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Intrinsic vulnerability mapping for small mountainous karst aquifers, implementation of the new PaPRIKa method to Western Pyrenees (France)

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ABSTRACT

The new intrinsic vulnerability mapping method PaPRIKa is proposed as a tool to assess groundwater protection of small karst systems exploited for drinking water supply purposes in the French Pyrenees. The specific characteristics of the discontinuous carbonate aquifers of mountainous areas are here considered and taken into account into the implementation of the methodology. The Orbe site from the French Western Pyrenees area is chosen as a test site because of the relatively well known structure and behavior of the aquifer system. Steep slopes, extremely developed dissolution features, thin soils and strong dipping of geological formations are the main points to be considered. PaPRIKa method appears as a tool to assess and illustrate both the resource and source vulnerability according to the site specificities provided that appropriate field observations at a relatively high density are carried out. The vulnerability of the resource was assessed for the entire catchment area, while source-orientated mapping was attempted for the catchment area of the main capture work used for drinking water supply.

1. Introduction

In the French Pyrenees groundwater from carbonate rocks are considered as a huge potential resource for water supply to satisfy drinking water needs. In the coming years, these resources will be necessary as a substitution to surface water resources which are constantly decreasing because of the intense agricultural activity within the area and which quality is more and more unable to meet European drinking water standards (Rey, 2007). The development of carbonate aquifer groundwater is planned through the capture of many springs scattered over large areas and mainly concerns the South of the Béarn Region and more precisely the area of the “Chaînons Béarnais”, here considered as a test zone. The discontinuous structure of these reservoirs is a main obstacle to the development and exploitation of groundwater, but since no other aquifer can be tapped in these areas, many communities have decided to improve their knowledge of the main springs of the region. A few of them are already used for drinking water supply, but problems linked to the lack of proper management can lead in some cases to water supply disruption because of quality problems especially during strong rain episodes. The French regulation on potable water quality inherited from the European Water Framework Directive 2000/60/CE and dated from the 23rd October 2000 forces administrations in charge of groundwater management and distribution to pay attention to resource protection. Efficient management is strongly correlated to the proper protection perimeter definition around springs and proactive regulation of land uses over the spring's catchment area (“impluvium”). For water supply managers the objectives are to minimize the potential cost of water treatment and to guaranty the continuous delivery of good quality water to consumers.

Vulnerability mapping appears as a tool to assess karst aquifer vulnerability and has been proposed as a basis for protection zoning and land-use planning (Daly et al., 2002; Zwahlen, 2004).

Eight main karst groundwater vulnerability mapping methods have been used up to now: EPIK (Dörfliger and Zwahlen, 1998; Dörfliger et al., 1999), REKS (Malik and Svasta, 1999); RISKE (Pételet-Giraud et al., 2000); RISKE 2 (Plagnes et al., 2005), PI (Goldscheider, 2005) and the Slovene approach (Ravbar and Goldscheider, 2007); KARSTIC (Davis et al., 2002) and the COP and COP + K method (Vias et al., 2002; Andreo et al., 2009). However resulting vulnerability maps based on these different methods on the same test site often leads to significant differences without carrying out treatment to compare them; the major difference is essentially due to the way of considering the variables related to overlaying layers and the respective applied weighting systems.

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Introduced by Kavouri et al. (2011), PaPRIKa is a new and improved intrinsic vulnerability mapping method derived from previous methods specially dedicated to karst aquifers. PaPRIKa method gives systematically two vulnerability maps: the resource-vulnerability map to be used as a tool for stakeholders in order to control diffuse pollution and to prevent further deterioration of the environment, and the source catchment vulnerability map to prevent contamination from accidental pollution and to help delineating the protection zones for public drinking-water supplies capture works in karst aquifers.

PaPRIKa method was developed having in mind the objective to be affordable in terms of costs, to be technically feasible for consulting hydrogeologists and stakeholders, and to use data easily available such as geological and soil maps, groundwater databases, field observations and technical reports.

The Orbe karst system is one of the nine pilot sites in France where this method was tested and improved. This site can be considered as an edge case and provides an interesting field of application for the vulnerability mapping due to its specificities: the catchment's area is particularly small (5 km^2), the epikarst and the karst network are well developed. The karst system is authigenic, disconnected from any river stream (Rey, 2007). The Orbe aquifer is exploited for the drinking water supply of the city of Arette in conjunction with alluvial groundwater resources.

The goal of this study is to implement the new PaPRIKa methodology to the very specific conditions of small scale mountainous karst aquifers and to discuss the potential adjustments necessary to use it adequately in such conditions.

2. Outlines of the PaPRIKa method

The PaPRIKa methodology is an intrinsic vulnerability mapping procedure to determine the protection level of karst aquifer areas. It is based on four criteria namely the protection (P), the reservoir (R), the Infiltration (I) and the karstification type (Ka). Based on the EPIK method proposed by Dörfliger and Zwahlen (1998) which was updated into RISKE and RISKE 2 methods (Pételet-Giraud et al., 2000; Plagnes et al., 2005; Pranville et al., 2008), PaPRIKa is extensively developed in Dörfliger and Plagnes (2009) and Kavouri et al. (2011).

The intrinsic vulnerability can be defined as a qualitative, relative, non-measurable and dimensionless property, considering the hydrogeological characteristics of an area, but independent of the type of contaminants and the contamination scenario (Vrba and Zaporozec, 1994; Kavouri et al., 2011).

Different from EPIK and RISKE methods, essentially focused on the resource, PaPRIKA relies on an origin-pathway-target model where origin is the location of a potential contaminant release, pathway is the itinerary from the point release to the target, and the target is the spring or the well (Plagnes et al., 2010; Kavouri et al., 2011). When resource protection is considered the groundwater surface is the target and the pathway is the vertical flow through the unsaturated zone. In source protection, the abstraction station whether spring or well is the target and the pathway also includes the horizontal flow within the saturated zone (Daly et al., 2002; Kavouri et al., 2011).

Table 1
Indexes to evaluate the protectiveness (P) of cover layers (from Kavouri et al., 2011).

