KARMA

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

Water Availability

Deliverable 2.8

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Executive Summary

The water budget is a necessary step in hydrogeology to assess the water availability, its renewable rate and consequently the aquifer capacity of infiltration, depending on the precipitation rate. In case of karst aquifers, this evaluation has to consider the different ways for infiltrating waters: in addition to the classical infiltration in soil and rock fractures, the allogenic component due to fast inflow through dolines, swallow holes and in general surface karst features, is an additional input which can have a limited up to main impact on aquifer recharge. This process influences not only the recharge rate, but also transfer times into the aquifer to the springs and aquifer vulnerability to pollution.

In WP2 of KARMA project, we tested six aquifers in different countries to analyse in detail, at the single aquifer or hydrogeological basin scale, their water budget, with the aim to check the potentiality of karst aquifer in the Mediterranean area, to compare methods for identifying the more reliable in this lithological and geographical context, and finally to verify the groundwater availability at the catchment scale. This Deliverable D2.8 intends to resume the activities carried out during the project in all study sites with quantitative purposes, illustrated by the previous deliverables (D2.1 to D2.7), and to offer the results in terms of water availability. In the conclusion chapter a summary of the groundwater availability at the test sites is provided.

In each study sites, several different methods have been applied to assess the water budget, starting from the individuation of the catchment feeding one or more springs in the same karst aquifer. The input has been assessed considering the rainfall, the allogenic contribution by runoff in karst system, and where necessary the snow coverage and the related snowmelt. The same water budget has been assessed by independent methods, as APLIS, which consider the lithological characteristics of outcropping rocks and the infiltration capacity of karst features. To validate the water budget, different methods have been applied: i) isotopic fingerprinting using water stable isotopes, which helped in verifying the recharge area of monitored springs; ii) tracer tests, fundamental in karst systems to distinguish the fast flow connecting rainfall with discharge areas from the slow flow contribution; iii) spring discharge monitoring, necessary not only to measure the water resources, but also to distinguish the different components of groundwater flow and the recharge and exhaustion periods, which it allows to calculate the exhaustion coefficients, very useful for simulating future scenarios.

The most reliable method for assessing the infiltration rate has been proved to be APLIS, because it directly includes the effect of the karst features into the recharge evaluation. The comparison of recharge rates assessed at the scale of study sites with the results obtained at a regional scale and published on the MEDKAM (see WP5) reveals interesting bias and uncertainties, moving from recharge assessment at the catchment scale up to the Mediterranean scale. The main finding highlights that recharge at local scale is usually higher than the one calculated at continental scale, causing a possible underestimation of real recharge in karst aquifers and consequently of the expected spring discharge. This bias can be due to several factors, as: i) impossibility to consider local altitude effects at the wider scale, due to the dimension of the pixels; ii) discarding of additional allogenic components due to the karst features at the local scale; the MEDKAM evaluation considers a general karst behaviour, but cannot evaluate enhanced local conditions; iii) seasonal effects, due to the regional conditions on Mediterranean area, where temperature is a relevant driver in influencing the duration and the entity of summer droughts. A future validation of the recharge evaluation method at the Mediterranean scale is expected and during this process it is recommended to take into account the above-mentioned factors emerged by local scale evaluations.

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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. At karst catchment scale, the main objective is to advance and compare 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.

The main objective of WP2 is the assessment of groundwater availability by investigating recharge, discharge and storage. Recharge consists of the downward flow of rainwater that reaches the water table. Recharge into karst and fissured aquifers can occur in two ways, (1) diffusely over carbonate outcrops, epikarst and soils (autogenic) or (2) from nearby non-karst areas where rainwater infiltrates through swallow holes or dolines (allogenic) (Figure 1.1).

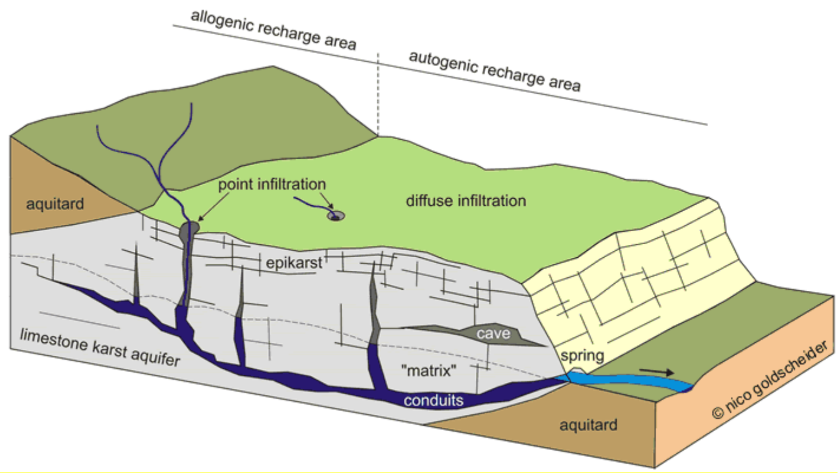


Figure 1.1. Schematic illustration of a heterogeneous karst aquifer system characterized by a duality of recharge (allogenic vs. autogenic), infiltration (point vs. diffuse) and porosity/flow (conduits vs. matrix) (Goldscheider 2019)

The available knowledge about these processes and how infiltration takes place in each KARMA test site highly influences the development of numerical models and vulnerability maps, as well as their accuracy. Therefore, in order to achieve a better hydrogeological understanding and to obtain reliable data for the calibration and validation of models and vulnerability maps, hydrological monitoring, isotope studies, and tracer tests have been carried out in addition to the recharge rate estimation. Different methods are traditionally applied for groundwater recharge assessment however none of them are free from uncertainty.

The following chapters summarize the results obtained by each research unit in their study area in calculating the water budget, at the end of the research carried out under the KARMA project. Taking into account the progress in evaluation of recharge and discharge values in each study site, described in detail in previous deliverables of the same WP2 (from D2.1 to D2.7), this report summarizes the results obtained in groundwater resource evaluation, defining the total water resource availability assessed in each study site, coupled with the indication of the methodology which has proved to be more reliable and consistent with field data for karst and fissured aquifers. A comparison of the recharge rate assessed at local scale with the infiltration derived by large-scale model for the entire Mediterranean area (shown in MEDKAM, see WP5) is also provided, with the consequent discussion on the uncertainties due to the upscaling process. Discharge values, when related to millions of m^3 per year have been expressed in the SI unit (1 hm^3/y = 1 million of m^3/y).

2. Results of water budget analysis from each study site

2.1 Gran Sasso aquifer (Case Study Italy)

2.1.1 Study Area

The Gran Sasso hydrostructure is a calcareous-karstic aquifer about 1034 km^2 wide, one of the most representative karst aquifers of the central Apennines, for its huge amount of water resources and the interaction between groundwater and underground works (Celico, 2005). The Gran Sasso hydrogeological system, characterised by Meso-Cenozoic carbonate units, is bounded by terrigenous units represented by Miocene flysch (regional aquiclude) along its northern side and Quaternary continental deposits (regional aquitard) along its southern side (Figure 2.1). The aquifer has high permeability for fracturing and karstification and by the high effective infiltration that feeds important springs located at its boundary (Amoruso et al., 2013). The groundwater resources are mainly exploited for human purposes and partially drained by highway tunnels (Celico et al., 2005; Figure 2.1).

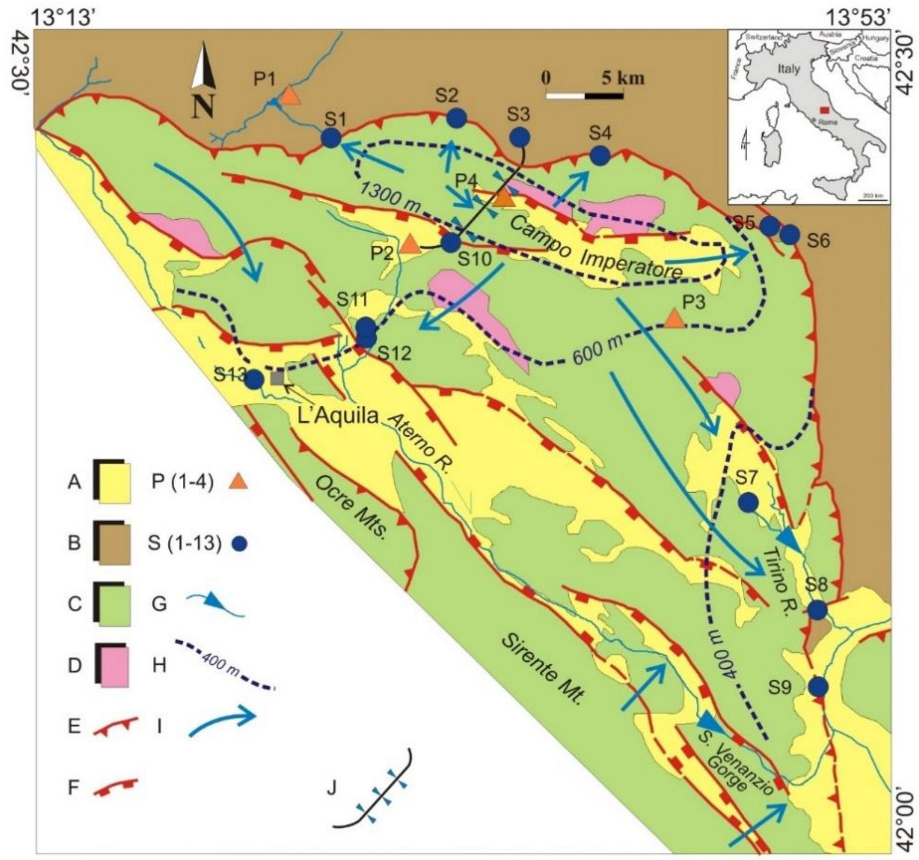


Figure 2.1: Simplified hydrogeological setting of the Gran Sasso aquifer. A Aquitard (continental detrital units of intramontane basins, Quaternary), B aquiclude (terrigenous turbidites, Mio-Pliocene), C aquifer (calcareous sequences, Meso-Cenozoic), D low permeability bedrock (dolomite, upper Triassic), E main thrust, F main extensional fault, P(1-4) selected climatic gauges, S(1-13) main springs, G streambed spring, H presumed water table elevation (m a.s.l.), I regional groundwater flowpath, J highway tunnel drainage (Lorenzi et al., 2022)

The Gran Sasso springs, located at the boundary of the system (Barbieri et al., 2005, Tallini et al., 2013) have a mean totale discharge between 18 m^3/s and 25 m^3/s which corresponds to a net infiltration of about 600 mm/year. The Gran Sasso aquifer is characterised by a hydraulic conductivity of 10^{-6}–10^{-7} m/s and a regional hydraulic gradient of 5–20 ‰ (Amoruso et al., 2013). At the massif core, an endorheic basin having a tectonic-karst origin, called Campo Imperatore basin (elevation 1650 m a.s.l.), acts as preferential recharge area of the Gran Sasso aquifer, fed by high rainfall and snow rate.

2.1.2 Water budget summary

The water budget of the Gran Sasso aquifer has been evaluated to improve the knowledge about its recharge rate with respect to the previously collected data. Following previous attempts (Scozzafava and Tallini, 2001) and with 20 years of climate data monitoring (2001-2020), two annual rainfall gradients have been calculated (see D2.2) (Lorenzi et al., 2022). By the same methodology applied for rainfall, an estimation of the temperature gradient and consequently isotherm map have been computed. Detailed information on water budget calculation is included in D2.2.
Moreover, to consider the snow contribution to the aquifer recharge, its monthly gradient has been assessed, by a correlation line between altitude and snow values in the period 1960-1990, referring to Fazzini and Bisci (1999). This gradient has been applied to the snow data recorded at the Campo Imperatore gauge (P4 in Figure 2.1 and in Table 2.1) to derive the recharge fraction due to snow melt (Lorenzi et al., 2022). In Table 1 the climate gauges selected to calculate rainfall, temperature and snow gradients are listed.

Id	*Name*	*Altitude [m a.s.l.]*	*Type of data*	*Period*	*Slope*	*Mean annual value*
P1	Campotosto	1344	Rain	2001-2020	Northern	1240 mm
P2	Assergi	991	Rain	2001-2020	Southern	850 mm
P3	Castel Del Monte	1346	Temperature	2001-2020	Southern	8.9 °C
P4	Campo Imperatore	2137	Snow	2010-2020	Southern	51.8 cm

Table 2.1: Climatic gauges selected as representatives for rainfall, temperature and snow parameters.

As explained in detail in D2.2 and D2.7, the hydrological budget for the Gran Sasso aquifer has been assessed using three different methods: Thornthwaite (Thornthwaite and Mather, 1957), Turc (1954), and Aplis (Andreo et al., 2008), for the 2001-2020 period.

Using the Turc method, the total average recharge value for the 2001-2020 period corresponds to 19.9 m^3/s, with a contribution due to snowmelt of 3.2 m^3/s. The mean evapotranspiration is 444 mm/y, while the average infiltration value from rainfall corresponds to 508 mm/y, added to 98 mm/y due to snowmelt. The year 2007 and year 2013 are the driest and the rainiest year, respectively. In 2007 the calculated recharge corresponds to 11.5 m^3/s (10 m^3/s from rainfall and 1.5 m^3/s from snowmelt), while in 2013 the total value of recharge reaches 30.7 m^3/s (Lorenzi et al., 2022). Figure 2.2 resumes the yearly recharge results obtained applying the Turc method.

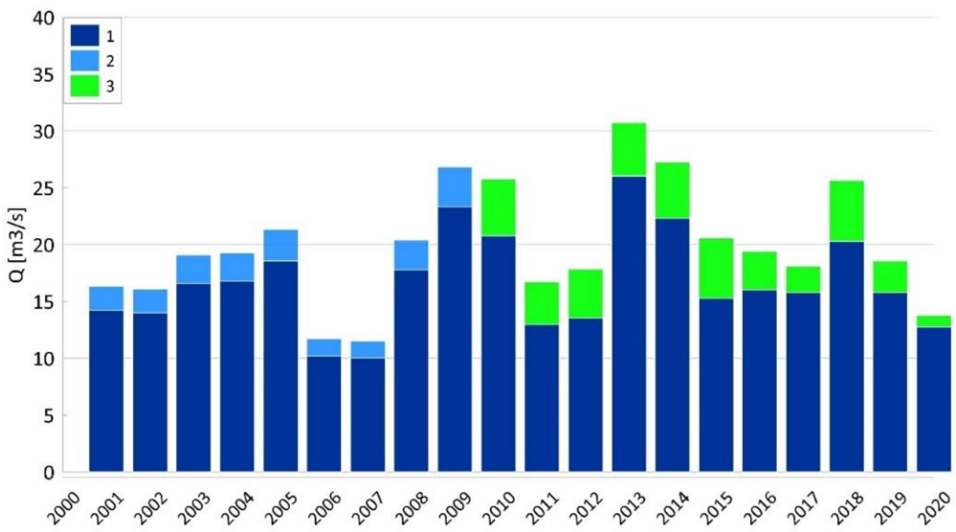


Figure 2.2: Yearly recharge results by Turc application: 1) recharge from rainfall; 2) estimated snow contribution (assumed as 15% of recharge); 3) calculated snow contribution

By the Thornthwaite method, a total average recharge for 2001-2020 period of 18.5 m^3/s (15.3 m^3/s from rainfall and 3.2 m^3/s from snowmelt) has been calculated. The real evapotranspiration value is 491 mm/y, while the total infiltration value is 558 mm/y, considering the infiltration from rainfall of 462 mm/y and infiltration from the snowmelt of 97 mm/y. Also in this case, the 2013 is confirmed as rainiest year, with a total recharge value of 27.3 m^3/s and a total infiltration value of 832 mm/y. On the other hand, as far as the driest year is concerned, this is identified as 2006, with a total recharge value of 9.8 m^3/s and with a total infiltration value of 297 mm/y (Figure 2.3) (Lorenzi et al., 2022). In addition, rainfall recharge obtained through both methods (Turc and Thornthwaite) over the entire monitoring period has been evaluated in terms of distribution over time and space (see D2.7 for more information).

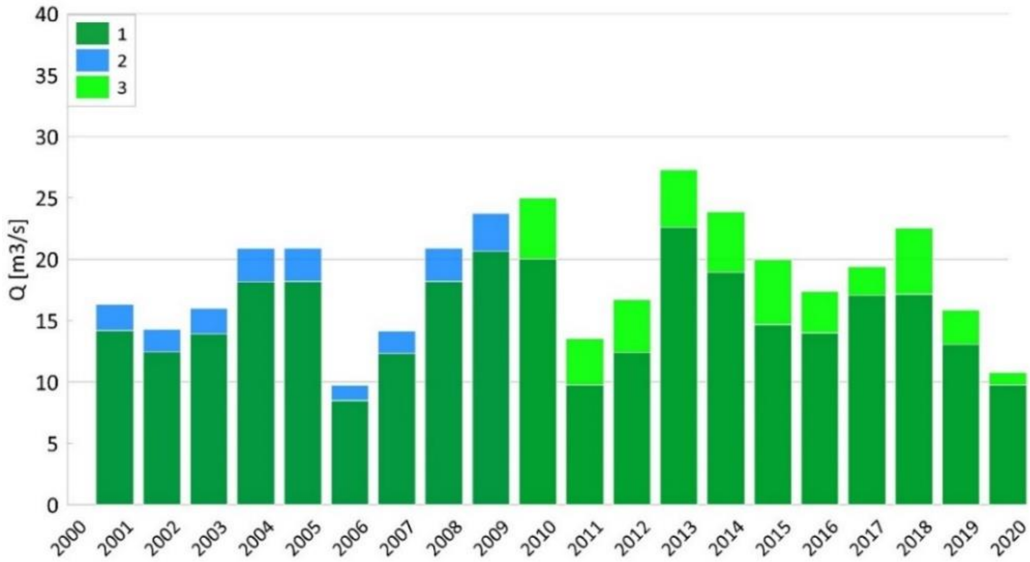


Figure 2.3: Yearly recharge results by Thornthwaite application: 1) recharge from rainfall; 2) estimated snow contribution (assumed as 15% of recharge); 3) calculated snow contribution

Through the Aplis method, the Gran Sasso aquifer recharge results in a percentage of effective infiltration of 51.6% with respect to total rainfall. The Gran Sasso massif, according to Aplis, is characterized by a preferential recharge area, the Campo Imperatore basin, with an infiltration rate of 76.7%. (Figure 2.4) (Lorenzi et al., 2022).

Overlaying the obtained recharge rate map (Figure 2.4) to the raster rainfall map obtained for each year, the yearly aquifer recharge has been evaluated (Figure 2.5).

The average recharge rate on long-term period is 19.4 m^3/s, and the average infiltration is 594 mm/y. The 2007 year represents the year with a minimum recharge rate of 13.7 m^3/s, while 2013 is characterised by the highest recharge rate of 21.3 m^3/s (Lorenzi et al., 2022). In D2.7 the results of long monitoring period (L), the driest (C) and the rainiest (R) years for the APLIS method are discussed.

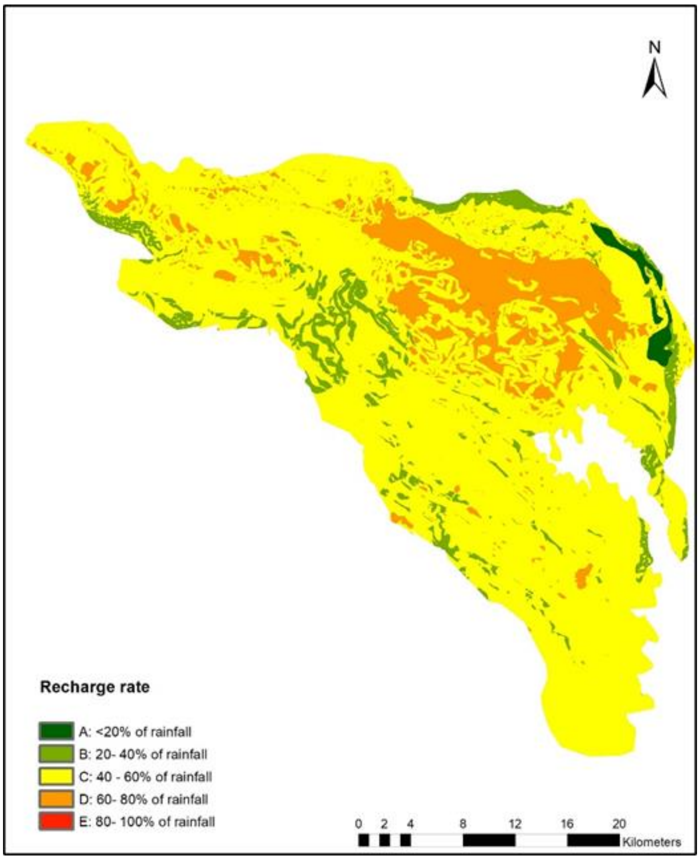


Figure 2.4: Recharge rate map obtained by Aplis method: letters refer to 5 infiltration rate classes (see D 2.2).

