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A Contribution of GIS Methods to Assess the Aquifer Vulnerability to Contamination: A Case Study of the Calcareous Dorsal (Northern Rif, Morocco)

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Abstract

Karst groundwater constitutes the main resource for drinking water supply in Chefchaouen region, North Morocco. However, the karstic aquifers are highly vulnerable to the pollution because of the deforestation which favors the soil erosion and the landslides. Therefore, the groundwater is loaded with suspended sediment. The fertilizers disseminated for agriculture can also infiltrate and concentrate in the saturated zone of the aquifer. In this study, the geographic information system (GIS) provides an effective tool for groundwater contamination risk assessment, because it facilitates multicriteria analysis and updates the models developed. The EPIK model based on GIS uses four environmental parameters (Epikarst, Protective cover, Infiltration condition and Karst network development) to evaluate the intrinsic vulnerability of groundwater contamination potential. Each of these parameters is presented as a thematic map. After adding all data, the final result provides vulnerability map according to the protection factor relation based on which the protection zones' map is created.

1. Introduction

Carbonate rock outcrops, of which a large part is karstified, cover about 7% - 12% of the planet's dry, ice-free land, and karst waters supply about 25% of the global population [1]. In Morocco, the Karst groundwater is a

very important source of drinking water supply for many regions. In fact, they contain 70 percent of the water resources [2].

Decreasing availability, declining quality, and growing demand for fresh water are creating significant challenges. The balance between demand (consumption) and supply (resource) is becoming untenable. More than 30 countries suffer from serious chronic water shortage, and groundwater is increasingly being used to cover the demand [3]. The study area is mostly composed of limestone in which the huge water reserves constitute the largest water tower in northern Morocco. Some spring water discharges increase due to rain or snowmelt, exceeding 100 liters per second.

Karst aquifers are considered to be highly vulnerable to pollution as a result of their particular structure; hence it appears that the supply is made by a dispersed input and the discharge—by a concentrated output. Due to this fact, contaminant elements' attenuation doesn't take place effectively, as in porous aquifers [4].

In order to map the groundwater vulnerability, karstic aquifers near to Chefchaouen city (Northern Rif, Morocco) were selected to test the sensitivity of vulnerability to selected values of ratings and weight in the EPIK method based on a Geographic Information System (GIS). It is considered as the first method taking into account the specific properties of karst [4] [5]. The acronym stands for the four factors that are considered: Epikarst (E), Protective cover (P), Infiltration conditions (I) and Karst network development (K).

2. Study Area

The study area forms part of the Septentrional Internal Rif. It corresponds to the segment of the external Calcareous Dorsale located precisely between the Oued Laou valley in the north, and the major fault of Jebha-charafate in the south (**Figure 1**). It consists of three stacked tectonic units: Jbel Tissouka unit, Jbel Lakraa unit, and
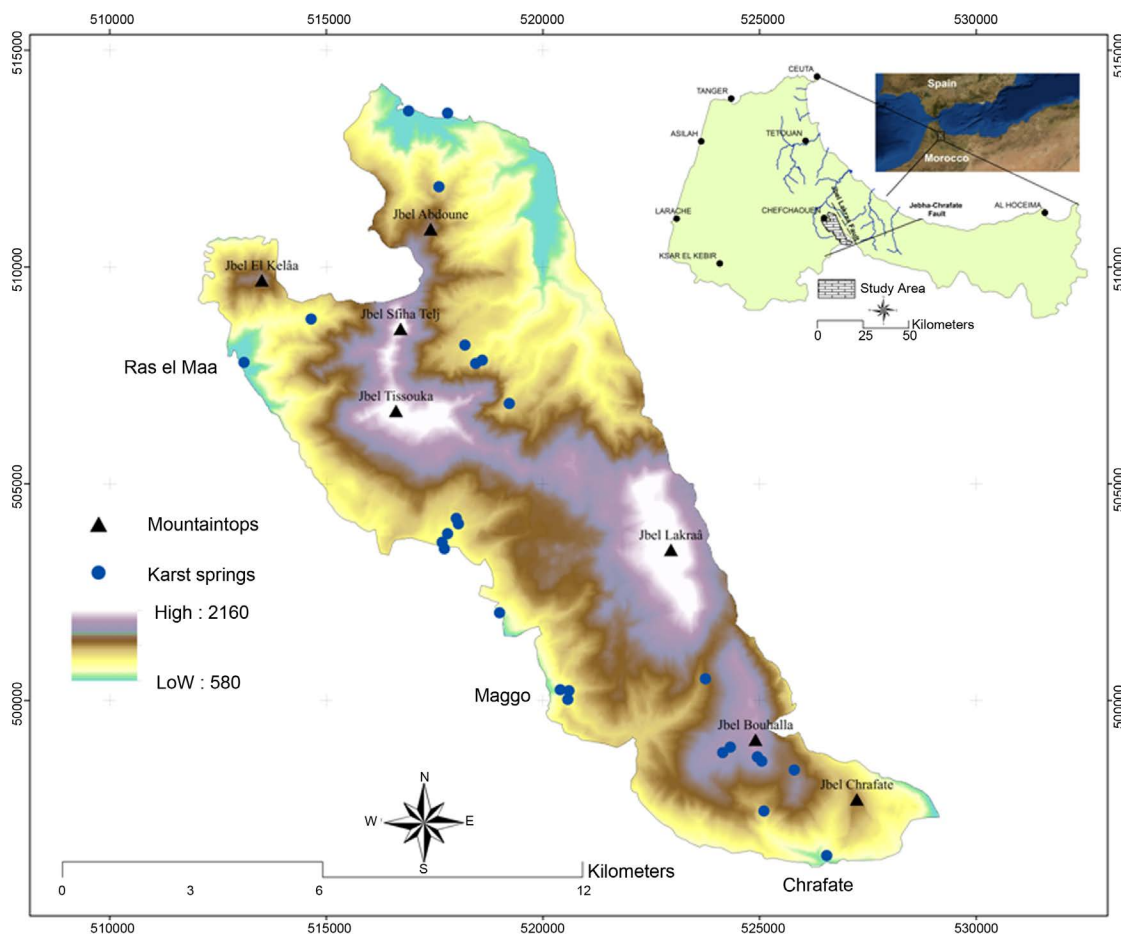

