



# Intrinsic groundwater vulnerability assessment by multiparameter methods, a case study of Suva Planina Mountain (SE Serbia)

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## Abstract

Karst terrains appear on all continents and karst aquifers produce drinking water for more than 9% of the world's population while being the most vulnerable to contamination. One of the main challenges in the management of a water supply that depends on groundwater is the possibility of the pollution of the karst aquifer which is usually open toward the surface and is highly permeable. Various environmental problems found in karstic areas demand a completely unconventional approach for this particular environment. To achieve and maintain high-quality groundwater that can be used for a public water supply, an effective prevention program must be designed and implemented. The process of determining the sanitary protection zones (SPZ) has been relying on new technologies, especially the use of a geographic information system (GIS) environment. An assortment of groundwater vulnerability assessment methods has been developed in the GIS environment, as a necessary basis for implementing preventive measures. Suva Planina Mountain is one of the greatest and the highest karst massifs in South-East Serbia. Almost all known karst features are present, and several karst springs exist at the foothill of the mountain. The largest springs have been captured for the water supply. The catchment areas of the springs are not populated and there is no industry, besides grazing and forestry; nevertheless, some limits for human impact must be enacted. This paper is an attempt at using the GIS-overlay spatial modeling technique for groundwater vulnerability assessment of Suva Planina Mountain. Maps of intrinsic vulnerability have been designed by the application of three multi-parameter methods for vulnerability mapping (EPIK, PI, COP). The maps that have been designed for Suva Planina Mountain show the existence of four classes of vulnerability, though in somewhat different arrangements and distribution.

**Keywords** Karst aquifer · Intrinsic vulnerability · EPIK · PI · COP

## Introduction

Karst areas have captivated human interest throughout history (Stevanović 2010). This specific type of topography is one where the landscape is formed by unique hydrogeological characteristics. Human curiosity regarding karstic regions has led to the development of specializations of scientific study such as speleology, karst hydrology/

hydrogeology, karstology, speleobiology, cave diving (speleodiving), etc. According to some estimates, around 20–25% of the world's population consume groundwater originating from karstic aquifers (Ford and Williams 2007), but recent results show that 9.16% of the world's population use karstic groundwater (Stevanović 2017). Preliminary results of the WOKAM (World Karst Aquifer Map) project indicated that different types of karstified rocks crop out over approximately 15% of ice-free land (Stevanović 2017). It was found that about 21.6% of the European land surface is characterized by the presence of carbonate rock, including 15.1% of “continuous” and 6.5% of “discontinuous carbonate rocks”. The total area of actual carbonate rock outcrops is 13.8%. (Chen et al. 2017). Special strategies are required to preserve the optimum quantity and quality of karst waters. The management of this resource is recognized in Europe as a high priority (Daly et al. 2002). Open karst aquifers in Mesozoic rocks of Serbia cover an area of approximately

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3,350 km<sup>2</sup> (Stevanović and Filipović 1994), while Suva Planina Mountain catchment area covers about 252 km<sup>2</sup> of that surface. The same author estimated exploitable reserves of karst groundwaters of the massif at the amount of 2.5 m<sup>3</sup>/s which is more than enough for a regional water supply system, hence the protection of this natural resource is essential.

Karst aquifers are particularly vulnerable to contamination due to thin soil, flow concentration within the epikarst and concentrated recharge via swallow holes. As a result, contaminants may easily reach the groundwater and be rapidly transported in karst conduits over large distances (Goldscheider 2005). For example, several dye tracing test results of karst aquifers of Eastern Serbia confirmed relatively high flow velocities of karst groundwater, ranging from  $V_{\min}=0.0045$  m/s to  $V_{\max}=0.222$  m/s, with an average value 0.0631 m/s (Stevanović 1991).

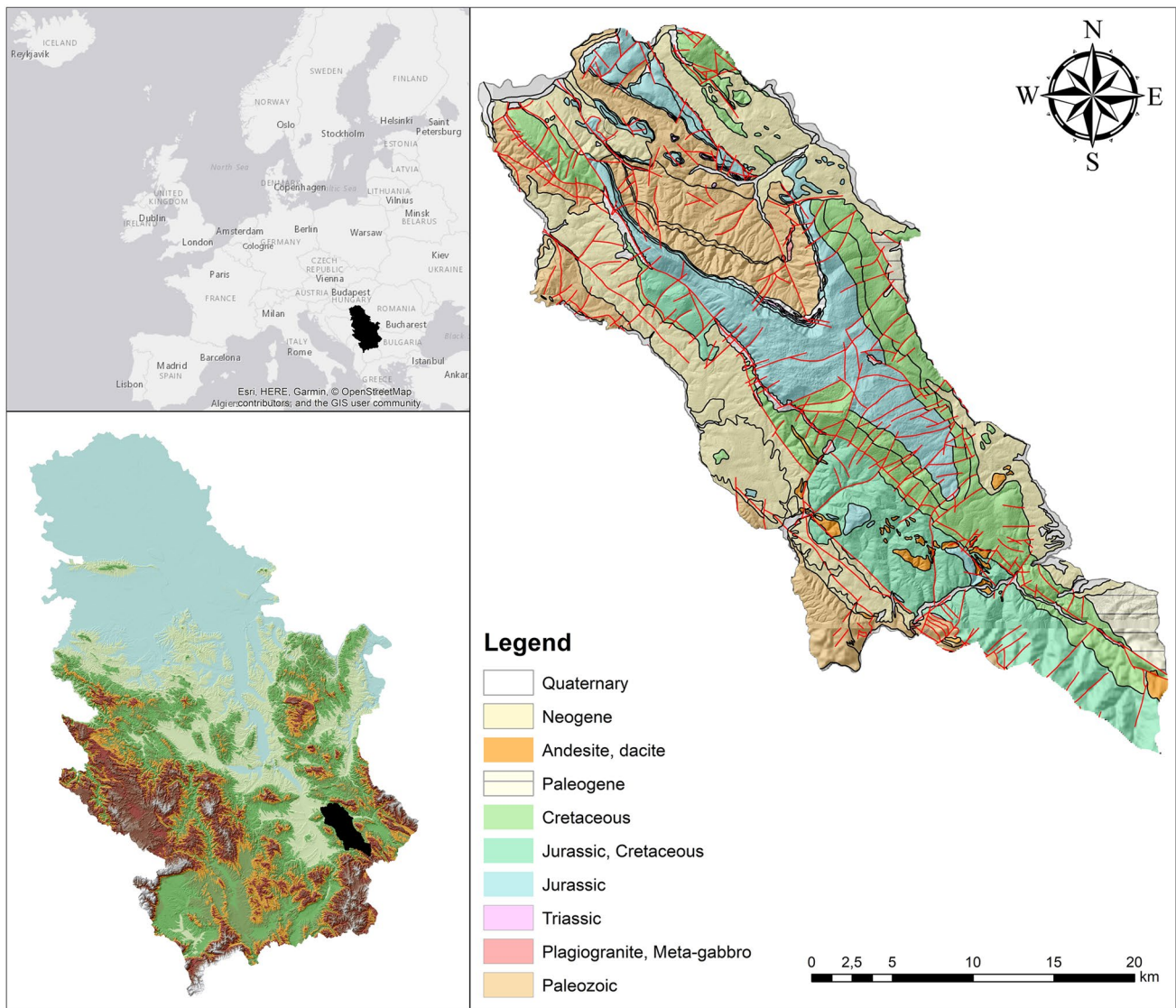
Preventive protective measures are the basis for the effective sustainable management of groundwater as one of the most precious natural resources. Groundwater vulnerability assessment methods have been developed to provide the necessary basis for implementing preventive measures (Živanović 2011). Since the first definition of groundwater vulnerability by Margat (1968) and Albinet and Margat (1970), the vulnerability concept has changed considerably and developed further in different ways. Two classes of vulnerabilities have been distinguished (Daly et al. 2002): intrinsic vulnerability and specific vulnerability. Intrinsic vulnerability considers only the hydrogeological properties of the system, whereas specific vulnerability additionally considers specific interactions with contaminants (Zwahlen 2004). Assessing the vulnerability of groundwater, either intrinsic or specific, to reduce any effects of human impact, is one of the most important problems in applied hydrogeology today. Neukum and Hötzl (2005) suggested that no generally accepted method for all hydrogeological system is available and the most suitable method (which describes the considered system the most appropriate) should be selected. Recognition of the high sensitivity of karst aquifers led to the evolution of different karst vulnerability assessment methods beginning in the late 1990s and the constitution of the European Approach as a framework (Iván and Mádl-Szőnyi 2017). According to some authors, groundwater vulnerability maps synthesize the wide range of information on lithology, pedology, hydrogeology, meteorology, hydrology and geomorphology and support decision making in environmental management, land use and water management. Additionally, they aid in communication between hydrogeologists and decision makers (Witkowski et al. 2007). The advantage of using many parameters can become a disadvantage at times, due to the difficulty in obtaining the large amount of necessary data (Kazakis et al. 2015). On the other hand, Foster et al. (2013) proposed considering vulnerability assessments as the “best professional synthesis” of data