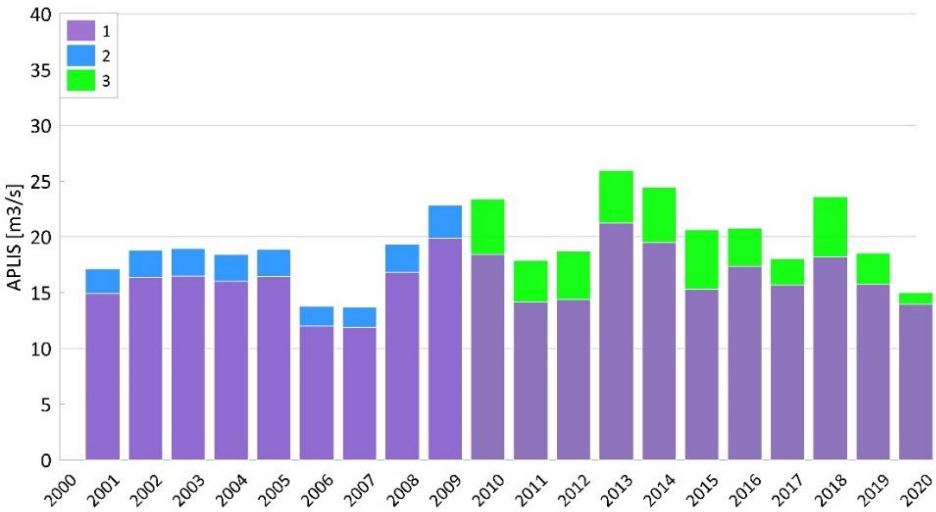


Figure 2.5: Yearly recharge results by Aplis application: 1) recharge from rainfall; 2) estimated snow contribution (assumed as 15% of recharge); 3) calculated snow contribution.

2.1.3 Water budget validation

To verify the reliability of the recharge values obtained with the application of different methods, the real total spring discharge (TSD) and the recharge values gathered from the three methods have been compared (Lorenzi et al., 2022). To assess TSD, all major springs have been considered (Figure 2.1). Figure 2.6 shows the comparison between the annual values of recharge obtained by the three applied methods and the measured discharge of the aquifer. Recharge obtained by Turc method and TSD values are well correlated (R^2=0.86) (Figure 2.6L), showing a slight overestimation of Turc method with respect to TSD for the rainy years and a slight underestimation for drought years. A similar match

(R^2=0.85) has been obtained by TSD and recharge calculated with Thornthwaite method (Figure 2.6C). In this case, a general underestimation of Thornthwaite method with respect to TSD has been observed, more evidently during driest years. The comparison between Aplis method and TSD shows the best alignment with respect to the X=Y line (Figure 2.6R) but with a lower correlation (R^2=0.81), confirming a slight underestimation trend of Aplis method with respect to TSD (Lorenzi et al., 2022).

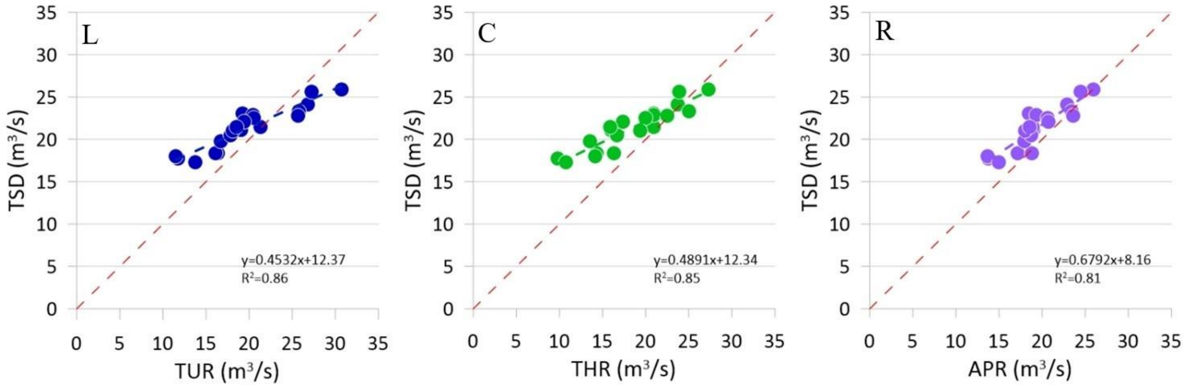


Figure 2.6: Correlation between the yearly recharge calculated in the three different methods: Turc (TUR), Thornthwaite (THR) and Aplis (APR) and the discharge of the springs (TSD) considered for each observation year.

Going deeper into the recharge – discharge comparison process, the annual mean discharge referred to each of the considered main springs of the Gran Sasso aquifer has been compared with the total recharge calculated with Turc method (Lorenzi et al., 2022). The position of the springs that have been considered are shown in Figure 2.1. Flow rate data for the monitoring period (2001-2020) are mainly provided by water suppliers and the Regional Environmental Agency. The mean discharge value of each spring for the period 2001-2020 is summarised in D2.7.

The discharge of springs located on the northern side of the Gran Sasso massif (S1 to S6 in Figure 2.1) shows a fast response to annual recharge variations. A clear example is represented by the Rio Arno spring (S2 in Figure 2.1), fed by the top level of the aquifer (Tallini et al., 2014). In fact, as shown in Figure 2.7, the annual Rio Arno spring discharge (blue dots) follows the variation observed for Turc method (orange bars).

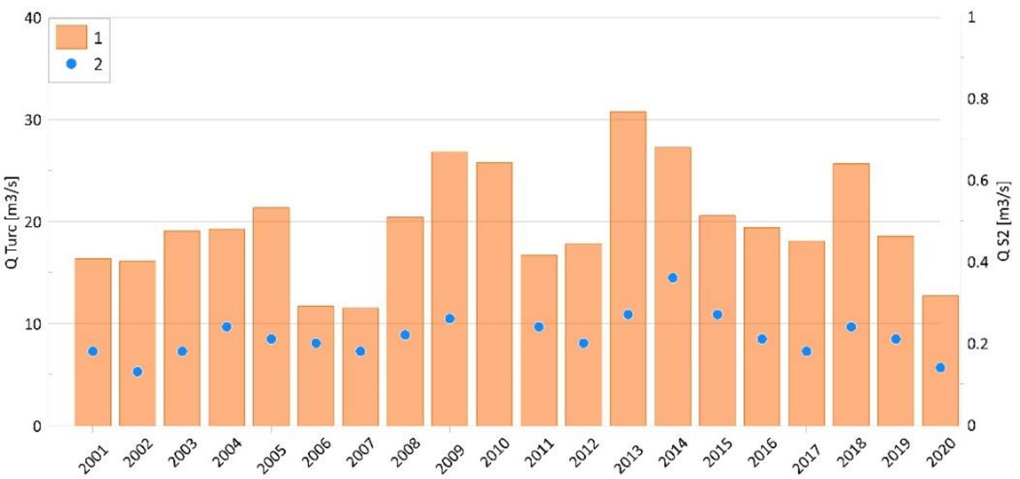


Figure 2.7: Comparison over time between calculated recharge with Turc method and S2 (in Figure 1) spring discharge (2); missing dots (2010) correspond to unavailable data periods.

Conversely, springs monitored on the southern side (S7-S13 in Figure 2.1) reflect the variation in aquifer recharge with some delay. The southern drainage discharge of the highway tunnel, for example, (S10 in Figure 2.1) is correlated with aquifer recharge after one year of delay (Figure 8a). The delay is more evident at the Tirino River (S9 in Figure 2.1), whereby the annual Turc value shows its effects approximately by a two-years delay (Figure 2.8b).

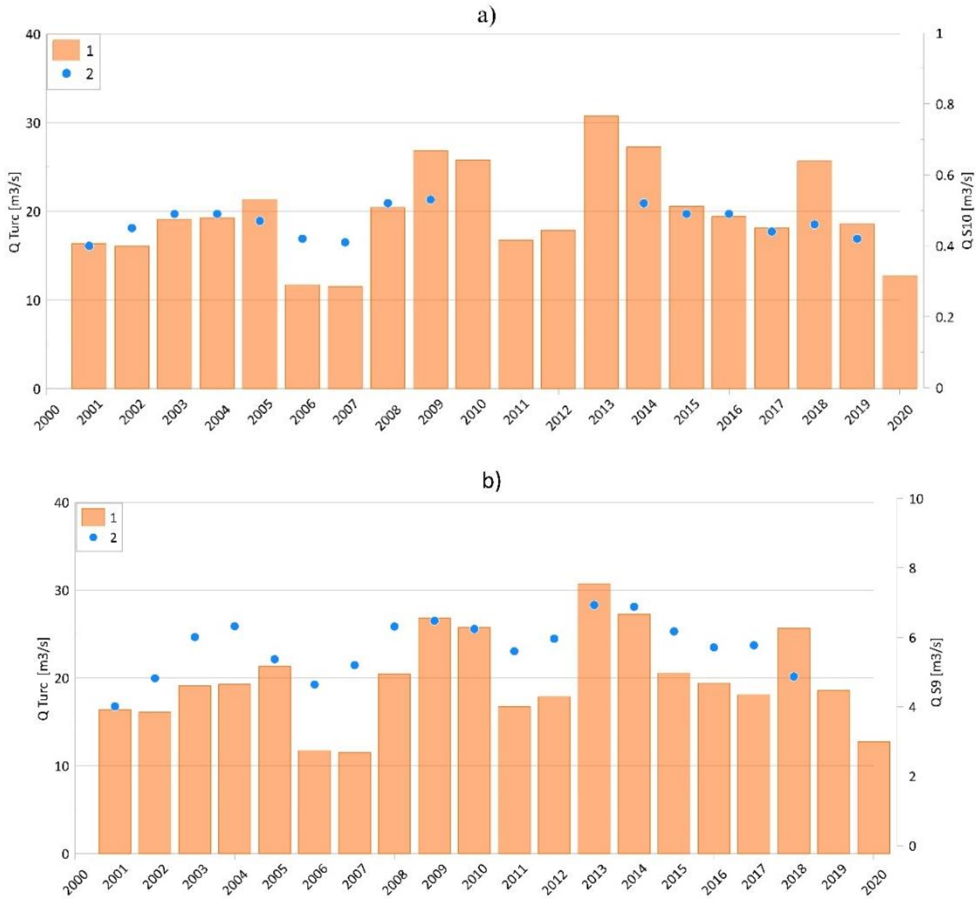


Figure 2.8: Comparison over time between calculated recharge with TUR (1) and discharge (2): a) one-year shifted S10 discharge and b) two-years shifted S9 discharge; missing dots mean not available data period.

2.2 The Qachqouch aquifer (Case Study Lebanon)

2.2.1 Synopsis on budget analysis

Three main methods were used to estimate recharge on the Qachqouch Catchment: 1) The Water Balance Method, 2) the APLIS Method, 3) the Numerical Modelling Approach. It was assumed that the Qachqouch spring is the only source draining the delineated catchment area. Additionally, the analysis of stable isotopes allowed to define the recharge elevation and infiltration that was not considered in the original delineation of the spring catchment.

2.2.2 Catchment delineation

The delineation of the catchment area plays an important role in the assessment of total recharge in all the adopted methods. The catchment was outlined based on geological information and conceptual boundary conditions (River, catchments of adjacent non-connected springs etc.), however information from isotopic signatures show that the spring receives a snow component which can be better quantified with a longer time series. The values of $\delta^{18}O$ and $\delta^{2}H$ vary respectively between -7.67 and -

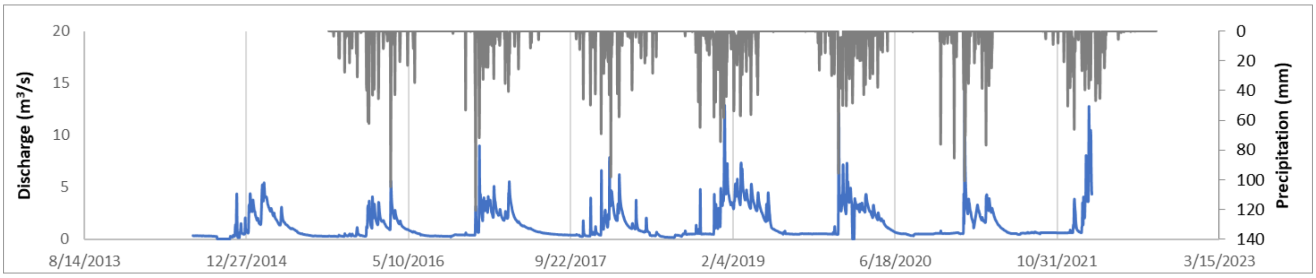
6.08‰, and -36.16 and -23.61‰ with means of 6.58‰ and 28.48‰ for n=141 samples. The distribution of stable isotopes values helps assess qualitatively the extent of the catchment, indicate altitudes ranging between 1000 and beyond 1500 m, which extends beyond the Jurassic Aquifer exposure.

The tracer experiments have shown that the river contributes from 3-5 % to the flow in the spring (Doummar and Aoun, 2018b). However, since the river fed by snowmelt from April to June, infiltrates into a sinking stream in the lower parts of the catchment and influences the stable isotope signature in the spring, the differentiation between allochthonous and autochthonous discharge can be done based on the detailed analysis of isotopic time series over more than a year. An infiltration of overflow may also occur in the Jurassic downstream exposures allowing for a delayed recharge and an increased storage effect (Dubois et al., 2020). Additionally, previous isotopic studies have shown that a ratio of more than 75 % should be coming from high altitudes than 800 m rather from the direct catchment at lower altitudes. This is in accordance with the presence of dolostones and point source infiltration (dolines) at these altitudes. Therefore, the area of the catchment may be higher than expected, or overland flow needs to be accounted for while computing the water balance of the Qachqouch Spring.

2.2.3 Comparison of the three methods

Water Balance

After the correction of discharge made to decrease uncertainties, especially in values observed in high flow where calibration curves are not applicable and where effective flow measurements were impossible, the estimation of recharge was estimated ***using the water balance method***. The total discharge of the spring varied between 30-76 hm^3/y, where 50%-73% of the budget consists of infiltrated water variably depending on the amount of precipitation and its intensity during a wet, dry or intermediate year (Figure 2.9; Figure 2.10). Potential evapotranspiration calculated using the Penman-Monteith method yield an overestimated evapotranspiration that cannot be used in water balance in the absence of a soil water balance model (Dubois et al., 2020).



Errore. L'origine riferimento non è stata trovata.*2.9: Precipitation volumes (1-hr) and discharge rates collected during the duration of the Karma Project with historic data (since 2014)*

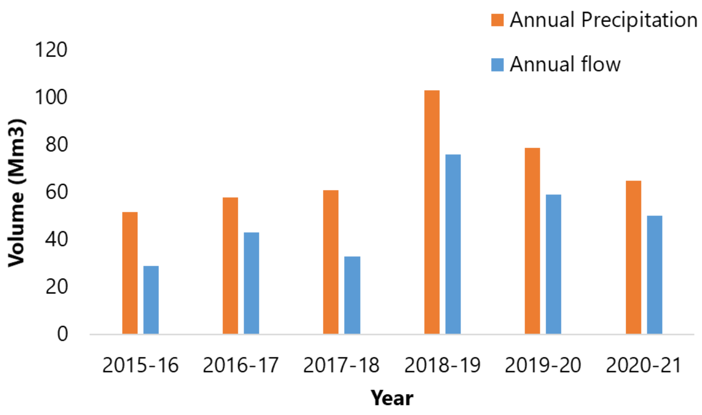


Figure 2.10: Recharge estimated based on the water balance method

Aplis Method

The recharge amounts estimated using the APLIS method were underestimated with respect to the other methods and to the discharge observed at the spring (Table 2.2). The recharge may vary according to the rain intensity, overland flow from layers outside the catchment, and saturation in the subsurface. However, the amount of recharge estimated using APLIS fall well within the ranges of spring discharge. A sensitivity analysis allowed a better understanding of the effect of varying APLIS parameters on the resulting recharge map.

Class (mm)	Wet year			Dry year			Intermediate year		
	Area (km^2)	Volume (Mm^3)	% of A_t	Area (km^2)	Volume (Mm^3)	% of A_t	Area (km^2)	Volume (Mm^3)	% of A_t
0-200	17.64	1.8	34%	17.64	1.8	34%	17.64	1.8	34%
200-400	0.97	0.3	2%	1.41	0.4	3%	0.01	0.0	0%
400-600	4.40	2.2	8%	15.17	7.6	29%	6.12	3.1	12%
600-800	14.20	9.9	27%	17.55	12.3	34%	22.44	15.7	43%
800-1000	14.24	12.8	27%	0.05	0	0%	5.62	5.1	11%
1000-1200	0.38	0.4	1%	0.00	0	0%	0.00	0.0	0%
Total (Mm^3)		**27.5**	**±5 Mm^3**		**22.1**	**±5 Mm^3**		**25.6**	**±5 Mm^3**

Table 2.2: Recharge classes, areas, and total average recharge values in m^3 per class area and as a percentage of the total area (A_t) as computed with APLIS

Numerical Models

The modelling approach using a lumped model with three reservoirs yielded similar results to the water balance methods for the years 2016-2018 (Dubois et al., 2020). In the baseline scenario (2016-17), the modelled precipitation, and evapotranspiration were respectively 966 mm, and 167 mm (17.2%) over a total catchment area of 56 km^2. Recharge was estimated to be between 70-82% of the total budget accounting for a high level of overland flow. The modelling using Karstmod (Cinkus et al., 2022) in WP4 yielded similar results.

2.3 The Djebel Zaghouan aquifer (Case Study Tunisia)

2.3.1 Study area

The Djebel Zaghouan is the most important Jurassic of the Zaghouan massif and it is located at about fifty kilometers from Tunis (Tunisia). This massif is constituted by monoclinals of limestone overlapping one on the other. It is also made of marls of the Cretaceous and Eocene (Castany, 1951). The Djebel Zaghouan is characterized by the presence of southern and transverse faults that have created individualized blocks. These faults allow the infiltration. The Zaghouan karst aquifer is about 19.6 km² area (Figure 2.11). It has an eastern part favorable to the storage of seepage water, contrary to its western part, its western part where marl deposits strongly decrease the storage coefficient (Djebbi, et al., 2001).

The geology of Djebel Zaghouan has made it an important water reserve used since antiquity for the water supply of Carthage, then Tunis. The Roman aqueduct (120 A.D.), still very well preserved, which connects the water temple to the city of Carthage, can be seen along the road linking Tunis to Zaghouan. Currently, the aquifer is 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 used as commercialized mineral water.

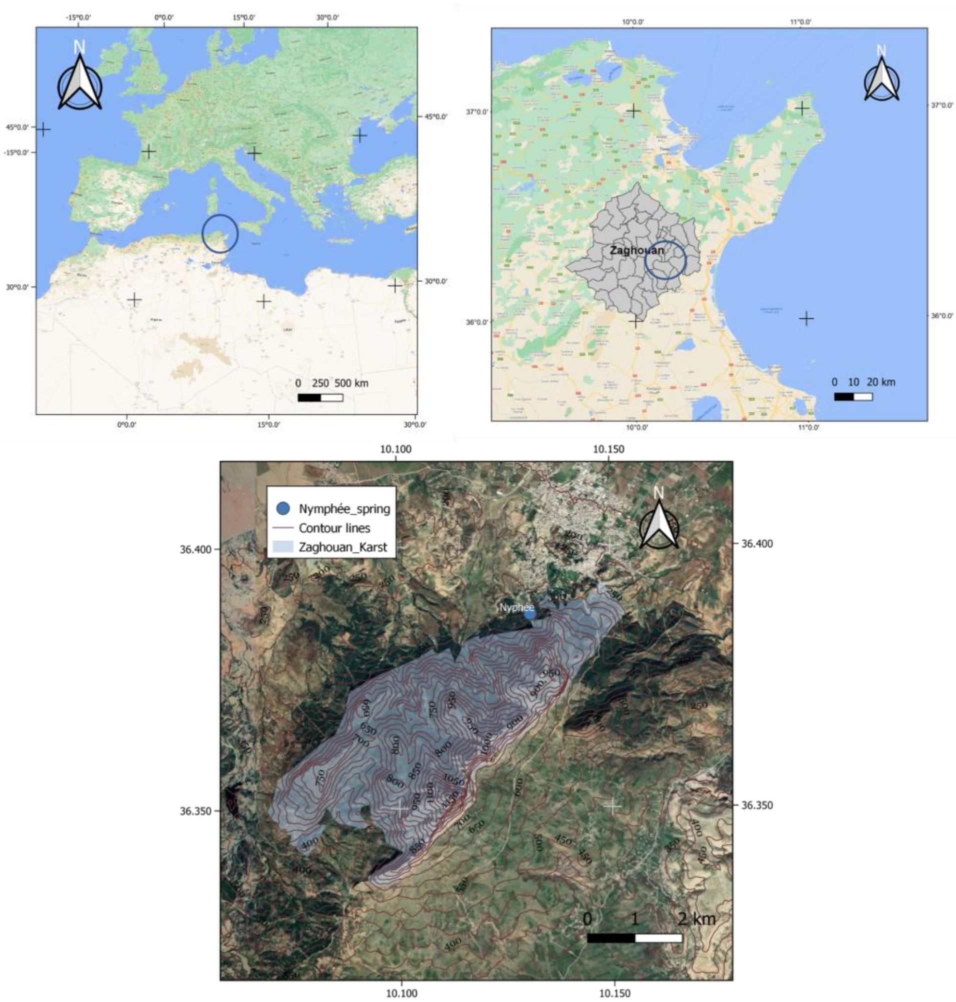


Figure 2.11: Location of the Djebel Zaghouan karst aquifer

2.3.2 Results of budget analysis and uncertainties

The water budget was principally based on the modeling study performed by (Djebbi, et al., 2001) and Sagna (2000). This study proposed to assess the water balance and to quantify the storage capacity of the aquifer associated with the Jurassic limestones of Djebel Zaghouan. The available flow data corresponding to the natural flow period was recorded from 1915 to 1927. Figure.12 presents the Zaghouan springs production before the digging of the galleries and Zaghouan springs production with exploitation by the galleries respectively. The natural flow period was marked by heavy rainfall of the 1920-1921 and a low rainfall during the 1926-1927 hydrological years, which resulted in high spring flow (6.5 hm^3/y) and a very low flow of 1.9 hm^3/y respectively. These observations are in conformity with the natural flow of the resurgences during this period.