Index of sinking-streams catchment area characterization (Ca)

Catchment area	Characterizations
Ca1	Highly permeable formations: sand, gravels
Ca2	Moderately permeable formations: altered granites, karstic limestones
Ca3	Low permeability formations: sandstone, conglomerate, magmatic and metamorphic rocks (non altered granites, gneiss, basalts)
Ca4	Very low permeability formations: marls, clays. Areas around temporary streams

Index of soil characterization based on soil nature and thickness (S)

Soil nature defined by 1–3 based on soil texture and % of gravel			
% Gravel	Soil texture		
	Clays	Loam	Sand
0–15%	1	1	2
>15–60%	1	2	3
>60%	2	3	3

Soil index		Soil nature			
		Unknown	1	2	3
Impervious formations		S0	S0	S0	S0
Soil thickness	>5 m	S1	S1	S1	S2
	1–5 m	S1	S1	S2	S3
	60–99 cm	S2	S2	S3	S4
	30–59 cm	S3	S3	S4	S4
	0–29 cm	S4	S4	S4	S4

Index of unsaturated zone characterization, defined by values 1–4 based on its lithology, thickness and fracturing (UZ)

Index of the lithology of unsaturated zone (L_{UZ}) as defined by values 1–3

Lithological index	Description
$L_{UZ}0$	Thick layers of clay
$L_{UZ}1$	Clay, marl, maly limestone (25–35% of clay mineral)
$L_{UZ}2$	Maly limestone (10–25% of clay minerals), limestone in small blocks
$L_{UZ}3$	Massive limestone and dolomite

		UZ thickness		
		<15 m	1–50 m	>50 m
UZ fracturing	Low-moderate	Lithology index + 1	Lithology index	Lithology index
	Significant	Lithology index + 1	Lithology index + 1	Lithology index
	Tectonic faults	4	4	4

Index of epikarst characterization (E)

Epikarst index	Description
E1	Perched aquifer, with productive boreholes and high piezometric level
E2	Epikarstic aquifer, laterally continuous with temporary springs characterized by a flow rate about 1L/s or more, capacitive function verified
E3	Epikarstic aquifer with perched springs of low flow rate and limited lateral continuity; limited delay effect
E4	No epikarst

PaPRIKa is a GIS-based methodology where information is summarized on a bi-dimensional basis for each parameter before a final calculation of both resource and source vulnerability indexes.

The protection of the aquifers (Pa) is based on a karst conceptual model considering both structure and hydraulic functioning of a karst aquifer. Two categories of factors are considered: the *structure group* with protection (P) and reservoir (R) factors and the *functioning group* with infiltration (I) and karstification (Ka) factors. Each factor is mapped independently and classified into five classes represented by a symbolic five-color scale: red for a very low level of protection (or very high vulnerability) and blue for a very high degree of protection (very low vulnerability).

2.1. P factors

Protectiveness contains all surface and subsurface features that can provide a significant delay to infiltration into karst aquifers, such as (Table 1):

- catchment areas of sinking streams (Ca)
- soil cover (S)
- unsaturated zone (UZ)
- epikarstic aquifer (E)

The final P map is the result of the combination of the sub-factors listed above. In each cell of the grid in which the test site is subdivided of the P map, the most protective value amongst all P sub-factors (Ca, S, UZ, E) is retained to evaluate the effectiveness of the protective cover layers.

2.2. R and Ka factors

PaPRIKa considers separately the type of (Table 2):

- the geological reservoir defined by the lithology and fracturing of carbonate rock (R)
- the karstification development of this reservoir (Ka) based mainly on the hydrogeological behavior of the system (hydrograph, chemograph, velocity of dye tracing tests) and the existence of karst conduits network

Table 2
Indexes to evaluate R and Ka factors (from Kavouri et al., 2011).

Index of rock reservoir characterization (R)	
R1	Low influence on vulnerability: marly limestones (25–35% of clay minerals) and chalk with a low fracturing degree
R2	Moderate influence on vulnerability: marly limestones (10–25% of clay minerals), highly fractured chalk, limestones and dolomites affected by homogeneous fracturing, limestones
R3	High influence on vulnerability: karstic and fractured massive limestones/dolomites, thick layers of limestones/dolomites with a dip higher than 45° enhancing flow towards the spring
R4	Very high influence on vulnerability: karstic network (drains and cavities) that are well known, faults zones when playing a role in the underground flow
Index of karstification degree (Ka)	
Ka1	Catchments <10 km^2 with low mean annual discharge where the karst system is characterized by a low functionality behaviour (low variability of hydrograph and chemographs) and there is an absence of indications of fast groundwater flow
Ka2	Catchments >10 km^2 without water losses, having low functional behaviour or a limited catchment around a borehole intercepting fissured media + complex karst systems such as defined by Mangin (1975)
Ka3	Catchments >10 km^2 or limited catchment around a borehole intercepting fissured media. Karst systems with high level of functionality which do not present water losses; or karst systems with low level of functionality which present water losses. The underground drainage network is well developed with a presence of a moderate network connected to the surface. Fast transit velocity demonstrated with tracer tests (50–100 m/h). Domain 2 of Mangin's classification (Mangin, 1975)
Ka4	Catchments < or >10 km^2 + karst systems with water losses. Underground drainage network very well developed with the presence of large conduits connected to the surface. High level of functionality. Very fast transit velocities demonstrated with tracing tests (>100 m/h). Domain 3 or 4 of Mangin's classification (Mangin, 1975)

Table 3
Index of infiltration conditions (I) from Kavouri et al. (2011).

I0	Slopes higher than 50% inducing major runoff and a negligible infiltration
I1	High slopes (15–50%) in favor of runoff
I2	Moderate slopes (5–15%) + areas where the runoff is limited in carbonate terrains (dry valleys, karren-fields)
I3	Low slopes (0–5%) where infiltration dominates the runoff + dolines and poljes + karren fields with high vertical development (cracks of meter size).
I4	Swallow holes and sinkholes with concentrated infiltration because of stream losses + their catchment areas

2.3. I map

- *for resource vulnerability mapping*: I factor distinguishes concentrated from diffuse infiltration and is considered as the main factor in determining intrinsic vulnerability (Kavouri et al., 2011). I factor is defined by various parameters like slope gradient and karst features which allow concentrated infiltration through sinkholes, dolines or karrenfields. The I factor allows assessing the possible sensitivity of groundwater due to bypassing the protective layers by surface and subsurface flows (Table 3).
- *for source vulnerability mapping* (I_{source}): to get the source-vulnerability map, the first three factors remain the same (P, R, Ka) while a new I (I_{source}) factor is introduced and mapped.

The previously defined I factor remains identical where horizontal flows and underground flow paths are considered. The I_{source} map corresponds to the addition of transit time isochrones to the I map. These isochrones are defined from the source point by coupling velocity and recovery percentage data from the available tests with karst conduits maps (or any kind of similar data indicating hypothetical groundwater flow paths from speleological surveys) (Kavouri et al., 2011). Since information on transit time in the saturated zone is not generally available, the time from the surface to the source is considered. Four isochrones were defined (12, 24, 36 and 48 h) in the PaPRIKa methodology corresponding to the different intervention delays possible according to different scenarios for drinking-water supply in case of accidental pollution (Kavouri et al., 2011). The aim of this procedure is to highlight the zones where concentrated infiltration and rapid horizontal transfer toward the capture is the most probable. For such areas, the class of the maximum senisitivity for groundwater (I4) was preserved only in the areas within the capture works and the proposed isochrones lines (I_{source}4). A restricted area around the karst conduit has also been classified as very high sensitivity even when no karst features are noticed on surface.