available and using them as a screening tool. With the right data vulnerability maps can be an essential tool for groundwater protection and environmental management (Vías et al. 2005). The advent of geographic information system (GIS) technology, especially after the 1990s, visualization, interpretation and presentation of groundwater quality evaluations over large spatial scales has been drastically improved (Machiwal et al. 2018). The GIS is capable of capturing, storing, analyzing, manipulating, retrieving and displaying a large volume of spatial data for swift organization, quantification and interpretation for decision-making in areas including engineering and environmental sciences.

The natural protection most groundwater receives from the overlying strata is not available for surface waters (rivers, lakes and artificial reservoirs) which also can be used for public water supply. Due to the special characteristics of karst systems, it is much more difficult to define the recharge conditions and predict measures for water protection when compared to other geological settings. It is obvious that in karst aquifers the classical hydrogeological approach is generally inoperative because of the inability to show the existence of conduits (Bakalowicz 2005). Thus, the careful study must be provided to ensure safe drinking water from a karstic aquifer. The application of vulnerability mapping should be considered an important and necessary first step in defining the sanitary protection zones of karst groundwater sources. EPIK is the first method of intrinsic vulnerability mapping which was designed to assess karst water vulnerability (Doerfliger et al. 1999). The PI method (Goldscheider et al. 2000) and the COP method (Vías et al. 2006) could be recognized as modern versions of the EPIK method which involve two parameters. However, there are 12 sub-parameters that must be assessed, and using this additional information means that more detailed maps can be created. Identification of the most appropriate method depends on the available data and the specific hydrogeological conditions of the aquifer concerned (Gogu et al. 2003; Kazakis and Voudouris 2011). A proposal for defining sanitary protection zones of the groundwater sources in the foothills of Suva Planina Mountain is made according to the legislation of Serbia (RS Official Gazette, No. 30/2010 and The rulebook on the manner of determining and maintaining the sanitary protection zones of water supply sources 2008) and is compared to suggestions from the vulnerability mapping application.

## Study area

The study area in total covers around 630 km<sup>2</sup> of terrain of Suva Planina Mountain and its surroundings with very different geological and hydrogeological characteristics. Suva Planina Mountain lies 250 km SE of Belgrade (Fig. 1),



**Fig. 1** Geographical location of Suva Planina Mountain and simplified geological map (geological setting according to Basic geological map of SFRY; Federal Geological Survey of SFRY 1980)

generally oriented in the NW–SE direction. The name of the mountain originates from the fact that there are only a few springs on the whole massif. Two springs on higher slopes of the mountain, that discharge almost all year are Bojanine vode Spring (under Sokolov Kamen Peak, at 860 m a.s.l.) and Rakoš česma Spring (under Trešten Peak, at 1280 m a.s.l.). Suva Planina Mountain is a part of the long mountain chain of the Carpatho-Balkanides, geologically heterogeneous and morphologically very dissected belt of an orogenic system stretching across Central and Southeast Europe, more than 2000 km long. Suva Planina Mountain is an asymmetrical, normal anticline, plunging towards the SE, and the geological setting is very complex due to multiple thrusting and faulting in the area that occurred during the Caledonian Orogeny, the Hercynian orogeny and finally

the Alpine orogeny (Federal Geological Survey of SFRY 1980). Regional folding of the Mesozoic sedimentary layers together with Paleozoic rocks created the Suva planina anticline and the longitudinal Lužnica regional fault, both oriented in a NW–SE direction. Tectonic movements lead to the uplift of the NW part of the mountain and the creation of a plunging anticline. The process of erosion in the ascended part caused the destruction of the Cretaceous and Jurassic limestone and dolomite to the core of anticline which is mainly made up of Paleozoic rocks (mostly Devonian and Permian sandstone, conglomerate and shale) (Fig. 1). Local faults are transversal to the above-mentioned regional dislocations supposedly causing the enhancement of the karstification process in the limestone and dolomite. On the northeast side of the mountain one can see rocky cliffs

about 1,000 m deep. The middle part of the Suva Planina Mountain looks more like a plateau which consists of many dolines and small uvalas covered with grass. The most typical forms of surface karst morphology are dolines. They are developed mainly on sub-horizontal limestone parts, while on slopes they are much rarer or are completely missing. In some parts of the terrain, the dolines are very common (over 100 per 1 km<sup>2</sup>), especially in the area named “Valožje” (Cvijić 1912). Numerous dolines are chaotically scattered over the entire surface of around 55 km<sup>2</sup>, but it is noticeable that some of them occur in arrays, along the faults, or in small groups. A sinkhole (jama), 10 to 20 m deep, one can find in a few dolines in the “Valožje” area. Dolines can also be found at the rocky cliffs on the northern part of Suva Planina Mountain. On the other hand, the absence of macro-morphological forms—karst poljes, the existence of only a few small caves and the presence of considerable vegetation cover, distinguishes Suva Planina Mountain relief from that in the Dinarides, where the influence of geological and climatological characteristics had a much larger effect on the karstification process.