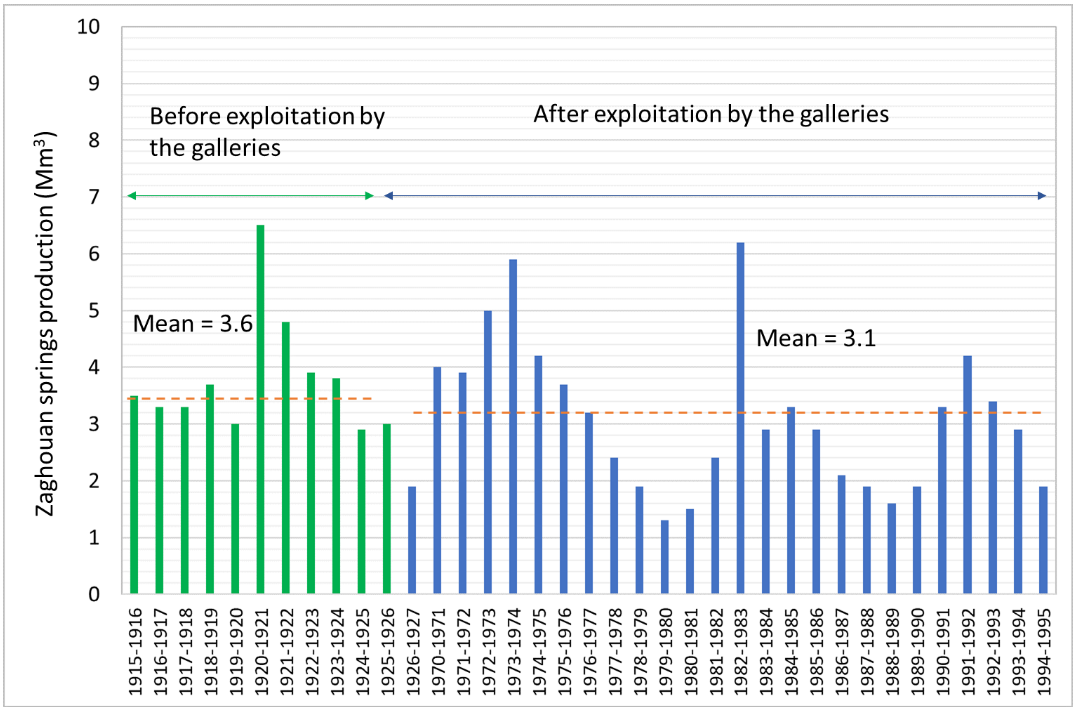


Figure 2.12: Zaghouan springs production (10^6m^3)

Sagna (2000) considered the most continuous and overlapping series of both dry and wet years. The average interannual rainfall calculated over a time series of 47 years was 501 mm with a standard deviation of 170 mm. Observations were recorded at the TPSM rainfall station. Temperature was taken from bibliography and monthly mean evapotranspiration was calculated using Thornwaith formula.

(Djebbi, et al., 2001) and Sagna (2000) also developed a conceptual deterministic model to transform the rainfall received by the calcareous solid mass into the sum of the discharge flows (springs and galleries). The model was validated using meteorological and hydrodynamic collected data. Calculation time step is daily. Model was run for a calibration period corresponding to the natural functioning of the system from 1915 to 1927 and a validation period from 1970 to 1995 including the aquifer exploitation via galleries and wells. The performance of the model was acceptable with a Nash criterion ranging between 0.54 % and 0.77 %.

Table 2.3 and 2.4 provide Djebel Zaghouan water budgets summary (rainfall, infiltration rate, runoff and evapotranspiration) for the calibration and the validation period respectively. It provides (all of which represent the components of a natural water budget (1915-1927)) (Sagna, 2000), after the classical methodology of calibration and final validation in the model.

Year	Rainfall (mm)	Flow (hm^3/y)	RET (hm^3/y)	Runoff (hm^3/y)	Water budget (%)	Infiltration coefficient (%)
1915-1916	480	3.4	4.5	0.37	110	38
1915-1917	461	3	6.1	0.21	93	35
1915-1918	442	3	4.8	0.29	103	36
1915-1919	550	4	4.8	0.45	113	38
1915-1920	347	3	4.7	0.15	83	47
1915-1921	867	5.2	7.1	0.75	126	31
1915-1922	393	5	3.4	0.32	84	68
1915-1923	400	4	4.1	0.28	91	53
1915-1924	525	4.4	4.8	0.41	103	45
1915-1925	380	3.4	4.8	0.2	86	48
1915-1926	520	2.9	7	0.21	95	30
Average	488	3.8	5.1	0.33	99	43

Table 2.3: Water budget for the calibration period (1915-1927)

Errors and uncertainties are principally due to methods and time step measurement as well as data processing. Indeed, discharge series were available in graphical form (Figure 2.13) from 1915 to 1927 at irregular time scales. Discharges were then obtained by linear interpolation on a daily scale. Thus, several sources of uncertainties are issued from the rough data and its interpolation. In fact, measurements were taken on a weekly, twice-weekly, or once-monthly basis rather than daily (Figure 2.13). Besides, we can cite uncertainties related to the measurement techniques used at the beginning of the 20th century and based on weirs and their calibration curves.

Besides, and since the installation of the valves to control the flows supplied by the galleries, the system is no longer natural. The flows observed from 1958 to 1962 and from 1971 to 1995 are very random and indicate that they are highly dependent on the openings of the gates. These openings depend on several contingencies, in particular the daily demands made by SONEDE to meet the water needs of its users.

The rainfall data comes from the TPSM station, which is situated at 184 meters altitude. They span the years March 1908 to August 1998, but there are significant gaps in the data. Records from the nearby DGRE station have helped fill in some of the gaps.

Due to the lack of daily potential evapotranspiration data, it was calculated on a monthly scale using Thornwaith's method based on monthly mean temperatures and the massif's latitude. The average monthly temperatures were taken at the Kébir dam, which is 37 kilometers from Zaghouan.

Year	Rainfall (mm)	Flow (hm^3/y)	RET (hm^3/y)	Runoff (Mm^3)	Water budget (%)	Infiltration coefficient (%)
1970-1971	448	4.3	3.2	0.42	93	50
1971-1972	642	5.3	5.7	0.51	94	43
1972-1973	686	6	5.2	0.6	92	46
1973-1974	547	5.9	4.9	0.4	108	57
1974-1975	472	4.7	4.6	0.3	109	53
1975-1976	506	4	6.2	0.3	110	42
1976-1977	341	3	4.1	0.2	114	48
1977-1978	373	2.5	5.1	0.16	110	35
1978-1979	352	2.3	4	0.2	98	34
1979-1980	425	1.9	6.7	0.1	108	23
1980-1981	339	1.9	4.3	0.17	99	30
1981-1982	409	2.3	4.6	0.25	92	30
1982-1983	641	5.5	3.4	0.7	79	46
1983-1984	252	2.7	4.6	0.02	154	57
1984-1985	551	3.2	5.8	0.37	90	31
1985-1986	334	2.5	4.5	0.15	113	40
1986-1987	498	3	5.7	0.3	96	33
1987-1988	232	1.6	4.4	0	137	37
1988-1989	273	1	4.1	0.05	101	21
1989-1990	609	2.5	7	0.39	86	21
1990-1991	567	4.4	4.3	0.52	85	40
1991-1992	687	4.8	7.6	0.44	98	37
1992-1993	463	3.8	5.6	0.26	110	44
1993-1994	292	2.7	4.1	0.1	126	49
1994-1995	192	1.4	3.6	0	138	38
Average	445	3.3	4.9	0.28	106	39

Table 2.4: Water budget validation of model (1970-1995)

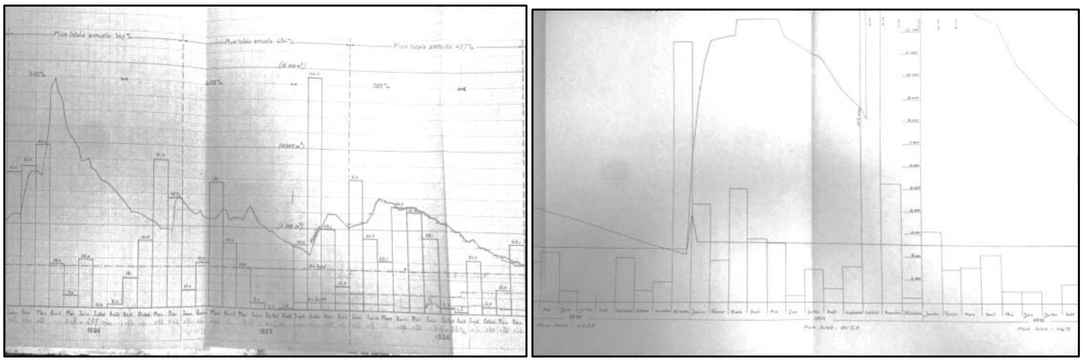


Figure 2.13: Examples of non-digitized discharge from 1915 to 1930

2.4 Merinos-Colorado-Carrasco and Ubrique test site (case study Spain)

2.4.1 Merinos-Colorado-Carrasco aquifer

2.4.1.1 Test site description

The Merinos-Colorado-Carrasco system (Eastern Ronda Mountains) is located, approximately, 20 km to the east of Ronda city and is composed by the three -so called- Sierras which show an alignment in direction NE-SW. The stratigraphic sequence is defined by three main groups (Martín-Algarra, 1987): clays with Triassic evaporites, Jurassic limestones (upper) and dolostones (lower), 500 meters thick and Cretaceous-Paleogene marly-limestones. This site presents outcrops of Flysch sandstones and clays (Cretaceous-lower Miocene) represented in the eastern sector (Figure 2.14) and overthrust the previously mentioned geological formations. Discordant above the upper Miocene sequence, calcareous sandstones of the Ronda basin are found in the western part. The geological structure is constituted by box-type folds, oriented NE-SW and plunging toward NE (Martín-Algarra, 1987).

From a hydrogeological outlook, Jurassic limestones cover a large area in the study area and these (aquifer) lithologies are represented on surface, as karst exposures, or in depth, as buried aquifer segments. Dolomitic rocks, which comprise the lower levels of the Jurassic aquifers, can reach higher positions in the lithological sequence, and even appear on surface. Gypsum bearing formations (Triassic clays with gypsum), which thickness is still imprecise, constitute the lower limit of the main aquifers and can uplift through faults.

Recharge takes place by rainwater infiltration through limestone and dolostone outcrops, while discharge is made through springs located at the borders, between the permeable carbonate rocks and the impervious layers (Cretaceous marly limestones and clays from Flysch). Hence, several outlets emerge in the middle of cretaceous rocks where Jurassic limestones are shallower (Figure 2.14).

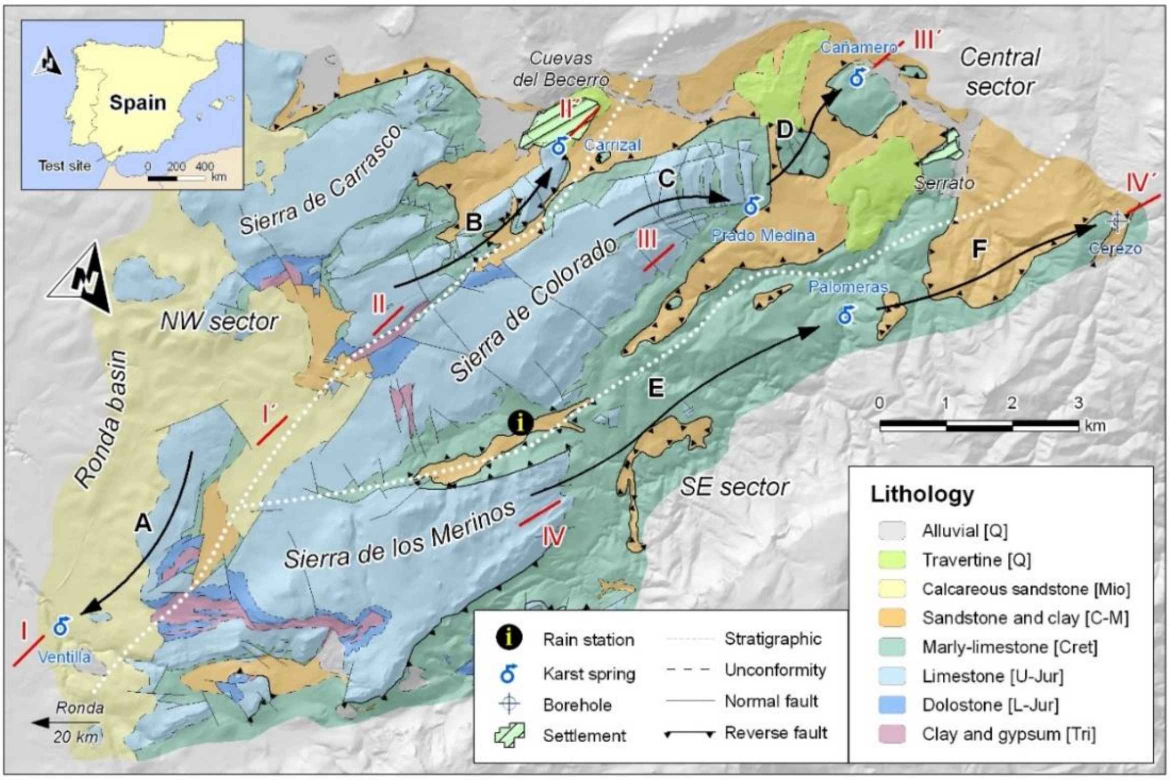


Figure 2.14: Hydrogeological setting of Merinos, Colorado y Carrasco aquifer (Barberá et al., 2012)

Three hydrogeological sectors have been identified in this area, on the basis of strictly geological, hydraulic and hydrochemical criteria: 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).

In Merinos-Colorado-Carrasco test site recharge area is mainly composed by surfaces located at high altitude (700-900 m.a.s.l.) and mean annual precipitation has been estimated to 733 mm (31.7 hm^3/year) by isohyet planimetry (Barberá, 2014) (Figure 2Figure.15). This aquifer system is highly karstified and carbonate formations constitute preferential zones for direct infiltration which correspond to karren fields, dolines and uvalas.

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.), Prado Medina (660 m a.s.l., an overflow type associated with the latter), Palomeras (560 m a.s.l.) and Carrizal (740 m a.s.l.). In addition, groundwater transference toward the porous aquifer of the Ronda basin (overlying the Jurassic aquifer) exists and, the shallower (visible) discharge takes place via Ventilla spring (740 m a.s.l.).

2.4.1.2 Hydrodynamic characterization. Spring discharge monitoring

The hydrodynamic characterization has been carried out through spring discharge data analysis, both from the historical record (Barberá, 2014; Sánchez et al., 2018) as well as from the hydrodynamic data obtained during the investigation period.

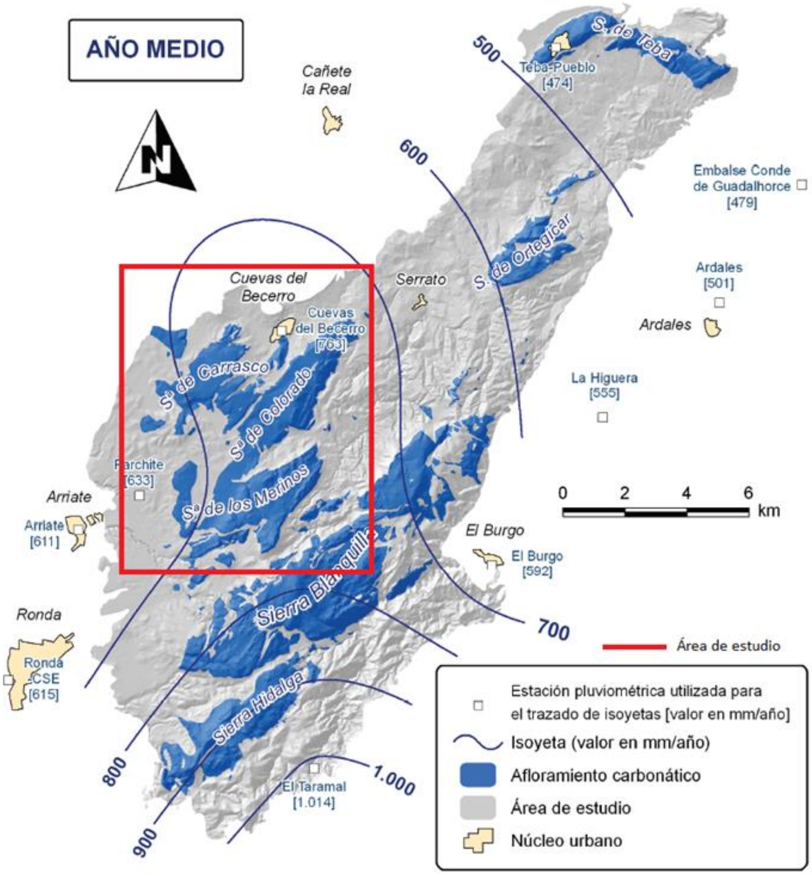


Figure 2.15: Isohyet map corresponding to mean year on the historical period 1964/65-2009/10 (Barberá, 2014)

The continuous spring discharge monitoring during KARMA study period allowed complete hydrodynamic control of springs. The main statistical variables (minimum, maximum and mean spring discharge) are described in Table 2.5Table . The three springs in Eastern Ronda Mountains show similar minimum values than in previous long-term research (Barberá, 2014) but ≈9 times lower maximum spring discharge.

	KARMA study period			Previous researches		
Spring	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**
Cañamero	18.9	497.3	135.2	24.9	4530	374
Carrizal	2.15	85.5	22.7	0.6	783	86
Ventilla	0.5	24.2	11.5	2	163	38

Table 2.5: Main statistical descriptors (maximum, minimum and mean) of spring discharge values in Merinos-Colorado-Carrasco test site

Time series of spring discharge measured through continuous recording equipment springs of the Eastern Ronda Mountains are shown in Figure 2.16. These data, jointly to historical data, allow to analyze the recession curve by well-known methods in karst hydrogeology and allow to measure spring discharge with high accuracy. The comprehensive analysis of spring discharges at this test site showed a totally different hydrogeological functioning regarding discharge rates and hydrograph shapes. Ventilla spring hydrographs suggest a complex hydrodynamic functioning which is conditioned by the groundwater transfer from the Jurassic formations to the Miocene basin of the Ronda depression and the discharge through calcareous sandstone. Carrizal spring, in contrast, appears to show a more inertial behaviour and lower karstification degree. Finally, Cañamero spring shows the highest discharge rates of Eastern Ronda Mountains and the typical karst behaviour, with steep rising limbs and softer recession curves.

The details about the monitoring of the main springs of Sierras of Merinos-Colorado-Carrasco aquifer can be found in D2.6.

