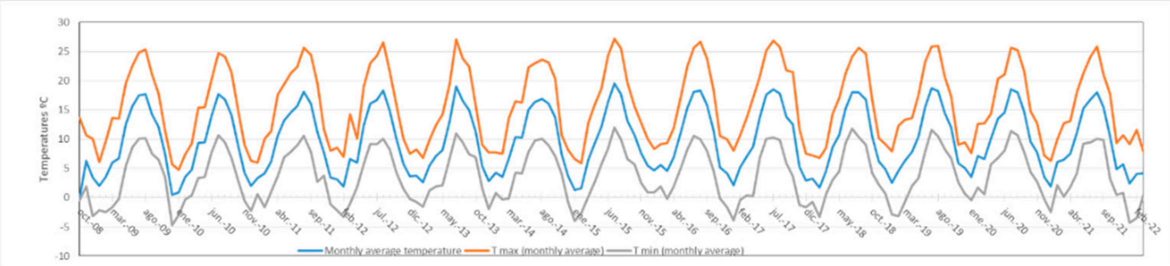

Figure 4. Evolution of temperatures in the station 2243A Aguilar de Campoo (Source: data from AEMET).

2.1.4. Hydrology

Las Loras UGGp includes the catchment divide between the hydrographic basins of the Ebro River flowing southeast into the Mediterranean Sea and the Duero River flowing west into the Atlantic Ocean. Within the Duero basin, the most important rivers are the Pisuerga (Figure 5), and its tributaries (Camesa, Lucio, Monegro and Sauquillo, on its left bank; the latter three originate in the area of the geopark). The Odra and Brullés rivers rise in the Geopark and flow south, the Brullés River being a tributary of the Odra river, and this, in turn, of the Pisuerga river. In addition, the Urbel river runs to the east, flowing into the Arlanzón river, a tributary of the Arlanza river, and this, in turn, of the Pisuerga river. The Ebro River borders the Las Loras UGGp to the NE and E, along with the Rudrón River to the E, which rises as the Hurón River in the central area of the Geopark, and disappears into the Cueva del Agua sinkhole in Basconcillos del Tozo, to resurface 2 km to the northeast, as the Rudrón River.

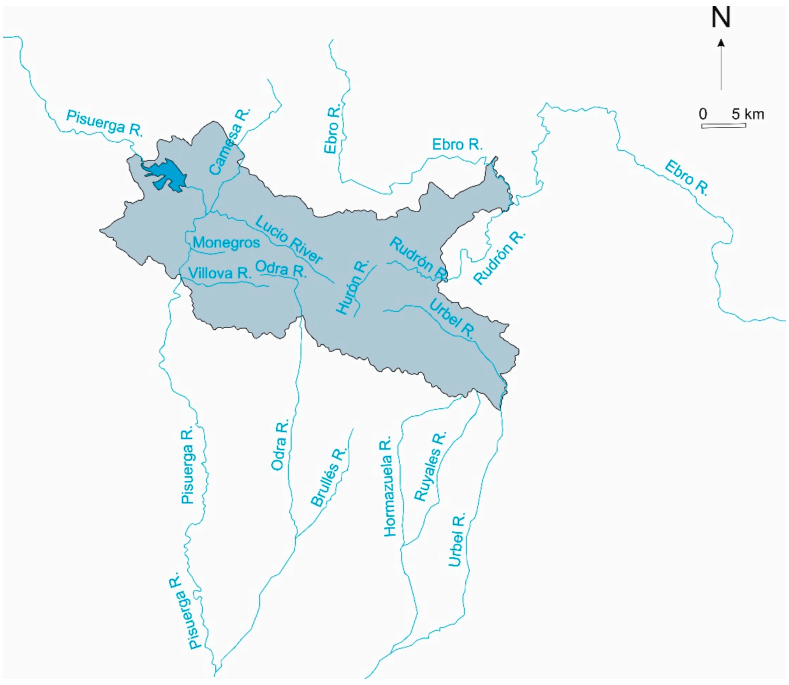

Figure 5. Main rivers in the Las Loras UGGp.

2.1.5. Aquifers and Groundwater Bodies

The Las Loras UGGp overlies two adjoining groundwater bodies (GWBs): The Páramo de Sedano y Lora GWB, to the north, belonging to the Ebro River Basin District; and Quintanilla-Peñahorada-Lora, belonging to the Duero River Basin District [19], Páramo de Sedano y Lora GWB is constrained in the southeast, by subsidence of the Cretaceous under the continental Cenozoic of La Bureba; in the northeast by the Mesozoic–Neogene contact of the Padrones de Bureba inlet; and in the North by the Wealdic core of the Zamanzas anticline. There is a semi-permeable boundary to the northwest with the top of the Utrillas formation; and the GWB is open to the south at the Ebro–Duero hydrographic divide. The main direction of groundwater flow in this GWB is to the east, parallel to the Rudrón riverbed, and to the northeast, towards the Ebro river.

The limits of the Quintanilla–Peñahorada–Loras GWB are formed by contact with the Cenozoic detrital area of the Duero Basin on the southwest flank, towards the Valdavia, Villadiego, Castrojeriz and Burgos GWB (Figure 6). The northwest edge corresponds to the basin boundary. Materials from the Cervera de Pisuerga GWB (to the west) form an impermeable edge in the northwest. The recharge in this karstic groundwater system is from infiltration of rainwater, discharged both by the drainage of the incised rivers and where the permeable limestone of the Quintanilla–Peñahorada–Loras GWB is in contact with the less permeable rocks of the Valdavia, Villadiego and Castrojeriz GWBs to the south (Figure 6) [19,20].

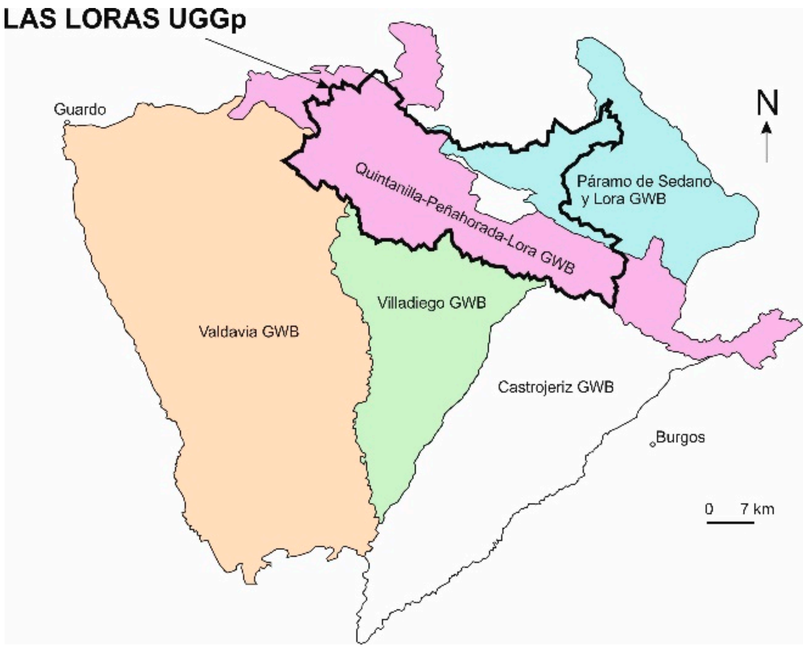

Figure 6. Hydrogeological context of Las Loras UGGp (data obtained from [20]).

Two types of aquifers are distinguished: an unconfined aquifer, and a deep confined or semi-confined aquifer [21,22]. The former is made up of permeable materials from the Upper Cretaceous (dominantly limestones); and the deeper aquifer corresponds to the Jurassic sediments.

2.2. Methodology

2.2.1. Literature Review

This study is based on a bibliographic review including: the institutional databases of the National Geographic Institute of springs, the institutional documentary databases (IGME, universities), as well as the IGME's resources [23,24] and the platforms available at the Ministry of Ecological Transition. In general, the bibliography available on the study area is regional, dating back several decades. The Hydrogeological Atlas of the Province of Burgos [13] and more recently, the hydrogeological study carried out in the western sector of the Geopark for the construction of the High-Speed Train from Nogales de Pisuerga to Reinosa [25,26] are important resources.

2.2.2. Field Campaigns

Water sampling, measurement of unstable parameters, and field reconnaissance were conducted in August 2021, October 2021, December 2021, April 2022, June 2022 and August 2022. Field observations verified changes and contrast in permeability between outcropping materials and allowed the recognition of geological units that had been previously overlooked.

Water Samples

The water samples were stored in new polyethylene bottles, washed with the same water that was sampled and filled to the brim to avoid interaction with atmospheric gases. No chemical preservatives were used and prior to analysis, the samples were kept refrigerated at 4 °C + −2 °C. Water temperature, pH, Electrical Conductivity and Redox Potential were measured in the field, in situ, at the time of sampling with a multiparameter pH/conductivity/temperature/redox potential instrument (Hanna HI 9828, Hanna Instrument, Woonsocket, RI, USA); and in the laboratory. Details of the 46 water samples (Figure 7) are provided in Table S1 (see supplementary material, SM files).

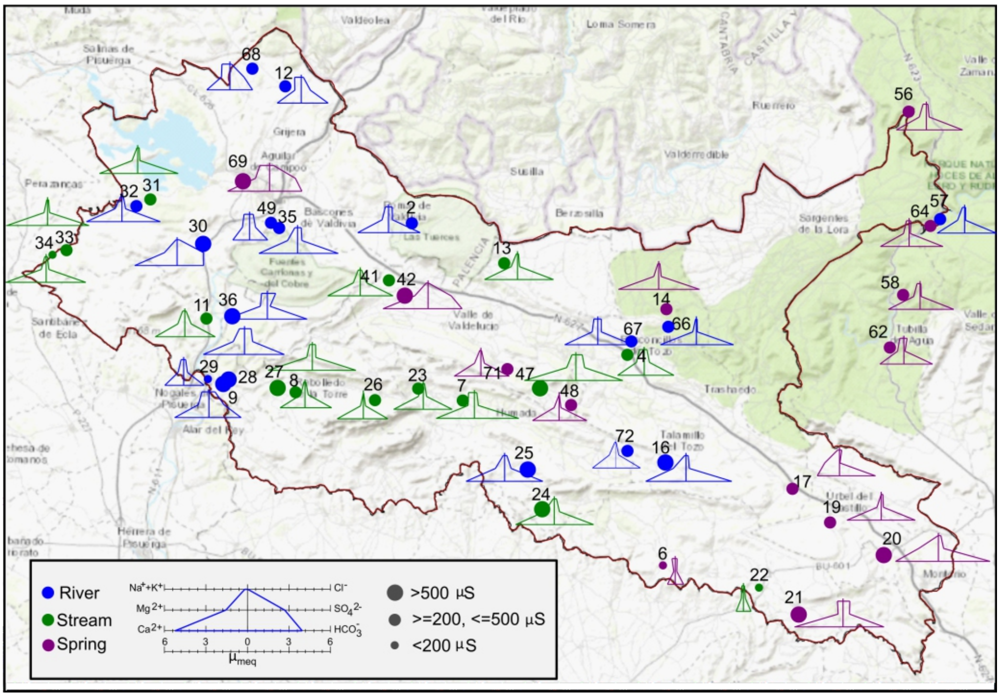

Figure 7. Location of the water samples with the hydrochemical facies and distribution of major ions represented by Stiff graphs [27] and mineralization (Electrical Conductivity) by circles. Table S1 (supplementary material) shows the coordinates of each of the points represented and their identifying name.

Physical–Chemical Analysis of Water

Chemical analyzes were carried out in the IGME laboratories, accredited according to the requirements of ISO/IEC 17025, using validated standard methods: pH by electrometry, anions and cations by absorption spectrophotometry, heavy metals by mass spectrometry with inductively coupled plasma, excepting iron, which was determined by inductively coupled plasma atomic emission spectroscopy.

