

# Karst groundwater protection: First application of a Pan-European Approach to vulnerability, hazard and risk mapping in the Sierra de Líbar (Southern Spain)

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## Abstract

The European COST action 620 proposed a comprehensive approach to karst groundwater protection, comprising methods of intrinsic and specific vulnerability mapping, validation of vulnerability maps, hazard and risk mapping. This paper presents the first application of all components of this Pan-European Approach to the Sierra de Líbar, a karst hydrogeology system in Andalusia, Spain. The intrinsic vulnerability maps take into account the hydrogeological characteristics of the area but are independent from specific contaminant properties. Two specific vulnerability maps were prepared for faecal coliforms and BTEX. These maps take into account the specific properties of these two groups of contaminants and their interaction with the karst hydrogeological system. The vulnerability assessment was validated by means of tracing tests, hydrological, hydrochemical and isotope methods. The hazard map shows the localization of potential contamination sources resulting from human activities, and evaluates those according to their dangerousness. The risk of groundwater contamination depends on the hazards and the vulnerability of the aquifer system. The risk map for the Sierra de Líbar was thus created by overlaying the hazard and vulnerability maps.

*Keywords:* Karst; Sierra de Líbar; Pan-European Approach; Intrinsic vulnerability; Specific vulnerability; Risk assessment

## 1. Introduction

### 1.1. Background

Groundwater is a natural drinking water resource often subjected to severe human impact. Strategies are

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required to preserve optimum groundwater quality, and so management of this vital natural resource has become a worldwide priority. In the last years, the international scientific community has shown great interest on this topic and, thus, many works focused on environmental management for groundwater protection (Adams and Foster, 1992; Drew and Hötzl, 1999; Arnaud, 2001; Morris, 2001; Eliasson et al., 2003; Gerth and Forstner, 2004).

After the definition of vulnerability to contamination given by Albinet and Margat (1970), many methods have been proposed for vulnerability mapping. Vrba and Zaporozec (1994) and Gogu and Dassargues (2000) provide an overview of the most current methods.

Groundwater from karst aquifers is among the most important resources of drinking water supply of the worldwide population. In Europe, carbonate terrains occupy 35% of the land surface, and in some countries, karst water contributes 50% to the total drinking water supply. In some regions, it is the only available freshwater resource (COST 65, 1995). At the same time, karst aquifers are particularly vulnerable to contamination. Due to thin soils, flow concentration in the epikarst, and point recharge via swallow holes, contaminants can easily reach the groundwater, where they may be transported rapidly in karst conduits over large distances. The residence times of contaminants are often short, and processes of contaminant attenuation therefore often do not work effectively in karst systems. Therefore, karst aquifers need special protection. However, most of the previously available methods of vulnerability mapping do not consider the special characteristics of karst systems. The EPIK method was the first method specifically dedicated to karst (Doerfliger and Zwahlen, 1998). It is now used for source protection zoning in karst aquifer systems in Switzerland. The acronym stands for the four factors that are considered: Epikarst, Protective cover, Infiltration conditions and Karst network development. However, there are some drawbacks in this method limiting its applicability under different climatic and hydrogeological settings.

Therefore, the European Commission set up the COST Action 620 on “vulnerability and risk mapping for the protection of carbonate (karst) aquifers”. COST stands for Cooperation in Science and Tech-

nology. 51 delegates from 15 European countries contributed to this action, which begun 1997 and finished 2003 (Zwahlen, 2004). The project was given additional impetus by the European Water Framework Directive (2000), which is intended to provide a common framework for water resource policy and management.

COST 620 distinguished two main concepts of groundwater vulnerability, following the definitions proposed by Vrba and Zaporozec (1994): intrinsic and specific vulnerability. Intrinsic vulnerability takes into account the hydrogeological characteristics of an area but is independent of the nature of the contaminants. Specific vulnerability additionally takes into account the properties of a particular contaminant (or group of contaminants) and its relationship to the hydrogeological system (Daly et al., 2002; Zwahlen, 2004). COST 620 consisted of three Working Groups. Group 1 proposed a conceptual framework for intrinsic vulnerability mapping. Based on this framework, several individual methods were developed, which allow for flexible application under different hydrogeological conditions and data availability. Group 2 developed a conceptual framework and method of specific vulnerability mapping. Group 3 proposed a procedure for hazard mapping and outlined a framework for risk assessment. COST 620 also proposed methods to validate vulnerability maps.

Different elements of this Pan-European Approach were applied in twelve test sites all over Europe. However, the Sierra de Líbar (Fig. 1) is the only test site where all elements were applied during cooperation between research groups from the Universities of Málaga (Spain), Karlsruhe (Germany) and Neuchâtel (Switzerland).

### *1.2. Test site characteristics*

The Sierra de Líbar covers a surface area of 103 km<sup>2</sup> and is located between the provinces of Málaga and Cádiz in Andalucía, Southern Spain (Fig. 1). The area is characterized by high seasonal rainfall, with a mean annual precipitation of over 1500 mm. The test site is formed of Jurassic dolomites and limestones, and Cretaceous marls and marly limestones (Martín-Algarra, 1987). Jurassic rocks form a large anticline (N40E), whilst Cretaceous rocks remained in the synclines and tectonic grabens. This fold structure was

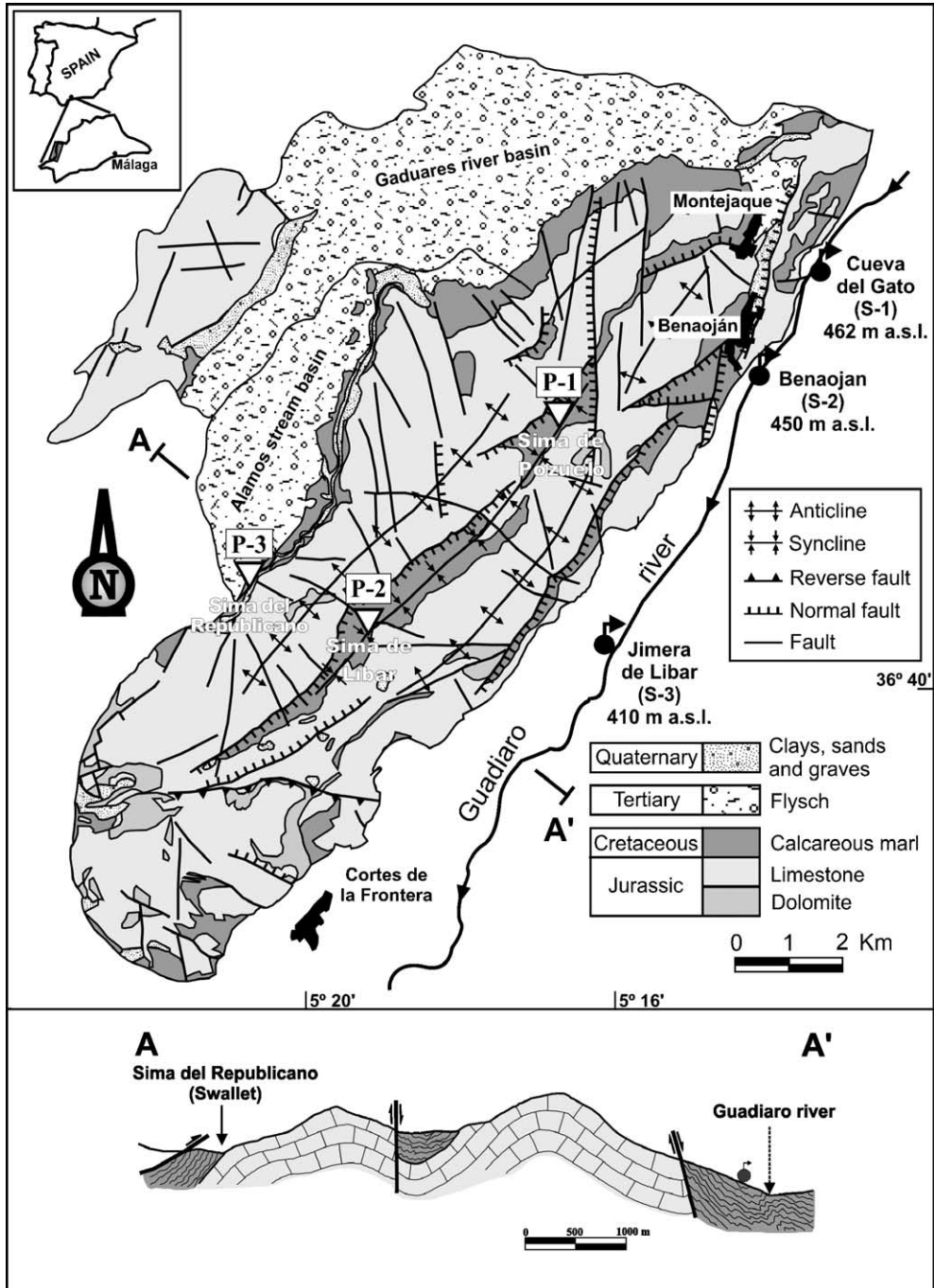


Fig. 1. Geographical and geological setting of Sierra de Líbar.

overthrust by clayey tertiary Flysch and subsequently cut by transverse faults. The lithology and geological structure predetermine a landscape charac-

terized by steep slopes and plateau-shaped mountain ridges. There are a large variety of well-developed karst landforms, including karrenfields, vertical shafts,

and cave systems. Poljes developed in the synclines, where Cretaceous marls outcrop. Rainfall often generates surface flow on the polje floors, which are drained by swallow holes (Delannoy, 1987). The karst aquifer is formed of Jurassic rocks with a total thickness of over 400 m. The aquifer system drains via karst springs on its S and E borders, towards the Guadiaro River. The discharge rates and hydrochemical composition of these karst springs react rapidly on precipitation events (Sánchez et al., 1998, Jiménez et al., in press). Soils are largely absent on limestone and dolomite outcrops, while the marly polje floors are covered by soils.