2.4.1.3 Water budget summary

The recharge rate of this aquifer was estimated using APLIS (Andreo et al., 2004 y 2008; Marín, 2009), as it introduces a higher number of parameters and gives more accurate results than those obtained with Thornthwaite (1948), Kessler (1967) methods in comparison with historical records (1964/65-2009/10) (Barberá, 2014) (for additional information about water balance see D2.1).

APLIS showed up a mean recharge rate for Sierras of Merinos, Colorado and Carrasco of 56,71 % with a diverse spatial distribution due mainly to altitude differences (see details in D2.2). As annual mean precipitation (P) for the historical period is 31,7 hm3/year, a value of effective runoff (PU) of 17,9 hm3/year is therefore estimated (Figure 2.17). The total recharge obtained through APLIS method for each scenario is presented in Table 2.6.

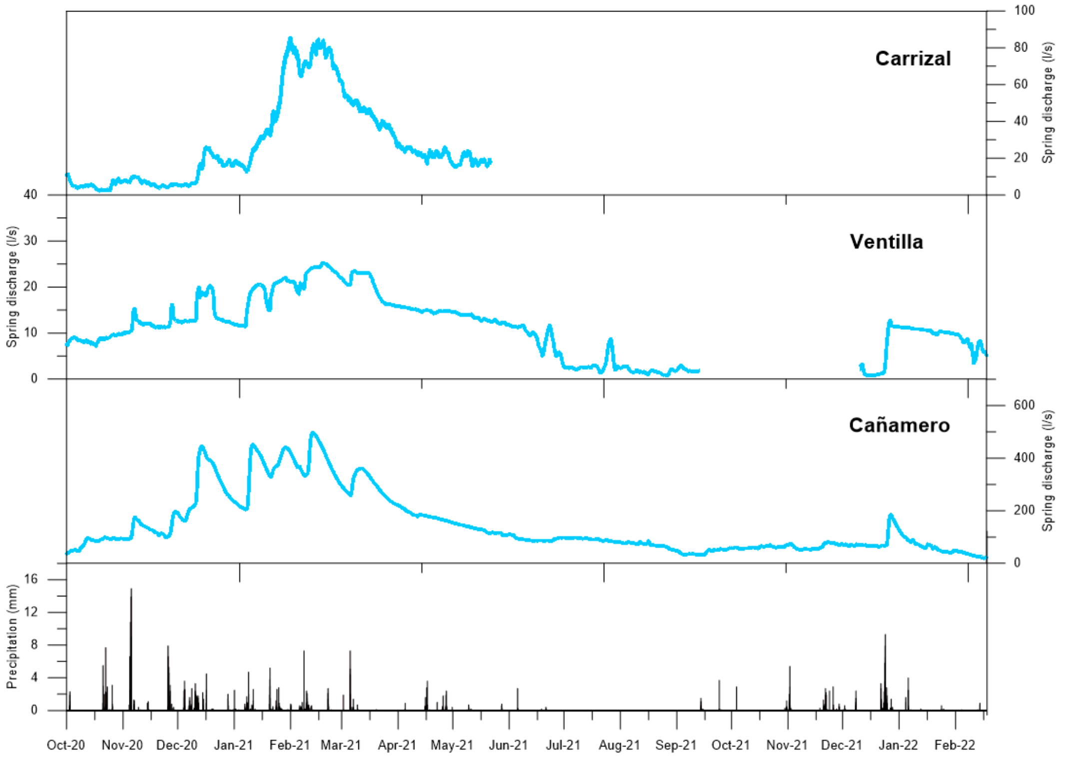


Figure 2.16: Time series of spring discharge at the main drainage points of Eastern Ronda Mount

	Wet (2009/10)	Average (64/65-09/10)	Dry (1998/99)
Total recharge (hm^3/yr)	29.25	17.96	8.01

Table 1.6: Total volumes of recharge at Merinos-Colorado-Carrasco test site obtained through APLIS method.

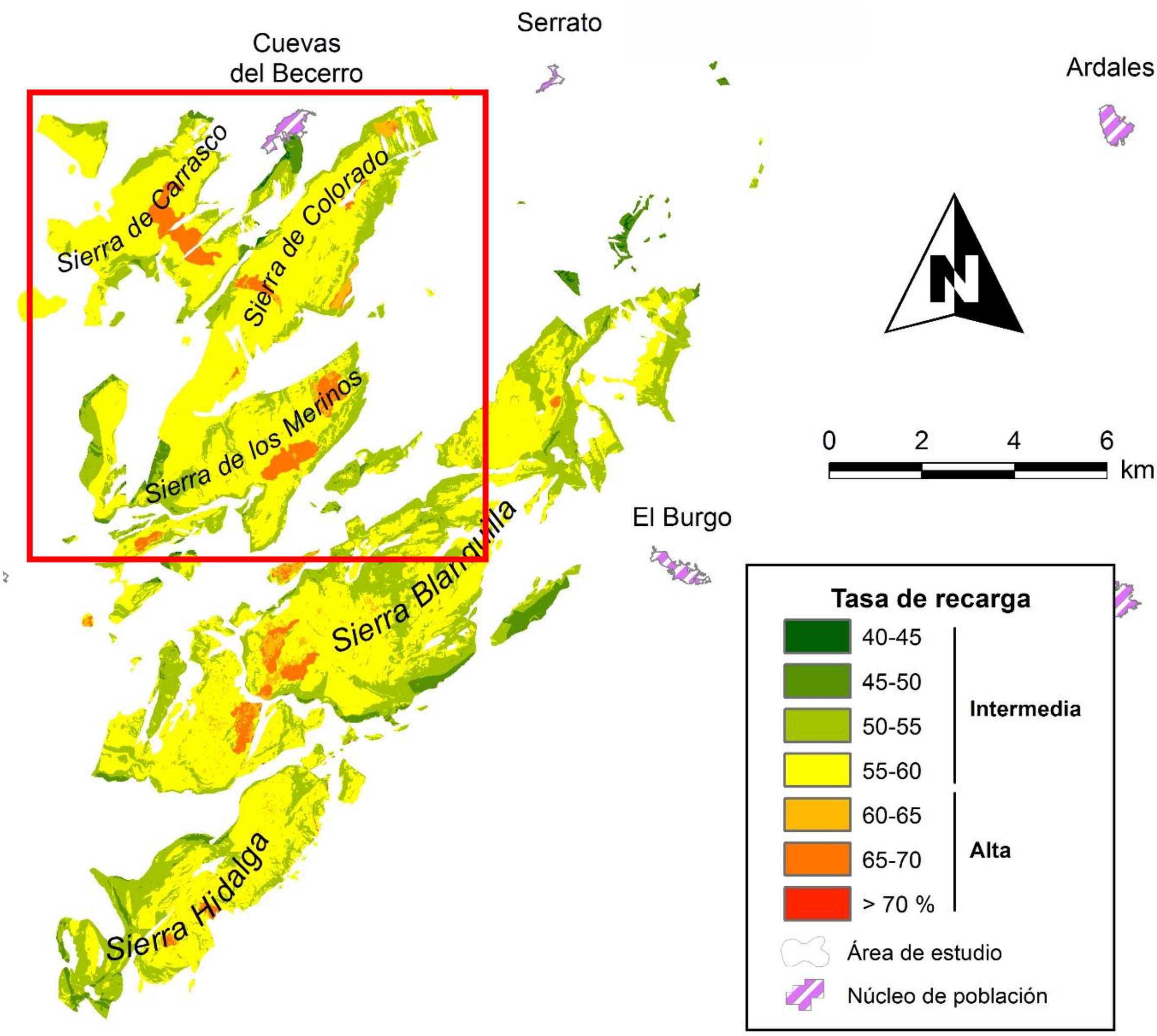


Figure 2.17: Recharge rate distribution obtained through the application of APLIS method for Merinos-Colorado-Carrasco test site (on red box) (modified from Barberá, 2014)

2.4.2 Ubrique aquifer

2.4.2.1 Test site description

The Ubrique aquifer is a binary karst system located at NE of the Cádiz province, southern Spain (Figure 2.18). It has a total surface of 26.06 km^2, of which 24.03 km^2 are constituted by permeable limestones and dolostones outcrops and the remaining 2.03 km^2 constitutes the effective endorheic area of the Villaluenga swallowhole (comprised of Flysch complex clays and sandstones). The karst system is formed by two mountainous massifs (Caíllo and Ubrique Sierras) with an irregular topography (altitude ranges from 317 to 1395 m a.s.l.) and constituted by Jurassic limestones and dolostones, which are considered as the main aquifer lithologies (Martín-Algarra, 1987). The geological structure is characterized by NE-SW open anticline folds and narrow synclines, affected by reverse faults which give place to overthrusts developed with vergence N-NW. A complex tectonic structure of imbricate thrusts, locally folded, with Cretaceous marls below the Triassic thrust basement is found. The entire structure has been affected by normal faults, in a mainly NNO – SSW direction, and oblique strike-slip fractures, caused by extensional accommodation of prior structures (Martín-Algarra, 1987).

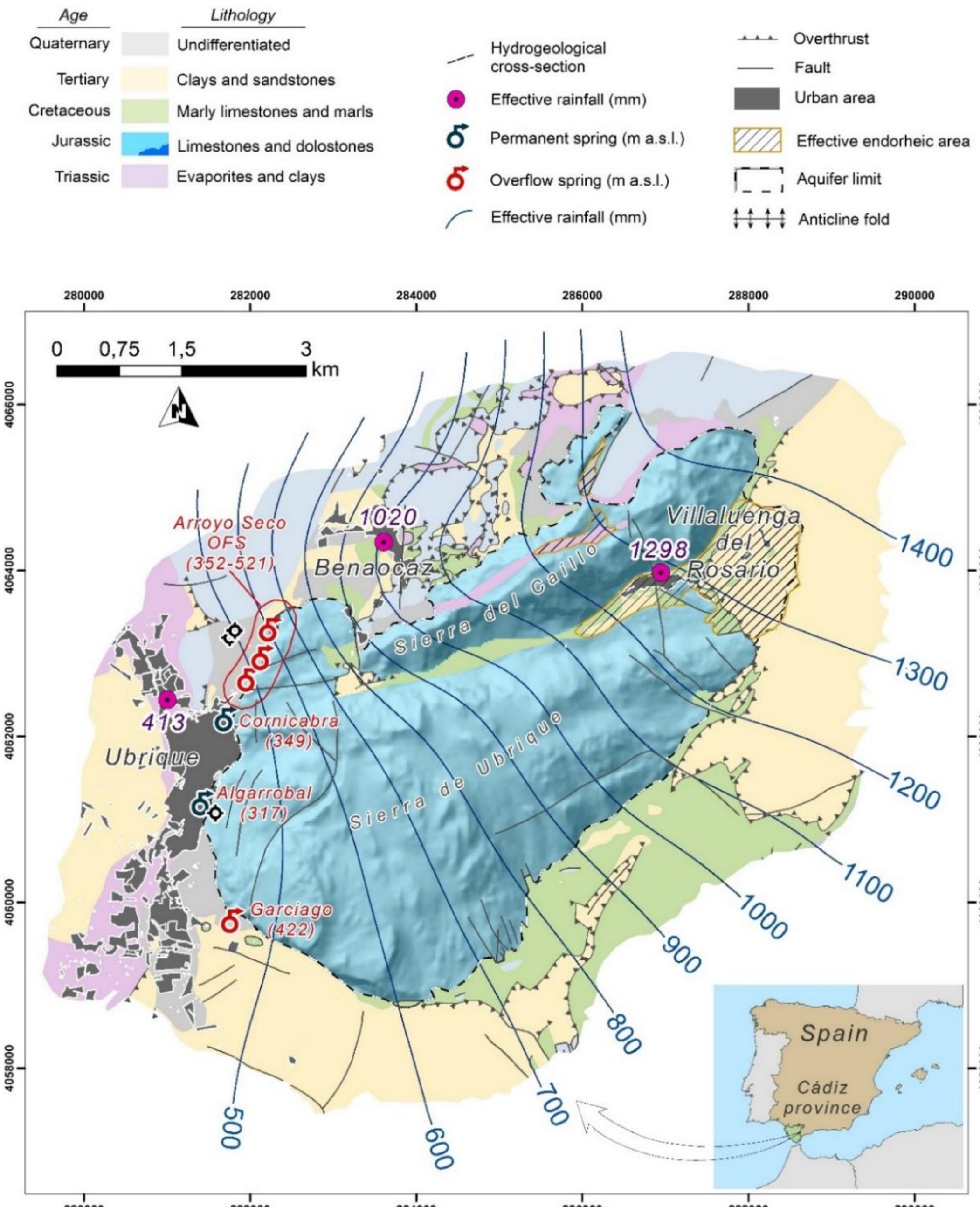


Figure 2.18: Hydrogeological setting of the Sierra de Ubrique aquifer system

The climate regime in the area is Mediterranean-humid type, with a marked seasonal pattern in the annual distribution of precipitations and air temperature. Rainfall mainly occurs from autumn to spring, related to wet winds coming from the Atlantic Ocean. The mean annual precipitation values recorded in this area (2012/13 to 2017/18) were 1,288 mm.

Spatial distributions of precipitation values are mostly determined by the altitude and the orientation of major hillsides. Its quantification has been carried out by mapping the single rainfall values provided by nearby stations (Figure 2.18). The large outcrops of highly fractured Jurassic limestones, together with the prevailing climate conditions, enhanced the development of exokarst landforms (Delannoy, 1987; 1999) and the existence of high annual average of available water resources.

The most part of the recharge area range between 600 and 1200 m.a.s.l. and presents abundant surfaces with slope below 30%, which cause very low runoff generation. Lithology favors the development of karstification, and thus, infiltration landforms such as karren fields and dolines can be found over the carbonate outcrops especially in the top areas. Some of the dolines and swallow holes that exist in this area are highly developed and numerous speleological expeditions have been documented. Thus, in Ubrique test site, the recharge takes place mainly by the infiltration of rainwater through limestone outcrops and an allogenic recharge which enters the system through Villaluenga del Rosario shaft.

Groundwater discharge appears along the eastern border of the carbonate outcrops, through two perennial springs located within Ubrique urban area (Cornicabra and Algarrobal springs, located at 349 and 317 m a.s.l., respectively), plus the overflow spring located at the southwestern border of the Sierra de Ubrique (Garciago, 422 m a.s.l.) and a group of minor overflow springs located nearby Cornicabra spring (Arroyo Seco OFS 352-521 m a.s.l.).

Several dye tracer tests carried out during 2018 spring (Marín et al., 2021; Martín-Rodríguez et al., 2022) allowed to verify the hydrogeological connection among several infiltration points located in the recharge areas of the aquifer and the main springs that drained the aquifer. This allowed us to define the system boundaries and characterize key features of the hydrogeological functioning, such as mean flow velocities, recovery rates and preferential drainage flow paths.

2.4.2.2 Hydrodynamic characterization. Spring discharge monitoring

The hydrodynamic characterization has been carried out through spring discharge data analysis, both from the historical record (Sánchez et al., 2017) as well as from the hydrodynamic data obtained during the investigation period.

The main statistical parameters (minimum, maximum and mean spring discharge) are described in Table 2.7. As this table shows, the maximum spring discharge during KARMA study period is 1,604 l/s for Cornicabra spring, 917 l/s for Algarrobal and 4,518 l/s for Garciago spring. However, the maximum spring discharge values since 2013 (Andreo and Sánchez, 2013; Sanchez et al., 2017) are slightly higher than those observed during KARMA study period.

	KARMA study period			**Previous researches (2012/13 – 2017/18)**		
Spring	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**
Cornicabra	2	1604	123.66	23	2623	324
Algarrobal	8.23	917	287.5	32	2689	127
Garciago	0	4518	302.9	0	10039	147

Table 2.7: Main statistical descriptors (maximum, minimum and mean) of spring discharge values in Ubrique test site.

Time series of spring discharge measured through continuous recording equipment in the springs of the Ubrique test site are shown in Figure 2.19. These data, jointly to historical data, allow to analyze the recession curve by gauging methods and allow to measure spring discharge with high accuracy. The comprehensive analysis of spring discharge at Ubrique test site suggests a well-developed conduit system through which the rapid circulation of groundwater occurs, reflected as narrow and sharp hydrographs.

The details about the monitoring of the main springs of Ubrique aquifer can be found in D2.6.

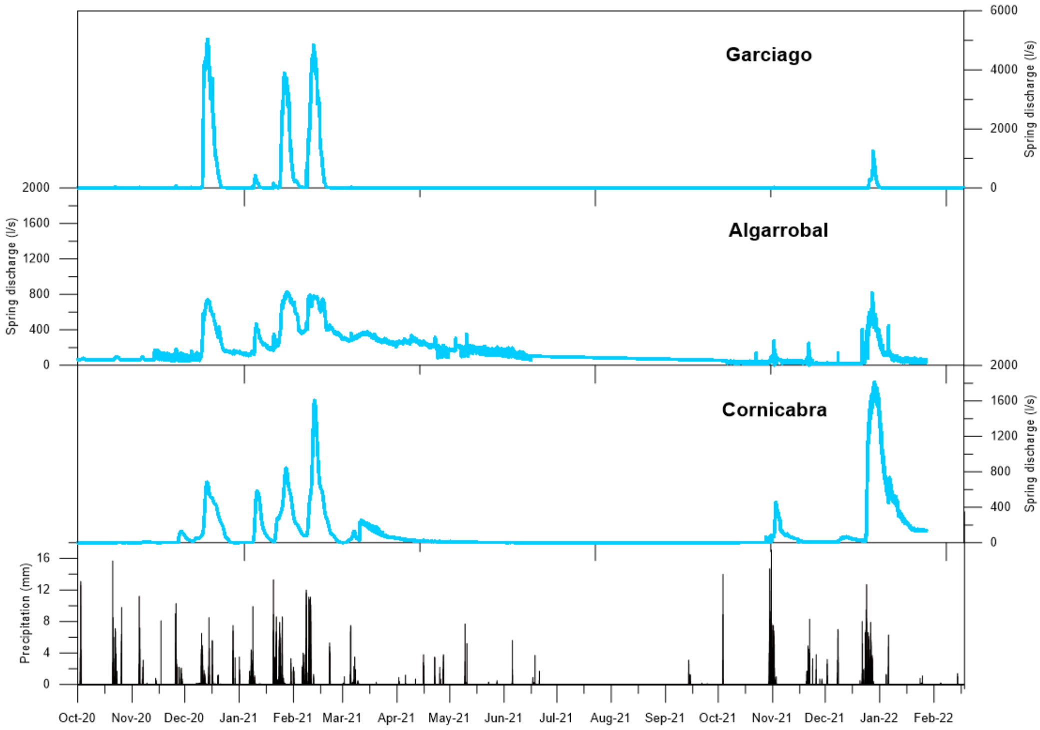


Figure 2.19: Time series of spring discharge at the main drainage points of Ubrique test site

2.4.2.3 Water budget summary

In the test site, mean effective rainfall was estimated using daily average precipitation and air temperature data from 2012/13 – 2017/18 period. As a first step, the Potential Evapotranspiration (PET) was estimated from the air temperature data series, using the equation described by Hargreaves and Samani (1985). Subsequently, the real evapotranspiration (ETR) and effective rainfall (PU) data series were obtained by means of the model proposed by Thornthwaite (1948). The soil water capacity was quantified at 50 mm, considering the scarce edaphic development in the aquifer recharge areas. In this scenario, effective rainfall is considered to be equivalent to recharge, due to the minimal development of surface runoff over the Jurassic carbonate outcrops. Furthermore, it is also assumed that there are no significant changes in water storage during the control period, so the calculation of the PU can be simplified as follows:

$$PU = (P - ETR)$$

Table 2.8 summarizes the precipitation (P), effective rainfall (PU) and recharge rate values obtained in the study area for the period 2012/13 - 2017/18 calculated through water budget in soil (Hargreaves equation) with field capacity 50 mm for the 2012/13-2017/18 period.

2012/13			2013/14			2014/15			2015/16			2016/17			2017/18			Mean study period		
P	PU	R. rate	P	PU	R. rate	P	PU	R. rate	P	PU	R. rate	P	PU	R. rate	P	PU	R. rate	P	PU	R. rate
hm^3/año		%	hm^3/año		%	hm^3/año		%	hm^3/año		%	hm^3/año		%	hm^3/año		%	hm^3/año		%
49,96	38,12	76,3	28,45	18,86	66,3	24,70	14,49	58,7	25,81	14,89	57,7	20,16	9,88	49,0	42,49	30,76	72,4	31,93	21,17	66,3

Table 2.8: Mean precipitation, recharge values and recharge rates calculated through water budget in soil (Hargreaves equation) with field capacity 50 mm for the 2012/13-2017/18 period

According to this study, the mean value of precipitation (P) and effective rainfall (PU) during the study period was 31.93 and 21.17 hm^3 respectively, which represented a recharge rate of 66.3%. The wettest hydrological years were 2012/13 (PU = 38.12 hm^3/y) and 2017/18 (PU = 30.76 hm^3/y), while during 2016/17 the lowest recharge values were recorded (9.88 hm^3/y).