The hydrochemical information was analyzed and represented using the INAQUAS software [28].

This information is duly reported in the results section.

Construction of Hydrogeological Profiles

Geological and hydrochemical information was used to develop stratigraphies with a highly exaggerated vertical scale in order to better visualize the differences in elevations and the active processes. In these profiles, the elevation was extracted using the digital elevation model that underpins Google Earth.

Analysis of Springs and Comparison Criteria

The hydrogeological characterization of springs was approached in two stages of work: (1) Review of the existing inventory of springs, from the database of the National Geographic Institute (IGN) [29]. (2) Analysis of the geological, hydrogeological, geomorphological and topographical characteristics of selected springs was enhanced with field observations. (3) Comparative analysis considering the following key criteria:

(a) Upwelling level.
(b) Stratigraphical formation(s) to which it is associated.
(c) Hydrochemical facies, based on the results of the water analyzes carried out.
(d) Electrical Conductivity as an estimate of the salinity of the water.

Integration of Results and Representation in Arc Gis

The information collected from the different sources was integrated as a spatial database in Arc GIS Pro [30].

3. Results and discussion

3.1. Geodiversity of Las Loras UGGp

3.1.1. The Ubierna Fault

The Ubierna fault is the primary feature that configures the tectonic structure, geomorphology and hydrogeology of Las Loras UGGp (Figure 1). It constitutes a fault with Quaternary neotectonic activity [31–33].

This Ubierna fault has a slightly sinuous NW-SE orientation. It includes numerous associated structures [13–17], which define what constitutes in structural terms, the “fault zone” (Figure 8). The fault represents a tectonic event of significant magnitude, as indicated by its considerable depth [33–35]. This fault has been interpreted as an extensional fault formed in relation to rifting at the end of the Jurassic and beginning of the Lower Cretaceous and which has undergone a strong tectonic inversion during the Cenozoic. Another significant feature of the Ubierna fault is the presence of Keuper evaporite outcrops along its path [36].

3.1.2. Caves

Nine caves associated with the karstic environment occur within Las Loras UGGp and they have been identified and described in reports published by the Edelwiss Speleological Group of the Cueva de los Franceses and the Orbaneja Water Basin [37].

They are Cueva de los Franceses, Cueva de Villaescobedo and Cueva del Toro, in the Páramo de la Lora de Valdivia; Cueva de los Moros, on the north face of Mount Bernorio; Cueva del Agua, in Basconcillos del Tozo; Cueva de Valdegoba, in Huérmeces, at the southeastern end of the Geopark; Cueva de la Reina, in the Lora de Peña Amaya; Cueva Corazón and Cueva de Valdorao, in Lora de Las Tuerces; Cueva del Agua in Orbaneja del Castillo (Figure 3).

The Cueva del Pozo Azul also stands out, a cavity of more than 14 km in length [38], although its full extent has not been mapped. It is located at the eastern end of the moorland of la Pata del Cid and its entrance is in the Pozo Azul upwelling.

Figure 8. (**1**) Fault zone in the vicinity of the Ubierna fault within Las Loras UGGp. (**2**) Detail of the subvertical position of the carbonate outcrops near the Ubierna fault. (**3**) Detail of carniola found near the Ubierna fault. (**4**) Detail of a flower structure close to the fault plane.

3.1.3. Springs

Among the geological diversity of Las Loras UGGp, the springs are of particular interest not only because they are windows to hydrogeological processes, but also because they have a long history of cultural significance for people in the region.

The Cueva del Agua (Orbaneja del Castillo), already mentioned, an important karstic spring, has generated a large deposit of calcareous tuff partly within the town of Orbaneja del Castillo. Some of the buildings within the town are impacted because of the dynamics of the landforms associated with the springs [39].

The Pozo Azul (Covanera) consists of a concavity with a diameter between 7 and 8 m and a depth of 10 m (Figure 9(1),(2)). The spring discharges through the Pozo Azul cave from a subhorizontal conduit that follows an E-W direction (Figure 9(3)), clearly conditioned by the stratification of the karstic massif. The submerged gallery has been explored to a distance of 14 km. It has an average flow of 1 m^3/s, drains from the Upper Santonian carbonate aquifer, in which the Lower Santonian marls form the base of the karstic aquifer. The temperature of its waters is constant throughout the year, varying between 9 and 11 °C [40]. It is located on the right bank of the Rudrón River, about 330 m from the main channel of the stream.

The resurgence of the Rudrón River after crossing the Valle Ciego, in the Cueva de Los Moros, near Barrio Panizares, has been the subject of various studies [13].

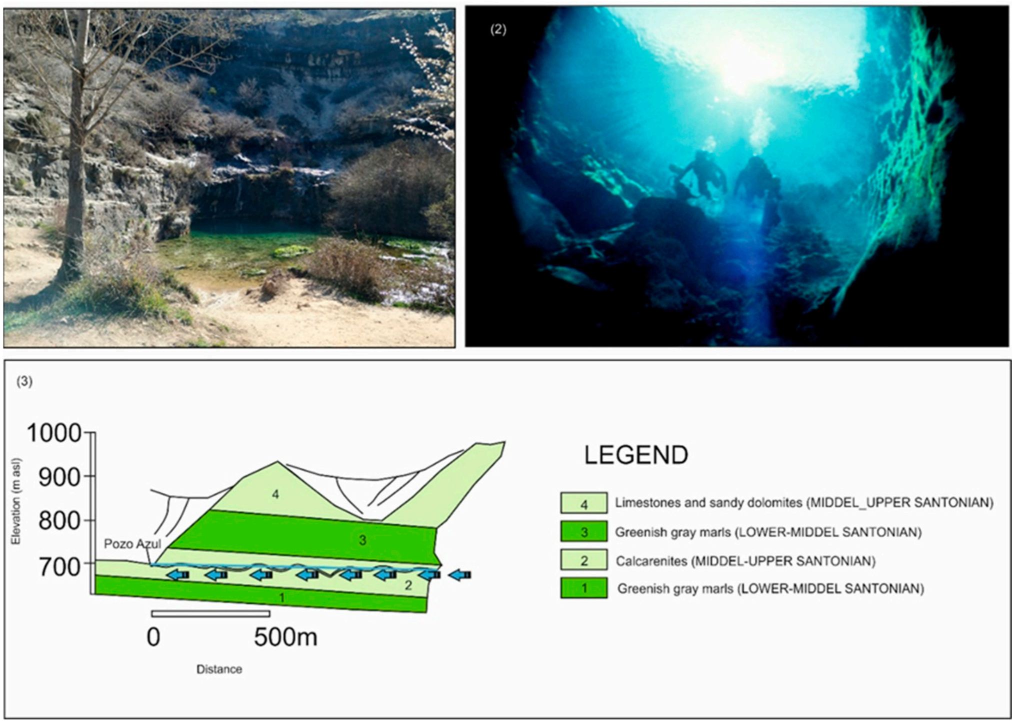

Figure 9. Pozo Azul. (**1**) Photograph of the Pozo Azul taken on 6 June 2022. (**2**) Beginning of the subemergent gallery tracing the groundwater flow [38]. (**3**) Diagram of hydrogeological functioning (modified from [38]).

3.1.4. Travertine Buildings

In Las Loras UGGp, there are several active springs that show the presence of a tuff/travertine building. Thirteen systems of travertine building (Table 1) and associated waterfalls are located in: Orbaneja del Castillo, Tubilla del Agua, Hoyos del Tozo, Villaescobedo, Moradillo del Castillo, within the scope of the Ebro basin; Covalagua-Revilla de Pomar, Rebolledillo de la Orden, Fuenteodra and Barriolucio, within the scope of the Duero basin. The processes that build these structures are not active throughout the year. The tuffs in the Upper Ebro are associated with two well-differentiated geomorphological contexts, the slope and the bottom of the valley. These positions in the landscape determine the typology of the tuff and their magnitude (Table 1). The spring that gives rise to the Orbaneja del Castillo waterfall is permanent [41]. It is located on the left bank of the Ebro River, on the northeastern edge of the Geopark. It features a waterfall several meters high, along which, waterfall travertine, barrier travertine and travertine terrace have formed [38]. The Ebro Hydrographic Confederation have historical data on flows in the Cueva del Agua (so called, upwelling of the spring that generates the Orbaneja waterfall). The Orbaneja spring hydrograph (water point 19075 ORA according to [13]) ranged between 0.1 and 1400 l/s in 1996, with the higher peaks in the winter and spring months. Other waterfalls are probably only active in the winter and spring months.

There is a large outcrop of inactive travertine (approximately 20 m^2), a few meters upstream from the Valdelateja spa, on a terrace on the left bank of the Rudrón River. Although recognized by González Amuchástegui and Serrano Cañadas (2013) [42], it is not mapped by IGMA on the MAGNA50 sheets, probably because of its small size. It represents an inactive geological process of outstanding educational and scientific value. This outcrop should be a new geosite to consider in the Geopark's geosites inventory.

Table 1. Travertine buildings inventoried in Las Loras UGGp.

River	Name	Geomorphological Context	Altitude (m asl)	Site	Reference
Rudrón	El Tobazo	Hillside	≈850	Tubilla del Agua	[42]
Rudrón	La Toba	Hillside	≈850	Tubilla del Agua	[42]
Rudrón	Tubilla-La Fuentona	Valley bed	810–710	Tubilla del Agua	[42]
Rudrón	La Tobaza	Hillside	≈850	Tubilla-Covanera	[42]
Rudrón	Spa	Valley bed	670	Valdelateja	[42]
Rudrón	Valdelateja	Valley bed	660	Valdelateja	[42]
Rudrón	Ebro-Rudrón	Valley bed		Valdelateja	[42]
Ebro	Agua Cave-Orbaneja	Hillside *	800–720	Orbaneja	[42]
Ebro	La Tobaza	Hillside	≈730	Orbaneja	[42]
Lucio	Barriolucio	Waterfall/Hillside	≈990	Barriolucio	[43]
Covalagua	Covalagua	Waterfall/Hillside	≈1030	Revilla de Pomar	[43]
Rudrón	Moradillo del Castillo	Waterfall/Hillside	≈810	Moradillo del Castillo	[43]
Mundilla stream	Villaescobedo	Waterfall/Hillside	≈1100	Villaescobedo	[43]

* In the opinion of the authors, waterfall, slope and terrace.

Of the several waterfalls in Las Loras UGGp Yeguamea, Cascada de la Churrera is associated with a vertical carbonate wall. Others are associated with the formation of travertine buildings (Orbaneja del Castillo, Tubilla del Agua, Covalagua, Barriolucio) (Figure 10); while others, such as Valdelateja, are associated with riverbeds.

