

Groundwater vulnerability assessment for the karst aquifer of Tanour and Rasoun springs catchment area (NW-Jordan) using COP and EPIK intrinsic methods

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Abstract Groundwater vulnerability maps were constructed for the surface water catchment area of Tanour and Rasoun spring (north-west of Jordan) using the COP and EPIK intrinsic groundwater vulnerability assessment methods. Tanour and Rasoun springs are the main water resources for domestic purposes within the study area. A detailed geological survey was carried out, and data of lithology, karst features, precipitation, vegetation and soil cover, etc. were gathered from various sources for the catchment area in order to determine the required parameters for each method. ArcGIS software was used for map preparation. In the resulting COP vulnerability map, spatial distribution of groundwater vulnerability is as follows: (1) high (37%), (2) moderate (34.8%), (3) low (20.1%), and (4) very low (8.1%). In the EPIK vulnerability map, only two out of four vulnerability classes characterize the catchment area: very high vulnerable areas (38.4%) and moderately vulnerable areas (61.6%). Due to limited soil thickness, the low vulnerability class is absent within the catchment. The high percentage of very high to moderately vulnerable areas displayed by both the COP and EPIK vulnerability assessment methods are reflected by different pollution events in Tanour and Rasoun karst springs especially during the winter season. The high sensitivity of the aquifer to pollution can be explained by different factors such as: thin or absent soil cover, the high development of the

epikarst and karst network, and the lithology and confining conditions of the aquifer.

Keywords Karst aquifer · Groundwater vulnerability assessment · EPIK · COP · Jordan

Introduction

The “vulnerability of groundwater to contamination” term was introduced for the first time by Margat (1968). Foster and Hirata (1988) defined “aquifer pollution vulnerability” as the “intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load”. Over time, different vulnerability assessment methods have been developed especially for karst aquifers by using different hydrological and hydrogeological parameters, e.g. COP (Vias et al. 2002, 2006); EPIK (Doerfliger et al. 1999); PI (Goldscheider et al. 2000); and VULK (Jeannin et al. 2001).

The groundwater vulnerability concept is based on the fact that the physical environment itself provides natural protection and purification capability to groundwater against pollutants, especially against contaminants that enter the sub-surface environment due to the human impacts (Vrba and Zoporozec 1994). During the pollutants passage through the unsaturated zone, natural attenuation and purification of the pollutant’s and its concentration will occur due to the physico-chemical interactions between the rock materials in the unsaturated zone and the pollutants (Sililo et al. 2001; Pronk et al. 2009) as well as on biological activity.

Goldscheider (2003) distinguished between two types of groundwater vulnerability assessments and mapping in

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karstic environments: (1) intrinsic vulnerability assessment and (2) specific vulnerability assessment. The first type takes into considerations the natural characteristics of the aquifer itself (geological, hydrological and hydrogeological characteristics), while the second type of vulnerability assessment is taking into consideration the intrinsic vulnerability in combination with the properties of the contaminant itself and the contamination scenarios.

The EPIK method (Doerfliger et al. 1999) (*E* epikarst, *P* protective cover, *I* infiltration, *K* karst network) is one of the intrinsic vulnerability methods that has been developed especially for karst areas based on different weighting and rating parameters. According to Gogu and Dassargues (2000), the EPIK method uses specific features for the karst aquifers due to the fact that conduits network and the connected joints and fractures divides a more compact zone of limestone. On the other hand, the COP groundwater vulnerability assessment method (*C* flow concentration, *O* overlying layers, *P* precipitation) was developed during the COST Action 620 (2003) for the assessment of intrinsic vulnerability of karstic aquifers based on four factors presented in the European approach conceptual model (Fig. 1), and it was tested in southern Spain (Vias et al. 2002, 2006).

Jordan is considered as one of the poorest countries in the world related to available water resources (UNDP 2015). The water supply per capita ranged between 129 and 154 L per capita and day between 2000 and 2013 (MWI

2013a). The average annual abstraction from all basins in Jordan exceeds the renewable average of recharge and currently stands at 159% of that average (MWI 2016), due to the over-exploitation of groundwater compared with the low natural replenishment (low rainfall amount and high evaporation rate).

Tanour and Rasoun springs are the main water resources for drinking purposes within the study area. Most of the wells drilled within the area failed due to the complexity of the geological, tectonic and geomorphological settings of the karst area. Frequently, the water supply from the two springs has to be interrupted due to contamination events. The source of pollution is either from: (1) microbiological contaminants resulting from wastewater leakage from septic tanks in the surrounding villages (detected in both springs), or (2) wastewater from local olive oil presses (only detected in Tanour spring).

Groundwater vulnerability assessment maps are a valuable tool for decision-makers in order to protect groundwater resources from pollution. Within this research work, two intrinsic groundwater vulnerability assessment maps were constructed for the karst aquifer within the Tanour and Rasoun spring catchment area by applying the EPIK and COP vulnerability assessment methods. The two maps and methods are compared in order to better understand processes, leading to karst aquifer vulnerability within the catchment of the two springs.

