Groundwater vulnerability assessment in the Loussi polje area, N Peloponessus: the PRESK method

R. Koutsi[2], G. Stournaras[1]

[1]Professor of Hydrogeology and Engineering Geology, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, GR 157 84, Panepistimioupolis Zografou, Athens, Greece, stournaras@geol.uoa.gr
[2]Dr Geologist, Athens, reginakoutsi@yahoo.gr

Abstract Loussi polje, located in North Peloponnesus on the SE of Kalavryta village is a very interesting but little studied karst area. Water from karst springs and boreholes that drain the local carbonate aquifers is exclusively used for water supply and irrigation purposes in this scarcely populated area. An attempt to delineate protection zones in karstic aquifers was made, by assessing the groundwater vulnerability to pollution. PRESK, an adaptation of the RISKE groundwater vulnerability method of carbonate aquifers was applied. Modifications were necessary in order to meet with the specificity of Loussi karst terrain. PRESK method takes into account the protective role of topography in combination with vegetation (P factor), the nature of geological formations (R), the presence of epikarst (E), the existence of an overlying soil cover above carbonate aquifers (S) and the degree of karstification of the carbonate formations themselves. Groundwater vulnerability was assessed for both Olonos - Pindos and Tripolis carbonate aquifers of the study area.

1 Introduction

Karstic aquifers are particularly vulnerable to contamination, due to their nature and heterogeneous structure showing either a dual or triple permeability, often with matrix or granular permeability and always with fractures and conduits (Daly et al. 2002). In karst aquifers, the residence time of contaminants is often short and natural attenuation processes do not occur effectively (Vias et al. 2006) since filtration and auto-purification phenomena are not enabled (Petelet - Giraud 2000). Several vulnerability methods especially for karstic environments have been developed during the last decade including EPIK (Doerfliger et al. 1998), PI (Goldscheider et al. 2000), RISKE (Petelet - Giraud 2000), COP (Vias et al. 2006) taking into account the peculiarities of karst. In Greece karst terrains occupy 35% of the land surface and a large proportion of the total drinking water supply is mainly contributed by karst groundwater. Therefore it is of vital importance for an opti-

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mum quality and quantity preservation of these waters. The paper proposes PRESK method that takes its inspiration from RISKE. It is a modified approach which follows the accepted norm of an index-based mapping method with criteria weighting as well as the additional RISKE's aspect according to which it characterizes the vulnerability to infiltration and is a preliminary step of vulnerability characterization which does not lead to a determination of protection areas (Petelet-Giraud 2000). Since there was a lack of available data for Loussi polje study area, a necessary modification and simplification of the factors' values and categories was made according to the area's characteristics. The method follows five important steps (Petelet-Giraud 2000): mapping in a 1/20000 scale of each factor which is then subdivided in 4 indexes, discretization of each map, calculation of the Ig index and its subdivision in 4 vulnerability classes and finally the validation of the vulnerability map.

2 PRESK method and its characteristics

Five factors that control the groundwater pollution potential were defined, whose initials form the acronym PRESK: Protection, type of Rock, Epikarst, Soil Cover and Karstification degree. Every factor is divided into 4 categories from the less (index 0) to the most vulnerable (index 3), showing the degree of each one's impact, as far as pollution is concerned. The category index of each factor is multiplied by the factor's weight. The final Vulnerability Index (I_g) derives from the addition of all the obtained values.

The P Factor (Protection): The degree of a karst formation's vulnerability is determined by how easily or not a potential pollutant, mainly through water from precipitation, reaches the aquifer's saturated zone. The movement of water on the surface may be hindered and delayed by two key subfactors, which in turn play a protective role on karst aquifers. The slope (or inclination, I) and the vegetation (V) covering the surface are used for the assessment of P factor.

The topographic slope (I) deals with the inclination of the ground, the geomorphological characteristic that favors more or less the runoff at the expense of infiltration of water to greater depths (Petelet-Giraud 2000). Infiltration is directly linked to the topographic slope. The greater the slope, the more it encourages surface runoff away from the aquifer. Low topography promotes diffuse infiltration. Subfactor I is divided into four categories: I_0 Very steep slope >45^o, I_1 steep slope 25-45^o, I_2 moderate slope 5-25^o, I_4 low relief area 0-5^o.