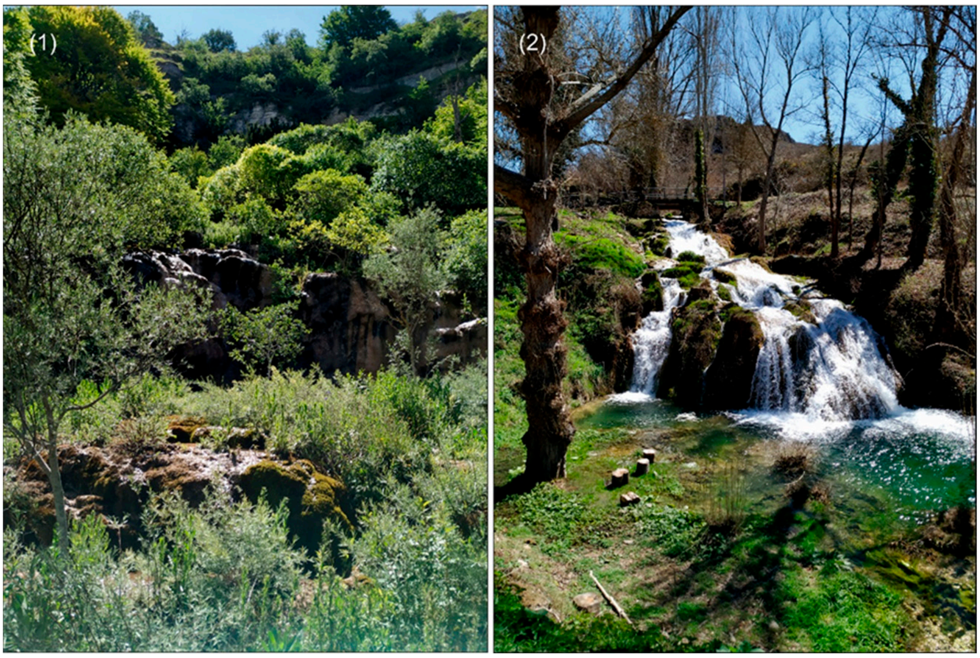

Figure 10. (**1**) Covalagua Waterfall taken 26 June 2021. (**2**) Tubilla del Agua Waterfall taken 6 April 2022.

Orbaneja is a karstic spring forming a stream which only emerges through the Cueva del Agua itself when rainfall is intense (Figure 11). After going through part of the town and following a channel towards an old mill, it forms a majestic waterfall that descends rapidly towards the Ebro River. The Orbaneja del Castillo waterfall [44] is a product of cascading, barrier and terrace travertines [38]. It is a distinctive and valued feature of the town but the inhabitants of Orbaneja need to build barriers to prevent flooding by the waterfall bypass.

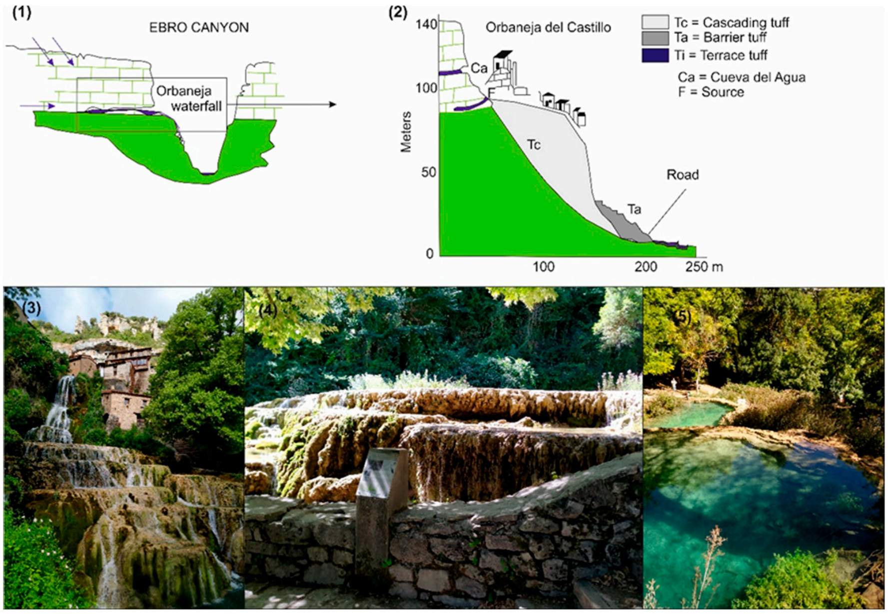

Figure 11. (**1**) Cross-sectional profile of the Ebro riverbed at Orbaneja del Castillo. (**2**) Detail of the waterfall in the section between the Cueva del Agua, point of upwelling, to the travertine terraces downstream of the BU-643 road (modified from Grupo Espeleológico Edelwiss, 2009 [39])). (**3**) Orbaneja del Castillo waterfall taken from the road on 7 June 2022. (**4**) Detail of the barrier travertines; picture taken 21 August 2022; (**5**) Image of the travertine terraces that generate the so-called "Pozas de la Turquesa", waters below the road indicated in the profile diagram taken 7 June 2022.

3.1.5. Peat Bogs

Peat bogs are located in La Piedra, Urbel del Castillo, Humada, Fuencaliente de Puerta, Corralejo del Valdelucio. There are also peat farms in Basconcillos del Tozo and another restored after its exploitation in Villanueva de Puerta. The processes that have allowed for the development of peat bogs in this area are poorly known.

3.1.6. Canyons and Sickles

In the north-eastern boundary of the Geopark, the canyons and gorges of the Ebro (Figure 12(1)) are spectacular elements of the landscape. There are also the Rudrón gorges in the centre and the Horadada canyon in the western sector of the Geopark (Figure 12(2)).

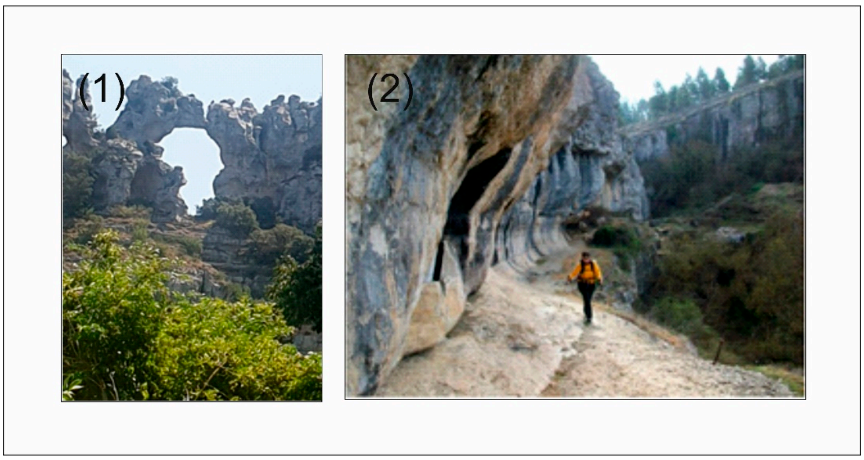

Figure 12. (**1**) Sickles of the Alto Ebro in the surroundings of Orbaneja del Castillo. (**2**) La Horadada Canyon (Pisuerga River) north of Mave (Source: Las Loras Geopark).

3.1.7. Sinkholes

There is a sinkhole of the Hurón River in the Cueva del Agua, located in Basconcillos del Tozo.

3.1.8. The Moorlands

Moorlands have formed on extensive slightly deformed carbonated platforms [10]. They are located in the northern half of Las Loras UGGp at Páramo de la Lora de Valdivia and la Pata del Cid. The moorlands are much more extensive than the loras, which occupy the flat tops of individual hills (Figure 13).

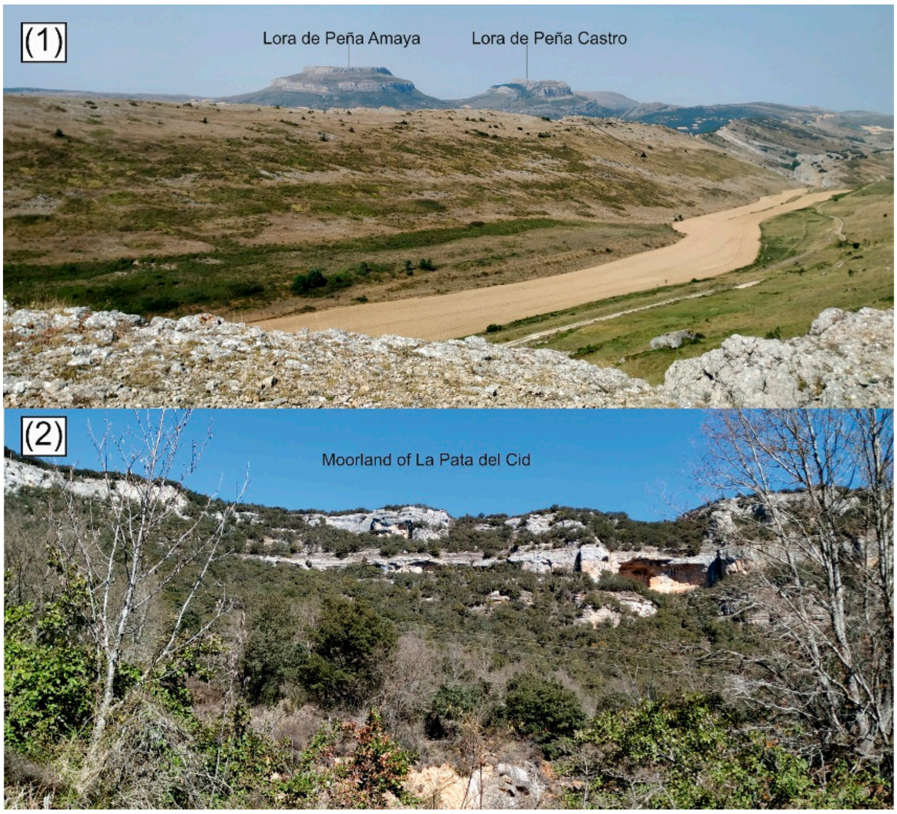

Figure 13. (**1**) Loras de Peña Castro and Peña Amaya from the La Lorilla viewpoint; the valley corresponds to the warping of the synclines. (**2**) Moorland of la Pata del Cid.

The Ubierna fault configures the arrangement of the geological formations, the geomorphology and conditions the hydraulic relationships between them. Other geological elements to highlight are moorlands, loras, caves, springs, travertine buildings and waterfalls associated with them, canyons and gorges, karst sinkholes, upwellings and resurgences, all of them associated with the karst landscape. Many of them are identified as geosites, however, specific data are required for their characterization, and to serve as a starting point for their monitoring.

3.1.9. The Loras

The loras are hanging synclines in a landscape undergoing compression with subsequent erosion by Quaternary fluvial incision. The result is a hanging folded relief that gives a distinctive morphology to the landscape. The formation of the loras dates back to the Jurassic (Figure 14). The medium-large radius folds are of variable length between 5 and 20 km, with separation between hinges of 1 to 2.5 km [10].

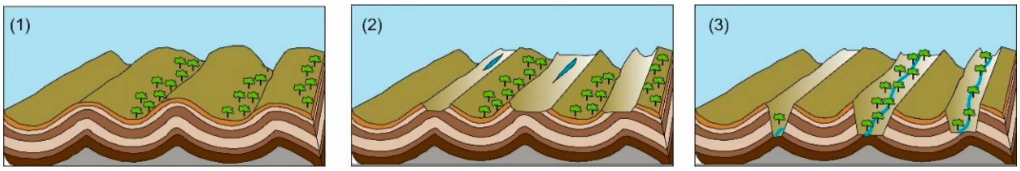

Figure 14. Formation process of a lora 65 million years ago: (**1**) the collision between Iberia and Europe caused marine sediments to emerge, and the formation of large folds and fractures, forming the mountain ranges of the Pyrenees and the Cantabrian Mountains. (**2**) The relief is a result of different erosive processes that are still active: erosion by rain and wind. (**3**) Limestone, more resistant to wear, forms the highest areas of the Loras, with sandstone and marl, prone to erosion, in the valleys.

Martínez Arnáiz, 2013 [10] distinguishes a total of 12 loras (Figure 1).

The vast mesas and moors, the plains interspersed between the tabular culminations, the narrow valleys cutting off the moorland and the rugged relief of mountains provides a landscape of great contrasts. The Ebro and Rudrón rivers chamfer the high Moorland of la Pata del Cid into narrow and deep valleys several hundred meters deep. The Rudrón has maximum relief between San Felices and Valdelateja, less than 3 km from its mouth in the Ebro, where its valley is at 660 m and the peaks on the right bank are at 1040 m. There are 380 m of unevenness in a distance of 500 m on the plane, with an average slope of 37° (76%). The relief represents the sequence of Cretaceous floors. Those of the Upper Cretaceous build the mountainous profiles of the Loras and the wide moorland, while the Lower Cretaceous is represented in the valleys. Some facies of the Cretaceous are in abnormal contact and outcrop discontinuously and irregularly. The Lower Cretaceous sediments have little exposure but have a great role in the relief [10]. In general terms, the loras reach higher altitudes than the moorlands (Table 2), with the exception of the highest point in the Moorland of la Pata del Cid, which exceeds the heights reached by the loras.