## 2. Overview of the Pan-European Approach proposed by COST Action 620

The Pan-European Approach to vulnerability, hazard and risk mapping proposed by COST Action 620 is based on an origin-pathway-target model, which applies for both resource and source protection. The origin is the assumed place of release of a contaminant. The pathway is the flow path of a contaminant from its origin, through the system, to the point that has to be protected. For resource protection, the pathway consists of the downward passage through the layers overlying aquifer; for source protection it also includes the lateral passage in the aquifer. The target is the water that has to be protected. For resource protection it is the groundwater in the aquifer, for source protection it is the water in a well or spring (Goldscheider, 2004a). Hazards are potential sources of contamination resulting from human activities, mainly at the land surface (De Ketelaere et al., 2004). The risk of groundwater contamination thus depends on the hazard (origin), the vulnerability of the system (pathway) and the potential consequences of a contamination event, i.e., its impact on the groundwater resource or source (target) (Daly et al., 2004).

In the case of an accidental contamination event, there are three practical questions to be answered (Brouyère, 2004): How long does it take until the contamination reaches the target (groundwater resource or source), at which concentration will the target be contaminated, and for how long will the contamination last? The Pan-European Approach mainly considers the first two aspects, i.e., the

transit time of a contaminant from the origin to the target, and the concentration decline along its pathways.

The conceptual framework for intrinsic groundwater vulnerability mapping proposed by COST Action 620 considers four factors: overlying layers (*O*), flow concentration (*C*), precipitation regime (*P*) and karst network development (*K*). Resource vulnerability maps are prepared by a combination of the *O*, *C*, and *P* factors. For source vulnerability mapping, the *K* factor needs to be considered additionally (Daly et al., 2002; Goldscheider and Popescu, 2004). Several individual methods can be used within this conceptual framework, dependent on the hydrogeological framework, and the available time, data and financial resources. Two of these methods were tested in the Sierra de Libar: the PI method (Goldscheider et al., 2000), and the COP method (Vías et al., 2002, 2004).

COST Action 620 also proposed different methods to validate vulnerability maps, including the interpretation of spring hydrographs and chemographs, the use of natural and artificial tracers, and modeling (Neale, 2004). Some of these methods were applied in the test site in order to validate the two intrinsic vulnerability maps.

Intrinsic vulnerability methods do not consider the large variety of specific contaminant types and contamination scenarios. A specific vulnerability assessment is indicated if a particular contaminant is identified posing a threat to groundwater quality allowing its individual behavior to be incorporated into groundwater vulnerability studies. Specific attenuation processes, such as sorption, biodegradation or chemical transformation, influence contaminant fate and transport in the subsurface. Contaminants are thus subjected to retardation and degradation effects, which lead to increased protection values compared to intrinsic vulnerability. The effectiveness of specific attenuation processes depends both on the characteristics of the subsurface and on the nature of the contaminant concerned. For carbonate environments, typical karst phenomena also need to be considered, such as the bypassing of strata by preferential conduit flow.

The COST Action 620 concept considers a specific weighting factor (*S* factor) to be required in order to incorporate the additional specific attenuation processes into vulnerability assessment (Sinreich et al.,

2004a). A standard procedure was established in order to allow qualitative  $S$  factor evaluation for different hydrogeological settings and various kinds of contaminant (Sinreich et al., 2004b). Specific attenuation assessment results can then be used complementary to any intrinsic vulnerability method.

In the context of groundwater contamination, a hazard is defined as a potential source of contamination resulting from human activities taking place mainly at the land surface. The hazards have been classified according to the type of land use (infrastructural, industrial and agricultural development). A hazard assessment considers the potential degree of harmfulness for each type of hazard and is determined by the toxicity and quantity of harmful substances as well as the likelihood of a contamination event.

Several definitions of risk to groundwater have been introduced in the technical literature. The definition of groundwater contamination risk proposed by Morris and Foster (2000) “*as the probability that groundwater in the aquifer will become contaminated to an unacceptable level by activities on the immediately overlaying land-surface*” has been adopted within the framework of the COST Action 620. This approach uses the interaction between the infiltrating contaminant load and the vulnerability of the aquifer at the location concerned. The risk assessment followed in the Sierra de Líbar test site describes the impact intensity from a potential contamination load at the surface. Considering the intrinsic vulnerability and the hazard assessment scheme with their definitions, the risk definition in this assessment scheme can be described as the risk to groundwater pollution from each hazard when its contamination load is released. The risk maps therefore show the risk to groundwater pollution of each mapped hazard in the sense of resource protection. Thus, the groundwater and the characteristics of the saturated zone of the aquifer are not included in the risk assessment.

### 3. Intrinsic vulnerability mapping

#### 3.1. PI method

The PI method of vulnerability mapping was developed prior to the Pan-European Approach and uses

the same conceptual model and factors, but a slightly different nomenclature (Goldscheider et al., 2000). COST 620 proposes this method as one possibility of intrinsic resource vulnerability mapping, mainly if detailed data are available. The method is applicable for all types of aquifers and provides specific methodological tools for karst. The protection factor  $\pi$  is assessed as the product of two factors (1): protective cover ( $P$ ) and (2): infiltration conditions ( $I$ ):

$$\pi = P \cdot I. \quad (1)$$

A high protection factor corresponds to a low vulnerability and vice versa. The  $P$  factor describes the protective function of all layers between the ground surface and the groundwater table: soil, subsoil, non-karst rock, and unsaturated karst rock (i.e., the “overlying layers” of the Pan-European Approach). It is calculated using a modified version of a method proposed by Hölting et al. (1995) and divided into five classes; from  $P=1$  for a very low degree of protection to  $P=5$  for very thick and protective overlying layers.

The  $I$  factor (infiltration conditions) describes the degree to which the protective cover is bypassed as a result of surface and shallow subsurface flow in the catchment of swallow holes (i.e., “flow concentration” of the Pan-European Approach). The  $I$  factor takes into account the soil properties controlling runoff generation, the vegetation, the slope gradient and the position of a given point inside or outside the catchment of a sinking stream. It ranges between 0.0 (swallow holes, sinking streams, and steep slopes generating surface runoff towards these) and 1.0 (diffuse infiltration and percolation).

The PI method was first applied in a test site in the Swabian Alb, Germany (unpublished diploma works by Markus Klute and Sebastian Sturm; Goldscheider, 2005). Brechenmacher (unpublished diploma work) applied it in the Sierra de Líbar (Fig. 2).