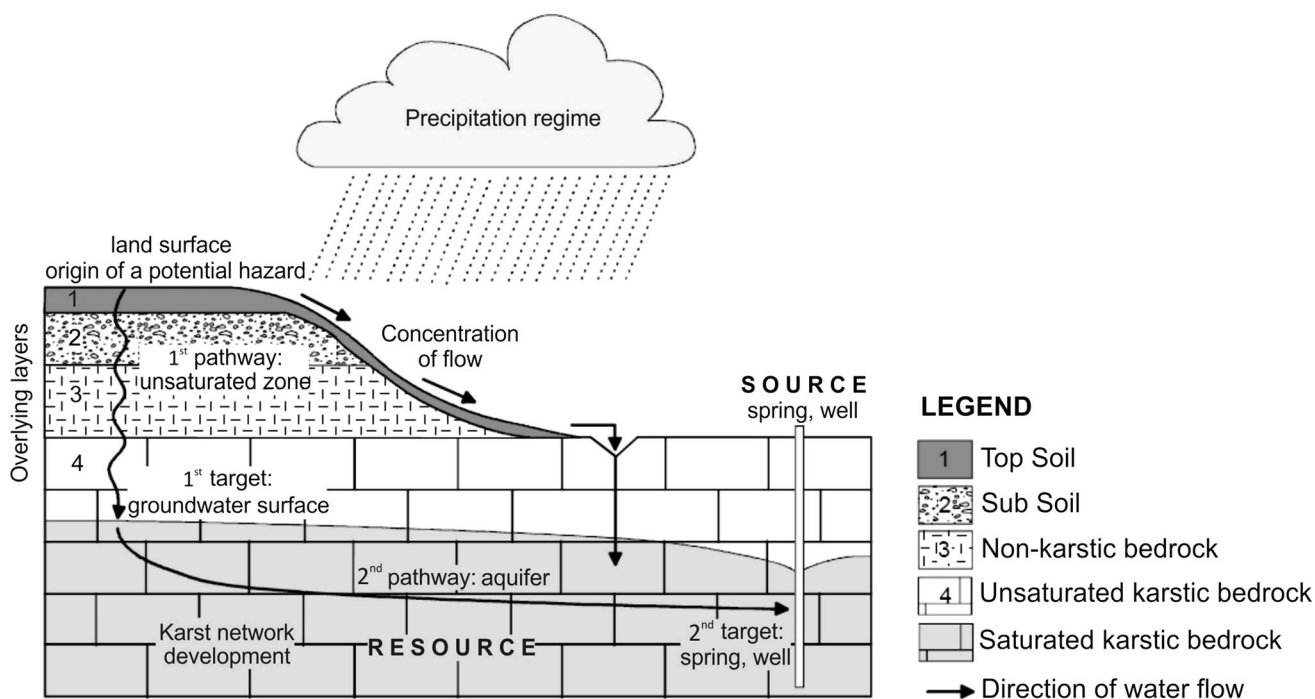


Fig. 1 European approach conceptual model (Goldscheider 2002)

Study area

Description of the study area

The catchment area of the Tanour and Rasoun springs is located in the north-eastern part of the Ajloun governorate, about 75 km north-west of the capital of Amman (Fig. 2a) and covers around 36 km². The study area is considered as one of the areas in Jordan that receives the highest amount of precipitation during the winter season and is characterized by cold winters and moderately warm summers. Historical meteorological data from the Ras Munif meteorological station (AH0003; Fig. 2a) for the time period 1968/1969–2013/2014 (MWI 2013b, 2014a; JMD 2014) indicate long-term average monthly minimum temperatures between 2.5 and 4.5 °C in the winter season (December and January) and 16 °C during the summer season (July and August). Long-term average monthly maximum temperatures are 8–10 °C between December and February and reach 27 °C during summer (June to

August). The long-term average annual precipitation is 545 mm/year.

Based on the digital elevation model, using ASTER data with 30-m resolution (USGS 2014a), elevations within the catchment area are between 617 m asl in the north-west to 1187 m asl in the south-east (Fig. 2b). According to Hamdan et al. (2016), three land cover types were classified: (1) forests (dense trees) (11.50 km² or 32%), (2) urban areas (2.80 km² or 8%), and (3) bare and low to very low vegetated areas (21.70 km² or 60%) (Fig. 2c).

The long-term average discharge of Tanour and Rasoun springs (monthly measurements) between 1963 and 2014 (MWI 2015a) is 260 and 90 m³/h, respectively. The calculated yearly production (based on the monthly production values) for the time period between 1996 and 2014 (MWI 2015b) was around 1,135,000 m³/year for Tanour spring and 125,350 m³/year for Rasoun spring. Note that discharge is higher than production because not all water can be used for water supply during pollution events, due to high water turbidity during recharge events, due to lack of

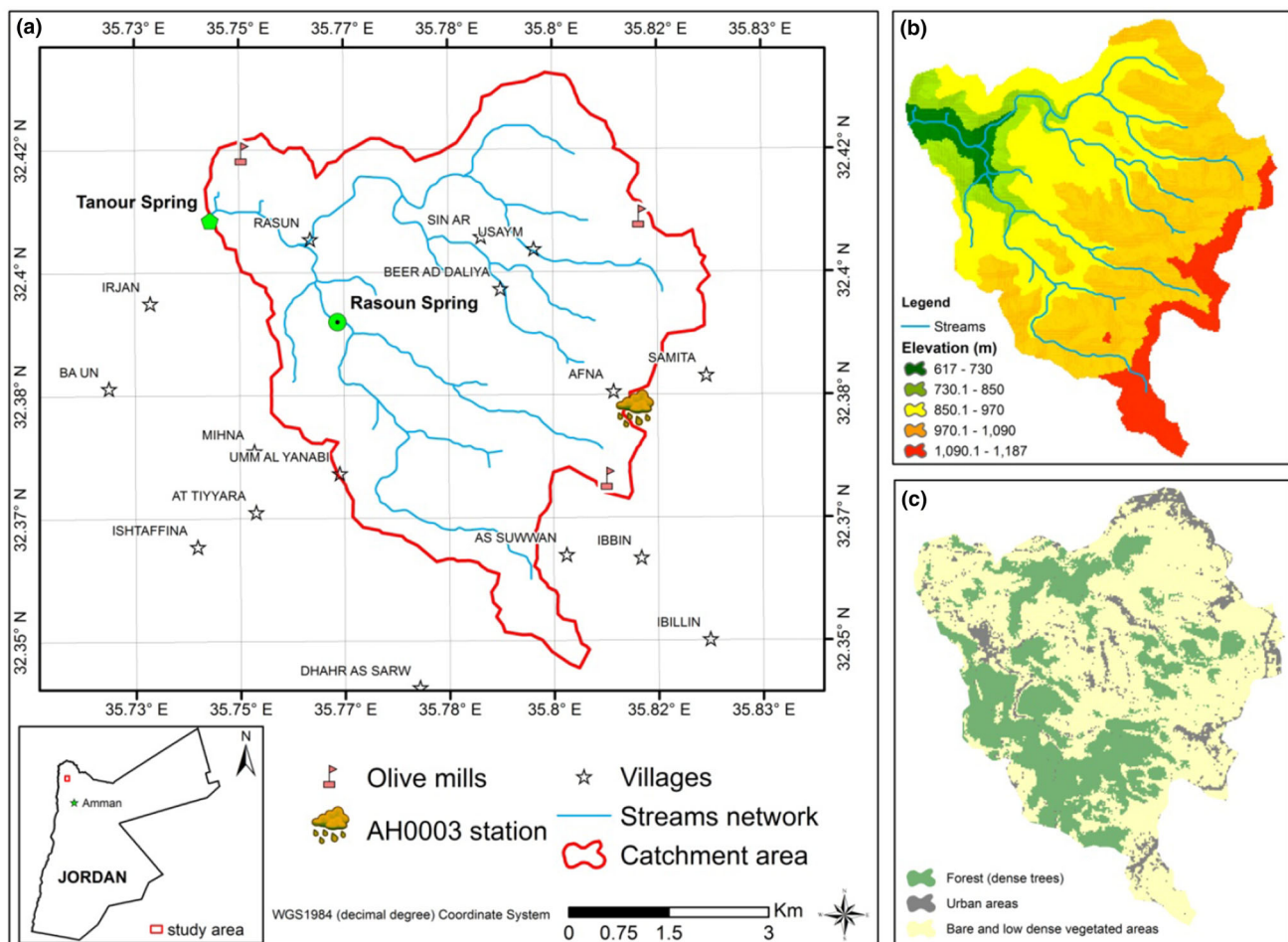


Fig. 2 Overview map showing, **a** general overview map for the study area, **b** elevation [based on ASTER data with 30-m resolution (USGS 2014a, “ASTER GDEM is a product of METI and NASA”)], and **c** land cover (modified after Hamdan et al. 2016)

