KARMA

Karst Aquifer Resources availability and quality in the Mediterranean Area

Vulnerability mapping, validation and risk assessment in Mediterranean karst sites

Deliverable 3.4

Authors (by alphabetical order):

Bartolomé Andreo Navarro (UMA), Juan Antonio Barberá Fornell (UMA), Joanna Doummar (AUB), Jaime Fernández Ortega (UMA), Ana Isabel Marín Guerrero (UMA), Jihad Othman (AUB), Natasa Ravbar (ZASU).

Date: August 2022

This project has received funding from the European Union's PRIMA research and innovation programme

Technical References

Project Acronym	**KARMA**
EU Programme, Call and Topic	PRIMA, Multi-topic 2018, Water resources availability and quality within catchments and aquifers
Project Title	Karst Aquifer Resources availability and quality in the Mediterranean Area
Project Coordinator	Prof. Dr. Nico Goldscheider, Karlsruhe Institute of Technology (KIT), nico.goldscheider@kit.edu
Project Duration	September 2019 - March 2023
Deliverable No., Name	D3.4 Vulnerability mapping, validation and risk assessment in Mediterranean karst sites
Dissemination Level	PU (public)
Work Package	WP3: Water Quality
Task	Task 3.3 Vulnerability mapping
Lead beneficiary	University of Malaga (UMA)
Contributing beneficiary/ies	University of Malaga (UMA), American University of Beirut (AUB), Karst Research Institute (ZRC SAZU)
Due Date	Month 33
Actual Submission Date	Month 35

Version History

Version	Date
1.0	August 2022
2.0	September 2022

Project Partners

(Coordinator)

Executive Summary

Karst aquifers are especially vulnerable to pollution due to their hydrological behaviour derived from karstification processes. In order to protect its groundwater resources, priority actions must be given to prevent the water degradation. The groundwater vulnerability mapping in karst aquifers has undergone important progresses in the last 20 years, being a solid, useful and effective tool in the protection of water resources. Groundwater vulnerability assessment methods have been developed to provide the necessary basis for implementing preventive measures facing groundwater protection, being the delimitation of protection zones one of the most relevant. Therefore, the availability of consistent water-related databases, its validation and interpretation, are of utmost importance in complex hydrogeological systems as karst aquifers.

This deliverable (D3.4 Vulnerability mapping, validation and risk assessment in Mediterranean karst sites.) comprises the core activity of the Task 3.3 "Vulnerability mapping" where the groundwater vulnerability to pollution of the KARMA test sites have been mapped by the application of multiparametric method based on the conceptual agreed under the COST Action 620 "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers" (i.e. COP method,). This deliverable is framed under WP3 that aims to acquire a deep understanding of key hydrogeological processes affecting karst groundwater quality across different research scales.

The report presents groundwater vulnerability maps of Unica springs catchments (Slovenia), the Lez spring catchment (France), Ubrique test site (Spain) and Qachqouch Spring catchment (Lebanon). The individual results of each test site are shown in detail in its respective section of this report.

The overall results show high spatial heterogeneity in the study area extents where the higher vulnerability areas correspond to highly karstified limestones and thin/bare soils or also drainage areas of sinking river and endorreic areas, whose natural drainage occurs through swallow holes hydrologically connected with shafts and other endokarst features. In general, aquifer sectors that are influenced by exokarstic forms that favor infiltration tend to be less vulnerable than karst swallow holes, such as karren field or dolines, although in some systems they can present extreme vulnerability, similar to that of karst swallow holes. On the other hand, COP identifies as Low or Very low vulnerable areas the sectors where low permeability soils and lithology overlying the aquifer.

Since the final goal of any vulnerability mapping is to support stakeholders for decision-making and to promote a land-use management compatible with the water protection, the accuracy and reliability of the obtained maps is a needed requirement for its solid and practical applications. This becomes most relevant in karst media due to the strong heterogeneities in the recharge mechanisms and hydraulic characteristics, both spatial and temporal scales. A solid understanding of the hydrogeological functioning of the aquifer comprises the fundamental pillar for groundwater vulnerability assessment.

The validation of the vulnerability maps has been carried out for two test sites. Validation may involve a wide range of methods and techniques such as field tracing experiments, analysis of natural responses of karst springs, study of environmental tracers, numerical modeling, etc. (Marín et al. 2015). In general, the vulnerability maps show coherent results with those obtained from the analysis of hydrochemical and hydrodynamic responses at the springs as well as dye test tracer, when exist.

The following sections present the main results obtained in almost all the KARMA studies area about groundwater vulnerability assessment and the actions for validating the results by the hydrogeological knowledge obtained from previous tasks developed in the framework of this project are shown.

Table of contents

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 modelling 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 overall objective of the WP3 is the acquisition of a deep understanding of key hydrogeological processes affecting karst groundwater quality across different research scales, from single springs to aquifer/catchment. The gained hydrogeological knowledge will serve as a basis for an appropriate groundwater management and protection in such as highly vulnerable aquifer systems. Specific goals include significant advancements in: a) development of early-warning systems against karst groundwater pollution for a near real-time drinking water management practices in urban settlements and; b) vulnerability assessment of karst aquifers facing future land use planning and environmental challenges for water managers. To achieve that, novel research focused on water quality will be tested in five selected Mediterranean karst aquifers of distinctive geographical, geological and climatological contexts.

Concretely, this document sums up the actions developed under Task 3.3 about groundwater vulnerability mapping. The objective of contamination vulnerability mapping is to identify the most vulnerable zones of catchment areas and to provide criteria for defining protection regulation that avoids the water quality degradation. Vulnerability to contamination has been widely defined (Margat 1968; Foster 1987; Zaporozec 1994; among others). In this study, we used the concept of “intrinsic vulnerability of an aquifer” that concerns its sensitivity to contamination, taking into account its geological, hydrologic and hydrogeological characteristics, independently of the nature and scenario of the contamination (Daly et al. 2002; Zwahlen 2004).

Vulnerability to pollution is not a characteristic that can be directly measured in the field, so indirect methodologies for its assessment are required. The widely used methodologies are based on multiparameter systems. Each parameter represents environmental variables involved in groundwater vulnerability that are discretized using scored intervals according to the relative degree of sensitivity to contamination. The method used in KARMA project has been COP method and COP+K (Vias et al. 2006 and Andreo et al. 2009) that has been applied with the assistance of geographic information systems (GIS) and remote sensing (RS). The GIS permits to match data on the characteristics of the study aquifer keeping the geographical framework as reference and producing spatially explicit information as result.

Karst aquifers are particularly vulnerable to contamination due to flow concentration within the epikarst layer and concentrated recharge via swallow holes. As a result, contaminants may easily reach the saturated zone and then be rapidly transported through karst conduits over large distances (Goldscheider 2005). Many methods have been developed to assess groundwater vulnerability to contamination. These include methods that take account of the geological, hydrological, and hydrogeological characteristics of a karst system and climate variables such as precipitation dynamics.

The European COST Action 620 aimed to develop an approach for vulnerability and risk assessment of karst aquifers in the European framework (Zwahlen 2004). It proposed a conceptual approach, named the origin-flow-target (Figure 1.1), to define two general approaches for groundwater protection: resource protection and source protection (Daly et al. 2002). According to the European guideline for vulnerability mapping, the assessment of resource vulnerability considers processes that control the flow of infiltrated water from the surface (all the modalities) to the main phreatic zone. An additional characterisation of groundwater flow through the saturated zone makes possible the mapping of the vulnerability of a water source.

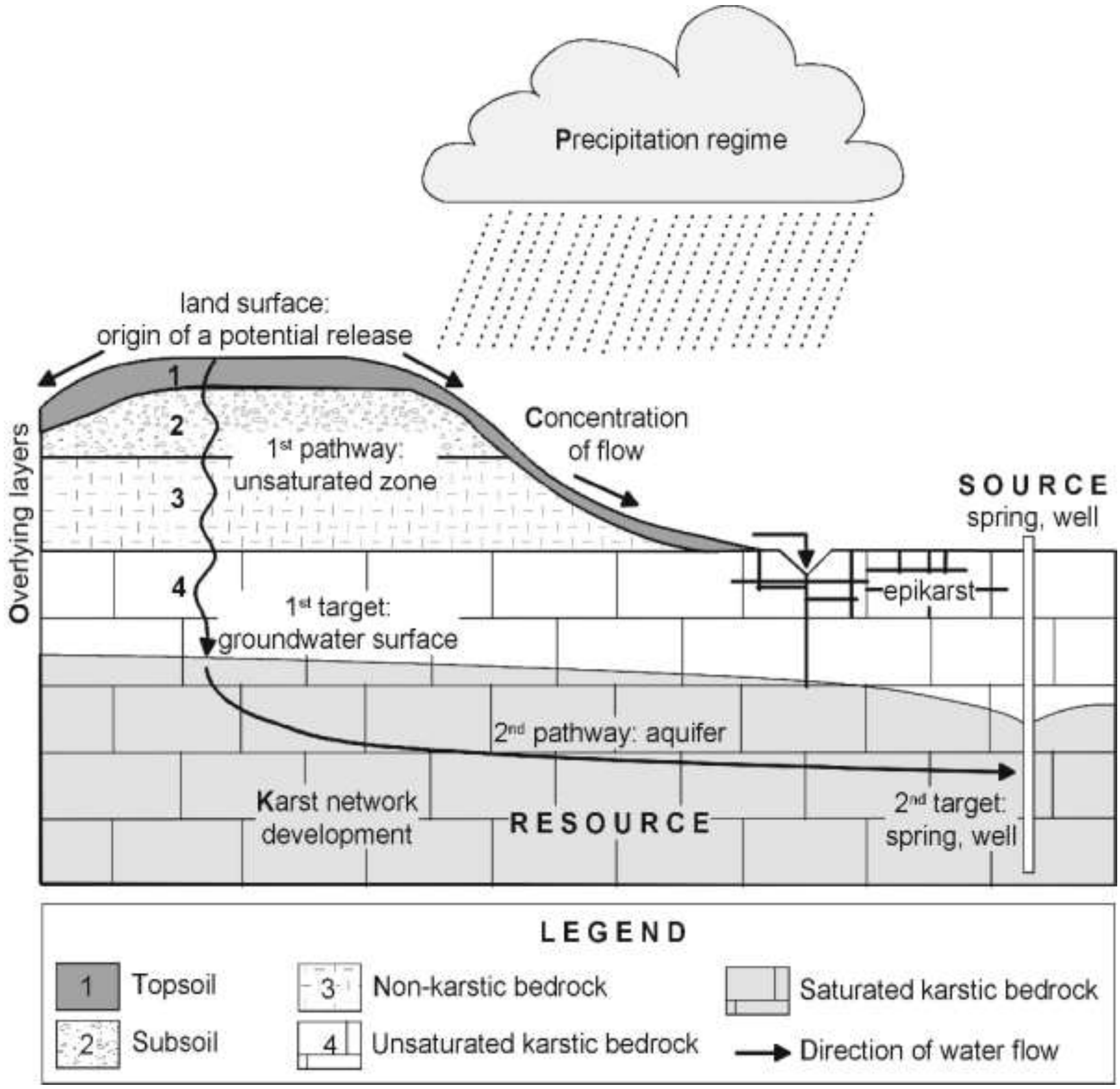

Figure 1.1 The *origin-pathway-target model for groundwater resource and source protection after European COST Action 620 (Goldscheider et al. 2000; Daly et al. 2002; Zwahlen 2004)*

From the early EPIK method (Dörfliger & Zwahlen 1998) several intrinsic groundwater vulnerability assessment schemes have been developed, many of them in line with the European COST Action 620 guidance such as: PI (Goldscheider et al. 2000), VULK method (Jeannin et al. 2001), COP (Vías et al. 2006) or the Slovene Approach (Ravbar & Goldscheider 2007) among others.

The vulnerability assessment requires prior knowledge and characterization of the hydrogeology and other environmental parameter of the aquifer to be protected. The considered variables depend on the method selected for vulnerability mapping. However, there are a set of variables generally included into the assessment. These variables represent physical characteristics of the study area and can be grouped into:

- external factors (climatic, which influences the recharge)
- topography, including altitude, slope and additionally vegetation (influence to runoff capacity),
- related to the unsaturated zone: rock permeability, karstification, fracturing, thickness, soil development (texture and thickness).

In general, the most significant variables that determine the capacity of natural aquifer protection against possible contaminants are included in the applied methodologies.

Under task 3.3 "*Vulnerability mapping*" the groundwater vulnerability to pollution of the KARMA test sites have been mapped by the application of multiparametric method based on the conceptual agreed under the COST Action 620 "Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers (i.e. COP method, and similar methods if required).

The following sections present the main results obtained in almost all the KARMA studies area about groundwater vulnerability assessment by means of COP method and the actions for validating the results by the hydrogeological knowledge got from previous tasks developed in the framework of this project are shown.

2 Methodology: COP and COP+K methods

Detailed conceptual instructions and guidelines for vulnerability mapping were provided in Vias et al. 2006 and Andreo et al. 2009.

The COP method (Vías et al. 2006) was developed in the framework of European COST Action 620. This method has been applied, among others, by Vías et al. (2006 and 2010); Yildirim & Topkaya (2007); Polemio et al. (2009); Plan et al. (2009); Marín et al. (2012). The COP method considers the characteristics of layers overlying the water table (O factor), the parameters which control the flow concentration (C factor) and the precipitation (P factor). The O factor reflects the protective capacity of the overlying layers provided by soils (texture and thickness) and the lithology of the unsaturated zone (fracturing, the thickness of each layer and the confining conditions). Karst geomorphology, slopes and vegetation cover are taken into account in the C factor, which discriminates between areas where the infiltration is concentrated via swallow hole and where the overlying layer might be bypassed, and the rest of the area. Karst features may be present in each of these infiltration scenarios. In the first case, the existence of swallow holes is usually associated with drainage of the karst landforms (poljes, dolines, etc.). In the rest of the area, karst features and the presence or absence of surface layers are considered because these parameters control the relation between runoff and infiltration processes. The P factor considers both the spatial and temporal variability of precipitation, which plays a role in the transfer of contaminants, especially in large aquifers. The COP vulnerability index value is obtained by multiplying the C, O and P scores (Figure 2.1).

The COP method was designed to assess resource vulnerability. However, this was later modified to assess the source vulnerability map by the addition of the K factor. The COP+K method (Andreo et al. 2009) is an extension of the COP method that requires, firstly, the resource vulnerability map (using COP) and, additionally, to assess the flow path through the saturated zone (K factor).

1.1 O Factor (overlying layers)

The O factor considers the protection provided to the aquifer by the physical properties and thickness of the layers above the saturated zone. Two layers with important hydrogeological roles are used in order to evaluate the O factor: Soils (O_S) and the lithological layers of the unsaturated zone (O_L)

1.1.1 O_s factor (Soil)

The O_s factor represents the soil, i.e., the texture and thickness of the soil cover. The thicker the soil cover, the higher the likelihood of contaminant attenuation. Furthermore, fine soil textures (i.e., clay) have lower hydraulic conductivity, higher exchange capacities and high specific surface areas. and are therefore characterized by higher transit times. Additionally, due to their sorption capacity for ionic species, they are more likely to attenuate some types of contaminants (ionic or charged species). The O_S factor increases with increasing thickness and fining soil texture denoting a low vulnerability.

1.1.2 O_L factor (Lithology)

The O_L factor is representative of the unsaturated zone. It defines the layers directly overlying the aquifer. It consists of one the one hand of the type of lithology, the confinement of the aquifer, and the thickness of the unsaturated zone. It is calculated according to the following equation, where the product of ly and m is calculated separately, reclassified, and multiplied by the degree of confinement. The lower the value of the product of ly and m the lower is the protection value, i.e., the higher is the vulnerability.

$$O_L = [ly.m].cn$$

Values representative for each type of lithology are given to the various types of rocks outcropping in the catchment area. The higher the value, the lower the vulnerability (e.g., karstic rocks are given a value of 1, whereas clays a value of 1500.