Intergranular aquifers were formed in Quaternary and Neogene sediments, and fissured aquifers formed locally in magmatic rocks of a different age. Complex aquifers can be identified in Miocene formations along the E and NE rim of Suva Planina Mountain. However, aquifers in the research area have been created, mainly, in cracked, fissured and karstified carbonate rocks of the Jurassic and Cretaceous periods (Figs. 2, 3). The recharge of aquifers is precipitation based; average annual precipitation is around 630 mm. Effective infiltration into the karst aquifer was estimated as 55% of total precipitation (Stevanović 1991). Faulting and plunging caused the creation of groundwater flows within the karst aquifer which follows a radial direction from the Suva Planina Mountain anticline axis toward its limbs. However, afterwards karstification contributed to a change in the dominant groundwater flow directions and a redistribution of quantities of groundwater discharged through observed springs. The integrated conduit network in karst is a supplementary heterogeneity that is organized at a different scale (Bakalowicz 2005). It can be taken into consideration only by considering it as a whole. At the beginning of the development of the groundwater flow, regional faulting and thrusting played a dominant role in directing water flow towards the southeast. Local faults provoked the enhancement of the karstification process in the limestone and dolomite, and the groundwater flow has been changed to a direction that is transversal to the original NW–SE direction. Additional karstification provided further and finer division of the groundwater flow and resulted in quite a few orifices of the aquifers in the foothill of Suva Planina Mountain. To prepare a representative vulnerability map of the karst system effective, thorough, monitoring should also be included

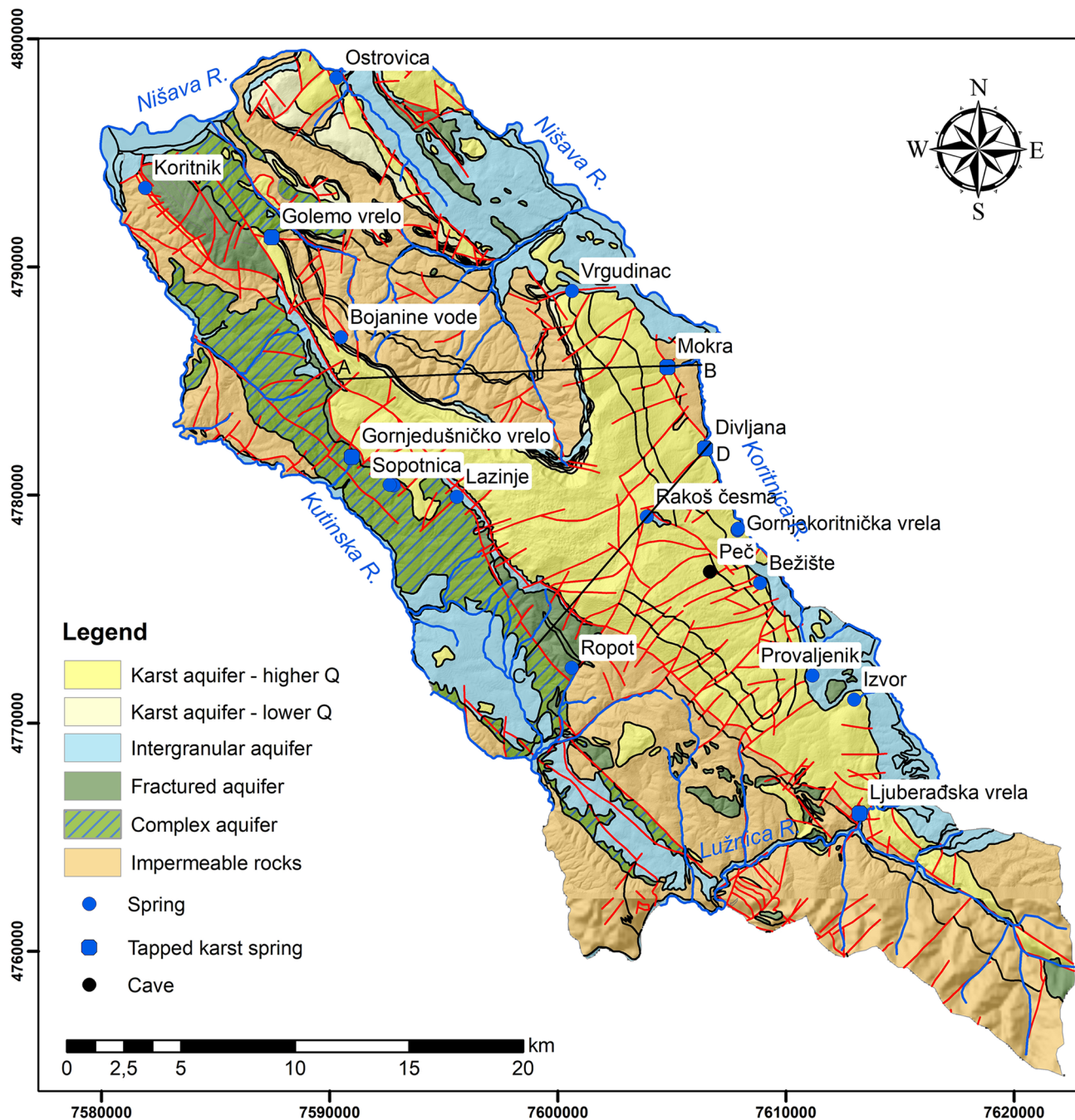
(Kazakis et al. 2018). However, in the presented case study, only few parameters of the karst system were monitored as long as needed.

Aquifers in the researched area are mostly discharged via springs (karst, fissured and complex aquifers) and domestic shallow wells (intergranular aquifer), as well as underground pathways into adjacent aquifers. Several large karst springs at the foothill of the mountain, are a result of a developed process of karstification and a contact of karstified limestone or dolomite with less permeable deposits of Neogene period or impermeable sediments of the Paleozoic period (Petrović 2014). Springs that originate from carbonate rocks of Suva Planina Mountain are (Figs. 2, 3): Mokra karst spring, Divljana karst spring, Gornjekoritnička vrela springs (on the east side); Ljuberađa karst spring (on the south side), Lazinje karst spring, Sopotnica karst springs and Gornjedušničko vrelo karst spring (on the west side), Golemo vrelo spring (on the north side), and Rakoš česma spring ( $Q_{\min} \sim 1$  l/s) (on Suva Planina Mountain itself). During the '80 s of the last century, a few of the karst springs have been captured for a water supply of the nearby villages, towns and city of Niš: Mokra ( $Q_{\text{avg}} \approx 550$  l/s), Divljana ( $Q_{\text{avg}} \approx 450$  l/s), Ljuberađa ( $Q_{\text{avg}} \approx 850$  l/s), Gornjedušničko ( $Q_{\text{avg}} \approx 200$  l/s), Golemo ( $Q_{\text{avg}} \approx 300$  l/s).

## Methods

The EPIK method is a multi-attribute method for vulnerability mapping which takes into consideration the specific hydrogeological behavior of karst aquifers. This method is based on a conceptual model that suggests considering four karst aquifer attributes: (1) Epikarst, (2) Protective cover, (3) Infiltration conditions and (4) Karst network development. A multiplier, reflecting the relative importance weighting, is assigned to each attribute. The ratings for each class of any given attribute are multiplied by the weight related to the attribute and then the products are added up to arrive at the final score. The higher the score, the greater the natural protection of the area, i.e. the less vulnerable the area is (Doerfliger et al. 1999).

