Environ Geol (2007) 51: 701–706
DOI 10.1007/s00254-006-0382-2

ORIGINAL ARTICLE

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Hydrogeology and vulnerability map (Epik method) of the "Supramonte" karstic system, north-central Sardinia

Received: 9 October 2005
Accepted: 23 May 2006
Published online: 9 August 2006

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Abstract The Supramonte limestone complex, of Jurassic–Cretaceous age, lies within the municipal borders of Urzulei, Oliena and Orgosolo (north-central Sardinia). For the most part, the Supramonte groundwater drains towards the outcrops in the northernmost part of the massif. A minor, almost negligible quantity of water drains towards a series of outcrops along the edge of the carbonate structure, with numerous subaerial and submarine springs. The groundwater in the entire system represents one of the most important water resources in Sardinia, especially for drinking purposes. Taking into consideration the development of karst cavities, permanent groundwater reserves were cautiously estimated to be at least 144 Mm^3. Intrinsic vulnerability to pollution has been assessed by means of the EPIK method.

Keywords Karst aquifer · Groundwater · Vulnerability · GIS · Sardinia

Introduction

The karst system of the Supramonte ("highland") covers a surface of 110 km^2 in the north-central part of Sardinia, with in the municipal borders of Urzulei, Oliena and Orgosolo. If rationally developed, its groundwater could be used during occasional periods of drought to satisfy the increased drinking water demands of most villages of the Ogliastra–Baronia area. Especially the northwestern part of the aquifer is highly vulnerable and in jeopardy of being degraded by the surface water of the River Cedrino reservoir, whose maximum hydrodynamic level is higher than the karst water table.

The Supramonte aquifer system

Physiography

The Supramonte stands out of its basement as an imposing block with steep sides. Its morphology is very rough, with peaks in the northwestern region from altitudes of 1,400 m asl which rapidly dip downward to the east to less than 200 m, and heights at the eastern border rising up from 550 to 700 m to above 1,200 m.

Reliefs are interspaced by bleak plateaus, soil overburden being generally thin and scanty. Highlands are interrupted by deep valleys. Dolines, uvalas and polje, and sinkholes connect the surface with the underground karst hydrography.

Geology

Up to 1,000 m thick, the Supramonte limestone massif is a large remnant of the Mesozoic calcareous–dolomitic series which overlays the Hercynian crystalline bedrock peneplane (Amadesi et al. 1960; Assorgia et al. 1974; Calvino et al. 1972). According to Dieni and Massari (1985, 1987), from bottom to top the series consists of Lower Malm microcrystalline dolomite, Lower Malm compact oolitic limestones and Upper Malm biostromal limestones. The thickness of these three formations is respectively, in the order of 100, 200–300, and up to

Table 1 Epikarst attribute (E) classes

Epikarst	Class E	Karst morphology
Highly developed	$E1$	Shaft, sinkholes or dolinas (of any type), polje, caves, karren, and springs
Moderately developed	$E2$	Intermediate zones along aligned dolinas, and dry valleys
Low or null	$E3$	No evidence of karst features, and low fracture density zones

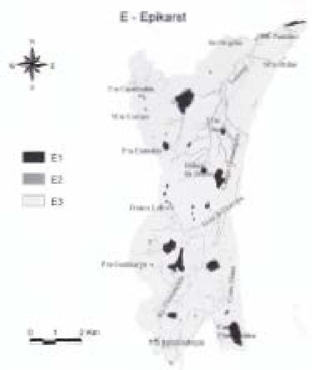

Fig. 2 E attribute classes

Epikarst

Epikarst was defined by a morphological analysis made with aerial photographs and topographical and geological maps, so that different super-imposable layers could be obtained. Thus, dolinas, polje, main faults, dry valleys, sinkholes, caves and springs could all be represented in scale. Morphological data were elaborated by a GIS to define different classes of the Epikarst attribute E as in Table 1.

The three E classes were then mapped as in Fig. 2.

Protective cover

No detailed soil maps are available for the area, the only one being at the scale 1:250,000. The protective cover parameter P (Table 2) was therefore mainly estimated on the basis of soil use and soil cover.

Four P classes were then defined as shown in Fig. 3.

Infiltration condition

The parameter I (Fig. 4) represents the conditions of concentrated or diffused water infiltration into the karst as shown in Table 3.

A digital elevation model (DEM) was developed and then converted into a triangulated irregular network (TIN) with a GIS to obtain a 3D morphology representation with contour lines of the surface hydrography.

Karst network development

Karst network attribute (K) classes are shown in Table 4 and Fig. 5. Two distinct karst structures were recognised in Supramonte: a well developed independent drainage type in the NE sector with a K1 class value, and a less developed dominant primary style in the remaining part of the area with a K2 class value.