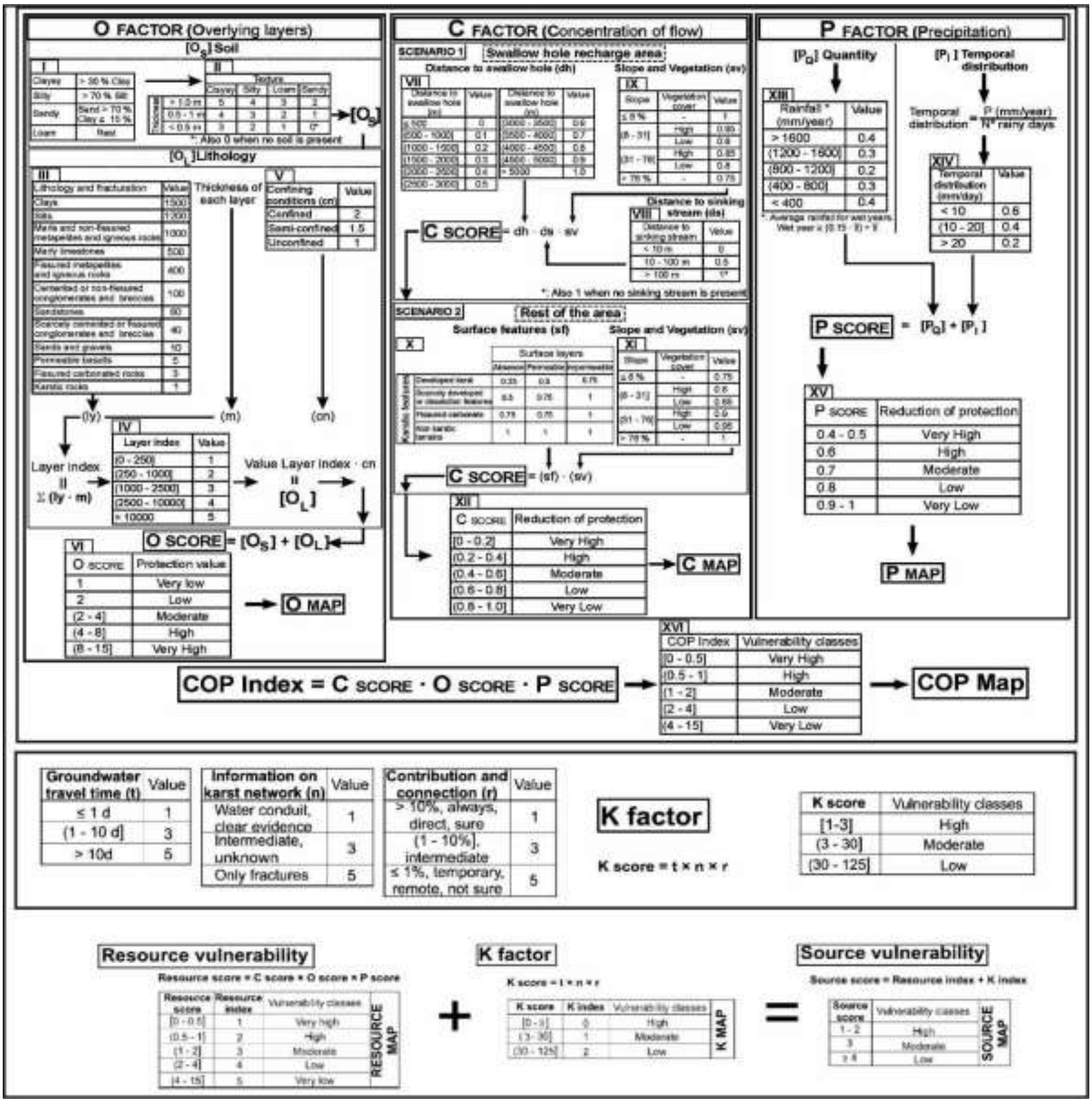

Figure 2.1 Diagram of the COP + K method (modified of Vias et al. 2006 and Andreo et al. 2009)

1.2 C Factor (flow concentration)

The C factor is the *flow concentration* map and represents the types of infiltration occurring on the catchment. Karst systems are characterized by a duality of infiltration, where infiltration can occur diffusively on the entire catchment and/or concentrated in sinkholes or dolines (fast flow pathways). In the COP method, the catchment is divided into two main zones. The first zone (Scenario 1) includes the concentrated recharge by sinkholes. The second zone (Scenario 2) consists of the rest of the area, where the recharge occurs in a diffuse mode. The C factor for Scenario 1 consists of the multiplication of three main factors (Equation1; distance to swallow hole (dh), vegetation and slope (sv) and distance to sinking stream (ds)). The C factor for Scenario 2 is the result to combine vegetation and slope (sv) and surface features (sf) characteristics.

$$C = dh.ds.sv \quad \textit{Equation 1}$$

$$C = sf.sv \quad \textit{Equation 2}$$

1.3 P Factor (Precipitation)

The P Factor represents the climatic conditions in the catchment. It is the sum of two sub factors (P_Q and P_I) defining the amount and intensity of yearly precipitation respectively. P_q represents the amount of precipitation, it ranges between 0.20 and 0.40. P_I reflects the intensity of precipitation, in other terms the ratio of precipitation amount and number of rainy days. This factor ranges between 0.2 and 0.6. The P factor considers that the higher the precipitation i.e., the likelihood for recharge and the higher the intensity during precipitation events, the more vulnerable the investigated area.

1.4 COP Vulnerability index – Resource vulnerability

The factors of the COP method have been combined to evaluate the intrinsic vulnerability of a groundwater resource, as proposed in the following formula:

$$\textit{COP Index} = C \cdot O \cdot P$$

The final numerical representations of the C, O and P factors (the C, O and P scores) are multiplied. Within the COP method, the values for the intrinsic vulnerability index range between 0 and 15. These values are grouped into five vulnerability classes (Very High, High, Moderate, Low and Very Low vulnerability). See Figure 2.1.

1.5 K factor (Karst satured zone)

The K factor assessment involves the degree of karstification or drainage system development and the identification of the underground water flow paths. This also includes information on groundwater flow velocities within the saturated zone and the variability of water flow and drainage divides arising from different hydrogeological settings or hydrological conditions.

Concretely, K factor conconsiders the following subfactors: travel time (t subfactor), connection and contribution degree of different parts of aquifer to the spring (r subfactor) and information of karst conduits with active drainage (n subfactor). See Figure 2.1.

The final K factor is a product of the three subfactors ranging from 1 to 125. The final values are subdivided into three classes: high vulnerability, medium vulnerability and low degree of vulnerability of a source to contamination.

1.6 COP + K vulnerability index – Source vulnerability

The integration of the K scores (section 1.5) and COP index values (resource scores, 1.4) is made by the transforamtion in the relevant indexes. The summing of the COP (resource) and K indexes offers a source vulnerability score assessment ranging between 1 and 7. The values are distributed in three classes of vulnerability: values 1 and 2 signify high source vulnerability, 3 and 4 medium vulnerability and more than 4 low source vulnerability. See Figure 2.1.

3 Methodology: Validation

The vulnerability map has become routine procedure to support the land use planning as measure to protect the groundwater quality. However, about vulnerability maps, it is necessary to know what really means the protection grade of the surface aquifer. Using the vulnerability guidance, the vulnerability mapping by one of the existing methods is relatively easy to implement after knowledge on GIS and on hydrogeology.

The weaknesses of groundwater contamination vulnerability mapping, implicit in the choice of method and the subjectivity of its application, are obvious. Nevertheless, it remains a tool with great potential for groundwater quality protection. It is relatively simple to apply, if supported by appropriate hydrogeological studies and baseline maps, and its implementation within land-use planning policies is intuitive, since the outcome of this technique is a map that shares a common territorial basis with the working environment.

One key question is if the results are coherent with the real vulnerability of the study area. What does a high, moderate or low vulnerability mean? Several authors (Vías et al. 2005; Neukum & Hötzl 2007; Ravbar & Goldscheider 2009; Marín et al. 2012) highlighted that the maps of groundwater contamination vulnerability obtained by the different methods differ significantly, although they were all obtained by methods developed for karst aquifers, using the same sources of information and applying by the same person. So, the validation is an essential element of any contamination vulnerability assessment.

The current challenge is facing researchers to obtain versatile and straightforward methods to test and validate vulnerability maps. For a comprehensive validation of the maps a wide range of methods and techniques can be applied to characterise fast and slow flows within the system, the responses in both high and low water condition, the overall response and the response to short- term signal, etc.

There are a range of variables that could be used to validate the vulnerability map (Zwahlen 2004) such as analysis of the hydrochemical response at springs, tracers (natural or artificial) or hydrodynamic modelling. Neither of them is concluding, each of these instruments informs about certain processes within the aquifer. The key is combining several of them to support the resulting map.

Analysis of hydrochemical responses, especially the natural tracers coming from the aquifer surface (TOC, NO_3^-, natural fluorescence and bacteria), constitutes a useful tool to know transit times and the overall vulnerability of the aquifer. Natural tracers as chemical and isotopic composition of the water are transported within the aqueous solution, and they permit to deduce flow conditions, speeds and transit times (Batiot et al. 2003; Baker et al. 1997; Mudarra et al. 2011). The evolution of the concentration of these groundwater components during recharge periods is a descriptor of the system overall response to water entry distributed over the aquifer surface. Analyses of the evolution of TOC, NO_3^- and natural fluorescence, together with the hydrographs and chemographs of other components, permit to characterise the general response of the aquifer and the vulnerability to contamination (Marín et al., 2012).

The main limitation in the application of natural tracers is that to validate groundwater vulnerability mapping their point of origin in aquifers cannot be accurately located in most cases. Therefore, it is not possible to estimate flow velocities, although the arrival of water infiltration at the spring can be identified and estimated average transit times.

Day tracers are widely applied to validate the vulnerability maps (Perrin et al. 2004; Andreo et al. 2006; Ravbar & Goldscheider 2007; Goldscheider, 2010; Marín et al. 2012). This tool permits to know the flow path as well as the connections and the contribution between surface and discharge points and thus enhance the knowledge for delineating the boundaries of the catchment area. The tracer tests allow us to estimate the transit time and to deduce the concentration decline of a potential contaminant (artificial tracer) from the injection point (origin) to a sampling point (target), following the origin – pathway - target model. The intrinsic vulnerability is usually validated by conservative tracers such as uranine or several other fluorescent dyes or salt tracers, such as chlorides, whereas for validating specific vulnerability reactive tracers should be used. To validate a source vulnerability map, the tracer breakthrough must be recorded at the spring or well. For resource vulnerability, the tracer breakthrough should be recorded at the basis of the unsaturated zone (water table), which is, however, often not possible.

The validation of vulnerability map by tracer tests is based on the analyses of the breakthrough curves which permit to estimate:

- Travel time of a contaminant from the origin to the target as the mean transit time, the time of the first arrival and the time of the maximum concentration.
- Relative quantity of the contaminant that can reach the target as the recovery rate which shows the degree of 'attenuation'.
- Duration of a contamination event when tracer concentration exceeds a given limit.

Tracer tests are a powerful tool to validate vulnerability maps, although this technique is not exempt of problems and limitations (Goldscheider et al. 2001). First at all the tracers test only allows checking the vulnerability in the injection points not in the large areas where the vulnerability has been assessed. The results obtained during the tracer tests depend on the hydrologic conditions and on the injection points due to the anisotropy and heterogeneity of karst aquifer. So, the results should be carefully analyzed in the frame of the hydrogeological context, and they cannot be extrapolated to the whole of the area, even if the vulnerability class is the same.

The natural and artificial tracers are useful techniques to validate the vulnerability maps. Despite the potential and the utility of both types of tracers (Figure 3.1), they are not commonly used in conjunction to validate the maps (Marín et al. 2012). However, the natural and artificial tracers complement each other enhancing the knowledge of karst aquifer (infiltration processes, recharge mechanisms and vulnerability).

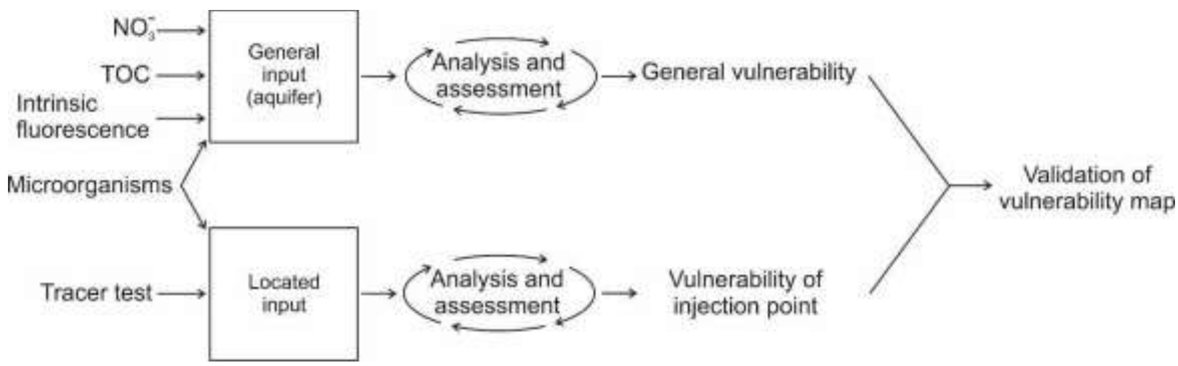

Figure 3.1 Natural and artificial tracers as techniques for validation of the vulnerability maps (Marín and Andreo, 2015)

4 Groundwater vulnerability to pollution of KARMA study areas

4.1 The Qachqouch aquifer (case ctudy Lebanon)

4.1.1 General description of the test site

Qachqouch Spring (Figure 4.1), is located within the Nahr el Kalb Catchment and originates from the Jurassic karst aquifer at about 64 meters above sea level. During low flow periods, the spring is used to complement the water deficit in the capital city Beirut and surrounding areas. Its total yearly discharge reaches 35-55 Mm^3 based on high-resolution monitoring of the spring (2014-2019; Dubois et al., 2020). Flow maxima reach a value of 10 m^3/s for a short period following flood events; discharge is about 2 m^3/s during high flow periods and 0.2 m^3/s during recession periods.

About 67% of the area in Lebanon consists of karstified (6,900 km^2) rock sequences (Dubois, 2017). The catchment area drained by the Qachouch spring is delimited to the North by Nahr El Kalb River and extends for more than 55 km^2 of mountainous nature at a maximum elevation of 1650 m.a.s.l. (Dubois, 2017). Tracer experiments show a relationship between the Nahr El Kalb River and the Qachqouch Spring through a sinking stream (Doummar and Aoun, 2018b).

The spring originates from a carbonate aquifer composed of the Jurassic formation sequence of massive fissured limestone of more than 100 m in thickness. Dolostones characterized by a higher porosity (10-12%) are found in the lower part of the formation because of the diagenetic dolomitization and along leaky faults and dykes because of hydrothermal dolomitization (Nader et al., 2004). The investigated area is located in the tectonic regime of a major fault, Yammouneh Fault, causing tectonic deformation and fracturing of the catchment area. Multi-level karstification in the Mediterranean was developed during the Messinian salinity crisis and Quaternary glacial events causing deep karst systems with features such as large dissolution conduits, dolines, sinkholes, and caves (Bakalowicz, 2005; Dubois et al., 2020). The area is characterized by a duality of infiltration portrayed by the point source infiltration in preferential pathways (dolines, permeable faults) and diffuse recharge in bare fissured rocks.

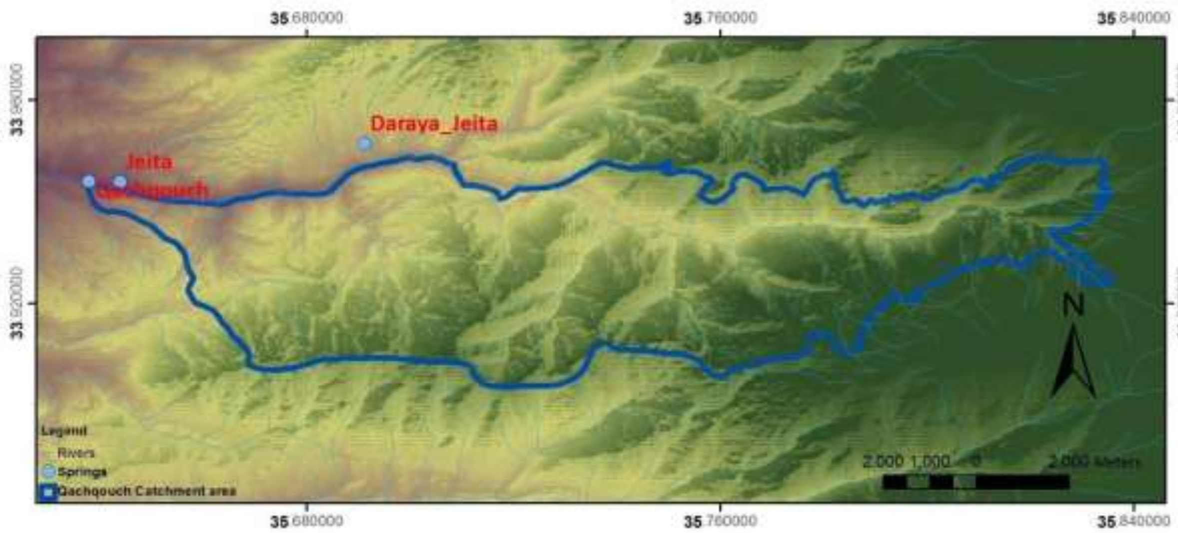

Figure 4.1 The catchment area of the investigated Spring (Qachqouch). Nahr el Kalb River acting as a boundary condition in the northern part of the catchment.

4.1.2 Vulnerability assessment

4.1.2.1 C Factor

- **Slope and vegetation (sv)**

The slope is extracted with ARCGIS from the Digital Elevation Model (DEM) in percent, and reclassified into 4 categories (≤8%, 8<S<31, 31<S<76, and >76), which were assigned weights accordingly. Based on the land use / land cover maps provided by the BGR, land use was divided into two main types, mainly "no vegetation" (including bare soils and rocks, grassland or low sparse vegetation) and "vegetation".

Slopes and type of vegetation were assigned values as per Table 4.1.

Table 4.1 Classification of slope and vegetation in the lower catchment and calculation of the factor sv

Slope	Value (s)	Vegetation	Value (v)	s+v (sv)	Reclassification sv
≤8%	1	Yes	0.05	1.05	1
	1	No	0	1	
8<S<31	0.9	Yes	0.05	0.95	0.95
	0.9	No	0	0.9	0.9
31<S<76	0.8	Yes	0.05	0.85	0.85
	0.8	No	0	0.8	0.8
>76	0.7	Yes	0.05	0.75	0.75
	0.7	No	0	0.7	

- **Swallow hole recharge area (dh)**

The distance to swallow holes consists of a series of buffer zones located at determined distances from fast recharge karst features (such as dolines). The locations of the dolines were provided by BGR (Margane & Abi Rizk, 2011). The recharge areas of dolines consist of the buffer around each identified doline. It is assumed that the area located around a doline is characterized by a high vulnerability. A series of increasing Buffers (500 m each) using the Arc Toolbox was created around each doline. Each buffer was attributed a respective factor (dh).

Scenario 2 is considered to include the area located outside the buffer zone extending 5000 m from the dolines. The final C factor is illustrated in Section 4.2.

4.1.2.2 O Factor

- Os factor

The Os factor map was developed based on the soil map. Four main categories of Os factor are prevailing in the study area, the factor "3" is mainly attributed to the lower catchment area on the Jurassic aquifer, where most of the soil has a thickness that exceeds 1 meter and is classified as loam. Most of the Os factor map was interpolated based on geology and the 166 samples collected from various formations over the catchment.