In areas located outside the isochrones lines in the catchment, the maximum sensitivity is retrograded to “high sensitivity” (I_{source}3). The source-vulnerability grid is then recalculated by replacing the resource I map with the I_{source} map. Neither the maps of P, R and Ka factors nor the weighting factors are modified.

2.4. Resource and source vulnerability calculation

Calculating the resource and source vulnerability maps (V_g) is obtained from the combination of the four maps in a grid according to the following relation:

$$V_g = i\mathrm{I} + r\mathrm{R} + p\mathrm{P} + k\mathrm{Ka} \quad (1)$$

The I or I_{source} factor is used to calculate resource or source vulnerability, respectively. The sum of the affected weight (i, r, p, k) is equal

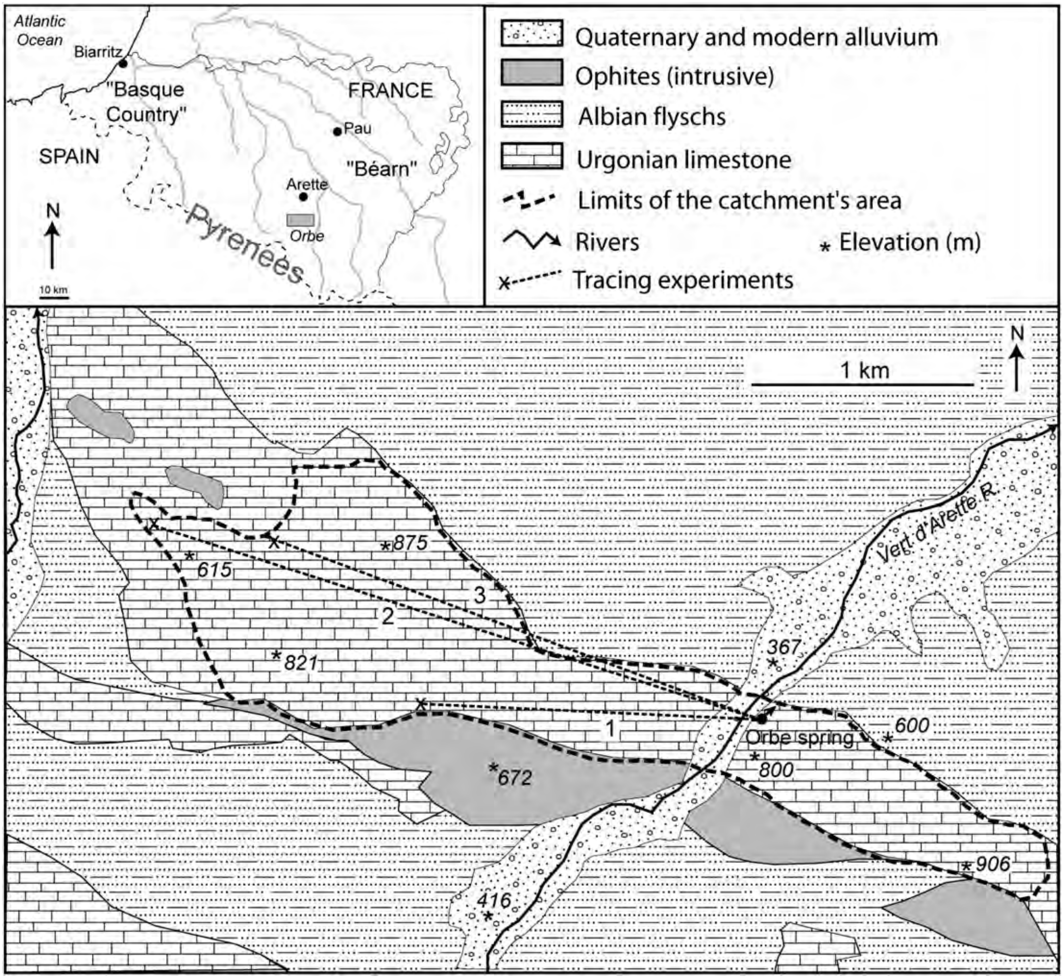

Fig. 1. Location of the spring and simplified geological map of the study area. The numbering of the tracing experiments refers to Table 5.

to 1. The weighting values comply with an empirical rule, based on personal experience and judgment of the hydrogeologist (Kavouri et al., 2011), this rule considers that the global vulnerability is mainly associated with the two function criteria (I and Ka), for which the sum of the weights corresponds to 50–65% of the total weight, whereas the sum of the weights of the structure criteria (P and R) reaches 35–50%. More details about the rating equation can be found in Kavouri et al. (2011).

Different weighting values combinations have to be tested, but the final intrinsic vulnerability map has to be chosen according to the following rules: (i) all the most vulnerable karstic features (sinkholes, dolines, karrenfields) have to appear on the final map as "high sensitivity" areas,

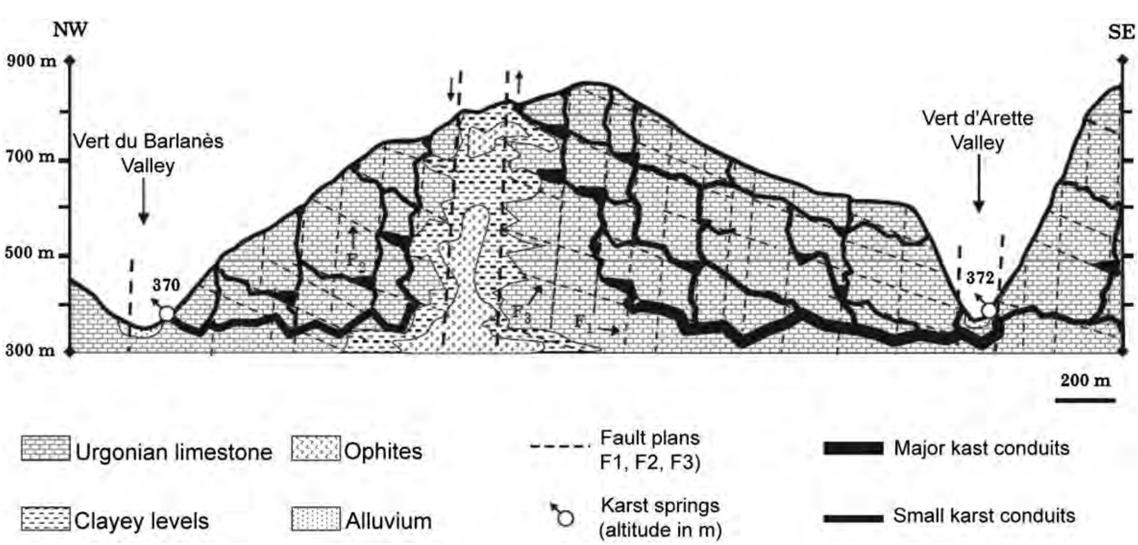

Fig. 2. Schematic cross section through the Orbe Spring aquifer system, modified from Rey (2007).