The PI method is a GIS-based approach to mapping the intrinsic vulnerability of groundwater resources. The acronym PI stands for the two factors protective cover (P factor) and the infiltration conditions (I factor). It is based on a source-pathway-target model: ground surface is assumed to be the potential source of contamination; the groundwater table in the uppermost aquifer is the target (Goldscheider et al. 2000). Thus, the pathway includes everything between the ground surface and the groundwater table. The P factor shows the protective function of the layers overlying groundwater as a function of their thickness and properties, and the I factor shows the degree to which the protective cover is

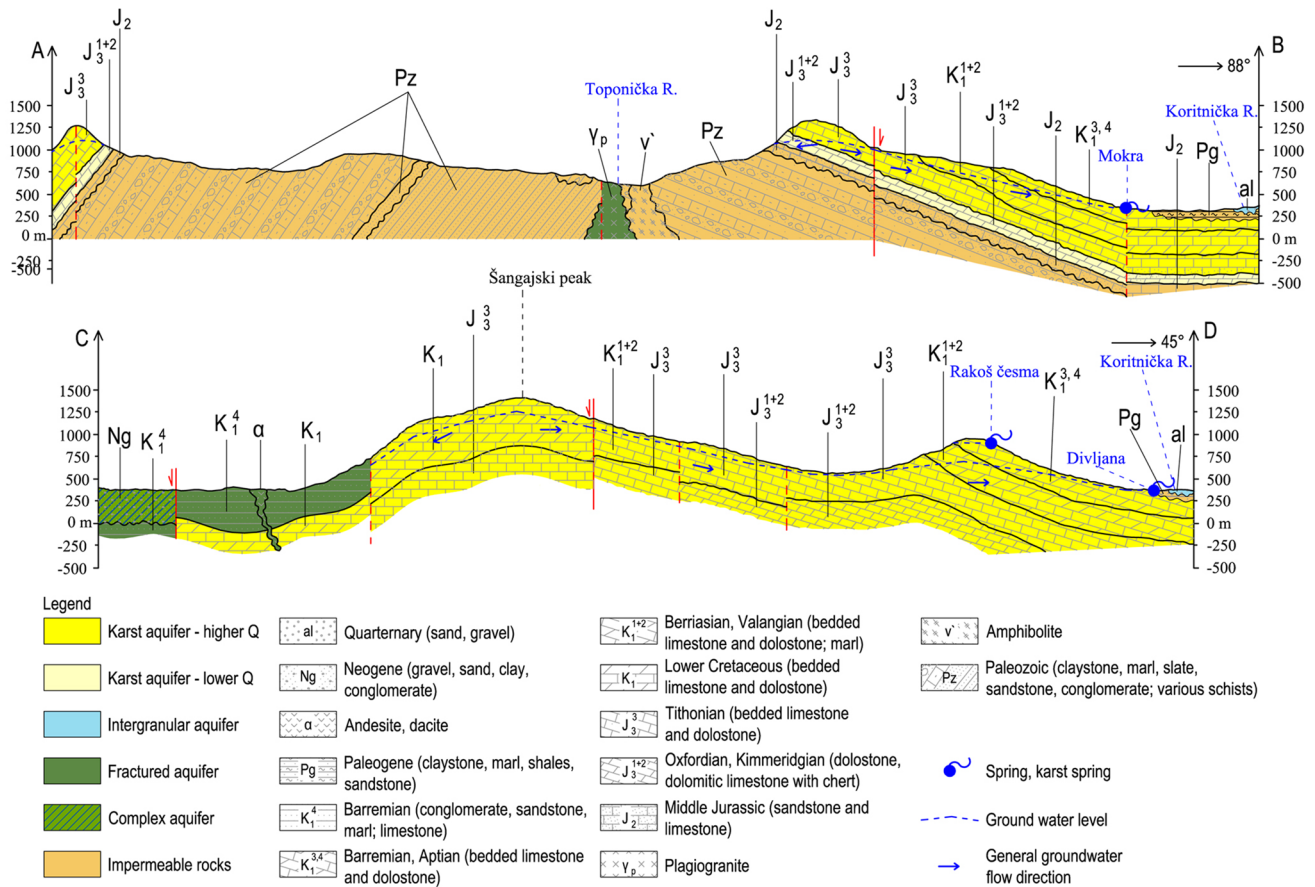


**Fig. 2** Simplified hydrogeological map of Suva Planina Mountain with location of springs (according to Basic geological map of SFRY; Federal Geological Survey of SFRY 1980)

bypassed by lateral surface and subsurface flow, and subsequent concentrated recharge.

The COP method has been developed for the assessment of intrinsic vulnerability of carbonate aquifers in the frame of the European COST Action 620. This method uses the properties of overlying layers above the water table (O factor), the concentration of flow (C factor) and precipitation (P factor) over the aquifer, as the parameters

to assess the intrinsic vulnerability of groundwater (Vias et al. 2006). The conceptual basis of this method is to assess the natural protection of groundwater determined by the properties of overlying soils and the unsaturated zone, and to estimate how this protection can be modified by the infiltration process—diffuse or concentrated—(C factor) and the climatic conditions (P factor—precipitation). The factors of the COP method have been combined to evaluate



**Fig. 3** Simplified hydrogeological cross section of Suva Planina Mountain (according to Basic geological map of SFRY; Federal Geological Survey of SFRY 1980)

the intrinsic groundwater vulnerability. The method can be applied in different climatic conditions and different types of carbonate aquifers (diffuse and conduit flow systems). In addition, the COP method uses variables, parameters and factors in line with those proposed in the European Approach (Vías et al. 2006).

Due to inadequate or data missing for the assessment of some parameters (factors) for the terrain south from the Lužnica River (Fig. 2), that small area has been omitted from further analyses and final maps. The thematic maps for each parameter needed for vulnerability mapping were generated using ArcGIS software. Maps allowed for the identification of areas that are more likely to become contaminated. Results will lead to better decision-making and more appropriate selection of the groundwater protection zones, which need special management to have good quality, sustainable groundwater for future use. Superimposed geographic information system (GIS) layers were built-up to include all the decisive parameters or criteria, which were suggested by authors for the groundwater vulnerability mapping of the study area (Figs. 4, 5, 6). The maps reflect the aquifer's inherent capacity to become

contaminated and represent the range of the vulnerability indices.

## Results and discussion

The methods mentioned above have been used to evaluate the intrinsic groundwater vulnerability of Suva Planina Mountain, to calculate vulnerability indices and to produce vulnerability maps, with four rating possibilities, from “very high” to “low”.