- O_L factor

The O_L factor is the product of the layer index and the degree of confinement (cn). The layer index is the product of the type of lithology and fracturing (ly) and the thickness of the unsaturated zone. Each formation was assigned a value for *ly* and *cn* as in Table 4.2. The confinement conditions are identified for each aquifer, notably the main aquifer, depending on the impervious properties of overlying and underlying layers. The depth to groundwater is mainly representative of the thickness of the unsaturated zone under static conditions.

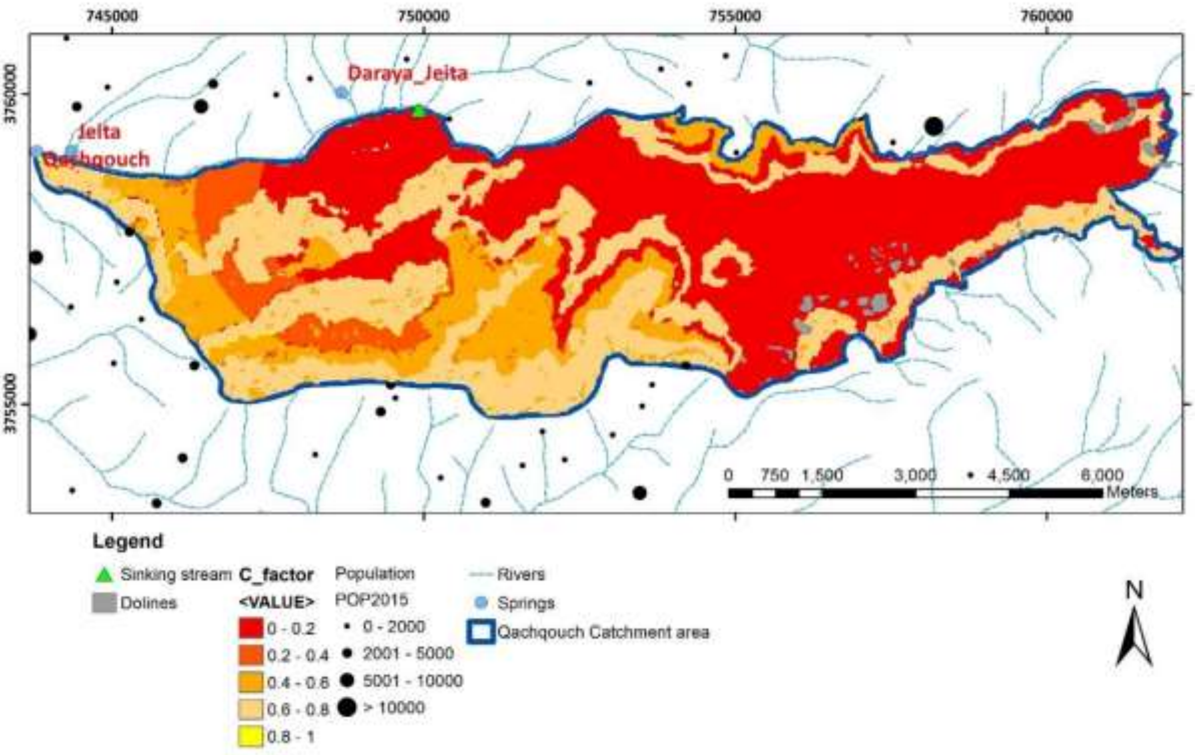

Figure 4.2 Map for C factor of Qachqouch aquifer

Figure 4.3 shows the final O factor map resulting from the summation of both O_L and Os factors.

Table 4.2 Values attributed to the lithologies outcropping on the investigated catchment (ly refers to the type of lithology and cn refers to the degree of confinement as per the COP method)

Type of lithology	Nomenclature	Age	Value_cn	Value_ly
Limestones, highly karstified	J4	Jurassic	1.5 (J5 basalts)	1
Fissured fractured limestones	C2b, J6	Cretaceous, Jurassic	1.5 (C3 basalts/marls)	3
	J7, C2a	Cretaceous, Jurassic	1 (non-confined)	3
Sandstones	C1	Cretaceous	1.5 (C1 basalts)	60
Marly limestones	C3	Cretaceous	1 (non-confined)	500
Basalts	J5	Jurassic	1 (non-confined)	1000

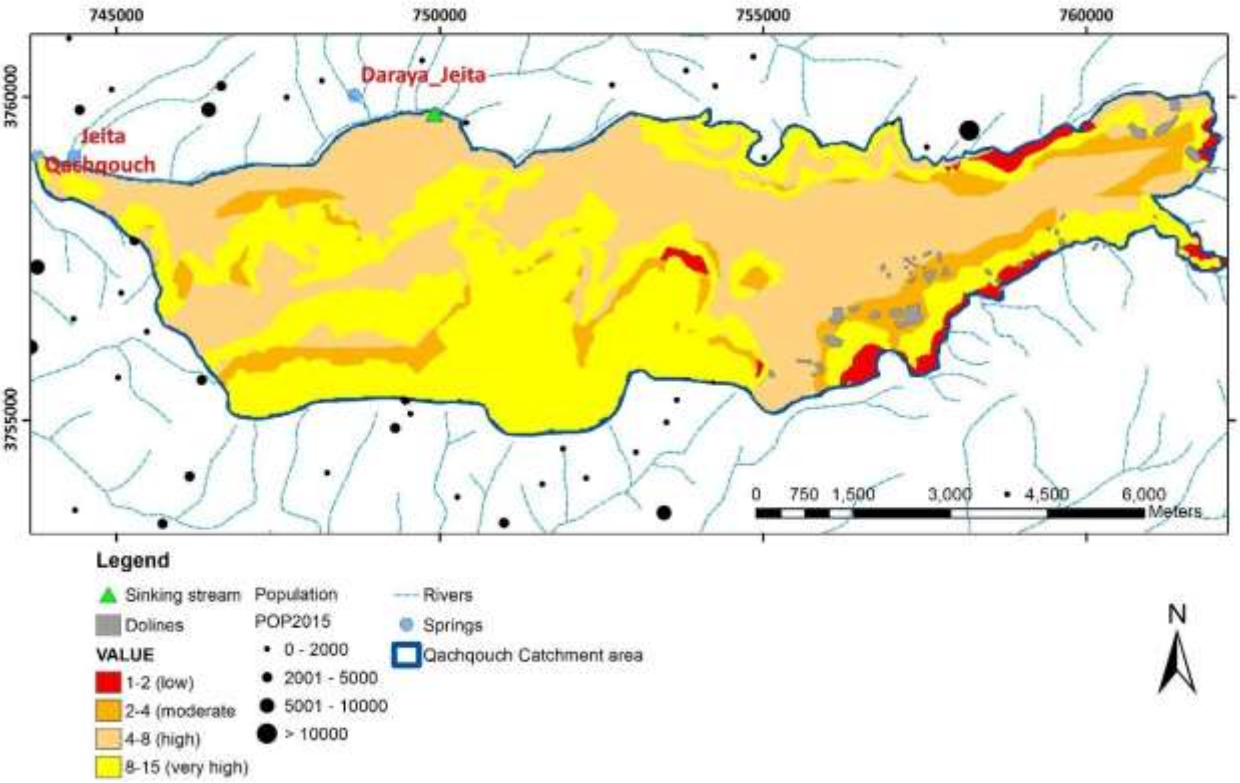

Figure 4.3 Map for O factor of Qachqouch aquifer

4.1.2.3 P Factor

The P Factor represents the climatic conditions in the catchment. It is the sum of two sub-factors (P_Q and P_I) defining the amount and intensity of yearly precipitation respectively.

- Precipitation Quantity P_Q

The Precipitation map (Section 2: FAO/UNDP, 1973) can be reclassified, where intervals are attributed values as per the following:

Table 4.3

Rainfall (mm per year) (for a wet year)	Value
>1600	0.5
1200-1600	0.5
800-1200	0.6
400-800	0.8

- Precipitation Intensity P_I

The precipitation intensity is the ratio of the amount of precipitation to the number of rainy days (for a wet year: P_I/ number of rainy days; Figure 4.4). The number of rainy days in Lebanon ranges for a wet year at around 80 days per year, based on the analysis of precipitation data for the Beirut (Beirut International Airport AIB) or the years 1999-2010. For recent years (2014-2021), the total amount of rainy days calculated for data collected at 1700 m above sea level is about 98 days per year.

Table 4.4 Numbers of rainy days (1999-2010); comparison of Pi ranges for different elevations

Hydrological year	Total (mm/year)	number of rainy days	Precipitation range (P_I values) 400	800	1200	1600
2015-2016	1105	85	5.71	11.43	17.14	22.86
2016-2017	1005	87	6.06	12.12	18.18	24.24
2017-2018	1084	87	4.65	9.30	13.95	18.60
2018-2019	1838	127	4.94	9.88	14.81	19.75
2019-2020	1405	105	8.51	17.02	25.53	34.04
Average (AVE)	1287	98	6.26	12.52	18.78	25.03

By dividing the amount of precipitation by the number of rainy days (estimated at 98 days), a precipitation intensity contour map could also be generated. The summation of P_Q and P_I generates the P score as shown in next figure.

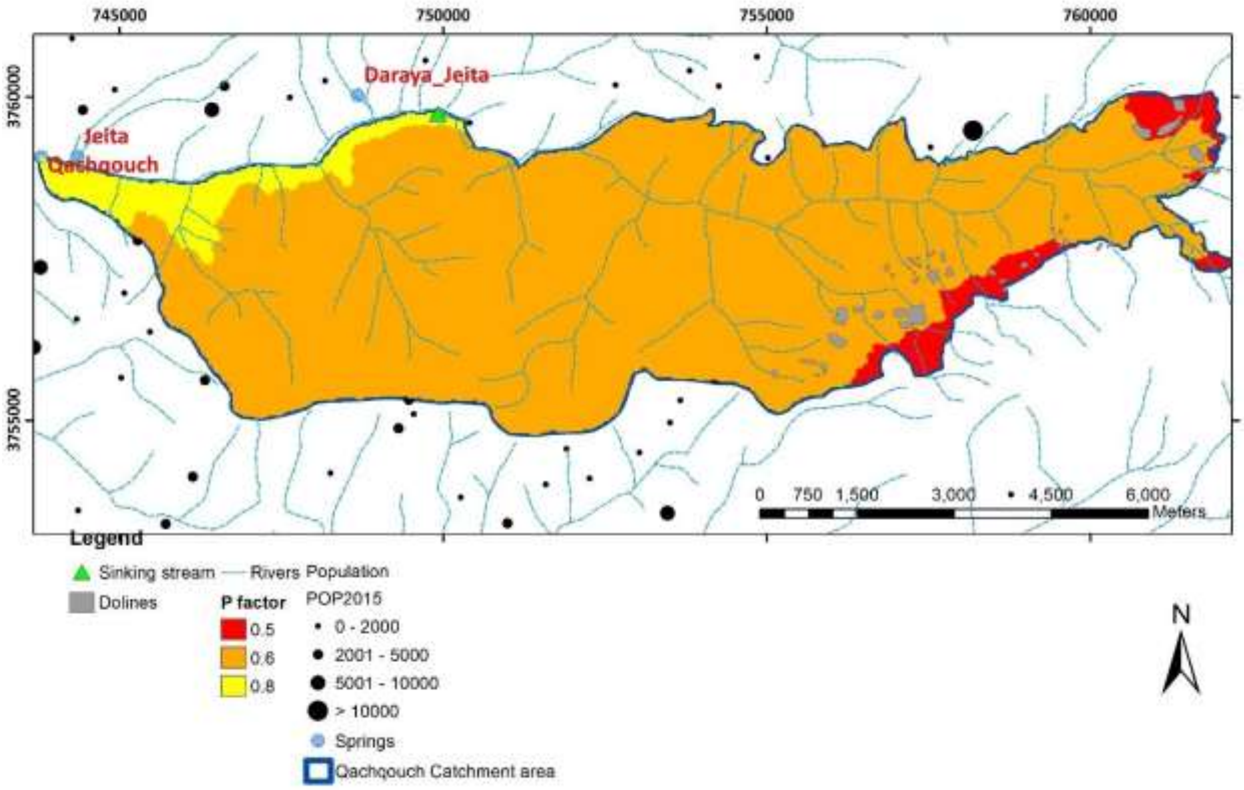

Figure 4.4 P factor map of Qachqouch aquifer

4.1.2.4 Results: COP Index

The multiplication of the three maps for each score, namely C, O, and P yields as per the following equation the resulting COP factor for the lower catchment. The final map is reclassified according to the vulnerability classes as per the COP method (Figure 4.5).

$$COP = C.O.P$$

Five different vulnerability classes ranging from very low to very high are identified on the COP map. The C factor seems to highly influence the final COP map, mainly because the area located within a

500-m distance from the dolines has a weighting value of 0, which highly affects multiplication with vegetation and slope and the two other factors (O or P) as well and reduces their weight to zero.

The very highly vulnerable area consists of a relatively significant portion of the total investigated area, i.e., about 43.9% of the total area (23.3 km^2) including the villages of Hemlaya, Beit Chabab, and partially smaller villages in the upper southern flank of the Nahr El Kalb River. A large portion of the highly vulnerable area consists of the area buffering the sinking stream, and buffers around dolines and sinkholes. High vulnerability zones (8.5%) are delineated in areas close to the major faults where soil thickness is limited, and permeability is assumed to be higher even in lower permeability rock facies. The moderately vulnerable areas extend and cover an area of about 1.9 km^2 (3.6% of total area) and include areas directly upstream to the spring, also in heavily populated rural areas, where soil thickness is limited. The areas with low and very low vulnerability mainly include the non-karstic formations located upstream in the catchment and cover the rest of the area, i.e., 44%.

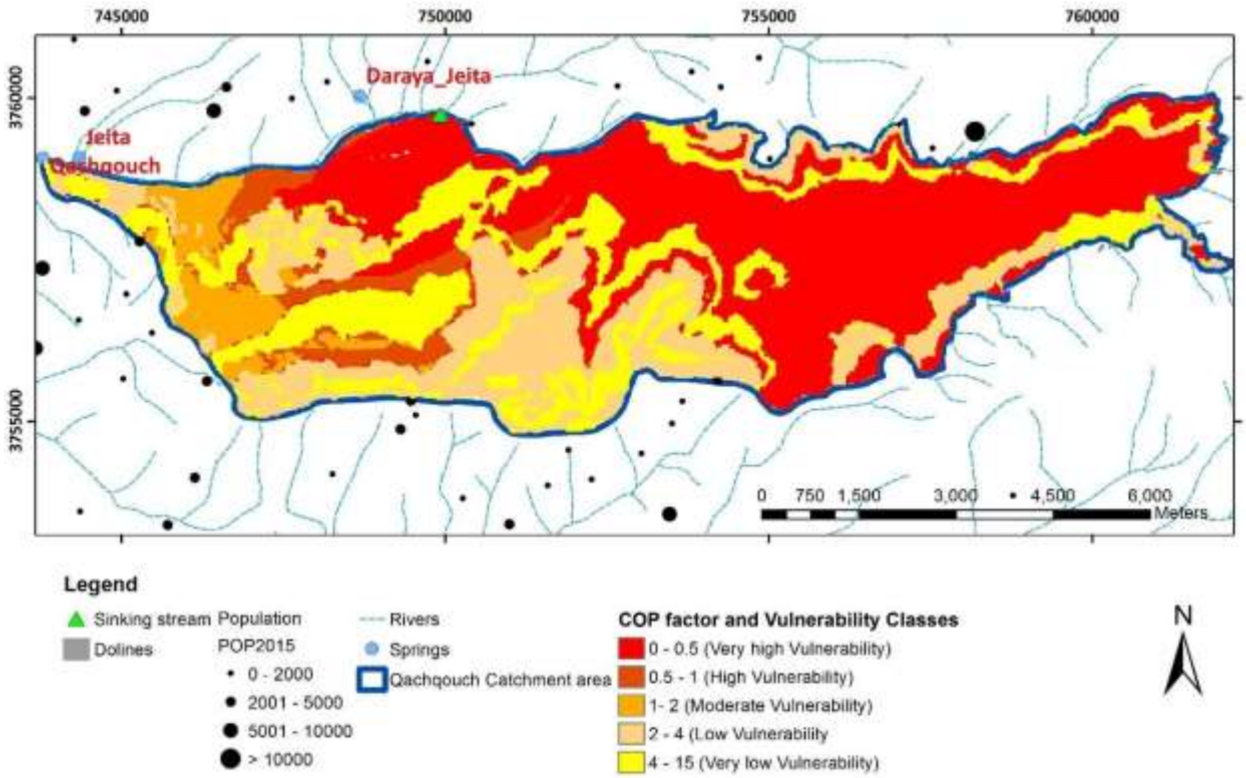

Figure 4.5 Groundwater vulnerability map based on COP method of of Qachqouch aquifer

4.1.3 Discussion and final remarks

Table 4.5 Vulnerability classes and their respective areas according to COP

Vulnerability	Value	Count	Area (km²)	% of total area
Very high	0-0.5	24708	23.3	43.9%
High	0.5-1	4792	4.52	8.5%
Moderate	1-2	2017	1.90	3.6%
Low	2-4	17701	16.7	31.4%
Very low	4-15	7069	6.67	12.6%
Total		**56287**	**53.1**	**100**

The maps provide a classification of the extent of vulnerability of each parcel located in the study area. Those maps are primordial to secure a sustainable groundwater resources management and ensure the preservation of water quality, given the importance of the Qachqouch Spring.