Table 2. Characteristics of the loras and moorlands in the Las Loras UGGp (Figure 3). The source of springs is Iberpix (IGN) [45]. It is indicated in the rows in white, the moorlands; and in the rows in gray color, the loras identified in the area of Las Loras UGGp.

No	Name	Maximum Altitude (m asl)	Length (km)	Width (km)	Nearest Villages	Springs
A	Moorland of la Lora de Valdivia	1222	6.85	4.92	Revilla de Pomar-Villescobedo	Covalagua, Villaescobedo
B	Moorland of la Lora de la Pata del Cid	1063	22.20	14.14	Villaescobedo, Orbaneja, Valdelateja	Upwelling of Rudrón river, Ceniceros, Valdelateja
1	Lora de Peña Amaya	1370	5.3	2.7	Amaya-Villamartín de Villadiego	Fuente Prabal, Manantial de las Quintanas, Fuente de Oncejuelo
2	Lora de Albacastro	1349	6.78	2.7	Albacastro, Puentes de Amaya	Manantial de la Ceña, Manantial de Hoya Redonda, Fuente de la Legaña, Fuente de la Turquilla
3	Lora de Rebolledo de la Torre	1243	7.96	2.55	Rebolledo-Castrecias	Manantial de la Raposa, Fuente de San Roque
4	Lora de Ulaña o de Humada	1206	7.09	1.4	Humada-Ordejón de Abajo	Fuente de San Pedro, Manantiales de Vallejo, Fuente del Carril

Table 2. *Cont.*

No	Name	Maximum Altitude (m asl)	Length (km)	Width (km)	Nearest Villages	Springs
5	Lora de Barriolucio	1193	25.5	2.99	Barriolucio-Fuenteodra	Barriolucio, Manantial de la Magdalena
6	Lora de Pinza	1107	7.38	6.6	Urbel del Castillo	Manantial de la Recova, Manantial del Pradal, Manantial de Tarancón, Manantiales del Olmo, Manantial de las Matas, Manantial de los Pradillos, Manantial de la Pedrosa, Manantial de los Milagros
7	Lora de Corralejo	1161	6.7	1.65	Corralejo-Solanas de Valdelucio	Fuente Cuevas, Fuente de Ostra
8	Lora de Fuente Urbel	1085	5.15	3.05	S de Fuente Urbel	Fuente Urbel, Manantial de Valledrías, Manantial de Trescuevas, Manantial de Valdehayas
9	Lora de Cuevas de Amaya	1150	3.65	1.57	Rebolledillo-Cuevas de Amaya	Fuente del Obispo, Fuente Ritoba, Fuente Junquera
10	Lora de Villela	1077	2.38	3.16	Villela-Rebolledillo de la Orden	Fuente Gatón, Fuente Mijo
11	Lora de Monte Carrascal	1035	4.26	1.61	San Pantaleón del Páramo-Montorio	Manantial de Valdemudo
12	Lora de Las Tuerces	1087	6.85	2.63	Villaescusa de las Torres	-

Expressed in km.

3.2. Interpretation and Hydrogeological Significance

3.2.1. Analytical Results

The analytical results and the parameters calculated for the hydrochemical characterization of the Las Loras samples are collected in three tables that are attached as complementary material. Table S1 contains the analytical results, Table S2 the descriptive statistics, and Table S3 the result of the calculation of various indices and hydrochemical parameters.

The waters present throughout the sampled area have very similar hydrochemical facies (see Figure 15 and Table S3), mostly of the calcium bicarbonate type. Points 30, 42, 68 and 69 are an exception as their facies are sulphated bicarbonates. Among these, point 42 (Manantial de la Pisadera), whose rSO_4^{2-}/rCl^- ratio is 95.2, and point 30 (Riotobas), whose rSO_4^{2-}/rCl^- ratio is 12.14, stand out for their high sulphate content (Table S1). This group could include the Peñalonga spring, whose sulphate ion content is very high, although the rSO_4^{2-}/rCl^- ratio (6.64) remains within the typical values of the area. The high proportion of sulphate at these sites corroborates the idea that they are fed by waters that have greater residence time and are sufficiently deep to contact with clay and gypsums from the Keuper. Some of this deep groundwater occurs outside the park boundary. The uniformity of the spatial distribution of the facies and of the total mineralization (represented as electrical conductivity) is evident in the Stiff diagram (Figure 7). However, to the west, a north–south strip can be seen that includes all points between 68 and 12 to the north and 9 to the south. The points of this strip differ because of their small but appreciable content of Cl^- and Na^+ ions. It is possible that there is a structural reason explaining this difference, since this strip approximately coincides with the Becerril de Carpio thrust.

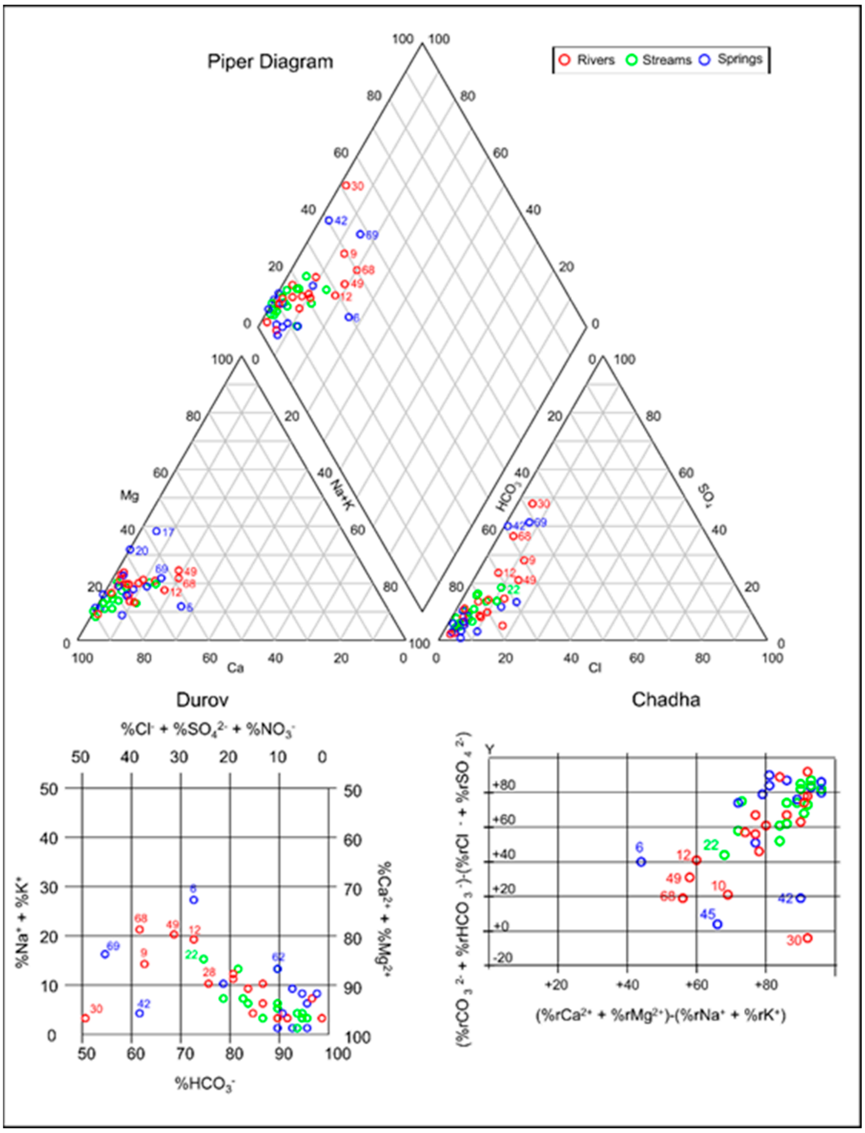

Figure 15. Representation of the water samples taken in Las Loras UGGp using Graphs of Piper [46], Durov [47] and Chadha [48]. In the case of the Durov and Chadha plots, only the portion of the plot in which the samples are grouped is shown.

The analysis of the Piper, Chadha and Durov diagrams presented in Figure 15 shows that the facies and ionic relationships in streams is notably more homogeneous than in rivers and springs. For example, in the Chadha diagram all samples are located in the sub-field 5 (alkaline-earth metals and anions of weak acids both exceed alkali metals and anions of strong acids, respectively), indicating waters with temporary hardness characteristics resulting from the dissolution of carbonate rocks without contact with highly soluble evaporites. The homogeneity of the stream samples is probably due to the fact that the main contribution of water is directly from surface and sub-surface runoff (hypodermic flow), which drains the most superficial carbonate outcrops, giving rise to hydrochemically very homogeneous waters with low mineralization.

The pH values of the springs are mostly in the range between 7.13 and 8.18 pH units, consistent with calcium bicarbonate waters without dissolved carbon dioxide. The pH of some of the samples (23, 26, 42, 32 and 21) reaches relatively high values, between 8.17 and 8.18, sufficiently high to suggest an influence from CO_3. The spring waters are also low mineralization waters, from a minimum of 125 µS/cm in sample 6 to a maximum of 693 µS/cm in Peñalonga Spring. In Figure 7 the spatial distribution of the total mineralization of the water has been represented and, as was the case with the facies, a north–south stripe can be seen to the west in which none of the samples is found in the group with the lowest electrical conductivity.

All the calculated ionic ratios (see Table S3) again indicate that the mineralization of water comes from contact with carbonate materials and that, of the salts more soluble than carbonates, sulphates prevail over chlorides in most cases. In this sense, as has already been explained in previous paragraphs, samples 30 and 42 constitute a particular case.

In the types of water at Las Loras UGGp, the content of nitrogenous species and phosphorus can be used as indicators of agricultural pollution. Phosphate levels have been measured in eight of the analysed samples, between 0.1 and 0.8 mg/L. These values are relatively high given the carbonate nature of the soil matrix that tends to remove phosphate in the form of apatite precipitates and insoluble hydroxyapatite. Ten of the samples present NO_3 values above 10 mg/L and four are above 20 mg/L (points 58, 20, 21 and 47). Of the latter, the first three are springs and the fourth, a stream. Given the limited agricultural activity in the area, these moderate values demonstrate the vulnerability of the system to contamination. All waters are of excellent quality for any use, including human consumption, with the possible exception of sample 47 (Arroyo de las Solanas) which has nitrites, ammonium and phosphorus values indicating some type of organic contamination.

Samples 64 and 6 (Valdelateja spa and Manantial de la Cárcava respectively) have the temperature values indicating some geothermal activity (Table S2). Valdelateja is well known as a hot spring and has an upwelling temperature of 20 °C, nine degrees above the annual atmospheric average. However, in the case of the Cárcava Spring, the temperature readings may be an artefact of the high silica content. This possibility is supported by the low mineralization of the water of this spring, only 115 µS/cm and the lowest value in the dataset. Pisadera Spring (number 42) has been described as thermal with upwelling temperature of 18 °C [43] the current temperature of the spring is close to average and does not indicate geothermalism.

