KARMA

Karst **A**quifer **R**esources availability and quality in the **M**editerranean **A**rea

Design and implementation of the Mediterranean karst springs monitoring network

Deliverable 3.1

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Executive Summary

The project is structured into five work packages (WPs), led by different project partners, and pursue different goals attending to the framework scale. Advances in chemical water quality will be achieved through the tasks framed in **WP3**, which main objective is the acquisition of a deep understanding of key hydrogeological processes affecting karst groundwater quality across different scales, from single springs to aquifer/catchment. Thereby, Task 3.1 includes the installation of a high-resolution water-quality monitoring network at karst springs and other discharge points.

In order to accomplish the objectives established in WP3, novel research focused on water quality will be tested at five selected Mediterranean karst aquifers of distinctive geographical, geological and climatological contexts. These test sites selected for KARMA project show similar features regarding groundwater use (drinking water supply, crop irrigation) and face the same threats (pollution episodes, climate change).

In this document (D3.1) the design and installation, from each local partner contributing to Task 3.1, of single or multiple monitoring stations as novel demonstrators aiming to reduce natural and anthropogenic impacts on groundwater quality, with special focus on drinking-water infrastructures and national/international regulations for potable use is summarized.

Previous studies exist in all test sites from different times, most of them since decades and suppose a reliable starting point for this task. Thus, spring monitoring network can be easily improved or updated in order to accomplish the project requirements. This set of demonstrators include the characteristics of site-specific monitoring stations of all test sites, depending on its geographical, geological and hydrogeological features:

- Field devices: properly calibrated and installed will provide accurate information necessary to carry out the following tasks of WP3.
- Set-up: the equipment must be installed at specific points on the springs so that the physical-chemical properties are not altered. Weather stations also should be established in representative locations.
- Target parameters: climate (rainfall, air temperature), spring discharge and different physical-chemical (water temperature, electrical conductivity, major ions, water isotopes, faecal bacteria, enzyme activity and turbidity) parameters will be recorded.
- Measurement/sampling strategies and time frame: as far as possible, most of parameters will be measured in continuous. For those date acquired by single measurements, sampling frequency will be increased during rainfall events.

The gained knowledge will serve as a basis for an appropriate groundwater management and protection in such highly vulnerable aquifer systems. Specific goals include significant advancements in: a) at the scale of individual springs, developing and implementing monitoring and early-warning systems (EWS) for groundwater contamination, focusing on short-term contamination events, but also addressing long-term trends; and b) at the catchment or aquifer scale, advancing and comparing transferable modeling tools for improved predictions of climate-change impacts and better-informed water management decisions, and to prepare vulnerability maps as tools for groundwater quality protection. Hydrological monitoring, isotope studies and tracer tests will be carried out to achieve better hydrogeological understanding and to obtain data for the calibration and validation of models and vulnerability maps.

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1. Introduction

The overarching objective of the KARMA project is to achieve substantial progress in the hydrogeological understanding and sustainable management of karst groundwater resources in the Mediterranean area in terms of water availability and quality. WP3 is focused on water quality and includes the implementation and improvement of early-warning systems for spring-water contamination in collaboration with water companies, the application of vulnerability mapping and an assessment of groundwater-dependent ecosystems. The first step on the development of **WP3** consist on the installation of a high-resolution water-quality monitoring network at karst springs and other discharge or pumping points.

Climatic data such as rainfall and air temperature will be acquired through the installation of weather stations or those included in the state monitoring network, which also provide historical records. Karst spring discharge (input from WP2) or water level variations in boreholes and a wide range of physical, chemical and microbial parameters that condition water quality are controlled by means of on-site continuous measurements and water sampling:

- Water temperature (T), electrical conductivity (EC), dissolved oxygen (DO), turbidity and particle-size distribution (PSD) are measured continuously in most cases and by single measurements using adequate multi-parameter probes and data loggers.
- Total and dissolved organic carbon (TOC/DOC) are measured using conventional techniques and novel, fluorescence-based monitoring methods.
- Water chemistry (major and trace components) are measured in samples at event-based and seasonal timescales and analyzed using ICP-MS (all metals that typically occur as cations), IC (anions), titration (bicarbonate) and other methods where appropriate.
- Nitrate is a major concern in several of the karst aquifer test sites and is analyzed in samples (using IC).
- Microbial water quality is measured using conventional cultivation methods (MPN, Colilert) and novel online-monitoring techniques, such as β-D-glucuronidase activity using the mobile ColiMinder device.

At some of the selected springs and boreholes, additional parameters are already or will be measured, such as rare earth elements and other dissolved trace metals (ICP-MS), dissolved CO_2 and radon (^{222}Rn) gas. Recorded data and background information will be processed and advanced using numerical and statistical methods, in particular time-series analyses and artificial neural networks (ANN) to identify relations between relevant contaminants (e.g. fecal bacteria, pesticides) and parameters that can be measured continuously, such as rainfall, turbidity, TOC or nitrate.

The acquired data will also serve as an input for recharge area assessment, validating hydrological connections through traces test, and comparing obtained trends with historical records on WP2 as well as a basis for the calibration and validation of different modeling techniques on WP4. It also presents implications in the elaboration of MEDKAM and vulnerability maps at the scale of the Mediterranean area on WP5.

2. Gran Sasso Aquifer, Central Italy (Case Study Italy)

2.1. Field site description

The Gran Sasso aquifer is a karst-partitioned aquifer of about 700 km^2 (Celico, 1983; Boni et alii, 1986). It is one of the most representative karst aquifers of the Apennines because it contains huge groundwater resources usable for human purposes and it is characterised by a significant interaction between groundwater and underground works (tunnels and underground lab – Monjoie, 1980). Moreover, it hosts protected areas (natural parks and wetlands) with high environmental value.

The Gran Sasso hydrogeological system is composed of Meso-Cenozoic carbonate units (aquifer) referable to the "Platform laziale-abruzzese" to which are associated silico-calcareous-marly lithologies, of the same age, referable to the "Umbrian-Marche basin" (Accordi et alii, 1988). It is bounded by terrigenous units represented by Miocene flysch (regional aquiclude) along its northern side, and by Quaternary continental deposits (regional aquitard), along its southern side.

The stratigraphy and the structural elements affect the characteristics of the Gran Sasso calcareous complex, permeable for fracturing and karstification. Permeability limits are constituted to the main overthrust, located in the northern and eastern areas, with direction E-W and then N-S, dipping respectively to the South and West (Figure 2.1). The limits of the hydrogeological structure of the Gran Sasso aquifer are well defined on both the northern and eastern sides. However, it is still not well defined the limit in the southwestern area and in detail the relationships with the hydrostructure of Mt Sirente and Mt Morrone, giving rise to groundwater exchanges (Petitta & Tallini, 2002). The hydrogeological system can be divided into several hydrogeological complexes each characterized by a specific lithology and porosity, placed in contact with each other for stratigraphic and tectonic reasons. The hydrogeological complexes of the area take into consideration are:

- The complex of recent and ancient continental detrital deposits;
- The complex of recent continental debris Units;
- The complex of the ancient continental debris Units;
- The complex of marine terrigenous Units;
- Marly complex;
- Limestone complex;
- Dolomite complex

The Gran Sasso karst aquifer hosts a unique regional-wide groundwater table. This groundwater feeds the major basal springs, characterized by high and steady discharge rates (0.5-7 m^3/s) and located on the margins of the massif along the low permeability boundary, in contact between the carbonate rocks and the impermeable land sediments (Petitta et alii, 1994). The springs certainly fed by the Gran Sasso are located both on the northern side at altitudes above 1000 m but above all are concentrated on the southern one, with a total discharge of more than 18 m^3/s, corresponding to a net infiltration of more than 700 mm/year (Massoli-Novelli & Petitta, 1998). These springs have been organized into six groups based on groundwater flow and hydrochemical characteristics, as illustrated in Figure 2.1 (Amoruso, 2012). Discharge from the Gran Sasso springs has decreased significantly after tunnel excavation in the 1980s and subsequent groundwater drainage and probably also as a result of climate change (Dragoni, 1998; Massoli Novelli, 1997). In subsequent years (1996–2000), spring discharge has risen slightly, indicating that the aquifer groundwater, also thanks to drainage by the tunnels, has reached a new steady-state (Petitta, 2002).

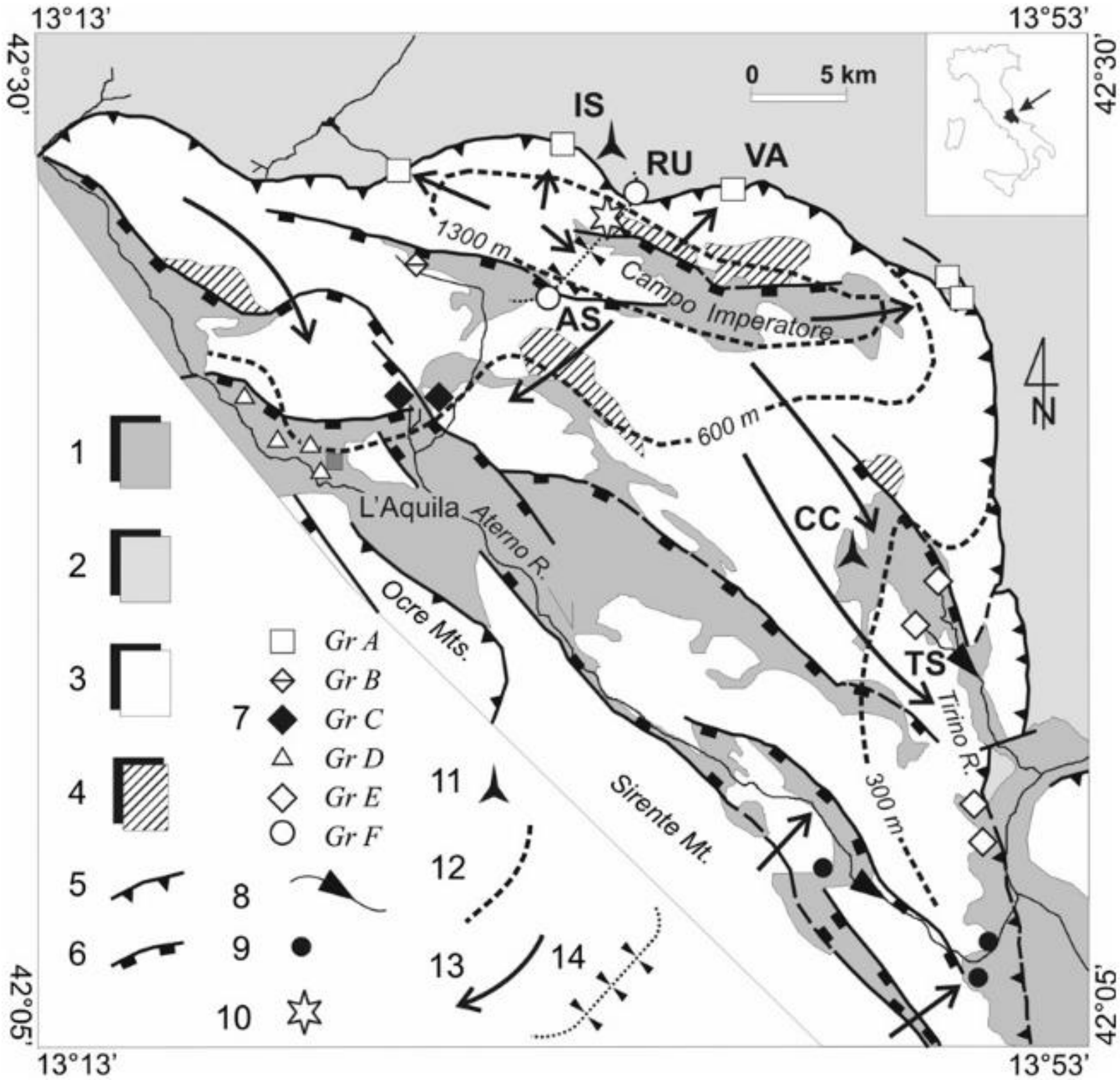


Figure 2.1: Gran Sasso hydrogeological outline. 1: aquitard (continental detrital units of intramontane basins, Quaternary); 2: aquiclude (terrigenous turbidites, Mio-Pliocene); 3: aquifer (calcareous sequences of platform Meso-Cenozoic); 4: low permeability substratum (dolomite, upper Triassic); 5: thrust; 6: extensional fault; 7: main spring: AS: Assergi drainage; RU: Ruzzo drainage; VA: Vacelliera spring: TS: Tirino springs; symbols refer to the six spring groups identified in Barbieri et al. (2005); 8: linear spring; 9: springs belonging to a nearby aquifer; 10: INFN underground laboratories (UL in the text); 11: meteorological station (IS: Isola Gran Sasso, CC: Carapelle Calvisio); 12: presumed water table in m asl; 13: main groundwater flow path; 14: highway tunnels drainage. (Amoruso, 2012).

At the massif core, an endorheic basin having tectonic-karst origin, called Campo Imperatore, acts as preferential recharge area of the Gran Sasso aquifer, fed by high rainfall and snow rate. The combination of intense rainfall with endorheic morphology gives rise to concentrated infiltration phenomena, where an important role is played by the level of fracturing, by the presence of vegetable coverings and by the characteristics and thickness of the soil. The preferential directions of groundwater flow are locally conditioned by the main tectonic discontinuities and are guided by the heights of the hydrogeological limits. In fact, most of groundwater is directed towards the most depressed sectors of the aquifer, where the limits of permeability are placed at lower altitudes, moving through a regional groundwater flow.

Taken into consideration the bibliographic data sets and the last flow-rate measurements (June-October, 2019), the main springs analysed having discharge consistency over time are the following:

- The *Vomano* river basin (that includes the group of *Chiarino* springs, the *Rio Arno* spring and the *Mavone* spring),
- The *Tavo* river basin (that includes the *Mortaio d'Angri* spring and the *Vitella d'Oro* spring),
- The *Tirino* river basin (that includes *Tirino Capodacqua & Presciano spring* and *Basso Tirino sprng)*
- The *Aterno* river basin (that includes the *Tempera*, *Capovera*, *Vetoio* and *Boschetto* springs).

The Figure 2.2 shows the position of the different springs taken into consideration, using the Google Map service. The springs, for easy recognition on the image, have been named by an abbreviation and listed in Table 2.1, clockwise starting from the North East.

Figure 2.2: Position of the different springs taken into consideration (Photo: Google Earth app).

Table 2.1: Name of the different springs analyzed with their abbreviation.

GS1	Chiarino	**GS9**	Vitella d'Oro
GS2	Rio Arno	**GS10**	Tirino S. Martino
GS3		**GS11**	Tirino Bussi Officine
GS4	Mavone	**GS12**	Tempera
GS5		**GS13**	Capovera
GS6	Ruzzo	**GS14**	Vetoio
GS7	Mortaio d'Angri	**GS15**	Boschetto
GS8			

2.2 Gran Sasso karst springs available data

The monitoring survey is usually performed mainly during the summer season, when the climatic conditions allow attributing the flow-rate measured to the drainage of the basal aquifer.

The instrument for the acquisition of the flow data of the springs is the magnetic induction flow meter, which directly supplies the speed of the water through sensors that are placed below the instrument without helix (Figure 2.3A). This instrument calculates the flow velocity as the hydrometric reel through the magnetic field variations induced by it. The counter is a small instrument connected to the magnetic flowmeter that each operator can keep on his neck by means of a small belt and is used to have flow data digitally (Figure 2.3B).

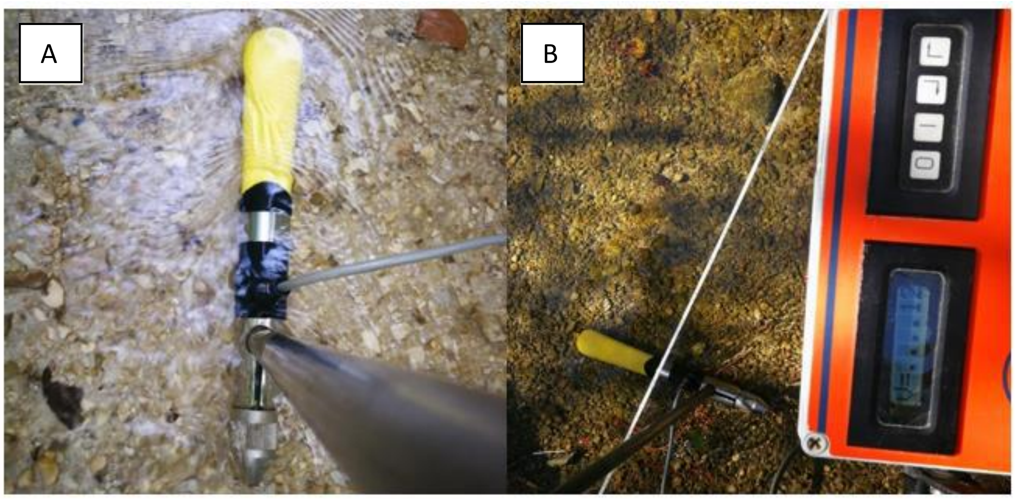


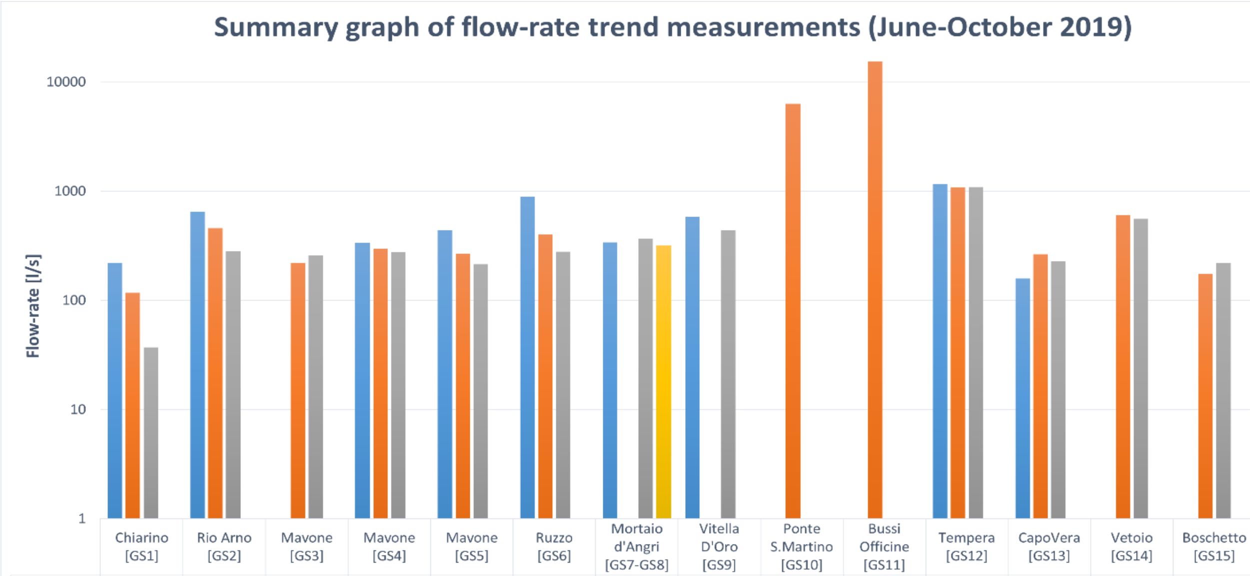
Figure 2.3: A) magnetic induction flow meter (Photo: Francesca Banzato); B) The counter connecting to the magnetic flow meter (Photo: Valeria Lorenzi).