Figure 1. Location map and DEM (Digital Elevation Model) of study area.

the Jbel Bouslimane unit, where some peaks exceed 2000 meters in high (2122 m in Jbel Tissouka and 2159 m in Jbel Lakraa).

3. Geological and Hydrogeological Setting

The units of study area are stacked in nappes with tectonic contacts dipping westward [6]. They are separated from the massif of Jbel Tazout by the directed NW-SE fault of Jbel Lakraa. The stratigrafic successions of the Calcareous Dorsal are described from bottom to top as [6] (**Figure 2**):

- Up to 900 m in thick of Carnian to Norian stromatolitic dolostones with intercalations of marly limestone;
- 80 to 300 m of limestone and dolomite alternation (Rhetian);
- Massive limestone and/or dolomite, their attribution to the Hettangian age is not strictly deducted;
- Flint limestone with marls and bituminous facies and intraformational breccias (from Sinemurian to Pliensbachian);
- The radiolarites and breccias of Dogger-Malm age;
- The conglomeratic and brecciated formations of Tertiary.

Hydrogeologically, the study area is crossed by many superficial streams. In addition, several springs gush at the foot of the limestone ridge, while others are dispersed geographically in the different formations. The most important springs are: Ras El Maa Spring located at west of the Jbel Tissouka unit whose it rises in the flint limestone; Ahramen and Aayaden Springs welling in massive carbonate formations of Hettangian age; and Chrafate Spring which is part of the Bouslimane unit and that gushes in the flint limestone of Pliensbachian age. For the whole area, these sources are the main water resources for both drinking water and irrigation.

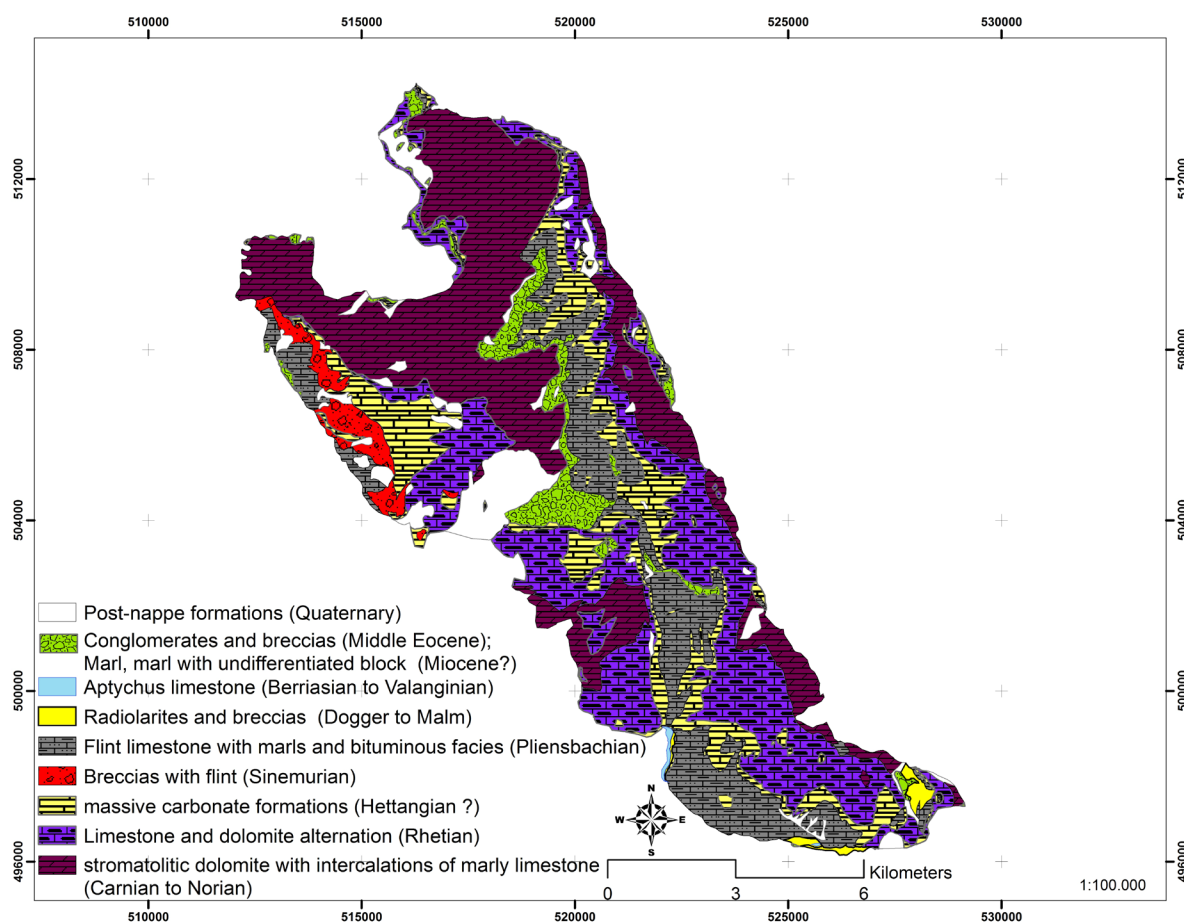Moreover, the rose diagram of hydrographic network (**Figure 3**) shows that N40-N50 oriented fractures pre-