Table 4
Coordinates and characteristics of the test sites springs.

Spring (location)	X	Y	Z (m.a.s.l.)	Discharge[a] ($m^3\ h^{-1}$)	Catchment size (km^2)
Orbe Spring (Arette)	43°04′23″N	0°44′33″W	376	180	2.4

[a] Average over the years 2005–2006 (Rey, 2007).

(ii) no major discrepancy between the final map and the different individual maps should appear and (iii) the final map should not show any discrepancy with the information gathered from the field investigations.

3. Study area, description of the test sites and field approach

The study area is located in the south-western part of France, around 50 km South from Pau city in the Western Pyrenees region (Fig. 1). The "Chaînons Béarnais" area constitutes the first piedmont relief of the Pyrenees coming from the North. The physiography of the region is an alternation of three semi-mountainous strong horizontal reliefs with depressions in between constituting the so-called "Chaînons Béarnais". These reliefs can reach an elevation of about 2050 m a.s.l. with an average of 1200 m a.s.l. The "Chaînons Béarnais" are crossed through by three main rivers, the Vert d'Arette River, the Gave d'Aspe River and the Gave d'Ossau River, which all flow from South to North and reach the Adour River Valley.

The geology of the "Chaînons Béarnais" structure is characterized by the abundance of carbonated formations from Jurassic to Cretaceous periods mainly composed of pure limestone with Urgonian facies, dolomitic limestones and dolomites (black dolomites from the Jurassic). These hard rocks constitute the three major reliefs of the area and often lye in sub vertical position; between them, west–east oriented valleys correspond to Albian marls and flysch from the Upper Cretaceous (Figs. 1 and 2). The actual geometry of the deposits results from the Pyrenean orogenesis during the Eocene and is attributed to compressive movements; as a result, the structure of the "Chaînons Béarnais" can be interpreted as a succession of tilted blocks with broken folds in between. During the Mesozoic, the region was under many extensive–distensive phases entailing the intrusion of magmatic rocks like lherzolite and ophite (doleritic basalts) within Triassic and Cretaceous sediments. These ultramafic igneous rocks are always wrapped in versicolor and gypseous more or less endured dolomitic marls attributed to Keuper by some authors (Azambre et al., 2004; Canérot et al., 2004; Rapaille et al., 2004) or to an hydrothermal layer resulting from the intrusion within the carbonates by others (Fabre et al., 2000; Desreumaux et al., 2002). Without paying too much signification to the exact origin of these formations it must be pointed out that it will play a major hydrogeological role in the definition of the low permeability limits to the aquifers (Rey, 2007; Jaunat et al., 2008).

The average amount of rainfall in the "Chaînons Béarnais" is about 1450 mm per year (average from 1980 to 2004). This quite important amount can be explained by the proximity of the Atlantic Ocean which brings numerous cool and humid air masses and by the Pyrenees Mountains which play the role of a climatic barrier. The climate in the study area can be considered as oceanic attenuated and is characterized by very rainy autumn and beginning of winter, rainy springs and relatively dry summer with sometimes intense storm episodes. Temperatures are cool in winter (4.9 °C) and mild in summer (18.7 °C), the annual average temperature is close to 11.2 °C (average from 1995 to 2005). The most favorable period for recharge processes is the beginning of winter and the end of spring. The average evapotranspiration calculated from 2004 to 2005 is around 970 mm. On the same period of calculation, the average amount of effective recharge to the local aquifers can be estimated about 595 mm per year i.e. approximately 40% of the total amount of rainfall.

3.1. Orbe spring

The Orbe spring is located at the western end of the third "Chaînon Béarnais", close to the village of Arette (Table 4). The general orientation of geological structures is N130 (Fig. 1). The almost vertical structure of the chaînon is made of approximately 250 m of sediments from Trias to Cretaceous and more precisely from Aptian to Albian. This structure is cut by the Vert de Barlanès River to the West and the Vert d'Arette to the East. The spring appears at the interface between Urgonian limestone and the Albian marls on the right bank of the Vert d'Arette River (Fig. 2). The limestone massif extending

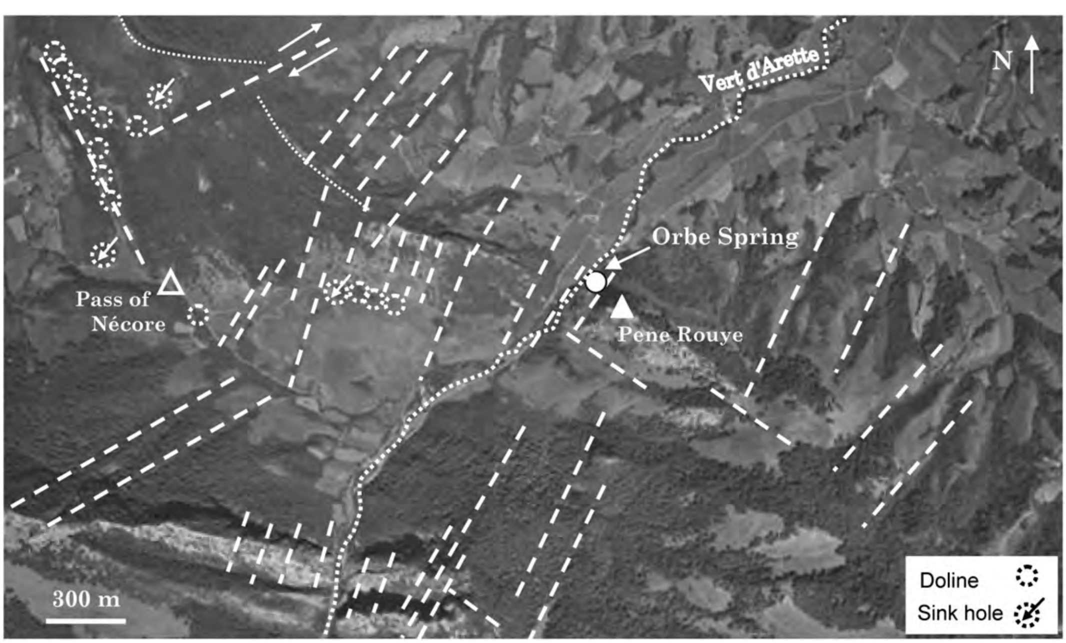

Fig. 3. Map of the karstic features and lineaments recognized on the Orbe catchment area, modified from Rey (2007).

west–east is limited to the South by an important intrusion of ophite. Between ophite and limestone, a continuous layer of sediments composed of limestone and gypseous marl occurs. From the hydrogeological point of view these sediments constitute a main obstacle to groundwater flow which shields groundwater from flowing southward. The Cretaceous flyschs in the North, made of marly deposits of very low permeability are the boundary of the Orbe aquifer. Numerous paleo-karstic features can be seen on the Urgonian cliffs overhanging the Orbe spring. At the southern interface between the hydrothermal layer and Urgonian limestone many sink holes and other abyss of various shapes and importance can be observed, clearly underlining the extreme development of dissolution processes in the whole carbonated reservoir. Many other surface dissolution features like lapiés, dissolution rills, clints and grikes can be observed all over the area (Figs. 3 and 4). The Orbe spring has been recognized as the main outflow of the aquifer, but it must be pointed out that the emergence should be more considered as a diffuse seeping area than as a punctual exsurgence. Many temporary springs, functional only during high water period, can be observed in the immediate vicinity of the main flow. The recharge

Fig. 4. Intense faulting and paleo-karstic features seen on the Urgonian cliffs overhanging the Orbe Spring.