storage capacities, and due to administrative constraints and maintenance processes.

Geological and hydrogeological situation within the study area

The geological formations within the catchment area are part of the upper Ajloun Group (A4, A5/6, and A7 formations) and the lower Belqa Group (B1 and B2 formations) (Fig. 3) and are of upper cretaceous age. According to Abdelhamid (1993, 1995) and Hamdan et al. (2016), the geological sequences in both of the groups are characterized as follows (from older to younger): (1) the Hummar Formation (A4 aquifer): this formation consists mainly of pink to yellow-grey limestone and dolomitic limestone; the average thickness of this formation within the catchment area is of 40–50 m, both the Tanour and Rasoun springs discharge from this aquifer. (2) The Shu'ayb Formation (A5/6 aquitard): this formation consists of fossiliferous massive crystalline limestone, yellow to yellow-grey thin to medium bedded of marly limestone and marls; the total thickness of this formation within the catchment area is

55–70 m. (3) The Wadi As Sir Formation (A7 aquifer): this formation consists of around 120–140 m of bedded and karstified limestone and dolomitic limestone. (4) The Wadi Umm Ghudran Formation (B1 aquitard): this formation considered mainly as the upper part of the Wadi As Sir (A7) Formation, where it composed of around 30–35 m of dolomitic marly limestone. (5) The Amman Silicified Limestone Formation (B2 aquifer), which is mainly consists of medium to thin bedded chert, silicified limestone, limestone and phosphatic chert with a total thickness within the catchment area of around 60–70 m. Formations (3) to (5) form the so-called Amman–Wadi As Sir (A7/B2) aquifer.

Within the catchment area, water is potentially found in 2 aquifers, the A4 and the A7/B2. According to Hobler et al. (2001), limestone, marly limestone, and dolomitic limestone are the predominant rock types in the entire lower Ajloun Group in the Yarmouk area (north to the study area), and there are interconnections between the A1/6 aquifer and the A7/B2 aquifer. According to Hamdan (2016), there is an extensive influence of widespread tectonic and karstic features on the aquifer system, suggesting

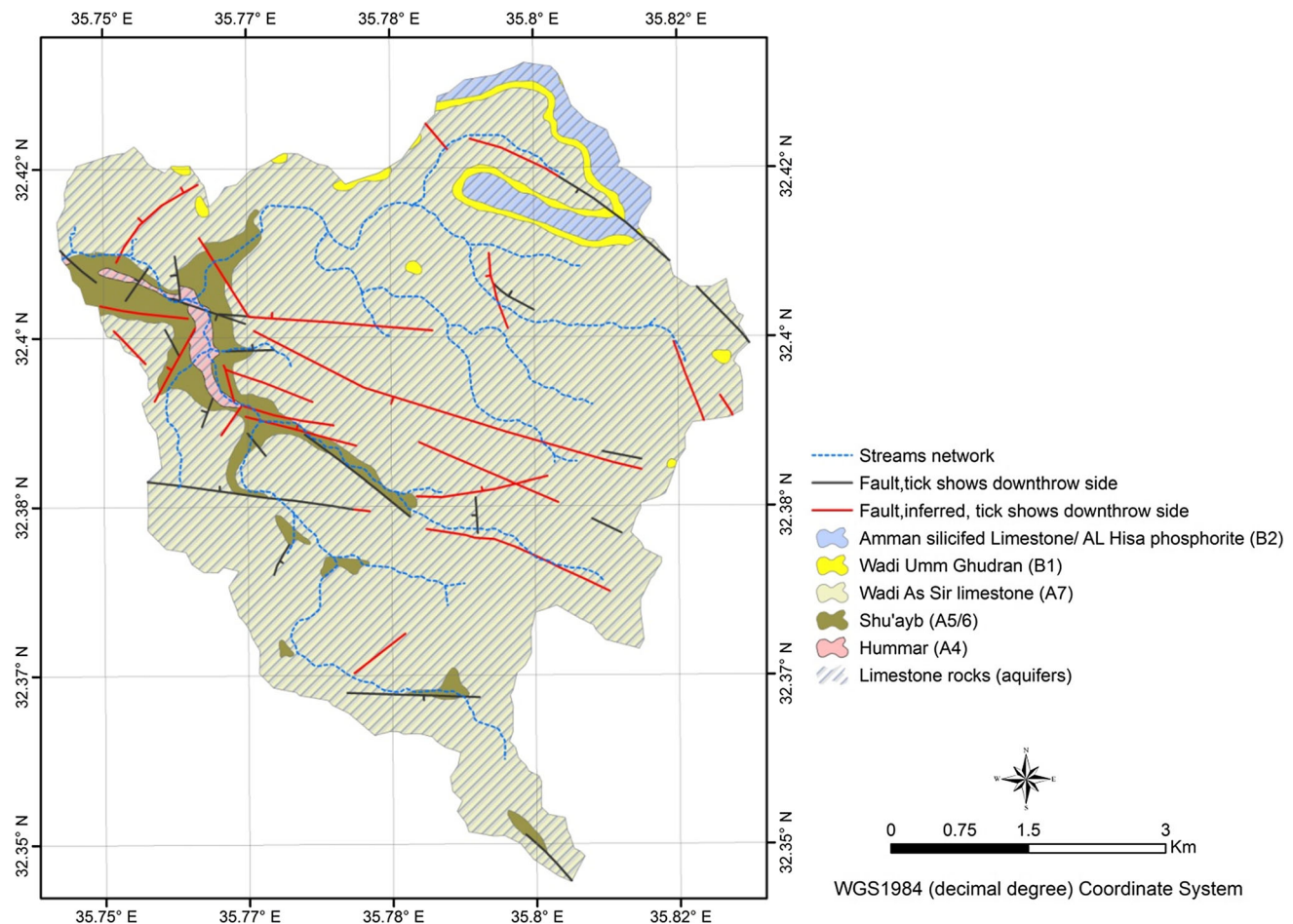


Fig. 3 Geological and structural map of the study area (modified after Abdelhamid 1993)