Additionally, in Ubrique test site, the recharge rate and, therefore, the water balance has been recalculated by APLIS method (Andreo et al., 2008, Marín, A.I., 2009) (see details in D2.2). According to APLIS, the mean recharge rate in 24.04 km^2 of carbonate outcrops is 64,4% (Figure 2.20).

The spatial distribution of rainfall at Ubrique test site was obtained through interpolation of in-situ data being the mean annual precipitation for the wet year is 2,428 mm, 1,292 mm the average year and 490 the dry one. By combining the spatial distribution layer of the recharge rate obtained with APLIS and the isohyet maps, recharge volumes shown in Table 2.9 were calculated.

	Wet (2009/10)	**Average (84/85-17/18)**	**Dry (2004/05)**
Total recharge (hm^3/yr)	37.57	19.99	7.58

Table 2.9: Total volumes of recharge at Ubrique test site obtained through APLIS method

Through the application of this approach, APLIS showed up a mean recharge rate for Ubrique of 64,4% with a diverse spatial distribution due mainly to altitude differences. As annual mean precipitation (P) for the historical period is 31,05 hm^3/y, a value of effective runoff (PU) of 19,99 hm^3/y is therefore estimated.

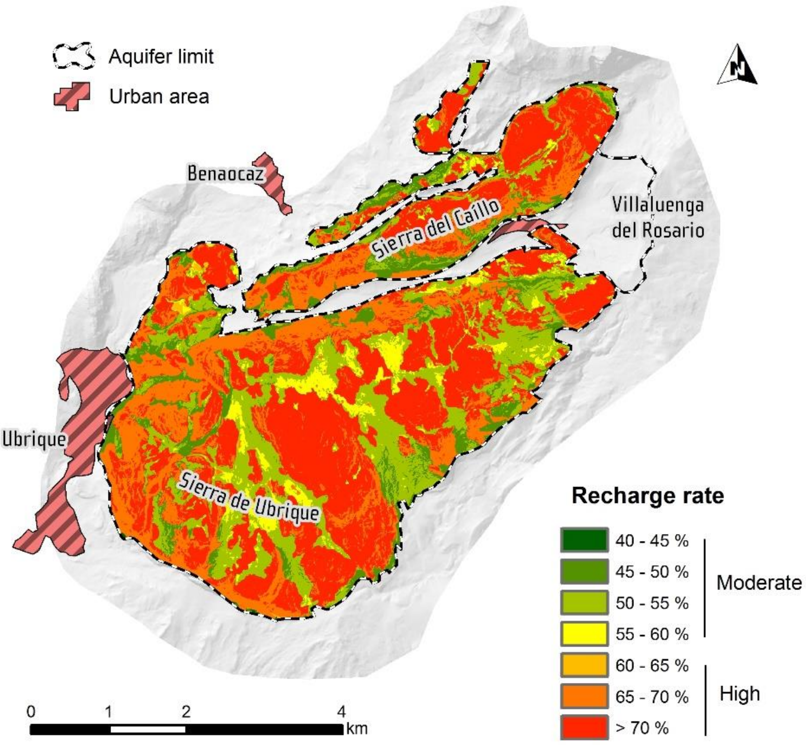


Figure 2.20: Spatial distribution of recharge rate through the application of APLIS method Ubrique test site

2.5 The Lez Karst Catchment (case study France)

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 (between 180 l/s and 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).

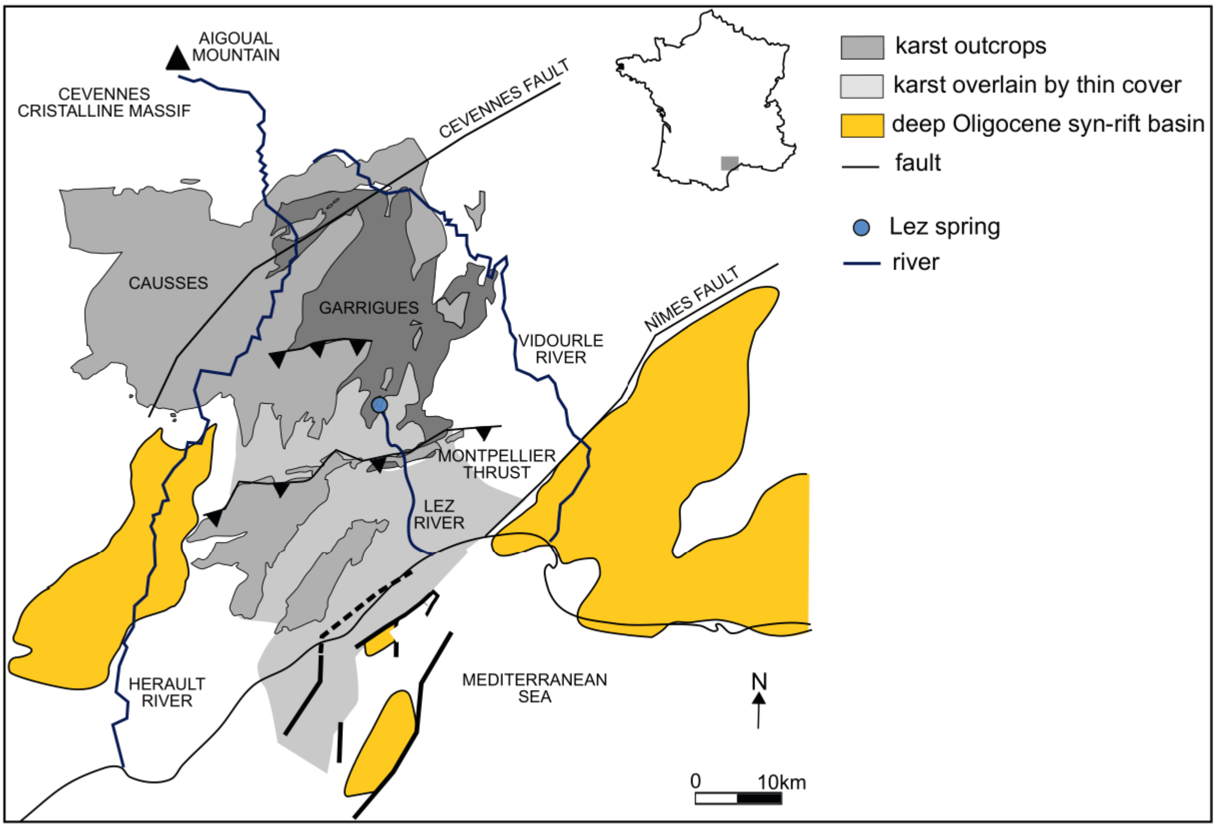


Figure 2.21: General situation of the Lez karst aquifer system. From Mazzilli, 2011, simplified after Camus, 1999.

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 (Figure 2.21). The boundaries of the karst system comprising the Lez aquifer can be roughly materialized by the Hérault and Vidourle rivers (western and eastern sides) and by the Cévennes 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 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.

The area is characterized by a typical Mediterranean climate with dry summers and rainy autumns. 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 600 mm (dry year) to about 1500 mm (wet year). The intense rainfall events in autumn are the main contributors to the annual recharge. Rainfall is also spatially variable with an increase from south to north due to the rising topography and the proximity of the Cevennes hills (Figure 2.21).

Discharge at Lez spring is regularly null during dry periods due to the pumping into the saturated zone of the aquifer (Figure 2.22). This anthropogenic perturbation disrupts the functioning of the aquifer, thus the monitored time series of the Lez spring discharge is not representative of the natural dynamics and draining of the Lez karst system.

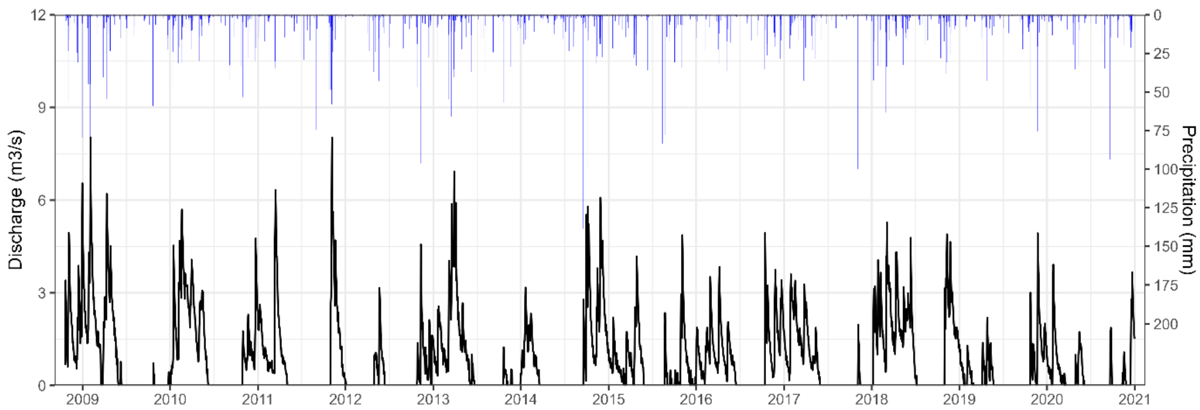


Figure 2.22: Lez spring discharge and precipitation on the Lez catchment.

The recharge on the Lez catchment was estimated using water balance and GIS methods (APLIS, Andreo et al. (2008), Marín (2009)).

Year	Precipitation	Annual recharge (hm^3/year)	
		APLIS method	Water balance method
Dry (1952–1953)	438	28.3	10.9
Intermediate (1955–1956)	916	59.5	58.3
Wet (1995–1996)	1763	114.5	161.8

Table 2.10: Estimation of the annual recharge on the Lez catchment according to (i) a water balance method and (ii) APLIS method.

The annual recharge for an intermediate year is estimated at 59.5 hm^3/y with the APLIS method and at 58.3 hm^3/y with the water balance method (Table 2.10). These results are very similar and consistent with the mean annual volume that leaves the system (natural flow at the spring and pumping) estimated at 58.5 hm^3/y. The annual recharge for a dry year is estimated to be lower with the water balance method (10.9 hm^3/y against 28.3 hm^3/y with APLIS), which may be related to the evapotranspiration processes that are not considered in the APLIS method. The annual recharge for a wet year is estimated to be higher with the water balance method (161.8 hm^3/y against 114.5 hm^3/y with APLIS), which is likely due to the run-off volume that is not considered in the water balance method but should be withdrawn to get the effective recharge.

For the **water balance method** both precipitation and evapotranspiration were considered as potential source of uncertainties. The precipitation time series is derived from 4 meteorological stations spread over the catchment area (Prades-le-Lez, Sauteyrargues, Saint-Martin-de-Londres, Valfaunès). The time series was interpolated with the Thiessen polygon method to obtain an equivalent precipitation over the catchment area. This equivalent precipitation was considered to be relevant for the Lez catchment. On the other hand, there are more uncertainties on evapotranspiration because of the complex spatial distribution of temperature and land uses over the catchments.

The **APLIS method** is less sensitive to such uncertainties and seems to provide an accurate estimation of the recharge at the scale of the Lez spring catchment, even though results might be improved by considering the land cover:

- The urban areas (approximately 20 km²) where the infiltration is insignificant.
- The vegetation, which intercepts a part of the precipitation and release water from the soil and vadose zone to the atmosphere via the process of transpiration. This volume may be significant, especially in summer where the demand from the vegetation is high and the evapotranspiration is larger than the precipitation.

3. Evaluation of the more suitable method at the scale of single site to assess groundwater recharge

3.1 Gran Sasso aquifer (Case Study Italy)

The results of the water budget analysis computed with three different approaches (Turc, Thornthwaite, and Aplis), are very similar to each other, resulting in a discrepancy lower than 10% for recharge assessment. In fact, for all methods, the highest recharge value has been recorded in 2013, while the driest years have been recognized in the 2006-2007 period. The similarity of the results obtained by the different methods confirms the reliability of the water budget. In this context, the more suitable method at the single scale has been analysed. Considering the infiltration result calculated with the three methods, the value obtained by Aplis is 594 mm/y agrees with the values previously calculated with conventional methods.

Indeed, the recharge value for the Gran Sasso karst aquifer calculated with Aplis without considering the snow contribution (484 mm/year) is similar to the net infiltration value calculated by Scozzafava & Tallini (2001) using the Thornthwaite + CN method (506 mm/y) (D2.2). Its suitability is confirmed also by discharge values. In fact, comparing the recharge values obtained with the Aplis method and the real total spring discharge (TSD), it has been verified the best alignment with respect to the X=Y line (Figure 2.6R) with a discrepancy not higher than 10%, which corroborates the applicability of the method.

Furthermore, the Aplis model validates how the Gran Sasso is characterised by an infiltration value marked as 'moderate' (51.6% of rainfall) and how the endorheic basin of Campo Imperatore has a higher recharge rate than the rest of the aquifer (76.7%). This confirms the relevance of that area (Campo Imperatore basin), marked as a preferential recharge area.

The Aplis method has proven to be a resilient approach for estimating the recharge rate in carbonate aquifers, expressed as a percentage of infiltration. It determines its spatial distribution accurately basing on specific characteristics that are not included in the classical rainfall/recharge analysis conducted by indirect and empirical methods such as Thornthwaite and Turc methods; these characteristics (altitude, slope, soil, infiltration landform) are fundamental to understand in detail the multiple recharge processes affecting karst aquifers.

3.2 The Qachqouch aquifer (Case Study Lebanon)

The spring is highly reactive to seasonality and climate variation (wet, intermediate and dry years). Based on additional obtained data till mid-2022, water availability was best estimated using the water balance method with a high-resolution monitoring of the spring discharge. It allows to define the high flow rates and volume available during times where water shortage is at its minimum (Jan-March), which amount to 13-22 hm^3/y that can be used as flood water storage. The numerical model allows to define a temporal variation of recharge and discharge and provides a numerical tool to estimate variation of discharge with varying input and future expected flow rates. The APLIS method provides a spatial distribution of recharge of the catchment area, even with an underestimation with respect to the discharge rates observed at the spring. The latter can be used to weigh more realistic values of distributed recharge in combination with the others used methods (Table 3.1).

Method	Advantages	Limitations and suggestions
Water Balance	50-70% Infiltration from P Total Recharge volume: 45-80 Mm^3/year	Uncertainties in catchment delineation and area Daily discharge values during flood periods impact yearly discharge volumes Lumped estimation of recharge
APLIS method	60 % of P Total Recharge volume: 30 Mm^3/year	Static recharge estimation that does not account for a change in precipitation intensity and overland flow Requires high resolution detailed raster coverage of parameters influencing recharge, especially infiltration
Numerical modelling (semi-distributed lumped model)	70-75 % of P Total Recharge volume: 50-60 Mm^3/year	Catchment delineation and area Daily discharge values during flood periods impact yearly discharge volumes Required calibration and validation and a proper parameterization
Isotopes	Volumes of fast infiltration per events: 0.3-4 Mm^3 depending on the saturation Catchment area extends beyond 1500 m above sea level from isotope signatures.	Does not allow to calculate total recharge

Table 3.1: Synopsis of the comparison of the methods used to estimate availability and recharge

3.3 The Djebel Zaghouan aquifer (Case Study Tunisia)

Recharge rates issued from the conceptual model for the natural flow period ranged from 30% to 68% (average 42%). For the period corresponding to the functioning of the system via galleries by regulating valves, the infiltration rates varied between 21% and 57 % (average 39.4 %).

Using the APLIS method, the majority of the study area has estimated infiltration rates in the ‘‘moderate’’ category (40–50 %) (Figure 3.1). The overall infiltration rate for the study area is 45%. Despite, the uncertainties of measurements of discharges and flow and climatic data processing, APLIS method gave recharge rates of the same range as the values calculated by the model.

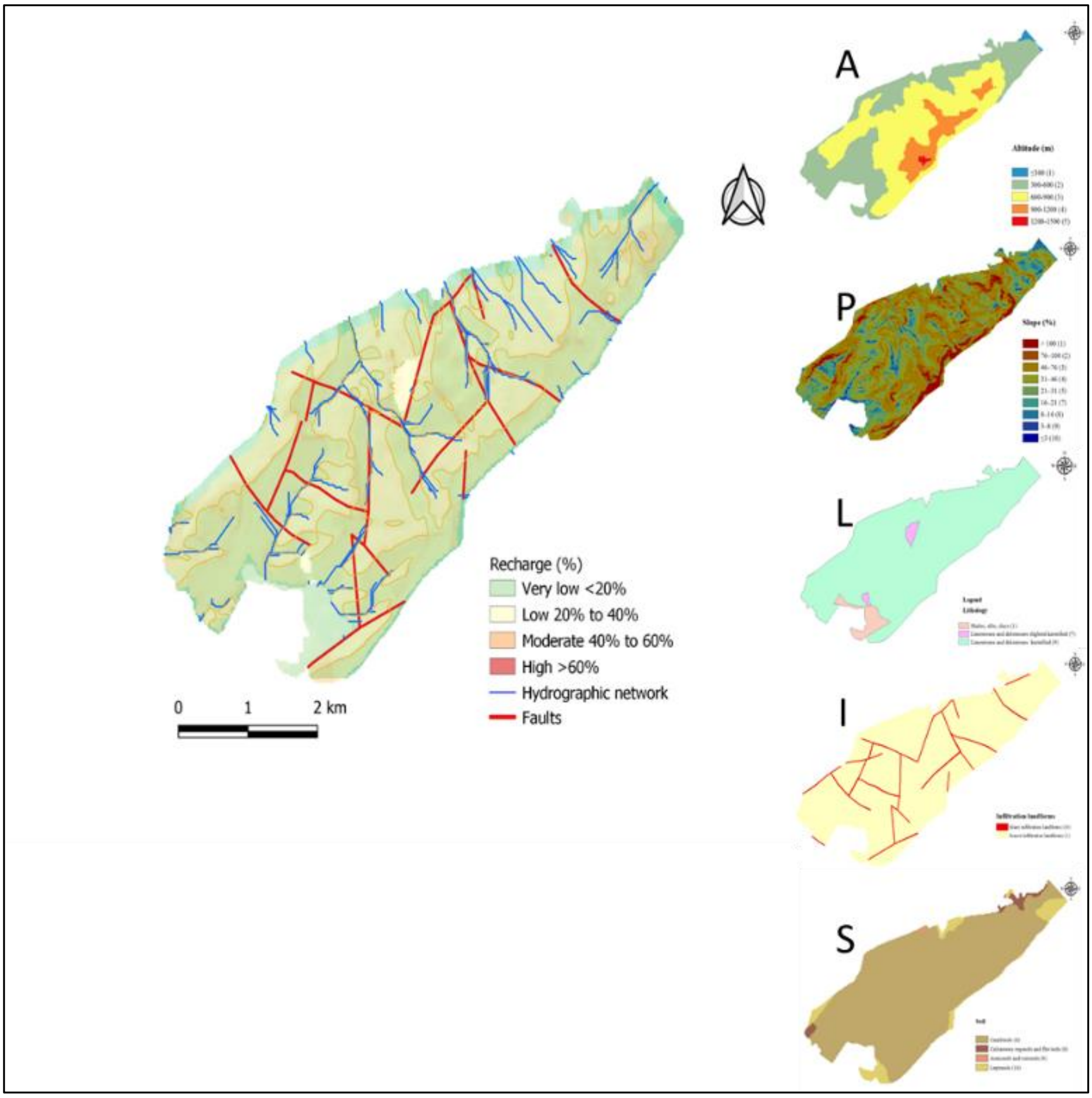


Figure 3.1: Groundwater recharge distribution by the APLIS method

3.4 Merinos-Colorado-Carrasco and Ubrique test site (case study Spain)

3.4.1 Merinos-Colorado-Carrasco

As already presented in deliverable 2.1 "Water balance ", the results obtained through the application of APLIS at Merinos-Colorado-Carrasco test site nearly coincide with previous researches (Table 3.2) (Barberá, 2014) which obtained the mean annual recharge through different methods from the one used on this report. In the same PhD Thesis, recharge rate was also calculated using Thornthwaite (1948) and Kessler (1967) methods. With the first one, recharge rate was estimated between 64.2% and 72.5%, in contrast with the second method a recharge rate between 54.7% and 56.8% was obtained, showing quite similar values to those achieved through APLIS method (17.96 hm^3/y) (Figure 3.2).

Therefore, APLIS method has proven to be a reliable approach for recharge estimation in this area as it provides recharge rate values that are consistent with the hydrogeological features and karstification degree of the system. In this way, it is possible to confirm that the uncertainty in the estimation of the average renewable resources in the Eastern Ronda Mountains system is very low.

	Fernández (1980)	IGME (1983)	DPM (1988)	Barberá (2014)
Sierras de Merinos, Colorado y Carrasco	24,3	17,99	17	17,96

Table 3.2 Mean renewable resources (hm3/year) at Merinos-Colorado-Carrasco test site estimated on previous studies (modified from Barberá, 2014).