3.2.2. Hydrogeological Context

The oldest rocks correspond to the Upper Triassic Keuper facies. These are marls and clays variegated with salts and gypsum, highlighting the presence of clear and orange bipyramidal quartz (hyacinths from Compostela). Its outcrop is limited to narrow strips of a few hectometers wide and a few km long, or to eyelets that do not exceed one kilometre on any axis. Spatially, they are restricted to the south (Quintanilla Pedro Abarca, San Pantaleón del Páramo and NW of Castrillo de Rucios) and to the west (around Los Ordejones, Amaya and Villela). Small elongated enclaves are also found along the Lomilla–Castrillo dislocation line, between the Corralejo and Valdelucio loras. However, its limited surface expression, its importance as a determinant of relief, is considerable. The very plastic behaviour of the Keuper materials has allowed them, during the compressive phases of the Alpine Orogeny, to move laterally, inject, perforate and disjoin the overlying strata as diapirs, causing very interesting nuances in the relief.

Pushed by the Keuper, other overlying materials have become elevated. Accompanying the perforations where the Keuper outcrops, appear small and unconnected outcrops of rhetian and liasic okerous carnioles (Figure 8(3)), which small ridges. Subjected to strong compressions, the fracture of these dolomitic limestones (Figure 8(4)), lacking plasticity, is pronounced. The intense fracturing together with their ochrous nature makes them very vulnerable to karstic dissolution. The high content of magnesium carbonate and iron minerals results in terra rosa soils suitable for cultivation or pasture [10].

The Keuper materials constitute the detachment level of the thrust that is mapped in the Becerril area, and also appears as extrusive material associated with some sectors of the Ubierna fault, as can be seen in the MAGNA 133 sheets [14] and 134 [13]. The permeability of this predominantly clayey formation is very low and this formation constitutes an impermeable barrier to underground flow.

The Jurassic materials, formed by limestone and ochrous dolomite, are linked either to the Becerril thrust or to the Ubierna fault in its westernmost sector, between Aguilar de Campoo and Fuencaliente de Lucio. They are stratigraphically disposed over the Keuper materials. The elevation of the Jurassic material is between 150 and 400 m. These materials have been extensively karstified as indicated by the presence of porous carniolar levels and they have also been subject to tectonization. Karst development increases permeability, generating preferential underground flow paths. The alternation of marl limestone and marl from the Jurassic presents average permeabilities of 0.0089 m/d and 0.0031 m/d [25].

The fluvial base levels are constituted by the channels of the Pisuerga River (in the western sector), with levels between 897 and 892 m above sea level; Lucio (in the central sector), with elevations between 980 and 875 m above sea level; and Urbel (eastern sector), with levels between 1010 and 900 m above sea level.

Three types of sediments have been considered in the analysis: aquifers themselves (which according to their dominant lithology can be carbonated or detrital), aquitards and aquifuges (Table 3).

Table 3. Classification of the formations ordered chronologically according to their hydrogeological behavior. Note: The Neogene/Paleogene is not present within Las Loras UGGp. Its presence is representative within the Duero detrital Tertiary, outside the southern limit of the Geopark.

Formation	Aquifer	Aquitard	Aquifuge
Quaternary	X		
Maastrichtiense			X
Campaniense	X		
Campaniense		X	
Upper Santoniense	X		
Lower Santoniense		X	
Coniaciense/Turoniense	X		
Cenomaniense–Albiense (Utrillas)		X	
Apt-Albiense		X	
Valong. Barremiense		X	
Portlandiense–Upper Kimmeridgiense (Purbeck)		X	
Dogger	X		
Dogger Batho.			X
Dogger Bajo.	X		
Upper Lias-Alb.		X	
Lower Lias-Alb.	X		
Trias			X

The upper aquifer in the Las Loras UGGp encompasses materials between the Lower Cretaceous and the Quaternary. A second deep regional aquifer is predominantly represented by marine Jurassic sediments. In the first case, most are outcropping aquifers, whose discharge points are above the level of the river valleys. In the second case, the aquifers are confined and in some cases, discharge under pressure at a level higher than the river valleys or at the same level.

There is no evidence of a connection between the two aquifer systems. The materials from the Lower Cretaceous provide an aquitard that isolates both aquifer systems.

(a) Upper multilayer aquifer

The aquifer–aquitard overlapping sequence in the upper reaches of the Cretaceous (Table 4) is the reason why fluvial erosion has isolated certain structures (mainly loras) in favor of semi-permeable materials, generating well-configured isolated aquifers such as the Valdivia Lora, the Barrio-Panizares Lora or the Barriolucio Lora.

Table 4. Stratigraphic series of the Cretaceous that makes up the sequence of free-type aquifers in the different types of lora.

Code	Geological Age	Description
C-7	Upper Santoniense–Lower Campaniense	Calcareous sandstones, dolomites and limestones with rudists and foraminifera
C-6	Upper Santoniense	Glauconitic marls and limestones
C-5	Medium Santoniense	Calcarenites with "Lacazina Elongata"
C-4	Lower Santoniense	Calcareous marls and marly limestones
C-3	Medium Turoniense–Upper Coniaciense	Sandy limestones, oolitic limestones and limestones with rudists
C-2	Medium Turoniense	Sandy loams
C-1	Cenomamiense	Sands, microconglomeratic sandstones
C-0	Utrillas Facies	Sands, microconglomeratic sandstones and clays

(b) Deep aquifer

The available data for the deep aquifer are scarce and come largely from the hydrogeological studies carried out in Sargentes de la Lora as a result of oil drilling. They are made up of Jurassic limestone and dolomite resting on Triassic clay and gypsum that acts as an aquitard (cf. Table 3).

In Las Loras UGGp, there are different superimposed aquifers that form a multilayer system in the geological formations of the Upper Cretaceous. The configuration of the outcrops determines that the phreatic surface reaches locations in the loras and moorlands with contrasting permeabilities, generating springs. They are typically positioned on the edge of the morrlands and loras, or as diffuse discharges in the riverbeds that surround them. To visualize this model, Section 3.4 shows an scheme of the geopark that begins at the Peñalonga spring, crossing the Las Tuerces, Rebolledo de la Torre and Peña Amaya loras, ending at the Odra riverbed, within the detrital Tertiary domain of the Duero basin. The springs and riverbeds align with areas where the upwelling level groundwater has a higher elevation than the topography.

The regional Jurassic aquifer is not subject to groundwater exploitation, and thus, there are no data on piezometric levels. This aquifer can function in a free regime, as in the outcrop generated by the Peñalonga spring, or in a confined or semi-confined regime.

3.2.3. Hydrogeological Characterization of Springs

Springs are the natural discharge points of aquifers and therefore, their analysis provides information for understanding the dynamics of groundwater.

Within the limits of Las Loras UGGp, there are 212 inventoried springs [29], many of them unnamed. Most of them are located in the Fold Band, revealing the consequences of compartmentalization and the evidence of changes in permeability between the geological formations in lithological contact. A series of springs that have different characteristics have been selected, based on the criteria discussed in the methodology.

Peñalonga Spring

Peñalonga spring is located in Aguilar de Campoo at the site of a monastery constructed by Premonstratensian monks in the 9th Century. The monastery has undergone changes throughout history, being known as a Romanesque monastery built for the most part between the 12th and 13th centuries, later abandoned in the 19th century, at the end of the 20th century it was rebuilt, currently housing a secondary teaching institute (Figure 16). The spring is still active and due to its upwelling temperature, 12 °C, it was used for air conditioning in the classrooms in the winter months (verbal communication from the monastery guides).

Figure 16. Peñalonga spring. (**1**) View of the Romanesque Monastery of Santa María la Real (Aguilar de Campoo) with the carbonate massif that houses the aquifer in the background. (**2**) Courtyard of the springs, where the spring is located, located at the foot of the massif; and (**3**) sampling point (Coordinates: −4,272; 42,796) in the current entrance courtyard to the monastery.

The spring emerges at the foot of a carbonate massif in its contact with the Keuper materials that act as a confining layer beneath the aquifer (Figure 17). The Keuper outcrop in this area is due to the existence of several thrust scales. The spring occurs at an elevation of 905 m and the waters have an electrical conductivity of 909 µS/cm (measured in situ on 19 August 2022) indicating calcic bicarbonates.

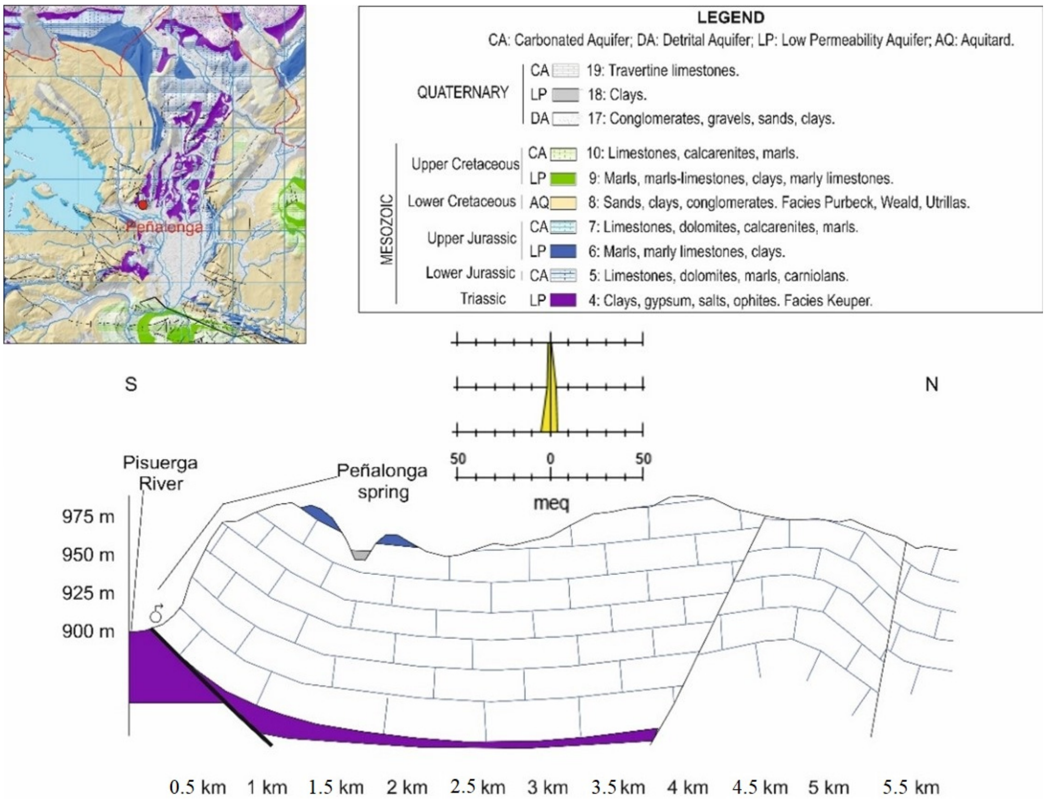

Figure 17. Location and hydrogeological cross-section of the Peñalonga spring with Stiff diagram of hydrochemical facies included.

Spring of La Pisadera

This spring occurs at the contact of the Ubierna fault with the less permeable materials of the Lower Cretaceous (Figure 18). The presence of the Jurassic aquifer at a relatively shallow depth would justify the spring feeding through the fault plane.