that the Hummar (A4) aquifer is hydraulically interconnected with the overlying Amman–Wadi Sir (A7/B2) aquifer. While there is little water in the A7/B2 aquifer, in spite of a vast outcrop area, most of the springs in the study area discharge from the Hummar Formation (A4), which has only limited outcropping areas. Due to that, the A7/B2 is considered to recharge the A4 aquifer which is almost fully saturated, while the A7/B2 aquifer carries water only seasonally. According to Hamdan (2016), the average hydraulic conductivity value K for the aquifer is 11.46 m/day. Different surface karst features are present at different scales, such as dolines, caves, dry valley, and highly fractured rocks (Fig. 4).

All the geological formations were assumed as unconfined layers, where the applied COP and EPIK vulnerability assessment methods within the catchment area were applied for the outcropping formations.

Methodology and data requirements

Data requirement

In order to apply the COP and EPIK vulnerability assessment methods, different data sources were evaluated and required information was collected (Table 1).

All data were processed and analysed using ArcGIS 10.3 software (ESRI Inc.©) with a grid resolution of 30×30 m.

COP method

The COP vulnerability assessment method is based on three main factors: (1) flow concentration (C factor), (2) overlying layers (O factor), and (3) precipitation (P factor). Figure 5 represents the schematic diagram for the



Fig. 4 Karst features within the catchment area (based on the geological survey for the area); **a** doline ($\sim 15 \times 10$ m), **b** dissolution in the rocks, **c** big fractures between beddings planes, **d**, **e** caves, and **f** dissolution and big pores inside the rocks

Table 1 Information required for applying COP and EPIK vulnerability methods

Parameter/property	Data/parameter values needed and its source
Karst features (epikarst) and network development	Field work within the study area to obtain (a) A detailed description of the karst features within the study area (b) Waypoints for the karst feature locations and their extensions using GPS
Slope and vegetation	Classified land cover map for the area (Hamdan et al. 2016) Digital elevation model, 30-m resolution type ASTER (USGS 2014a)
Protective cover (soil)	Soil units map with texture description and estimated thickness of each unit (MoA 1994)
Lithology	Outcropping geological formations for the area as a shape file, scale 1:50,000, including a lithological description for each formation (Abdelhamid 1993, 1995) Thickness of the unsaturated zone; based on (a) geological and hydrogeological description of the area (b) wells lithology and pumping test data (MWI 2014b)
Precipitation quantity and temporal distribution	Long-term daily rainfall data for a meteorological station within the study area (MWI 2014a)

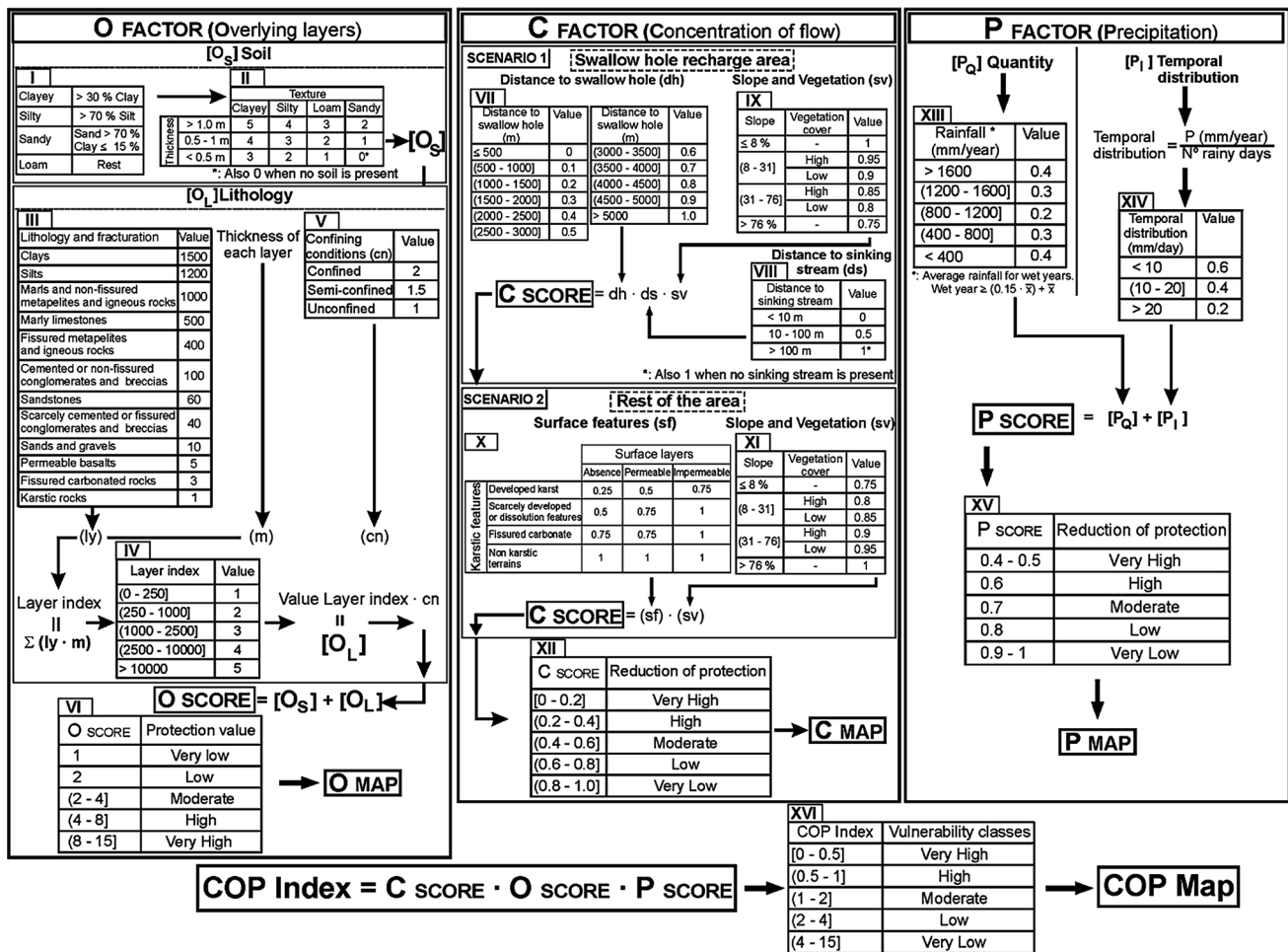


Fig. 5 COP method schematic diagram and numeric evaluation of Tables I–XVI (Vias et al. 2006, used with permission)