In some cases, it is necessary to use a hydrometric reel for bridge measurements, for springs with a very high level of water as in the case of Tirino (Tirino Ponte S. Martino and Tirino Bussi Officine). (Figure 2.4). It is generally joined with hydrodynamic weights (currently called "fish"), to reduce its resistance to motion.

Figure 2.4: Photo of hydrometric reel for bridge measurements (Photo: Francesca Banzato).

The main springs have been measured monthly for several years in the 90s' and during the following decades, allowing the building of a robust conceptual model of groundwater flow (Petitta & Tallini, 2002; Barbieri et al., 2005; Tallini et al., 2013; and references herein).

The last hydrogeological monitoring survey was carried out in the period between June 2019 and October 2019 to verify and integrate the available data concerning the surface hydrology. The data obtained have made it possible to highlight the different discharge in the monitored sectors, and to verify the reliability of the literature data by knowing the current conditions of water flow-rate. Below is presented a summary graph (Figure 2.5) of the flow-rate values measured in the main springs of the Gran Sasso aquifer, studied during the monitoring survey, and their trend during the June/October 2019 period. The graph on the ordinates is in logarithmic scale, since the flow-rate measurements of the Tirino springs are higher than the other water flow-rate measures. Moreover, the amount of water withdrawn each month for drinking purpose has been added to the measured flow, obtaining the total flow rate.



	Chiarino [GS1]	Rio Arno [GS2]	Mavone [GS3]	Mavone [GS4]	Mavone [GS5]	Ruzzo [GS6]	Mortaio d'Angri [GS7-GS8]	Vitella D'Oro [GS9]	Ponte S.Martino [GS10]	Bussi Officine [GS11]	Tempera [GS12]	CapoVera [GS13]	Vetoio [GS14]	Boschetto [GS15]
June	219	649		335	439	888	339	582			1158	158		
July	117	459	219	297	269	402			6310	15358	1079	264	600	174
September	37	282	257	277	214	279	367	439			1090	227	557	220
October							316							

Figure 2.5: Summary graph of the flow-rate trend measurements from June to October 2019.

From the flow-rate measures taken in the springs previously analyzed during four months, it can be seen that the flow rates tend to decrease from June to September/October. This is confirmed by the fact that normally in the summer period the flow rates decrease due to the high temperature and the low precipitation value.

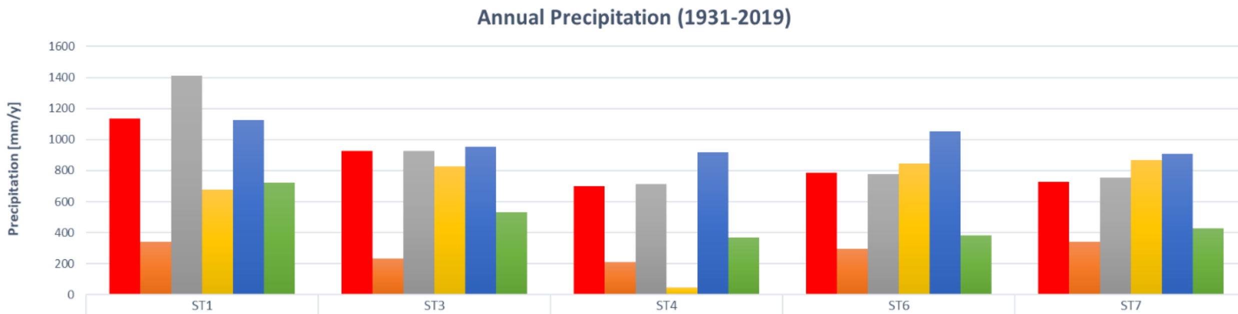
However, different behaviour affects the springs of Boschetto, Tempera and the spring located in Casale S. Nicola. In these springs, there have been some anomalies in discharge that seem to be caused by the influence of the motorway tunnel and its artificial drainage. In addition to this, the springs located in Casale S. Nicola are also influenced by two factors, the rupture of the surface-water collector channel (Canale di Gronda) and the amount of groundwater released by the motorway drainage tunnel, which could have caused anomalous discharge.

In addition to the problems mentioned above, it should also be noted that all the springs analysed are influenced by karst features. For these reasons, depending on the degree of karst of the recharge areas of each spring, there is a variability in the response to the rainfall variations. This can be seen especially in the Vitella d'Oro spring, which is the more affected by the karst conditions.

The groundwater collected by the drainage of the motorway tunnel in the Gran Sasso hydrostructure is used for drinking purpose. The artificial drainage, operated by the tunnel for a total flow of about 1500 l/s, lowered the level of the water table, leading to a change in the piezometric levels mainly in the area close to the axis of the tunnel. This condition affected in detail the springs of Tempera and Capovera, on the L'Aquila side, and that located in Casale S. Nicola, on the Teramo side. The construction of the motorway tunnel has therefore caused changes in the hydrogeological structure of the massif due to the adjustment of the hydrodynamic situation to the presence of these important underground drains.

The main chemical-physical parameters of the water, such as precipitation, temperature, and electric conductivity are collected and processed. The knowledge of the thermometric regime of the area under examination has been obtained thanks to the data relative to different pluvial-thermometric stations of the Abruzzo’s Servizio Idrografico from 1931 to 1997 (Banzato, 2005). The analysis of the rainfall data shows a general influence of the Apennine system on the distribution of rainfall. All stations show an Apennine rainfall climate with a maximum in November and a minimum in July. Rainfall is higher on the Teramo side than on the Aquila side and increases with altitude. The temperature is greatly influenced by external ones and the electric conductivity that increases with the decrease in altitude, indicating possible participation in a deeper hydrological cycle. The annual distribution of conductivity and temperature values of springs is very wide. The temperature fluctuates between 4 °C and 8 °C on average, which is evidence of surface circulation. The electric conductivity values are medium-low (200-300 μScm^{-1}) and confirm a limited water-rock interaction, typical of shallow aquifers.

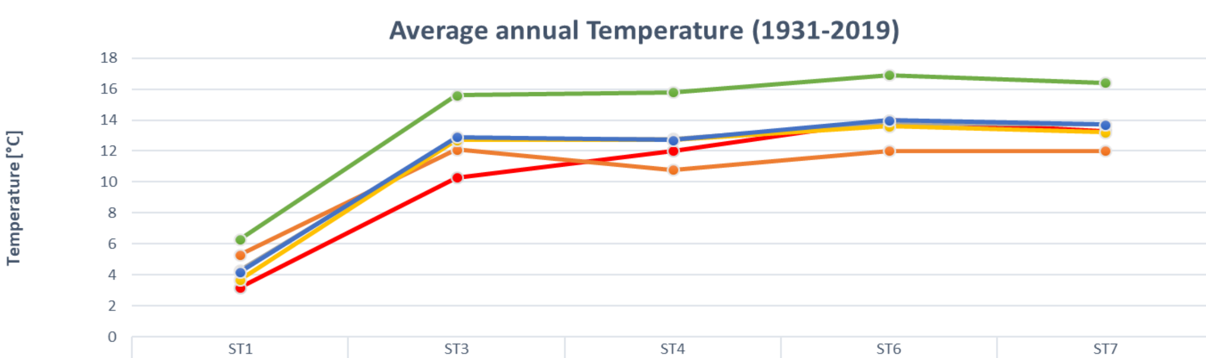
In addition to bibliographic data relative to different pluvial-thermometric stations of the Abruzzo’s Servizio Idrografico from 1931 to 1997 (Banzato, 2005), it has been possible to evaluate the maximum and minimum value of temperature and precipitation also for the period between 2015 and 2019, obtained from Regione Abruzzo database. The eight thermopluviometric stations, uniformly distributed in the study area, taken into consideration are: Campo Imperatore, S.Elia, Assergi, Centro Funzionale all' Aquila, Pizzoli, Ponte sul Tirino, Zona Industriale a Popoli, and Tossicia, identified by the acronyms ST1 to ST8 respectively. It has been taking into consideration also the temperature and precipitation data obtained from the thermopluviometric stations during the years 1931 to 1997, in particular the thermopluviometric station of Campo Imperatore (ST1), Assergi (ST3), L’Aquila (ST4), Bussi Officine (ST6) and Popoli (ST7) and compared them to the years from 2015 to 2019. The rainfall values from 1931 to 1997 are more intense than the year 2015 and the year 2019 and more similar to the values of 2016 (Figure 2.6).



	ST1	ST3	ST4	ST6	ST7
1931-1997	1137	925	698	788	726
2015	340.6	233.6	209.6	294	340.6
2016	1412.2	926.8	712.3	777.4	753
2017	676	827.2	48.4	845.2	865.8
2018	1126.8	952	917	1054.2	910.4
2019	723.8	531.8	369.5	381.6	429.2

Figure 2.6: Annual precipitation trend, comparing the average values of precipitation during the years 1931 to 1997 and the precipitation data of the years 2015, 2016, 2017, 2018 and 2019.

The average values of temperature relating to the years from 1931 and 1997 have a similar trend of the years 2016, 2017 and 2018. Moreover, compared to the data of the year 2019, it can be observed that the values of the temperature of the years 1931-1997 are lower than 2019 (Figure 2.7).



	ST1	ST3	ST4	ST6	ST7
1931-1997	3.2	10.3	12	14	13.3
2015	5.3	12.1	10.8	12	12
2016	4.3	12.7	12.8	13.8	13.7
2017	3.7	12.7	12.7	13.6	13.2
2018	4.2	12.9	12.7	14	13.7
2019	6.3	15.6	15.8	16.9	16.4

Figure 2.7: Annual temperature trend, comparing the average values of temperature during the years 1931 to 1997 and the temperature data of the years 2015, 2016, 2017, 2018 and 2019.

According to Banzato et alii (2011), for the characterization of carbonate aquifers, due to the morphology of mountain reliefs, in addition to the data collected must be taken into consideration also the meteoric inflow due to the variability of snowpack in the recharge area. The evaluation of the volumes of water that are stored in the Gran Sasso aquifer according to the melting of the snow is a fundamental parameter for the characterization of the relationships between the recharge and the groundwater resources delivered in the main springs. Through the detailed analysis of climatic parameters (temperatures, rain and snow), the recharge of aquifers by precipitation has been quantified and the regime of annual and multi-year variability has been analysed. Only by comparing the variations in piezometric levels and the flow-rate supplied by the aquifers is it possible, therefore, to determine the influence on the groundwater regime (Scozzafava et alii, 2001).

Snow generally falls to the ground in the period between the end of December and the months of February/March with thicknesses ranging from a few tens of centimeters to more than one meter (Banzato, 2005). Generally, the snow cover remains on the ground between December and April, when the rise in temperatures allows a rapid melting, which is also a function of the reached thickness. From the analysis carried out by the authors on the snowfall of nine measuring stations located in the Gran Sasso area, it is evident that it represents 10% of the total annual precipitation at an altitude of 500 m a.s.l. and reaches 50% of total precipitation at 2100 m a.s.l. The values of precipitation at high altitudes, where in the winter months snow fall is prevalent, do not appear reliable when recorded by thermopluviometric data, not very suitable for measuring solid precipitation. A different approach has been adopted to obtain the data of the snowpack using the method of remote sensing and the technique of photo-interpretation. By these data, therefore, it was possible to evaluate the variability in terms of area sizes of snow coverings at different altitudes and also evaluate the persistence. The satellite photos used to obtain the values of the quantity of snowpack in the Gran Sasso area come from *Sentinel-2, Landsat 8* and *Modis* (Matani, 2015). Obviously, this type of technique also has limitations regarding the time of review of the satellites is the same area and therefore the number of photos available for analysis.

Further information on the hydrogeology of the Gran Sasso has been derived from the analysis of the chemical-physical data and the chemical composition of the spring water. The observations on the chemical composition of the Gran Sasso's spring water come from a database of about 500 chemical analyses of the major elements, mostly carried out during the construction of the tunnel, but also specifically carried out within the activities of the Gran Sasso Research Consortium (Tallini et alii, 2000a). A substantial homogeneity of the waters (Figure 2.8) shows alkaline bicarbonate chemical composition, with a prevalent enrichment of the calcium ion, expected for a carbonate aquifer. There are no significant differences in the chemistry of the spring water, but by a more detailed examination of the chemical characteristics some minor significant differences appear. On the basis of electrical conductivity and temperature values, the hydrogeological context and the location of the springs, it was possible to divide them into six main groups, each with common characteristics. The study did not reveal substantial differences in the chemical-physical parameters of spring water on an annual scale, while for some emergencies seasonal trends are clearly observable (Barbieri et al., 2005).

The relationships between the different groups of springs in the massif, highlighted by the results of hydrochemical sampling, confirm a regional groundwater flow from the center of the massif towards the periphery, influenced by the structural geology, the development of karst features, the outcropping of the dolomitic low-permeability bedrock, the influence of local recharge and the geological conditions close to the springs. Groundwater chemistry also was altered by water/rock interactions in hydraulically connected alluvial aquifers and by anthropogenic activity at the aquifer boundaries.

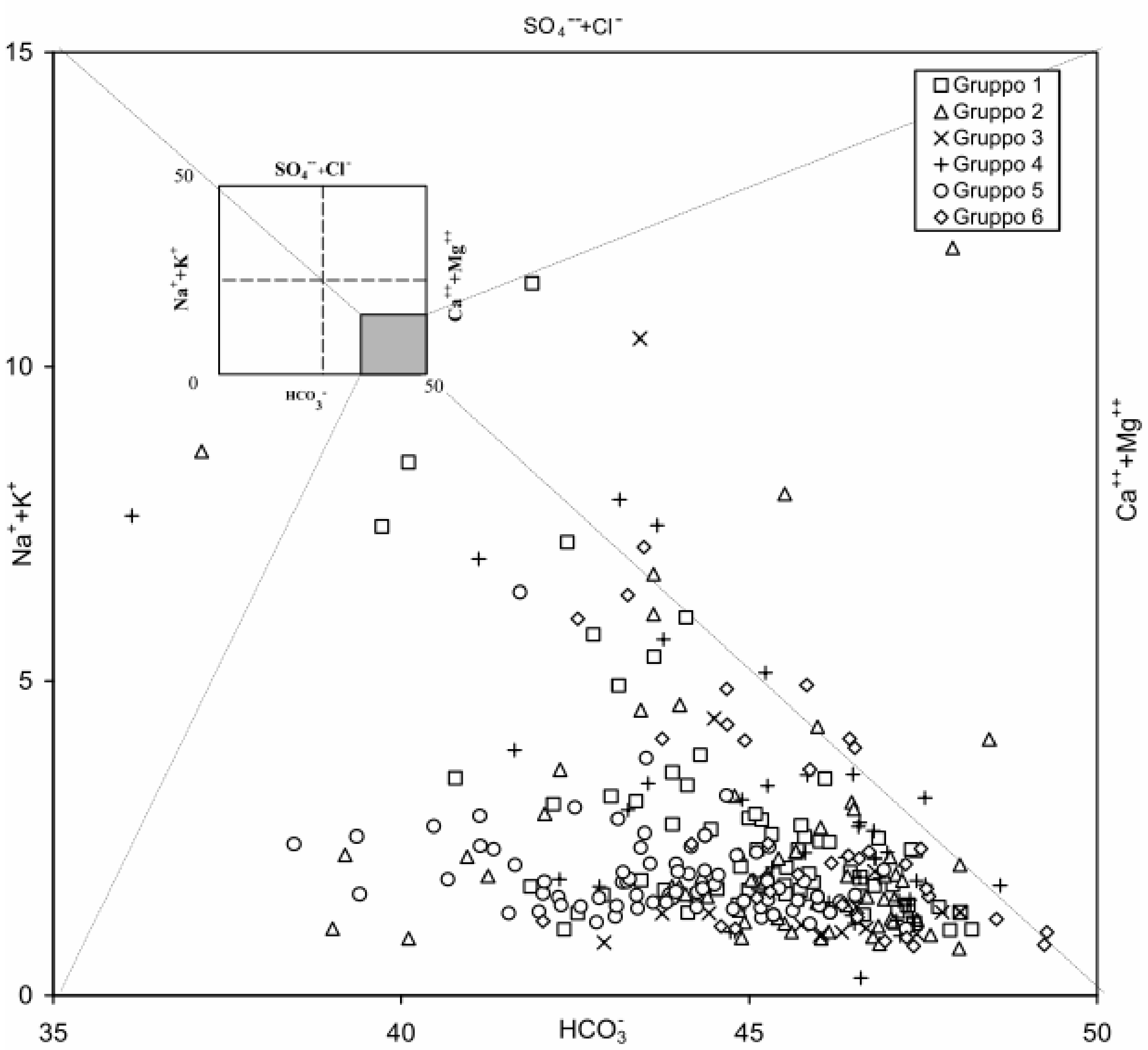


Figure 2.8: Diagram for the Gran Sasso springs. The values reported in the diagram refer to all the data measured during the 1970- 1999 period (Barbieri et al., 2005).

2.3 Gran Sasso karst springs monitoring network

For building the monitoring network, the main springs of the Gran Sasso aquifer will be taken into consideration are divided into six groups according to their hydrochemical and hydrogeological characteristics, as can be seen in Table 2.2. The value of the elevation, temperature, electrical conductivity and flow rate for each spring are also reported in the same Table. The springs are monitored mainly for drinking and hydroelectric purpose.

Table 2.2: Gran Sasso springs. The average temperatures and el. Conductivity values refer to the 1970-2000 period. The average discharge values refer to the 1970-1990 period (groups 1 and 2) and the 1994-2000 one (groups 3, 4, 5 and 6). Standard Deviation (Dev. St.) is not shown for data sets including less than 5 values (Petitta et al., 2002).