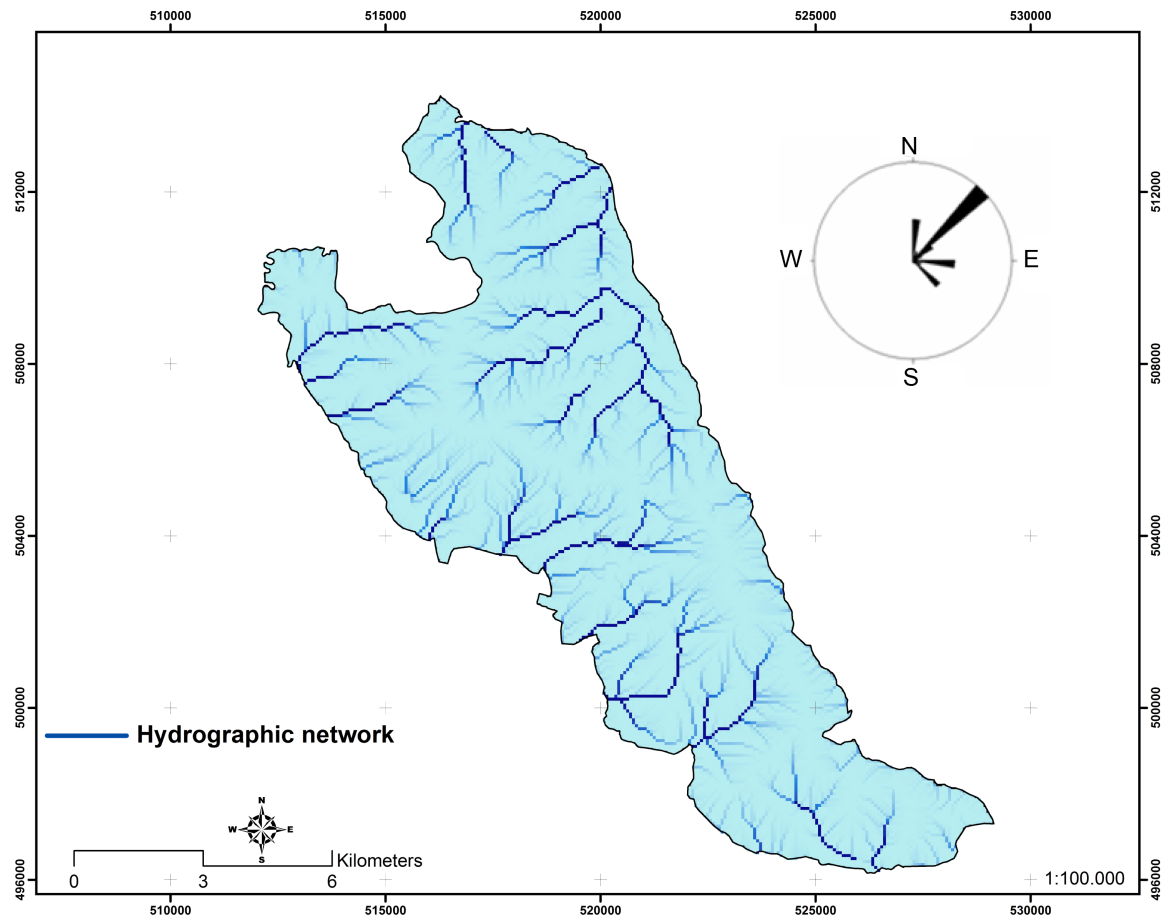**Figure 2.** Geological map of the study area.

Figure 3. Surface water network map.

sents the most dominant class which seems to be linked to the crossover network faults associated with N60-N80 direction of the Jebha-Chrafate major fault [7].

4. The EPIK Method

In case of groundwater resources, vulnerability map of the aquifers are an important tool for the groundwater management and protection [8]. Groundwater vulnerability defines the sensitivity of a groundwater source to contamination. Intrinsic vulnerability refers to the potential risk for contamination independent of the type of contaminant, while specific vulnerability considers the physico-chemical properties of the contaminant, mainly transit times, dispersion, degradation and decay of a specific contaminant etc. In this report, the term vulnerability refers to groundwater vulnerability to pollution [9]. In order to evaluate vulnerability mapping in the study area we use a multiparameter method called EPIK. It was defined in Switzerland to be applied only to the vulnerability assessment of karst aquifers [4] [10]. Four attributes are of main importance in this method, mainly Epikarst (E), Protective cover (P), Infiltration condition (I), and Karst network (K). Their evaluation is outlined in **Table 1**. Each parameter was attributed a weighting factor (**Table 2**) and a summation of the four layers allows to calculate a protection index value F, which varies from 9 to 34. The calculation is carried out as follows:

$$F = \alpha E_i + \beta P_j + \gamma I_k + \delta K_l \tag{1}$$

where α, β, γ, δ: Weighting coefficient of each parameter and E_i, P_j, I_k, K_l: Categories of each parameter.