SIERRAS DE LOS MERINOS-COLORADO-CARRASCO			
Área (km^2)	*P* (hm^3/a)	*ETR* (hm^3/a)	*PU* (hm^3/a)
43,21	**31,67**	**13,71**	**17,96**

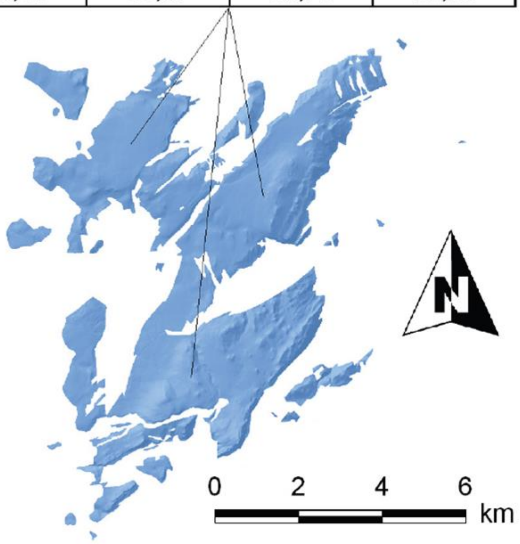


Figure 3.2: Mean values for water budget components at Merinos-Colorado-Carrasco test site for the historical period 1964/65-2009/10. Acronyms: P, precipitation; ETR, real evapotranspiration and PU, effective runoff (modified from Barberá, 2014).

3.4.2 Ubrique aquifer

The results obtained by the application of different method for estimating the annual recharge (PU) were validated by means the comparison among the estimated annual recharge with the discharge (S) measured (integration of spring hydrographs) at the discharge points. Table 3.3 summarizes the annual mean values of PU (recharge) and S (discharge) for each year of 2012/13 - 2017/18 period. Several methods for validating the water balance were applied in the framework of KARMA project and previous studies (see D 2.7).

The extended recharge control period until 2017/18, both for the APLIS method and for the water budget in soil, led to obtain more representative values and adjusted to the actual aquifer discharge. The average annual recharge value in the Ubrique aquifer obtained by APLIS was 19.58 hm^3/y. This value is lower than the mean discharge for that period (22.54 hm^3/y), the difference being 2.96 hm^3/y, which represents an underestimation of 11.9 % (Tab. 3.3).

However, in this aquifer, the results of estimating the annual recharge are significantly more accurate when calculated through water budget in soil (Hargreaves equation) with field capacity 50 mm (Table 3.2), resulting in a difference with the discharge of 2.25%.

2012/13			2013/14			2014/15			2015/16			2016/17			2017/18			Mean study period		
S	PU	Difference	S	PU	Difference	S	PU	Difference	S	PU	Difference	S	PU	Difference	S	PU	Difference	S	PU	Difference
hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3	hm^3
34,19	40,97	**6,78**	21,8	20,05	**-1,77**	15,5	15,24	**-0,24**	15,6	15,67	**0,06**	10,9	10,45	**-0,46**	34,2	32,83	**-1,39**	22,04	22,54	**0,50**

Table 3.3 Comparison of discharge (S) measurements and recharge values (PU) calculated through water budget in soil (Hargreaves equation) with field capacity 50 mm for the 2012/13-2017/18 period

3.5 The Lez Karst Catchment (case study France)

The results obtained with the APLIS method are consistent with our actual knowledge of the system, especially regarding the main recharge area of the catchment (estimated between 120 and 150 km^2 in previous studies):

- We can see on the APLIS recharge map (Figure 3.3) that the main Jurassic limestone outcrops (west and north-west parts of the basin) mostly contribute to the recharge of the aquifer, with a mean recharge rate of 47% for an area of 80 km^2. The recharge contribution from this area is about 60% of the overall recharge of the catchment.
- Other limestone outcrops within the hydrogeological basin, as well as particular geological features (major faults and sinkholes), also correspond to significant recharge locations.

The APLIS method seems to provide a consistent estimation of the recharge for the Lez aquifer, by considering many characteristics of the catchment that other methods do not consider (geology, soil, altitude, slope). Indeed, the estimated mean annual recharge with APLIS (~60 hm^3/y) is of the same order of magnitude as the mean annual discharge at the Lez spring. Analyses of hydrological cycles of the natural flow of the Lez source over the 1946-1968 period (Drogue, 1974) showed that the natural state of the system was characterized by an average daily discharge of about 2 m^3/s, corresponding to an average annual discharge of about 62 hm^3/y. Over the same period, the minimum discharge was measured in 1952 with an average daily discharge of about 0.9 m^3/s, corresponding to an average annual discharge of about 28 hm^3/y, which remarkably corresponds to the estimated annual recharge estimated with the APLIS method.

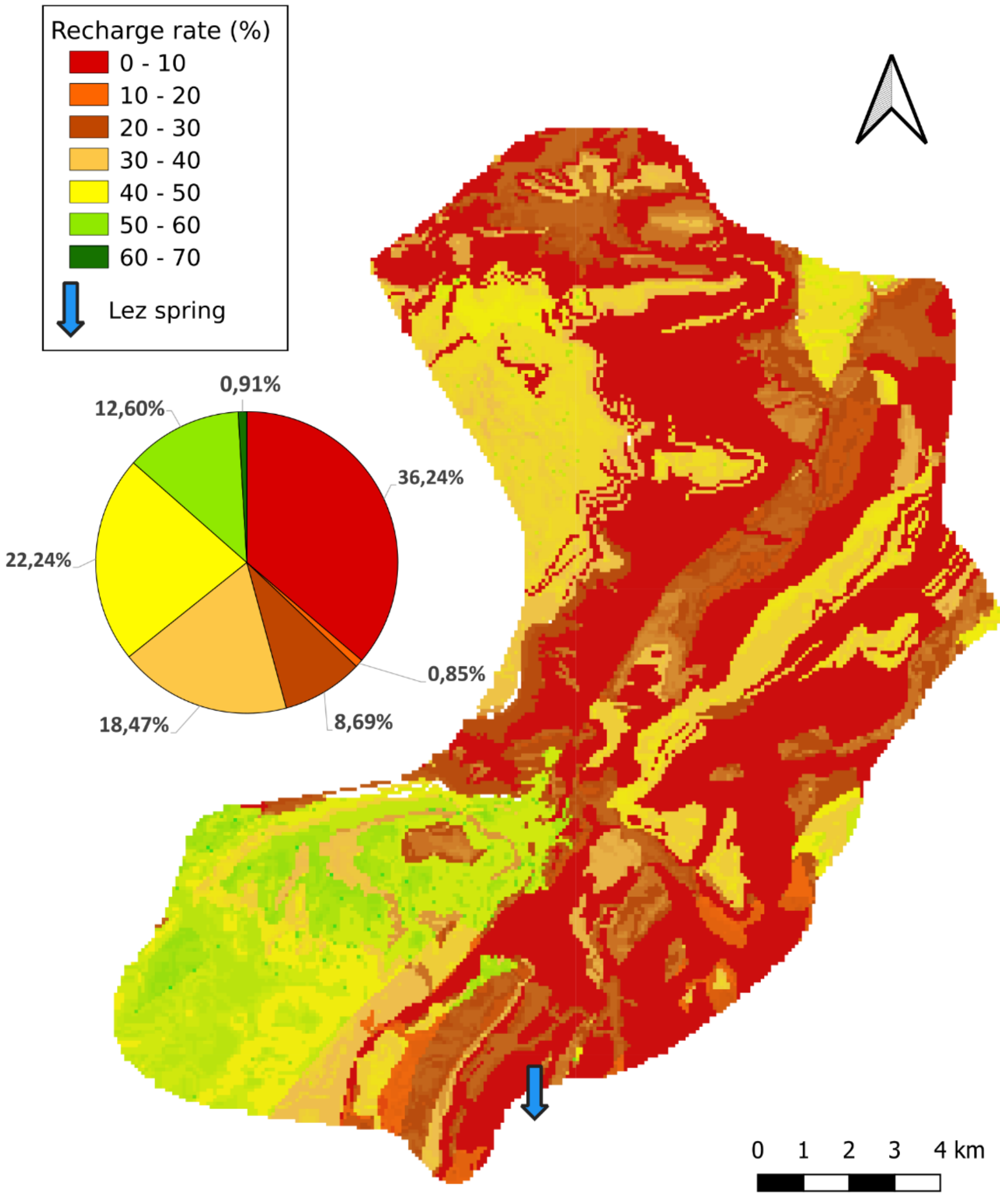


Figure 3.3: Recharge rate (% of total precipitation) on the Lez catchment.

4. Comparison between the recharge map produced for MedKAM and the results at the scale of test site

4.1 Gran Sasso aquifer (Case Study Italy)

The results obtained through the recharge map at the Mediterranean scale produced for MedKAM show an average infiltration value for the Gran Sasso area lower than 400 mm/year. This value results to be lower than the values obtained through the three different approaches here adopted for calculating the recharge. In fact, considering the average infiltration value calculated by the three methods described above, a value of 586 mm/y is obtained, which is therefore significantly higher than the infiltration calculated for the MedKAM map.

On the other hand, it was observed that both for the recharge rate (60%) and for the preliminary assessment of recharge, the modeling previously conducted at the continental scale are in very good match with our local scale results. In fact, the preliminary recharge assessment for the cells corresponding to the Gran Sasso aquifer results to range between 550-600 mm/year, which totally fit to our budget analysis.

The differences are probably due to the various versions of the large-scale model. While the preliminary dataset came from the old continental version of VarKarst (Hartmann et al., 2015), the new final dataset for MedKAM comes from a newer, global version (Hartmann et al., 2020). Although the new model includes better input data and simulates a longer and more representative mediation period of 30 years, the old version of the model experienced a calibration, which has not yet been performed with the new model. This may explain why the previous model is confirmed to be more accurate, moving from a larger to a local scale, at least in the study area of Gran Sasso aquifer.

4.2 The Qachqouch aquifer (Case Study Lebanon)

In MEDKAM, the total recharge rate estimated for Lebanon as a country ranges between 188 and 260 mm. The recharge appears to decrease inward towards the east despite the altitude effect. According to the recharge calculated using APLIS, the recharge of the catchment of Qachqouch varies between 40 mm and 1300 mm for a wet year and between 30 and 966 mm for an average year in accordance with the recharge estimated using the water balance method and numerical modelling. Precipitation on the catchment area varies between 800 mm and 1600 mm including snow as measured by the climatic stations located on the catchment (Figure 4.1). The relatively high recharge rate is related to the karstic nature of the area, the relatively low actual evapotranspiration, and to increasing precipitation with a precipitation lapse rate per altitude of about 6% per 100 m (Doummar et al., 2018). Recharge rates for areas in Lebanon estimated with numerical models and the water balance methods show that the values observed in MEDKAM are underestimated with respect to the calculated ones at pilot scale (Dubois et al., 2020, Doummar et al. 2018). Furthermore, an estimation of recharge over Lebanon using the GROWA method (Kunkel and Wendland, 2002, Frem 2021) yielded a recharge ranging between 100 and 910 mm, However the latter method does not account for the real effect of karstification and local fast infiltration.

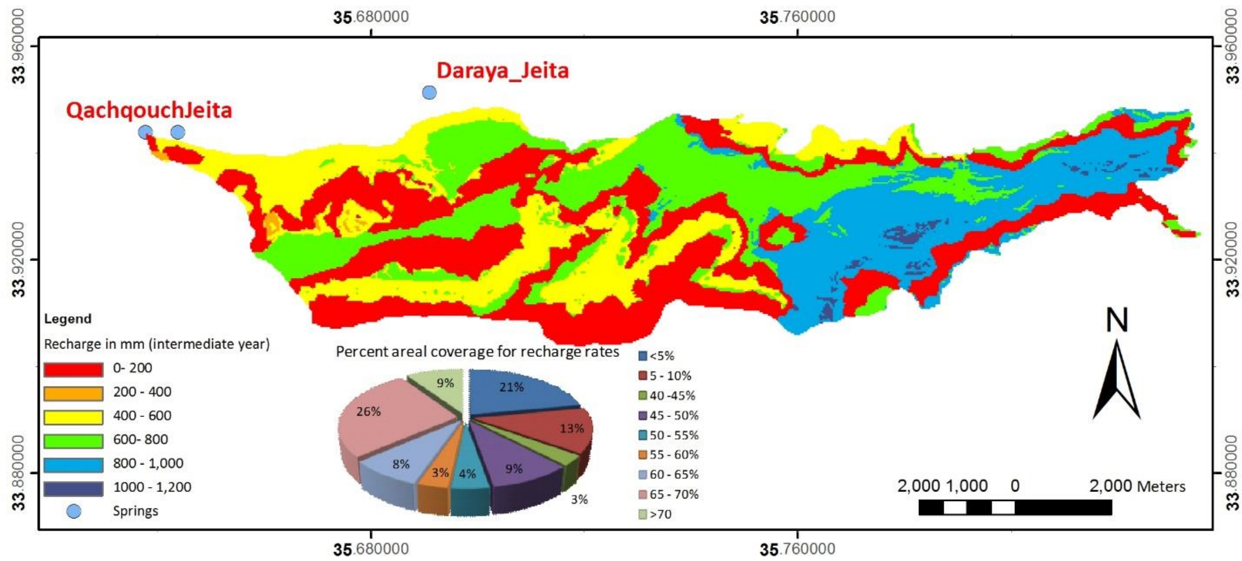


Figure 4.1: Recharge in mm/year estimated on the Catchment area using APLIS.

Lebanon has a total area of 10,452 km^2 and counts for a total of 3x5 cells on the MEDKAM map; the assessment of recharge was estimated for the entire region including the east and west. The altitude effect for precipitation and variation of climatic zones within Lebanon does not seem to be accounted for due to the scale of the regional map. Additionally, the variation of the degree of karstification and its effect on high infiltration cannot be considered at such a large scale (Figure 4.2).

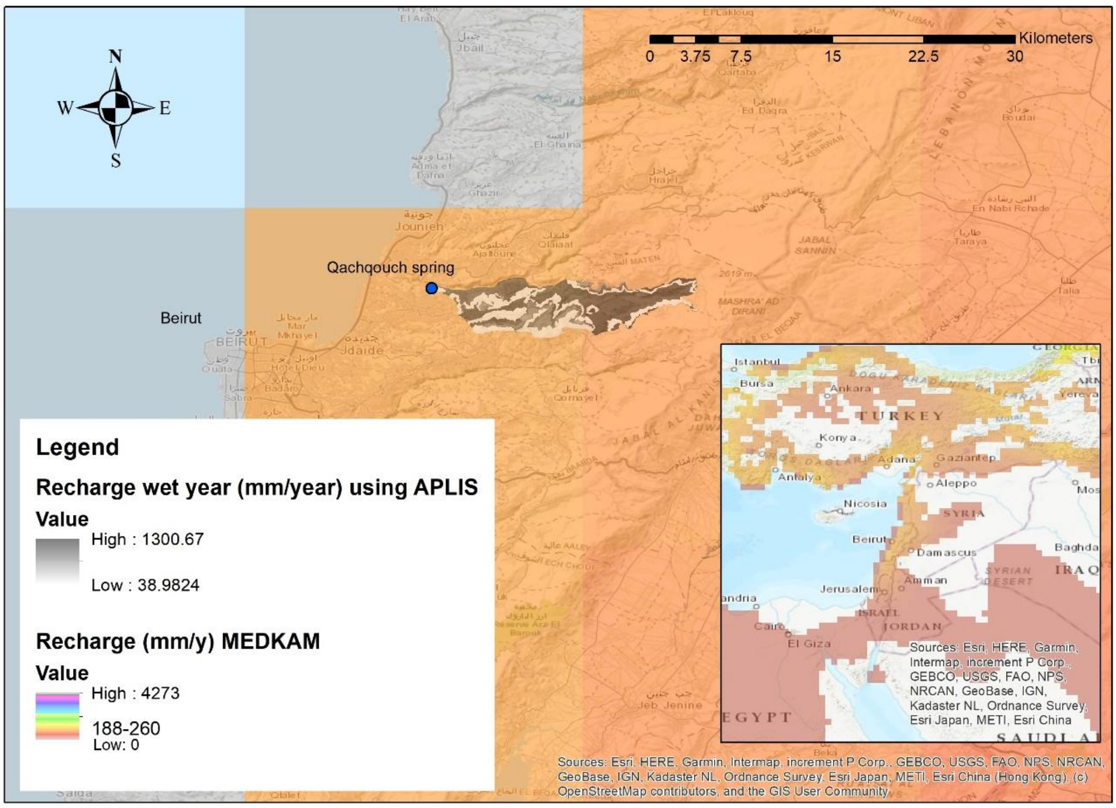


Figure 4.2: The catchment area portrayed on the regional map of MEDKAM showing the variation of recharge not exceeding 300 mm, while an average of 900 mm/ year was estimated using APLIS method

Additionally, such low recharge rate (assuming an average of 220 mm) yield about 16 hm^3/y of total yearly discharge at the Qachqouch spring, which amount to about 25-30 % of the total discharge recorded at the spring during wet and dry years. Therefore, in the case of Lebanon, recharge is better assessed at a catchment pilot scale for specific rock exposure especially in karst areas covering more than 67% of the Lebanese territory. Additionally, a high-resolution precipitation data should be collected at different elevations to account for the altitude effect that plays an important role in recharge. Accordingly, MEDKAM is not suitable for the case of Lebanon, but maybe suitable for neighboring semi-arid areas where recharge is not spatialy variable like in the case of Lebanon.

4.3 The Djebel Zaghouan aquifer (Case Study Tunisia)

Results from MEDKAM shows that recharge is about 162 mm which corresponds to 32.4% of median annual rainfall depth (based on a series of 30 years). MEDKAM gives a recharge value belonging to the range found using with APLIS (21% to 57%) and the developed conceptual model (30% to 68%).

4.4 Merinos-Colorado-Carrasco and Ubrique test site (case study Spain)

The comparison of recharge got with APLIS methodology and MEDKAM calculation has been done by the extraction of the MEDKAM recharge map that correspond to the 2 Spanish test sites. To obtain well-defined boundaries consistent with the boundaries of the aquifers studied, the MEDKAM raster has been resampled at 10m (change of cell size from 15km to 10m). This process modifies the cell size but not the value of each pixel because this is a splitting process.

Figure 4.3, Figure 4.4 and Table 4.1 present the result obtained under this comparative analysis. In general terms, due to the large cell size, the recharge maps obtained by MEDKAM approach do not show the spatial heterogeneity, in terms of outcrop lithology and karst forms, typical of the karst aquifers of southern Spain. This was to be expected and can be assumed because we are working with global maps at local scale. However, the major discrepancy obtained in the comparative analysis is that the resources obtained with the MEDKAM approximation underestimate the recharge values by about 50% (Table 4.1). According to the MEDKAM approach, the maximum infiltration value obtained in Ubrique is 226 mm/year, however, this area has a historical average precipitation of 1288 mm/year, reaching 1600 mm/year in the higher areas (see section 2.4.2.1). This would imply a recharge rate in the Ubrique aquifer of less than 20%, which is not consistent with either the characteristics of the study area or with the balance. A similar situation occurs in Merinos-Colorado-Carrasco, where all the values obtained by MEDKAM approach are included in the lower range of effective infiltration, being 202 mm/yr.