Table 2 Protective cover attribute (P) classes

Soil cover	P classes	Characterization	
		(a) Soil covering limestones or high permeability formations such as screes and glacial deposits	(b) Soil covering low permeability formations, such as clay and silt
Null	$P1$	Soil 0–20 cm thick	Soil covering formations < 1 m thick
Intermediate $P1$–$P3$	$P2$	Soil 20–100 cm thick	Soil covering formations < 1 m thick
Intermediate $P2$–$P4$	$P3$	Soil 100–200 cm thick	Soil < 100 cm or > 100 cm thick covering low permeability formations > 1 m thick
Present	$P4$	Soil > 200 cm thick	Soil > 100 cm thick covering very low permeability deposits or aquicludes > 5 m thick

200 m. The top of the Jurassic series is composed of Lower Cretaceous (Barremian) micritic limestone beds, 1–2 m thick and crossed with mud cracks. The area was affected by pre-Eocenic folding and ruptural deformations, partly rejuvenated, which eventually produced conspicuous displacements and uplifting of isolated calcareous blocks (Teichmüller 1931; Dieni and Massari 1970; Cocozza et al. 1974; Alvarez and Cocozza 1974).

The karst developed along fractures mainly directed N–S, E–W, NW–SE, and subordinately NE–SW, especially during past hot climatic phases with major rainfall. Furthermore, it was most likely activated by the high groundwater aggressiveness caused by an intense basalt volcanism developed along tension fractures in the Plio-Quaternary.

Karst hydrography

The surface hydrography consists of several catchments with straight sub-parallel channels mainly directed to the NE as the rivers Flumineddu, Sa Oche and Codula de Illune. The Supramonte is considered one of the most important karst aquifer systems in Italy. The karstic caves explored thus far are characterized by chambers higher than 50 m, series of several siphons, adits as long as 50–70 km, and altitude differences between the inlet and the outlet greater than 400 m, as seen in the Grotta dell'Edera (Ivy cave) near Urzulei (Mahler 1979; De Waele et al. 1995; De Waele and Pisano 1997).

Located in the northeastern part of the area, the spring of Su Cologone is the most important of the Supramonte, with an estimated yield varying from several hundred l/s in dry periods to a few tenth m^3/s in rainy seasons.

Considering that average rainfall in the catchments of the area ranges between 680 mm at Cala Gonone (25 m asl) and more than 1,200 at Genna Silana (1,010 m asl), a permanent storage of at least 144 Mm^3 and a recharge of 77 Mm^3/year were estimated, while the total spring yield is believed to be in the order of 46 Mm^3/year, i.e., 60% of the total recharge. Total losses were attributed to the underestimation of outflows and flood flows (Sanna 1995; European Commission 2004).

The Epik method

After several tests with different methods, the EPIK method proved to be a suitable parametric weight and point tool to quantify the vulnerability of different zones of Supramonte in jeopardy of water contamination. Considering the karst aquifer's geological, geomorphological and hydrogeological characteristics (Doerfliger and Zwahlen 1995; Doerfliger et al. 1999), the four parameters influencing flow and transport in karst taken into account by the method are as follows: epikarst (*E*), protective cover (*P*), infiltration condition (*I*) and karst network development (*K*) (Fig. 1).

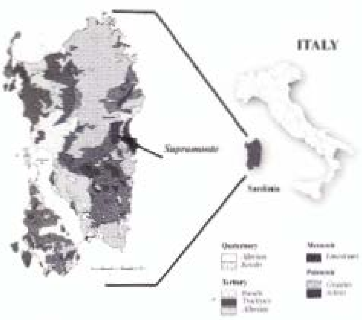

Fig. 1 Location map. Legenda of the Supramonte main geological formations

Table 1 Epikarst attribute (*E*) classes

Epikarst	Class *E*	Karst morphology
Highly developed	*E*1	Shaft, sinkholes or dolines (of any type), polje, caves, karren, and springs
Moderately developed	*E*2	Intermediate zones along aligned dolinas, and dry valleys
Low or null	*E*3	No evidence of karst features, and low fracture density zones

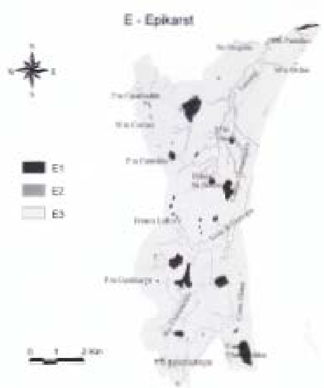

Fig. 2 *E* attribute classes

Epikarst

Epikarst was defined by a morphological analysis made with aerial photographs and topographical and geological maps, so that different super-imposable layers could be obtained. Thus, dolinas, polje, main faults, dry valleys, sinkholes, caves and springs could all be represented in scale. Morphological data were elaborated by a GIS to define different classes of the Epikarst attribute *E* as in Table 1.

The three *E* classes were then mapped as in Fig. 2.

Protective cover

No detailed soil maps are available for the area, the only one being at the scale 1:250,000. The protective cover parameter *P* (Table 2) was therefore mainly estimated on the basis of soil use and soil cover.

Four *P* classes were then defined as shown in Fig. 3.

Infiltration condition

The parameter *I* (Fig. 4) represents the conditions of concentrated or diffused water infiltration into the karst as shown in Table 3.