Table 5
Main tracer tests performed on the Orbe spring catchment (from Rey, 2007).

Test nb.[a]	Injection point	Distance to the spring (m)	Tracer	Velocity of the tracer (m/h)	Arrival time after injection (h)	Restitution of the tracer (%)
1 (01/14/2004)	Sinkhole x = 43°04′18.06″N y = 0°45'28.53″O z = 660 m	1300	Sulforhodamine G	50	26	2.0
2 (01/16/2004)	Sinkhole x = 43°04′25.82″N y = 0°46′13.40″O z = 600 m	2550	Uranine	52	49	32.8
3 (07/29/2005)	Sinkhole x = 43°04′32.92″N y = 0°46′08.43″O z = 680 m	2350	Uranine	49	48	40.7

[a] Test numbering refers also to Fig. 1.

Fig. 5. Pictures of the epikastic features and soils over the Orbe spring impluvium. a) flanks of the hill, b) top of the Orbe hill.

processes to the aquifer are mainly diffuse and the Orbe karst aquifer can be considered as an autogenic system with no relationship with the Vert d'Arette River (Rey, 2007). Detailed geophysical investigations via electric prospecting have managed to localize a major karstic conduit a few meters in depth close to Orbe spring, this conduit is supposed to be the main collector to the exsurgence (Rey, 2007).

Land uses over the study area are mostly rural with deciduous forests on the highest reliefs and pasture lands in the valleys. Soils are mainly thin brown soils developed on carbonate rocks and most of the time filling more or less developed lapiez.

Several dye tracer tests (uranine and sulforhodamine G) were carried out from sinkholes at the interface between limestone and clay boundaries indicating for most of them a direct connection between karst conduits to the Orbe spring (Rey, 2007). These dye tracer tests results are displayed on Table 5 and Fig. 1.

The Orbe spring is also the main water supply source of the city of Arette and is exploited since the 1950s for this purpose.

Over the field area, more than 100 spots have been selected, assessed, ranked and indexed according to the PaPRIKa methodology. Only 30 spots have been accurately geo-referenced because of technical limitation of the GPS system caused by the density of the forest and steepness of the slopes. The major difficulty over the Orbe spring catchment area is the difficulty in terms of access to the different parts of the catchment because of steep to very steep slopes and the absence of passable roads.

The different maps have been designed under a GIS application using the finest Digital Elevation Model available on the area with a mesh of 25 m square cells.

4. Implementation of the PaPRIKa method to mountainous karst aquifers

For the whole area, the resource PaPRIKa map was based on the four proposed factors described in the following.

4.1. P map

The P map was worked out based on the combination of only three sub-factors (UZ, E and S). It was not necessary to generate the Ca map since no sinking-stream catchment occurs on the area. Hence we focused only on the protectiveness of the karstic features. Unsaturated zone protectiveness (UZ) of the Orbe karst system consists of massive layered limestone affected by an important faulting (Fig. 4). The thickness of the unsaturated zone is superior to 50 m (Rey, 2007) except in the Vert d'Arette River Valley where limestones are strongly eroded; in this valley a UZ = 4 index was attributed. In the rest of the catchment the UZ = 3 was attributed.

Protectiveness of the epikarstic aquifer (E factor) was estimated from field observations (Fig. 5). On the whole area, the development of the epikarst is homogeneous. It can be described as very well developed and very thick. Even if the observation of the epikarst over the entire area was not easy to carry out, field work has clearly

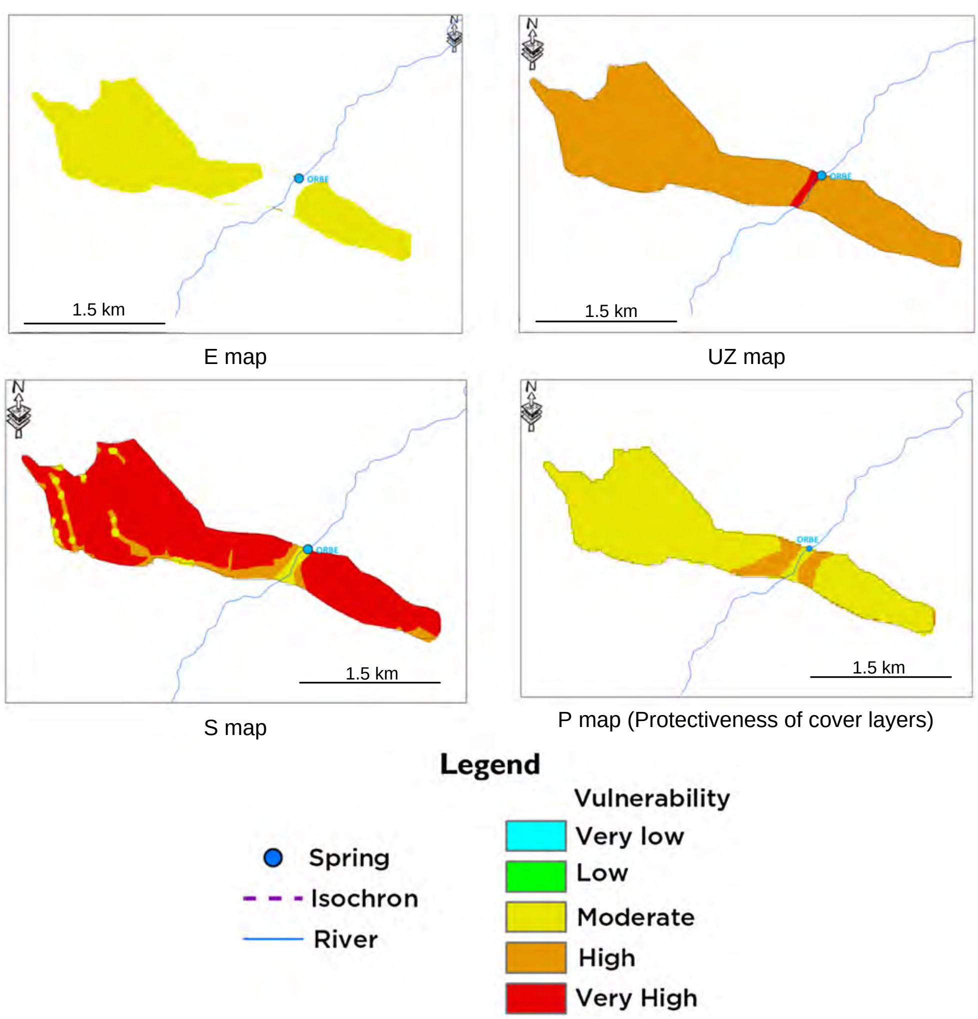

Fig. 6. The P map and the different criteria E, UZ and S for the Orbe karst aquifer.