The map obtained by the EPIK method (Fig. 4) shows a range from “very high” to “low” vulnerability. Based on statistical sensitivity analysis of impact factors (Petrović et al. 2017), parameters E and I have the strongest influence on the final vulnerability index F. One can notice a direct correlation of the (hydro)geological setting of the research area with the vulnerability index. “Very high” and “High” vulnerability are related to highly karstified areas with well-developed epikarst and a significant number of dolines. Due to this, effective precipitation is more rapid, hence, the parameter I has the greatest influence on the final

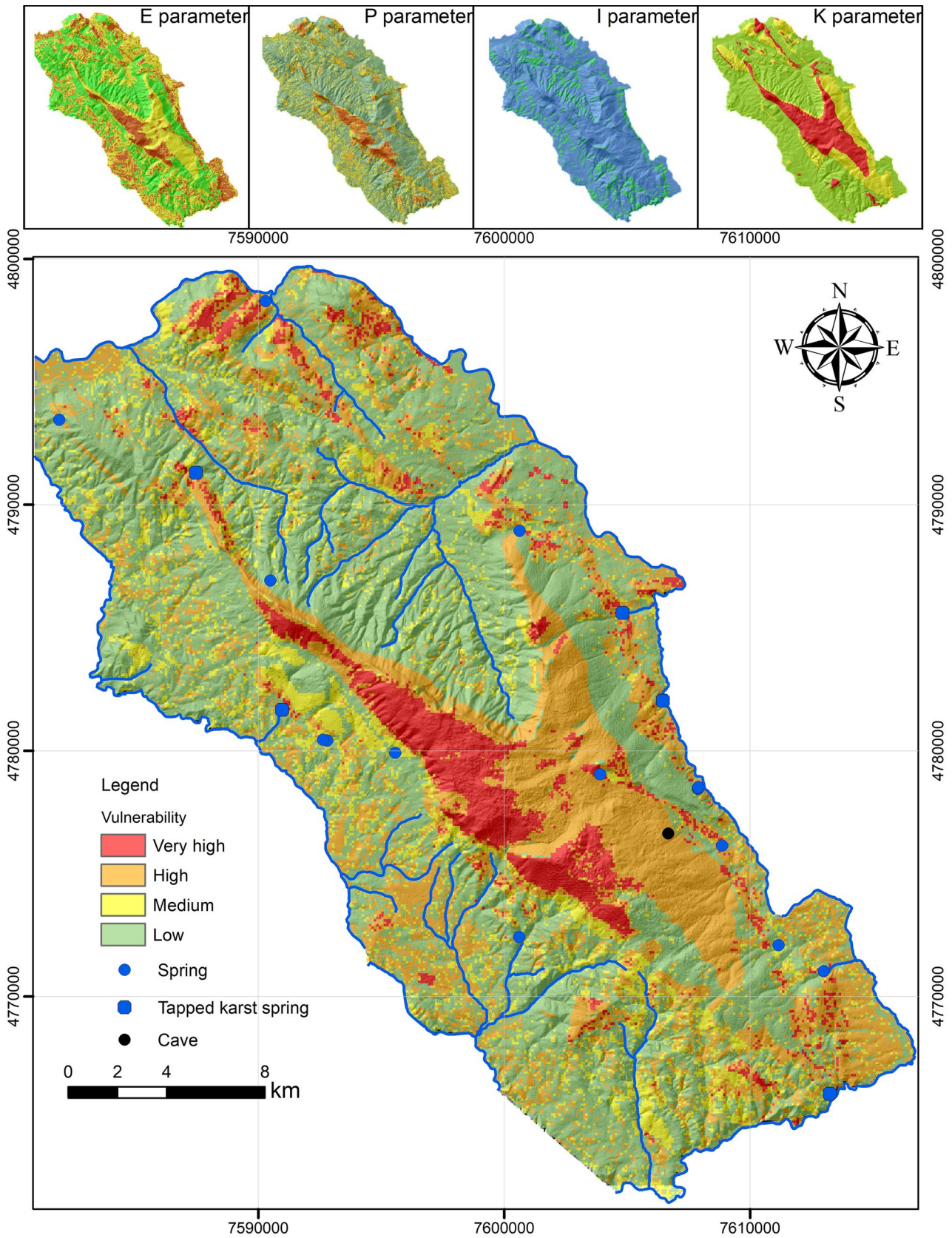