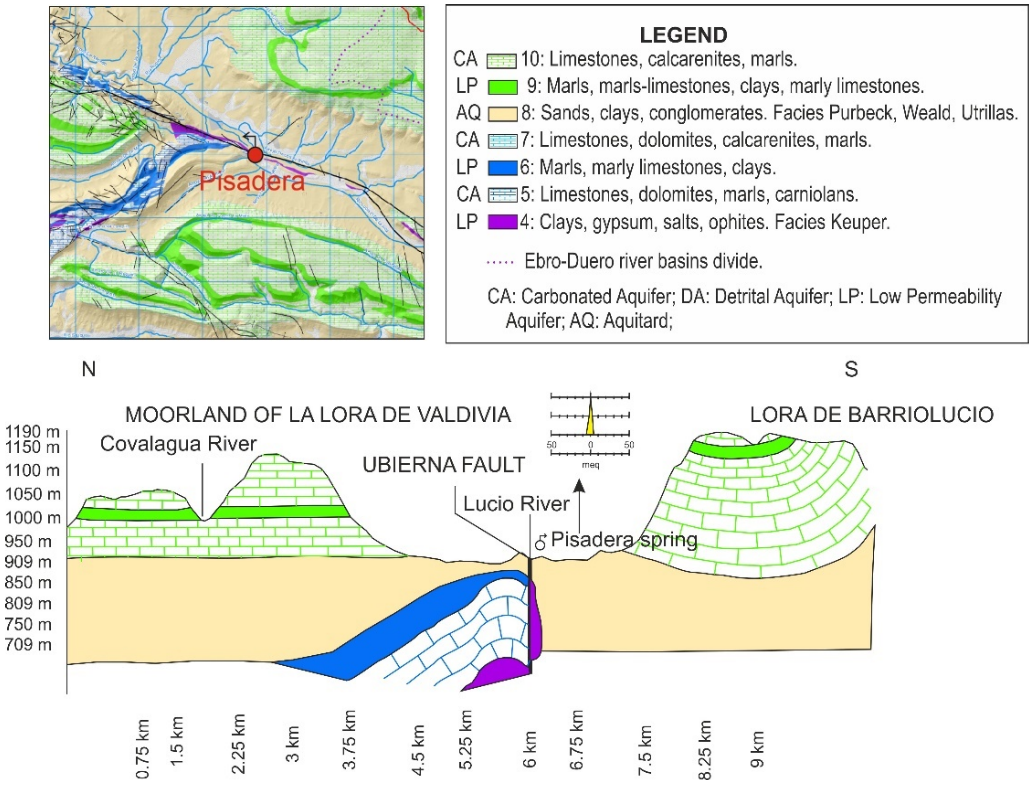

Figure 18. Location and hydrogeological cross-section of La Pisadera spring with Stiff diagram of hydrochemical facies included.

According to some bibliographical sources (Cidad, 1986) [49]), it is a thermal spring with a stable upwelling temperature of 18 °C all year round. A measurement quantified its flow of 10 l/s. Currently, no thermalism is detected, measurements in the field give an upwelling temperature of 13 °C, both in the April 2022 campaign and in June 2022, while in the August 2022 campaign, it was dry (Figure 19). There are no signs from mining or mineral paragenesis associated with metallogenetic deposits indicating the existence of hydrothermalism in this fault zone [43]. The literature review shows that no low enthalpy geothermal reservoirs have been found within the Las Loras UGGp.

Figure 19. Spring of La Pisadera. (**1**) Photograph taken on 4 April 2022; (**2**) Photograph taken on 19 August 2022 (Authors' own).

The factors that may have participated in the evolution of the Pisadera spring would require a more in-depth investigation than that developed here, including climatic and hydrogeological aspects. There is no record of groundwater levels in recent decades, but future monitoring is recommended.

Fuentehoz Spring in Barriolucio

The Lucio River rises in what is known as the Lucio River cave or the Hoz cave located just below the BU-621 road, between Km 25 and 26, below the Upper Santonian limestone cut (number 16 of lithological legend in MAGNA50-134 [14]). A stream of water emerging from its entrance is active most of the year. Adjacent to the cave, between the space that separates the Turonian–Coniacian–Santonian limestones (14), from the Upper Santonian limestones (16), there is a narrow band, affected by faults, of calcareous marls and sandy limestones with glaucinite from the Middle Santonian (15). The permanent upwelling of Fuentehoz fills the deposit located on the tuff platform, on the right side of the river, and supplies the town of La Riba de Valdelucio. The water flowing over the top of the tuff formation forms the Barriolucio waterfall.

It is a permanent spring and according to verbal testimony of an inhabitant close to this spring, it only ceases to flow in extremely dry years. Despite 2021/2022 being a dry year, the flow increased considerably between 21 July 2022 and 19 August 2022, generating a second pool to the easts of the main pool through which a somewhat smaller flow of water circulates, also in a cascade (Figure 20).

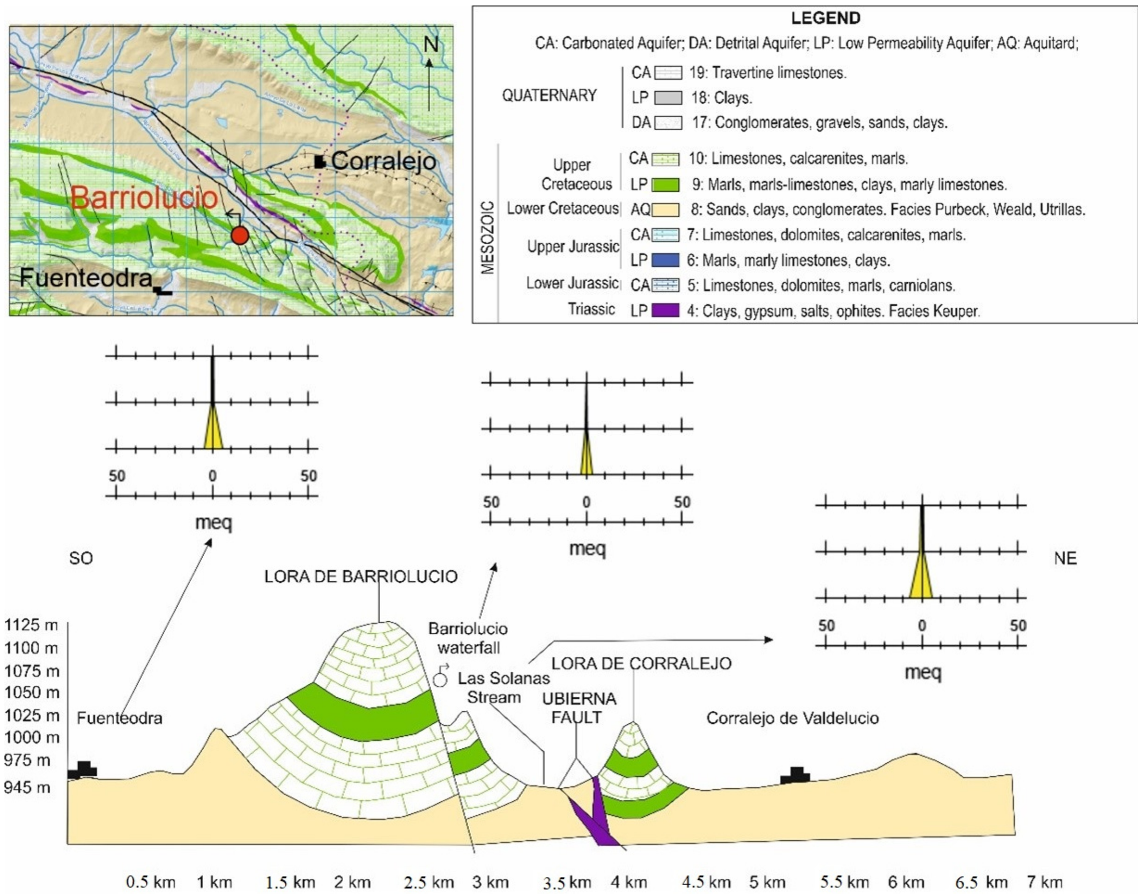

Figure 20. Location and geological cross-section of the Loras de Barriolucio and Corralejo transversal to the Barriolucio waterfall according to a Fuenteodra–Corralejo direction. The water sample of this waterfall is called Manantial de Barriolucio, No. 71 in our analyses of Tables S1 and S3.

This enclave constitutes a somewhat inhospitable place, in which the pristine conditions of this spring are preserved, despite the cultivated fields downstream.

The Barriolucio upwelling is located on the northern flank of the Lora de Barriolucio syncline, at the lithological contact between the Turonian–Coniacian-Santonian (14) limestones and the Cenomanian (12) sands and clays. This interpretation differs from the cartographic representation of Sheet MAGNA50 No. 134 [14] (where it is indicated that the spring is located near the intersection of the two faults that put the Upper Santonian limestones (16) in contact with the Turonian–Coniacian–Santonian limestones (14). The absence of Cenomanian loams (13) on the existing map may be a product of the small scale of the mapping, although the presence of such material is difficult to verify in the field because of the profuse vegetation and the travertine building.

As indicated in Sheet MAGNA50 No. 134 [14], the Cueva and Fuentehoz springs appear near the intersection of two faults that are part of a series of oblique faults associated with the Ubierna fault. This fault network affects the northern flank of the Lora de Barriolucio syncline, forming a duplex in echelon between the towns of Escuderos and Solanas de Valdelucio. There may be a water table between the Upper Santonian limestones (16) and the glauconite marls and limestones (15); and another between the limestones of the Turonian–Coniacian–Santonian (14) and the sands and clays of the Cenomanian.

The outcrop of the limestones at Barriolucio spring (Figure 21) is formed by a series of blocks in relief that owe their reason for being to a series of sigmoidal faults associated with the Ubierna Fault. The block in which this spring is located is the southernmost in the series. A structure disrupts the continuity of the Turonian–Coniacian–Santonian limestone outcrop (14) and may provide a conduit supplying the spring and the feeding of the waterfall (results of the chemical analysis is shown in Table 5). However, it is not possible to define the recharge zone with the current data.

Figure 21. (**1**) Photograph taken at the Barriolucio waterfall on 21 July 2022 with two of the co-authors. (**2**) Barriolucio Waterfall on 19 August 2022. The rocky level at the foot of the rock located to the right of the photograph is flooded and behind this rock there is another pool similar to the one seen in the photograph. (**2**) contrasts with the image taken on 21 July 2022 (**1**) in which it can be seen that said step was dry. This may be due to an increase in the discharge flow as a result of possible recent rains, or to a modification in the construction of the travertine building that has produced a new waterfall from behind the rock located on the right of the photograph. In any case, the new volume of water is excessive to assume that it is the result of the low rainfall that occurred in the area on previous dates.

Table 5. Measurements of unstable parameters in situ in the Barriolucio Waterfall.

Parameter	6 June 2022	19 August 2022
EC (µS/cm)	-	612
pH	7.15	6.47
T (°C)	10.76	14.8
Redox Potential (mV)	-	25.5

A more detailed hydrogeological study using techniques (tracers, isotopic analysis) is required to determine the provenance and origin of the water.

San Bol Spring

The San Bol spring is located in the easternmost sector of the northern flank of the Barriolucio syncline (Lora de Barriolucio). It is located at the foot of a carbonated hill (Figure 22). This spring, located in Sheet MAGNA50 134 [14], corresponds to an upwelling associated with lithological contact between the Upper Santonian limestones (16) and the Lower-Middle Santonian marls (15).