demonstrated the existence of the epikarst at any place within the catchment area. In the vicinity of the Vert d'Arette River Valley steep slopes the epikarst was not characterized and is omitted on the E map. For the rest of the area, an E2 index was assigned. Even if dissolution features like karrenfields are well developed over the major part of the catchment area, which can be considered as adverse to the protection of the reservoir, the study carried out by Rey (2007) has clearly demonstrated the existence of a functional epikarst. The behavior of the epikarst is considered as complex and closely linked to the hydrologic antecedent conditions of the system. Hence, the protectiveness of the epikarst can be considered as maximum after dry periods and minimum during the most rainy periods (Rey, 2007).

Finally, the protectiveness of the soil-cover factor (S) was assessed. Soil is rarely present at the Orbe karst surface and the contribution of this factor to the protection mapping is thus limited. An index of S4 was then attributed. Where some soil was present and enough developed like in the bottom of valleys or depressions a S2 or S3 index was chosen depending on the thickness of the soil layer (Fig. 5).

Maps of each sub-factors and the final P map are shown in Fig. 6. The most protective factor of each cell is represented on the final P map. In the case of the Orbe system it appears that the protectiveness of the epikarstic aquifer is largely dominant as also observed on other test sites (Kavouri et al., 2011).

4.2. R map

The aquifer is homogeneously made of densely fractured Urgonian limestone. The limestones show a strong dip superior to 70° towards the South. So the whole area is characterized by an attribute of R3. According to Rey (2007), in the vicinity of the Vert d'Arette River Valley, well developed karstic conduits were identified by geophysical investigations and dye tracer tests. A R4 index was then assigned (Fig. 7).

4.3. I map

The assessment of the I vulnerability map appears more difficult to carry out. I parameter is supposed to be gathered from the evaluation of slopes mapping of the occurrence of sinkholes and surface karstic features. The slope mapping has been obtained thanks to a very detailed field slope gradient determination. Some difficulties have arisen from karst features mapping. For example, the karrenfields are widely present all over the area, but show different degree of development with the elevation. In the lowest zones, the karrenfields are shallow and poorly developed; in the highest zones, they are well developed, with deep dissolution features (more than 10 m in depth) that can be assimilated to sinkholes. Field survey also showed that most of the 15 dolines and sinkholes take place along major lineaments more or less parallel to the major structure of the aquifer i.e. N100°E to N130°E direction, with long and narrow depression zones. Finally for the setting of the I map, the following index have been selected: I4 for sinkholes and their immediate vicinity, I3 for dolines, depressions and well developed karrenfields, I2 for the less developed lapiaz and mild to important slopes, I1 for very steep slopes (Fig. 7).

4.4. Ka map

The Ka index of the Orbe karst system was classified as high (Ka3) over most of the area. It is supported by the fact that this system is considered as autigenic with a very high degree of karstification. Based on information from dye tracing tests and geophysical surveys, further zoning of this criterion was attempted. Areas assumed to be directly connected to the main underground drainage axes close to the Vert d'Arette River Valley and close to the Orbe spring were mapped with the Ka4 class (Fig. 7).

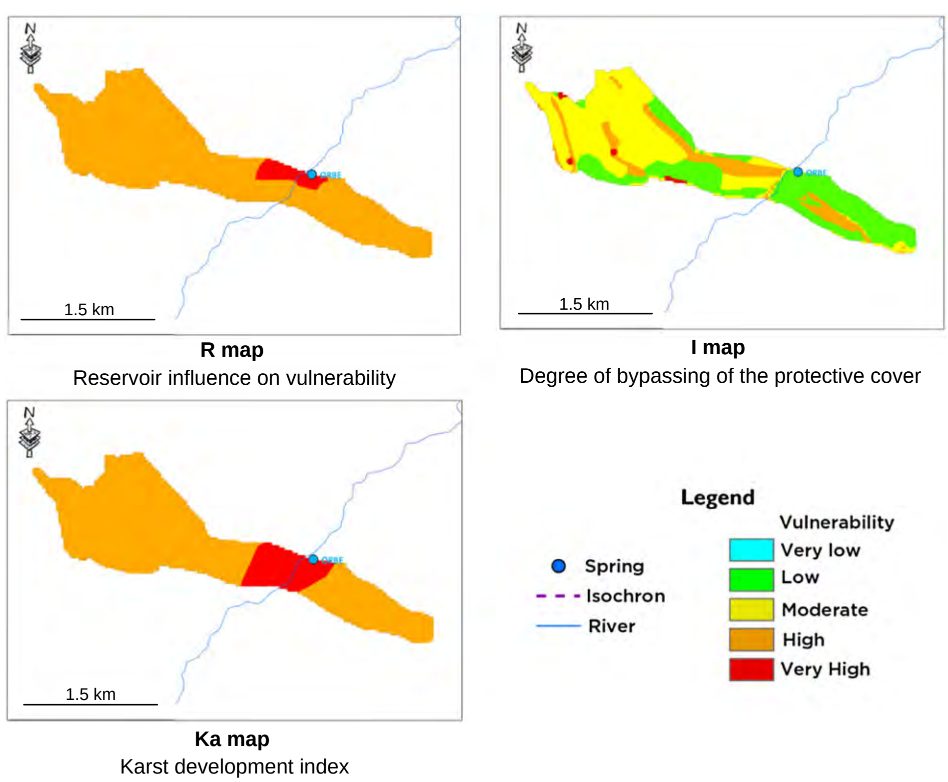

Fig. 7. R, I, Ka maps characterizing the intrinsic vulnerability of the Orbe karst system.

5. The intrinsic vulnerability map of the resource

For the calculation of the intrinsic vulnerability map, six weighting combinations were tested according to the rating scheme presented in the method outlines (Fig. 8).