A digital elevation model (DEM) was developed and then converted into a triangulated irregular network (TIN) with a GIS to obtain a 3D morphology representation with contour lines of the surface hydrography.

Karst network development

Karst network attribute (*K*) classes are shown in Table 4 and Fig. 5. Two distinct karst structures were recognised in Supramonte: a well developed ~~independent~~ drainage type in the NE sector with a K1 class value, and a less developed dominant primary style in the remaining part of the area with a K2 class value.

Table 2 Protective cover attribute (*P*) classes

Soil cover	*P* classes	Characterization	
		(a) Soil covering limestones or high permeability formations such as screes and glacial deposits	(b) Soil covering low permeability formations, such as clay and silt
Null	*P*1	Soil 0–20 cm thick	Soil covering formations < 1 m thick
Intermediate *P*1–*P*3	*P*2	Soil 20–100 cm thick	Soil covering formations < 1 m thick
Intermediate *P*2–*P*4	*P*3	Soil 100–200 cm thick	Soil < 100 cm or > 100 cm thick covering low permeability formations > 1 m thick
Present	*P*4	Soil > 200 cm thick	Soil > 100 cm thick covering very low permeability deposits or aquicludes > 5 m thick

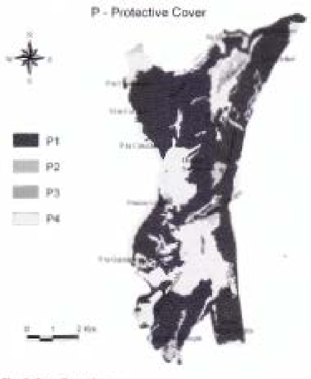

Fig. 3 *P* attribute classes

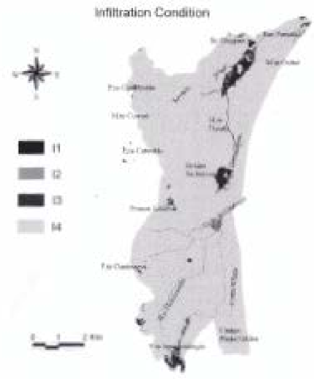

Fig. 4 *I* attribute classes

Weight definition

The weight coefficients of epikarst, protective cover, infiltration condition and karst network development given in Table 5 clearly show the higher relevance of *E* and *I*. Attribute *P* with a coefficient $B = 1$ had a minor influence in evaluating the final vulnerability index.

Vulnerability evaluation

Vulnerability was evaluated according to the following relation:

$F_{pi} = aE_i + bP_i + cI_i + dK_i,$

$i = 1,...,n$ is the grid cell number;
E_i, P_i, I_i, K_i = weights assumed in the *i*-cell;
a, b, c, d = attribute relative weights (constant for any attribute);
F_{pi} = *i*-cell protection factor (pertaining to *i*-cell). The lower the protection factor calculated for any *i*-cell, the higher the vulnerability of the karst aquifer, as shown in the vulnerability map of Fig. 6.

Table 3 Infiltration condition (*I*) attribute classes

Infiltration conditions	*I* classes	Characterization
Concentrated	*I1*	Losing ephemeral or perennial streams—ephemeral streams or streams into sinkholes and dolines—natural and artificial drainage basin
Intermediate *I1*–*I3*	*I2*	Concentrated infiltration areas (without artificial drainage systems) sloping > 10% in cultivated fields and > 25% in meadows and pasture land
Intermediate *I2*–*I4*	*I3*	Concentrated infiltration areas (without artificial drainage systems) sloping < 10% in cultivated fields and < 25% in meadows and pasture land
Diffuse	*I4*	Remnant land

Conclusions

The EPIK method gives clear evidence of the high vulnerability of the northern part of the karst aquifer of Supramonte, where groundwater is in jeopardy of degradation due to surface groundwater inflow.

The vulnerability map should be considered a fundamental document in reviewing the water resources master plan for the area.

Fig. 5 *K* attribute classes

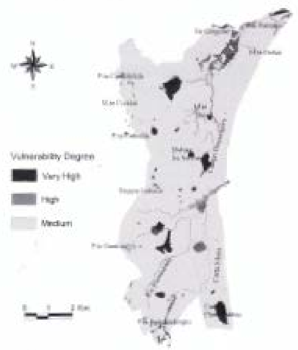

Fig. 6 Vulnerability map

Table 4 Karst network attribute (*K*) classes

Karst network	*K* classes	Characteristics
Well developed karst network	*K*1	Network channels 0.1–1 m wide
Slightly developed karst network	*K*2	Small network of channels poorly connected, < 0.1 m wide
Fractured aquifer only	*K*3	Fractured, non-karstic aquifers with springs locally issuing from porous media

Table 5 Weight coefficients concerning *E*, *P*, *I* and *K* attributes

Attribute	Coefficient	Weight
Epikarst	A	1
Protective cover	B	1
Infiltration condition	C	3
Karst network development	D	2

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