Soil texture and thickness highly influence the Overlying Layers (O factor), consequently the final protection value. Therefore, a detailed soil map with a high-resolution portraying texture and thickness of soil in various locations is primordial for an accurate assessment of the Os factor. The thickness of the unsaturated zone plays a major role in defining the O_L factor especially in karstic and fissured carbonate rocks. Therefore, the assessment of the latter in critical areas is very important for the definition of the O_L factor, especially when the thickness of the unsaturated zone is less than 100 m.

The main controlling layer in the C factor is the *dh* (doline and sinkhole) layer, because the areas located within 500 m from the doline are attributed a value of 0, which is able to cancel both O and P factor in the final calculations. Thus, it is very important to understand the mechanisms of rapid infiltration in the dolines and sinkholes delineated in the study area and the extent of their recharge areas. P factor plays a role only in the case of moderate to low vulnerability, whereas in the cases where C and O factors are very low, the precipitation factor (P) plays a negligible role.

It is important to mention the various limitations of the available data and their influence on the mapping exercise and provide recommendations for additional investigations to refine the above study. It is recommended to investigate thoroughly the following factors to achieve a better refinement of the vulnerability maps, given that the application of vulnerability maps have a major influence on land expropriation and land use patterns.

- A better assessment of the variation of the thickness of the unsaturated zone in the lower and upper catchments
- A higher resolution mapping of the soil texture and thickness over the entire area especially in areas of concentrated high infiltration, assessment of soil cover in riverbeds and degree of infiltration, especially in the presence of sinking streams if any.
- A differentiation between karstic rocks and fissured carbonate rocks on the basis of degree of fracturing and karst features.
- A more accurate estimation of spatial precipitation based a large amount of rain gauges (number of rainy days and precipitation gradient change) and effect of snow and delayed infiltration especially in the upper catchment.

4.2 Ubrique test site (case study Spain)

The result here presented have been published in the frame of KARMA project in:

Marín AI, Martín Rodriguez JF, Barberá JA, Fernández-Ortega J, Mudarra M, Sánchez D, Andreo B (2021). Groundwater vulnerability to pollution in karst aquifers, considering key challenges and considerations: application to the Ubrique springs in southern Spain. Hydrogeology Journal. Vol. 29 Issue 1, p379-396. 18p. [*10.1007/s10040-020-02279-8*](10.1007/s10040-020-02279-8)

4.2.1 General description of the test site

Sierra de Ubrique test site is located within Sierra de Grazalema Natural Park, in the eastern part of the Cádiz province and 35 km of distance from the Merinos-Colorado-Carrasco area. Aquifer formations in this area are also developed in Jurassic dolostones and limestones (Figure 4.6), resulting in highly fractured and karstified systems (Martín-Rodriguez et al., 2016). In the same way that happens in Eastern Ronda Mountains, clays and sandstones overthrust the previous geological formations in exception of some zones where Flysh materials structurally imbricate between Mesozoic rocks in the “Corredor del Boyar'' (Martín-Algarra, 1987). This corridor provokes the individualization of two hydrogeological systems: one in the north (Subbetic sector) and one in the south (Penibetic sector), in which the Sierra de Ubrique is included (Martín-Rodríguez et al., 2016).

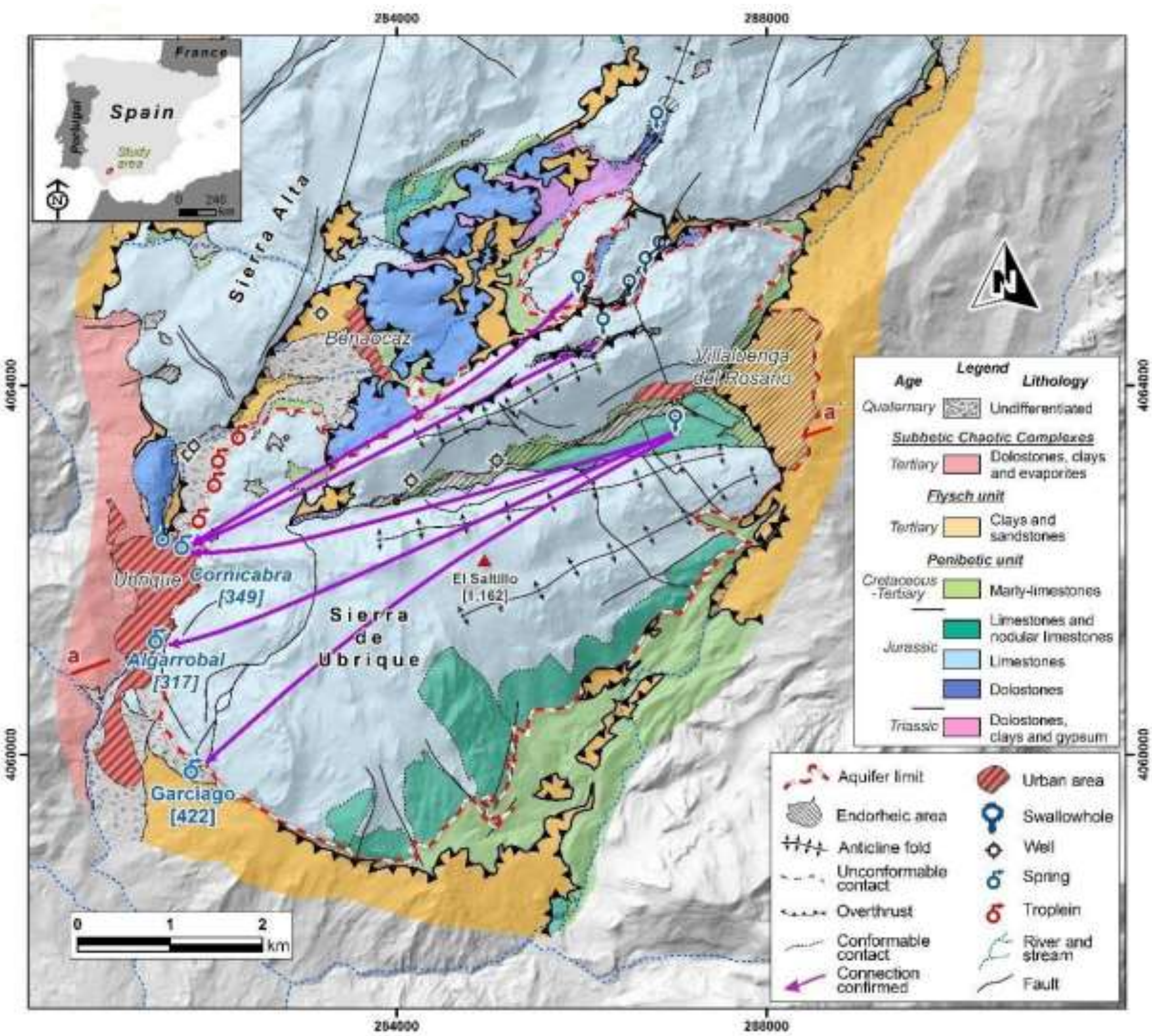

Figure 4.6 Hydrogeological setting of the Sierra de Ubrique aquifer system (modified from Sánchez et al., 2017) Additionally, confirmed karst connections from the tracer test performed in 2018 are displayed

The Ubrique aquifer is a binary karst system with the interpretation expressed by Bakalowicz (2005) and Mayaud et al. (2014) among others, since duality in recharge mechanisms was proved: more or less diffuse infiltration from rainfall through the carbonate outcrops (autogenic component), and the concentrated infiltration of water runoff from a small neighbour catchment formed by low-permeability materials (flysch clays and Cretaceous marls; Figure 4.6).

Superficial allogeneic input enters the system through the Villaluenga del Rosario shaft, which represents one of the most important hotspots in the aquifer from the protection of groundwater perspective. On the other hand, natural drainage occurs through the permanent and temporal (overflow) springs located at the SW border of the aquifer. The most significant ones are the Cornicabra (located at 349 m asl) and Algarrobal (317 m asl) perennial outlets, which have discharge rates of 10–2,460 L/s (mean 406 L/s) and 10 to 2,625 L/s (mean 157 L/s), respectively. Additionally, several overflow springs appear in this sector at increasingly higher elevations during high flow; the most relevant is Garciago spring (422 m asl) whose discharge rate is, on average, 311 L/s but ranges from 0 to 6,059 L/s (Sánchez et al. 2018). Cornicabra and Algarrobal supply drinking water for the neighbouring village Ubrique (18,000 inhabitants). These springs are periodically affected by high turbidity peaks linked to inorganic sediment particles during stormy periods as well as the runoff water infiltrated in the Villaluenga del Rosario shaft. These turbidity episodes generate operational constraints and hinder the exploitation of the available water resources from the aquifer.

4.2.2 Vulnerability assessment

Figure 4.7 shows the resulting maps from applying the COP method in the Ubrique aquifer. The O factor reflects the protective capacity of the overlying layers provided by soils (texture and thickness) and the lithology of the unsaturated zone (fracturing, the thickness of each layer, and the confining conditions). In the test site, the soil layer is scarcely developed, and the carbonate rock is roughly homogenous and uncovered over most of the aquifer's extent. One of the main challenges for mapping of the variables involved in the O factor is related to the absence of boreholes (or any observation point) in the inner part of the aquifer. This issue is particularly common in mountainous karst aquifers and leads to use of interpolation tools to simulate the approximate thickness of the unsaturated zone, for which the uncertainty and reliability depend on the number of measurements and their spatial distribution across the study area. Regarding the factor C, the individual map shows the two recharge scenarios provided by the COP method: concentrated recharge through the swallow holes (scenario 1) and the diffuse recharge (scenario 2). For the detection of exokarst features, aerial photos, digital terrain models, and satellite images can be used jointly with field surveys.

A digital elevation model (DEM) with 0.5 × 0.5 m grids and 0.1 m of vertical resolution, derived from light detection and ranging data (LiDAR) captured in 2014, was obtained from public databases for this study (PNOA, 2016). The DEM in raster format was corrected for no data values prior to being run in this analysis. Data correction was performed by filling null data with average values from the surrounding grids by applying the moving window method. In this research, 'doline' refers to any enclosed depression falling into defined morphometric attributes without consideration of their genetic features. The spatial delineation of the recharge basins of the swallow holes and sinking streams (scenario 1) should be based not only on topography criteria but also on lithology, both concepts will highly condition their functionality regarding concentrated recharge towards the sinking point. This explains the fact that in karst aquifers it is quite common that carbonate outcrop areas, with well-developed epikarst, do not generate or develop effective run-off even for the topographic basins of swallow holes due to its high permeability. These areas would be excluded from scenario 1.

Then, although GIS-based tools can readily calculate the drainage basins, the delimitation of the effective basin requires detailed field observations and in situ monitoring, particularly during the transitory activation of swallow holes. In the test site, the functional recharge areas of the swallow holes were defined by in-situ observations during heavy rain episodes because these points are activated under certain rainfall thresholds and during short time periods, of 1 or 2 weeks at maximum. On the other hand, to create the P factor map, the precipitation data of wet years from four rainfall stations from 1984 to 2018 were used. For this historical period, the mean annual precipitation of wet years ranges from 1,292 to 2,314 mm and the average occurrence of rainy days is 88 per year. The vulnerability is "high" and "very high" in most of the recharge area (Figure 4.7D). A large area is characterised as "very high" vulnerability due to the low natural protection of the karst aquifer (very low values of O factor), resulting from the physical properties as well as the thickness of the layers above the saturated zone and the important role of exokarst features that, in fact, are highly developed in the test site. Only in areas where carbonates are overlaid by marls, and the surface flow is not drained towards swallow holes, the vulnerability class is "low" or "very low", but these are very small patches and account for only small areas.

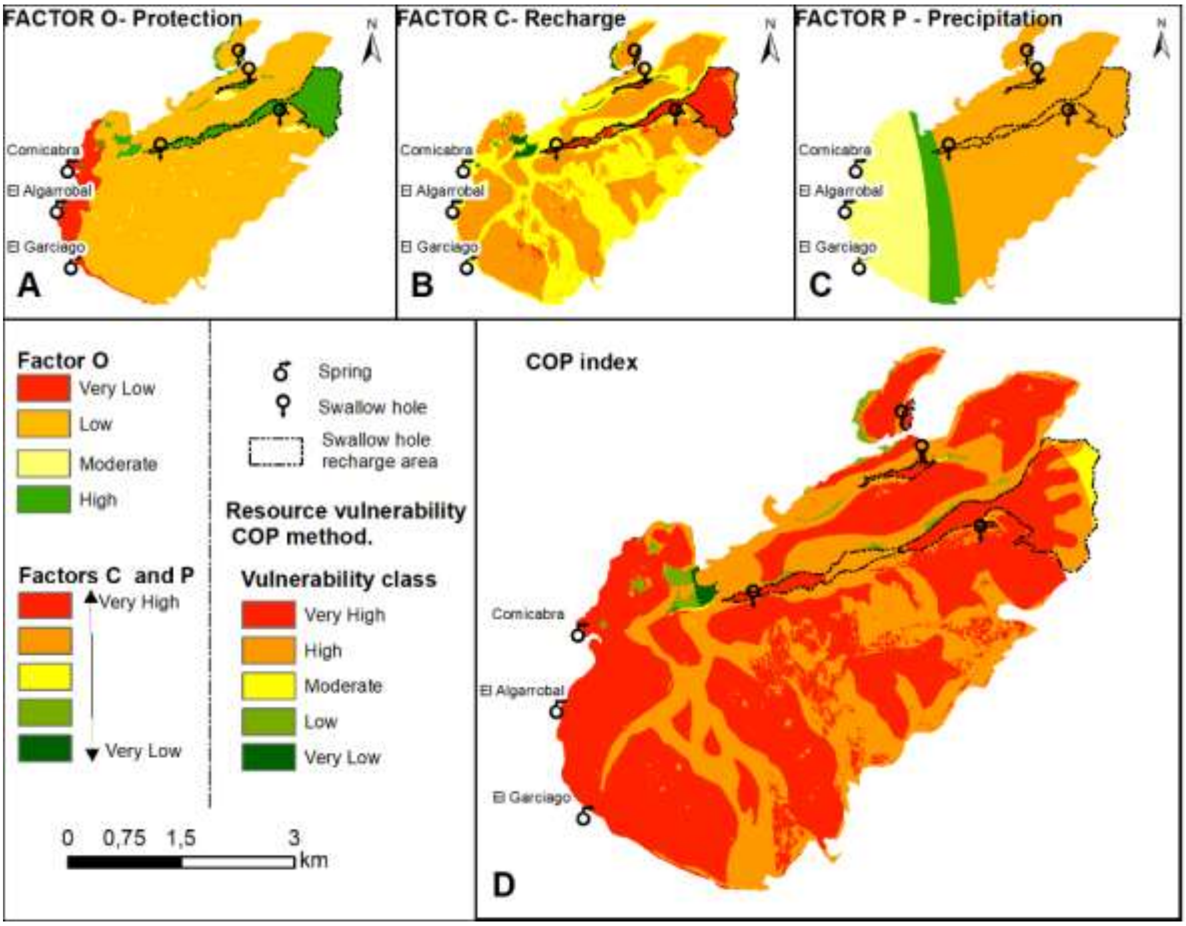

Figure 4.7 Maps of resource vulnerability to contamination in the Ubrique aquifer. a factor O, protective capacity of the overlying layers; b factor C, concentration flow; c factor P, precipitation condition; d COP method, resource vulnerability classes. Green colours mean favourable conditions (lower degree of vulnerability) and red colours mean unfavourable conditions (higher degree of vulnerability) for the protection of the groundwater

4.2.3 Validation

In this work, the validation of the vulnerability map has been done using the time series of TOC and NO_3^- contents and turbidity values detected in the spring waters, coupled to hydrodynamic responses. In addition, the results of two previous tracer tests carried out in the framework of hydrogeological investigations have been used to characterize the concentrated recharge and to calculate flow velocities for inferring vulnerability classes

In a similar framework to that used by previous research projects, discharge rates and selected hydrochemical parameters were monitored in the permanent springs as well as in the overflow points. Figure 4.8 displays the hydrodynamic behaviour of the two permanent outlets, plus Garciago overflow spring, in order to illustrate the functioning of the test site. Time series of spring discharge show a large variability, ranging in the case of Garciago spring from zero discharge to nearly 10 m^3/s discharge after

1 day from the main precipitation event. The magnitudes of the observed flood peaks in the springs are proportional to that of the recharge and they tend to recover pre-event values once the recharge effect is finished. In general, the studied outlets show a typical karst behaviour with sudden and rapid variations of hydrodynamic responses during rainfall events, as well as a low natural attenuation capacity against the rainfall. Therefore, the results obtained from the hydrodynamic analysis suggest a well-developed conduit network that enables a rapid groundwater flow within the aquifer. According to the latter hypothesis, rainwater infiltrates into the aquifer and rapidly moves through interconnected conduits and fractures, causing increases in hydraulic pressure transference and decreases in groundwater mineralization

The groundwater resources, drained by the springs and used for human consumption, are threatened quantitatively and qualitatively. Concerning the quantity of pumped groundwater resources intended for human consumption, the discharge rates during recession periods are almost zero in Algarrobal and zero in Garciago springs (Figure 4.8B). On the other hand, during flood events the water quality is impacted by high turbidity levels in the majority of karst outlets and by the relationship between turbidity and potential pollutant load. Turbidity or particle dynamics (considered as natural tracer) highlight the arrival of water from the surface and/or from dry/flooded conduits (or saturated syphons) within the aquifer system. Turbidity evolution observed in karst springs during high-flow periods shows fast increases after an intense precipitation event, with narrow peaks detected 25 h (on average) before the peak discharge (Figure 4.8B; Martín Rodríguez et al. 2019). In a similar way, the TOC and NO_3^- contents show rapid increases after the precipitation events due to the arrival of recently infiltrated waters in the aquifer through vertical karstic dissolution conduits or fractures, which rapidly reach the saturated zone. The effects of rainfall on the water mineralization are noticeable after several hours. All these results denote an overall high vulnerability for the Ubrique aquifer. Three dye tracers (pyranine, sulforhodamine B and aminorhodamine G) injected into swallow holes in 2018 were detected in the main outlets of the Ubrique aquifer. The results of tracer tests (carried out in high-water conditions), with a modal flow velocity ranging between 92.2 and 117.4 m/h, inferred an important degree of inner karstification.