All data collected for this study were converted into digital format to be implemented in a Geographical Information Systems (GIS). A relational geodatabase was designed to permit the simultaneous analysis of all type of data. Taking this approach, the result is color-coded map representing areas of relative vulnerability to ground-

Table 1. Evaluation of E, P, I, and K parameters (modified from [4]).

Status	Code	Score	Description	
			Epikarst	
Karstic morphology observed (pertaining to epikarst)	E1	1	Caves, swallow holes, dolines, karren fields, ruine-like relief, cuestas	
	E2	2	Intermediate zones situated along doline alignments, uvalas, dry valleys, canyons, poljes	
Karstic morphology absent	E3	3	The rest of the catchment	
			Protective Cover	
			A. Soil resting directly onlime stone formations or on detrital formations with very high hydraulic conductivity[*]	**B.** Soil resting on >20 cm of low hydraulic conductivity geological formations[**]
	P1	1	0 - 20 cm of soil	**-**
Protective cover absent	P2	2	20 - 100 cm of soil	20 - 100 cm of soil and low hydraulic conductivity formations
	P3	3	>1 m of soil	>1 m of soil and low hydraulic conductivity formations
Protective cover important	P4	4	**-**	>8 m of very low hydraulic conductivity formations or >6 m of very low hydraulic conductivity formations with >1 m of soil (point measurements necessary)
			Infiltration Condition	
	I1	1	Perennial or temporary swallow hole-bands and bed of temporary or permanent stream supplying swallow hole, infiltrating surficial flow-areas of the water course catchment containing artificial drainage.	
	I2	2	Areas of a water course catchment which are not artificially drained and where the slope is greater than 25% for meadows and pastures	
Concentrated infiltration Diffuse infiltration	I3	3	Areas of a water course catchment which are not artificially drained and where the slope is less than 10% for ploughed (cultivated) areas and less than 25% for meadows and pastures Outside the catchment of a surface watercourse: bases of slopes and steep slopes (greater than 10% for ploughed (cultivated) areas and greater than 25% for meadows and pastures) where runoff water infiltrates	
	I4	4	The rest of the catchment	
			Karst Development	
Well-developed karstic network	K1	1	Well-developed karstic network with decimetre to metersized conduits with little fill and well interconnected	
Poorly developed karstic network	K2	2	Poorly developed karstic network with poorly interconnected or in filled drains or conduits, or conduits of decimetre or smaller size	
Mixed or fissured aquifer	K3	3	Porous media discharge zone with a possible protective influence-fissured non-karstic aquifer	

[*]Examples: scree, lateral glacial moraine; [**]Examples: silts, clays.

Table 2. Weighting coefficient attributed to the E, P, I and K parameters.

Parameter	E	P	I	K
Weighting coefficient	α	β	γ	δ
Relative weight	3	1	3	2

water contamination from the surface, which also represent protection zone [11].

5. Results and Discussion

5.1. Epikarst (E)

The epikarst or subcutaneous zone is located at the top of the aerated or vadose zone in carbonate rocks. The vadose zone in karst comprises the soil (if there is any), the epikarst zone, and the transmission zone. From the epikarst, water percolates downwards through a zone dominated by transmission rather than storage that delivers recharge to the saturated or phreatic zone [12]. The epikarst parameter mapping was made using the interpretation of aerial photography, the field verification and geomorphological studies. These data have been georeferenced and implemented in a GIS-database.

According to [5] the Epikarst parameter is subdivided into three classes that indicate decreasing vulnerability as shown in **Table 1**. Morphological data were elaborated by a GIS to mapping these classes (**Figure 4**).