COP vulnerability assessment method. Based on Daly et al. (2002), the concentration of flow (*C*) factor depends mainly on the availability of the karst features that make the flow concentrated, in addition to the availability of the parameters and factors that control and affect the runoff, like slope and vegetation cover. The overlying layer (*O*) factor refers to the protection of the unsaturated zone against contaminants based on the soil texture and thickness (O_S), and the characterization of the aquifer (O_L) with respect to the lithology and fracturation, the thickness of the unsaturated zone, and the confining conditions of the aquifer. On the other hand, the *O* factor represents the ability of the unsaturated zone within the karst aquifer to filter out the contaminants and reducing their effects (Vias et al. 2003). According to Daly et al. (2002), the precipitation (*P*) factor considers the quantity and the temporal distribution of the precipitation, where both of them can have a major effect on the final infiltration rate and quantity. The overall COP index is calculated as: $COP\ index = C_{SCORE} \times O_{SCORE} \times P_{SCORE}$.

EPIK method

EPIK is an acronym for four parameters: epikarst (*E*), protective cover (*P*), infiltration condition (*I*), and karst network development (*K*). Figure 6 represents the EPIK vulnerability method standard classification.

Klimchouk (1997) defined the epikarst zone as “the uppermost zone of outcropping karstified rocks, in which permeability due to fissuring and diffuse karstification is substantially higher and more uniformly distributed than in the rock below”. The epikarst zone has been divided into three *E* parameter classes based on the karst morphological features: E1, E2, and E3. The infiltration condition factor considers the type of recharge to the karst aquifer, and it does not include the recharge in terms of quantity or location. The infiltration *I* factor was divided into 4 categories (from I1 to I4) according to the change in the infiltration conditions from concentrated to diffuse infiltration. The *K* factor reflects the presence or absence of a karstic network, as well as the development degree of that network (Doerfliger and Zwahlen 1998). A well-developed karst network has network openings with decimetres to metre size.

The overall protection index (*F*) for EPIK method is calculated using the following formula (Doerfliger et al. 1999):

$$F = \alpha E + \beta P + \gamma I + \delta K$$

where α , β , γ , and δ are the weighting coefficients. Table 2 represents the standard rates and weighting coefficients value for each parameter of the EPIK vulnerability assessment method.

Based on the weights and rates for the protection index (*F*) calculations, the protection index (*F*) can obtain values ranging from 9 to 34. Table 3 shows the different vulnerability classes based on the protection index (*F*) values.

Results and discussion

COP layers

No swallow holes were identified in the study area. Therefore, scenario 2 (see Fig. 2) was used in all areas to calculate the final C_{SCORE} map which is merging the surface features with the slope and vegetations. Based on the available karst features within the study area and the surface features permeability, following values were assumed for the surface features (sf) layer:

- value 0.25: developed karst with the absence of surface features.
- value 0.75: scarcely developed or dissolution features with permeable surface features.
- value 1: non-karstic terrain.

On the other hand, the *sv* values were ranged between 0.75 and 1 based on the combination between the slope and the available vegetation cover. The C_{SCORE} map shows that the study area ranges from a very high to a very low reduction of protection areas (Fig. 7a).

The calculated O_{SCORE} map (as a result of the summation the O_S and O_L sub-factors) showed that the protection values can be considered moderate to very high (Fig. 7b). The final O_{SCORE} values were ranged between four and nine. On the other hand, based on long-term daily rainfall data from 1968/1969 to 2012/2013 (water year), P_{SCORE} was calculated as a fixed value of 0.7 which represents a moderate reduction of protection.

EPIK layers

The EPIK data layers for the study area were prepared based on a field survey, which was conducted focusing on karst features and the karst network. Other data layers (soil, geology, land cover, etc.) were prepared for the study area using existing data sources (see Table 1). The epikarst layer was divided into three subgroups E1, E2, and E3 based on the development of the epikarst. Figure 8a represents the epikarst (*E*) factor map for the study area. The *P* factor was determined (especially the P1 where the soil thickness was very thin) based on the soil depth data (MoA 1994), Google earth maps of the study area (Google Inc.©), and photographs from the field trip within the study area. Figure 8b represents the protective cover (*P*) factor for the study area, where P1 and P2 sub-factors are assigned. For

Epikarst (E)			
Epikarst		Karst Morphological Features	
Highly developed	E1	Sinkholes, dolines, caves, karrenfields or outcrops with high fracturing.	
Moderately developed	E2	Intermediate zones in the alignment of dolines or dry valleys. Outcrops with medium fracturing.	
Small or absent (rest of the catchment)	E3	No karst morphological phenomena. Low fracture density.	
Protective Cover (P)			
Protective Cover		Characterisations	
		A. Soil lying directly on limestone or on some high permeability coarse detritus layers, e.g. rock debris, or lateral glacial tills.	B. Soil lying on low permeability geological layers, e.g. lake silt or clays.
Absent ↓ Present	P1	0–20 cm of soil	0–20 cm of soil on layers that have a thickness of less than 1 m.
	P2	20–100 cm of soil	20–100 cm of soil on layers that have a thickness of less than 1 m.
	P3	100–200 cm of soil	< 100 cm of soil or > 100 cm of soil and > 100 cm of layers of low permeability.
	P4	> 200 cm	> 100 cm of soil and thick detritus layers of very low hydraulic conductivity or > 8 m of clay and clayey silt.
Infiltration (I)			
Infiltration Condition		Characterisation	
Concentrated ↓ Diffuse	I1	Perennial or temporarily losing streams – perennial or temporary stream feeding a swallow hole or a sinkhole (doline) – water catchment areas of these above-mentioned streams, including artificial drainage systems.	
	I2	Water catchment areas of streams in I1 (without artificial drainage systems) with a slope greater than 10% for cultivated areas and 25% for meadows and pastures.	
	I3	Water catchment areas of the I1 stream (without artificial drainage systems) whose slope is less than: 10% for cultivated areas and 25% for meadows and pastures. Low relief areas collecting runoff water and slopes feeding those low areas (slope higher than: 10% for cultivated sectors and 25% for meadows and pastures).	
	I4	The rest of the catchment.	
Karst Network Development (K)			
Karst Network		Characterisation	
Well-developed karst network	K1	Presence of a well-developed karst network (network with decimetre to metre sized channels that are rarely plugged and are well connected).	
Poorly-developed karst network	K2	Presence of a poorly-developed karst network (small conduits network, a poorly connected or filled network, or a network with decimetre or smaller sized openings).	
Mixed or fissured aquifer	K3	Presence of a spring emerging through porous terrain. Non-karst, only fissured aquifer.	