Four maps among the six generated (1, 2, 3 and 5) give very similar results with vulnerability varying from moderate to very high. The area around the Orbe spring is assessed as very vulnerable. Sinkholes are clearly marked on two map (1 and 3) corresponding respectively to a 0.4I + 0.2R + 0.2P + 0.2Ka and 0.4I + 0.15R + 0.2P + 0.25Ka combination. The maps 2 and 5 are unable to restitute the location of the sinkhole and hence should be rejected. Maps 1 and 3 are similar even with a weighting of the I criteria superior to the rating scheme proposed (0.5 instead of 0.3 to 0.4) and with a lower value for the Ka criteria (0.1 instead of 0.2 to 0.3). These maps tend to show an average to high vulnerability and clearly underline the very high vulnerability attributed to the sinkholes, dolines and well developed karrenfields. Two maps can be considered as good assessment of the intrinsic vulnerability of the resource, map 1: 0.4I + 0.2R + 0.2P + 0.2Ka and map 4: 0.5I + 0.2R + 0.2P + 0.1Ka.

This last combination gives the most realistic solution and is also the combination usually retained for the other test sites where PaPRIKa was standardized (Dörfliger and Plagnes, 2009).

These tests show the importance of testing various combinations of scoring in order to set up maps able to restitute the most discriminating karstic features like sinkholes.

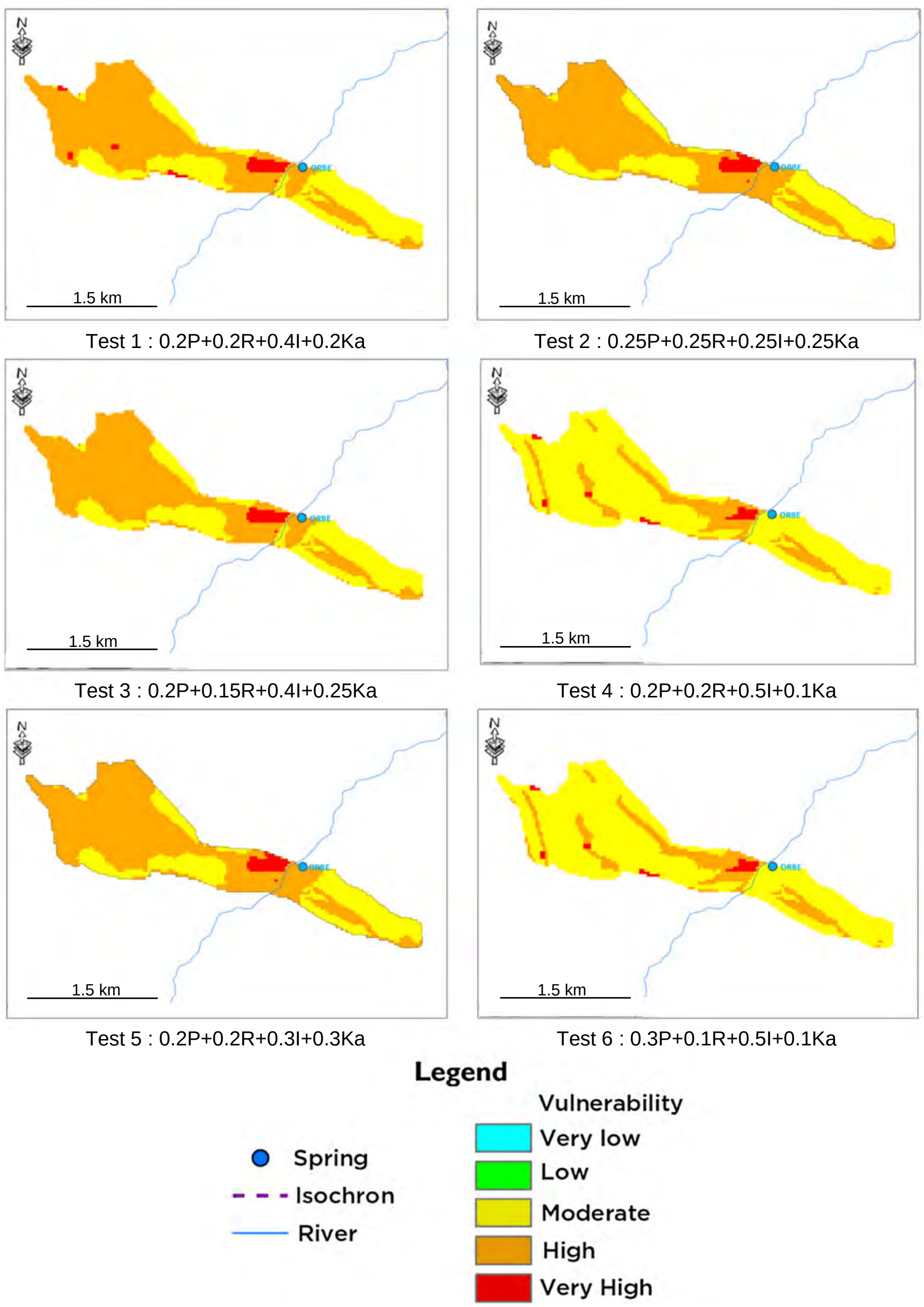

Fig. 8. Intrinsic vulnerability map for the resource of the Orbe spring.