The evaluation scheme for the  $P$  factor uses a subfactor for the degree of fracturing and epikarst development. This subfactor is zero in case of strongly developed epikarst, i.e., bare karrenfields connected with vertical shafts. As this situation occurs frequently in the Sierra de Líbar, vulnerability was classified as ‘very high’ on large areas, independent from the thickness of the unsaturated karstic bedrock. ‘Very high’ vulnerability was also assigned to areas inside

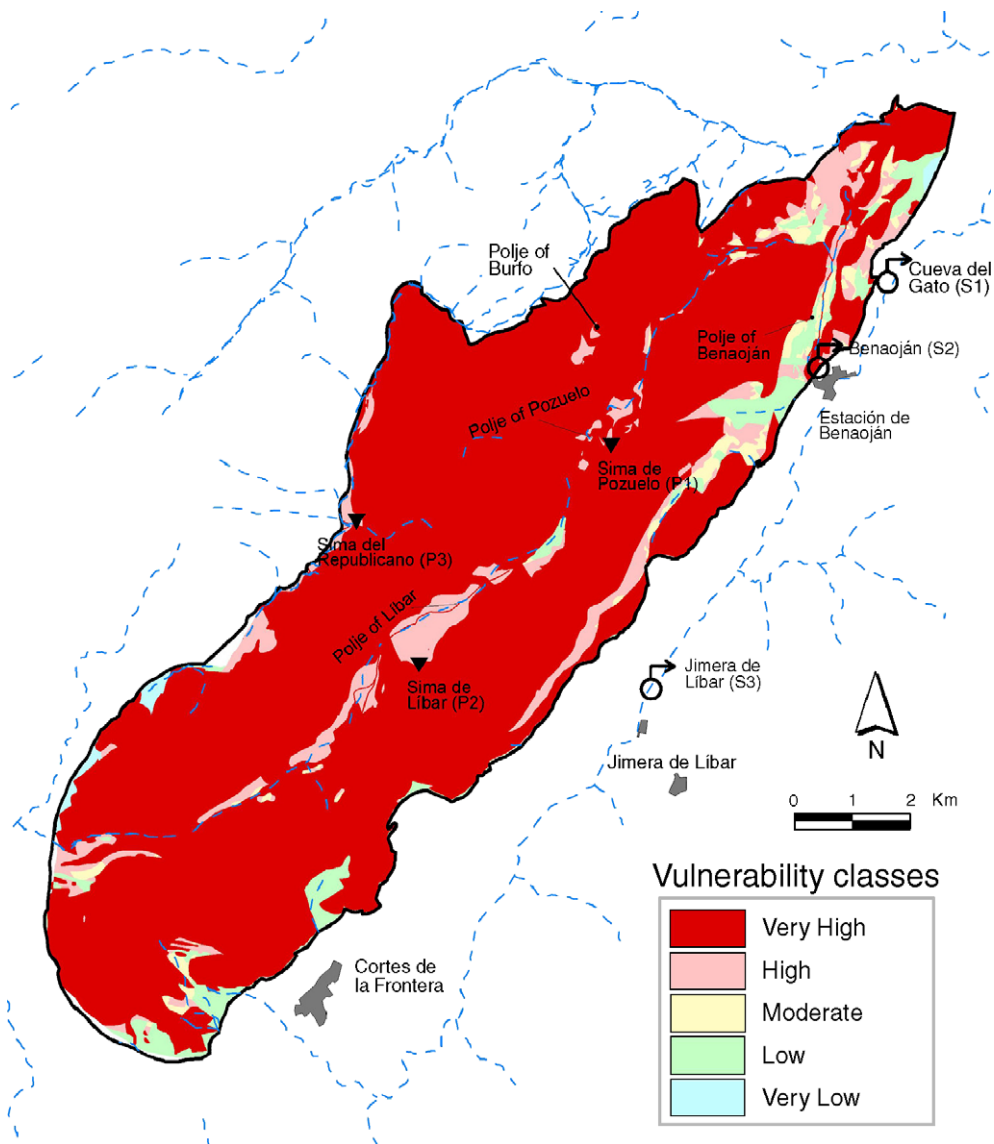


Fig. 2. Intrinsic vulnerability map by PI method with the five categories of vulnerability adopted in this study. Streams and rivers (blue dashed line) and springs have been marked.

poljes, which generate surface flow towards swallow holes ( $I=0.0$ ).

Vulnerability was classified as 'high' on areas where coarse-grained sediments overlay the karst aquifer (low  $P$  factor), and on areas inside the poljes where surface flow towards swallow holes occurs less frequently (low  $I$  factor). 'Moderate' to 'very low' vulnerability is present on areas, where the karst aquifer is covered by thick marly formations (high  $P$

factor) that do not generate surface flow towards swallow holes (high  $I$  factor).

### 3.2. COP method

The COP method (Vías et al., 2002, 2004) is based on the Pan-European Approach to intrinsic vulnerability mapping proposed by COST Action 620. Vulnerability is assessed as the product of three factors

(2): Concentration of flow ( $C$ ), Overlying layers ( $O$ ) and Precipitation ( $P$ ). As the method is made for resource protection, the karst network development inside the aquifer is not considered.

$$COP = C \cdot O \cdot P. \quad (2)$$

The  $O$  factor refers to the protection of the unsaturated zone of the aquifer against a contaminant event. It indicates the capability of the unsaturated zone to filter out or attenuate contamination and thus reduce its adverse effects. The  $C$  and  $P$  factors are used as modifiers that correct the degree of protection provided by the overlying layers ( $O$  factor). The  $C$  factor takes into account the surface conditions that control water flowing towards zones of rapid infiltration, which have less capacity to attenuate contamination. The  $P$  factor considers influence of precipitation, both quantity and intensity, on the transport of contami-

nants and, thus, in the vulnerability. The final vulnerability index is obtained by multiplying the three factors and from the resulting index five classes of vulnerability are obtained, ranging from Very Low to Very High.

The application of the COP method to Sierra de Líbar is summarized in Table 1, which shows the values of the different parameters observed, and the scores assigned to each one.

The COP final map (Fig. 3), within the carbonate outcrop, shows the differences in vulnerability (between “High” and “Very High” categories) depending on the presence of specific conditions of factors  $O$  or  $C$ . Thus, the  $O$  factor determines the “High” vulnerability in the outcrop of Jurassic limestones and dolomites, where the thickness of the unsaturated zone exceeds 250 m and the slope is greater than 8%. The “Very High” degree of vulnerability occurs in

Table 1  
Values for COP factors and variables in Sierra de Líbar site

Factor	Subfactor	Variable	Values			
$C$	<i>Scenario A: C</i> inside the catchment area of swallow hole	Distance to swallow hole	■Between 0 and 3500 m ■0–10 m ■10–100 m ■>100 m. or sinking stream absent	0–0.6 0 0.5 1		
		Slope and vegetation	■0–8% ■8–31% and without vegetation ■31–76% and without vegetation ■>76%	1 0.9 0.8 0.75		
		<i>Scenario B: C</i> rest of the aquifer	Surface features	■Karst well developed and uncovered ■Karst well developed covered by a permeable bed ■Karst scarcely developed and uncovered ■Absence of karst features	0.25 0.5 0.5 1	
			Slope and vegetation	■0–8% ■8–31% and without vegetation ■31–76% and without vegetation ■>76%	0.75 0.85 0.95 1	
				Texture and thickness	■Clayey and >1m ■Clayey and 0.5–1m ■Clayey and 0–0.5m ■Silty and 0.5–1m	5 4 3 3
	$O$	Lithology [ $O_L$ ]	Lithology and fracturation	■Marl Flysch ■Cretaceous marly-limestones ■Colluviums, rockfalls, sands and gravel ■Jurassic limestone and dolomites	1000 500 10 1	
			Confined conditions	■Unconfined	1	
		$P$	Quantity [ $P_Q$ ]	Average precipitation for wet years	■>1600 mm/year ■>1200 and ≤1600 mm/year ■>800 and ≤1200 mm/year	0.4 0.3 0.2
				Intensity [ $P_I$ ]	Precipitation and number of days	■>20 mm/year ■>10 and ≤20 mm/day