Class.		Sorgente	Quota [m s.l.m.]	Temperatura [°C] Valore medio	Temperatura [°C] Dev. St.	Conducibilità El. [µS/cm] Valore medio	Conducibilità El. [µS/cm] Dev. St.	Portata [$m^3 s^{-1}$]
Gruppo 1	S1	CHIARINO	1315	5,7		306		0,08
	S2	RIO ARNO	1524	3,9		310		0,1
	S3	S. NICOLA I	1600	7,6	3,44	271	46,87	0,116
	S4	S. VITTORE I	1600	7,0	3,36	305	45,93	0,156
	S5	S. VITTORE II	1500	6,1	2,76	198	16,46	0,052
	S6	ACQUA ZETA	1400	6,7	2,28	278	33,97	0,006
	S7	LAMA BIANCA	1300	5,4	0,82	198	18,37	0,055
	S8	FIUMETTE	1530	5,4	2,17	214	17,35	0,052
	S9	RUZZO	750-1600	5,5		298		0,3
	S10	MORTAIO D'ANGRI	650	7,4		263		0,28
	S11	VITELLA D'ORO	690	7,5		216		0,38
Gruppo 2	S12	ACQUA SANTA	730	10,1	0,34	418	24,78	0,042
	S13	FONTE DELLA FORMA	1000	10,9	0,73	300	18,93	0,004
	S14	VAGNATORE	900	9,3	0,97	333	21,23	0,007
	S15	SPUGNA II	940	9,6	1,14	363	26,37	0,0054
	S16	S. PIETRO	1150	9,5		295		0,0001
	S17	COSTA LATA	1010	7,2	0,45	199	8,85	0,0052
	S18	SANTA MARIA	900	7,9	0,60	254	14,52	0,041
	S19	ACQUAGROSSA	1200	11,0	3,64	208	14,20	0,0035
	S20	FONTE ANNORSI	1157	10,0	1,27	238	14,90	0,0016
Gr.3	S21	TEMPERA	650	7,8	0,47	237	13,25	0,8
	S22	VERA	650	7,9	0,48	238	10,88	0,19
Gruppo 4	S23	SCENTELLA-COLLE	694	10,9		561		0,002
	S24	FONTANILE S. GIORGIO	669	14,7		587		0,005
	S25	F.TE VECCHIA-S. VITTORINO	675	13,3		512		0,0001
	S26	COLLETTARA	710	12,0		602		0,0005
	S27	FONTE ARCONI - CESE	685	10,4		621		0,0002
	S28	S. GIUSTA-SASSA	677	12,6		772		0,0001
	S29	CASA MANNETTI	670	10,8		688		0,0001
	S30	VETOIO	640	10,7	2,06	459	17,77	0,43
	S31	BOSCHETTO ITALTEL	625	14,1	1,07	412	61,78	0,22
	S32	CASA BUCCELLA	630	11,2		443		0,02
	S33	SIDIS-STAZ. L'AQUILA	634	12,4		472		0,025
	S34	99 CANNELLE	635	11,6		580		0,05
Gruppo 5	S35	CAPO D'ACQUA	340	10,6	0,51	499	28,15	2,8
	S36	PRESCIANO	336	11,1	0,57	570	26,84	1,9
	S37	FRANCESCHELLI	327	11,4		392		0,02
	S38	GRUPPO DEL VIALE	325	11,3		385		0,025
	S39	SCASTELLO	315	11,4		388		0,05
	S40	FONTANELLE	310	11,2		380		0,4
	S41	BASSO TIRINO	300	12,0		544		5,5
	S42	S. CALISTO	300	11,6		560		2
	S43	S. LIBERATA	255	11,5		530		0,5
	S44	CAPO PESCARA	270	12,0	0,40	513	33,66	7
Gr. 6	S45	LATO L'AQUILA [PR. 0-5000m]	967	6,1	0,46	223	72,91	0,45
	S46	LATO TERAMO [PR. 5500-7000m]	964	5,0	0,33	227	84,35	0,9
	S47	LATO TERAMO [GALLERIA SERVIZI]	900	5,0	0,33	233	99,80	0,15

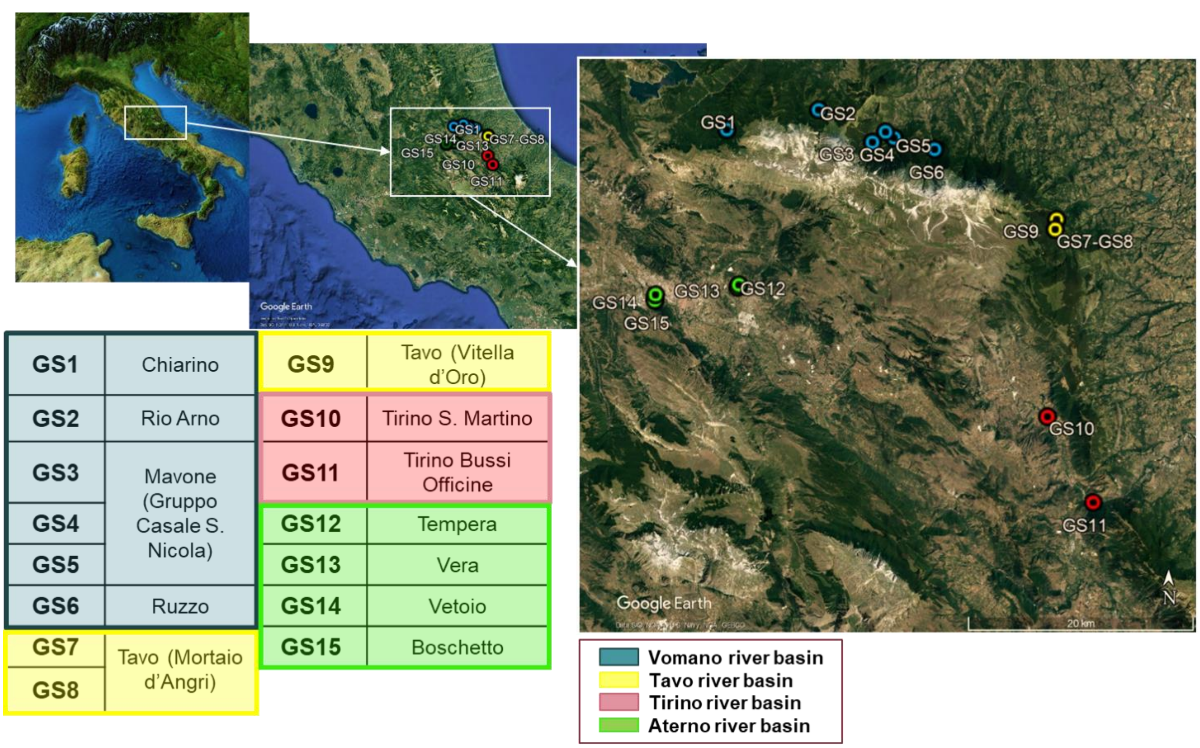
The springs of Group 1 and its tributaries are used for the production of electricity, for drinking purposes and irrigation purpose. The result is a very complex hydrological picture, in which the natural conditions of the springs and the flow of surface water have been influenced by human waterworks. The Vomano river basin, that includes Chiarino e Rio Arno springs, is one of the most important and complex hydropower systems in the region, which is regulated by the artificial lake of Campotosto. The ENEL water diversion project, launched in 1946, collects the outflows of the springs located on the northern sector of the Gran Sasso chain. ENEL's diversion works originate from the *Ruzzo* springs. The diversion is carried out through intake works that convey the water into a canal, mainly excavated underground, for the supply to the Rio Arno and to the hydroelectric power plant.

The Mortaio d'Angri and Vitella d'Oro springs are the two main springs of the Tavo river basin, located at the north-east boundary of the Gran Sasso aquifer. Since both are affected by water turbidity of the water, they require some preliminary treatment to be used for drinking purposes.

The springs of Group 2 are mainly used for irrigation purposes or to provide fountains. The Group 3 of the springs, located south-west of the aquifer, are currently used downstream for irrigation and industrial purposes, overlapped by the presence of small fish farming sites, which are fed by the main Group 4 springs. The springs of group 5 are located in the Tirino river basin, whose waters are immediately used for the hydropower-industrial purpose by private companies. For example, the spring of Capodacqua is used for the production of electricity through artificial damming and, in summer, for irrigation. Instead, the one downstream of the village of Bussi, known in the literature as the spring of Basso Tirino, is completely diverted by the industrial complex of Bussi Officine (Boni et al., 1986). The Group 6 refers to the drainage of the Gran Sasso motorway tunnel, built-in 1970, created local changes in groundwater hydrodynamics. This articulated drainage and collection system prevents the strong water pressures around the tunnels and therefore ensures the preservation of the lining structures of the highway tunnels themselves. Drainage points and water exploitation around the tunnels and at the foot of the excavation were then built to ensure the stability of the fault. The drainage waters are used for drinking water on the L'Aquila and Teramo sides of the massif, with consequent deficit of groundwater from some high elevation springs.

For more accurate monitoring of the main springs of the Gran Sasso aquifer, four OTT type dataloggers are being ordered to monitor water level, temperature and electrical conductivity. It was therefore decided to set the dataloggers in at least one spring for each spring group. The intention is to monitor one representative spring for each river basin, as shown in Figure 2.9.

The spring to be considered for the monitoring has not yet been selected, but it will be subsequently agreed and confirmed during the surveys that will take place in the coming months.



GS1	Chiarino
GS2	Rio Arno
GS3	Mavone (Gruppo Casale S. Nicola)
GS4	Mavone (Gruppo Casale S. Nicola)
GS5	Mavone (Gruppo Casale S. Nicola)
GS6	Ruzzo
GS7	Tavo (Mortaio d'Angri)
GS8	Tavo (Mortaio d'Angri)
GS9	Tavo (Vitella d'Oro)
GS10	Tirino S. Martino
GS11	Tirino Bussi Officine
GS12	Tempera
GS13	Vera
GS14	Vetoio
GS15	Boschetto

Figure 2.9: Location of the main springs of the Gran Sasso karst aquifer (Photo: Google Earth app.).

The electrical conductivity values must always be recorded in parallel with the temperature values. In addition, measurements of these parameters can also be carried out using two existing multiparameter well probes, installed in two different piezometers in 2014 in the Bussi Officine area (Barberio, 2018), respectively an OTT ecoLog 800 (Figure 2.10a), and a STS DL/N (Figure 2.10b).

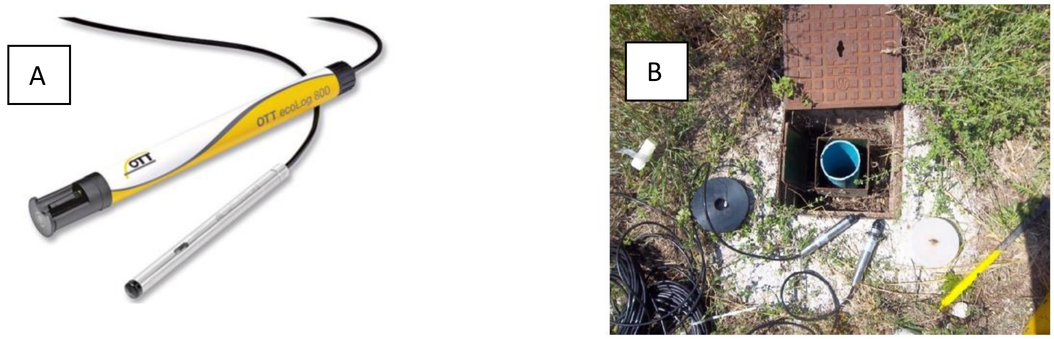


Figure 2.10: A) OTT ecoLog 800 probe (www.ott.com); and B) STS DL/N probe (Photo: Domenico Barberio).

The OTT ecoLog 800 is a device that allows continuous monitoring of the piezometric level (resolution 0.001 m, error ±0.05%), temperature (resolution 0.01 °C, error 0.1 °C) and electrical conductivity (resolution 0.001 mS/cm, error ±0.5% of the measured value). The device can store data in an internal memory and/or perform remote data transfer. The remote data transfer is carried out through a connection of the probe via GPRS, thanks to the use of a telephone SIM card, to a server located at the Earth Science Department and which can be accessed via desktop computer or mobile device at any time and from any place. The STS DL/N probe is a device similar to the previous one that allows the measurement of piezometric levels and temperature (Barberio, 2018). However, this probe is not equipped with sensors for measuring conductivity, nor with a device for the remote transmission of data, which are consequently stored in the internal memory and need to be downloaded manually. The two piezometers systems are installed in the same location, but they reach different depths and are flared at different depths.

As far as geochemical monitoring is concerned, the chemical-physical parameters can be measured in situ using the WTW Multi 350i multiparameter probe (Figure 2.11), in addition to the samples taken for the various laboratory analyses which will be taken following standard sampling procedures.

Figure 2.11: WTW Multi 350i multiparametric probe (Photo: Valeria Lorenzi).

This approach for geochemical monitoring was carried out for the springs of the Monte Morrone carbonate aquifer, which is closeby the Gran Sasso Aquifer, at its south-east boundary (Barberio, 2018) (Figure 2.12).

Sampling was carried out by monthly surveys since December 2015 until July 2018. For each spring the values of temperature, electrical conductivity and pH were measured and samples were taken for the analysis of the major and minor elements. Also, data were acquired and processed on the concentrations of Radon dissolved in water continuously recorded (every 10 minutes) at the Giardino spring to study the role of Radon as a seismic precursor. The data used in the study were recorded by the AlphaGUARD probe (Figure 2.13).

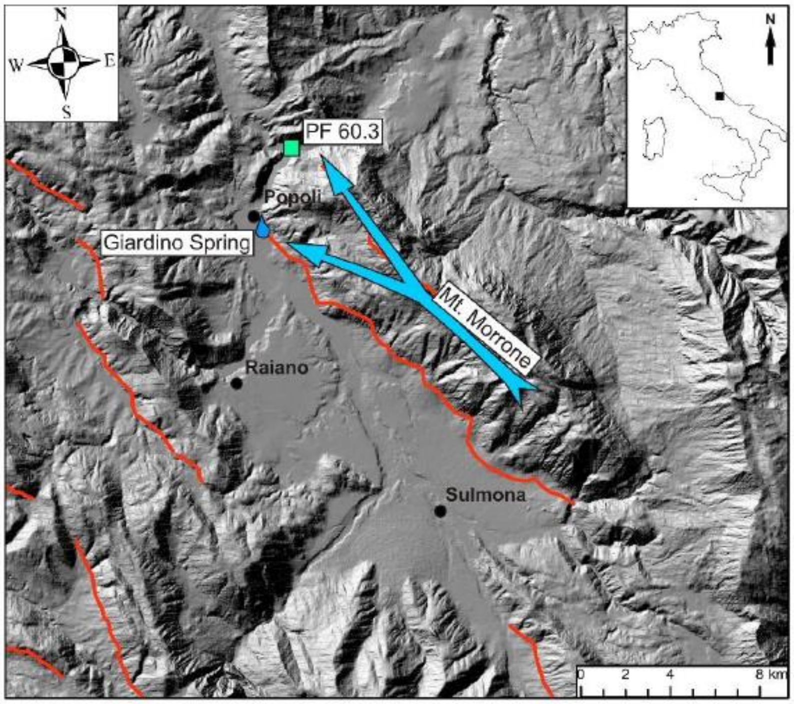


Figure 2.12: Map of Central Apennines (see location in upper right inset). Active faults (all extensional) are from the Ithaca database [36]). The base digital elevation model is from the ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) database SINAnet [37]). The location of the well (PF 60.3) and Giardino Spring, monitored in this work, are displayed with blue and green symbols, respectively. The blue arrow indicates the principal groundwater flow path of the Mt. Morrone aquifer (Barberio., 2018).

Figure 2.13: AlphaGUARD probe (www.bertin-instruments.com).

AlphaGUARD is a compact portable device able to constantly measure the concentration of Radon (for values between 2 and 2,000,000 Bq/m^3), with high storage capacity. In addition to the Radon concentration in the water, it simultaneously detects the ambient temperature, relative humidity and atmospheric pressure using specific sensors. By combining Radon monitoring with these associated environmental parameters, it is possible to draw valid conclusions regarding the spatial and temporal distribution of the gas. The same type of geochemical monitoring can also be performed in one of the springs of the Gran Sasso aquifer. Even if the Morrone aquifer the Gran Sasso aquifer are different, it is possible to carry out a study on radon (^{222}Rn), a radioactive isotope with a half-life of 3. 8 days, to evaluate the recharge dynamics of karst aquifer under varying hydrological conditions, in addition to the fact that both are affected by seismic activity.

We have also ordered in February 2020 the Albillia continuous flow field fluorometer for the realization of the tracer test sin spring and therefore to have continuous monitoring for different tracers (Figure 2.14).

Figure 2.14: Left: surface probe (FL30); Right: downhole probe (FL24) (www.albillia.com).

The best time to apply this type of technique in the Gran Sasso karst aquifer is probably during the maximum discharge when the snow melting begins, between April and June. Based on the data collected on the springs, it was agreed to start this monitoring activity at smaller local springs, and then expand this type of technique at wider scale. The spring selected for tracer test is Vitella d'Oro, which shows a mature karst system, characterized by the flow of water in karst pipes in most of its path. In addition to the Vitella d'Oro spring, the Mortaio d'Angri spring could also be considered. The analysis of the flow rates and the comparison with the precipitations highlighted the karst regime of the springs and the existence of some karst conduits that overlap the basal flow. Subsequently, if there will be the possibility to expand the area to be investigated with tracer tests, the area of Campo Imperatore will be selected. This endorheic plain, in the westernmost sector, is directly connected with the drainage of the Gran Sasso motorway tunnel. Otherwise, an alternative location for large tracer tests would be the area further east of Campo Imperatore, which is not directly connected with the tunnel (Figure 2.15).

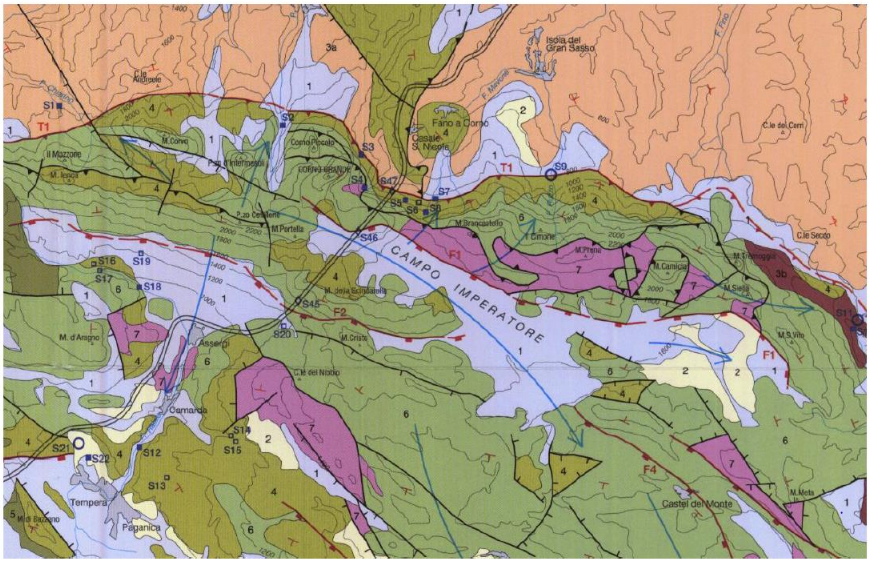


Figure 2.15: the crop from the hydrogeological scheme of the Gran Sasso massif the area of Campo Imperatore (Petitta et alii, 2002).