These data again provide evidence to support the hypothesis of high vulnerability of the system, especially when recharge water enters through the swallow holes. In summary, the analyses of natural and artificial chemical constituents in the karst spring water confirm the extreme vulnerability to contamination of the pilot site, which is coherent with the vulnerability map resulting from the application of the COP method. However, some sectors of the aquifer surface where karrenfields are quite well developed, display very high vulnerability in the areas close to swallow holes. To get a complete validation of the vulnerability map, an additional dye tracer test designed specifically for validating the vulnerability related to diffuse infiltration is further needed. This additional field experiment, in which fluorescent substances should be injected into karrenfields and swallow holes, would allow one to confirm whether the high development of exokarst features leads to a significant contribution to the concentrated recharge at depth or, by contrast, whether the vertical permeability is quite limited. If the results of the proposed additional fieldwork are conclusive, it would permit a rethink and re-design of the current conceptual hydrogeological model of the pilot site. In karst media, transferring improvements from conceptual modelling to vulnerability assessment must be constantly conducted to enhance understanding of the hydrogeological systems and better manage the water resources.

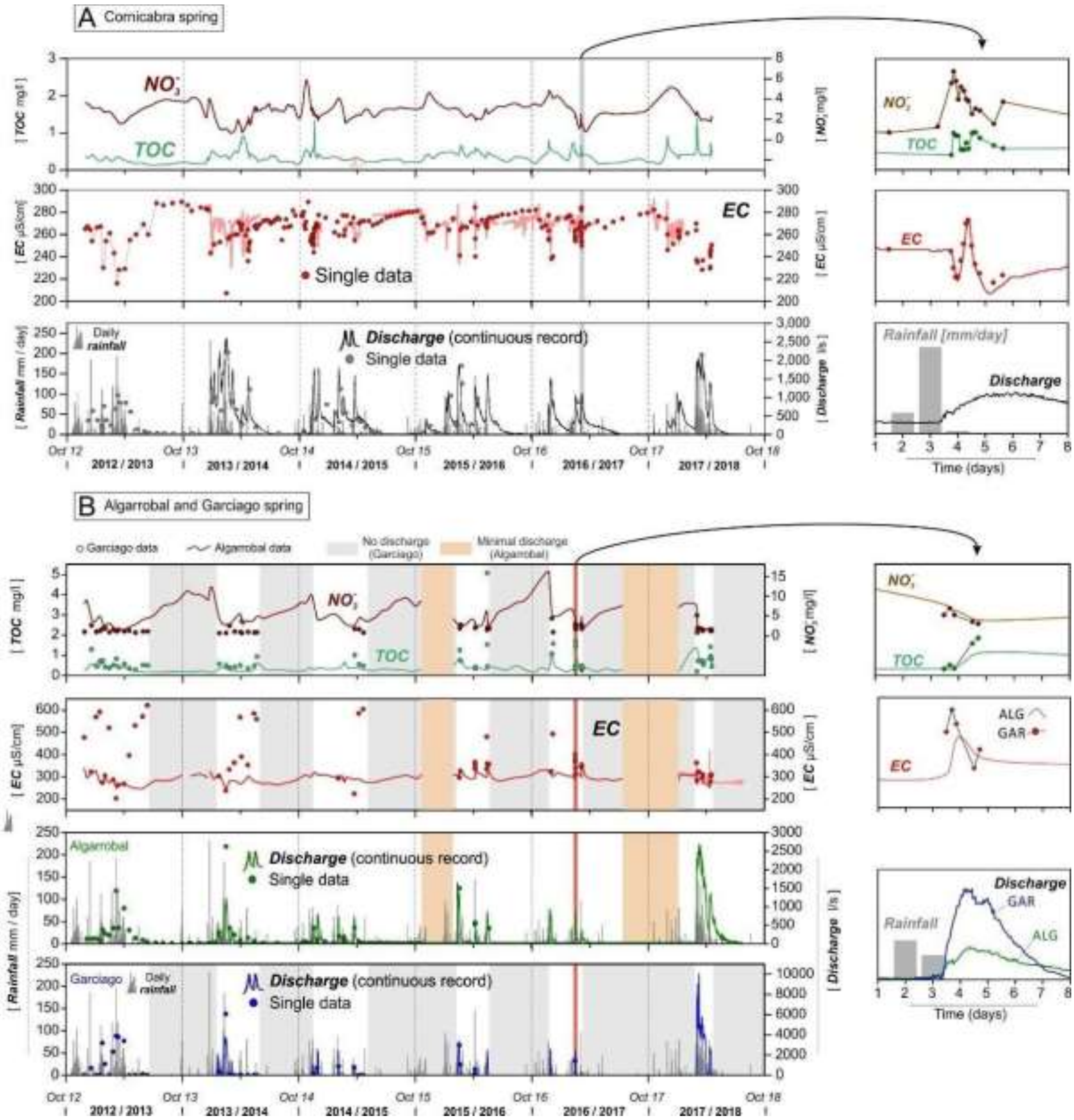

Figure 4.8 Seasonal (main panels) and single event-based (individual right panels) time evolutions of electrical conductivity (EC), TOC, and NO3− concentrations measured in a Cornicabra and b Algarrobal and Garciago springs (Marín et al. 2021)

4.2.4 Discussion and final remarks

The groundwater vulnerability map of Ubrique aquifer, attained by application of the COP method and validated by multiple in-situ observations, shows an extremely vulnerable system due to the absence of protective overlayers and the significant development of exokarst landforms, including shallow holes. In the case of the test site, the characterised karst behaviour and conduit flow system, and the significant contribution of the allogeneic component to the total recharge of the aquifer, permit the mobilisation of contaminants originating from livestock in the surrounding areas and from partially treated wastewater, as well as inorganic sediment particles when stormy rainfall events occur. Consequently, the protection of groundwater and the preventive principles must be considered as the appropriate strategies to minimise the water pollution risk and the potentially negative effects on human health.

This vulnerability map could constitute the basis for defining protection zones for the Ubrique springs; however, their comprehensive protection requires the implementation of monitoring tools and an effective management strategy, through an early warning system that assures stable environmental and hydrogeological conditions and improves operational procedures associated with the drinking water service.

4.3 The Lez spring catchment (case study France)

The results here presented have been published in:

- *Marín AI, Dörfliger N, Andreo B (2010) Comparative application of two methods (COP and PaPRIKa) for groundwater vulnerability mapping in the Lez karst system (Montpellier, South France). In: Andreo B, Carrasco F, Dura´n JJ, LaMoreaux JW (eds) Advances in research in karst media. Springer, Berlin, pp 329–334*
- *Marín AI, Dörfliger N, Andreo B (2012). Comparative application of two methods (COP and PaPRIKa) for groundwater vulnerability mapping in Mediterranean karst aquifers (France and Spain). Environ. Earth Sci. 65 (8), 2407–2421. http://dx.doi.org/10.1007/s12665-011-1056-2*
- *Marín AI (2012) Vulnerabilidad a la contaminación y protección de las aguas subterráneas en acuíferos carbonáticos. Groundwater vulnerability to pollution and protection in karst aquifers. Ph.D. Thesis, University of Málaga, Spain.*

4.3.1 General description of the test site

The Lez spring catchment is located 15 km north of Montpellier (France). It is located between the Hérault and Virdoule river valleys. The maximum extent of the hydrogeological basin which feeds the Lez spring is estimated to be about 380 km² due to regional drawdown resulting from continuous pumping at the karst spring (Thiéry & Bérard, 1983). The lithology of the Lez karst system corresponds to massive limestone of the Upper Jurassic (Argovian to Kimmeridgian) and of the lower part of the Early Cretaceous (Berriasian), with 650 to 1,000 m thickness. The marls and marly-limestone of the Middle Jurassic (Oxfordian) constitute the lower boundary of the aquifer. The marls and marly-limestone of the Early Cretaceous (respectively Lower and Upper Valanginian) constitute the upper boundary of the aquifer. The major tectonic events that influenced the Lez aquifer were the Hercynian/Variscan orogeny, the Pyrenees formation, and the opening of the Lion Golf.

This area was assessed, on the one hand, using dye tracer tests, performed in the 1960s (Paloc 1967), and on the other hand, by performing an analysis of groundwater levels and of their relation with rainfall discharge. As a large part of the hydrogeological catchment basin is relatively impervious, the Lez spring diffuse recharge area covers approximately 150 km^2 (Marjolet & Salado 1976; Fleury et al. 2009). The main recharge area over the catchment corresponds to the Jurassic limestone outcrops located by the western and northern limits of the basin. Localised infiltration occurs through fractures and sinkholes along the basin and through the major geologic fault of Corconne-Les Matelles, in the northern part of the basin. A certain number of fractures are also known to exist only just upstream from the Lez spring. The soils on the Lez catchment are essentially leptosols, with some areas of umbrisols in the southern part of the basin. The mean altitude is 191 m. The high altitudes correspond to the Jurassic limestone outcrops in the west and north of the catchment, with the maximum being 655 m. The mean slope is 10%.

The Lez catchment is exposed to a Mediterranean climate, which is characterised by hot, dry summers, mild winters and wet autumns. Analyses by the Meteo France show that on average 40% of the annual precipitation occurs between September and November with a high variability across years. The average annual rainfall rate for the 1945-2019 period is 916 mm based on a weighted average of four rainfall stations located on the Lez basin.

The Lez spring groundwater is actively managed to supply drinking water to the town of Montpellier and surroundings, using three pumps located within boreholes intercepting the karst conduits upstream from the Lez outlet. The mean pumping rate is around 1,300 l/s. Most of the studied area is covered by dense Mediterranean forests (scrubland). In addition, agricultural activity (mainly vineyards) is locally important, particularly close to the rural settlements in the northern part of the catchment area outside of the suburban areas.

4.3.2 Vulnerability assessment

Figure 4.9 and Figure 4.10 show the results of applying the COP method to the catchment area of the Lez spring. The area presents a high diversity of degree of vulnerability due to the complex composition and hydrodynamic behaviour of this study area. The Very high values correspond to areas close to the catchment area of sinking streams. The carbonate outcrops present a degree of vulnerability ranging from Very high to Moderate. This variability is influenced, in particular, by the thickness of the unsaturated zone. The Very low and Low vulnerabilities correspond to areas where the aquifer is protected by marls. Therefore, the carbonate outcrops above the aquifer and the catchment areas of sinking streams are highly vulnerable, according to the COP method, in comparison to the rest of the catchment characterised by the presence of overlaying layers (i.e., marls).

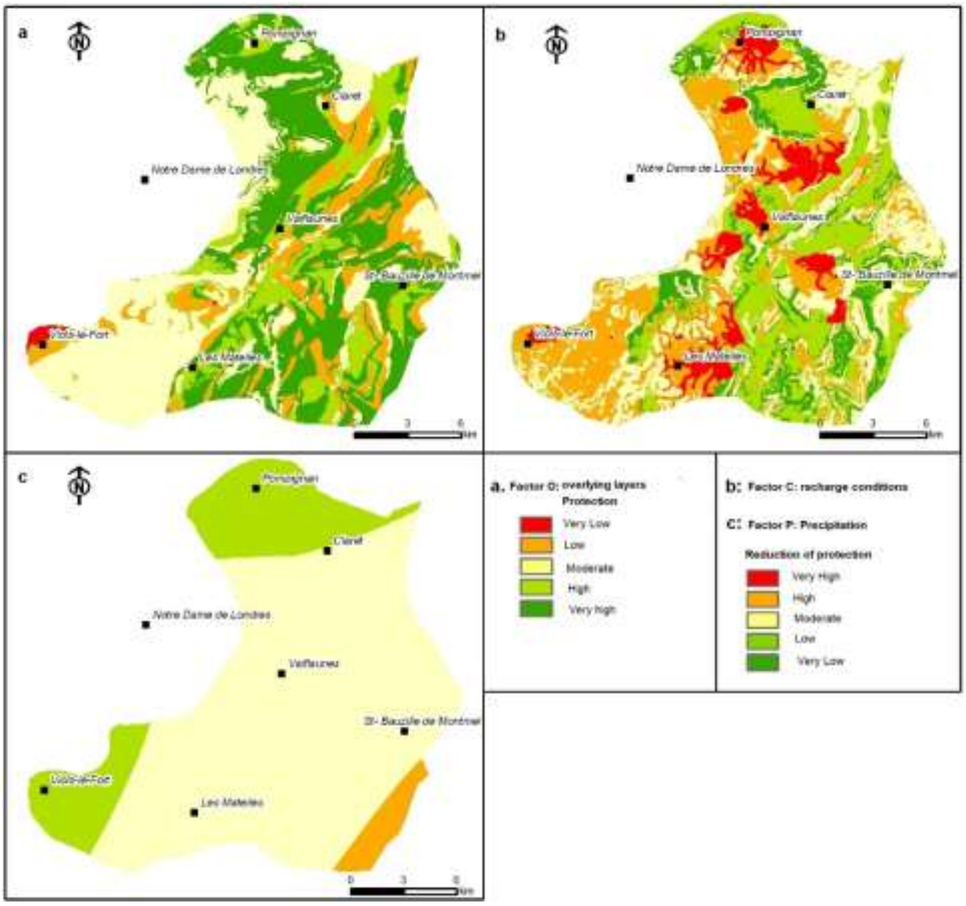

Figure 4.9 Maps of COP factors in the Lez aquifer. Source: Marín et al. 2012

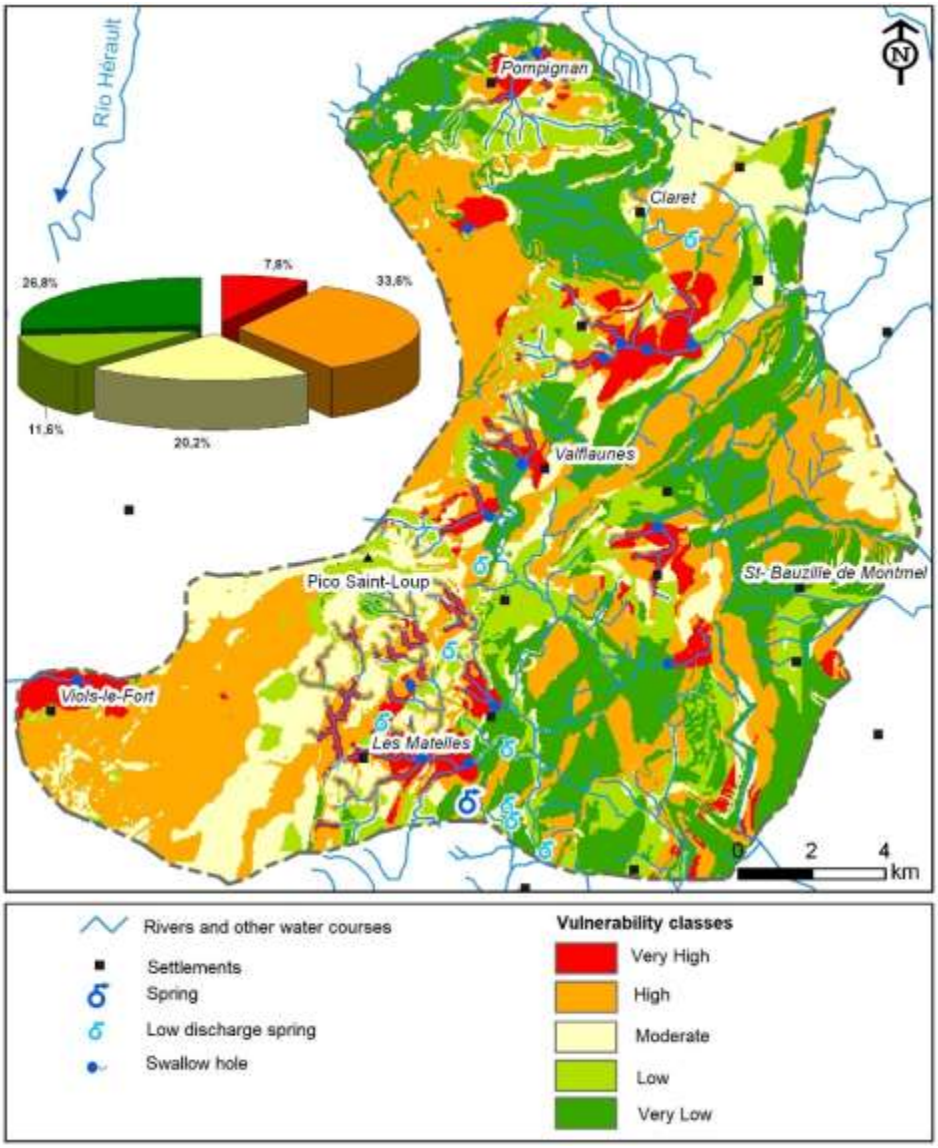

Figure 4.10 Groundwater vulnerability map of Lez aquifer by COP method (Source: Marín et al. 2012)

4.3.3 Validation

Studies carried out in the Lez karst system (Conroux 2007; Bosser 2009) show that it presents a relatively inertial behaviour, with mean infiltration times exceeding 100 days, according to analyses of the recession curve (Mangin 1975; Ladouche et al. 2006). Simple spectral analysis shows that the memory effect ranges from 42 to 60 days and that the regulation time exceeds 70 days (Conroux 2007).