Vegetation subfactor (V) takes into account the presence or absence of permanent vegetation and its density. Depending on the type of vegetation, the rate of average evaporotranspiration changes (Katzensteiner 1999). The four categories of V factor are: V_0 forests, V_1 sparse trees and dense shrubs, V_2 sparse shrubs and trees and cultivated fields and V_3 absence of vegetative cover.

Subfactors I and V, are weighted by 4/5 and 1/5 respectively. The sum of the combination of slope and vegetation with their weights provide the P factor: P=4/5I + 1/5V (Fig. 1).

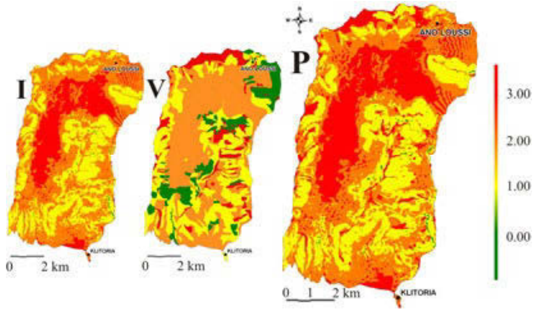

Fig. 1. Maps of Topographic slope (I-Inclination) and Vegetation of Loussi polje. The addition of the two to a 4/5 and 1/5 proportion respectively provides the Map of the P factor.

The R factor (Rock type): The R factor describes the type of lithology of the aquifer's formation in combination with tectonics which both control water's infiltration to a very large extent. All other formations are considered to play a protective role on karstic aquifers, by getting a zero value and therefore do not affect the final vulnerability index. R factor's categories are shown in Table 1.

Table 1. The four categories of the S factor and their characteristics.

Categories and characteristics of factor S	
Category	Characteristics
R0	Hard fissured rocks
R1	Alluviums, debris fall, conglomerates
R2	Thin bedded, slightly fractured limestones
R3	Massif, thick bedded, slightly fractured carbonate formations, thin bedded, heavily fractured limestones

The E factor (Epikarst): Epikarst is the uppermost weathered zone of carbonate rocks with substantially enhanced and more homogeneously distributed porosity and permeability than the bulk rock mass below it (Klimchouk 2003). Dissolution effectiveness and the secondary porosity are diminishing with depth, widened fissures taper downwards and become fewer (Williams 2003). The epikarst offers both a potential storage medium and potential pathways for contaminant migration into the aquifer (White 2003), however the recharge of the karst aquifer is partly delayed by a primary storage right below the ground surface (Bakalowicz et al. 1974). Recognition and mapping of different types of epikarst zones is difficult, especially where it is covered or where its lateral extention is discontinuous. However, the epikarst zone can be characterized indirectly, based on geomorphologic features which can easily be mapped (Doerfliger et al. 1998). The E factor is classified in four categories: E_0 highly developed epikarst >1 m of thickness, E_1 moderately developed epikarst of 50 cm to 1 m of thickness with temporary storage capacity of water near the surface, E_2 poorly developed epikarst with thickness <50 cm and E_3 absence of Epikarst. Storage capacity in Epikarst before it reaches the karst aquifer plays a significant role on the level of protection.

Pindos zone as Epikarst on Tripolis aquifer: Pindos zone is characterized by thrusts, where permeable formations (limestones) alternate with impermeable ones (e.g. flysch) resulting in the increase of the layers' thickness. Being overthrusted on Tripolis zone, with its more or less permeable formations lying directly above the Tripolis carbonate formations or flysch, Pindos zone can be considered to play the role of epikarst on Tripolis aquifer. Since tectonic stresses favor the good hydraulic communication between the two geological masses, a significant amount of water infiltrates from Pindos to the underlying Tripolis. Therefore, in this study, Pindos zone is regarded as the thick epikarstic zone of Tripolis aquifer with a very satisfactory protective capacity and is thus categorized as E0, with little or no impact on vulnerability.

The S factor (Soil cover): The soils create a protective cover above karstic aquifers which is very important for the final vulnerability index. The soil parameter that can be calculated relatively easily, if no other information is available, is thickness. Due to lack of data in the study area, the evaluation of S factor was based only on the soil thickness. Based on onsite investigations and mapping as well as on results from regional geophysical survey, four categories of the S factor were identified: thickness> 5 m, 1-5 m, < 1 m and poorly developed or total absence of soil cover.