Fig. 4 Vulnerability map of Suva Planina Mountain—EPIK method

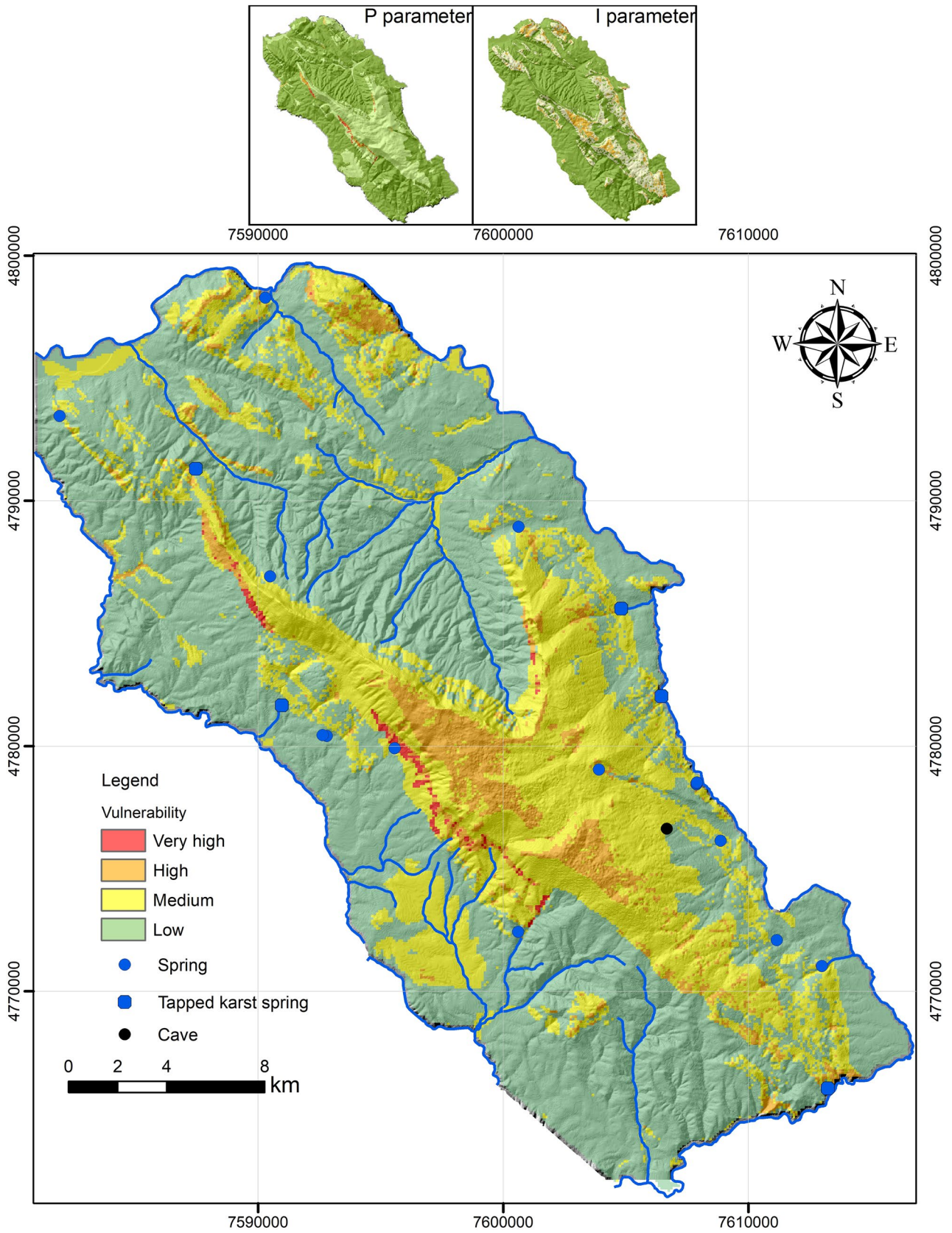


Fig. 5 Vulnerability map of Suva Planina Mountain—PI method



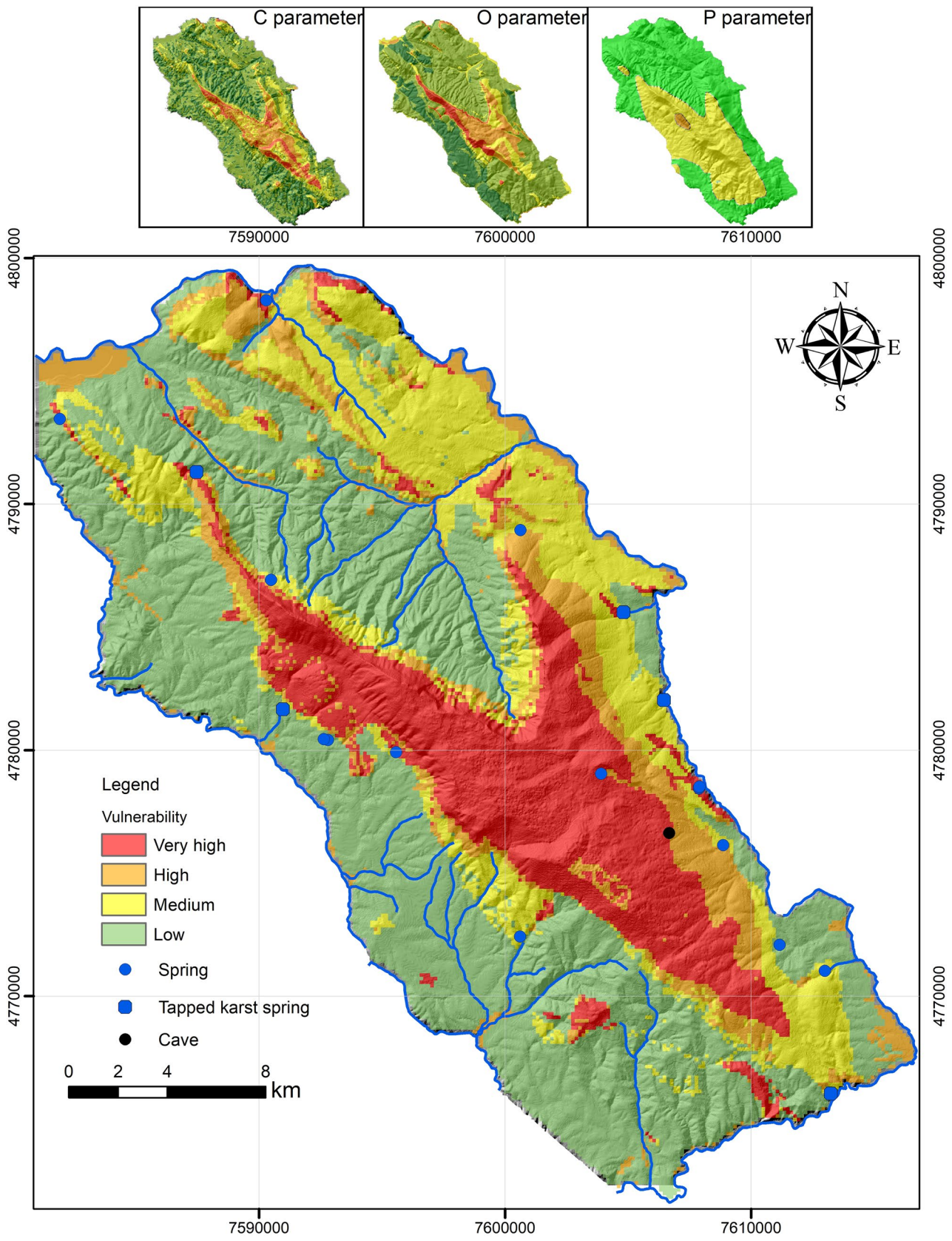


Fig. 6 Vulnerability map of Suva Planina Mountain—COP method

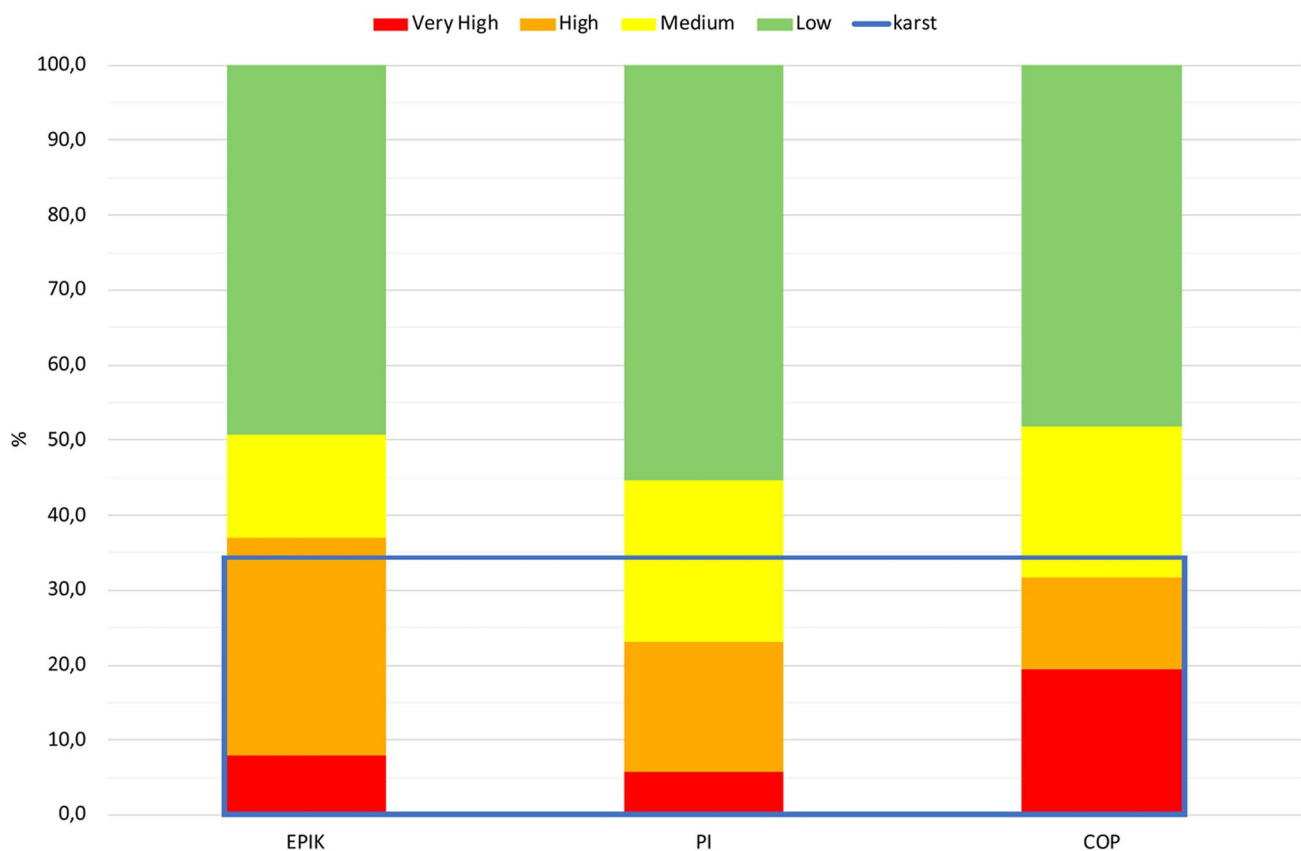
vulnerability factor. In addition, the EPIK method does not consider some dynamic characteristics, such as temporal variations of infiltration. Terrain that is characterized as “Medium” and “Low” vulnerability is on the rim of the Suva Planina Mountain and is comprised of fractured Paleogene/Neogene rocks with insignificant aquifers usually covered with clastic Quaternary sediments.