Furthermore, hydrogeological studies (Bicalho 2010) have identified diverse origins of the water drained by the Lez spring: some water originates from runoff and the epikarst, while the rest proceeds from the layers overlying the aquifer, is deep water or originates in the main compartment of Jurassic limestones. With respect to validating vulnerability maps, the most important finding of the Bicalho (2010) study, for the purposes of this work, is that a rapid response (2–3 days) at the spring was observed following precipitation episodes. This was characterised by a general dilution of the chemical parameters and increases in TOC, NO_3^- and the concentration of total and faecal coliforms (Figure 4.11).

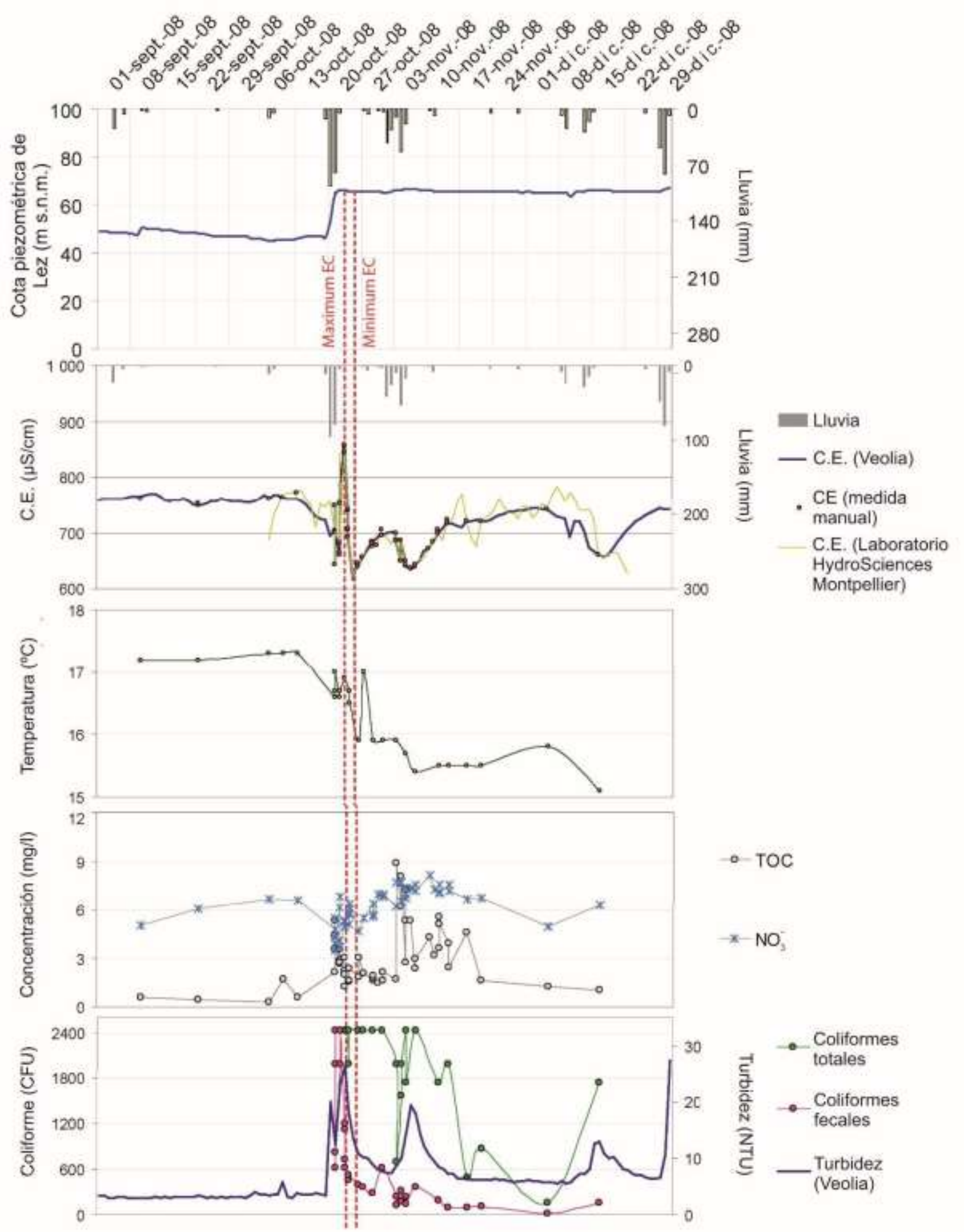

Figure 4.11 5 Hydrochemical and hydrodynamic parameters of Lez aquifer (source: Bicalho, 2010).

These results are consistent with those obtained by the precipitation–yield cross-correlation analysis, which indicated a mean response time at the spring of 2 days following rainfall episodes (Conroux 2007). From this result, it is concluded that the recharge area of the Lez spring presents rapid flow of infiltration water toward karstic dissolution conducted through vertical fractures or conduits, which rapidly reaches the saturated zone. This response time at the spring indicates high aquifer vulnerability, at least in the swallow hole basins; the water that is rich in TOC, $NO3^-$ and total and fecal coliforms appears to have originated from natural and artificial runoff within those basins. Water outlets from water treatment plants constitute in the low water stage period a permanent surface flow. The map obtained using the COP method indicates High vulnerability in general, in the carbonate outcrops and the catchment areas draining these sinking streams. These results are coherent with those obtained from the analysis of hydrochemical and hydrodynamic responses at the spring. However, the COP method produced a vulnerability gradient within the catchment area draining toward swallow holes (greater vulnerability in the areas closest to the swallow hole). There is no experimental data enabling us to identify the variables that control the vulnerability of catchment areas draining toward swallow holes. There is no data, apart from logical reasoning, to confirm the inverse relation between distance from the swallow hole and the level of aquifer vulnerability, as considered by the COP method.

On the other hand, COP identifies areas covered by low permeable materials as presenting Low or Very low vulnerability. Although useful data are not available in Lez to confirm the protective capacity of marls (when these do not form part of the catchment basin draining to swallow holes), the field experiments carried out by Perrin et al. (2004) showed that that low permeability soils and lithology overlying the aquifer protect groundwater against contamination episodes.

4.3.4 Discussion and final remarks

Lez spring is highly heterogeneous in terms of hydrogeological composition and behaviour. Lez karst aquifer, which presents two different sectors, one with Very high and High vulnerability (limestone outcrops and part of the catchment basin draining toward swallow holes) and another with Low and Very low vulnerability (parts of the aquifer overlain by low permeability materials) Both the O and the C factors present high effect on the COP value, reflecting the duality existing in this aquifer, where, on the one hand, there are extensive areas draining water toward swallow holes (controlled by the C factor) and, on the other, areas overlain by a thick layer of materials of low permeability that protect the aquifer (controlled by the O factor).

The overall vulnerability of the Lez karst system is consistent, and therefore validated with, hydrogeological studies. However, validation tests should be designed and carried out, and transport modelling from soil to karst aquifer must be improved to take into consideration heterogeneities.

4.4 Unica springs catchment (case study Slovenia)

In the catchment area of the Unica springs the COP+K method was applied (Vias et al. 2006; Andreo et al. 2009) and the results have not been published before.

4.4.1 General description of the test site

The Unica springs are located in southwestern Slovenia (Figure 4.12), which occupies the northern part of the Dinaric Karst, the largest continuous karst area in Europe, stretching along the Adriatic Coast. Two larger permanent springs emerge on the edge of a karst polje: Unica and Malenščica that join into the Unica River. The Malenščica is a regionally important drinking water source (Petrič 2010), which drains diffusely with discharges from 1.1 to 11.2 m^3/s. The Unica emerges through a network of large underground channels with common discharges ranging from 0.2 to 74.8 m^3/s. Two underground river channels (branches of the Rak and Pivka) converge underground. Part of the cave network includes a large Postojna-Planina Cave System, known worldwide for its rich biodiversity (Culver & Pipan 2013).

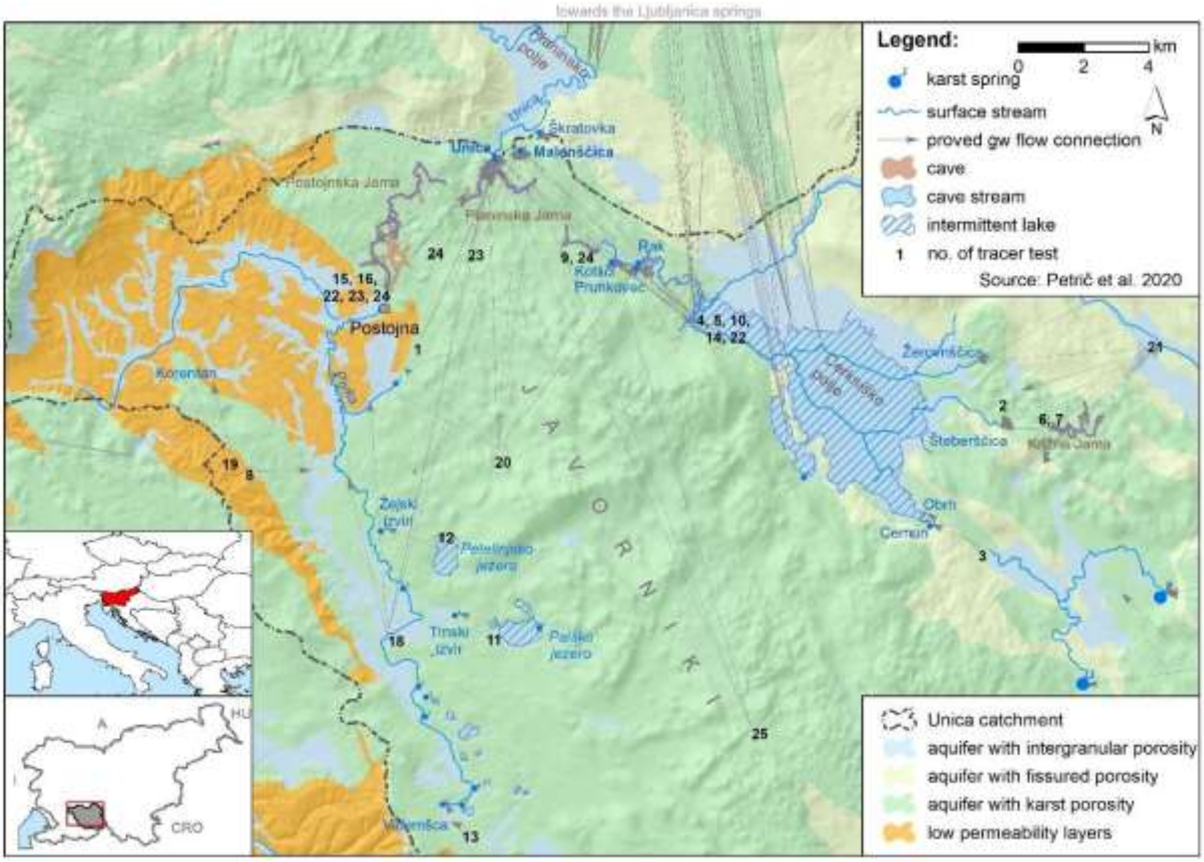

Figure 4.12 Hydrogeological situation of the study area with proven groundwater flow connections

The springs drain a complex binary aquifer system that extends over an area of about 820 km^2 and consisting of three distinct recharge areas: autogenic recharge from the extensive karst aquifer of the Javorniki Massif, allogenic recharge from Pivka River Basin to the west, and a chain of karst poljes to the east of the massif. The predominant lithology of the karst aquifer is Cretaceous rocks, mainly limestones, which in places change to dolomites and breccias. To a lesser extent, Jurassic and Paleogene carbonate rocks also occur. The northern part of the Pivka Basin consists of poorly permeable Eocene flysch, which conditions a superficial river network. In a narrow belt extending along the poljes, Upper Triassic dolomites predominate, changing to Jurassic limestones and dolomites in the south and west. These rocks form aquifers with fracture porosity, which in places have very poor to moderate permeability, and in some parts a superficial river network is developed. As the karst poljes follow each other in a row downgradient, the same water sinks and reappears several times. The alluvial sediments at the bottoms of the poljes and river valleys are of Quaternary age. They form smaller aquifers with intergranular porosity.

The area is considered pioneering for speleological and karstological research and belongs to the so-called Classical Karst area. The springs studied are located at an altitude of about 550 m above sea level and the peaks of the karst massif reach an altitude of 1,800 m above sea level. Climatologically, the area is located in a transition zone between Cfb and Dfb subtypes according to the Köppen-Geiger climate classification, with a mean annual precipitation (1991-2020, Postojna meteorological station) of 1,520 mm and a mean annual air temperature of 9.8°C (Jan 0.6°C, Jul 19.5°C; ARSO 2021a). Pronounced hydrological variability characterises the area, with groundwater level fluctuations of the order of tens of metres within a short period of time, leading to variations in flow velocities and directions and surface-groundwater interactions (Figure 4.13; Ravbar 2013).

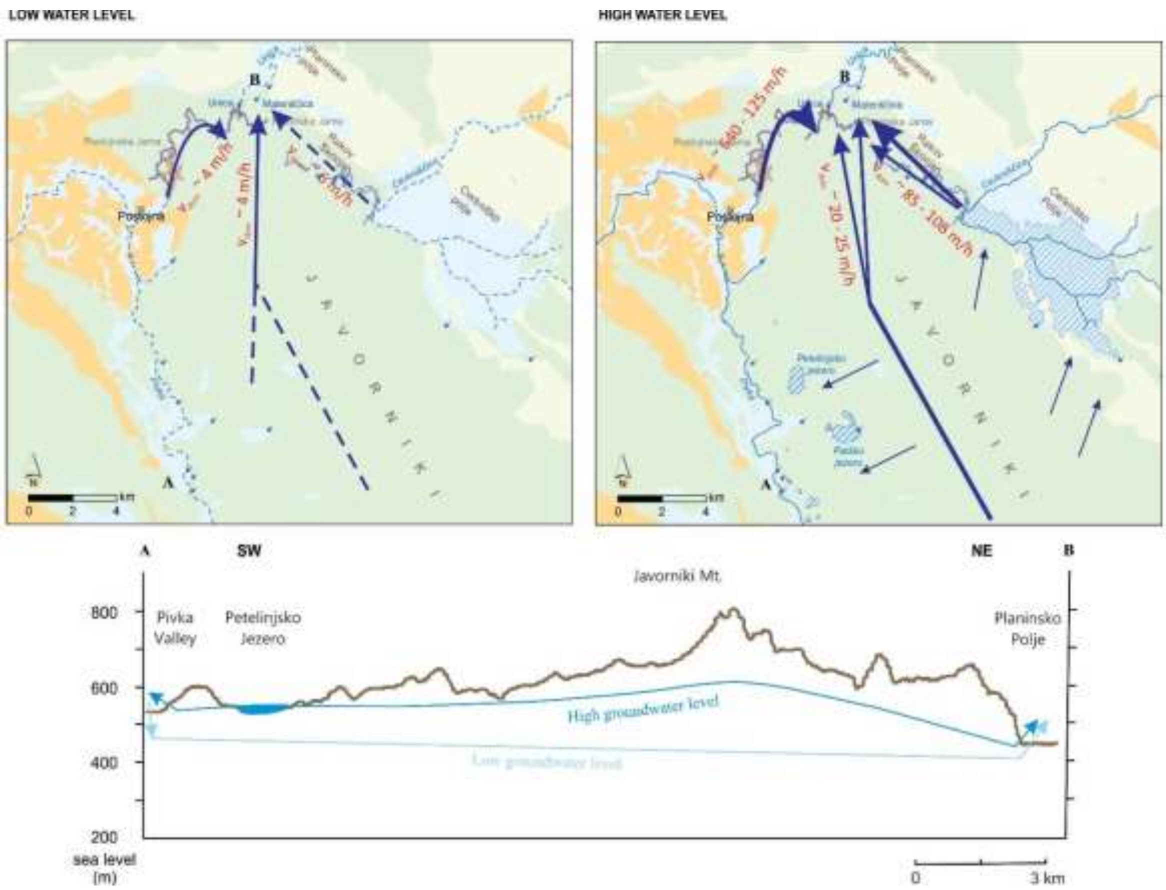

Figure 4.13 Schematic presentation of groundwater flow variability in the study area under different hydrological conditions (modified after Ravbar 2013, Petrič et al. 2020).

To date, various geological, geomorphological, speleological and hydrological surveys have been carried out, including several tracer tests (Petrič et al. 2020). Their main purposes were to record groundwater flow directions and velocities, delineate the catchment area and protection zones, and improve groundwater tracing techniques (Kogovšek & Petrič 2004). Groundwater tracing also proved flow bifurcations, which suggest the area belongs to the Adriatic-Black Sea watershed (Kogovšek et al. 1999). Recently, artificial tracers have been used for several other purposes, such as to study the effects of different land use patterns on water source quality (Kogovšek et al. 2008), the dynamics of prevailing water flow through the vadose zone (Petrič et al. 2018), the relationships between artificial and natural tracers (Ravbar et al. 2012), and to study karst vulnerability (Gabrovšek et al. 2010). Most of the injection sites were within 10 km of the sampling location, and the most distant was nearly 25 km away. Considering linear distance, maximum flow velocities range from 3.8 to 750 m/h and peak flow velocities up to 1127 m/h. Such high velocities are achieved by flow of sinking streams through well-developed channels toward large springs. For the same section of groundwater flow, flow velocities may be several degrees lower at low water levels than at high water levels.

4.4.2 Vulnerability assessment

To assess vulnerability of the Unica and Malenščica springs the COP+K method was applied (Figure 4.14). Detailed conceptual instructions and guidelines for vulnerability mapping were provided in Vias et al. 2006 and Andreo et al. 2009 and in Section 2 of this report.