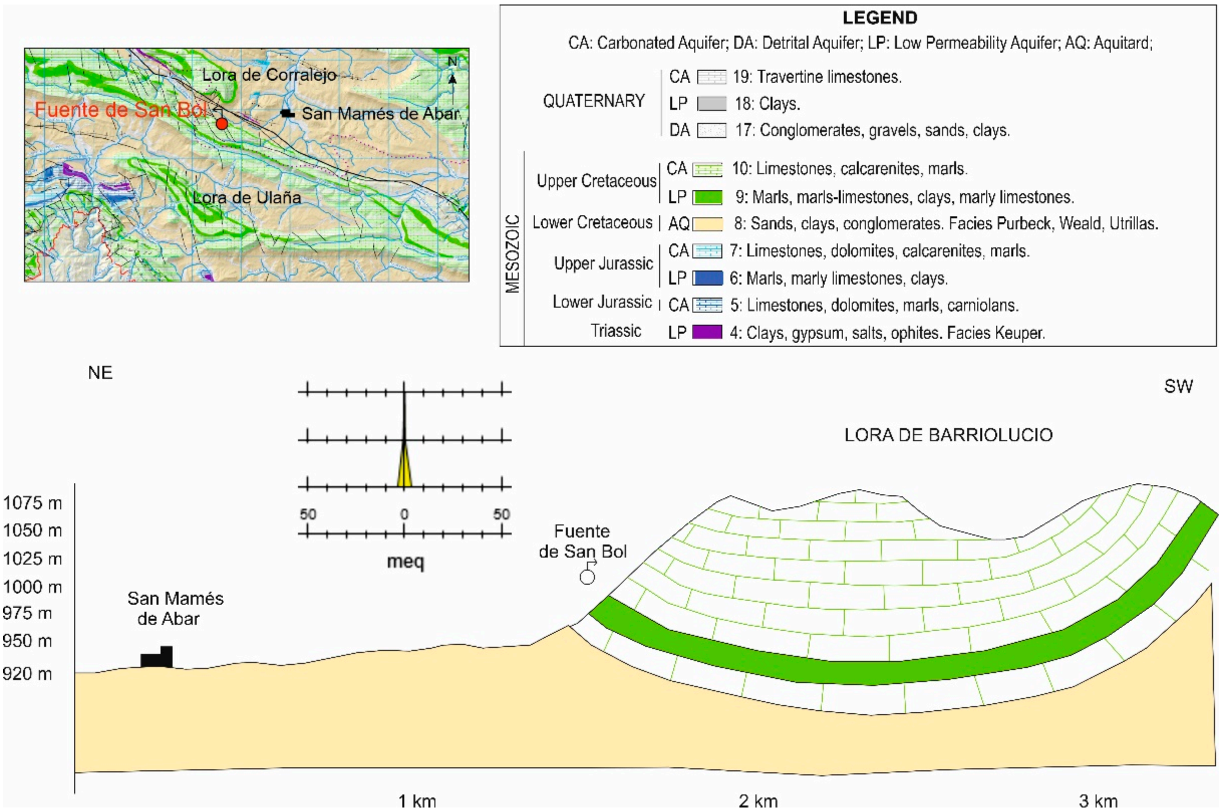

Figure 22. Location and geological cross-section of the Fuente de San Bol. The Fuente de San Bol is the sample No. 48 in the Tables S1 and S3 of the Supplementary files.

The chemical analysis of the sample taken on 4 April 2022 (Table 6) reveals that it is calcium bicarbonated water with an electrical conductivity of 339 µS/cm. The chloride content shows that it is continental water with short residence time in the aquifer.

Table 6. Chemical results of the water samples taken at Fuente de San Bol spring on 4 April 2022. Concentrations are expressed in mg/L. CE in µS/cm.

Cl	SO_4	CO_3H	CO_3	NO_3	Na	Mg	Ca	K	pH	CE	NO_2	NH_4	PO_4	SiO_2
1	10	197	0	0	0	7	62	0	7.63	330	0	0	0	2.8

Valdelateja Springs

The thermal springs of Valdelateja are located on the left bank of the Rudrón river, before its mouth in the Ebro river (No. 64 in Figure 3). Less than a kilometer upstream from the town center is the old Valdelateja spa, closed since 2008.

There are several springs with temperatures indicating thermalism in its surroundings. Water temperature are a constant 20 °C throughout the year. The level of the sampled upwelling is at the same level as the Rudrón riverbed, from which it is some 10 m distant.

According to IGME-SIEMCALSA (2008) [50], the waters are related to materials from the Cenomanian (Upper Cretaceous). Field observations confirm this; however, we disagree with the representation of the Upper Cretaceous unit immediately below the Rudrón riverbed at the height of the Spa, acting as a confining aquitard of the Lower Cenomanian sands and calcarenites. This is inconsistent with the presence of calcarenite where the spring vent occurs. The confined Lower Cretaceous calcarenite aquifer therefore outcrops at this point through some unmapped punctual structural discontinuity. The presence of this fault (Figure 23) is also revealed by the appearance of degassing phenomena in the Rudrón riverbed itself at the height of the river, and only at that point in the spa, where a faint and periodic bubbling is observed, ascending with bubbles of size between 1 and 7 mm.

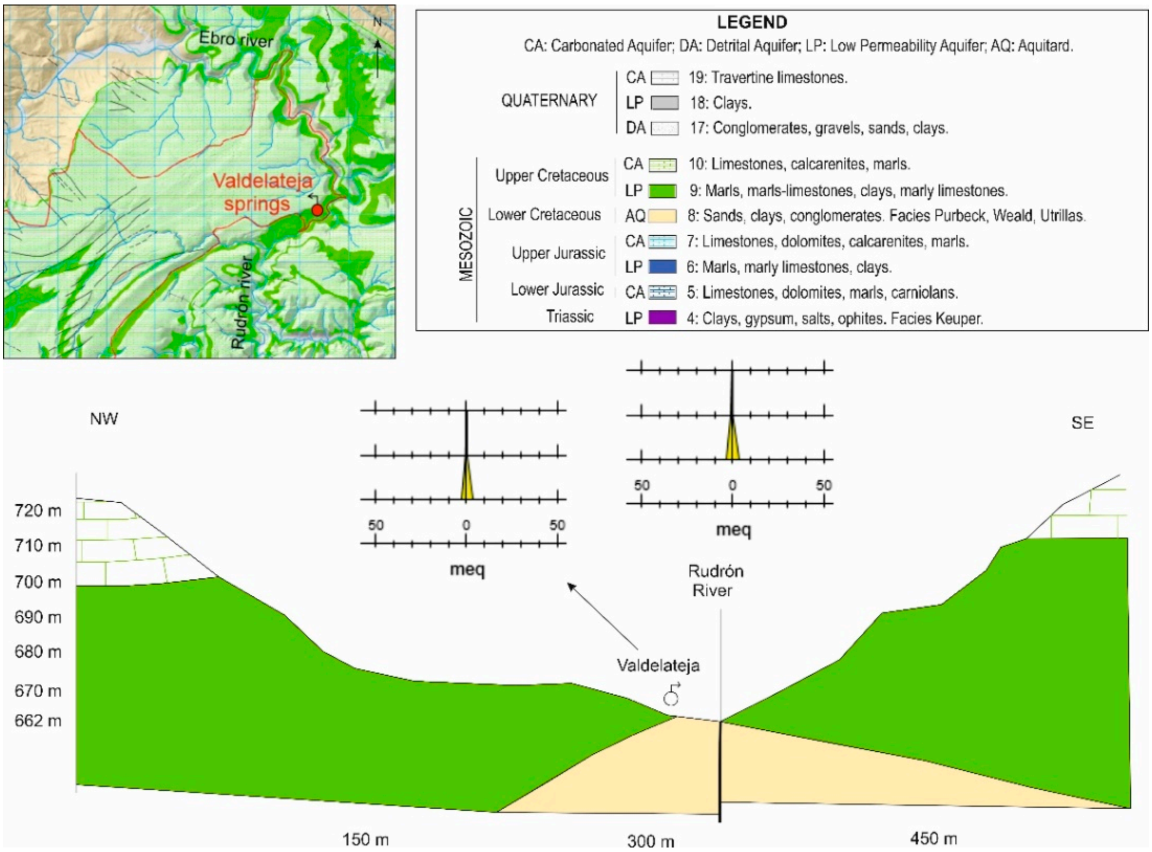

Figure 23. Location and geological cross-section of the Valdelateja spring in a transversal section to the Rudrón River at the height of the spa of the same name.

Springs of Orbaneja, Pozo Azul and Tubilla del Agua

These three locations are located in Figure 3 with the numbers 56, 58 and 62, respectively.

The three sites present calcic bicarbonated waters, with low mineralization, and electrical conductivities between 403–462 µS/cm for the samples taken on 6 April 2022 (Tables S1 and S3 of SM files).

Summary of Spring Characterization

Springs are most abundant are in the lithological contact between the Turonian limestones and the Cenomanian marls. Some examples of this typology are the springs of Covalagua, Villaescobedo (No. 2 and 13 in Table S1), in the Páramo de la Lora de Valdivia (A in Figure 3). These springs occur relatively high in the landscape and present waters belonging to calcium bicarbonate hydrochemical facies with electrical conductivities of the order of 400–460 μS/cm.

Other types of spring appear at lower topographical levels and have more mineralized water than the first type; the Peñalonga and La Pisadera springs (No. 69 and 42, respectively, Table S1) are examples. They present bicarbonated calcium facies waters with electrical conductivities of the order of 595–695 μS/cm.

Thirdly, there are springs located at intermediate topographic levels between the previous ones, with electrical conductivities of 595–695 μS/cm.

A summary of these typologies is shown in Table 7.

Table 7. Summary of the groups of identified springs.

Discharge Level (m asl)	Geological Formation	Hydrochemical Facies	EC (μS/cm)	Examples
970–1200	Upper Cretaceous	$CaCO_3H^-$	400–500	Covalagua, Barriolucio
940–960	Paleogene	$CaCO_3H^-$	350	Fuente Urbel
900–920	Jurassic	$CaCO_3H^-$	595–695	Peñalonga, Pisadera

3.3. Rivers

The main river is the Pisuerga River (No. 29 in Tables S1 and S3), which rises in Fuente Cobre, in the Sierra de Peña Labra, about 40 km NW of the Geopark. Along its route it feeds the Aguilar Reservoir and within the limits of the Geopark, it receives the waters of the rivers Camesa (No. 49 in Tables S1 and S3), Lucio (No. 35 in Tables S1 and S3) on its right bank and several streams on its left bank (Ritobas (No. 30), Constana, Sudría, Bustillo). All these channels are permanent, as reported in local studies. The MIRAME-CHD Information System [20] confirms this for the Rubagón, Camesa, Lucio and Pisuerga rivers. The Lucio River receives the waters of the Covalagua River (No. 2 in Tables S1 and S3) on its right bank.

Within the scope of the Geopark, the rivers Lucio, Odra, Urbel (the Duero basin) and Hurón (No. 67 in Tables S1 and S3)-Rudrón (No. 66 in Tables S1 and S3) (Ebro basin) are born, which are also rivers permanent according to official sources.

The Urbel river rises in the place called "las Fuentes" in the town of Fuente Urbel (No. 72 in Tables S1 and S3). This spring has its origin with baseflow at the contact of the limestones of the Middle Santonian (Upper Cretaceous) with the sands and clays of the Facies Weald (Lower Cretaceous).

The chemical analysis of the water samples taken at Fuente Urbel (No. 72 in Tables S1 and S3) shows that it is bicarbonated calcium water, with an electrical conductivity of 361 μS/cm, similar to the waters of the river Lucio.

Most of the samples from the streams and rivers sampled present bicarbonated calcium waters without great differences between them. However, the high concentration of salts in the Arroyo de las Solanas (No. 47 in Tables S1 and S3) are an exception with two possible causes: (a) contribution of more saline materials from the Lower Cretaceous at its source; (b) anthropogenic contamination;

3.4. Hydrogeological Conceptual Model

Burgalesa Platform (Figure 24) and the Folded Band (Figure 25) provide contrasting the hydrogeological settings in Las Loras Geopark.