5.2. Protective Cover (P)

In our case, the protective cover mainly consists of soil and it included as well as other geological formation. The soil is resting directly on limestone formations. In order to assess the parameter P, we used the slope map (**Figure 5**) generated from digital elevation model (DEM) in GIS system and the land-use map (**Figure 6**) which allowed to define the different soil classes along the study area according to their thickness (**Table 1**). Three P classes were then defined as shown in **Figure 7**.
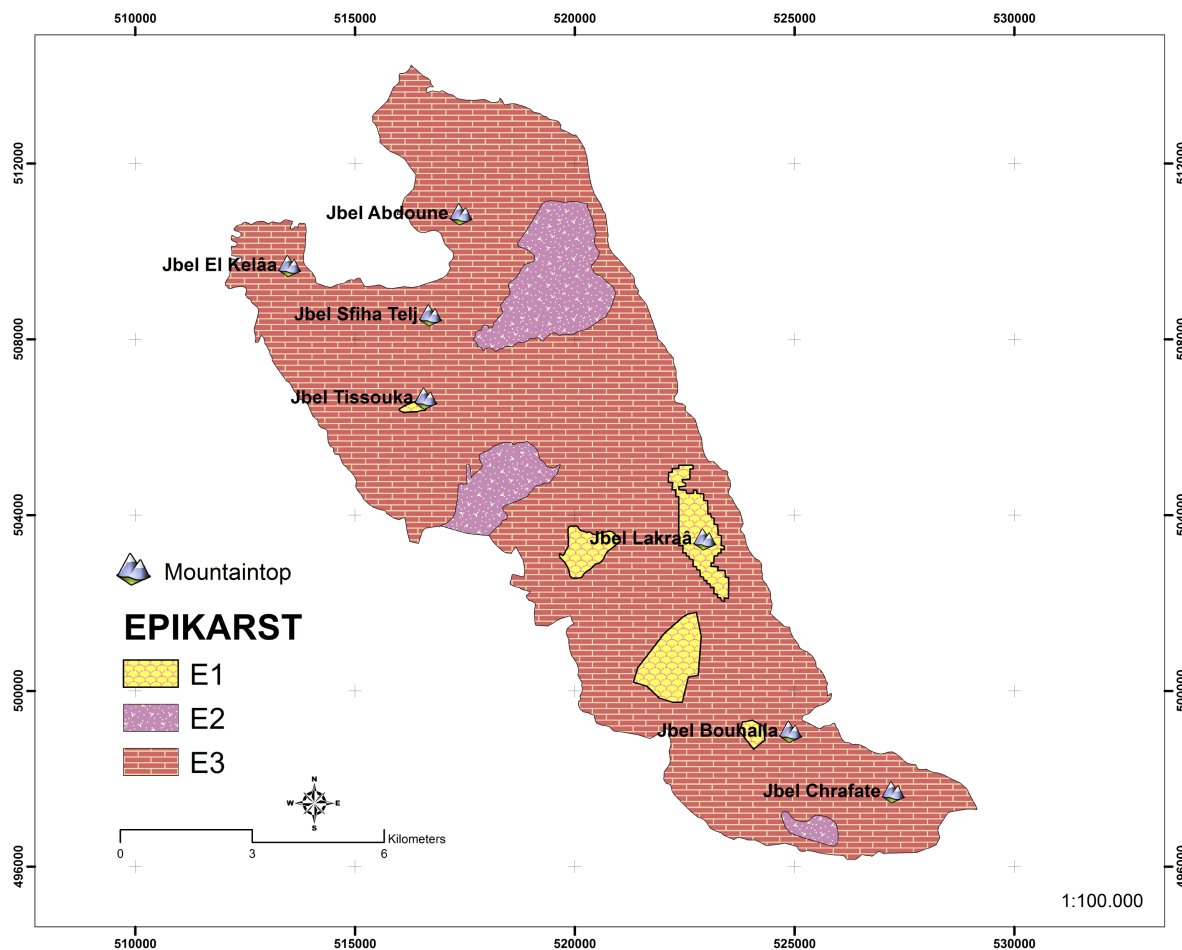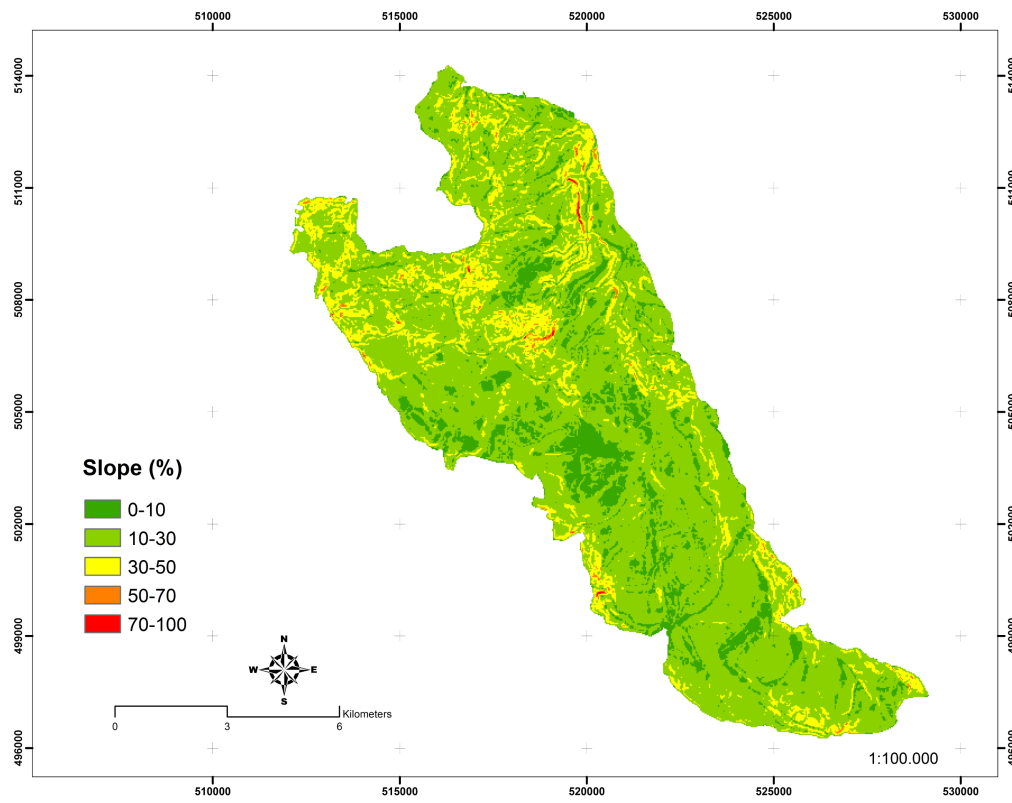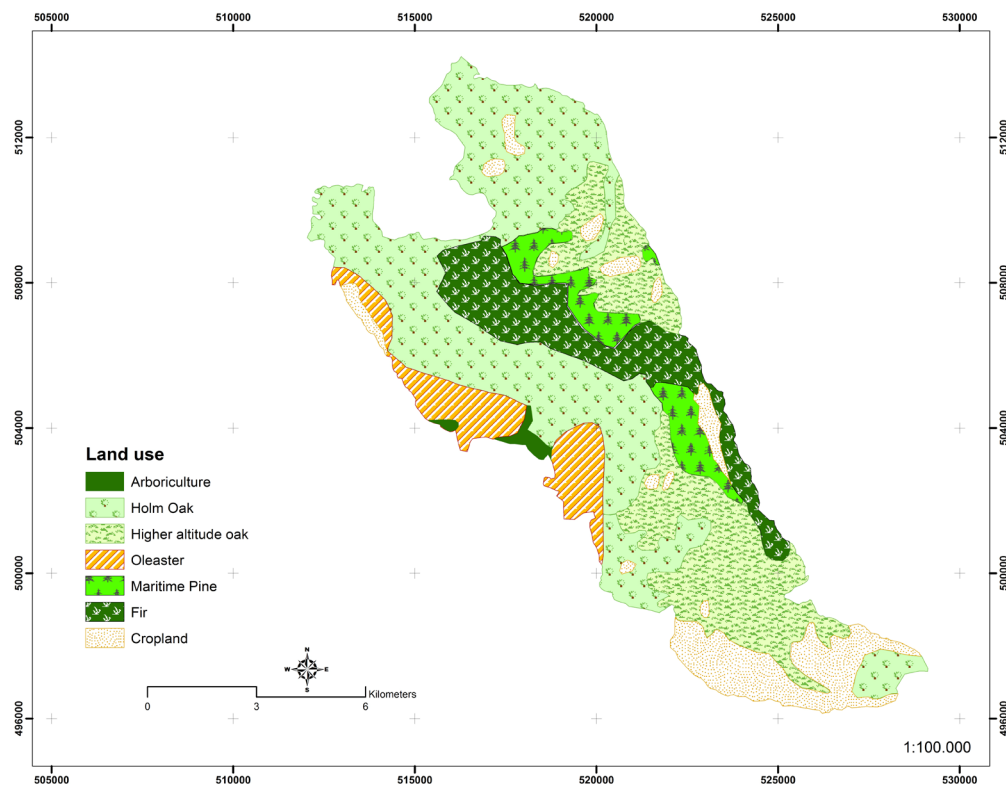