The relevant lithological, pedological, hydrogeological, meteorological, geomorphological, speleological and vegetation cover information was combined. The mapping was based on publicly available data, such as geological and hydrogeological maps (eGeologija 2021; ARSO 2021b), digital elevation model (DEM; Geoportal ARSO 2018), speleological information (Cave Registry 2022), tracer tests database (Petrič et al. 2020), soil and land use data (MKGP 2021). Karst depressions, such as dolines and collapse dolines were mapped using ArcMap Hydrology and Zonal Statistics tools. Similarly, slope inclination was calculated on basis of DEM using ArcMap Spatial Analyst tool. Precipitation amount and intensity were extracted from 15 abandoned or operable precipitation stations (ARSO 2021a). Additional hydrogeological information was derived from previous studies (Gabrovšek et al. 2010; Petrič 2010; Ravbar et al. 2012; Kaufmann et al. 2020) and continuously observed water physico-chemical properties, which also served to better characterise the groundwater flow properties. The mapping was done on a 12.5 × 12.5 m grid using ArcMap 10.6.1. Results of individual parameters are shown in Figure 4.14 and the final source vulnerability map is presented in Figure 4.15. Vulnerability (i.e. reduction of protection) indices were divided into categories, from high vulnerability areas, from which a pollutant can reach a source quickly and without significant effects of attenuation processes (e.g., dilution, sorption, etc.), to low vulnerability areas, from which the pollutant takes longer to reach sources and can also degrade along the way.

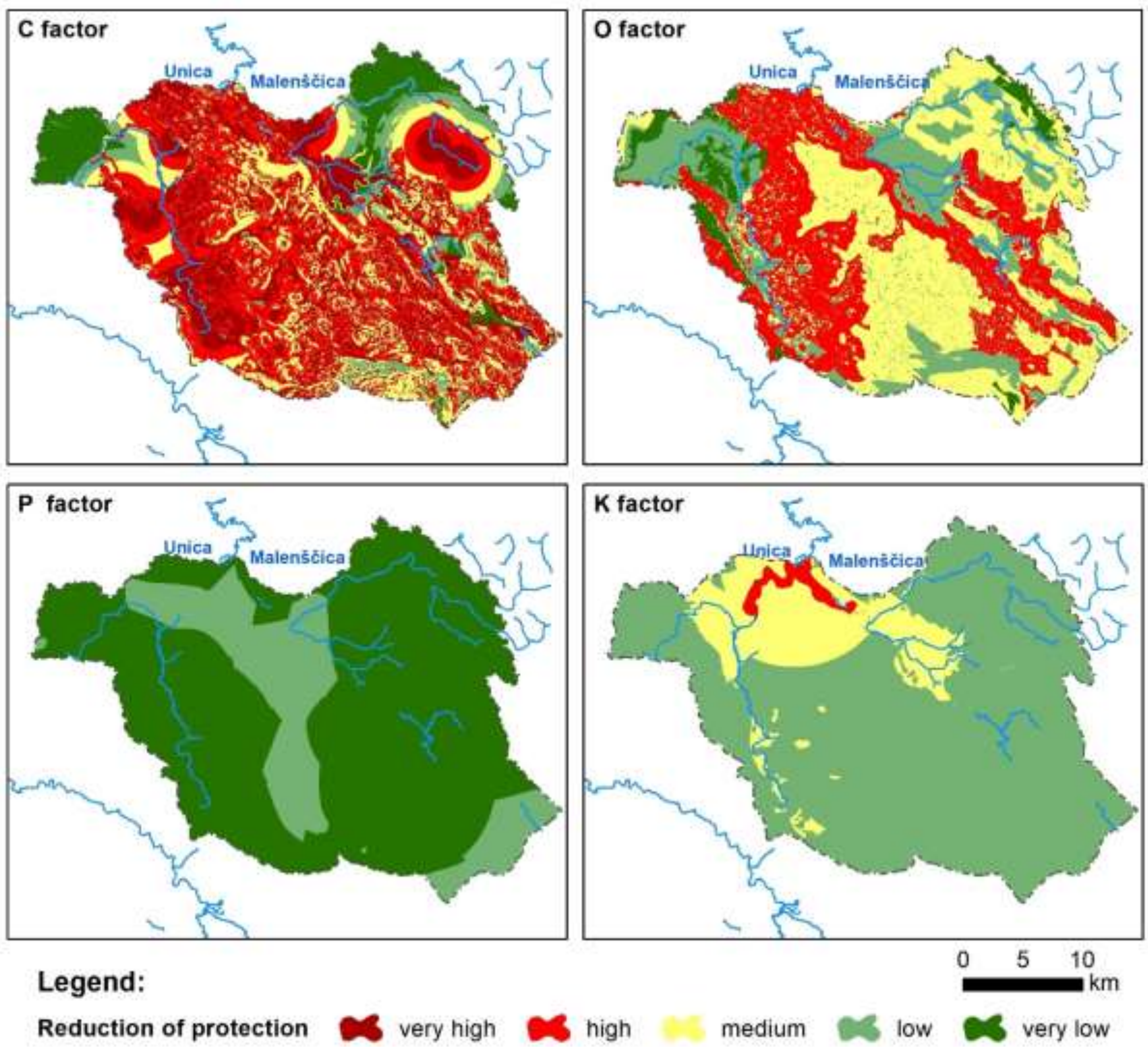

Figure 4.14 Maps of the individual parameters of the COP+K method, which are combined into source vulnerability map. A) map of the C (concentration of flow) factor, B) map of the O (overlying layers) factor, C) map of the P (precipitation) factor, D) map of the K (karst network development) factor.

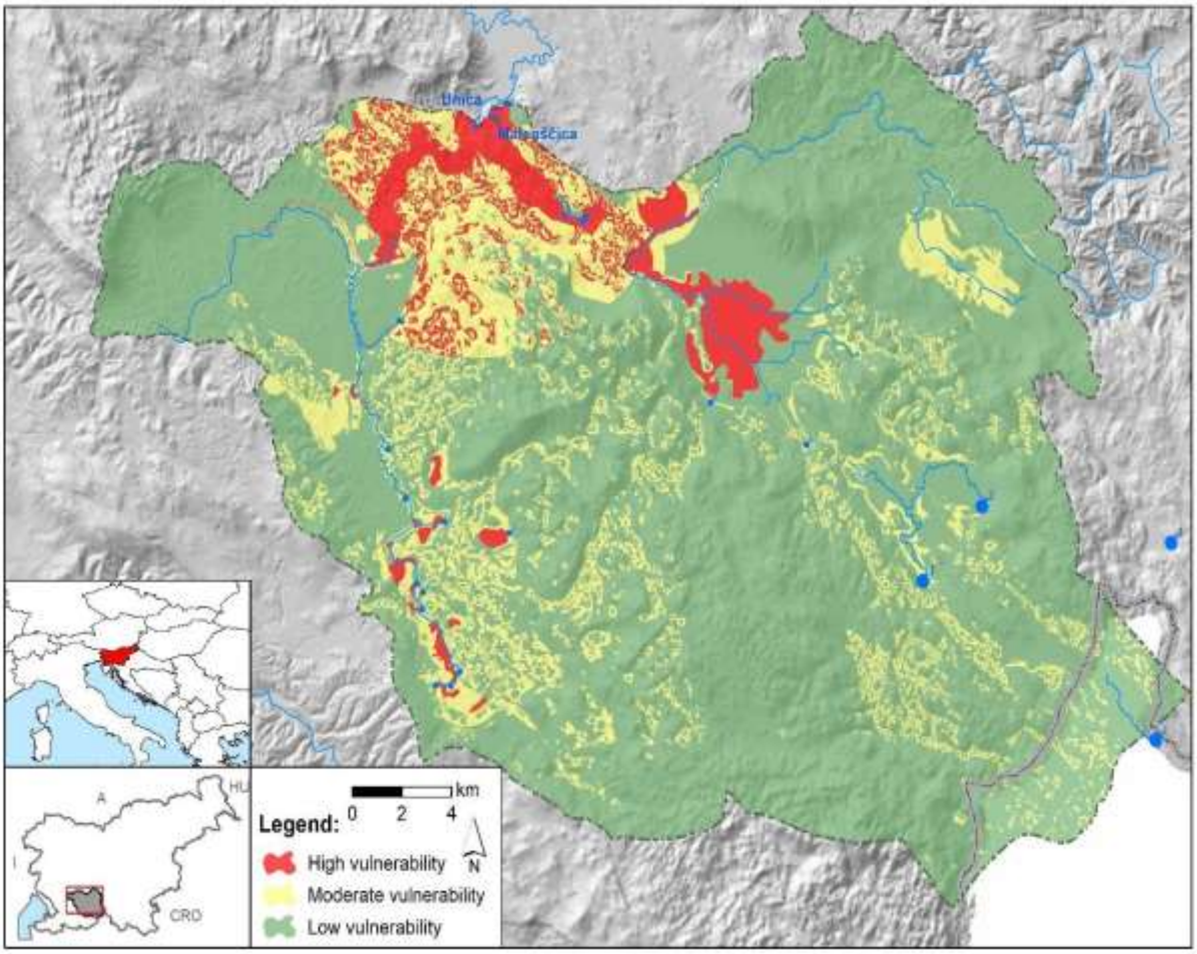

Figure 4.15 Source intrinsic vulnerability map of the Unica springs assessed by the COP+K method.

Vulnerability mapping revealed that about 50 km^2 or 6% of the area has high source vulnerability (Figure 4.15). These are areas with highly karstified limestones and thin soils, areas on the doline edges and above known cave passages in close proximity to the springs. Highly vulnerable are also drainage areas of sinking rivers and frequently occurring lakes. The results are determined primarily by the so-called C and K factors, which indicate rapid infiltration conditions, good hydraulical connections and contributions, and high groundwater travel times under worst-case pollution scenarios. Factor O has less influence on the final vulnerability indices and identifies areas with a lower thickness of the vadose zone and a general lack of protective overlying soil layers as more vulnerable. Factor P has no significant effect on the final vulnerability index values. Vulnerability is lower in areas with greater thickness of soil and vadose zone, greater distance from springs, and lower permeability of rocks. Consequently, areas with medium vulnerability account for about 140 km^2 or 17% of the area and areas with low vulnerability account for about 630 km^2 or 77% of the area.

4.4.3 Discussion

The COP +K method is based on various detailed environmental data, which provide information about the state and dynamics of hydrogeological processes of the considered area. Since the method requires extensive and complex collection of data sets and demands the necessary time, financial, and technical resources, it is one of the most sophisticated methods for groundwater vulnerability assessment. This is plausible in that such methods may be more legitimate when various environmental information is available.

Application of the COP +K method in the study area has shown that infiltration and groundwater flow conditions (hydraulic connections, travel times, and flow contributions) have a significant impact on the results. The distance criterion also plays a role in the vulnerability assessment of the water source under consideration. However, the type and accuracy of the input data largely determines the quality and reliability of the results.

Given the complexity of the hydraulic conductivities of the area under consideration, the characteristics of groundwater flow patterns that control the fate and transport of a contaminant are highly heterogeneous and anisotropic (Figure 4.16). Consequently, it is difficult to predict the residence times or flow rates of the individual parts of the hydrologic system. Therefore, the available information is evaluated only qualitatively, and certain simplifications of natural conditions are unavoidable. In order to summarize the information and meaningfully distinguish between areas with different levels of natural protection from contamination, errors and biases are inevitable. In general, the approach is particularly appropriate because it allows identification of areas that need the highest level of protection.

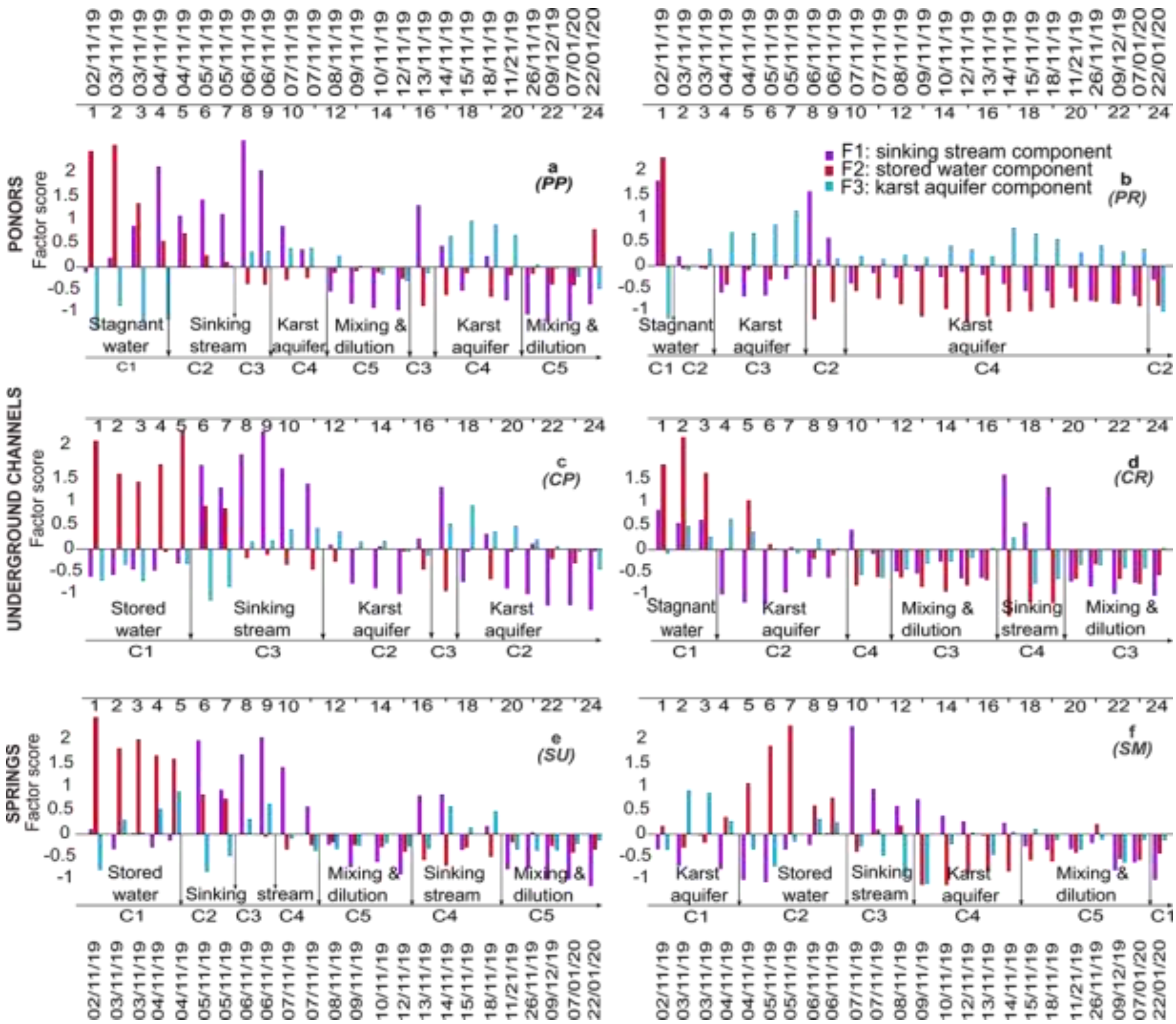

Figure 4.16 Multivariate statistical analysis of hydrochemical and microbiological analysis of water under a flood event of each sampling location: a) PP – ponor of the Pivka River b) PR – ponor of the Rak River, c) CP – Pivka channel, d) CR – Rak channel, e) SU – Unica spring, f) SM – Malenščica spring. The numbers 1-24 indicate the serial number of the samples (from Ćuk Đurović et al., in review).

Nevertheless, a vulnerability map should be validated. Since validation of vulnerability assessment has not become a standard practise and there is no universally accepted procedure (Ravbar & Goldscheider 2009), modern methods and techniques (i.e., numerical modelling, machine learning, process-based approach) can be used alongside traditional methods (i.e., hydrochemical analyses, artificial tracing, etc.). Such validation of the vulnerability map prepared for the considered area has not been performed so far. However, the results of multivariate statistical analysis of hydrochemical and microbiological analysis of water during a flood event together with interpretation of hydrodynamic behaviour of the aquifer system (Ćuk Đurović et al, in review) can be used for this purpose.

As part of the study, in addition to observing springs, ponors and water caves provided further insight and a holistic spatial view of the functioning of the hydrological system. The study showed that the responses of the springs studied are characterized by the different recharge dynamics of the hydrogeological sub-catchments that determine their behaviour. Their water quality is most variable during the first more intense rainfall after a long dry period. The developed spatio-temporal conceptual model of the system behavior during the flood event and the water quality characteristics indicate a high vulnerability of the system to pollution and a strong influence of the sinking rivers on the rapid transfer of contaminants through the hydrological system. This fact is justified by the highly vulnerable areas in the catchment of the considered springs and, in particular, the highly vulnerable areas of the ponors and the sinking rivers. The results of the vulnerability maps, in conjunction with the hazard maps, can help identify potential contamination in a timely manner and develop an early warning system for better water supply management.

5 Conclusions

The karst aquifers are especially vulnerable to pollution due to their hydrologic behaviour derived from karstification. The vulnerability mapping is one of the most applied tools to protect them. In the framework of KARMA project, the COP method was conducted on the studies areas to assess their groundwater vulnerability

The overall results show high vulnerability to pollution of the KARMA test sites. Karst swallow holes, and their closed catchment area, are points of maximum vulnerability. The maps obtained from applying the COP method classify the vulnerability of karst swallow holes as Very High. In general, aquifer sectors that are influenced by exokarstic forms such as karrenfield or dolines, favouring infiltration but tend to be less vulnerable than karst swallow holes, although in some systems they can present extreme vulnerability, similar to that of karst swallow holes due to the absence of soil or thin saturated zone.