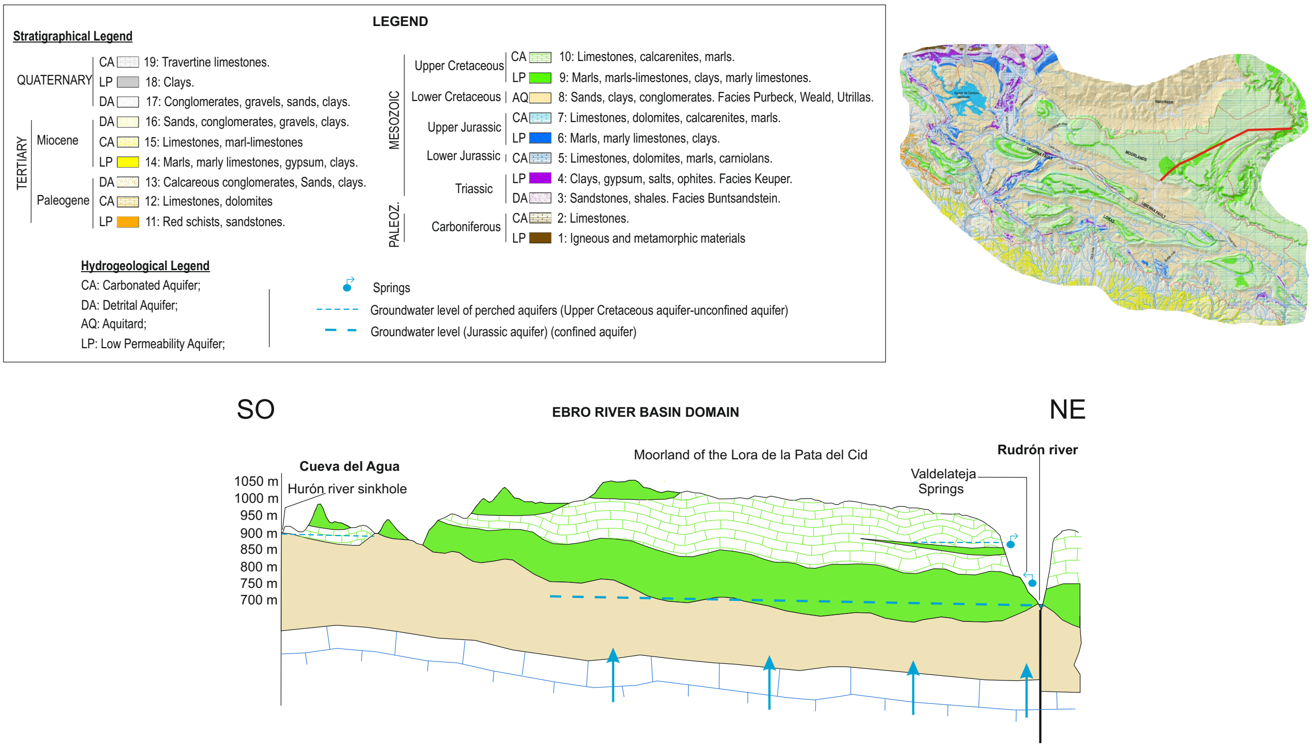

Figure 24. Hydrogeological section of the Burgalesa Platform in Las Loras UGGp.

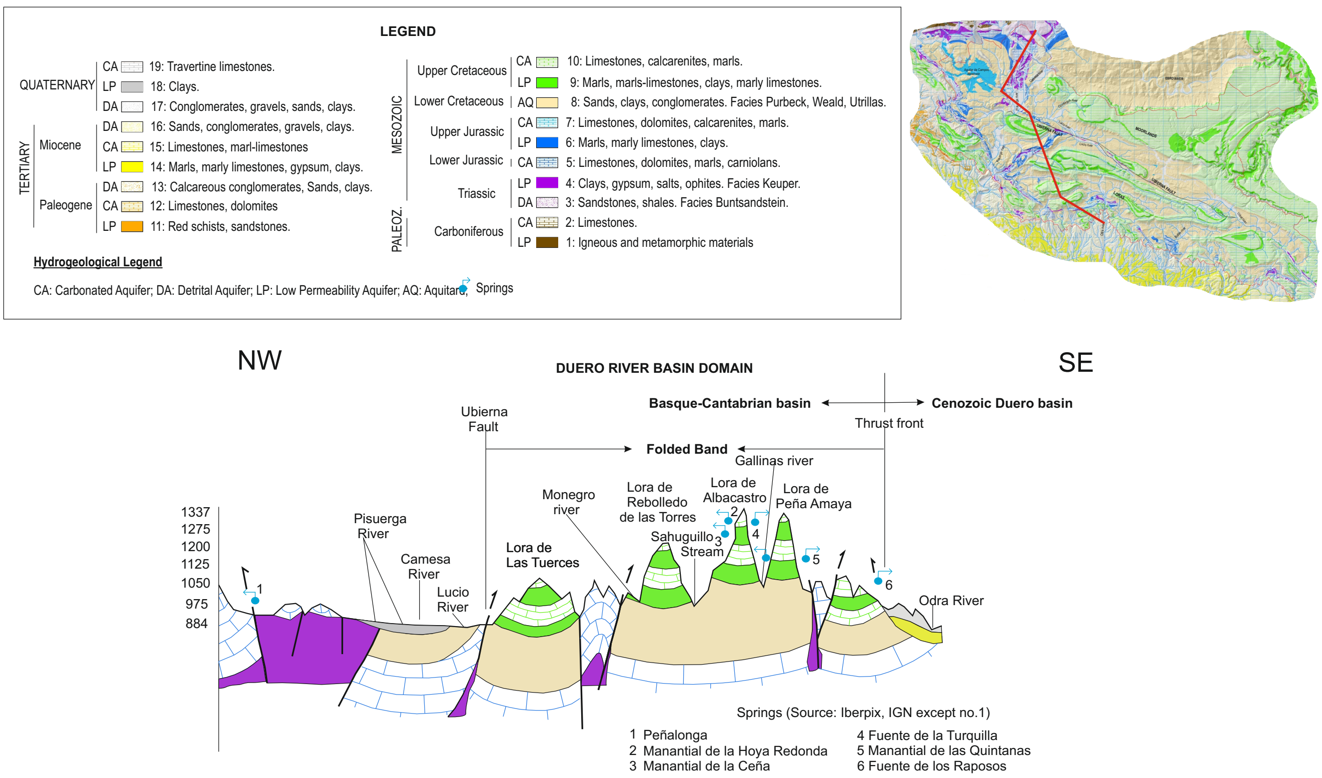

Figure 25. Hydrogeological section of the Folded Band in Las Loras UGGp.

In the Burgalesa Platform sector, surface flows have a southwest-northeast direction, towards the Rudrón riverbed, which acts as the main drainage axis (Figure 24). The springs appear in the peripheral fringe (old Ceniceros spring), associated with old terraces

(Orbaneja del Castillo), with small hanging aquifer levels, or appear in the Rudrón riverbed related to specific tectonic accidents (Valdelateja thermal springs).

In the Folded Band sector (Figure 25), the loras represent individual hanging synclines, with springs appearing on the peripheral edge of the limestone contact with the marl. The marl acts as an aquitard, impeding the downward flows of the upper materials (Upper Cretaceous). The base level is determined by the Lucio River, which is at a lower level than many of the springs that appear in the Upper Cretaceous, with upwelling levels higher than 1000 m above sea level (Figure 25).

The results presented in the preceding sections allow us to explain the conceptual model of Las Loras UGGp consisting of two superimposed aquifer systems: a lower aquifer, formed by Jurassic limestone, whose lithological continuity in depth is assumed given the results achieved by the ALGECO project [30], despite the intense fracturing that exists, especially in the fault zone (central zone of the Las Loras UGGp); and an upper multilayer aquifer system, formed by the alternation of permeable and slightly permeable materials outcropping in most of the extension of the Las Loras UGGp, which make up the moorlands and loras.

4. Conclusions

The current study identifies the geodiversity elements of Las Loras UGGp and explains its hydrogeological significance. The work is based on the dissection of geological (stratigraphy and sedimentology), hydrogeological and water physico-chemical characteristics of water-related geosites.

The Ubierna Fault drives the stratigraphical, geomorphological, structural and hydrogeological characterization of the region and conditions the hydrogeological behaviour of the existing aquifers within the Las Loras UGGp. The hydrogeological and hydrochemical characterization of the rivers and springs has made it possible to define the flow systems within the framework of regional hydrodynamics.

The waters in Las Loras show homogeneous hydrochemical facies of bicarbonated calcium, concordant with water of short residence time and rapid flow over carbonate materials. This means that almost all samples have low mineralization and are suitable for any use. On the other hand, the groundwater and surface water system of Las Loras is very sensitive to contamination, so that in some of the points analysed, an incipient contamination may be evident in some samples despite an environment little impacted by human activity.

The results of the integrated interpretation have been reflected in a preliminary hydrogeological map of the Las Loras UGGp (Figure 3) identifying: aquifer formations, hydraulic connection among them, interactions of groundwater with topography (caves, peatbogs, rivers), discharge points (springs, tuffs).

The conceptual hydrogeological model identifies a multilayer aquifer system in which the main aquifer is the deep Jurassic aquifer, presumably with continuity with outcrops of the same age to the N and NW of the Las Loras UGGp. Materials from the Upper Cretaceous that host the upper aquifers configure the outcrops of the moorlands (to the north of the Ubierna Fault) and the loras (to the south of it), giving rise to independent aquifers in which the springs are associated with the contact between limestone and marl, or less frequently, in the mechanical contact zone resulting from structural discontinuities. The carbonated materials of the Jurassic sediments make up the deep, semiconfined aquifer, whose piezometric level could be responsible for an upward flow providing permanent discharge into the riverbeds.

The moors located on the right bank of the Rudrón river (which includes Tubilla del Agua and Covanera-Pozo Azul) and the Bricia moorland (where Orbaneja del Castillo is located) are outside the current limits of the geopark. The right bank of the Pisuerga River presents geological, structural and geomorphological conditions different from those described here. These areas could be considered as extensions to the geopark.

Outstanding issues that require further study and resolution include the following:

(1) The depth of the Ubierna Fault and its subsurface architecture in relation to the sediments it intersects is unresolved. Given the critical importance of this feature, the resolution of these issues would enhance our understanding of the hydrogeology of the region.

(2) The characterization of the moorlands versus the loras allows one to clearly differentiate between them. However, confusion persists in cartography and toponymy, where both terms are used interchangeably, for example, Páramo de la Lora de Valdivia. This should be clarified.

(3) The definition of the hydraulic behaviour of the materials that make up the two aquifer systems identified in Las Loras UGGp (upper aquifer: Upper Cretaceous; lower aquifer: Jurassic), remains unresolved. The sediments of the Lower Cretaceous age have been interpreted as an aquitard but the direction of the groundwater flow path through it is unknown.

(4) The Upper Cretaceous outcrops of Las Loras UGGp do not present continuity with other Cretaceous outcrops in the broader region (the closest ones are found on the north coast within the province of Cantabria). Their association with the Jurassic aquifer at depth is unknown, and it is not ruled out that they may be connected due to the permanent nature of some of these springs and the limited surface area of the Cretaceous outcrops of Las Loras UGGp to provide sufficient recharge. The fact that the Lucio and Rudrón rivers constitute permanent rivers, whose channels are located at a lower level than the outcrops of the Upper Cretaceous, supports our hypothesis that these rivers receive an underground supply from the deep Jurassic aquifer. Further research is needed in order to characterize the Jurassic aquifer and its recharge and discharge areas. However, a hydraulic connection between the Jurassic limestone and the colluvial outcrop associated with the riverbeds is possible.

The inactive travertine outcrop located a few meters upstream from the Valdelateja Spa, on the left bank of the Rudrón River, has been recognised as a new potential important geosite with scientific, educational and tourism values. This outcrop should be added to the Geopark's geosites inventory.

The study of the hydrogeology of Las Loras UGGp is still ongoing and this preliminary assessment inspire new research projects. A deeper understanding of groundwater flow systems could be developed with isotope signatures. An advance in knowledge will contribute to improved strategies for management of the groundwater-related geoheritage of Spain and provide lessons for the world.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources12010014/s1, Table S1: Location of the sampled points and chemical analysis; Table S2: Descriptive statistics of the chemical analysis of the waters of Las Loras; Table S3: Geothermometers and hydrochemical facies.

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