The PI vulnerability map (Fig. 5) shows the intrinsic vulnerability and the natural protection of the uppermost aquifer. The map shows the spatial distribution of the protection factor  $\pi$ , which is obtained by multiplying the P and I factors. One can notice a smaller area of “Extreme” (Very High) vulnerability and this is related to the existence of dolines. Dolines serve as an indicator for extensively developed epikarst and for a low degree of protection provided by the unsaturated karstified bedrock. “High” and “Medium” vulnerability areas, in this case, coincide with the rest of the karstified terrain. However, “Medium” vulnerability exists due to the high depth-to-groundwater level, the presence of clayish soil and the existence of well-developed vegetation cover, especially on the eastern slope of Suva Planina Mountain. The rest of the area is characterized as “Low” vulnerability, as it is a non-karst area which consists of impermeable

Paleozoic and Neogene rocks, and clastic Quaternary sediments (mostly alluvial deposits: gravel and sand, with clay).

The vulnerability map that results from the COP method is a numerical representation of the multiplied C, O and P factors, because each one is considered in the assessment of the aquifer vulnerability (Fig. 6). Compared to other two methods, the map designed using the COP method shows more area with a “Very High” vulnerability. The “Very High” areas are mostly overlapping with karst aquifers, due to taking into consideration the high degree of karstification of the carbonate outcrops. The reasons for the larger area characterized as “Very High” vulnerability are due to the low natural protection of the karst aquifer, resulting from the physical properties as well as the thickness of the layers above the saturated zone (O factor) and the very high and high flow concentrations calculated using the C factor. The P factor (precipitation) has little or no impact on the vulnerability of the karst aquifer since this parameter remains the same over most of all the karstified area.

A histogram (Fig. 7) shows a comparison of the results obtained from the vulnerability mapping methods used in the study area. Of all the methods used, the COP method provides greater differentiation in vulnerability classes.



**Fig. 7** Percentage of surface area for each vulnerability class in the study area using different methods of assessment, compared to the percentage of karst outcrops

Namely, the “Very High” vulnerable category covers 19.4% of study area, while 12.3% of the research terrain is characterized as “High” vulnerability and 19.9% of the study area belongs to the “Medium” vulnerability class. The rest of the area (48.4%) is not in jeopardy, i.e. vulnerability is assessed as “Low”.

If one looks at the numbers for the PI and EPIK methods one can see that “Low” vulnerability is assessed in quite a similar area, 55.5% and 49.4% respectively. On the other hand, EPIK and PI methods as a result of the assessment deliver less than 10% of the study area as “Very High” vulnerable (7.8% and 5.6%, respectively). However, if we take into consideration two more vulnerability categories (“Very High” and “High”) and summarize them, we get 36.9% (EPIK), 23.0% (PI) and 31.7% (COP) of the study area. Terrain that is identified as a “Very High” and “High” vulnerable area has been built out of karstified limestone and dolomite, with thinner soil cover and sparse forest vegetation. Thus, we may say that all three methods gave good results in characterizing karstified rocks as vulnerable and prone to pollution.

The study area that is characterized as “Medium” in all three maps (EPIK, PI and COP) has values 13.7%, 21.5% and 19.9%, respectively. However, those areas consist of different geological formations. Nonetheless, the study area that is assessed as “Medium” vulnerability covers most of the rim of the karst massif of Suva Planina Mountain, which is comprised of fractured Paleogene/Neogene rocks with only locally important aquifers (intergranular and/or complex), usually covered with Quaternary and/or altered sediments (with a clay-rich, fine-grained clastic deposits).

Karstified terrain covers around 35% of the study area (blue rectangle on the Fig. 7) and that area is similar to the surface that is characterized as “Very High” and “High” vulnerable by the EPIK method, whereas the PI and COP

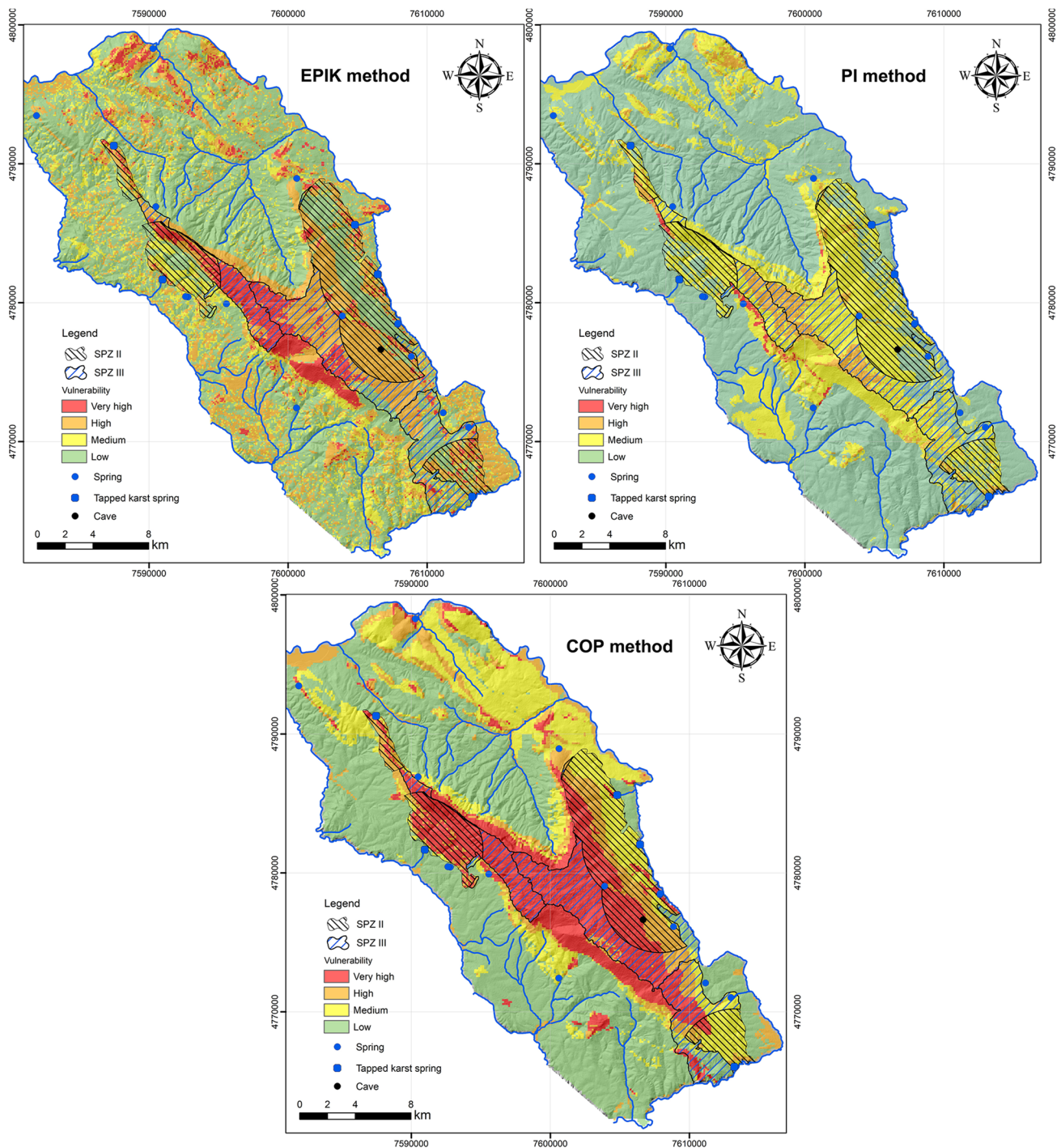
methods determine some of that karst as “Medium” vulnerability. This difference occurs from the fact that PI and COP methods take into consideration depth-to-groundwater, type and thickness of the soil, characteristics of the rocks in non-saturated zone, and the amount/intensity of precipitation, in addition to other parameters that EPIK analyzes as well.