Due to the highly heterogeneous functioning (large temporal and spatial variability) of karst media, the application of homogenised and extrapolated rules and criteria from aquifer to aquifer implies plenty of uncertainties and errors in the models applied. Then, a solid background of information on the hydrogeological operation of the aquifer is what will allow the technician to discriminate and score the different variables included in the methodological guides for vulnerability mapping with rational criteria, providing reliable and accurate results from the mapping procedure. Therefore, the assessment of vulnerability to contamination on KARMA test sites has integrated results and knowledge derived from other WPs of the KARMA project. Additionally, the vulnerability maps are decision making supporting tools for promoting land-use management compatible with water protection. So the maps should have reliable accuracy. Many works highlight that the maps of groundwater contamination vulnerability obtained by the different methods differ significantly, although they were all obtained by methods developed for karst aquifers, even if they are obtained from the same sources of information and applied by the same person.

In this project, we did efforts to validate the vulnerability maps for some of the test sites. We validated the results obtained on the basis of the hydrodynamic and hydrochemical responses of the main springs that drain the aquifer, together with the evolution of natural tracers of infiltration, and artificial tracer tests. However, additional efforts are necessary to complete the validation of the maps obtained in all areas and to implement and thus obtain an estimate of the uncertainty associated with the results and its validity to be transferred as a planning tool.

6 References

Andreo B, Ravbar N, Vías JM (2009) Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: application to pilot sites. Hydrogeology Journal, 17(3), 749-758. https://doi.org/10.1007/s10040-008-0391-1

Andreo B, Vías JM, Durán JJ, Jiménez P, López-Geta JA, Carrasco F (2008). Methodology for groundwater recharge assessment in carbonate aquifers: application to pilot sites in southern Spain. Hydrogeology Journal 16 (5), 911-925.

Andreo B, Goldscheider N, Vadillo I, Vías JM, Neukum C, Sinreich M, Jiménez P, Brechenmacher J, Carrasco F, Hötzl H, Perles JM, Zwahlen F (2006) Karst groundwater protection: first application of a Pan-European approach to vulnerability, hazard and risk mapping in the Sierra de Líbar (southern Spain). Sci Total Environ 357(1–3):54–73. https://doi.org/10.1016/j.scitotenv.2005.05.019

ARSO 2021a: Slovenian Environment Agency, Precipitation data archive. [Online] Available from: https://meteo.arso.gov.si/met/en/app/webmet/ [Accessed 14th May 2021].

ARSO 2021b: Hidrogeological map 1:250.000 (IAH). [Online] Available from: https://eprostor.gov.si/imps/srv/api/records/1c7a1b66-191c-46f0-a83c-8e398396083c [Accessed 14th May 2021].

Barberá JA (2014) Investigaciones hidrogeológicas en los acuíferos carbonáticos de la Serranía Oriental de Ronda (Málaga). PhD Thesis. University of Málaga, Spain. 591 p.

Barberá JA, Andreo B (2012) Functioning of a karst aquifer from S Spain under highly variable climate conditions, deduced from hydrochemical records. Environ Earth Sci 65, 2337–2349.

Batiot C, Liñán C, Andreo B, Emblanch C, Carrasco F, Blavoux B (2003) Use of TOC as tracer of diffuse infiltration in a dolomitic karst system: the Nerja Cave (Andalusia, southern Spain). Geophys Res Lett 30(22):2179. https://doi.org/10.1029/2003GL018546

Baker A, Barnes WL, Smart PL (1997) Variations in the discharge and organic matter content of stalagmite drip waters in lower Cave, Bristol. Hydrol Process 11:541–555

Bicalho CC (2010) Hydrochemical characterization of transfers in karst aquifers by natural and anthropogenic tracers. Example of a Mediterranean karst system, the Lez karst aquifer (Southern France) Ph.D. Thesis, University of Montpellier II, France, 172 pp

Bosser S (2009) Caractérisation d'un aquifère karstique méditerranéen, à partir des données hydrochimiques et hydrogéologiques disponibles. Mémoire de stage de 2ème année de Master Professionnel - Rapport BRGM, 79 pp

Cave Registry (2022) Cadastre of caves of the Karst Research Institute ZRC SAZU and Cave Association of Slovenia. Postojna, Ljubljana.

Conroux Y (2007) Caractérisation du fonctionnement hydrodynamique de l'aquifère karstique du Lez (Hérault) a l'etat naturel. Mémoire de stage de 2ème année de Master Professionnel —Université d'Avignon et des pays de Vaucluse et BRGM, 227 pp

Culver DC, Pipan T (2013) Subterranean ecosystems. In: Encyclopedia of Biodiversity, 2nd ed.; Levin, S.A., Ed.; Academic Press: Waltham, Massachusetts, USA, 2013; pp. 49–62, ISBN 978-0-123-84719-5.

Ćuk Đurović M, Petrič M, Jemcov I, Mulec J, Mazej Grudnik Z, Mayaud C, Blatnik M, Kogovšek B, Ravbar N (in review) Multivariate Statistical Analysis of Hydrochemical and Microbiological Natural Tracers as a tool for Understanding Karst Hydrodynamics (the Unica Springs, SW Slovenia).

Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P (2002) A knowledge-based approach to the statistical mapping of climate. Clim Res 22(2):99–113. https://doi.org/10.3354/cr022099

Doerfliger N, Zwahlen F (1998) Practical guide, groundwater vulnerability mapping in karstic regions (EPIK). Swiss Agency for the Environment, Forests and Landscape. Bern, Switzerland, 56 pp

Doummar J, Aoun M (2018) Occurrence of selected domestic and hospital emerging micropollutants on a rural surface water basin linked to a groundwater karst catchment, Environmental Earth Sciences, 77(9), 351, doi: 10.1007/s12665-018-7536-x.

Dubois E, Doummar J, Pistre S, Larocque M (2020) Calibration of a semi-distributed lumped karst system model and analysis of its sensitivity to climate conditions: the example of the Qachqouch karst spring (Lebanon), Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-90, in review.

Dubois, E (201/) Analysis of high-resolution spring hydrographs and climatic data: application on the Qachqouch spring (Lebanon), Master thesis, American University of Beirut, Department of Geology, Beirut, Lebanon. [online] Available from: https://www.researchgate.net/profile/Emmanuel_Dubois5/publication/320237930_Analysis_of_high_resolution_spring_hydrographs_and_climatic_data_application_on_the_Qachqouch_spring_Lebanon/links/59d69a76a6fdcc52aca7d05c/Analysis-of-high-resolution-spring-hydrographs-and-climatic-data-application-on-the-Qachqouch-spring-Lebanon.pdf,

eGeologija 2021: Basic geological map of SFRY. [Online] Available from: https://egeologija.si/ [Accessed 24th November 2021].

Fleury P, Ladouche B, Conroux Y, Jourde H, Dörfliger N (2009) Modelling of the functioning of a karst aquifer under active water management—Lez spring example. J Hydrol 36(3–4):235–243

Foster S (1987) Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: Van Duijvenbooden W, Van Waegeningh HG (eds) Vulnerability of soil and groundwater to pollutants 38. TNO Committee on hydrological research, TNO Committee, The Hague, pp 69–86

Gabrovšek F, Kogovšek J, Kovačič G, Petrič M, Ravbar N, Turk J (2010) Recent results of tracer tests in the catchment of the Unica River (SW Slovenia). Acta carsologica, 39/1, 27-37. https://doi.org/10.3986/ac.v39i1.110

Geoportal ARSO 2018: Environmental Atlas of Slovenia, [Online] Available from: https://gis.arso.gov.si/geoportal/catalog/main/home.page [Accessed 10th August 2021].

Jeannin PY, Eichenberger U, Sinreich M, Vouillamoz J, Malard A, Weber E (2013) KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation: assessment of groundwater reserves and resources in Switzerland. Environ Earth Sci 69(3):999–1013. https://doi.org/10.1007/s12665-012-1983-6

Kaufmann G, Mayaud C, Kogovšek B, Gabrovšek F (2020) Understanding the temporal variation of flow direction in a complex karst system (Planinska Jama, Slovenia). Acta Carsologica, 49(2-3), 213-228. https://doi.org/10.3986/ac.v49i2-3.7373

Kessler H (1967) Water balance investigations in the karstic regions of Hungary. Symposium on Hydrology of Fractured Rocks, Dubrovnik (Yugoslavia), AIHS-UNESCO 1, 91-95.

Kogovšek J, Petrič M (2004) Advantages of longer-term tracing - three case studies from Slovenia. Environmental geology, 47, 76-83. https://doi.org/10.1007/s00254-004-1135-8

Kogovšek J, Knez M, Mihevc A, Petrič M, Slabe T, Šebela S (1999) Military training area in Kras (Slovenia). Environmental Geology, 38, 1, 69-76.

Kogovšek J, Prelovšek M, Petrič M (2008) Underground water flow between Bloke plateau and Cerknica polje and hydrologic function of Križna jama, Slovenia. Acta carsologica, 37/2-3, 213-225. https://doi.org/10.3986/ac.v37i2-3.147

Ladouche B, Maréchal JC avec la collaboration de Desprats JF, Izac JL (2006) Fonctionnement hydrogéologique du système karstique de la fontaine de Nîmes en crue — Rapport final — BRGM/RP-54723-FR, 111 pp

Mangin A (1975) Contribution à l'étude hydrodynamique des aquifères karstiques. Annales de Spéléologie 29(3): 283–332, (4):495–601, 30(1):21–124

Margat J (1968) Vulnérabilité des nappes d'eau souterraine à la pollution: Bases de la cartographie: Orléans, France [Vulnerability of groundwater to pollution: basis of mapping: Orléans, France]. Document 68 SGL 198 HYD, Bureau de Recherche Géologique et Minière, Paris

Margane A, Abi Rizk J (2011): Guideline for Environmental Impact Assessments for Wastewater Facilities in Lebanon - Recommendations from the Perspective of Groundwater Resources Protection. - Technical Report No. 3 of Technical Cooperation Project "Protection of Jeita Spring", prepared by Council for Development and Reconstruction (CDR), Lebanon & Federal Institute for Geosciences and Natural Resources (BGR), Germany; 24 p.; Ballouneh

Marín AI, Martín Rodriguez JF, Barberá JA, Fernández-Ortega J, Mudarra M, Sánchez D, Andreo B (2021) Groundwater vulnerability to pollution in karst aquifers, considering key challenges and considerations: application to the Ubrique springs in southern Spain. Hydrogeol J 29, 379–396. https://doi.org/10.1007/s10040-020-02279-8

Marín AI, Dörfliger N, Andreo B (2012) Comparative application of two methods (COP and PaPRIKa) for groundwater vulnerability mapping in Mediterranean karst aquifers (France and Spain). Environ Earth Sci 65(8):2407–2421. https://doi.org/10.1007/s12665-011-1056-2

Marín AI (2009) Los Sistemas de Información Geográfica aplicados a la evaluación de recursos hídricos y a la vulnerabilidad a la contaminación de acuíferos carbonatados. Caso de la Alta Cadena (Provincia de Málaga). Tesis de Licenciatura, Universidad de Málaga. 131 pp.

Marjolet G, Salado J (1976) Contribution à l'étude de l'aquifère karstique de la source du Lez (Hérault). Etude du chimise des eaux de la source du Lez et de son bassin Tome IX-FASC II, Université des Sciences et Techniques du Languedoc (Montpellier II), France, 101 pp

Martín-Algarra M (1987). Evolución geológica alpina del contacto entre las Zonas Internas y Externas de la Cordillera Bética. PhD Thesis, University of Granada, Spain. 1171 p.

Martín-Rodriguez JF, Sánchez-García D, Mudarra-Martínez M, Andreo-Navarro B, López-Rodríguez M, Navas-Gutiérrez MR (2016) Evaluación de recursos hídricos y balance hidrogeológico en acuíferos kársticos de montaña. Caso de la Sierra de Grazalema (Cádiz, España). Book chapter on Las aguas subterráneas y la planificación hidrológica, 163-170. Spanish-Portuguese Congress. IAH Spanish Chapter. Madrid (Spain), November 2016.

Martín-Rodriguez JF, Mudarra M, Andreo B, Sánchez D (2019) Analysis of the water turbidity in karst springs from S Spain and its relationship with other natural responses, Contribution ID: 712, Poster at 46th IAH Congress, Malaga, Spain, September 2019

MKGP (2021) Pedological map and records of actual use of agricultural and forest land. [Online] Available from: https://rkg.gov.si/vstop/ [Accessed 6th August 2021].

Mudarra M, Andreo B, Baker A (2011) Characterisation of dissolved organic matter in karst spring waters using intrinsic fluorescence: relationship with infiltration processes. Sci Total Environ 409(18):3448–3462

Neukum C, Hötzl H (2007) Standardization of vulnerability maps. Environ Geol 51(5):689–694. https://doi.org/10.1007/s00254-006-0380-4

Paloc H (1967) Carte hydrogéologique de la France. Région karstique nordmontpelliéraine. Notice explicative. Mémoires du BRGM n_50. BRGM, Paris, 229 pp

Petrič M (2010) Characterisation, exploitation, and protection of the Malenščica karst spring, Slovenia.- In: Kresic, N. & Z. Stevanovic (eds.) Groundwater Hydrology of Springs. Engineering, Theory, Management and Sustainability. Butterworth-Heinemann, pp. 428-441, Burlington.

Petrič M, Kogovšek J, Ravbar N (2018) Effects of the vadose zone on groundwater flow and solute transport characteristics in mountainous karst aquifers–the case of the Javorniki–Snežnik massif (SW Slovenia). Acta Carsologica, 47(1), 35-51. https://doi.org/10.3986/ac.v47i1.5144

Petrič M, Ravbar N, Gostinčar P, Krsnik P, Gacin M (2020) GIS database of groundwater flow characteristics in carbonate aquifers: Tracer test inventory from Slovenian karst. Applied Geography, 118, 102191. https://doi.org/10.1016/j.apgeog.2020.102191

PNOA (2016) PNOA LiDAR. Instituto Geográfico Nacional, Gobierno de España PNOA (Plan Nacional de Ortofotografía Aérea). http://pnoa.ign.es/presentacion-y-objetivo. Accessed December 23, 2016

Polemio M, Casarano D, Limoni PP (2009) Karstic aquifer vulnerability assessment methods and results at a test site (Apulia, southern Italy). Nat Hazards Earth Syst Sci 9(4):1461–1470. https://doi.org/10.5194/nhess-9-1461-2009

Ravbar N, Barbera JA, Petrič M, Kogovšek J, Andreo Navarro B (2012) The study of hydrodynamic behaviour of a complex karst system under low-flow conditions using natural and artificial tracers (the catchment of the Unica River, SW Slovenia). Environmental earth sciences, 65/8: 2259-2272. https://doi.org/10.1007/s12665-012-1523-4

Ravbar N (2013) Variability of groundwater flow and transport processes in karst under different hydrologic conditions. Acta Carsologica, 42(2-3), 327–338. https://doi.org/10.3986/ac.v42i2.644

Ravbar N, Goldscheider N (2007) Proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia. Acta Carsolog 36(3):461–475. https://doi.org/10.3986/ac.v36i3.174

Ravbar N, Goldscheider N (2009) Comparative application of four methods of groundwater vulnerability mapping in a Slovene karst catchment. Hydrogeology Journal 17(3):725-733. https://doi.org/10.1007/s10040-008-0368-0

SAEFL. 2000. Groundwater Vulnerability Mapping in Karstic Regions (EPIK). Practical guide. Environment in practice. SAEFL, Berne, Switzerland, 56-57.

Sánchez D, Barberá JA, Mudarra M, Andreo B, Martín JF (2018) Hydrochemical and isotopic characterization of carbonate aquifers under natural flow conditions, Sierra Grazalema Natural Park, southern Spain In: Parise M, Gabrovsek F, Kaufmann G, Ravbar N (eds) Advances in karst research: theory, fieldwork and applications. Geol Soc London Spec Publ 466:275–293. https://doi.org/10.1144/SP466.16

Sánchez D, Barberá JA, Mudarra M, Andreo B (2017) Hydrogeochemical tools applied to the study of carbonate aquifers: examples from some karst systems of southern Spain. Environmental Earth Sciences, 74, 199–215.

Thierry D, Bérrard P (1983) Alimentation en eau de la ville de Montpellier—captage de la source du Lez—études des relations entra la source et son réservour aquifère. BRGM, Montpellier

Thornthwaite C.W (1948) An approach toward rational classification of climate. Geographical Review 38 (1), 55-94.

UNDP/ FAO. Pluviometric map of Lebanon (1939-1970). 1973

Vías JM, Andreo B, Ravbar N, Hötzl H (2010) Mapping the vulnerability of groundwater to the contamination of four carbonate aquifers in Europe. J Environ Manage 91(7):1500–1510. https://doi.org/10.1007/s10040-006-0023-6

Vías, JM, Andreo B, Perles MJ, Carrasco F, Vadillo I, Jiménez P (2006) Proposed Method for Groundwater Vulnerability Mapping in Carbonate (Karstic) aquifers: the COP method: Application in Two Pilot Sites in Southern Spain, Hydr. J. 14 (6), 1-14.

Vías JM, Andreo B, Perles MJ, Carrasco F (2005) A comparative study of four schemes for groundwater vulnerability mapping in a diffuse flow carbonate aquifer under Mediterranean climatic conditions. Environ Geol 47(4):586–595. https://doi.org/10.1007/s00254-004-1185-y

Yildirim M, Topkaya B (2007) Groundwater protection: a comparative study of four vulnerability mapping methods. CLEAN Soil Air Water Poll 35(6):594–600. https://doi.org/10.1002/clen.200700144

Zaporozec A (1994) Concept of groundwater vulnerability. In: Vrba J, Zaporozec A (eds) Guidebook on mapping groundwater vulnerability. International Contributions to Hydrogeology, vol 16. Heise, Hannover, Germany, pp 3–8

Zwahlen F (ed) (2004) Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. Final report of COST Action 620. European Commission, Directorate-General XII Science. Research and Development, Brussels