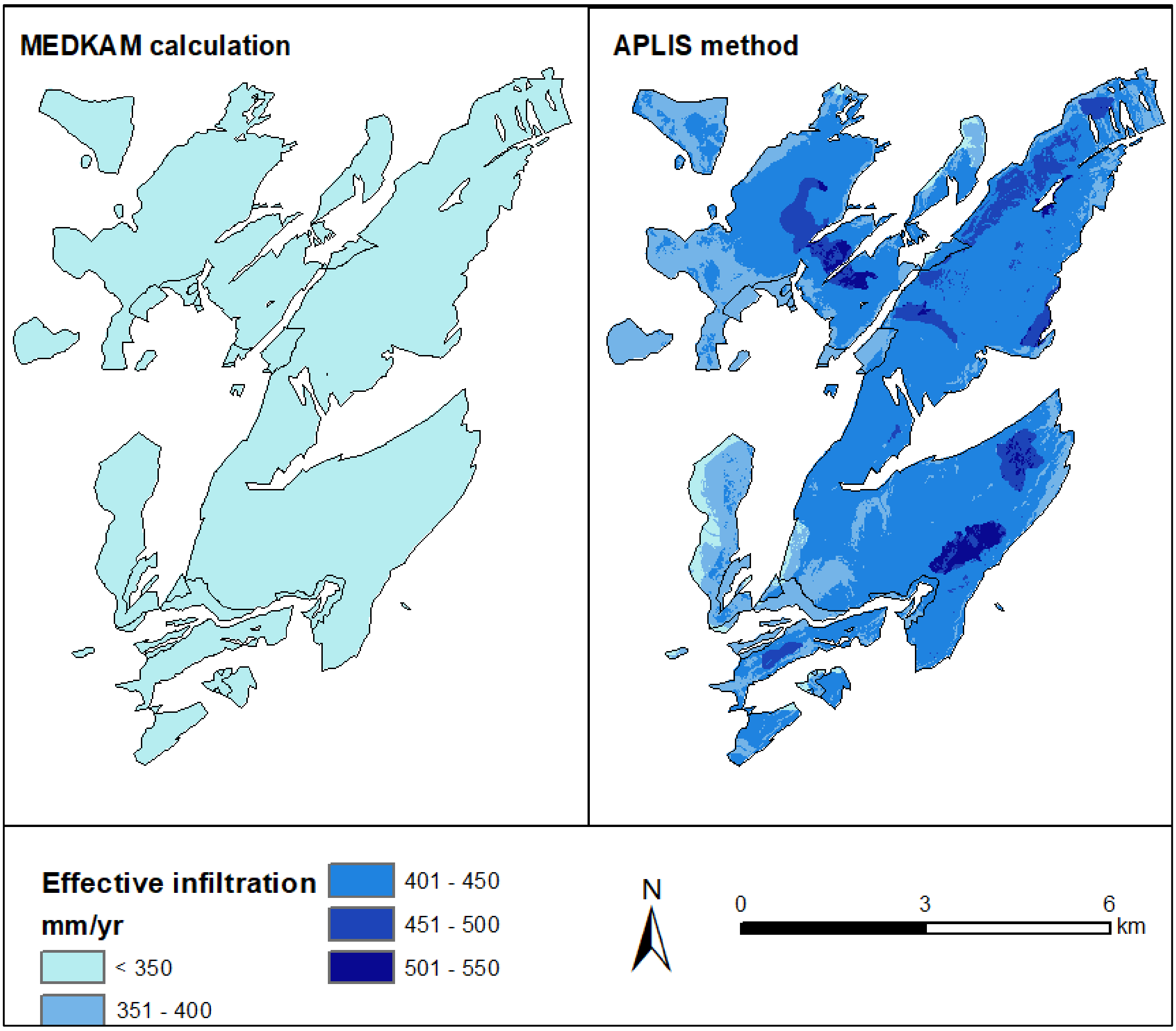


Figure 4.3: Effective infiltration distribution maps in Merinos-Colorado-Carrasco system aquifer obtained by MEDKAM approach (left) and APLIS method (right).

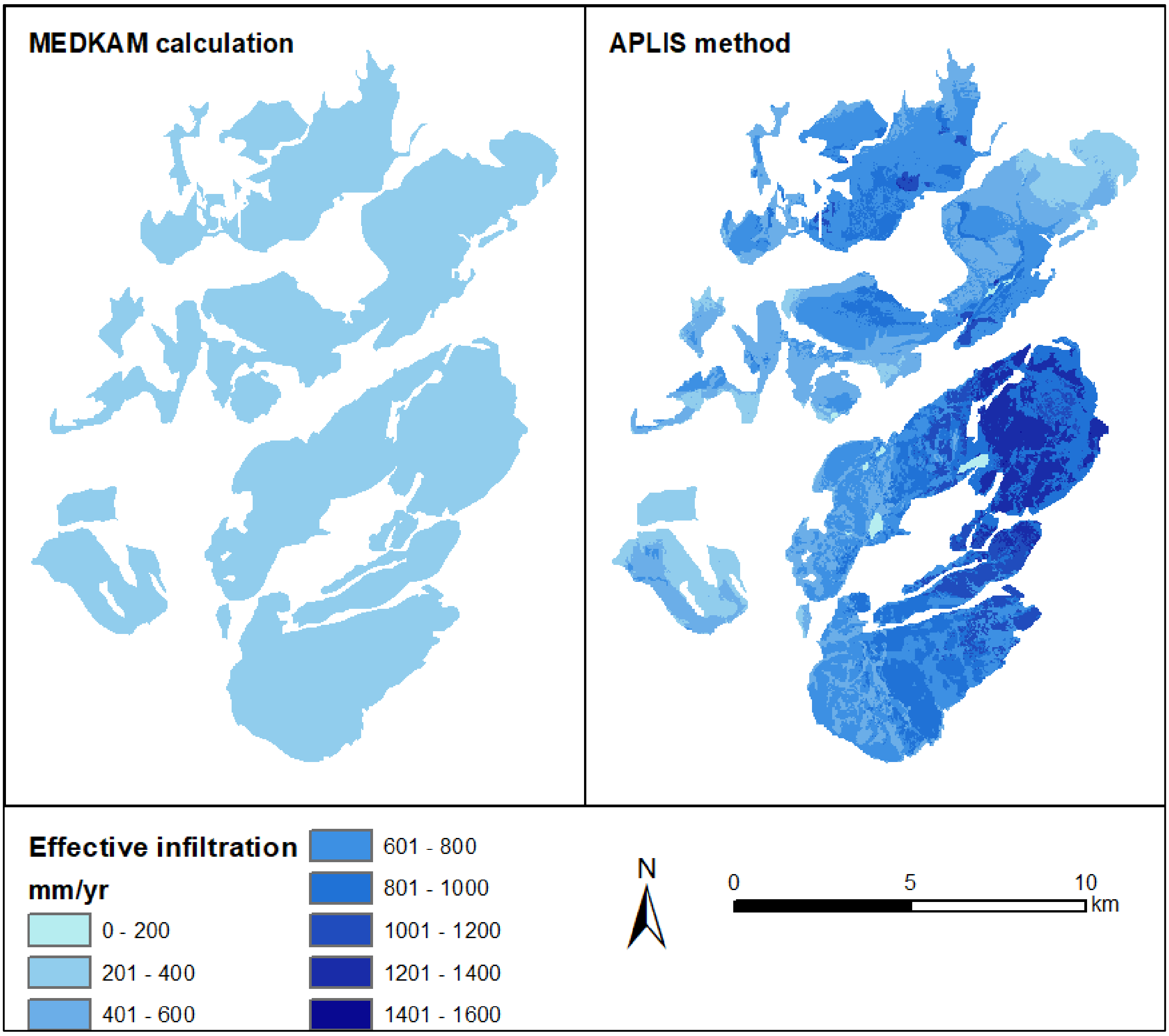


Figure 4.4: Effective infiltration distribution maps in ubriwue aquifer obtained by MEDKAM approach (left) and APLIS method (right).

	Total recharge (hm^3/y)		
	MEDKAM	APLIS	Difference (%)
Los Merinos	7,50	17,96	-58,24
Ubrique	9,68	19,58	-50,54

Table 4.1 Comparison of recharge values of KARMA Spanish test sites calculated by MEDKAM approach and APLIS method.

This comparison there are uncertainties associated with:

- The difference in scales and spatial resolution map. The MEDKAM methodology, which is derived from a global scale, is designed to obtain regional values, and perform trend analysis.
- We are comparing values of effective infiltration, for which it has been necessary to include the variable precipitation and its distribution in space in the calculation of this value. In this case and given that we are not certain of the data included as precipitation, we assume that the calculation of effective infiltration is for the average annual rainfall of a historical series of at least 30 years. The comparison will be more reliable if the same rainfall period is compared.

4.5 The Lez Karst Catchment (case study France)

The Lez catchment extends over three different tiles of the recharge map produced for MEDKAM, which each corresponding to an annual recharge of 381, 346 and 343 mm (Figure 4.5). The northern part of the Lez catchment has the higher value (381 mm) for 27.5% of its area, while the two other values are similar: 346 mm for the south western part (8% of the area) and 343 mm for the rest of the catchment (64.5% of the area).

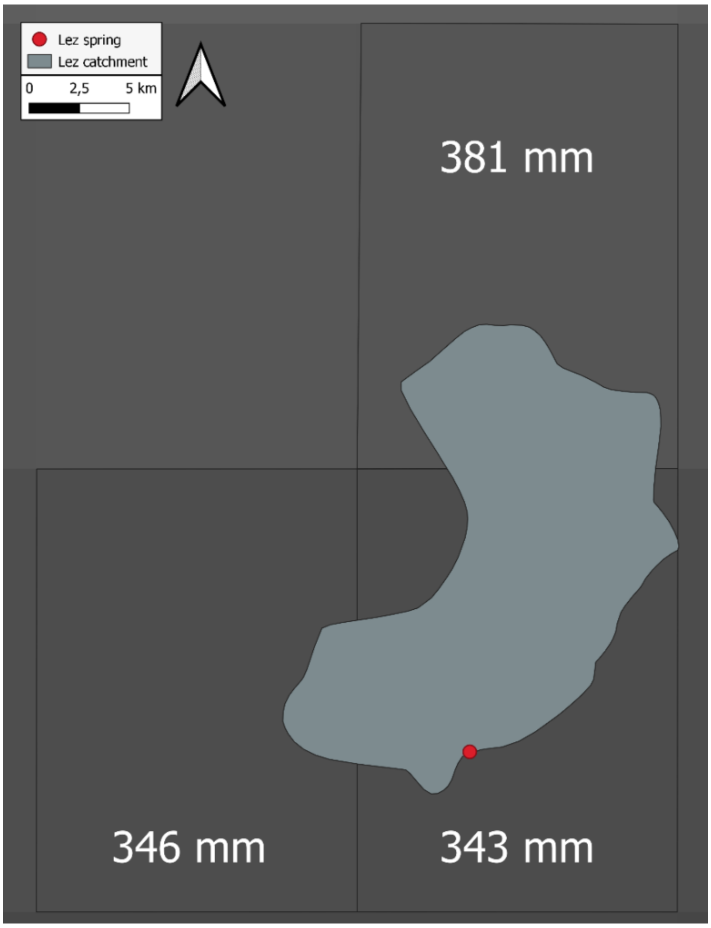


Figure 4.5: Raster tiles from the MEDKAM recharge map covering the Lez catchment.

The average recharge over the Lez catchment is estimated by ponderation with the following calculation:

$$381 * 0.275 + 346 * 0.08 + 343 * 0.645 = \mathbf{353.69\ mm}$$

Table 4.2 presents the mean annual recharge of the Lez catchment calculated with the estimated value of 353.69 mm issued from the MEDKAM recharge map, alongside the results from other methods, for the 1984–2017 period. When considering the whole area of the Lez catchment (240 km^2), the mean annual recharge is estimated at 84.9 hm^3/y – higher than the estimations of the APLIS (58.1 hm^3/y) and water balance (63.6 hm^3/y) methods. However, this estimation implies that the whole basin contributes equally to the recharge. As a large part of the hydrogeological catchment is relatively impermeable, due to the presence of marls and marly-limestones, the Lez spring recharge catchment ("efficient recharge area") covers in fact a smaller area. This recharge mainly corresponds to the Jurassic limestone outcrops located by the western and northern limits of the basin. Due to the complexity of interaction between the hydrological and hydrogeological catchments, runoff over the marls and marly limestones sinking into the aquifer during heavy precipitation events also has to be considered. As a consequence, the "efficient recharge area" is difficult to precisely assess but has been estimated to be between 120 and 150 km^2 in former studies (Marjolet and Salado, 1976; Jourde et al., 2014) and about 130 km^2 from hydrogeological modelling (Fleury et al., 2009, Mazzilli et al., 2011). When considering this "efficient recharge area" (between 120 and 150 km^2), the annual recharge is estimated to be between 42.5 and 53 hm^3/y – slightly lower than the estimations of recharge with either the water balance or APLIS methods.

Method	Mean annual recharge (hm^3/year)
MEDKAM – 240 km^2	84.9
MEDKAM – 130 km^2	**46.0**
APLIS	58.1
Water balance	63.6

Table 4.2: Estimation of the mean annual recharge on the Lez catchment according to the MEDKAM recharge map and comparison with the water balance and APLIS methods, on the 1984–2017 period.

In the case of the Lez aquifer, the MEDKAM recharge map provides a somehow accurate although higher estimation of the recharge in comparison to other methods, when the whole hydrogeological catchment is considered. On the contrary, this recharge estimation is lower when only the estimated "efficient recharge area" is considered.

The MEDKAM recharge map thus provides information that can be valuable at the scale of the Mediterranean basin, especially in a scarce data context. However, in catchments such as the Lez spring karst catchment, where the interaction between surface water and groundwater are complex, the provided MEDKAM recharge map needs to be adjusted while considering an "efficient recharge area" to properly assess the mean annual recharge.

Besides, further uncertainties also need to be considered to correctly appreciate the obtained results:

- As there is no information on the amount of precipitation for dry/intermediate/wet years associated with the values of the tiles (MEDKAM recharge shows an average recharge per year), this can induce strong uncertainties on the recharge estimation. Indeed, the recharge for dry and wet years can be significantly lower of higher than this mean value.
- As MEDKAM recharge is estimated without account on the geological specificities of the different parts of the catchment, the estimated recharge can be significantly higher if relatively impermeable parts of the catchment are considered to contribute as much to the recharge as other more permeable parts (case of the Lez spring catchment where marls and marly limestone prevent an "efficient recharge" in some parts).

5. Verification of possible common response in groundwater availability/discharge at each test site during the monitoring period

5.1 Gran Sasso aquifer (Case Study Italy)

In order to observe the variability of recharge values in recent years, compared to previous years, Figure 5.1 shows the recharge evaluation obtained by three different methods, coupled with their long term (2000-2020) average value by dashed lines. The calculated recharge for the years 2019 and 2020 is lower than the average recharge value. Furthermore, the recharge rate for 2020 appears to be comparable to the absolute minimum values of the drought period 2006-2007.

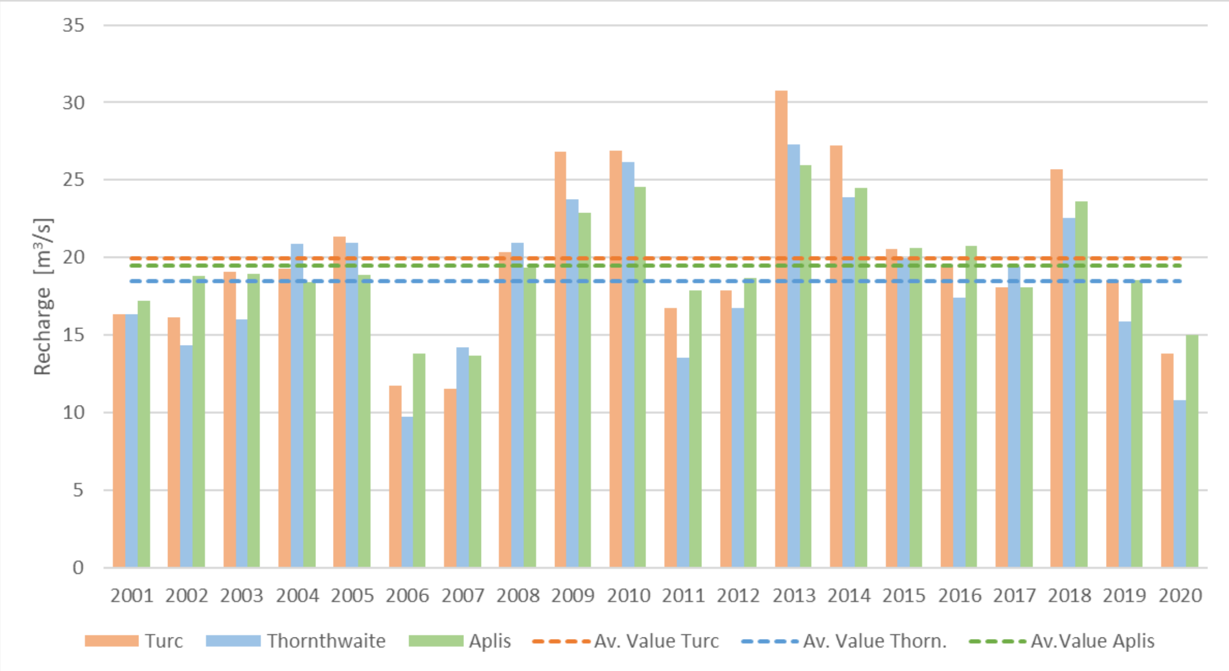


Figure 5.1: Annual variability of recharge calculated for the period 2001-2020 by applying the Turc, Thornthwaite and Aplis methods. Average recharge values are shown in dotted lines

By comparing the volumes of water entering the hydrostructure (Qin), obtained with the three methods, with those of measured discharge (Qout), obtained from the evaluation of the annual flow rates delivered by the springs, it is clear how in dry years the total discharge delivered by the aquifer is higher than that expected from the recharge evaluation (Figure 5.2). In addition, in years having high recharge rate, we do not record a corresponding increase in total flow rates, which frequently is raising but without reaching the volumes expected by recharge values (see years 2009, 2010, 2013, 2014, 2018).

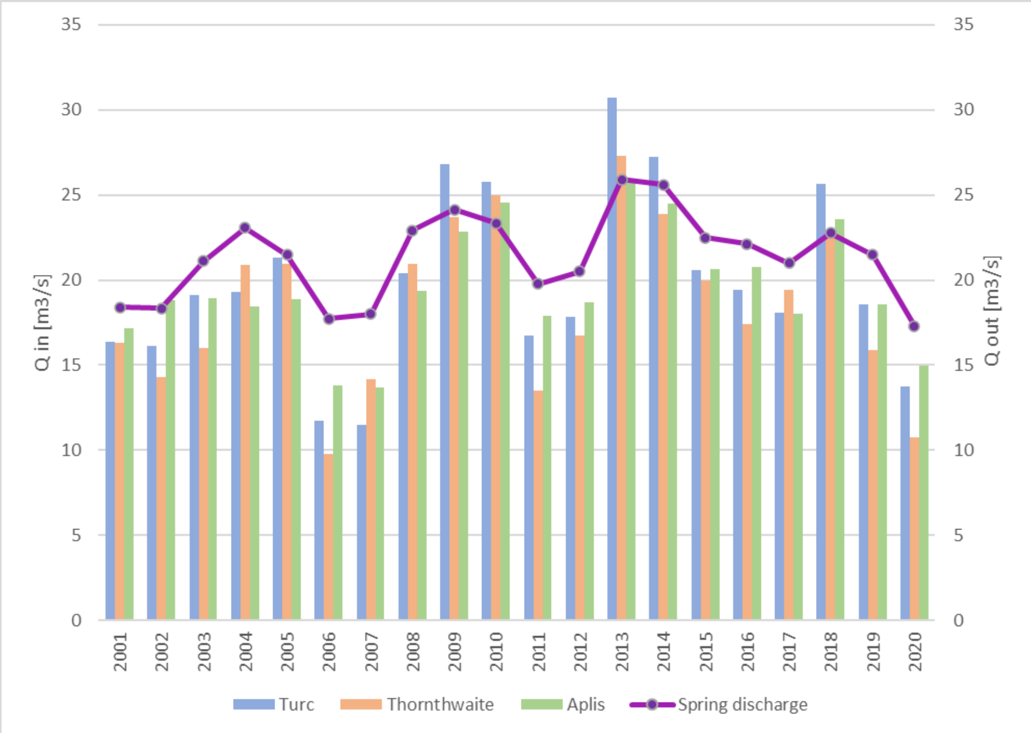


Figure 5.2: Qin (aquifer recharge) and Qout (spring discharge) of the Gran Sasso aquifer in 2001-2020 period

The water budget calculation indicates for the year 2020 a reduction in the flow delivered compared to the driest years (2006-2007) that cannot be fully justified by the low recharge rate entering the aquifer. In fact, there is a higher recharge value for 2020 than for the two-year drought period.

However, this condition agrees with similar observations in other Apennine carbonate aquifers. It has been observed that water resource depletion is not only linked to drought years but also to consecutive years having below-average rainfall (Fiorillo & Ventafridda, 2010). It is therefore well known that in Apennine contexts, a fractured carbonate aquifer can accumulate a progressive recharge deficit, resulting in multi-year droughts. According to this scheme, the flow delivered in 2020 by the Gran Sasso carbonate aquifer would be the result of a progressive recharge deficit determined by the succession of drought years since 2016 (except for the 2018 only).

5.2 The Qachqouch aquifer (Case Study Lebanon)

The Qachqouch spring is determined by total annual flow rate reaching 35-55 hm^3/y during the 2014-2019 period (Dubois et al., 2017). The maximum flow rate reaches a value of 80 hm^3/y for a short period of time following flood events and 6 hm3/y during recession periods.

The flow rate data for 2018/2019 and 2019/2020, as seen in Table 5.1, are very high, and it reaches this value only during flood periods and, therefore, has a low probability of occurrence. For this reason, flow rates above 80 hm^3/y recorded by the rating curve during high flow periods can be further corrected through the Manning-Strickler equation. Table 5.1 shows the errors in annual spring volumes before and after correction, particularly for very wet years.