Figure 4. Epikarst map.

Figure 5. Slope map.
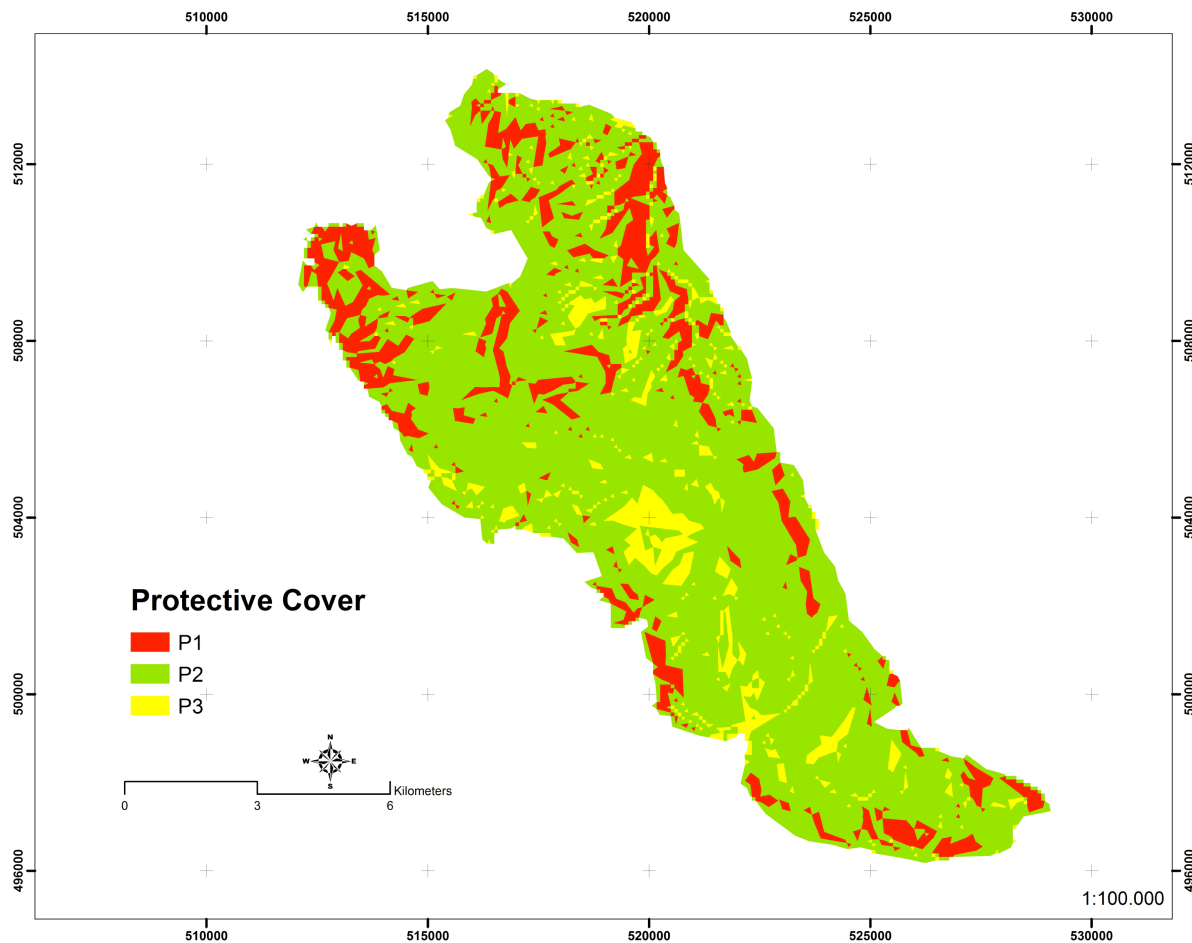

Figure 6. Land use map.