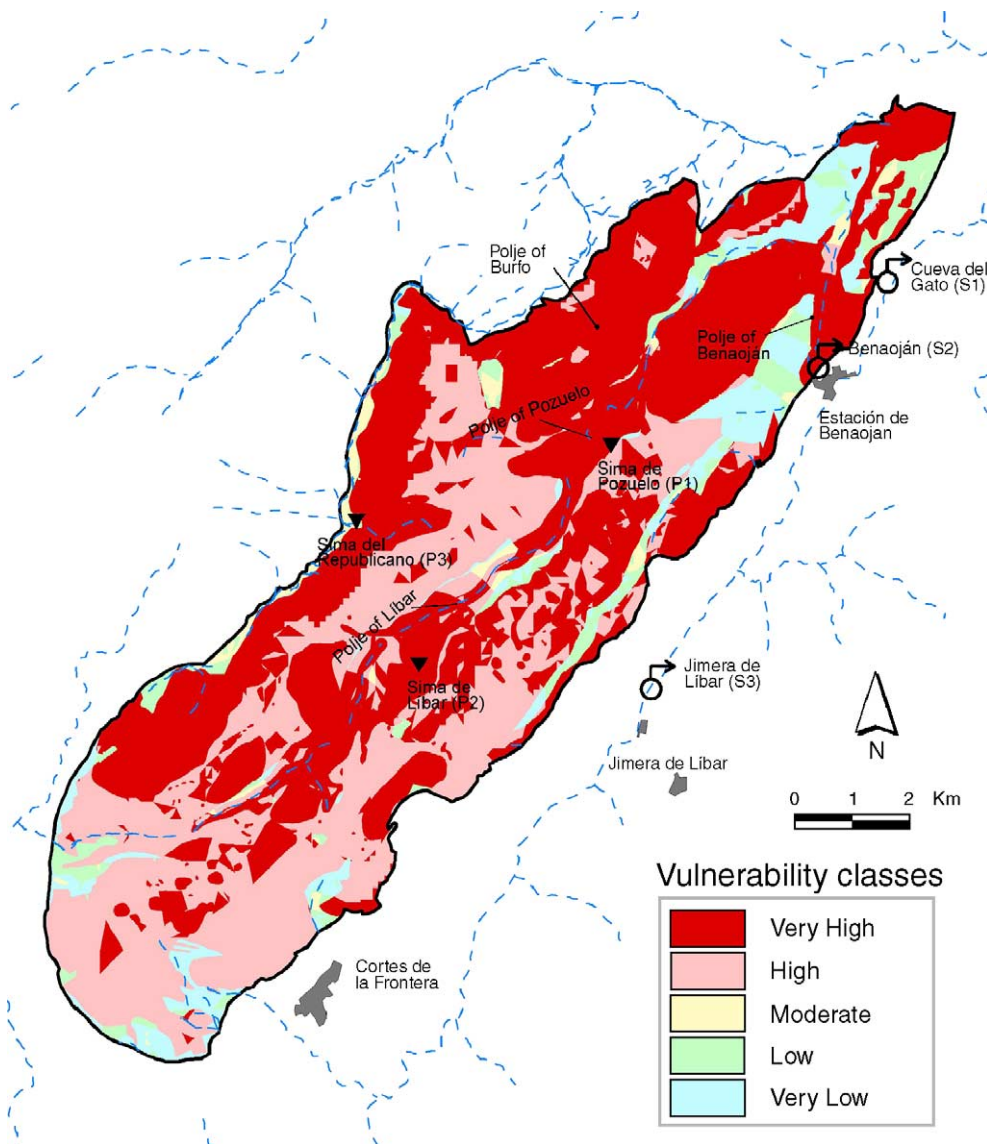


Fig. 3. Intrinsic vulnerability map by COP method.

areas where the thickness of the unsaturated zone does not exceed 250 m, as in the case, for example, on the NW boundary of the aquifer. The  $C$  factor, on the other hand, is crucial in determining the “Very High” vulnerability in areas where the surface cover favors infiltration processes rather than runoff, for example where karst forms are not covered by an impermeable layer or where karst is not highly developed but the shallowness of the slope and the presence of vegetation favors infiltration. The poljes of the central part of

the aquifer, those of Libar, Pozuelo and Zurraque, are classified as being of “Very High” vulnerability due to the presence of swallow holes that bypass the protective capacity of the unsaturated zone of the aquifer minimizing the transit time of the water through the unsaturated zone.

In certain areas, the vulnerability is “Moderate” where carbonate outcrops are covered by a layer of soil or by Quaternary materials, i.e., areas with Cretaceous marly-limestones where the  $C$  and  $P$  factors

(because of the shallow slope and the high intensity, respectively) reduce the potential attenuation capability assigned to the unsaturated zone by the  $O$  factor.

The “Low” and “Very Low” vulnerability areas correspond to the outcrops of Cretaceous marly-limestones, beyond the poljes, and of marly Flysch, where the low permeability of the surface cover and the gradient of the slope favors runoff towards the external part of the aquifer.

### 3.3. Comparison between the two intrinsic vulnerability maps

Both methods classify large areas as zones of elevated vulnerability, which is consistent, as large parts of the test site are characterized by bare karren-fields and abundant vertical shafts. However, the PI method classifies all these areas as zones of ‘very high’ vulnerability, because  $P=0$  in case of extreme epikarst development. In contrast, the COP method differentiates between zones of ‘high’ and ‘very high’ vulnerability, dependent on the thickness of the unsaturated zone.

Both methods classify swallow holes and areas generating runoff toward sinking streams as zones of ‘very high’ vulnerability. This is a consequence of the karst-specific factors  $I$  (infiltration conditions) and  $C$  (flow concentration), which describe the degree to which the overlying layers are bypassed by surface flow in the catchment of swallow holes. According to both methods, vulnerability is ‘very low’ to ‘moderate’ on areas where the aquifer is covered by thick formations of low permeability (high values for  $P$  and  $O$ ), which do not generate surface flow towards the karst aquifer (high values for  $I$  and  $C$ ).

Only the COP method allows taking into account the precipitation regime of this test site, which is characterized by high annual precipitation and high rainfall intensities.

### 3.4. Validation of the intrinsic vulnerability maps

Tracer tests can be used to validate a groundwater vulnerability assessment, as they allow observing the transit time and concentration decline of a potential contaminant from the injection point (origin) to a sampling point (target). Conservative tracers can be used to validate intrinsic vulnerability; reactive tracers

allow validating specific vulnerability. For validating a source vulnerability map, the tracer breakthrough should be observed at the spring or well. For resource vulnerability, it should be observed at the basis of the unsaturated zone, which is, however, often not possible. Tracer tests allow for validation at certain points only, while large surfaces cannot be validated with this method (Goldscheider et al., 2001, Goldscheider, 2004b).

A multi-tracer test was done in the test site in order to validate the intrinsic vulnerability maps (Andreo et al., 2004). Three fluorescent dyes (Eosine, Uranine, Sulforhodamine B) were injected into three swallow holes (P-1, P-2 and P-3 in Fig. 4) during a period of high-flow conditions. All karst spring in the area were sampled in order to observe the possible tracer breakthrough. Strictly spoken, the set up of this experiment applies for the validation of a source vulnerability map (sampling at the springs), while the PI and COP map show the vulnerability of the groundwater resource. Nevertheless, the tracer test gave useful information on the vulnerability of the aquifer system: all tracers reappeared at one or several karst springs between 3 and 5 days after the injection. The maximal linear flow velocities, calculated from the time of first tracer detection, range between 77 and 119 m/h. These results confirm the ‘very high’ groundwater vulnerability in all areas within the poljes that generate surface runoff towards swallow holes. The tracer test also showed that a contaminant release in the catchment of the swallow holes P-1 and P-2 would threaten springs S-1, S-2 and S-3, whilst contamination in P-3 would only affect spring S-4.

Spring hydrographs and natural tracers can also be used to validate a vulnerability assessment. In contrast to artificial tracer tests, these methods cannot be used to check the vulnerability at specific points, but provide information on the global response of the aquifer system on external impacts. Fast and strong hydraulic, hydrochemical and isotopic reactions on hydrologic events indicate high vulnerability (Bakalowicz, 2004, Kralik and Mudry, 2004).

In the Sierra de Líbar, the variations of discharge rate ( $Q$ ), electrical conductivity (EC) and isotopic composition ( $\delta^{18}\text{O}$ ) of the spring and rainwater were used to validate vulnerability. The Gato and Benaoján springs (S-1 and S-2) served as main sampling points.