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3 The Qachqouch aquifer (Case Study Lebanon)

3.1 Qachqouch Spring

Qachqouch Spring (Figure 3.1, Figure 3.2a), is located within the Nahr el Kalb Catchment, and originates from the Jurassic karst aquifer at about 64 meters above sea level. During low flow periods, the spring is used to complement the water deficit in the capital city Beirut and surrounding areas. Its total yearly discharge reaches 35-55 Mm^3 based on high resolution monitoring of the spring (2014-2019; Dubois et al., submitted, Dubois, 2017). Flow maxima reach a value of 10 m^3/s for a short period of time following flood events; it is about 2 m^3/s during high flow periods and 0.2 m^3/s during recession periods.

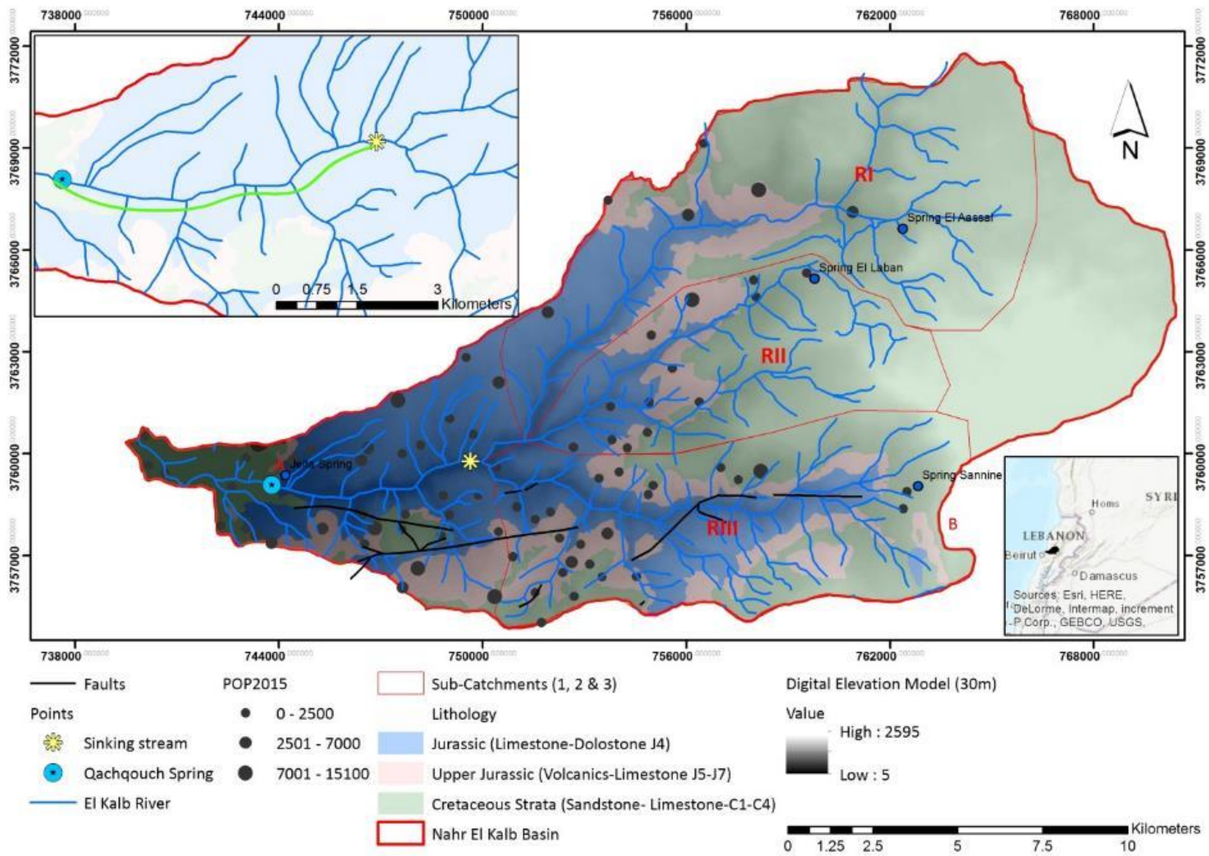

Figure 3.1: Investigated Spring (Qachqouch) and River (Nahr el Kalb) watersheds showing the relationship between a sinking stream on the River and the spring (Aoun, 2019).

Figure 3.2: A) Qachqouch spring during high flow (Photo: Joanna Doummar, February 2020); B) Nahr el Kalb River- a pressure transducer was installed in November 2019 (Photo: Jihad Othman, January 2020).

3.2 Nahr El Kalb – Dog River

Nahr El Kalb River (Figure 3.2b) is originating from springs in the highlands of Kesrouane area, in addition to interflow and runoff occurring shortly after rain events and snowmelt. Its catchment is about 249 km^2, and extends from the outlet of the River on the coast to about 22 km to the east in the Lebanese Mountains (Aoun, 2019). Its southern and northern boundaries were delineated based on topography highs. The river consists of three sub-catchments (RI -Nahr El Salib; RII-Nahr el Ouadi, and RIII- Nahr Abou Mizane; Figure 3.1) joining together to form the main branch of the River (Figure 3.1). Its peak discharge reaches a maximum of 22 m^3/s, with a yearly discharge volume of 80.0- 230 Mm^3 (based on River measurements from 2014-2017; Doummar and Aoun, 2018b, Aoun, 2019).

3.3 Catchment Monitoring, Data Collection, and Analysis

3.3.1 Data Collection and monitoring

Monitoring data is currently being collected on the Qachqouch catchment (including River and spring; Figure 3.3) as follows (Table 3.1). Table 3.2 presents the sampling and frequency of laboratory analysis.

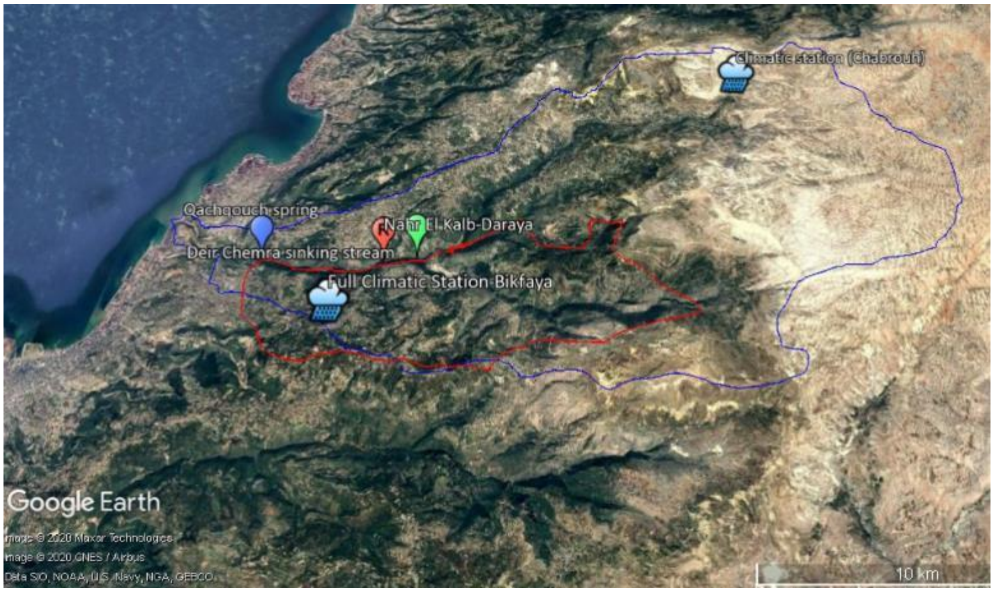

Figure 3.3: Schematic map showing the distribution of equipment on the catchment of Nahr El Kalb and Qachqouch spring (Photo: Google Earth app.).

3.3.2 Rationale for data monitoring: Input and Output

- Climatic stations for the measurement of precipitation (including snow) at two different altitude (950 and 1700 m above sea level) for the assessment of potential evapotranspiration and input precipitation (frequency of 15 -60 min)
- Flow monitoring in both River and spring is done using pressure transducers for water level measurement. Discharge is estimated using a rating curve based on monthly measurement of discharge. Concerns arise during high flow where accessibility to both spring and River is constrained.
- *In situ* physico-chemical parameters are measured with a multi parameter probe (for EC, Temperature, Turbidity and pH, and Dissolved oxygen) installed on the spring
- An automatic sampler scheduled every 3 days to collect samples for the spring for the following analysis:
  - Stable Isotopes (Oxygen and Deuterium) for WP2 and recharge analysis (3-days basis)
  - Major ions (including heavy metals) on a weekly basis for water types and pollution assessment (occasionally to weekly)
  - Bacteriological analysis on a weekly basis for the tracking of bacteriological evolution in River and spring (weekly)
  - Particle size distribution for the assessment of suspended particles leading to turbidity (3 days basis)
- A field fluorometer installed at the spring for the upcoming tracer experiments to be conducted in both River and doline as injection points.
- Potential additional equipment might include a real time logging with telemetry of parameters at the spring (to be installed) for the purpose of Early Warning System implementation.

Table 3.1: Collected data from the monitoring equipment, frequency and duration of monitoring.

Data monitoring	X Y Z (WGS; 1984)	Equipment specifications	Frequency of monitoring	Time frame And Funding Project
Precipitation and other climatic series (Rain; no heated gauge, humidity, wind speed and direction, net radiation, temperature)	Bikfaya 33.918003°N 35.676299°E 950 m asl	HOBO full climatic station (Figure 3.4a)	15 min	Continuing (since 2014) USAID (PEER Science; 2014-2018)
Precipitation and other climatic series (precipitation and snow equivalent; heated gauge; humidity, wind speed and direction, net radiation, temperature)	Chabrouh 34.025252°N 35.835905°E 1700 m asl	Campbell Scientific Alpine version (Figure 3.4b)	60 min	Continuing (since 2015) USAID (PEER Science; 2014-2018)
River water level, and temperature	Daraya 33.946700°N 35.689756°E 343 m asl	Insitu (level troll 400)	2 hours	Nov, 15, 2019- continuing University Research board (URB-AUB-2019-2021)
River flow		1) Discharge app 2) Electromagnetic flow meter (Valeport) (Figure 3.5b)	Monthly	Nov, 15, 2019- continuing (URB-AUB-2019-2021)
Spring discharge (Qachqouch)	Qachqouch 33.943985°N 35.637690°E 60 m		Monthly	Nov, 15, 2019- continuing (URB-AUB-2019-2021) USAID (PEER Science; 2014-2018)
Spring water level	Qachqouch 33.943985°N 35.637690°E 60 m	Insitu (Aquatroll)	30 min	Sept 2014- continuing USAID (PEER Science; 2014-2018)
Electrical Conductivity, Temperature, Turbidity, and pH			30 min	Sept 2014- continuing USAID (PEER Science; 2014-2018)
DO			30 min	Sept 2018- continuing USAID (PEER Science; 2014-2018)
Automatic sampler for grab sample analysis		Hach Sigma (1-Liter bottle) (Figure 3.5a)	Every 3 days	Nov 27, 2019- continuing (URB-AUB-2019-2021)
Field Fluorometer		Albilia surface model GGUN (718)	15 min	March 2020-ongoing (URB-AUB-2019-2021)

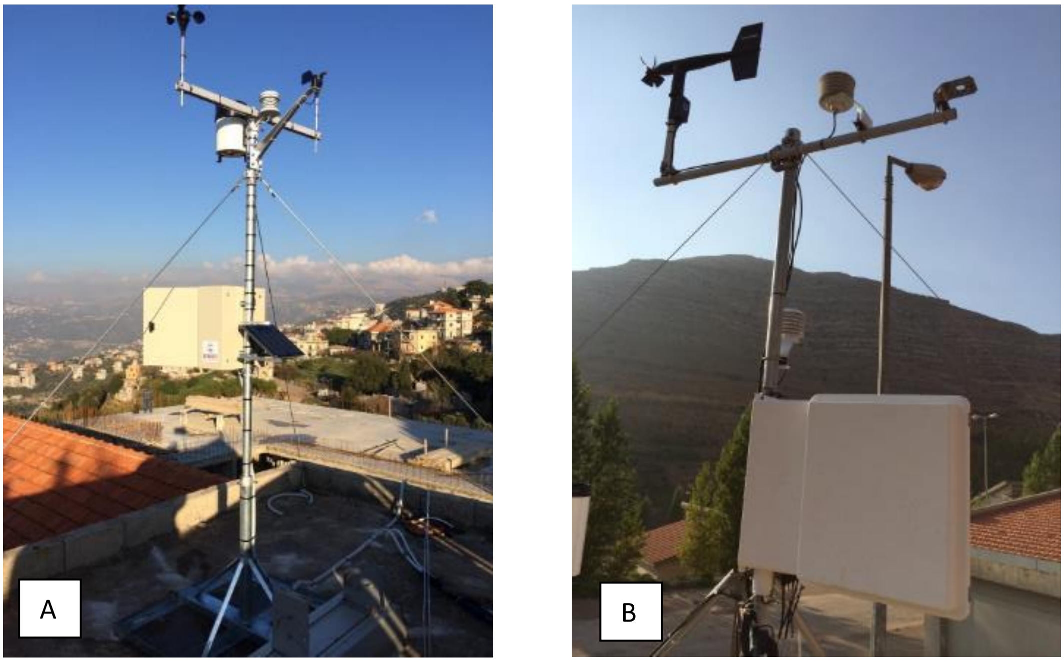

Figure 3.4: A) At 950 m (asl) installed in the framework of a USAID (PEER Science supported project); and B) Climatic Station at 1700 m (above sea level; asl). (Photos: Joanna Doummar).

Figure 3.5: A) Automatic sampler (Sigma Hach) for water sampling every 72 hours (Photo: Joanna Doummar); B) flow measurements using a Valeport electromagnetic portable velocity meter (Photo: Michel Aoun).

Table 3.2: Laboratory analysis performed on collected samples from River and spring

Lab Analysis	Location	Equipment specifications	Frequency of monitoring	Time frame
Isotope lab analysis (spring)	Spring/ River	PICARRO Isotopic analyzer (L2130-i)- Geology Lab-AUB	Every 3 days	Nov 27, 2019-continuing
Major ions Chemical lab analysis	Spring	Ion Chromatography (Corelab-AUB)	occasional	-
Particle size distribution	Spring/ River	Coulter counter multi sizer 4 Beckman Geology Lab-AUB	Every 3-days	Mid-Jan, 2020-ongoing
Bacterial analysis (River and spring; *e-coli, enterococci, pseudomonas aeruginosa*)	Spring/ River	Culture and count Geology Lab-AUB	weekly	Mid-Jan, 2020-ongoing

3.4 References

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4 The Eastern Ronda Mountains (Case Study Spain)

4.1 Field site description

Eastern Ronda Mountains (Fig. 4.1), located in the north-western region of Málaga province (southern Spain), constitutes the main study site covering a total surface of ca 110 km². Between 2007 and 2010, former hydrogeological investigations (Barberá, 2014) were accomplished over this area, comprising a solid scientific framework for further research. This will also allow to maintain the monitoring network with novel techniques and new field equipment as described below. In addition to the main test site, a further detached karstic area of 26 km^2 in Ubrique area (eastern border of the neighbour Cádiz province) has been included in the study area for the development and testing *Early Warning Systems* (EWS) due to its favourable hydrogeological features. Previous investigations have been carried out in this area since 2012 (Sánchez et al., 2016; Martín-Rodriguez et al., 2016; Sánchez et al., 2017) and part of its related hydrogeological infrastructure and monitoring network just need to be updated.

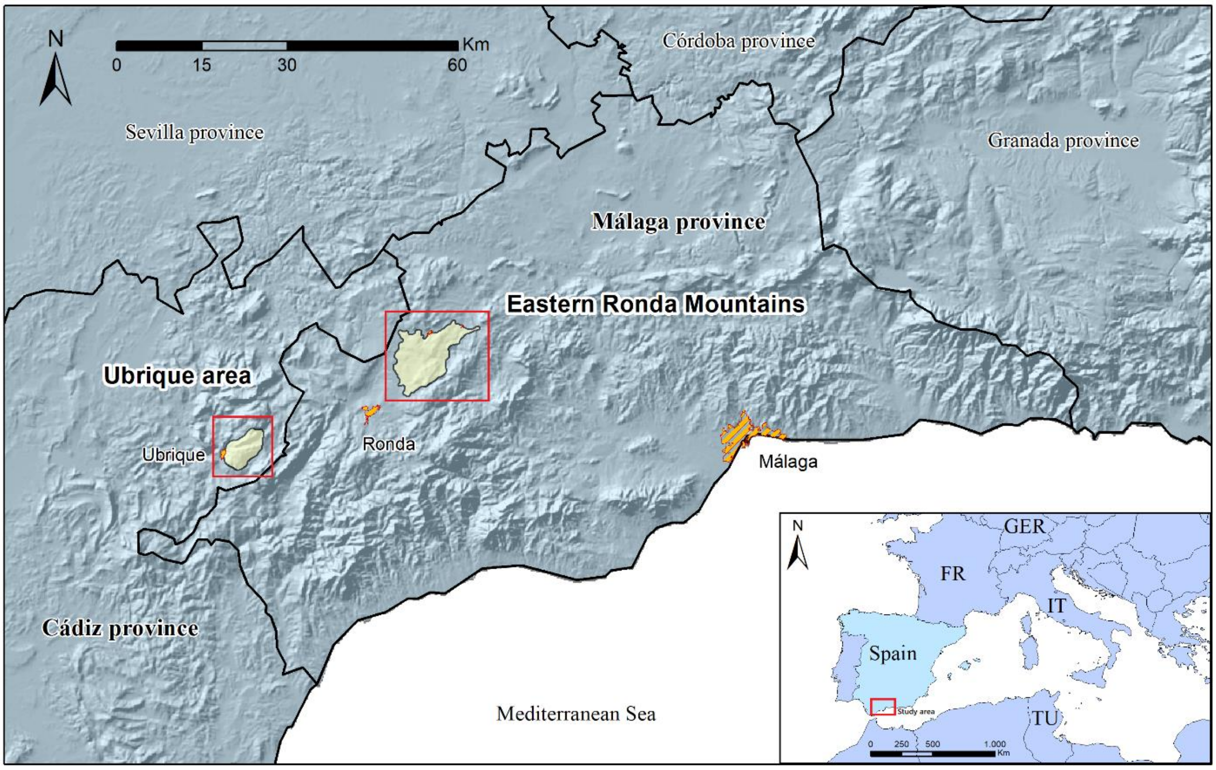

Figure 4.1: Geographical context of the Eastern Ronda Mountains and Ubrique area.