Figure 7. Protective cover map.

5.3. Infiltration Condition (I)

The infiltration condition parameter was evaluated based on the combination of digital elevation model (DEM) and the land-use map. Steep slopes and poor vegetation leads to higher vulnerability, because it is assumed that there is more runoff that will infiltrate in the flow relief areas [4]. The indexed class I1 presents the higher vulnerability, it was assigned to areas of concentrated infiltration like sinkholes, caves and swallow holes. The majority of the study area is indexed I3 and I4 (**Figure 8**), which I3 corresponds to the area where the slope is greater than 10% for cultivated area and greater than 25% pasture where runoff water infiltrates, and I4 forms the rest of catchment.

5.4. Karst Network Development (K)

Vulnerability is evaluated in terms of the presence of a karstic network and the degree to which the network is developed [5]. The karstic landforms such as sinkholes, caves and swallow holes constituted the first indicator of a karst system. Another indicator is provided by the lot of springs present in the study area. According to [13], a poorly developed system will very often possess many springs. This concept is based on the hypothesis that there is a karstic network hierarchy. In light of the above, the entire catchment of these springs has been indexed into K2.

5.5. Protection Zone Map

The raster calculator geoprocessing tool in ArcGis was used to create and execute a vulnerability map (**Figure 9**) by overlaying the previous four layers according to the relation (1).
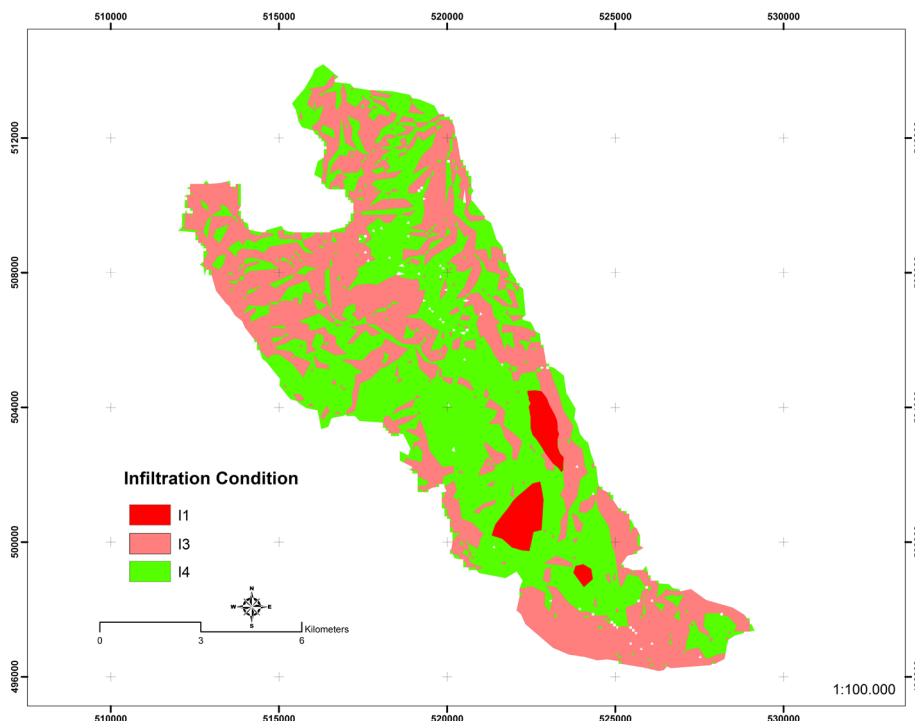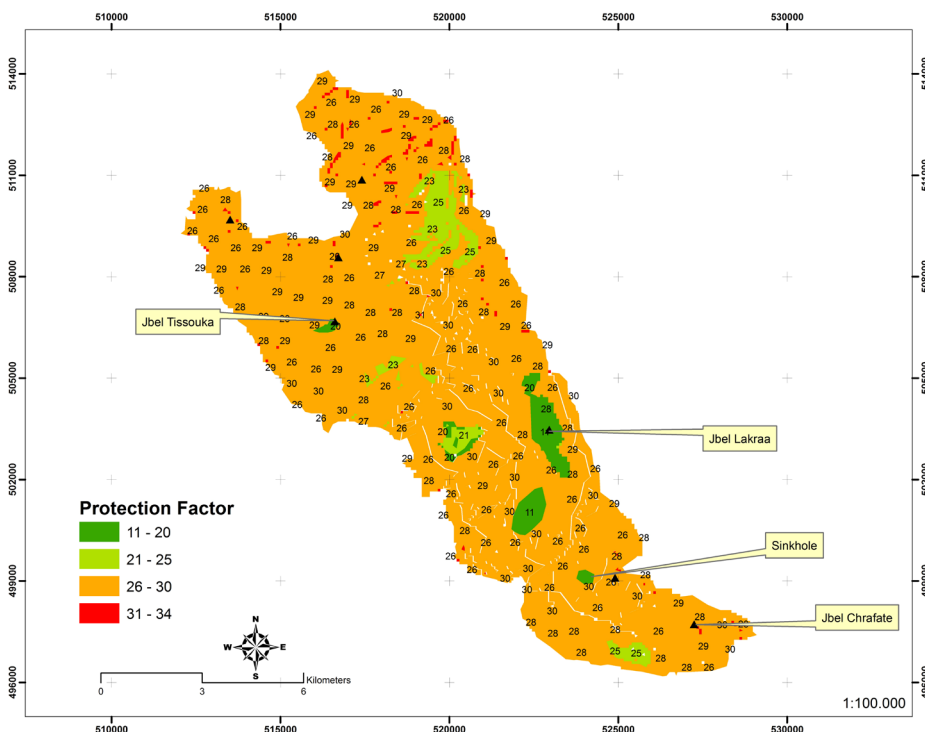
Figure 8. Infiltration condition map.