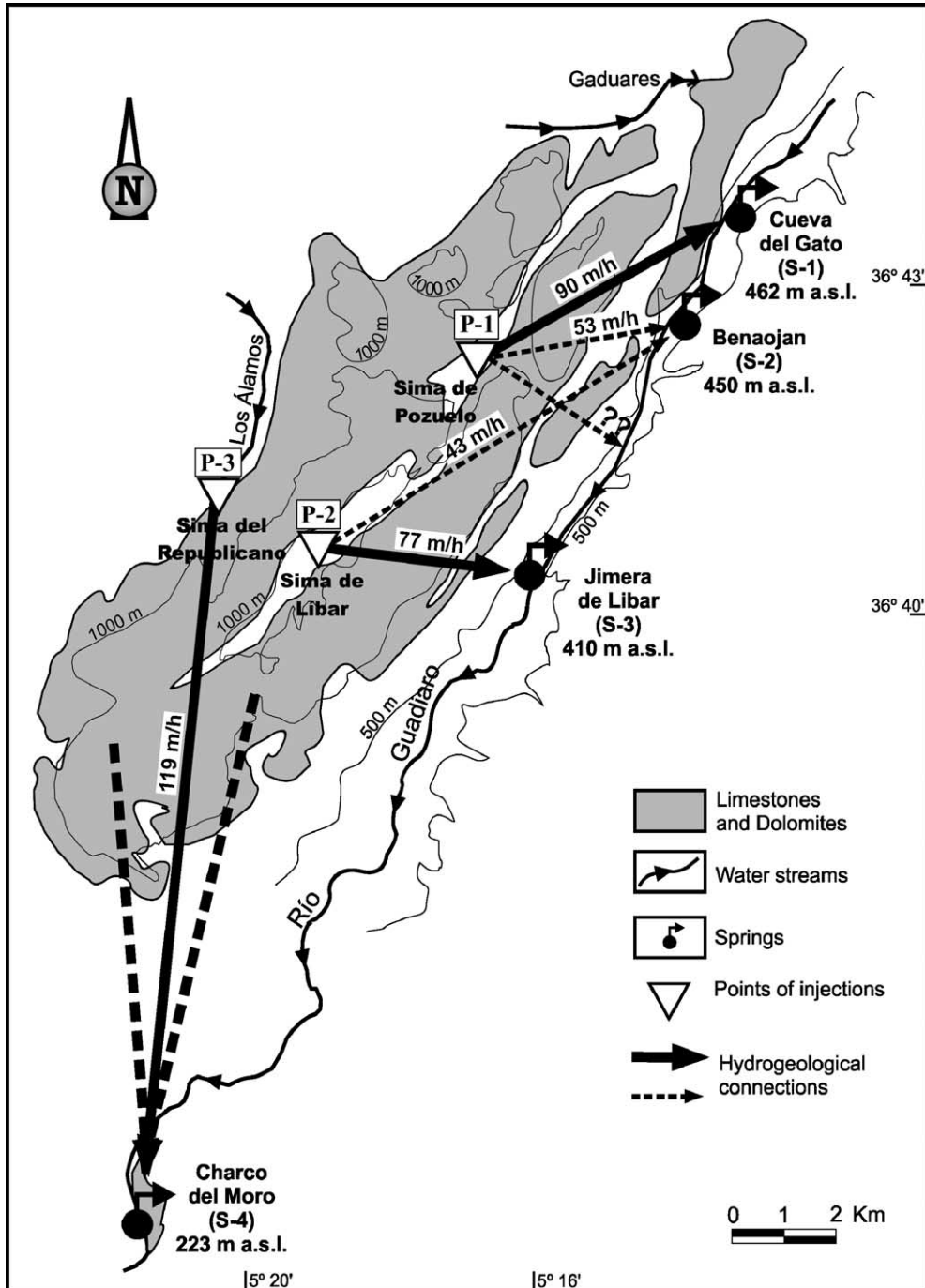


Fig. 4. Main results of the tracer test carried out in Sierra de Libar.

The hydrodynamic response of these springs to rainfall events is very fast (occurs during 3–4 days after the rain) and produce a rapid increasing in flow,

from zero to several thousands L/s (Fig. 5). Hydrograph analysis reveals that fast decreases in flow occur in these springs. So, depletion of the spring

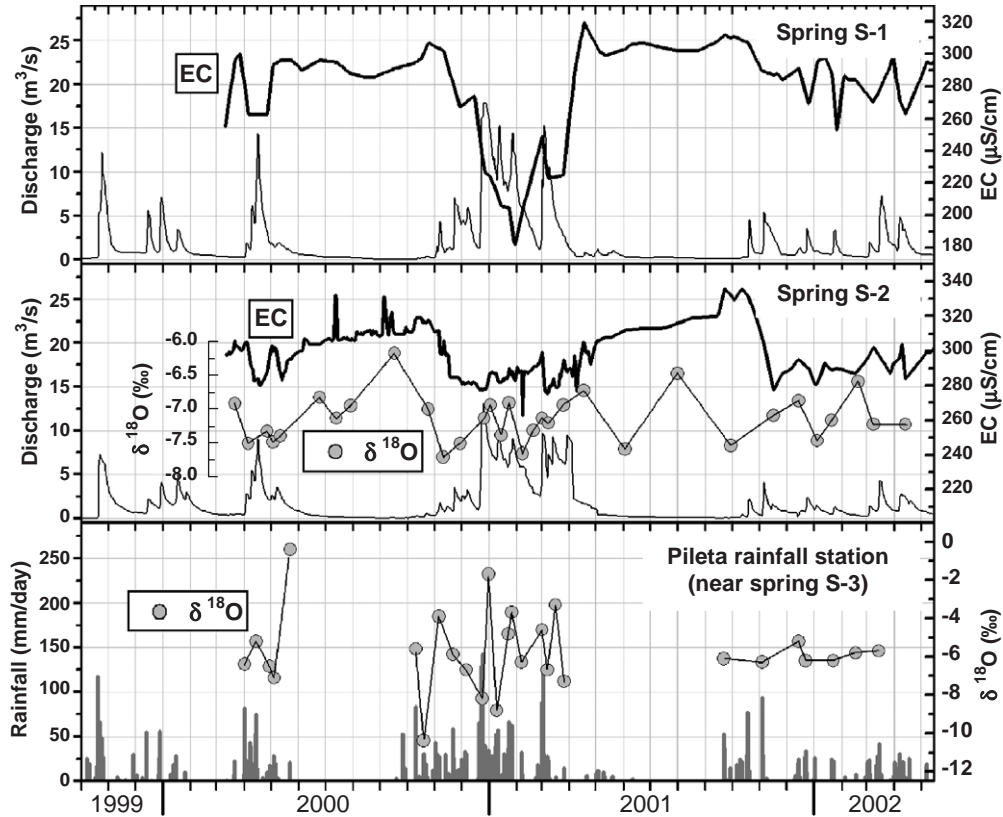


Fig. 5. Time evolution of hydrodynamic, hydrochemical and isotopic parameters.

waters is characterized by exhaustion coefficient ( $\alpha$ ) values of around  $10^{-2}$  days $^{-1}$  (Carrasco et al., 2001; Jiménez et al., 2003) and moreover the results of the application of correlation and spectral analysis reveals the low inertia and the rapid response to rainfall (Jiménez et al., 2003).

So, at the same time than the hydrodynamic response decreases in the electrical conductivity of water occur, the magnitude of which varies from 50 to 120  $\mu\text{S}/\text{cm}$  (Fig. 5). All this evidence suggests that residence times are short and the existence of an important functional karstification (Jiménez et al., 2002, 2004) because the calcareous rocks have developed a karstic drainage pattern (conduit flow).

The analysis for the variations in the isotopic contents of rainwater and groundwater of the Benaoján spring allows deducing the same results previously obtained of the hydrodynamic and hydrochemical point of view (Jiménez et al., 2003). So, if it is

considered the sampling rhythm (3–4 per month), the response of the Benaoján spring is very pronounced. Besides, the conservation of the rainfall signal during the hydrodynamic response is indicative of the existence of a rapid infiltration of rainwater without significant mixing with groundwater of the saturated zone.

Therefore, the artificial and natural tracers corroborate the high vulnerability of Sierra de Líbar karst aquifer.

#### 4. Specific vulnerability mapping

##### 4.1. Method description

The specific vulnerability methodology developed within the framework of COST Action 620 (Sinreich et al., 2004b) emanates from the definition of relevant

contaminant types, for which an assessment is indicated. Two groups were selected for specific vulnerability mapping in Sierra de Líbar considered being the main potential contaminants in the catchment: microbial and hydrocarbon contaminants. Microbial contaminants (faecal coliforms) may derive from urban sewage leakage and livestock farming. In the study area, they may be released as diffuse contamination in the course of manure application or as point contamination next to villages and cattle or sheep farms. Hydrocarbon contaminants, especially aromatic hydrocarbons (BTEX), may derive from the petrol station and from oil-fuel and petrol tanks for private and agricultural purposes. Also mountain roads constitute a noteworthy BTEX hazard.

Both contaminant types have drastically differing physical and chemical characteristics and are thus assumed to show significant distinctions in transport behavior. However, only specific attenuation processes are diverse, whereas hydrodynamic flow characteristics represent a uniform basis for any contaminant transport. The proposed method thus evaluates a specific weighting factor ( $S$ ) to be linked to the results of an intrinsic vulnerability assessment. The  $S$  factor deduces from input data concerning layer properties and contaminant properties. These data allow qualitatively estimating the effectiveness of relevant processes that may cause retardation and degradation of contaminant concentration by using a sequence of empirical matrices. For example, the process capacity of a certain layer depends on its thickness and on associated key properties, including clay content, organic matter content, pH value, temperature etc. In general, specific attenuation processes may become effective if they are favored by both layer composition and contaminant properties. Nonetheless, process effectiveness may be reduced due to the bypass of protective layers by preferential drain in karst features. Consequently, the index value, which is assigned to the  $S$  factor, is restricted according to the rate of diffuse flow in each layer.

The assessment provides a specific attenuation index for the sum of all layers at each point of the catchment. Associated specific attenuation classes may range from 'very low' (e.g., in case of uncovered karst) up to 'high' where the karst is maybe overlain by topsoil and/or other protective cover. For the Sierra de Líbar, results of the specific attenuation assessment

were linked to the intrinsic vulnerability map derived using the COP method. In doing so, specific attenuation classes were combined with the  $O$  factor of the COP method. More precisely, specific attenuation classes enhance the score of the  $O$  factor, since specific attenuation is an additional protective effect of the overlying layers. The so modified  $O$  factor ( $O_{\text{mod}}$ ) is then multiplied with the  $C$  factor and  $P$  factor in analogous manner to intrinsic vulnerability assessment using the COP method in order to obtain specific vulnerability classes (3):

$$\text{COP} = C \cdot O_{\text{mod}} \cdot P. \quad (3)$$

Input data that is needed for the contaminant-specific assessment derived either from literature (contaminant properties) or were estimated based on field observations or on reference values (layer composition). Layer thickness distribution was directly adopted from existing databases. For the rate of diffuse flow estimation, a uniform range was assigned to each layer taking into account the geological and geomorphologic features of the outcrops and the hydrodynamic and hydrochemical characteristics of groundwater (Jiménez et al., 2003).