The relief in these areas presents common features such as an alignment NE-SW with steep slopes that range from 800 to 1200 m.a.s.l. for Eastern Ronda mountains and from 800 to 1400 m.a.s.l for Ubrique area. From a geological standpoint, both test sites are characterized by similar geological formations (from the bottom to the top): Triassic evaporites with clays, Jurassic limestones (upper) and dolostones (lower) -500 meters thick-, and Cretaceous-Paleogene marly-limestones (Cruz-Sanjulián, 1974; Martín-Algarra, 1987). The geological structure is defined by anticline folds, in which core limestones and dolostones can be found, and synclines matching with depressions constituted by younger marly-limestones materials. From a hydrogeological point of view, the study sites constitute fractured and karstified aquifer systems where recharge takes place by the infiltration of rainwater through limestone and dolostone outcrops, while discharge is made through springs located at the borders, between the permeable carbonate rocks and the impervious layers (mainly Cretaceous-Paleogene marly-limestones).

Eastern Ronda Mountains are constituted by three main reliefs, which names are Sierra de los Merinos, Sierra de Colorado and Sierra de Carrasco (Fig. 4.2). Recharge is mainly produced from the diffuse rainfall infiltration through permeable carbonate outcrops at high altitude (700-1200 m.a.s.l.) and mean annual precipitation has been estimated to 733 mm (Barberá, 2014). Three hydrogeological sectors have been identified in this area, on the basis of strictly geological, hydraulic and hydrochemical criteria (Fig. 4.2): the NW sector (Sierra de Carrasco), including the eastern part bordering with the Ronda basin, the central sector (Sierra de Colorado) and the SE sector (Sierra de los Merinos).

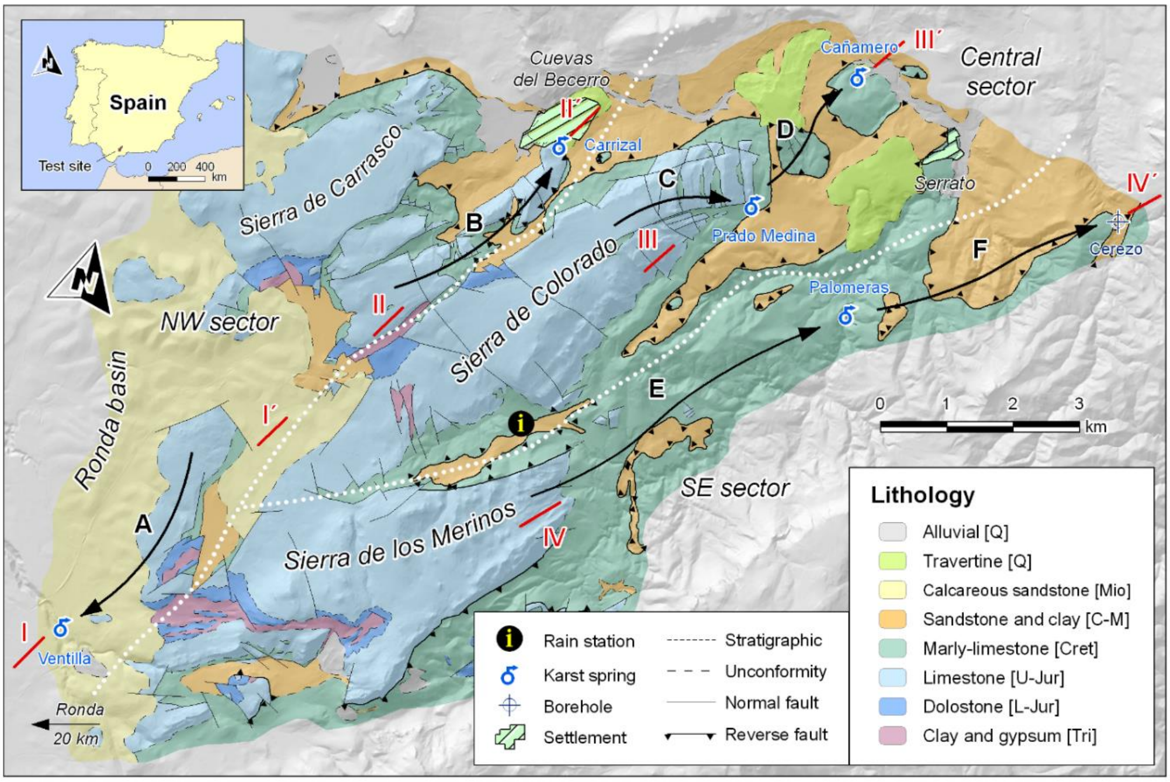

Figure 4.2: Hydrogeological setting of Merinos, Colorado y Carrasco aquifer systems and main groundwater flowpaths (Barberá et al., 2012).

Drainage in the Merinos-Colorado-Carrasco aquifer system is made in natural regime, mainly towards NE border, through the springs of Cañamero (540 m a.s.l.) and Carrizal (740 m a.s.l.) (Barberá et al., 2012). In addition, groundwater must be transferred toward the SW, to a porous aquifer (Ronda basin; Fig. 4.2), which overlaps with the Jurassic aquifer, and the visible discharge takes place via Ventilla spring (740 m a.s.l.). Despite other discharge points exist (overflow springs and boreholes), monitoring network is focused on the three main outlets since they provide the most representative information about the system.

Ubrique area is exclusively composed by the homonymous mountain (or Sierra, Spanish term), which constitutes an entire aquifer system (Fig. 4.3). Recharge in this area is produced in two ways, diffuse infiltration from rainfall through carbonate outcrops and concentrate flow from a small neighbour catchment which enters the system throught the Villaluenga shaft. The use of artificial tracers allowed to verify hydrogeological connection between direct infiltration points and main springs as well as estimate maximum flow speed, which resulted in 183,6 m/h for Garciago spring, 128,9 m/h and 177,7 m/h for Algarrobal (Fig. 4.4) and Cornicabra springs respectively. Mean annual precipitation in this area has been estimated around 1350 mm, however, it can variate depending on the altitude and sector from 900 mm to 1800 mm in the highest zones (Sánchez et al. 2016).

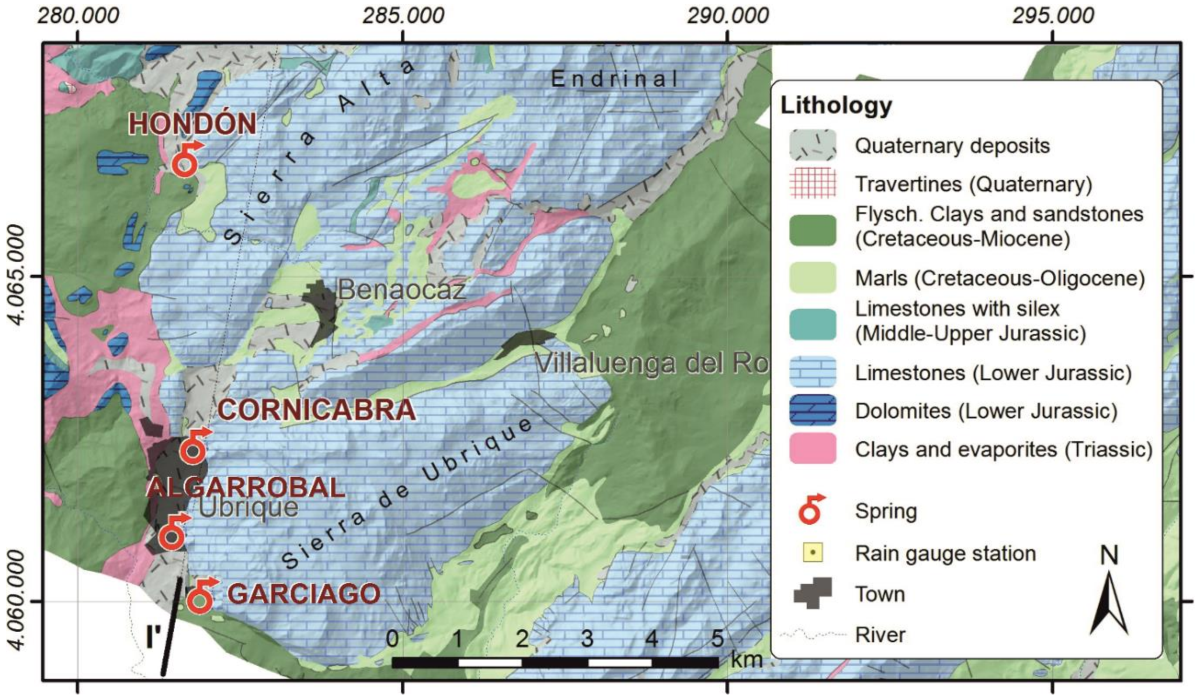

Figure 4.3: Hydrogeological setting of Sierra de Ubrique aquifer system (Sánchez et al., 2017).

Drainage mainly occurs through the springs of Cornicabra (349 m a.s.l.) and Algarrobal (317 m a.s.l.) (Martín-Rodriguez et al., 2016), located in the western border of the area and which provide drinking water for Ubrique village. In the same way that happens in the main site, other discharge points exist (such as Garciago spring, 422 m a.s.l., an overflow type associated with the previous springs) but only the two previously mentioned are being monitored. Ubrique area is the most suitable test site for EWS due to its important allogenic recharge and carries the fecal remains of the livestock from the surrounding areas in addition to inorganic sediment particles when stormy rainfall occurs after a long dry period (summer season). This special condition results in high turbidity and associated bacterial contamination discharge events (Fig. 4.4) which endanger Ubrique village drinking water supply, hindering the total exploitation of the available resources since in these situations it is not possible to pump water from the aquifer. In Spain, Royal Decree RD140/2003, February the 7th, establishes the sanitary criteria for the quality of water for human consumption among which are the parameters that generate this kind of problems in Ubrique drinking water.

Figure 4.4: Algarrobal spring during high turbidity conditions, March 2018 (Photo: Jose Francisco Martín Rodríguez).

4.2 Equipment setting

Information provided by this monitoring network will allow the quantitative and qualitative assessment of groundwater, and thus, to achieve the required knowledge for planning, managing and protecting water resources as extreme hydroclimatic conditions are expected in the Mediterranean area in the future.

The monitoring network has been stablished in the most representative points of the study area, such as main springs (for example, Algarrobal spring, Fig. 4.4) and recharge areas, in order to acquire detailed climatic and hydrogeologic data about:

- Hydroclimatic variables (rainfall, air temperature, humidity, solar radiation, wind speed and wind direction): three weather stations located in strategic points such as recharge areas and surface water divides. Regional and national weather stations data is also available, and thus, allowing to realize a correct hydroclimatic characterization of the study area. Rain collectors will be installed along different altitudes of the recharge areas for completing the monitoring network and achieve a deeper knowledge about rainfall distribution and isotopic signal.

- Soil water: soil moisture capsules will be located in the recharge areas of both test sites at different depths (30 and 60 cm) in order to analyse water isotopes, major ions, metals and physical-chemical parameters (prioritizing according to the volume of water). Also, single measurements of Rn^{222} activity in soil air concentration will be done to assess the infiltration processes and the transference of input signal toward the discharge areas.

- Discharge and physical-chemical parameters of karst groundwater: continuous and single measurements at Cañamero, Carrizal, Ventilla, Cornicabra and Algarrobal springs and Villaluenga shaft, as well as water analysis at the main drainage points. Chemical analysis will be performed at Centre of Hydrogeology of University of Malaga (CEHIUMA) laboratory. In addition to former hydrogeological investigations, all collected data will contribute to precise internal flow processes in the studied karst systems and to achieve an exhaustive hydrogeological characterization.

- Continuous measurement of enzyme activity and particle size distribution for the development of an early warning system (EWS): at several springs and at Villaluenga shaft, the enzyme activity (with the novel ColiMinder device) and particle size distribution (PSD) (with the novel particle counter) will be measured continuously by KIT in close collaboration with CEHIUMA. Microbial contamination will be monitored by using grab samples and the IDEXX® method.

The monitoring network consists of 8 sites for groundwater and rainfall/soil water data acquisition (Fig. 4.5): five springs and three plots at the recharge area hosting weather stations and soil capsules. At some locations like Carrizal, Ventilla and Cornicabra springs, part of the equipment is installed and well protected within the water supply administration infrastructure (building, fences).

On the other hand, at places like Algarrobal and Cañamero springs, the equipment is set on the outside and must be hidden from public viewing to prevent theft cases. Weather stations and soil moisture capsules are also set on the outside but in this case the equipment must be protected from animals: a metal fence has been built around the settlement in order to keep the equipment safe.

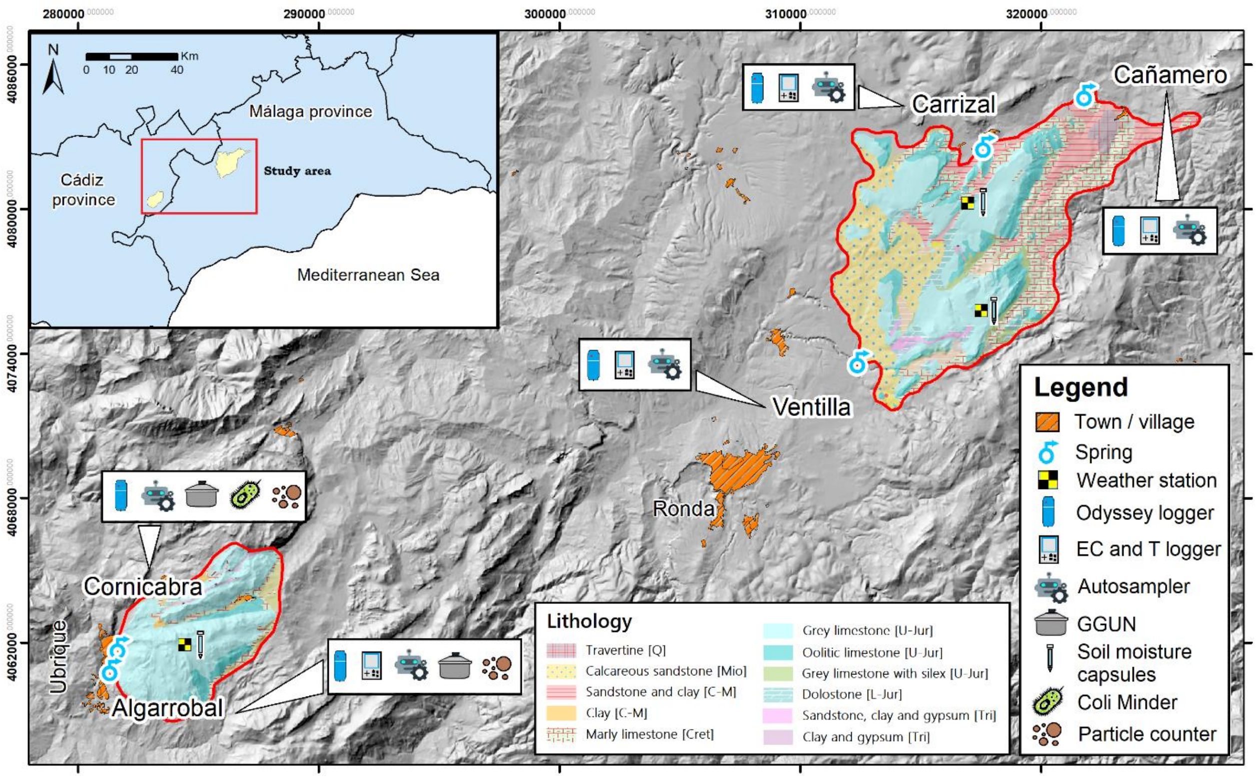

Figure 4.5: Summary of the monitoring network spatial distribution within the study area.

Taking into account the different techniques available for this research, three different ways for data collection are being used:

- Continuous measurements of physical-chemical and weather parameters (Tab. 4.1).
- Single field measurements of physical-chemical groundwater parameters (Tab. 4.2).
- Laboratory analysis of water samples taken at the main springs, rain collectors and soil moisture capsules (Tab. 4.3).

Table 4.1: Field data monitoring network and description of different equipment. RH=Relative Humidity, GW=Groundwater, EC=Electrical Conductivity, DOM=Dissolved Organic Matter, LW=Low Water and HW=High water.

Data monitoring	Location	Equipment specifications	Monitoring frequency	Time frame
Rain, air temperature and RH	Sierra de Ubrique (1.029 m.a.s.l.) (Fig. 6a)	WatchDog Weather Station	1 min	(March 2020-ongoing)
	Sierra de los Merinos (900 m.a.s.l.)	Davis Weather Station		Installation in progress
	Sierra de Colorado (1.054 m.a.s.l.)			Installation in progress
GW discharge	Cañamero spring	Odyssey logger for water level recording	15 min	(2007-2010) (March 2020-ongoing)
	Carrizal spring (Fig. 6b)			
	Ventilla spring			
	Cornicabra spring (Fig. 6c)			(February 2020-ongoing)
	Algarrobal spring			
	Villaluenga shaft			Installation in progress
EC and temperature	Cañamero spring	WTW Cond 3110	60 min	(February 2020-ongoing)
	Carrizal spring (Fig. 6d)			
	Ventilla spring			Installation in progress
	Algarrobal spring	HOBO U24 logger		(February 2020-ongoing)
GW samples	Cañamero spring	Autosampler- Hach AS950	24 hours on LW conditions Hourly on HW conditions	Installation in progress
	Carrizal spring			
	Ventilla spring			
	Cornicabra spring (Fig. 6e)	Autosampler- ISCO 3700		(March 2020-ongoing)
	Algarrobal spring			
EC / uranine / turbidity/ DOM / tryptophan	Cornicabra spring (Fig. 6e)	Field fluorometer GGUN - Albillia	15 min	(March 2020-ongoing)
	Algarrobal spring			Installation in progress
Particle size distribution	Cornicabra spring	Klotz - PCSS fluid lite	1 hour	Event scale
	Algarrobal spring			
	Villaluenga shaft	Klotz - Abakus mobil fluid touch		
Enzyme activity	Cornicabra spring	ColiMinder CMI-02	30 min	Event scale
Soil moisture and stable water isotopes (H, O)	Both test sites recharge area	Macro Rhizon capsules - Eijkelkamp	Monthly/dependent on the water sample volume	Installation in progress

Table 4.2. Physical-chemical parameters measured in the field and their technical description. LW=Low Water and HW=High water.