The K factor (Karstification degree): The karst network development and its degree of organization plays an important role on water velocity flow and therefore on the vulnerability (Doerfliger et al. 1998). Calculating the K factor, especially when surface features are absent, is difficult and indirect methods are usually used. Here, the degree of karstification was assessed by (a) the presence of caves and avens (b) the results of recession curves analysis from springs' hydrographs proposed by Mangin (1975), (c) tracer tests on both polje's sinkholes. K factor categories are: K_0 aquifer with poorly developed network or absence of karstic fissures, K_1 fissured but not karstified aquifer, K_2 poorly karstified aquifer, K_3 well and very well developed karst network. Where the degree of karstification is low then the aquifer retains some natural protection.

3 Vulnerability index

The calculation of the final vulnerability index (Ig) was based on the following formula:

$$Ig = \beta P_i + \alpha R_j + \varepsilon E_n + \delta S_k + \gamma K_m$$

where Ig: the final vulnerability index, *α, β, γ, δ, ε*: weight of each factor, P_i, R_j, S_k, K_m, E_n: values of the factors for each category. The values of the Ig index are also grouped into four vulnerability categories (Very Low, Low, Moderate, High). The assessment of the weighting values was based on Analytical Hierarchy Process developed by Saaty (1977). A pairwise comparison matrix was formed (Table 2) in order to hierarchically organize the factors and to calculate their weights. According to their weights, the importance of each factor in PRESK method can be described as follows: S>P>E>R>K. Therefore the formula of the Final Vulnerability Index becomes:

$$Ig = 0.263P_i + 0.097R_j + 0.160E_n + 0.419S_k + 0.062K_m$$

Table 2. Hierarchical organization of the PRESK factors and their relative weights (left) and Definition of vulnerability categories according to the final vulnerability index (right).

	P	R	E	S	K	Weight
P	1	3	2	1/2	4	0.263
R		1	1/2	1/4	2	0.097
E			1	1/3	3	0.160
S				1	5	0.419
K					1	0.062

Ig categories	Vulnerability categories	
0 – 0.8	0	Very Low Vulnerability
0.8 – 1.6	1	Low Vulnerability
1.6 – 2.4	2	Moderate Vulnerability
2.4 – 3	3	High Vulnerability

4 Field Application: Loussi Polje

Vulnerability mapping using the PRESK method was carried out in N. Peloponnesus at Loussi Polje, an area of around 20 km^2 SW from Kalavryta with mean altitude from 940 to 1100 m. Manna River drains a part of the area into two sinkholes at an altitude of 967 m. Geotectonic zones of Olonos – Pindos and Tripolis are present with the first overthrusting the second. The appearing geological formations are: (1) recent alluvium and talus cones, which form the totality of the polje's surface sediments, and emanate mainly from Pindos formations (2) flysch of Eocene, (3) stratified limestones of Upper-Cretaceous, (4) radiolarites of Upper-Jurassic, (5) Upper-Triassic limestones of Pindos zone and from Tripolis zone Upper-Cretaceous carbonate series in the NE.

The two most important karstic aquifers of the region are Pindos Upper-Cretaceous limestones and Tripolis thick-bedded limestones. The first is a fissured karstic aquifer of small to moderate thickness, intensively tectonized and folded in alterations with the flysch and radiolarites of the same zone. Near the surface circulation of groundwater predominates and most of the aquifer's discharge is through springs around the polje at the contact with the more impermeable formations. On the other hand, Tripolis carbonate series is a karstic aquifer of considerable thickness (up to 1000 m), with a deep and large conduit flow system. The discharge from the aquifer is through springs with significantly great volume, at lower altitudes than in Pindos zone. Planitero spring in Tripolis zone at the SE outside the field area partly drains water from Loussi sinkholes (Koutsi and Stournaras 2005).

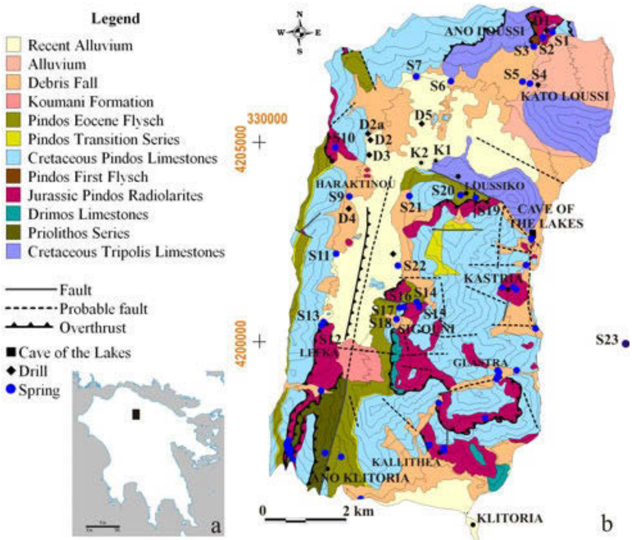

Fig. 2. a. Schematic map and **b.** geological map in the study area. **K1, K2:** the two Loussi polje sinkholes.