#### 4.2. Comparison between intrinsic and specific vulnerability maps

Faecal coliforms may suffer retardation and degradation in the subsurface by sorption, physical filtering and die off. These processes can mainly be assigned to the clayey topsoil layer and the marls of the non-karst rock. However, where fast preferential flow is favored due to conductive macropores, soil cracks or enlarged fissures none of these attenuation processes can be assumed as a major mechanism of contaminant concentration lowering.

The microbiological-specific vulnerability map differs only slightly from the intrinsic vulnerability map compiled using the COP method. In areas of 'very high' or 'high' intrinsic vulnerability, the protection is not increased for microbiological contaminants (Fig. 6). These areas are composed of limestone and dolomite outcrops with a total absence of soil and non-karst bedrock. Since the rate of preferential flow of these formations is estimated more than 90%, residence time is very low and bacteria may not be significantly subjected to die off and other attenuation

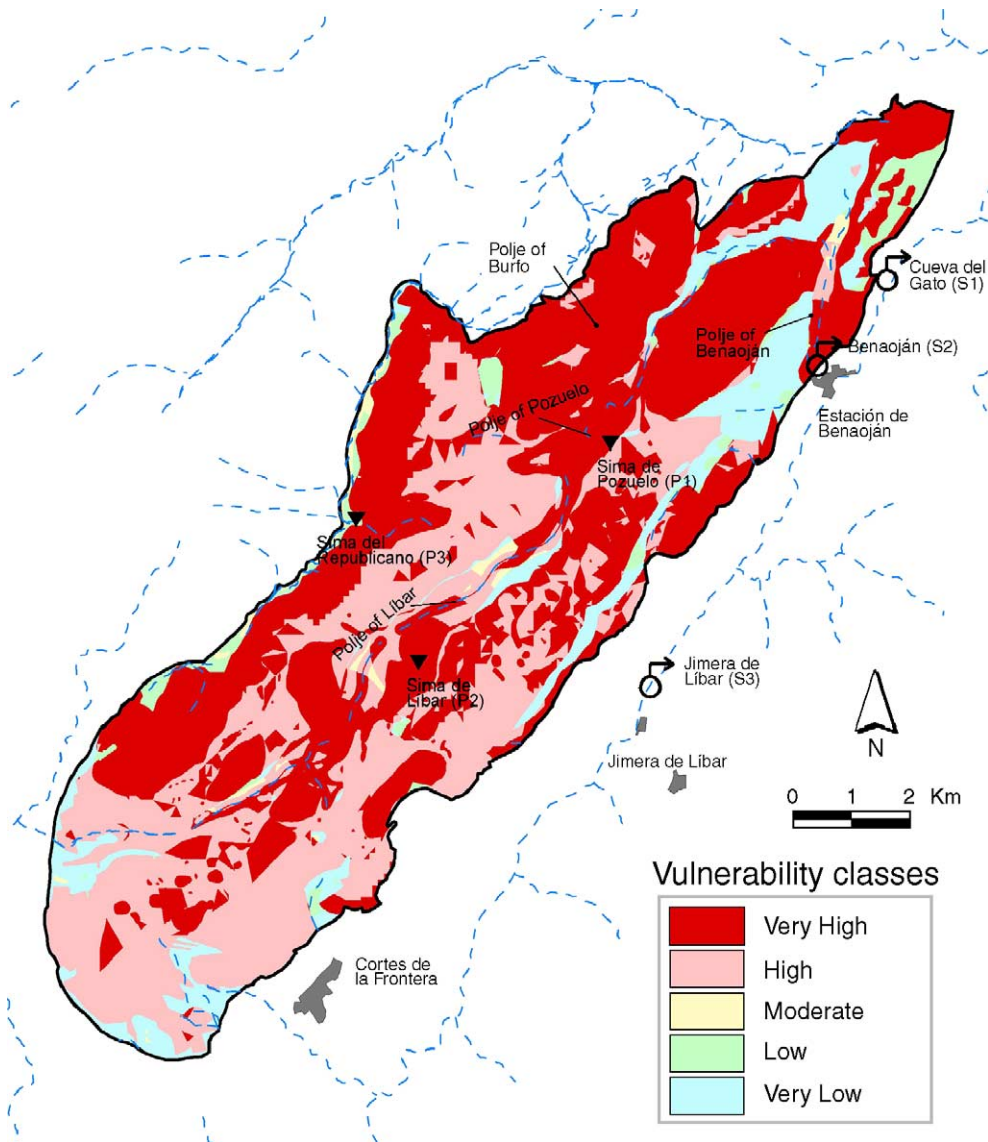


Fig. 6. Specific vulnerability map for microbiological (faecal coliforms) contamination scenario.

processes. In contrast, for areas with 'moderate' or 'low' intrinsic vulnerability additional protection is provided due to specific attenuation. These areas coincide with soil covered marly limestones and Flysch. The clay content in these layers, jointly with a more pronounced diffuse flow, allows interaction with the media and increased process effectiveness, resulting in classes of 'low' to 'very low' specific vulnerability.

Organic compounds can potentially be affected by sorption, biodegradation and volatilization. BTEX

form the water-soluble components of gasoline and their components are included among the group of compounds termed volatile organic compounds (VOC). Volatilization is thus an important degradation process, especially in karst environments. The applied method assumes volatilization to be bound to turbulent groundwater flow, conditions to be met in karst conduits. The location in the south of Spain with relatively high mean temperature also benefits the process of volatilization in the catchment. As the

BTEX group generally is not very prone to adsorption, this process is omitted for the vulnerability assessment. Finally, BTEX could be microbiologically degraded with the involvement of organic matter. Since even the topsoil layer contains only little organic matter, biodegradation is also a process regarded as not significant for BTEX attenuation in Sierra de Líbar.

The BTEX-specific vulnerability map (Fig. 7) is significantly different to the COP intrinsic vulnerabil-

ity map indicating an overall higher protection towards BTEX than towards conservatively behaving contaminants. BTEX reach a high specific attenuation where the unsaturated zone is relatively thick, whereas the topsoil lost its prominent role for specific attenuation in that situation. Therefore, nearly everywhere in the catchment, vulnerability decreased at least by one grade. The majority of surfaces, assigned to 'very high' or 'high' intrinsic vulnerability, have changed to classes of 'high' and 'moderate' vulnerability. Only