Field parameter	Equipment specifications	Monitoring frequency	Time frame
Water temperature and EC	WTW Cond 3110	2 weeks – LW conditions Daily – HW conditions	(January 2020- ongoing)
Dissolved O_2 / pH / Eh	HACH multiprobe HQ40D		
Turbidity	HACH turbidity pocket meter 2100Qis		
Soil/water Rn^{222} activity	SAPHIMO – AlphaGuard PQ2000 PRO 4800 (Fig. 6f)		
GW discharge	OTT C2 SalinoMadd		

Table 4.3: Laboratory analysis of water samples and description of different equipment. LW=Low Water and HW=High water.

Laboratory analysis	Equipment specifications	Monitoring frequency	Time frame
Major ions	Metrohm mods. 881 Compact IC pro and 792 Basic IC	2 weeks – LW conditions Daily – HW conditions	(January 2020- ongoing)
Total alkalinity	Metrohm mod. 888 Titrando		
Total organic carbon	Shimadzu mod. TOC-V_{CSN} + TNM_{-1}		
Stable water isotopes (H, O and C)	Isotope Analyzer Picarro mods. L_{2120i}-CRS and G_{1111i}-CRDS + OI-A Aurora 1030		
Metals and other minority elements	Thermo Scientific ICAP- RQ		
Natural fluorescence	Perkin Elmer LS-55		

Figure 4.6: A) Weather station (WatchDog) at Sierra de Ubrique; B) Water level logger (Odyssey) at Carrizal spring; C) Water level logger (Odyssey) at Cornicabra spring; D) Conductivimeter with datalogger (WTW) installed at Carrizal spring (GW supply of Cuevas del Becerro village); E) Automatic sampler for GW collection (ISCO 3700) and field fluorometer (GGUN FL30) at Cornicabra spring (GW supply of Ubrique town) and F) Portable detector (AlphaGuard) and outgassing unit for field measurement of ^{222}Rn activity in groundwater. (Photos: Jaime Fernández Ortega and José Francisco Martín Rodríguez).

4.3 References

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5 Lez Karst Catchment (Case Study France)

5.1 Field site description

The Lez system, located north of Montpellier, is a major Cretaceous and Jurassic limestone karstic aquifer that supplies drinking water to about 350 000 inhabitants of metropolitan Montpellier area. This large karst system located in the Mediterranean basin, South East of France, is referred to as the Lez aquifer because it feeds the Lez spring (mean discharge ~ 2200 l/s). The present water management scheme allows pumping at higher rates than the natural spring discharge during low-flow conditions, while supplying a minimum discharge rate (~ 230 l/s) into the Lez river to ensure ecological flow downstream, and reducing flood hazards via rainfall storage in autumn (Avias, 1995, Jourde et al., 2014). The Lez aquifer is located in the karst Garrigues area, which is encompassed between the Hercynian basement of the Cévennes to the north and the Mediterranean Sea to the south (Fig. 1). The boundaries of Lez aquifer system can be roughly materialized by the Hérault and Vidourle rivers (western and eastern sides) and by the Cevennes fault and Montpellier faults (southern and northern sides). It is ranked between the Cévennes crystalline massive at the north, and the littoral plain at the south. The topography rises gently from the south to the north of the area. The topographical heights range from 15 m.a.s.l (Vidourle's banks) to 658 m.a.s.l (Saint-Loup mountain).

The area is characterized by a typical Mediterranean climate with dry summers and rainy autumns.

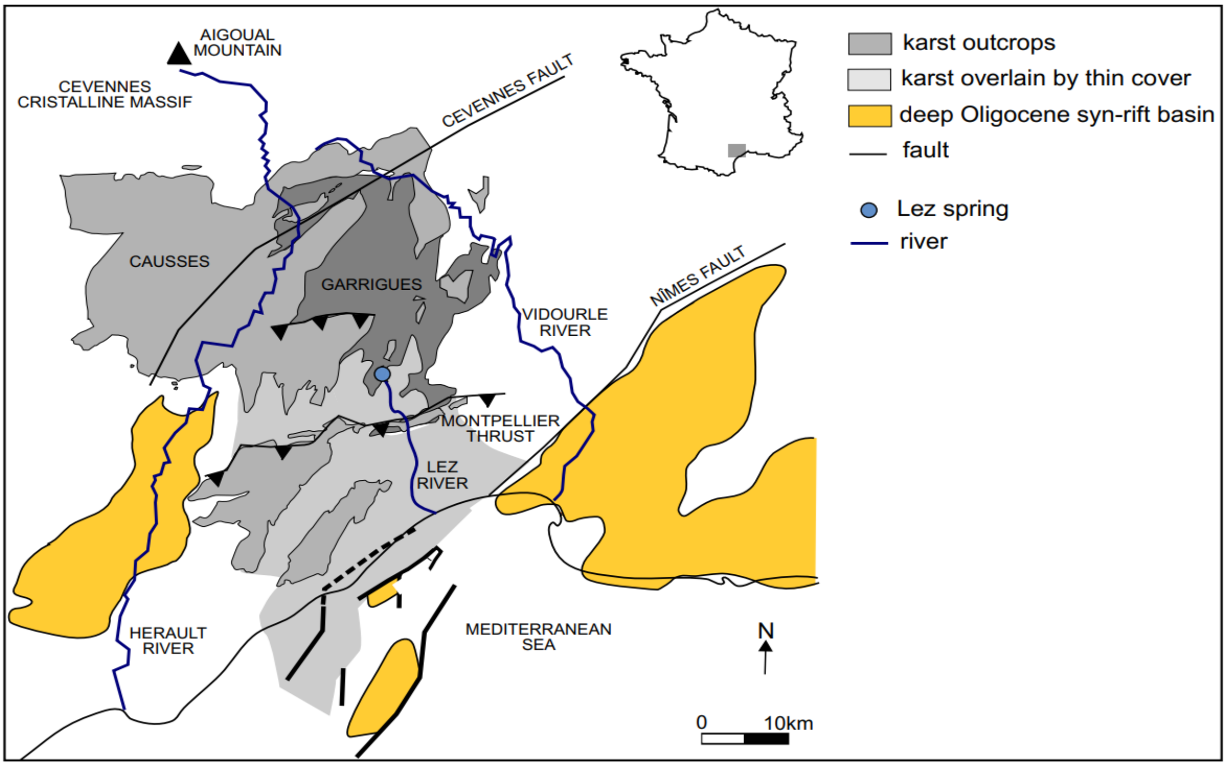

Figure 5.1: General situation of the Lez karst aquifer system (from Mazzilli, 2011, simplified after Camus, 1999).

The temperatures are hot in summer (mean temperature about 22 °C) and mild in winter (mean temperature about 5 °C). Rainfall is characterized by both monthly and annual irregularity. Annual rainfall is bi-seasonal, occurring primarily from September to December and in a lesser extent from March to May. Precipitations may range from about 600mm (dry year) to 1200mm (wet year). The intense rainfall events in autumn are the main contributors to the annual recharge. Annual rainfall occurs primarily from September to December and to a lesser extent from March to May. The mean annual precipitation ranges from about 600 mm (dry years) to more than 1500 mm (wet years). Rainfall is also spatially variable with an increase from south to north due to the rising topography and the proximity of the Cevennes hills (Fig. 5.1). At a more local scale, the geographic situation of the study area bears important consequences on the rainfall repartition. The mean annual cumulated precipitations increase from the south to the north of the study area due to the rising topography and the proximity of the Cevennes massive. The region is also prone to intense convective rain events during the autumn season, the so-called Cevenols or Mediterranean episodes. The cumulated daily rainfall may reach several hundreds of mm (e.g. 473mm recorded at the Ceyrac rain gauge the 08/09/2002, 272mm recorded at the Montpellier rain gauge the 22/09/2003).

The northern part of the study area is little urbanized. Carbonate facies are predominant. Soils are either inexistent, or shallow and little developed. The residues of limestone dissolution may fill topographic lows and open fractures. This area is mostly covered by low scrublands and woods that are well suited to drought. The south-eastern part of the study area is characterized by vineyards and an increased urbanization.

5.1.1 Geological and hydrogeological context

The Lez aquifer is composed mainly of Upper Jurassic and Early Cretaceous limestone. These sedimentary rocks overlie the Callovian–Oxfordian marls (Jurassic) and may locally be covered by a thick succession of Early Valanginian (Early Cretaceous) marls and marly limestone (Fig. 5.2, Fig. 5.3). The Lez aquifer shows a high degree of karstification developed

Period	Epoch	Stratigraphic unit	Main lithology	Thickness (m)	main hydrodynamic behaviour
Neogene	Miocene	Burgdalian	molassic limestone, marls and molasse		aquitard
Paleogene	Oligocene	Chattian	conglomerates, marls and sandstones		
		Rupelian			
	Eocene	Ludian	lacustrine limestone		
		Bartonian	conglomerates and marls	0 to 300	
		Lutetian	lacustrine limestone	50 to 100	aquifer
	Paleocene	Selandian	sandstone and pink marls	0 to 50	aquitard
Cretaceous	Late	Maastrichtian			
	Early	Late Hauterivian	gravel limestone	100	aquifer
		Early Hauterivian	marls	100	aquitard
		Late Valanginian	bioclastic limestone	50 to 200	aquifer
		Early Valanginian	marly limestone	200 to 800	aquitard
		Late Berrasian			
		Early Berrasian	pelletoid, fossiliferous and marly limestone	50 to 100	aquifer
Jurassic	Late (Malm)	Portlandien	massive limestone	150 to 200	
		Kimmeridgian			
		Oxfordian	marly limestone (small beds)	60 to 100	
			marly limestone	300	
			blue marls	20 to 50	aquitard
	Middle (Dogger)	Callovian	marly limestones and glauconic marls	80 to 100	
		Bathonian	limestone and dolomite	100 to 300	aquifer
		Bajocian	cherty, marly and oolitic limstone	100 to 150	
		Late Aalenian			
	Early (Lias)	Early Aalenian	black marls	150	aquitard
		Toarcian			

Figure 5.2: Litostratigraphy of the study area and main hydrogeological units (from Mazzilli, 2011).

during different geological periods, from the Middle Cretaceous to the current period (Leonardi et al., 2011). In particular, the possibility of deep karstification is attributed to the Messinian salinity crisis (about 5.5 My ago) when the sea-level of the Mediterranean Sea dropped by more than 1000 m due to the closing of the Gibraltar straights (Audra et al., 2004; Clauzon et al., 2005). The karstification is the result of chemical processes (that govern the dissolution of the carbonate rock) and power processes (that produce the energy for carrying and draining of the solution). It is governed by multiple factors with possible antagonistic effect: geographical and geological conditions of the exposure of the rock, climate, time available for the process evolution, direction and intensity of the hydraulic gradient, rock properties (and possible weaknesses), maturity of the karst system. Polycyclicity and polygenesis are typical features [Bosák, 2003]. Two main periods favourable for karstification are identified:

1. an emersion period between the Bajocian and Bathonian (Dogger) allows the karstification of the Lias and Late Aalenian limestones (Durand et al., 2009),
2. at the end of Barremian (Early Cretaceous), the emersion of the entire area sparks an intense karstification of the Late Jurassic and Early Cretaceous formations (Séranne et al., 2002) (N-S hydraulic gradient (Léonardi et al., 2011; Tissier, 2009).

Continental deposition prevails from the Late Cretaceous on:

1. during the Late Cretaceous and Early Paleocene, high amplitude (> 400m) successive drops of the base level (Combes et al., 2007; Husson, 2010; Séranne et al., 2009) may be related to the closure of a marine gulf. Opening and closure of the strait may be controlled by tectonic movements along the active orogenic axis of the Pyrenean Range and eustatic variations of the Paleocene World Ocean (Combes et al., 2007; Séranne et al., 2009),
2. during Eocene, a compressive stress is associated to a continuous drop of the sea level which results in an increase in the karstification (Dörfliger et al., 2008). The hydraulic gradient during that period is directed towards the South (Léonardi et al., 2011; Tissier, 2009),
3. during Messinian (-5Myr) the closing of the Mediterranean straits triggers the partial drying of the Mediterranean Sea (Messinian salinity crisis). This crisis can be subdivided into two phases, with sea level drops of around 600m and 1500m respectively (Suc et al., 2007). It caused the formation of deep karst systems and the reactivation of the existing karst systems (Audra et al., 2004; Mocochain et al., 2006), in particular the deep paleocene systems (Husson, 2010). Geomorphological studies have evidenced the fact that the Hérault Messinian paleovalley was perched during the Messinian Crisis. Due to this perched position, both the Hérault and Vidourle valleys were drained by streams, sinking while crossing limestone outcrops. The underground bypasses were connected at depth to the Lez karst aquifer that drained the whole area at this time (Audra et al., 2004). By that time the Lez aquifer discharged at the Mediterranean base level through a hydrogeologic watergap in the eastern part of the anticline of the Montpellier thrust (including limestones of the Gardiole massif) (Audra et al., 2004). Subsequent flooding of the Mediterranean Basin (5.32 Myr) caused the adaptation of the Messinian karst systems to the raised base-level (chimney-shafts formation), and plugging of the Messinian outlets by sedimentary infilling (Mocochain et al., 2006),
4. the Quaternary time is characterized by eustatic-climatic oscillations of the sea level from -120 m.a.s.l (Würm glaciation, -15 kyr) to 0 m.a.s.l during interglacial periods.

The aquifer is divided by NE-SW normal faults related to the Pyrenean orogeny (Eocene) and later impacted by the Oligocene extension phase. The Corconne fault and the associated faults (Fig. 5.3) have a major impact on the circulations within the aquifer. The vertical displacement associated with the normal, Oligocene functioning of these faults is responsible for the division of the aquifer system into a raised north-western compartment, where the Jurassic aquifer outcrops and a lowered south-eastern compartment where the Jurassic aquifer is mainly covered by impermeable formations. The western compartment contains the Upper Jurassic limestone at the outcrop while the eastern compartment primarily contains cretaceous formations of the Early Valanginian at the outcrop (Fig. 5.3). An important consequence is that the Jurassic aquifer is mainly unconfined west of the Corconne fault, whereas it is mainly confined east of the Corconne

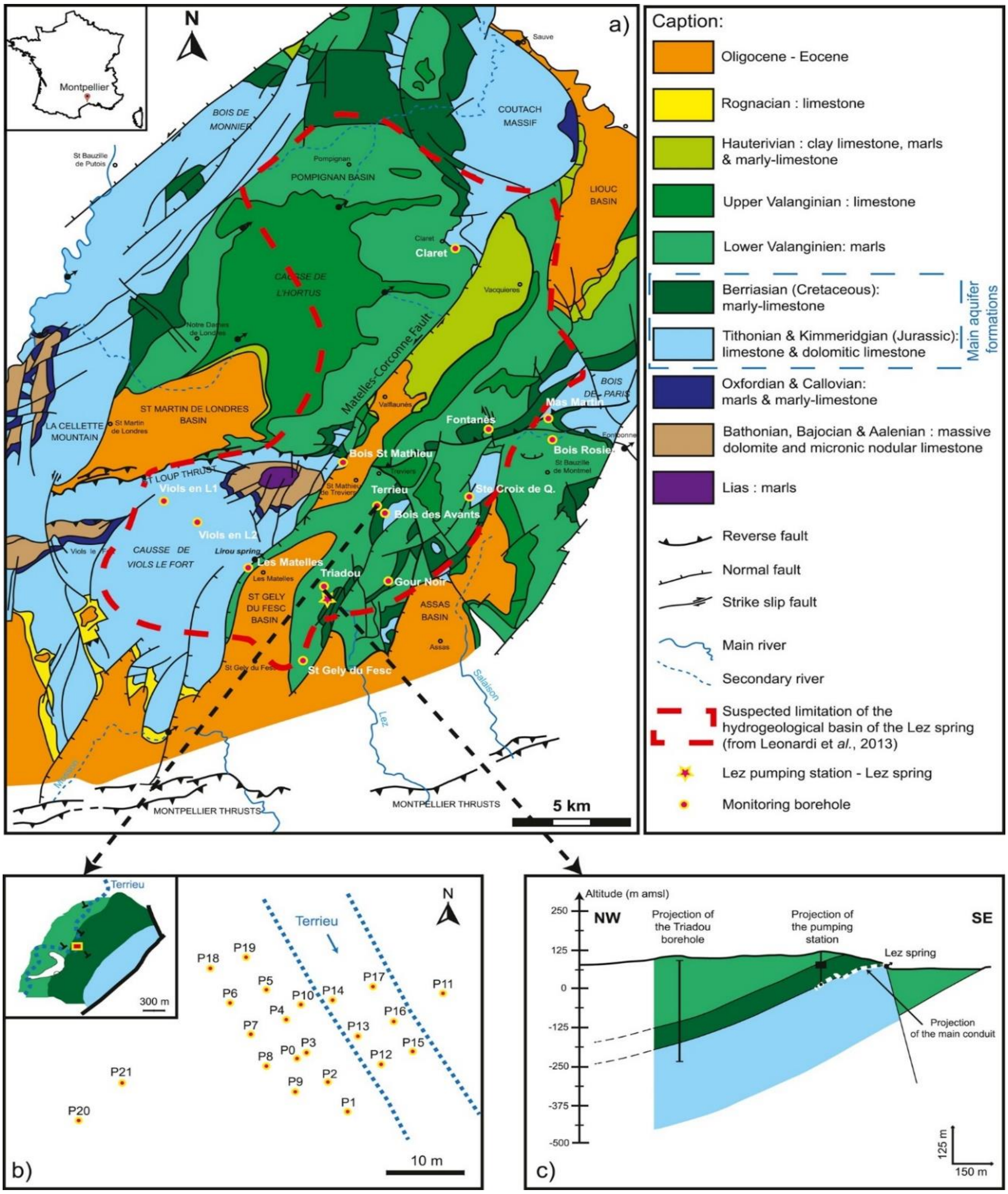

*Figure 5.3 **:** From from Dausse et al., 2019 : A) Geological map and groundwater monitoring network on the Lez aquifer; B) Geological location of the Terrieu experimental site and spatial distribution of boreholes; C) Simplified geological cross-section through the Lez spring and the Triadou borehole (after Leonardi et al., 2013).*

fault. Another consequence of the vertical displacement is the juxtaposition of aquifer and aquitard compartments, which is responsible for the settlement of the Lez spring but also of numerous seasonal overflowing dammed-type karst springs (Lirou, Restinclières, Sauve, Fontbonne springs among others).