Based on the corrections applied, the flow value recorded in the last two years (2019-2021), equal to 50-59 hm^3/y, is slightly higher than the average of the flow values considered from 2015 to 2018 (average value: 36 hm^3/y).

Total Precipitation (mm) Value at 950 m asl	Discharge	
	Qr (rating curve) without correction	Corrected Qc (Qachqouch) and error ((Qr-Qc)/Qr)
921 mm (2015-16)	35 Mm^3 (2015-16)-652 mm (70%)	29 Mm^3 - 17%
1034 mm (2016-17)	47 Mm^3 (2016-17)- 839 mm (81%)	43 Mm^3 - 8%
1089 mm (2017-18)	50 Mm^3 (2017-18)- 892 mm (81%)	33 Mm^3 - 34%
1838 mm (2018-19)	105 Mm^3 (? Too high) High uncertainties in high flow measurements	76 Mm^3 - 27%
1405 mm (2019-20)	81.3 Mm^3 (? Too high)- High uncertainties in high flow measurements	59 Mm^3 - 27%
1160 mm (2020-21)	49.8 Mm^3 890 mm (77%)	50 Mm^3 - 0%

Table 5.1. Total annual flow calculated based on the rating curve and based on the corrected discharge for values above 10 m^3/s especially in very wet years.

5.3 The Djebel Zaghouan aquifer (Case Study Tunisia)

The aquifer is being exploited by 9 boreholes and galleries for the purpose of providing drinking water. Due to water shortages in the city of Zaghouan, two additional boreholes were drilled in 2017 and 2018 to supplement the supply. The daily amounts of water extracted from these boreholes were collected with the assistance of SONEDE and CRDA.

Errore. L'origine riferimento non è stata trovata..3 shows the temporal evolution of the static level at t he piezometer located in the site Ain Ayed (near the dry spring and the new boreholes) as well as the monthly produced amounts (both natural discharge and extracted from boreholes) and the monthly rainfall. We note that :

- The natural discharge and that produced through the galleries nearly stopped since 2015
- The static level follows a continuous declining trend since 2002, with an expectation of a slight rise recorded in 2012 following a snow event. Indeed, the recorded groundwater level dropped from -0.7 m (2002) to more than -100 m (2022) (below soil level), the total depth of the piezometer being surpassed making it dysfunctional. The continuous depletion of the groundwater seems to be mainly linked to overexploitation (due to urban expansion) than a state of meteorological drought.

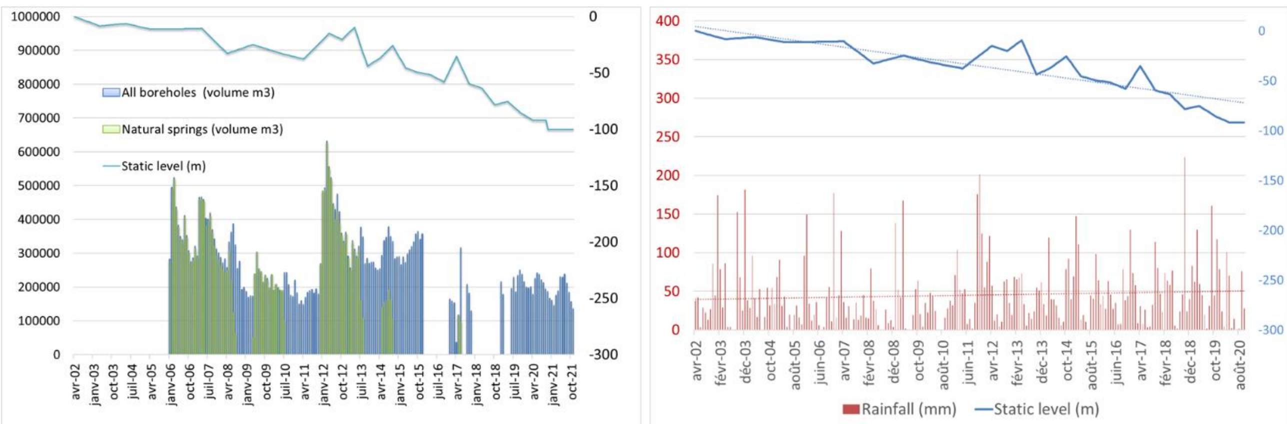


Figure 5.3: temporal evolution of the static level at the piezometer, monthly produced amounts and monthly rainfall

Figure 5.4 depicts the variation of the monthly calculated SPEI and SGI from 2002 to 2020. The Standardized Precipitation-Evapotranspiration Index (SPEI) is a drought index that was first introduced by (Vicente-Serrano , et al., 2010). It is based on the Standardized Precipitation Index (SPI) (McKee et al., 1993). SPEI characterizes meteorological drought by taking into account both precipitation and evapotranspiration. It is calculated by comparing the difference between precipitation and evapotranspiration with the long-term average for a specific location and time period. Typically presented on a scale from -3 to +3, a positive SPEI value indicates that the moisture balance is above average (wet conditions), while a negative value indicates that it is below average (drought).

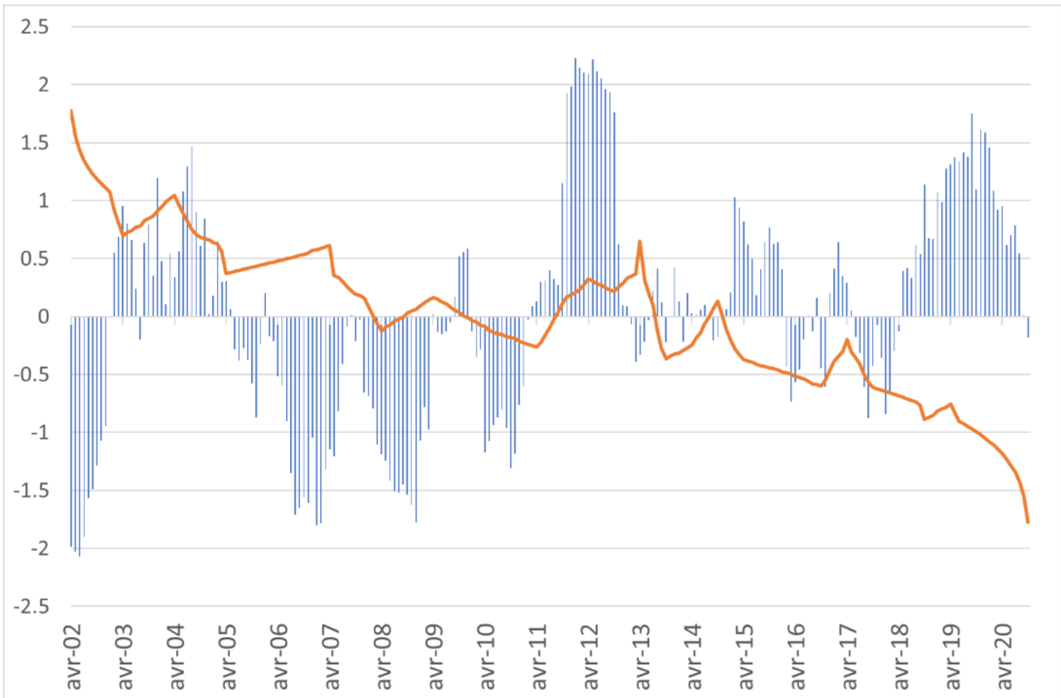


Figure 5.4: Variation of the monthly calculated SPEI (blue bars) and SGI (red line) from 2002 to 2020

The Standardized Groundwater Level Index (SGI) is a drought index that characterizes groundwater droughts; it was first introduced by Bloomfield and Marchant (2013). It is built on the Standardized Precipitation Index (SPI). Unlike meteorological droughts, groundwater droughts are characterized by a decline in groundwater levels, rather than a lack of precipitation. The SGI is calculated using a continuous variable, the groundwater level, which is collected from monitoring wells. Because groundwater level is a continuous variable, there is no need to accumulate it over a specified time period, as it is with precipitation data. The SGI is calculated using a normalization technique that allows the comparison of groundwater levels across different time periods and locations.

Results of calculated SPEI values (figure 5.4), for a time series of 18 years, show the occurrence of several drought events between 2002 and 2011 which can explain the groundwater level decline. The slight groundwater water level recovery indicated by the reversing trend of the SGI recorded between 2011 and 2013 is correlated to the wetness condition (SPEI > 2). From 2018, despite normal and wetness condition the SGI shows severe groundwater drought (SGI < -1.5).

5.4 Merinos-Colorado-Carrasco and Ubrique test site (case study Spain)

During the study period, the three springs in Eastern Ronda Mountains (Marinos-Colorado-Carrasco hydrogeological system) show similar minimum values than in previous long-term research (Barberá, 2014) but ≈9 times lower maximum spring discharge (Table 5.2). Thus, the highest spring discharge during KARMA study period is 497.3 l/s for Cañamero spring, 85.5 l/s for Carrizal and 24.2 l/s for Ventilla. This shortage respect with previous maximum values is easily explainable because recharge conditions were extremely wet during the previous investigation period (2007/2010). As the maximum values, the average flow rate also is decreased compared to previous research.

In the case of the three springs of Ubrique test site, the maximum spring discharge during KARMA study period is 1604 l/s for Cornicabra spring, 917.6 l/s for Algarrobal and 4518.5 l/s for Garciago spring (Table 5.2). However, the maximum spring discharge values since 2013 are slightly high than those observed during KARMA study period. At the same time, as for the Eastern Ronda Mountains springs, the minimum flow values are quite similar for the two observation periods. The mean discharge at the Cornicabra spring is significantly lower than in the past, while the discharge of Algarrobal and Garciago springs was about the double during the KARMA project, respect with the previous long-term data.

	KARMA study period			Previous researches		
Spring	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**	**Min. discharge (l/s)**	**Max. discharge (l/s)**	**Mean discharge (l/s)**
Cañamero	18.9	497.3	135.2	24.9	4530	374
Carrizal	2.15	85.5	22.7	0.6	783	86
Ventilla	0.5	24.2	11.5	2	163	38
Cornicabra	2	1604	123.66	0	2605.5	290.1
Algarrobal	8.23	917.6	287.5	6	2897.8	144.7
Garciago	0	4518.5	302.9	0	8977.2	151.2

Table 5.2. Main statistical descriptors of spring discharge values in the two Spanish KARMA test sites

5.5 The Lez Karst Catchment (case study France)

Figures 5.5, 5.6 and 5.7 present the daily, monthly and yearly analyses of the Lez spring discharge time series, respectively. Over the 2009-2021 period, the pumping discharge represents more than 50% of the total volume with a mean pumping of about 1.02 m^3/s and a mean natural discharge at the spring of about 0.84 m^3/s when considering the whole time series. Due to the pumping, the spring discharge is regularly null during dry periods. The minimum and maximum observed discharges over the monitored period are 0 and about 8.2 m^3/s respectively. The mean discharge at the spring is also variable at the annual scale, with a maximum annual mean of 1.5 m^3/s in 2018 and a minimum of 0.33 m^3/s in 2012 and 2020. It is mainly correlated with precipitation, although the year of minimum annual precipitation (2017 with 560 mm) does not correspond to the minimum annual mean discharge in 2012 (for which annual precipitation was about 692 mm). Due to the short length of the time series (12 years), it is difficult to identify long term (i.e. interannual) trend.

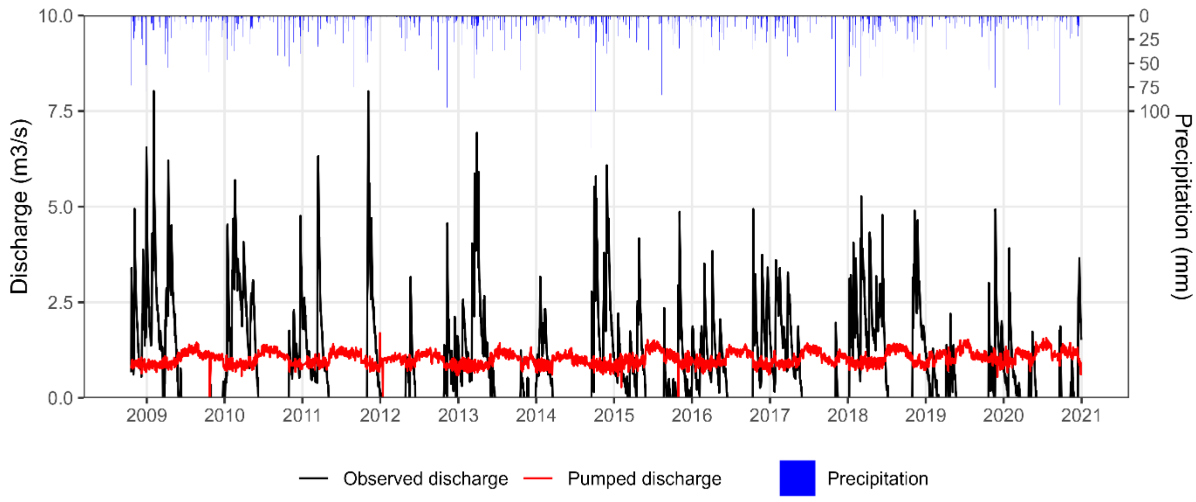


Figure 5.5: Daily discharge and pumped discharge with daily precipitation over the 2009-2020 period.

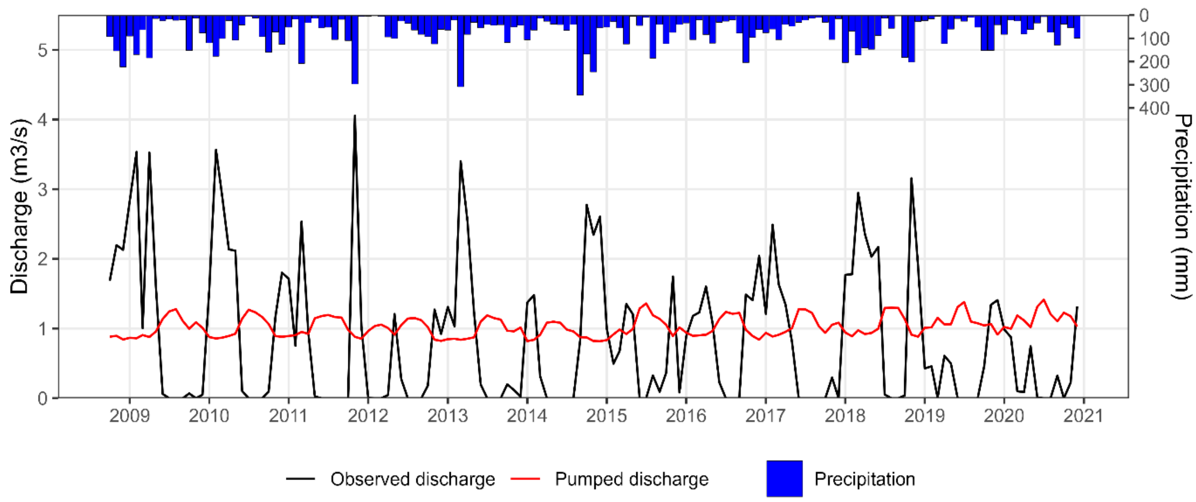


Figure 5.6: Mean monthly discharge and pumped discharge with monthly precipitation over the 2009-2020 period.

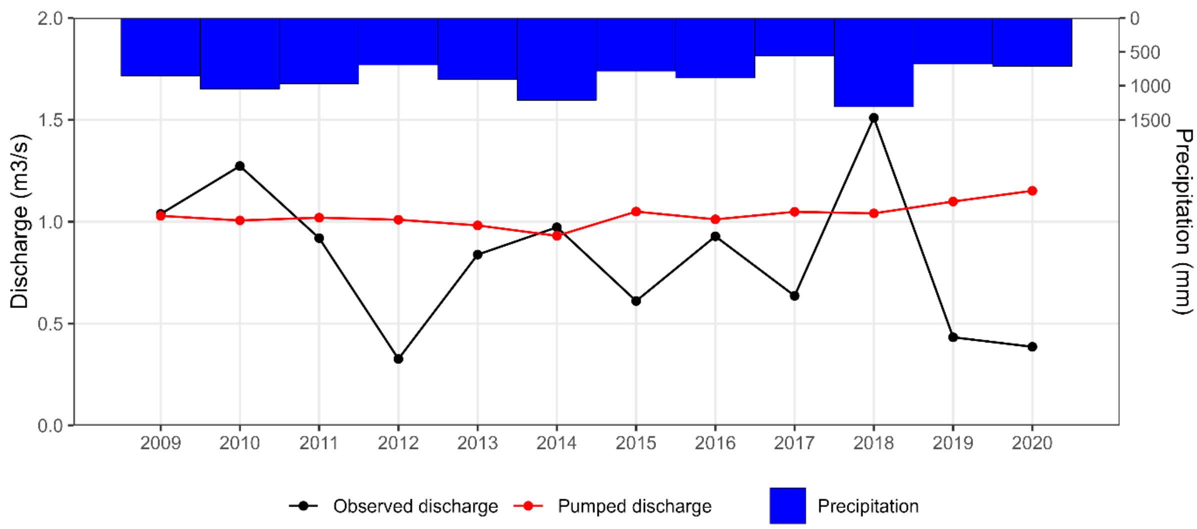


Figure 5.7: Mean annual discharge and pumped discharge with yearly precipitation over the 2009-2020 period.

6. Conclusion

In this report, the recharge rates evaluated at all the different study sites have been discussed and they are summarised in Table 6.1. The comparison of the water budgets obtained by different methods in each study area clearly gives an idea of the advantages and disadvantages of the different methods, thus trying to find the most suitable one for the context. The adoption of the APLIS method, based on geological and morphological information, proves to be a valid tool for calculating recharge in all study areas. In addition to being a valid method for karst systems, the Aplis method resulted in almost high and very similar recharge percentage values among test sites, ranging from a minimum of 45% to a maximum of 64% respect with precipitation amount. The recharge values obtained have been then validated through different approaches. The recharge rates of the aquifers in each study area are discussed in terms of reliability, to assess the uncertainty that may be due to the lack of and gaps in the recharge assessment (see Table 6.1 for values).

The comparison between recharge rates assessed at the scale of the study sites and the results obtained at the regional scale and published in MEDKAM shows discrepancies for almost all test sites, revealing that they do not seem to be automatically suitable, at the actual stage, during the transition from basin-scale to Mediterranean-scale recharge assessment. The main result shows that recharge at the local scale is usually higher than that calculated at the continental scale, with potential underestimation of the actual recharge in karstic aquifers and consequently of the expected spring discharge. A future validation of the Mediterranean-scale recharge assessment method is therefore planned to improve the effective groundwater resource evaluation, and consequently to ensure the capability of upscaling procedures.

The discharges recorded during the KARMA observation period (2019-2022) by the aquifers selected as test sites have been compared with the previously available data for the same aquifers and springs. In some cases, recorded discharges are slightly higher than in previous periods (as in Lebanon), and in other cases they show lowering in discharge values (as in Tunisie and in Spain). In general, a significant oscillation with years has been observed (as in Italy and France), which demonstrates the influence of rainy and/or dry years on spring discharge in karst aquifers and consequently the concept of a recharge variability due to climate conditions, significantly regulated by local effects. In fact, we did not observe common responses for the KARMA observation periods in all test sites.

Test site	**Recharge assessment method**	**Recharge values and rate**		**Discharge**		**Period**
		[m³/s]	***[hm³/y]***	***[m³/s]***	***[hm³/y]***	
Gran Sasso (Italy)	Turc Thornthwaite Aplis	11.5 - 30.7 9.8 – 27.3 19.4 **(51.6%)**	362 - 968 309 - 861 611 **(51.6%)**	21.2	669	2001-2020
Qachqouch (Lebanon)	Water budget Numerical model Aplis	1.4 – 2.5 1.6 – 1.9 0.8 **(60%)**	45 - 80 50 - 60 30 **(60%)**	0.9 – 2.4	30-76	2014-2021
Djebel Zaghouan (Tunisia)	Conceptual model Aplis	0.2 **45%**	4.9 **45%**	0.09 – 0.1	3.1 – 3.6	1915-1927 1970-1995
Merinos-Colorado-Carrasco (Spain)	Kessler Thornthwaite Aplis	0.54 – 0.57 0.64 – 0.72 0.6 **(56.7%)**	17.3 - 18 20.3 – 22.9 17.9 **(56.7%)**	0.5 – 0.7	17-24.3	1964-2010
Ubrique (Spain)	Water budget Aplis	0.7 0.6 **(64.4%)**	21.2 19.9 **(64.4%)**	1.11	35.1	1984-2018
Lez (France)	Water budget Aplis	1.8 1.9 **(47%)**	58.3 59.5 **(47%)**	1.9	62	1945-2019

Table 6.1: Summary of calculated recharge and of measured discharge values for each test site

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