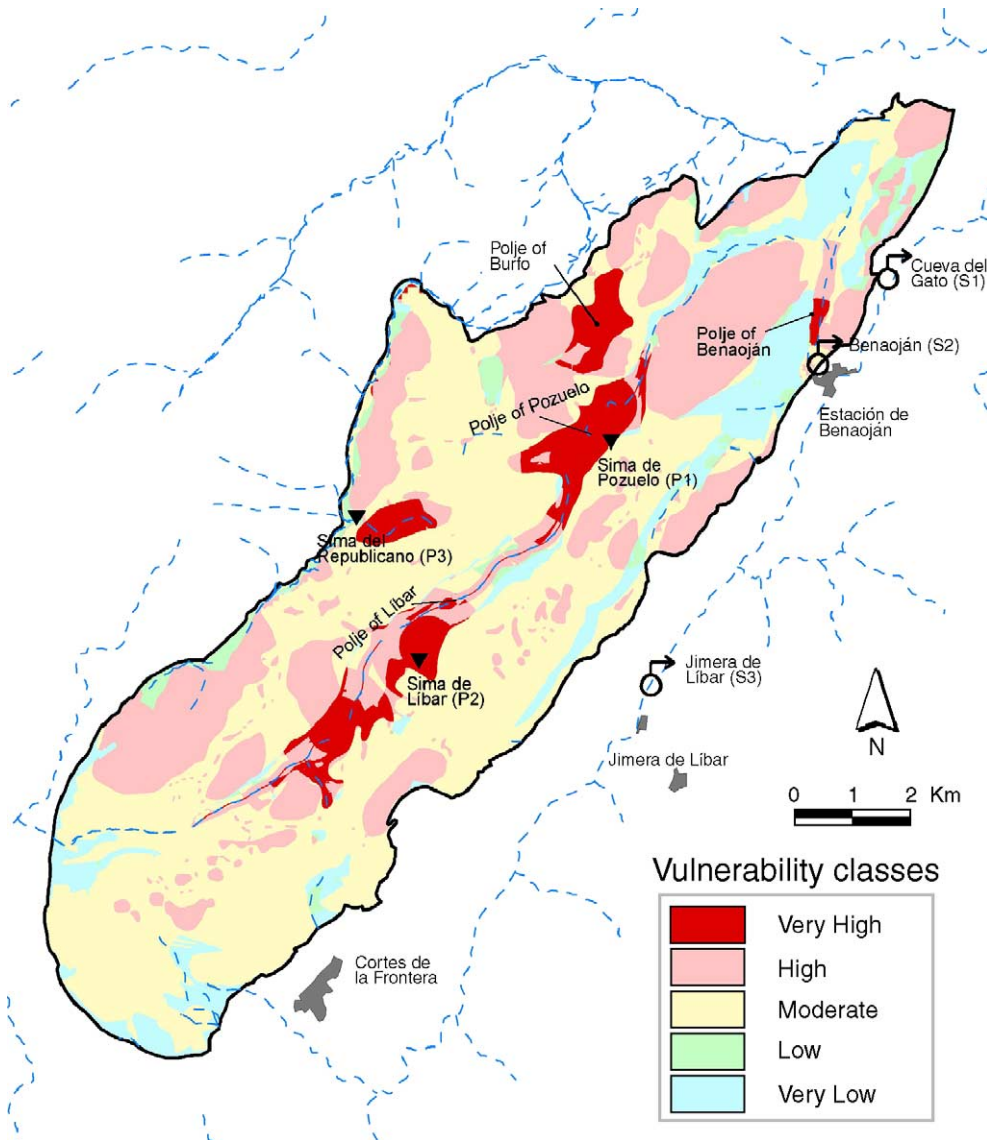


Fig. 7. Specific vulnerability map for aromatic hydrocarbons (BTEX) contamination scenario.

the poljes in the central part of the catchment maintain their 'very high' vulnerability values, due to the lower depth to the groundwater resource in these parts of the aquifer.

## 5. Hazard mapping

The hazard estimation concept as proposed by COST Action 620 considers three factors which control the degree of harmfulness of each hazard (4). First a weighting factor ( $H$ ) defined by the type of hazard concerning the toxicity as well as the properties regarding solubility and mobility of the pollutant is to be assessed. The ranking factor ( $Q_n$ ) enables the comparison between hazards of the same type by the estimation of the relative quantity that can be released. Finally the reduction factor ( $R_f$ ) includes the likelihood of a contamination event to occur with respect to the specific hazard, incorporating factors like technical status or level of maintenance. The hazard index is calculated as follows:

$$HI = H \cdot Q_n \cdot R_f \quad (4)$$

where HI=Hazard index,  $H$ =Weighting factor,  $Q_n$ =Ranking factor,  $R_f$ =Reduction factor.

The Hazard assessment in the Sierra de Líbar starts with the identification of all relevant hazards using the hazard inventory list proposed by the COST Action 620 (De Ketelaere et al., 2004). According to this list all weighting values were acquired, whereas infrastructural information was mostly delivered by topographic maps. The ranking procedure as well as the estimation of the reduction factors was done by field investigations as site-specific information is mostly best determinable in surveying processes. Unfortunately exact values in terms of quantity and the factors leading to a reduction of a certain hazard are rarely available. Therefore estimations including contamination potential size and age of infrastructural installations are often the only possible basis for hazard assessment. In the Sierra de Líbar the factors  $Q_n$  and  $R_f$  were estimated in this manner, as more precise possibilities were not available.

The following hazards were identified in the test site: urbanization with leaking sewer pipes and sewer systems, houses and villages without sewer systems, waste water discharge into surface watercourses, gar-

bage dump, gasoline station, road unsecured, railway line, railway tunnel unsecured, railway station, graveyard, food industry, animal barn and feedlot.

As the main part of the test site is uninhabited the hazards are concentrated on the three villages that are situated in the northern part of the test site, which hosts most of the industrial activities and small farms. The two largest poljes in the central part of the Sierra de Líbar are used as feedlots for cattle, sheep, horses and pigs (Fig. 8).

The Hazard Index classification ranges between very low and low. This reflects only a small portion of the possible bandwidth from very low to very high but the rural characteristic of the test site seems to be well described.

## 6. Risk mapping

### 6.1. Risk assessment

Coming back to the idea of the origin-pathway-target model, risk assessment should describe not only the effect but also the consequences of a contamination to the target. In relation to groundwater protection, the groundwater is defined as the target in the sense of resource protection. In this case vulnerability mapping considers only the starts with the hazards to the groundwater and ends up with the potential impact of pollutants on the target. In this study only the impact intensity is considered whereas risk sensitivity (Hötzl, 2004) was surrender, because crucial data for risk sensitivity assessment of the complex karst aquifer of Sierra de Líbar are not yet available.

Risk intensity assessment logically includes all activities that consider the possible origins of contaminations and all processes that can lead to a reduction of the contaminations along the pathways to the target. The points of potential contamination release are determined within the hazard assessment where all possible origins of contamination and the likelihood of its release are considered. The processes that lead to a reduction of the contamination along the pathway are considered within the intrinsic vulnerability map. Simple matrix relations are used to combine the hazard and vulnerability classifications to attain the risk assessment.

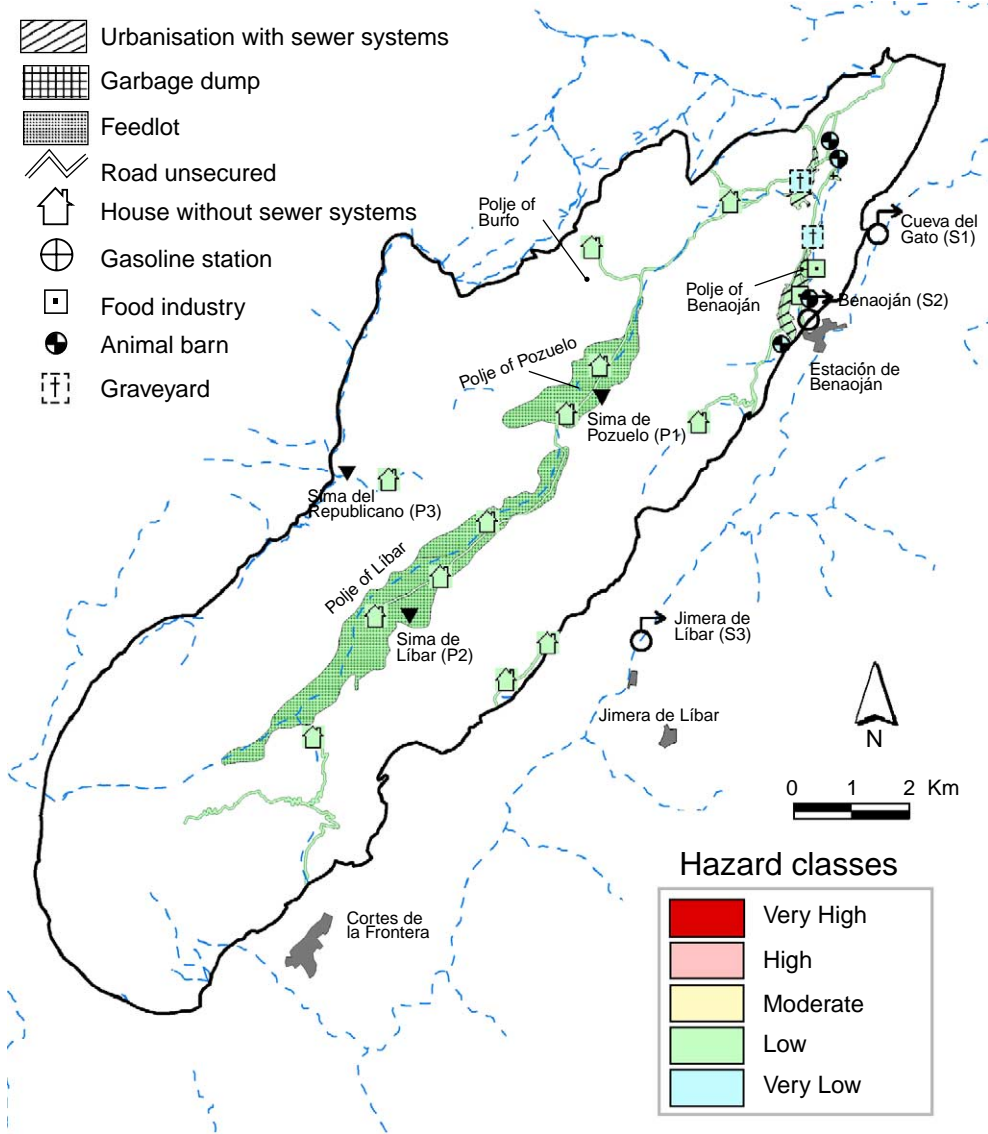


Fig. 8. Hazards map.