Fig. 6 Standard classification for EPIK parameters (Doerfliger and Zwahlen 1998; Doerfliger et al. 1999, used with permission)

Table 2 Standard rates and weighting coefficient for the EPIK parameters (Doerfliger and Zwahlen 1998)

Parameter	Epikarst			Protective cover				Infiltration condition				Karst network		
Weighting coefficient	$\alpha = 3$			$\beta = 1$				$\gamma = 3$				$\delta = 2$		
Standard rate for each sub-parameter	E1	E2	E3	P1	P2	P3	P4	I1	I2	I3	I4	K1	K2	K3
	1	3	4	1	2	3	4	1	2	3	4	1	2	3

Table 3 Vulnerability classes for the EPIK method based on the protection index (F) (Doerfliger and Zwahlen 1998)

Vulnerability class	Protection index (F)
Very high	F lower or equal to 19
High	F between 20 and 25
Moderate	F higher than 25
Low	$F > 25$ with the presence of $P_4 + (I_{3,4})$ categories

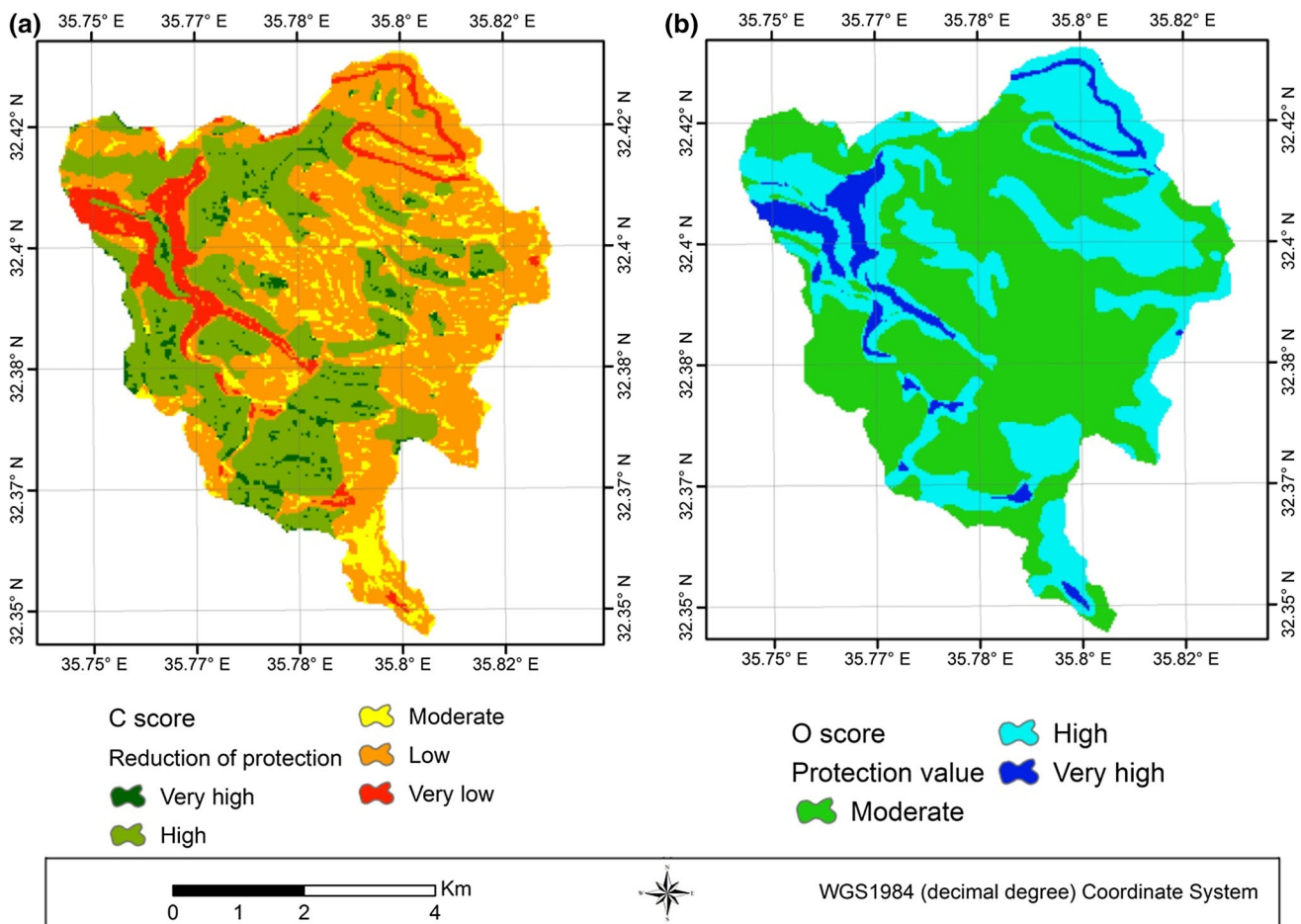


Fig. 7 a C_{SCORE} map for the study area, b O_{SCORE} map for the study area

the infiltration condition, the I4 sub-factor, i.e. diffuse infiltration, was assumed for the whole catchment. For the karst network development, sub-factors were divided into three groups according to the degree of the karst network

development. Figure 8c displays the karst network (K) map, where K1 represents areas with highly developed karst networks, and K3 represents non-karst areas (only fissured aquifers).