5 P, R, E, S and K factors and Final Vulnerability Map

Each factor of the PRESK method was mapped individually in the field at 1:20000 scale and then was digitized in MapInfo GIS. Vulnerability maps were constructed for every factor according to the given categories. The Final Vulnerability Map is the result of the multiplication of every map's category by the corresponding weight and their final addition. In PRESK map of Loussi polje (Fig. 3) all four vulnerability categories are represented, with moderate vulnerability being quite increased due to the presence of carbonate outcrops which in majority are poorly karstified.

Most of the High vulnerability areas are found on the top of carbonate formations where the karst landforms are not covered by soil, their degree of karstification moderate to high and the topography is low (5^o<) in combination with little or absence of vegetation.

The Manna River is drained into two sinkholes, and therefore its basin is classified as High vulnerability. It is considered as if there is not any soil cover protection and as if it is an area of a very high degree of karstification since water travels rapidly bypassing any protection.

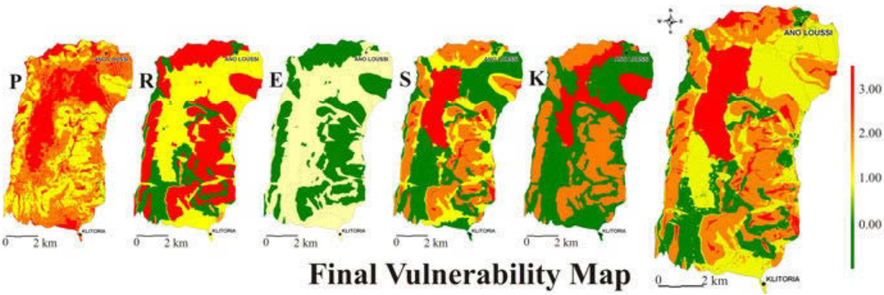

Fig. 3. Maps of the 5 vulnerability factors P, R, E, S, K and the Final Vulnerability Map of Loussi polje resulting from the Final Vulnerability Index $\mathbf{Ig} = 0.263\mathbf{P_i} + 0.097\mathbf{R_j} + 0.160\mathbf{E_n} + 0.419\mathbf{S_k} + 0.062\mathbf{K_m}$.

The areas of moderate vulnerability constitute over one third of the study area. The majority of Pindos limestones and Tripolis carbonate formations belong to this vulnerability category which indicates the primary role of factor R. These areas show a soil cover of thickness from less than 1m up to 5m and a moderate to high degree of karstification. The predominance of steep slopes and of the epikarst appearance lowers the vulnerability values to one category.

Scattered throughout the region, low vulnerability areas are characterized by: soil cover of thickness 1 - 5 m, absence or low topographical relief (from 0 to 45°), absence of karstification, sparse shrubs and trees and cultivated fields. The biggest areas of this category are situated in the NE and S part of the polje.

The lowest vulnerability category occurs where above the aquifer low permeability material (eg recent alluvium) and formations (eg radiolarites) are present. It covers approximately 20% of the region and reflects very high relief areas (> 45°), where infiltration is diminished and soil cover thickness exceeds 5m, there is a lack of karstification and usually a significant vegetative cover.

6 Conclusions

The PRESK method, an adaptation of RISKE method, was applied in Loussi polje. The specificity of the region, as well as the lack of necessary data led to a general modification upon the factors' categories and weightings. The five factors used are: Protection (P), Rock type (R), Epikarst (E), Soil Cover (S) and degree of Karstification (K), which were mapped and categorized according to the new categories. The Final Vulnerability Index and Map were obtained. All four vulnerability categories are represented with the Low and the Moderate being the most extended ones. The presence of the two sinkholes changed the way the factors S and K were categorized, taking high category values at the polje's area where Manna River flows until it reaches the sinkholes.

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