6.2. Risk map of Sierra Libar using Hazard map and COP vulnerability map

The risk of groundwater to contamination in the Sierra de Libar (Fig. 9) is characterized by high risk-levels where hazards are situated. The agricultural activities are concentrated in the poljes resulting in high risks due to the high vulnerability of these areas. High risk in a polje and its catchment area is due to the swallow hole, although there are no hazards and is founded in the fact

of contamination disposal through air pollution. These swallow holes are important recharge points of the aquifer where surface flow infiltrates rapidly in the underground bypassing the protective cover. Roads and railway lines have also high potential risk to contaminate the groundwater as they are completely unsecured towards leaking contaminants. The northern part of the test site represents the area with the highest probability of groundwater contamination, as human activities are concentrated in this part.

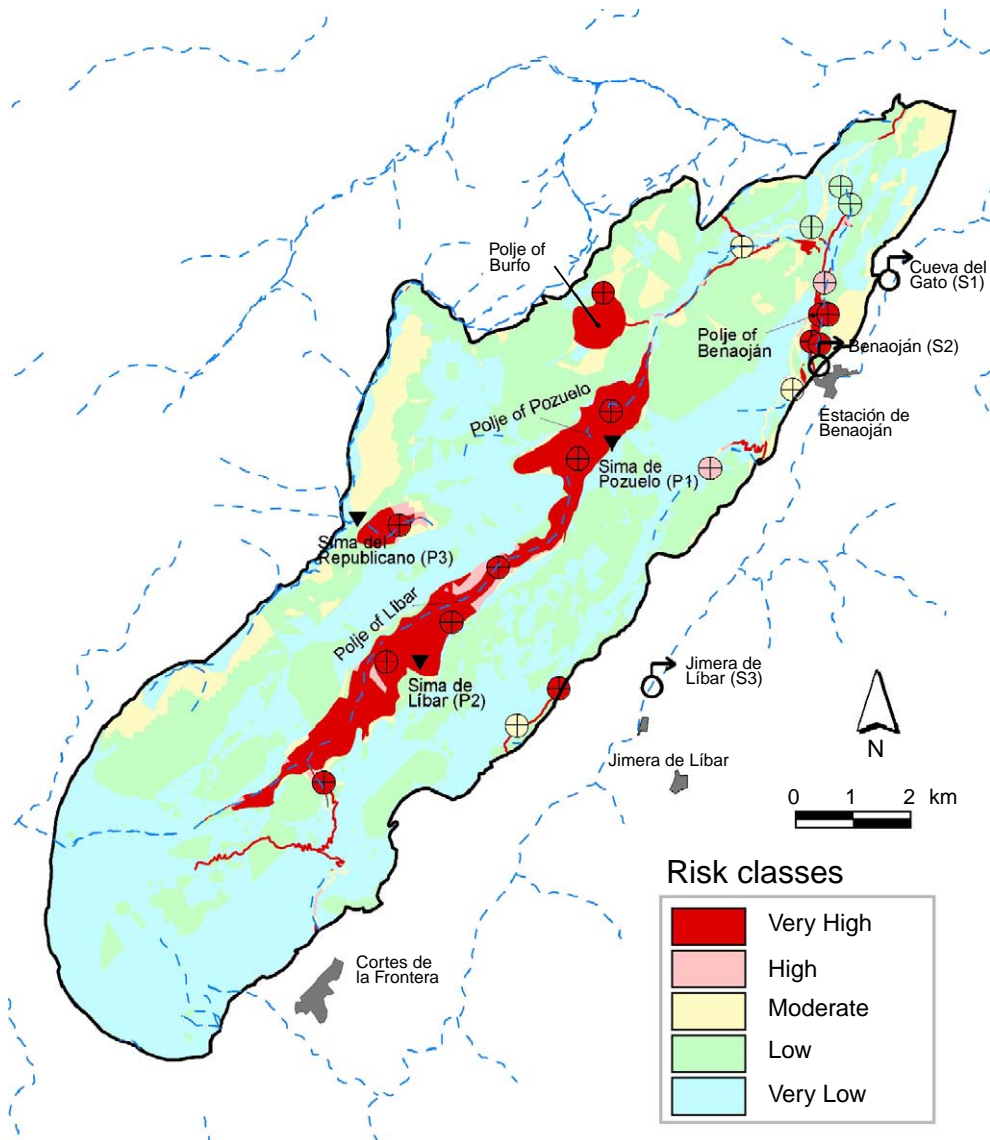


Fig. 9. Risk map made by overlaying the COP vulnerability map (Fig. 3) and the hazards map (Fig. 8). Same caption as Fig. 1.

In the rest of the aquifer the absence of hazards implicate a low and very low level of risk. The differences between risk classes in these areas are due to variations in the vulnerability and the distribution of the hazards (Fig. 8). Therefore, the risk is higher in strongly karstified areas (i.e., karrenfields) than others zones where the karstification is less developed. The relief features of the Sierra are not favorable to develop human activities and the hazards are concentrated on a few points.

## 7. Conclusions

The application of all elements of the Pan-European Approach to groundwater protection (Zwahlen, 2004) in the karst hydrogeological system of the Sierra de Líbar showed the advantages of this methodology, but also revealed some drawbacks.

The two intrinsic vulnerability maps (PI and COP) give largely consistent results. The main difference between the two maps is that the PI method classifies

all areas made of bare karrenfields as zones of ‘very high’ vulnerability, while the COP method differentiates these areas into zones of ‘high’ and ‘very high’ vulnerability, dependent on the thickness of the unsaturated zone. Both methods classify swallow holes and areas generating surface runoff toward sinking streams as zones of ‘very high’ vulnerability. Both methods assign a ‘very low’ to ‘moderate’ vulnerability to areas where the karst aquifer is covered by formations of low permeability, which do not generate lateral flow towards sinking streams.

Compared to previously existing methods of vulnerability mapping, this is a significant progress. Comparative application of previous methods in karst areas often resulted in contradictory and inconsistent results (Gogu and Dassargues, 2000, Goldscheider, 2005). There are two main recharge types in karst areas: autogenic recharge, i.e., infiltration through soil and epikarst, and allogenic recharge, i.e., surface flow sinking into the karst aquifer via swallow holes (Ford and Williams, 1989). Most previous methods fail in areas of allogenic recharge: Areas made of thick impervious formations are often classified as zones of low vulnerability, even if they generate surface runoff towards swallow holes. In contrast, the PI and COP method are applicable for areas of both autogenic and allogenic recharge.

A major drawback of vulnerability mapping is the difficulty to validate vulnerability. COST Action 620 outlined some possibilities how this could be done. The vulnerability maps for the Sierra de Líbar were validated both in a global way (hydrograph analysis, natural tracers and isotopes) and for selected points (artificial tracers). This validation, although incomplete, confirmed both the globally high vulnerability of the karst aquifer system and the extreme vulnerability in the at the swallow holes and in their surface catchment areas.

The specific vulnerability maps of Sierra de Líbar for faecal coliforms and aromatic hydrocarbons (BTEX) illustrate the different behaviors of the particular contaminants, which are associated to land use in this catchment. This is due to the different contaminant properties and their interaction with the individual layers. Low residence times due to preferential conduit flow inhibit microorganisms to be significantly subjected to degradation between land surface and karst groundwater table. Thus, additional

specific attenuation is very poor for faecal coliforms and the specific map resembles to the intrinsic vulnerability map compiled using the COP method. On the other hand, specific vulnerability to BTEX is significantly decreased in practically the whole area, due to the importance of contaminant degradation by volatilization. The Sierra de Líbar application showed that for special purposes it could be worthwhile to produce contaminant-specific vulnerability maps. The user may benefit from the comparability of these maps since they are based on the same intrinsic vulnerability module.

In large parts of the Sierra de Líbar, hazards are absent because extreme karstification (bare karrenfields) makes land use impossible. Most settlements and agricultural activities, and the resulting hazards, consequently focus on the polje floors. According to the COST 620 methodology, these hazards are relatively harmless. However, as some of these hazards are located on areas that frequently generate surface flow towards swallow holes, i.e., highly vulnerable areas, the risk of groundwater contamination is elevated in these zones. It is also possible to combine a hazard map with a specific vulnerability map, in order to produce a risk map showing the risk of groundwater to be contaminated by a specific substance, e.g., the risk of microbial groundwater contamination. However, this was not yet done in the test site.

The results of the tracer test, together with the vulnerability, hazard and risk maps could serve as a scientific basis for sustainable land use planning and groundwater management in the Sierra de Líbar. For example: The intrinsic vulnerability map together with the results from the tracer test could be used as a basis to delineate protection zones for the karst springs. The risk map shows the zones where the groundwater is at risk to be contaminated by human activities. Action should be taken in these zones.

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