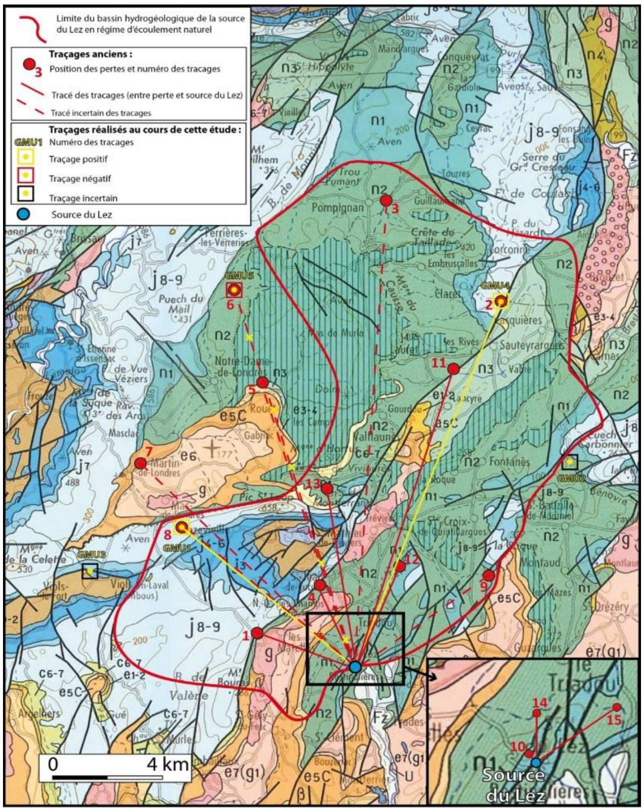

Figure 5.4: Pattern of former and more recent artificial tracing tests and boundaries of the presumed Lez spring groundwater basin under a natural flow regime (Leonardi et al., 2014).

Many tracer tests have been conducted in the basin since the 1960s to determine the hydraulic connections and underground water transit times. However, the findings of most of these tests are questionable because of the detection methods used at this time (mainly active carbon and visual detection). In the framework of the 'Lez karst catchment multipurpose management' project (Jourde et al. 2011; Leonardi et al. 2012), five new tracing tests were conducted to check some uncertain tracings and outline the limits of the Lez spring groundwater basin (Fig. 5.4).

The Lez spring (65 m.a.s.l), is located about 15 km north of Montpellier (Fig. 5.5a). It is of Vaucluse-type with a maximum discharge of approximately 15 m^3/s. However, the discharge at the Lez spring is generally small or nil due to the active pumping management of the aquifer, which supplies about 30 to 35 Mm3 of water per year to the metropolitan area of Montpellier and also reduces downstream floods (Jourde et al., 2014). The aquifer also discharges into several seasonal overflowing springs, the largest corresponding to the Lirou Spring (85 m.a.s.l), where high turbidity occurs during high discharge events (Fig. 5.5b).

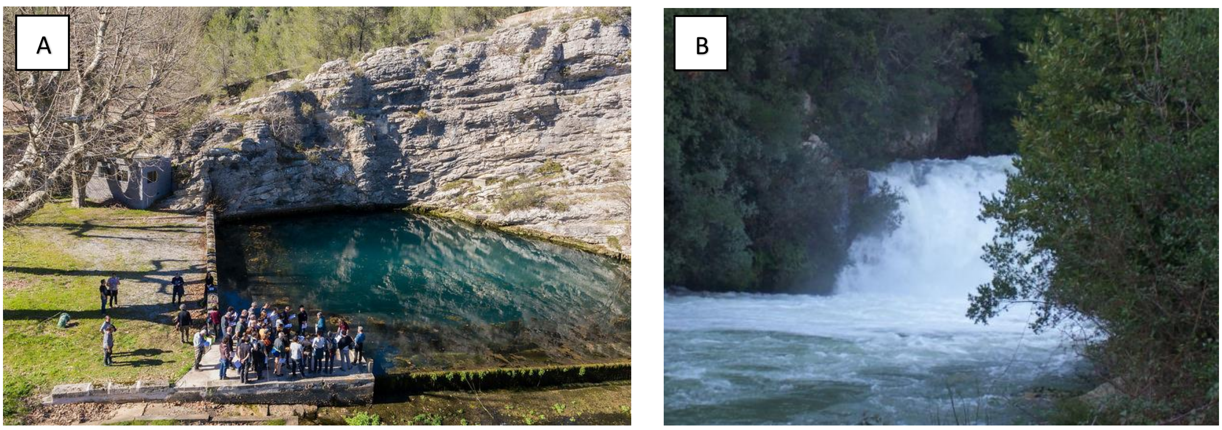

Figure 5.5: A) Aerial photograph of the Lez spring (Photo: Hubert Traguet); and B) Lirou spring during flood events (Photo: Hervé Jourde).

The Lirou spring is located west of the Viols cause and may drain up to 15 m^3/s during flood events, 20 m^3/s including nearby springs (Chemin, 1974; Drogue, 1969). Its mean annual discharge ranges from 0.4 to 1.8 m^3/s (Drogue, 1969]. The spring catchment area is around 65 km2 (based on hydrologic balance) (Drogue, 1969). The spring acts as an overflow outlet of the Viols-le-fort causse. On both springs, turbidity and associated bacterial contamination can be observed during high discharge events (Bicalho et al., 2011), so that pumping at the Lez spring for drinking water supply stops during such events.

The particularity of this karst aquifer lies in the management of the water resource, which consists in pumping water directly within the karst conduit at a depth under the level of the spring outlet (overflow level of the spring) extracting only part of the naturally renewable stock (Avias, 1995; Jourde et al., 2014). After a period during which only the natural overflow of the spring was used (until 1965) water was pumped in the spring down to -6.50 m below the overflow level of the

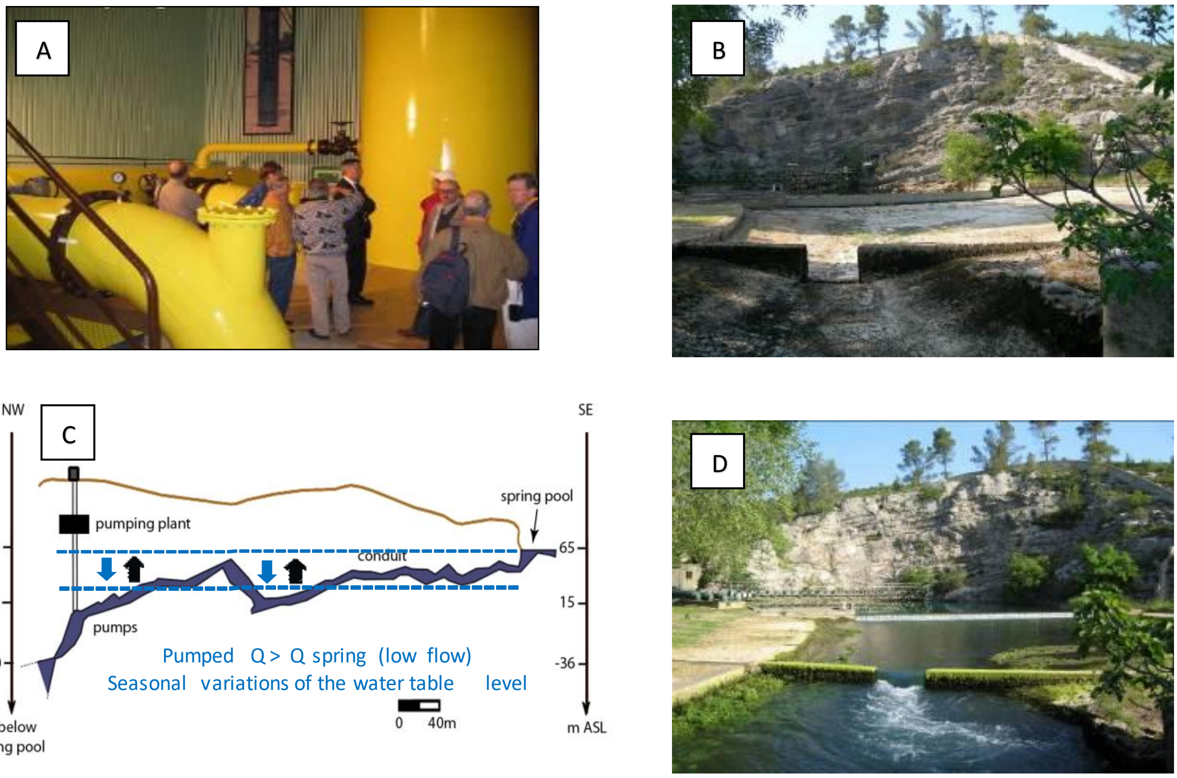

Figure 5.6: A) Underground Pumping station, B) Lez spring during low flow and D) high flow condition (Photos: Hervé Jourde; and C) seasonal variation of the water table level (Lez spring simplified topography from Mazzilli, 2011, after original topography by P. Rousset (G.E.P.S diving group, 1972).

spring (65 m.a.s.l). It allowed pumping 800 l/s for Montpellier water supply, even when the natural outflow of the spring was lower than 200 l/s (Avias, 1995). When the needs of Montpellier increased above 800 l/s, four deep wells were drilled (Fig 5.6a). These wells reached the karst conduit feeding the spring, 48 m below the overflow level of the spring (17 m.a.s.l). Pumping these wells allows up to 1700 l/s to be withdrawn under low-flow conditions, while the average annual pumping flow rate is about 1100 l/s (1988–2009). This type of management is possible as long as the mean pumped flow rate does not exceed the mean annual discharge of the spring that is about 2200 l/s (Avias 1992). Note that the natural spring discharge displays a high inter-annual variability (Fig 5.6c) as highlighted by extreme values for the discharge monitored before pumping within the spring (after Drogue 1974): in 1952 (dry year, 590 mm annual rainfall) the mean annual discharge of the spring was estimated to be 1500 l/s, while it was estimated to be 2800 l/s in 1962 (wet year, 1150 mm annual rainfall) (Fig 5.6d). During low-flow conditions, when the pumping rates exceed the natural discharge of the karst aquifer, the water level in the karst conduit and in the spring drops below the overflow level. Pumping then causes a drawdown of almost 30 m at the end of the low-water period, and the spring dries up (Fig. 5.6b). During autumn and winter, the karst aquifer is recharged and its reserves are renewed.

5.2 Equipment setting and monitoring network

Information provided by the monitoring network will allow the quantitative and qualitative assessment of groundwater, and thus, to achieve the required knowledge for planning, managing and protecting water resources as extreme hydroclimatic conditions are expected in the Mediterranean area in the future. This monitoring network will complete the monitoring operated for the French test site since 2006 on the MEDYCYSS Observatory (Fig. 5.7), which is part of the SNO KARST network (www.sokarst.org) and OSU OREME.

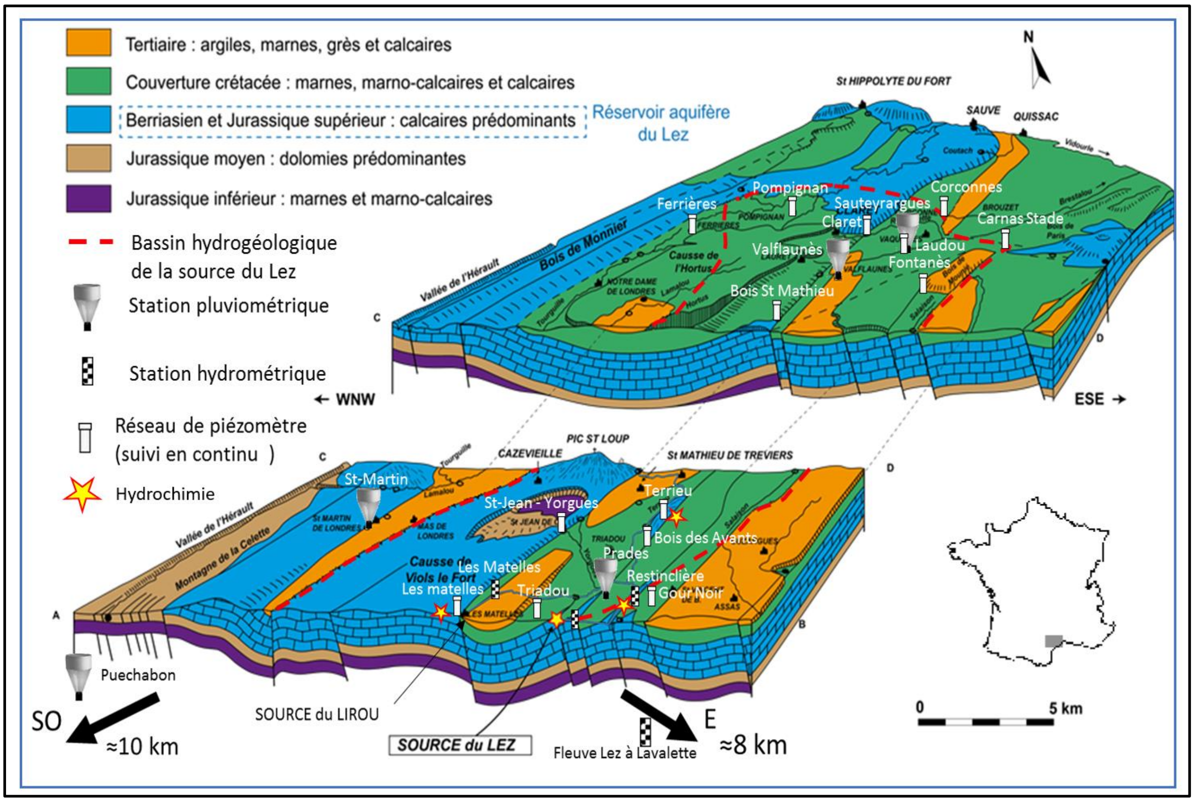

Figure 5.7: *MEDYCYSS Observatory - Lez River basin monitoring network (modified after Dausse, 2015).*

This monitoring network provides quantitative and qualitative knowledges on groundwater resource assessment for planning, managing and protecting the water resources. The objectives are i) the observation and characterization at different scales of the hydrodynamics of karstic aquifers submitted to climatic and anthropogenic forcing, ii) the observation and understanding of fast hydrological processes during flash floods in Mediterranean karstic watersheds and iii) the observation and determination of the contamination risks of the groundwater resources by a coupled monitoring of hydrodynamics and hydrochemistry.

The monitoring network is developed around the most representative site of the study area (main springs and bore-holes in order to acquire high frequency data related to:

- Hydroclimatic parameters (precipitations, air temperature, humidity, solar radiations wind speed and direction): two meteorological stations are operated in the vicinity of the test site. Six rain gauge stations are distributed over the watershed to estimate the temporal and spatial rainfall distribution.

- Discharge and physico-chemical parameters of groundwater are continuously recorded at the perennial (lez spring) and temporal karstic springs (Lirou, Restinclières) and at representative bore-holes (Triadou and Terrieu site). Punctual samplings for water chemistry will be realized every two weeks and with a short time step during flood events. The chemical analyses will be performed at HydroSciences Montpellier laboratory from University of Montpellier (France).
- Water table levels at numerous observation wells distributed from a few meters to several kilometers (i.e., 15 km) from the pumping station (Fig. 5.3 & Fig. 5.7). One of these observation wells, the Triadou, is located 580 m upstream of the Lez pumping station and was drilled to a depth of 335 m (Fig. 5.8). It was equipped with the Multi-level monitoring PMPS system (SolExperts ®), which allows pressure/temperature monitoring in different intervals isolated by packers and the sampling of groundwater by means of capillaries allowing pumping by overpressure of nitrogen in the sampling line. Since July 2014, five zones are continuously monitored with pressure/temperature sensors and groundwater sampling is carried out on 6 intervals (Fig. 5.9).

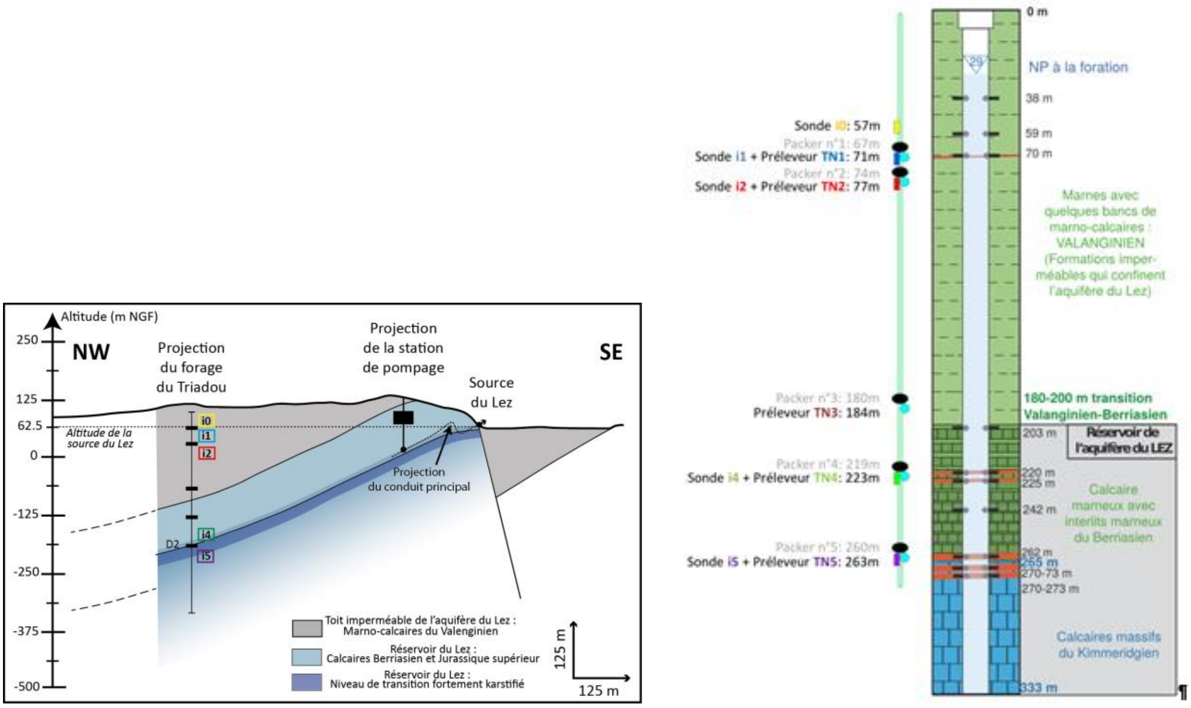

Figure 5.8: Location of the Triadou borehole, pumping station and Lez spring (modified after Leonardi et al., 2013), and Triadou borehole logging and equipment (ANR EQUIPEX CRITEX) (Durepaire et al., 2016).

According to the different techniques or equipment existing at HydroSciences Montpellier, the monitoring of the parameters will be undertaken following three strategies:

- Continuous monitoring of meteorological, physico-chemical and hydrodynamic parameters (Table 5.1).
- Punctual field measurements for physico-chemical parameters and water sampling (Table 5.2).
- Laboratory chemical analyses of water samples from precipitations, springs and wells (Table 5.3).

Table 5.1: Field data monitoring and equipments. T°C: temperature, GW: groundwater, EC: electrical conductivity, DO: Dissolved Oxygen, Cl-: chlorides, NOM: Natural Organic Matter, TOC: Total Organic carbon, DOC: Dissolved Organic Carbon, NO3: nitrates.