Figure 9. Groundwater vulnerability map.

The F protection factor values may be divided into four classes of vulnerability: very high (9 - 20), high (20 - 25), moderate (25 - 30) and low (30 - 34). The Reclassify tool in ArcGis software allows representing these intervals of protection factor in a protection zone map (**Figure 10**).
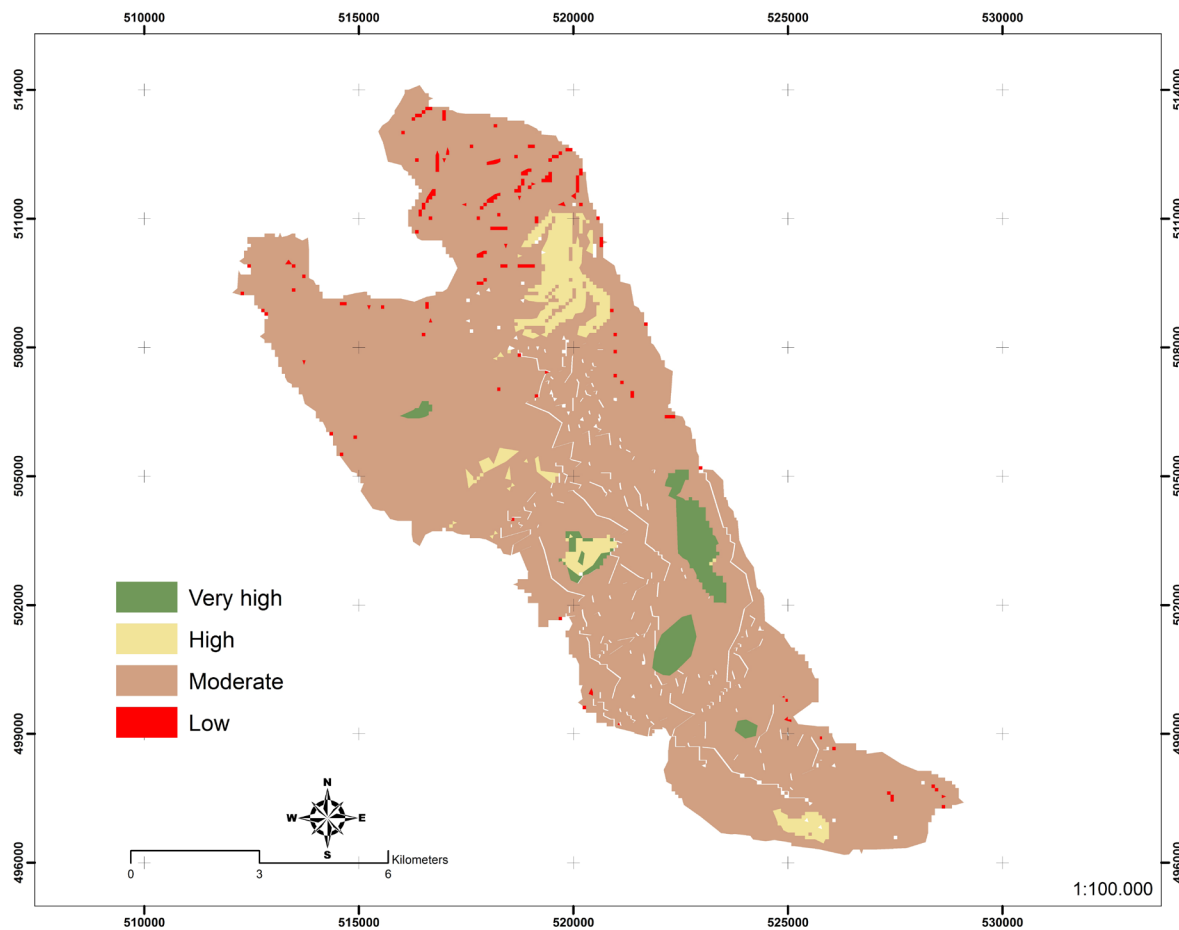
Figure 10. Protection zone map.

6. Conclusions

This study reveals that the use of Geographic Information System (GIS) is an effective tool to assess the ground-water vulnerability in the calcareous dorsal, to the west of Chefchaouen City. Four parameter layers were established in GIS environment and the vulnerability map was created using raster calculator tool of ArcGis software according to the relation (1).

The protection zone map highlighted that the study area shows aquifer vulnerability that ranges from moderate to very high. The highest contribution to vulnerability was due to karstic landforms such as sinkholes, caves and swallow holes.

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