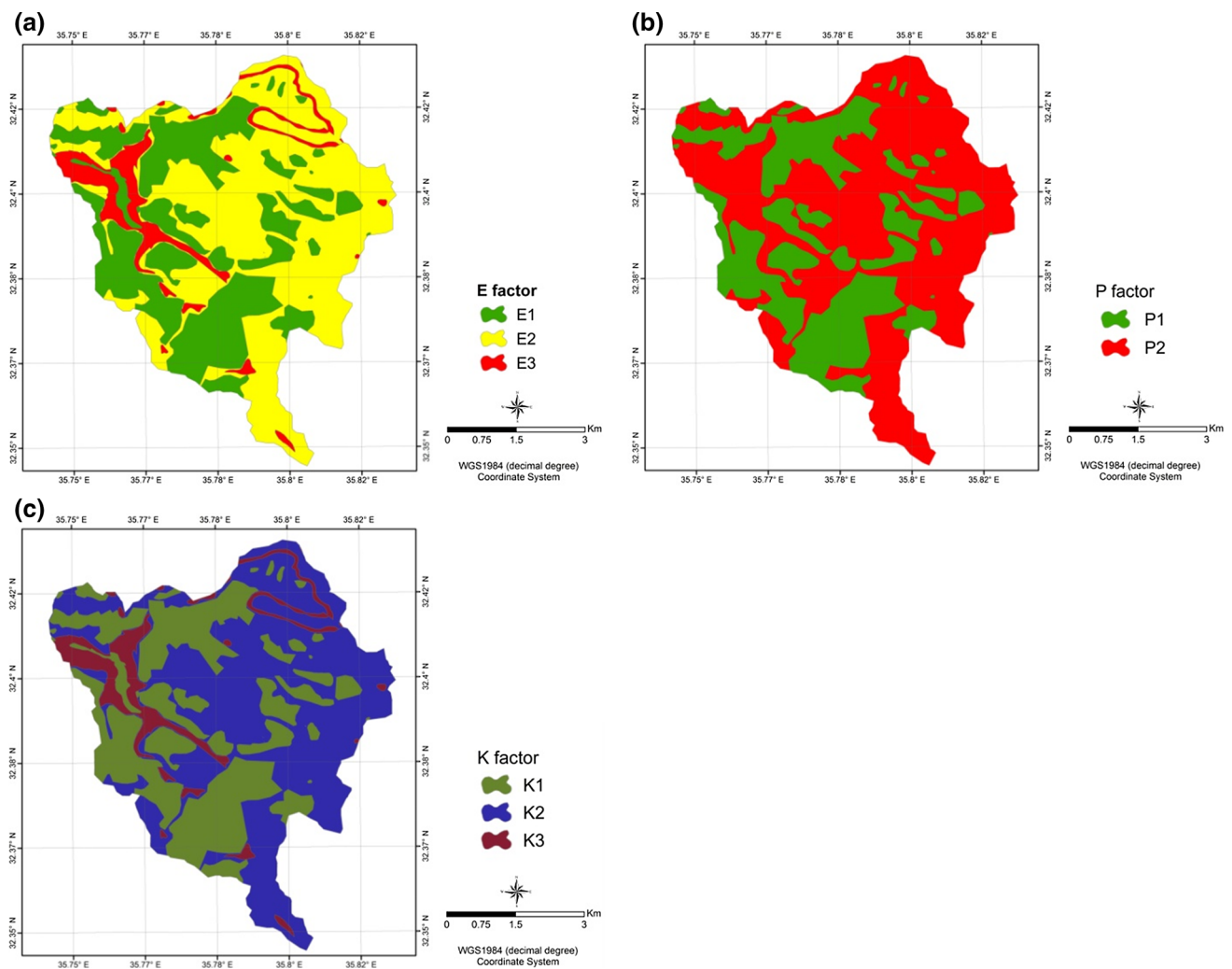


Fig. 8 Shows **a** epikarst (*E*) factor map for the study area, **b** protective cover (*P*) factor map for the study area, and **c** karst network development (*K*) map for the study area

Final COP and EPIK vulnerability maps

After preparing all required factors for both COP and EPIK vulnerability assessment methods in a digital format using ArcGIS software, the final calculation was done based on the equations for the COP ($COP\ index = C_{SCORE} \times O_{SCORE} \times P_{SCORE}$) and EPIK ($F = \alpha E + \rho P + \gamma I + \delta K$) methods in order to obtain the final vulnerability map from both of these methods. Figure 9a, b represents the final COP and EPIK groundwater vulnerability maps for the study area, respectively.

Based on the final vulnerability maps from COP and EPIK, the area for each vulnerability class was calculated. For the EPIK method, the area of the very high vulnerability class was 13.8 km² or 38%, compared to the moderate vulnerability class, which was 22.1 km² or 62%. On the other hand, the area for the COP vulnerability classes was calculated as follows: high vulnerability (13.3 km² or

37%), moderate vulnerability (12.5 km² or 35%), low vulnerability (7.2 km² or 20%), and very low vulnerability (2.9 km² or 8%).

From the final vulnerability maps, it can be noticed that in the EPIK method, there are only two vulnerability classes (very high and moderate), compared to the COP method, where four vulnerability classes are present (high, moderate, low, and very low). In the COP method, the *O* factor considers the lithology and thickness of the unsaturated zone as well as the confining conditions, which is not considered in the EPIK method. For example, in the COP method, non-karstic formations like marl and marly limestone formations are classified as areas of very low vulnerability. However, in the EPIK method, this is not differentiated, so that these areas are considered as moderately vulnerable. In addition, the COP method considers the quantity (P_Q) and the temporal distribution (P_T) of the precipitation within the catchment area, while in the EPIK