Data monitoring	Location	Equipment specifications	Monitoring frequency	Time frame
Meteorological station (rain, wind, air T°C)	Prades-le-Lez	MTO Campbell	15 min	ongoing from 2010
Flux tower (rain, wind, radiations, humidity, CO2 flux)	Ceyrac	Eddy covariance system	15 min	January 2020-ongoing
Rain gauge stations	Prades-le-Lez, Sauteyrargues, Viols-le-Fort	HYDREKA		ongoing from 2006
GW discharges	Lez spring	HYDREKA flowmeter	15 min	ongoing from 2007
	Lirou spring			ongoing from 2007
	Restinclières spring			ongoing from 2012
Piezometry, T°C	Triadou well (330 m)	Multi level monitoring PMPS	15 min	ongoing from 2014
Piezometry, EC, T°C	Lez spring	SDEC CTD probes	1 min	ongoing from 2012
	Lirou spring			ongoing from 2008
T°C, pH, EC, DO, Cl^-	Lez spring	YSI6920 V2-2-SV probe	60 min	ongoing from 2015
NOM/turbidity	Lez spring	GGUN FL620	15 min	ongoing from 2015
TOC, DOC, NO3, Turbidity	Lez spring	spectro::lyser s::scan	60 min	installation in progerss
GW samples	Lez spring		2 weeks	ongoing from 2006
	Lirou spring			ongoing from 2008
	Restinclières spring			
	Triadou well		monthly	ongoing from 2015
Bacteriology	Lez spring	Colilert18	2 weeks	ongoing from 2008
	Lirou spring			
	Restinclières spring			
Radon-222	Lez spring	RAD7 Durridge	60 min	ongoing from 2016

Table 5.2: Physical-chemical parameters measured in the field and devices description.

Field parameter	Equipment specifications	Monitoring frequency	Time frame
Water T°C, pH, EC	WTW Cond/WTW pH 3110	2 weeks Daily -Flood conditions	ongoing from 2006
Radon in water activity	Aphaguard PQ2000 + Aquakit		ongoing from 2011

Table 5.3: Laboratory analyses with dedicated equipments.

Laboratory analyses	Equipment specifications	Monitoring frequency	Time frame
Major elements	ICS 1000 Dionex	2 weeks Higher frequency - Flood conditions	ongoing since 2006
Total alkalinity	Compact Titrator G20 Mettler Toledo		
Total Organic Carbon	Shimadzu TOC-V_{CNS}+		
Natural Organic Matter	Shimadzu RF-5301PC+		
Stable water isotopes (H,O)	ISOPRIME IRMS		
Trace elements	Thermo Scientific ICAP-TQ		
TC+Escherichia Coli	Colilert18 IDEXX		

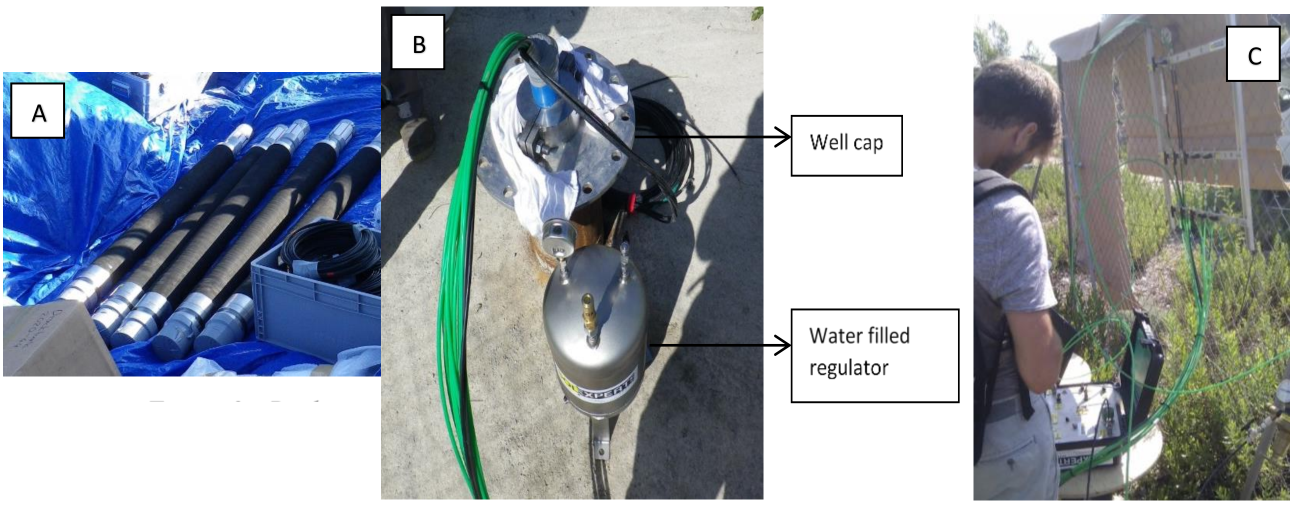

Figure 5.9: A,B) Multi-level monitoring PMPS system (SolExperts ®on the Triadou Borehole: Packer, well cap, and water filled regulator (Photos: Hervé Jourde) and C) console for the sampling control (Photo: Jean-Luc Seidel).

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6 Djebel Zaghouan aquifer (Case Study Tunisie)

6.1 Field site description

6.1.1 Geographical context

The Zaghouan massif extends from the East-west extension valley of the Rmal wadi in the north, to the transversal syncline of Loukanda which follows, in the south, the bridge road from Fahs to Saouaf-Infidha city (Fig. 6.1). It is made up of a series of Jurassic points, the most important of which is in the north, the Djbel Zaghouan, our field of study.

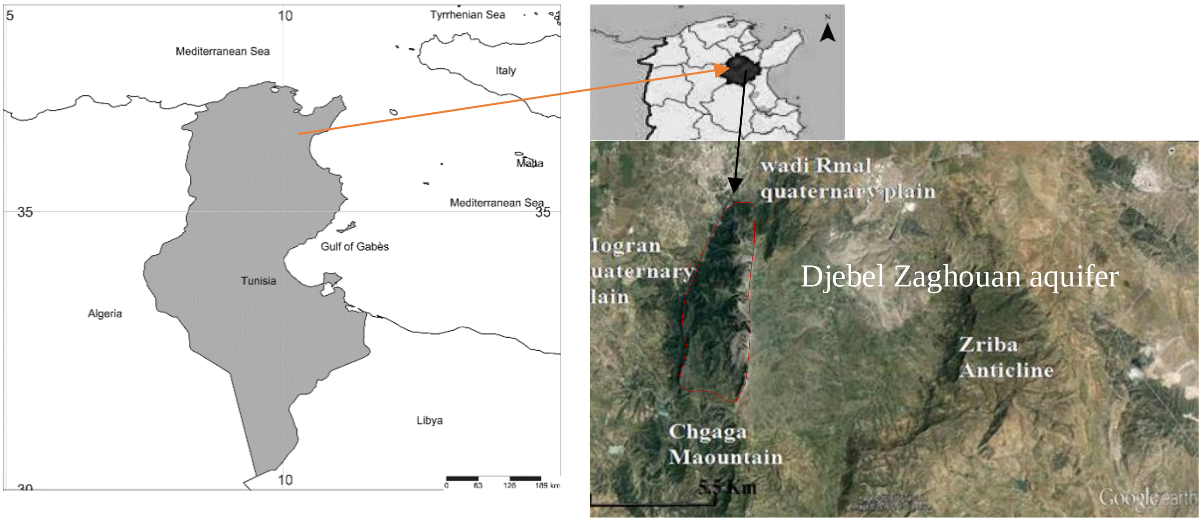

Figure 6.1: Location of the Djebel Zaghouan aquifer (Aerial photo: Google earth app.).

The region of Zaghouan is characterized by an upper semi-arid to subhumid climate with an average annual rainfall of 467 mm presenting heterogenous spatial distribution and a large time fluctuation (from 245 to 625 mm). The average annual temperature is about 17.7°C.

6.1.2 Geological context, aquifer geometry and springs

The Zaghouan anticline is mainly constituted by Jurassic limestone. It's limited by the rock-fall and the cretaceous formations. The Figure 6.2 shows that the geology of the Djebel is characterized by the presence of southern and transverse faults that have created individualized blocks. These faults which allow an infiltration of meteoric waters are between jumps: the Kef El Orma fault, the Great Peak fault and the Achilles fault.

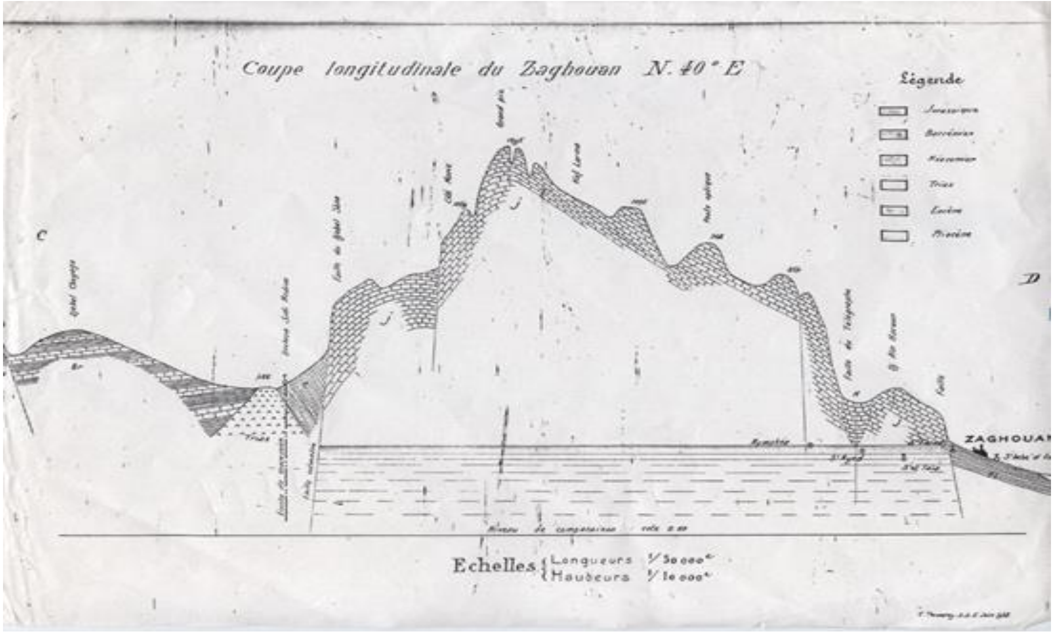

Figure 6.2: Geological context of Djebel Zaghouan (Castany,1951).

The Jurassic limestone block is a trapezoidal, cavernous and fissured limestone with a longitudinal dimension of about 8 km along a north to 40°East direction, and an average of 2.4 km in the transverse direction, along a north to 45° West direction. It has a surface area of 19 km^2 at the altitude of 300 m NGT. The massif is surrounded by marly soil acting as a watertight barrier and can be subdivided into 3 compartments running from north to south.

- Small Zaghouan which gives birth to Ain Haroun.
- Transmission station massifs, Kef El Orma, Kef El Blidah and Djebel Stâa; they are the most extensive compartment, which give rise to the most important springs including Water temple (Nymphaeum), Aïn Ayed and Aïn Oued El Guelb.
- The great peak massif which gives birth to the source of Sidi Medina.

The general dip of the limestone layers and the topographical configuration towards the north-west explain the presence and importance of the springs of both slope and east massif.

The massif contains 14 springs. The most important springs are on massif north-western slope among them: Nymphea, Ain Ayed, Ain ElGuelb, Gallerie 44 and Gallerie 47 and Ain Haroun, shown in Figure 6.3.

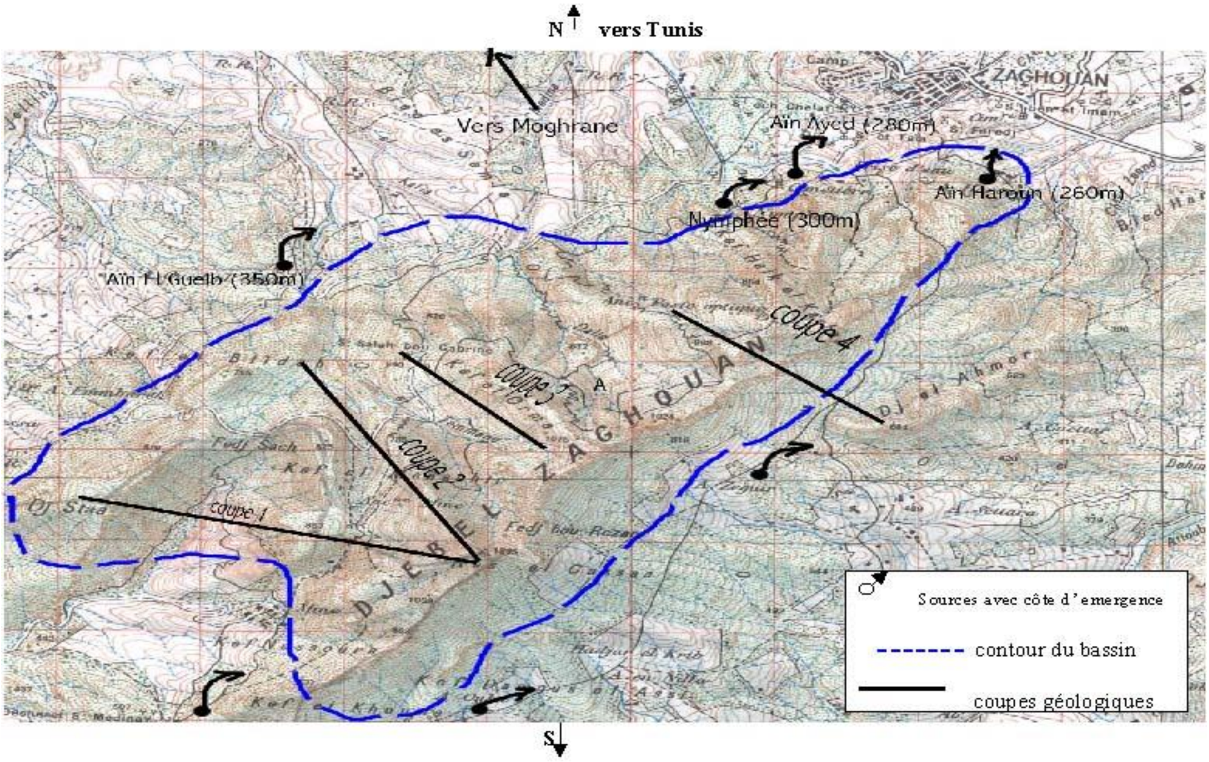

Figure 6.3: Springs location map (extract Zaghouan map n°25 at scale 1:50000).

Djebel Zaghouan limestone aquifer is the one of the most important water resources of good quality in the region and is currently exploited by mainly 9 boreholes and galleries intended for the drinking water supply of the city of Zaghouan and the surrounding rural agglomerations. Three of these wells are used as commercialized mineral water (Cristaline, Aqualine and Prestine). Since galleries 44 and 47 are dry and to cope with water shortage that Zaghouan city suffers from, two other boreholes (Water temple and Ain Haroun 3bis) were drilled in 2017 and 2018.

6.2 Experimental set up

The preliminary design of the experimental set up of the Djebel Zaghouan is still being discussed with the two principle stakeholders at a local and central levels. Indeed, two water authorities are involved in the aquifer management: The National Water Distribution Utility (SONEDE) and the Regional Commissary for Agricultural Development (CRDA). SONEDE is responsible for the production and distribution of drinking water whereas the CRDA is the regional department managing groundwater and surface water for different end-users.

6.2.1 Historical hydrodynamic and quality data

Daily discharge flow values (under natural functioning) within records of the further exploitation data through galleries and boreholes were recorded from 1915 and are available at SONEDE archives. The available time series continued to the year 1995 with data gaps for certain years.

The CRDA measured Salinity (TDS) and nitrates (NO^{3-}) from 2009 to 2018 in Ain Ayed once a year. Major ions, nitrates and other bacteriological analysis are available for boreholes exploited by SONEDE and we are in discussion with them for the transfer of existing data and for their involvement in carrying out frequent sampling and/or automatic monitoring of water quality. The objective is the set up and the implementation, at the long term, of an Early Warning System.

A study carried out by Dziri et al. (2016) aimed to understand the groundwater origins and the mineralization in this karst system, as well as the impact of many decades of intense water exploitation. The sampling was carried out all over the calcareous massif and surrounding points. 36 water samples were collected from wells, boreholes, springs, galleries and dams. Results revealed that water resources were vulnerable to anthropogenic pollutions indicated by high nitrate contents observed in certain springs used for drinking water supply

6.2.2 Hydrodynamic and exploitation monitoring design

The CRDA are using a network of four piezometers in monitoring groundwater levels. We are willing to equip one to two of them with automatic dataloggers recording water level, electrical conductivity and temperature (we have experience with CTD divers https://diver-water-level-logger.com/diver-water-level-loggers/ctd-diver.html). Exploitation data, related to boreholes extractions, will be updated from both SONEDE and CRDA annual reports. Automatic measurements of soil water content and temperature using FDR sensors were programmed in the project. The equipment is expected to be acquired and installed in a secure area in concertation with CRDA. The objective is to set up a data base for the recharge estimation and modelling. Besides, geophysical investigations are programmed with colleagues from other research institutions to map the karst morphology. The possibility and opportunity of performing tracer tests is still a relevant issue as the functioning of system is completely controlled by heavy extractions, yet colleagues from the university of Sfax recently performed a tracer test and we contacted them to have a feedback of their experience.

6.2.3 Quality Monitoring

During the project, at least one field campaign will be dedicated to the assessment of groundwater origins and mineralization processes at a large scale (Dziri, 2016). This will include isotopic investigations. The study will then focus on the quality of the two principle boreholes managed by SONEDE and producing drinking water that are Ain Haroun (water temple) and Ain Ayed. During the last field visit in February 2020, Ain Ayed well was dry because of the exceptional low seasonal recorded rainfall. However, we discussed with SONEDE representatives the installation of an automatic multiparameter datalogger. The multiparameter probe is available (EXO Multiparameter Water Quality Sonde https://www.ysi.com/EXO2) but we still need to acquire the adequate datalogger and to secure its installation in one of the boreholes' sites.

The EXO probe measures depth, electrical conductivity, temperature, pH + Redox, dissolved oxygen, and turbidity. Besides, periodic water sampling for geochemical investigations will be programmed with SONEDE. Data analysis and a modelling study (Nazoumou, 2000) showed that the system response to winter rainfall varied between two to three months. Thus, a high frequency sampling in spring would be interesting. The sampling frequency will mainly depend on the ongoing discussions with the central administration of SONEDE as they can be involved in the water chemistry and bacteriological analysis performed by their central accredited Lab in Ghdir El Golla (Tunis).

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