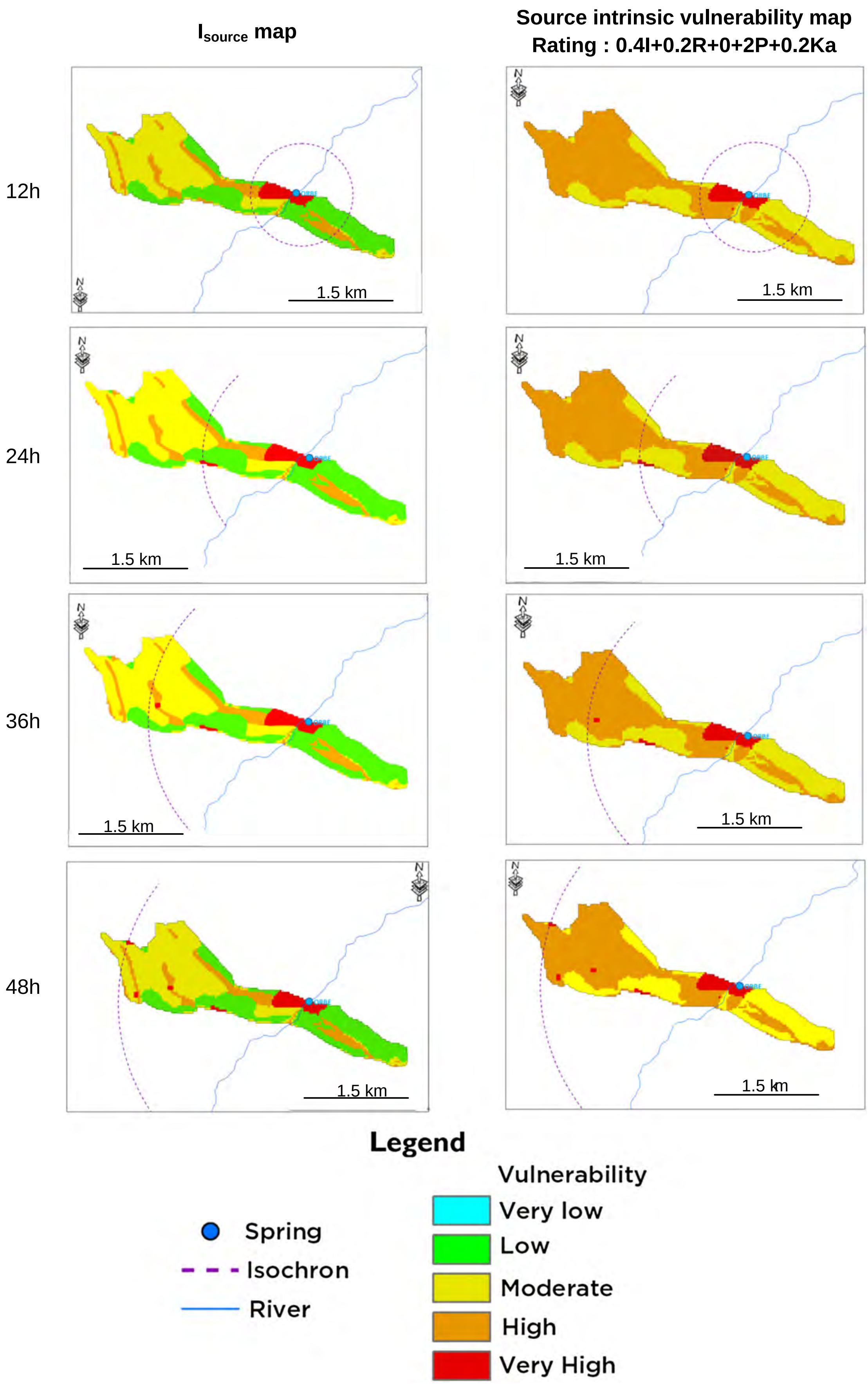

Fig. 9. I_{source} maps and the corresponding source-vulnerability maps for the 4 isochrones (12, 24, 36, 48 h) considered by PaPRIKa methodology.

6. Spring vulnerability mapping

The intrinsic vulnerability for the capture work of the Orbe spring was also assessed. Four I_{source} maps have been generated considering the 12, 24, 36 and 48 h isochrones which were determined based on the results of dye tracing tests carried out by Rey (2007). The Table 5 displays the location and results of the main dye tracing tests available for the Orbe spring catchment. Main karst conduits identified by geophysical investigations in the vicinity of the Vert d'Arette River are considered as highly vulnerable zones. The different tracer tests carried out by Rey (2007) have clearly demonstrated the absence of any noticeable hydraulic link between the Vert d'Arette River and the Orbe spring. Three dye tracing tests, all carried out during high water stage, can be used to assess the I_{source} vulnerability map (Table 5). These tests are located in the western part of the catchment at a distance varying from 1 to 2.5 km from the Orbe spring. The average velocity of groundwater within the system is about 50 m/h for recovery percentages of the tracer up to 41% (Table 5). The different maps for the four isochrones are displayed on Fig. 9. One dye tracing test is also considered here but with a very low recovery rate of about 2% explained by adverse climatic conditions during the test (Rey, 2007). This latter has also proven a hydraulic link between the southern boundary sinkholes and the Orbe spring.

The pattern of the isochrones is based on the information provided by these three dye tracing tests, also considering that the recovery rate of the dye tracing test no. 3 is higher (more than 40%). No dye tracing test is available for the right bank of the Vert d'Arette River.

The four intrinsic vulnerability maps generated for the Orbe spring allows to distinguish 3 main classes of vulnerability and strongly highlights a very highly vulnerable area in the immediate vicinity of the spring. In this area the karst conduit network is very dense as recognized by geophysical surveys. When the intervention time is longer than 12 h (Fig. 9), the sinkholes are integrated into the vulnerability map of the spring. The vulnerability map generated for an intervention time of 48 h highlights the vulnerable areas around the sinkholes, areas that should be protected in priority for the sustainable exploitation of the spring. These areas as well as the area immediately around the spring have to be protected and included into a first class protection zone (immediate protection zone). The area with highly vulnerable index will be classified as second class protection zones (close protection zone) and the rest of the catchment area can be considered as a third class protection zone (remote protection zone) according to the French legislation on the protection zone of drinking water supply catchments.

These maps will help the stakeholders to propose the best adapted-protection zoning to protect the catchment from accidental pollution.

7. Conclusions

The new PaPRIKa method proposed by Kavouri et al. (2011), for resource and source-vulnerability mapping in karst aquifers has been developed, updating previous specialized methods and taking into consideration the European guidelines. The PaPRIKa method, designed for intrinsic vulnerability assessment, is based on structural and hydraulic behavior factors according to karst conceptual model proposed by Mangin (1975). It provides resource-vulnerability maps as well as source-vulnerability maps by estimating the horizontal travel time and modifying the I factor.

The factors P and R characterize the structure of the karst aquifer. The P factor combines various criteria such as soil cover, epikarstic aquifer, unsaturated zone and the surface stage of stream water losses in terms of water catchment. The characterization requires pedologic and geological data. The epikarstic aquifer is characterized using field outcrop observations as well as hydrogeological observations (perched spring, wells in epikarst layers). This mapping is not easy and requires good hydrogeological field observations. The R factor is determined using a geological map and geological outcrop observations, as well as a borehole database. This latter factor had to be adapted to the specific conditions of mountainous karst systems like Orbe in the sense that the very steep character of the limestone outcropping and the important dipping of about 70° oriented in the direction of the flow to the spring was considered as a major vulnerability factor. It was then necessary to considerer the R factor as highly to very highly vulnerable over the whole impluvium.

The Ka and I factors characterize the system's hydraulic behavior. Even though the I factor is relatively easily determined using the digital elevation model and field observations, the Ka factor requires detailed information related to discharge time series and physical and chemical time series, as well as dye-tracer-test information and data on the size and development of the karst conduit network. If all these detailed data are not available, which is often the case, the model can be simplified. However, providing full explanations of the values chosen for the Ka factor remains essential (Kavouri et al., 2011).

As the Orbe spring is a relatively small mountainous karst system, it provided the opportunity to test the method in a spatially very different context and hydrogeological environment, mainly because of the steep character of its impluvium. It appears that all the impluvium has to be protected but different levels of protection can be organized according the occurrence of important karst features like sinkholes of major faulted areas around the spring. The highest level of protection has then to be maintained along the southern border of the Urgonian limestone at the interface with the ophite intrusions since most of the sinkholes can be located in this area. This zone can be directly linked to the immediate vicinity of the spring or considered as a satellite area. An intermediate level of protection has to be guaranteed of the places where the epikarst is the most developed and can act as a direct transfer zone towards the saturated zone of the aquifer.

In the future, it is necessary to carry out further field investigations, especially in terms of dye tracing tests, to allow a better estimation of the areas where the fastest circulations of groundwater are observed.

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