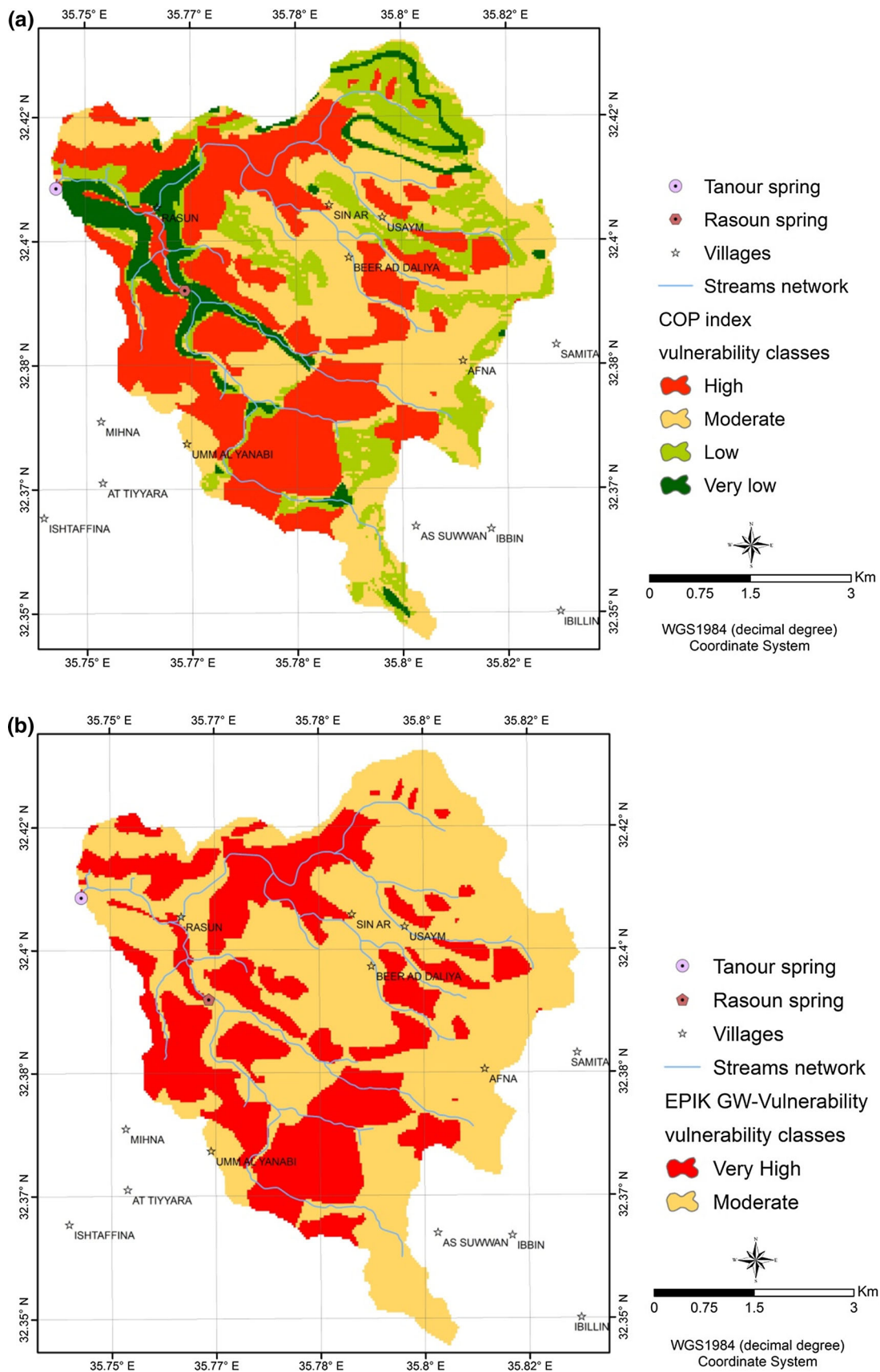


Fig. 9 COP groundwater vulnerability map (a), and EPIK groundwater vulnerability map (b) of the study area

Table 4 Intersection percentages between each land cover type within the catchment and vulnerability classes for both, COP and EPIK vulnerability maps

Land cover classes	COP (%)				EPIK (%)	
	High	Moderate	Low	Very low	Very high	Moderate
Bare and low dense trees	11.6	28.0	15.0	5.8	12.5	47.8
Urban	0.5	3.5	2.5	1.1	0.6	7.1
Forest	25.0	3.4	2.5	1.1	25.8	6.2

method the precipitation quantity and temporal distribution are neglected.

Both the EPIK and COP methods consider karst feature presence and karst network development within the study area by determining the *C* factor in the COP method and the *E* and *K* factors in the EPIK method. Determining these factors requires a highly detailed field work survey for karst feature and karst network characterization within the study area, which is sometimes difficult due to, for example, a large extent of the study area, difficulties reaching parts of the study area, amount of time required, and costs.

The COP method allows many factors to be easily obtained (precipitation, soil, geological data, etc.) and provides, compared to EPIK, a higher level of applicability for different hydrogeological settings. EPIK is suitable for pure karstic environments only.

A direct comparison (through the intersection command in ArcGIS) between both, the COP and EPIK vulnerability maps, with the land cover map was performed. Table 4 represents the intersection percentages between each land cover type and each vulnerability class in the COP and EPIK vulnerability maps.

Table 4 shows that high vulnerable areas of the COP method and the very high vulnerable areas of the EPIK method represent more than one-third (~38%) of the catchment area. This high percentage compared to the low share of low and very low vulnerability class areas (especially in the COP method) reflects the high contamination sensitivity of the catchment. This sensitivity is reflected by the high number of the pollution events that occurred in the Tanour and Rasoun springs during the past years, especially during the winter season, due to the high flow velocity in the karst system.

The presence of karstic features, karst network development, protecting soil thickness, lithology, and the thickness of the unsaturated zone are considered as important factors in determining the highly vulnerable areas within the catchment, where pollutant movement from the surface to the saturated zone is accelerated. According to Hamdan et al. (2016), Tanour spring showed a fast response to precipitation events with an average maximum travel time of 8 days. This fast response of the Tanour spring to the precipitation events is reflecting the high percentage of “very high” to “moderate” vulnerable areas within the catchment.

Conclusion

The application of the COP and EPIK intrinsic groundwater vulnerability methods for the karst aquifer of the Tanour and Rasoun springs catchment area provides valuable information about the karst aquifer sensitivity to pollution, which can help decision-makers for any future land and water use planning activity. All necessary property and parameter maps needed for the application of the COP and EPIK vulnerability assessment methods were obtained using ArcGIS software which is an efficient tool, especially with respect to the required raster calculations.

The availability of a protective cover layer plays an important role in assessing aquifer vulnerability. Within the investigated catchment area, the protective cover above the highly karstified limestone is either absent or very thin; therefore, a large proportion of the area can be classified as highly vulnerable.

Based on the COP groundwater vulnerability map, the catchment area was divided into 4 vulnerability classes (high, moderate, low, and very low), while based on the EPIK groundwater vulnerability map, the catchment area was classified into two groups (very high and moderate). This difference in the vulnerability classes within the same catchment occurred because of using different parameters in each method and a different classification system. For example in the EPIK vulnerability method, the very low vulnerability class is not available at all, and the low vulnerability class can appear only under specific conditions ($F > 25$ with the presence of $P_4 + (I_{3,4})$ categories). The COP method showed a higher level of flexibility with respect to different hydrogeological conditions.

The high percentage of the very high to moderate vulnerable areas (either in COP or EPIK vulnerability methods) reflects the urgent need to effectively protect the catchment area of the Tanour and Rasoun springs, by applying a good land use management and developing a water safety plan in the area. Also, frequent monitoring of water quality and monitoring of activities by the local olive mills, and the related illegal dumping of wastewater in the wadis should be performed.

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