According to Serbian legislation (Law on Water 2010), a project for defining a sanitary-protective zone (SPZ) is an obligatory measure for effective protection of groundwater intake structures, where a special regime of exploitation of a territory is set. The aim of establishing a special regime of use is to prevent the pollution of a public drinking water source. The situation in the research area apropos of SPZ is somewhat good, due to the existence of projects for defining SPZ for captured springs (Mokra, Divljana, Ljuberađa, Gornji Dušnik and Golemo vrelo, shown on Figs. 2, 3). Furthermore, the absence of permanent settlements on Suva Planina Mountain provides almost pristine conditions for aquifers. If we now compare areas that have been protected by the application of imposed boundaries and areas that should be protected considering vulnerability maps, discrepancies may be noticed (Table 1, Fig. 8).

The summarized surface of SPZ II and SPZ III that should be under protection, if one strictly apply Serbian legislation (The rulebook on the manner of determining and maintaining the sanitary protection zones of water supply sources 2008), that said that around object of water supply system should be imposed protective area on surface from which groundwater could reach spring in 1 day (SPZ II) and whole catchment area (SPZ III), one can sum up surface area of 165.05 km<sup>2</sup>. SPZ II and SPZ III would span over a smaller region of the mountain if we could apply a rule that only areas with medium, high and very high vulnerability need protection. The area under protection would be 28% smaller if we apply the EPIK

**Table 1** Comparison of the surface of the areas that have been protected by the application of imposed boundaries and areas that should be protected considering vulnerability maps

Protection type	Type of SPZ	Surface area that should be protected (km <sup>2</sup> )	Sum of surface area
Serbian legislation	SPZ I	0.0031	165.083
	SPZ II	92.72	
	SPZ III	72.32	
Surface area that should be protected (km <sup>2</sup> ) considering vulnerability maps			
EPIK	SPZ I	0.0031	118.183
	SPZ II	61.39	
	SPZ III	56.79	
PI	SPZ I	0.0031	122.133
	SPZ II	67.72	
	SPZ III	54.41	
COP	SPZ I	0.0031	155.033
	SPZ II	90.99	
	SPZ III	64.03	



**Fig. 8** Sanitary protection zones (SPZ) according to legislation (shaded areas) compared to vulnerability maps

method for defining second and third SPZ, 26% smaller if we apply the PI method and 6% smaller if we apply the COP method. On the other hand, if we apply a rule that only areas with high and very high vulnerability should be under transparent protection, the surface area will be reduced to 32% of the area proposed by the legislation if we apply EPIK method, 11% of the area proposed by

legislation if we apply the PI method and 35% of the area proposed by legislation if we apply the COP method.

Needless to say, the application of the rule that water supply company should clearly mark areas of SPZ (The rulebook on the manner of determining and maintaining the sanitary protection zones of water supply sources 2008), in remote areas such as this one is very difficult and might be

impossible. However, warning signs should be placed along the country and forest roads.

## Conclusion

Groundwater contamination in karst regions is not inevitable, and for sustainable protection of groundwater resources, priority must be given to prevention. Determination of the groundwater sanitary protection zones in the observed area is feasible and could be very efficient if properly delineated. Groundwater vulnerability maps can assist in developing groundwater protection strategies. This approach has the advantage of assessing the aquifer vulnerability at an early stage of the research, allowing the selection of a simplified method for further investigation for uncomplicated cases. More detailed research, including an evaluation of the aquifer's heterogeneity or tracer experiments and similar, are required for more complicated cases (high or very high vulnerability). A vulnerability map is not a stand-alone element but should be integrated into a comprehensive groundwater-protection scheme (Goldscheider 2005). COST Action 620 proposes such a scheme, comprising intrinsic and specific vulnerability mapping for both resource and source protection, validation techniques, and hazard and risk assessment (Zwahlen 2004).

The results of this study emphasized the fact that the karst aquifer in the study area shows vulnerability that ranges from "Low" to "Very high" (extreme). The highest contribution to the vulnerability of the karst aquifer was due to karstic features such as dolines, in all three maps. The COP map has the greatest areal extent of the "Very High" vulnerability area due to the presence of large amounts of carbonate rocks on the surface, that produce low natural protection and concentrated flow in dolines. The PI map shows that most of the karstified area has "Medium" vulnerability due to a high depth-to-groundwater level in the karstified limestones and the presence of clayish soil over a wider area. The vulnerability map designed with the EPIK method is "more balanced" compared to the other maps, though "Very High" and "High" vulnerable portions of the terrain could still be noticed.

Comparing the vulnerability maps that were created using the three different methods, it is noticeable that the methods do not produce completely consistent results. On the EPIK map, areas without bare karst features are always evaluated to be moderately vulnerable (or even low vulnerable), even when the karst rock is only covered by shallow soils. On the COP map, these areas are classified as highly vulnerable due to the modified assessment scheme for the O parameter. Otherwise, only small areas are classified as extremely vulnerable in the PI map. Another difference among the maps is

that the PI map always shows the vulnerability of the uppermost aquifer.

Although the concept of vulnerability mapping is an improved approach for the assessment of protection zones, further research is always recommended to characterize weathering, soil development, occurrence of vegetation, presence of karst depressions, fracturing degree of limestone (dolomite) and epikarst development. Hence, the necessity of the validation of the created vulnerability maps must be highlighted. Improvements of maps could be done with direct field investigation and/or indirect methods. The mandatory steps are hydrogeological observations, statistical analysis, modelling, vulnerability and risk assessments (Kazakis et al. 2018).

The differences in the percentages of the vulnerability areas that we can see in the study area show that methods for vulnerability mapping must be selected based on the best available data while using as much data as possible about the study area and organizing a thorough field investigation will help in selecting correct values for parameters/factors.

Based on these maps, a proposal for redefining the sanitary protection zones of the karst aquifers of Suva Planina Mountain, along with additional field research is made. New maps should help decision makers when considering water supply protection and should support sustainable development of this geographic area, especially since one part of Suva Planina Mountain was proclaimed a Special Nature Preserve in 2012.

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