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Protection of Jeita Spring

TECHNICAL REPORT NO. 7b

Vulnerability Mapping Using the COP and EPIK Methods

Goettingen and Ballouneh
October 2012

Technical Report No. 7b: VULNERABILITY MAPPING USING THE COP AND EPIK METHODS

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1	Site Selection for Wastewater Facilities in the Nahr el Kalb Catchment – General Recommendations from the Perspective of Groundwater Resources Protection	January 2011
2	Best Management Practice Guideline for Wastewater Facilities in Karstic Areas of Lebanon – with special respect to the protection of ground- and surface waters	March 2011
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4	Proposed National Standard for Treated Domestic Wastewater Reuse for Irrigation	July 2011
5	Artificial Tracer Tests 4B - May 2011*	September 2011

Report No.	Title	Date Completed
6	Artificial Tracer Tests 5A - June 2011*	September 2011
7	Mapping of Surface Karst Features in the Jeita Spring Catchment	October 2011
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2	Locating the Source of the Turbidity Peaks Occurring in April - June 2012 in the Dbayeh Drinking Water Treatment Plant	June 2012
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* prepared in cooperation with University of Goettingen

PROTECTION OF JEITA SPRING - LEBANON -

- SPECIAL REPORT VI-

VULNERABILITY MAPPING USING THE COP AND EPIK METHODS

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1 INTRODUCTION

This report presents parts of the results of the work undertaken in the Framework of the Cooperation between the Institute for Geosciences and Natural Resources in Germany (BGR) and Georg-August University in Göttingen as partial fulfillment of contract 10037409. The work is part of the German-Lebanese Technical Cooperation Project Protection of the Jeita Spring funded by the German Ministry of Economic Cooperation and Development (BMZ) and implemented on the German side by BGR.

About 67% of the area in Lebanon consists of karstified (6,900 km^2) rock sequences. The project area is the Jeita karst catchment drained by Jeita spring. It is considered one of the most important springs in Lebanon, which provides the capital Beirut with water for domestic use. Given its importance, it is primordial to secure a sustainable management of the spring resources and ensure its protection against potential sources of contamination. For this purpose, the project undertaken by BGR aims at delineating groundwater protection zones in the catchment area of Jeita spring. The catchment of Jeita spring was delineated based on a series of tracer experiments conducted in the catchment area by BGR (2010-2011; Doummar et al., 2010, Doummar et al., 2011). The delineation of groundwater protection zones implies assessing vulnerability of a catchment for contamination, in other terms, outlining areas/layers that are of major importance in water infiltration and flow throughout various pathways e.g., unsaturated zone and saturated zone, until it reaches a target, being a well, a lake, or a spring like in the case of Jeita spring (Goldscheider, 2002).

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. Intrinsic vulnerability of the Jeita spring is assessed using two methods namely COP (Vias et al., 2006) and EPIK (Doerfliger and Zwahlen, 1998). These methods were developed especially for karst areas, as they take into account the heterogeneity observed in karst aquifers. This report presents the results of the groundwater vulnerability assessment and provides vulnerability maps generated based on the overlay of various attributes as specified by the two adopted methods. Section 2 provides a description of the study area and the available data required for the groundwater vulnerability mapping, Section 3 discusses the methodology and application of the COP method, while Section 4 presents the application of the EPIK method in the study area. Section 5 consists of an elaborate discussion of the results as well as a comparison of the two methods given the limitations. Finally Section 6 presents some conclusions and recommendations.

2 STUDY AREA

2.1 GENERAL

Jeita Spring is an important karst spring located north of Beirut in Jounieh area. It constitutes the main water source for the Greater Beirut Area and its northern suburbs for domestic use. Governed by open channel flow, Jeita Spring drains a catchment extending east in the Lebanese Mountains.

The Jeita cave is developed in limestone of Jurassic age over a total length (including subsidiaries) of 9000 m. The topography of the grotto was delineated underground as well as on the surface (Hakim et al., 1988). The Jeita cave is also accessible from a tunnel located downstream to Ballouneh village, about 4500 m east of Jeita Spring.

2.2 INVESTIGATED CATCHMENTS

In order to assess the vulnerability of Jeita spring, the investigated area was divided into two main catchments. The lower catchment will refer in this report to the direct catchment area of the Jeita spring as delineated by BGR, while the upper catchment will refer to the direct recharge area of four springs from north to south, Afqa, Qana, Assal, and Laban springs.

The investigated area will be mainly divided into two catchments main sub- zones (Figure 1):

- **Lower groundwater catchment (LC)** consisting of the area upstream of Jeita spring. Its lithology is mainly composed of rocks of Jurassic age (mainly limestone and dolostones) overlain by rocks of Lower to Middle Cretaceous age (basal Cretaceous sandtones, Aptian limestone and Albian marly limestone rocks).
- **Upper groundwater catchment (UC)** consisting of the area upstream to the Assal, Laban, Qana, and Afqa springs. The main lithology outcropping in the upper catchment is limestone of Middle Cretaceous age (Cenomanian).

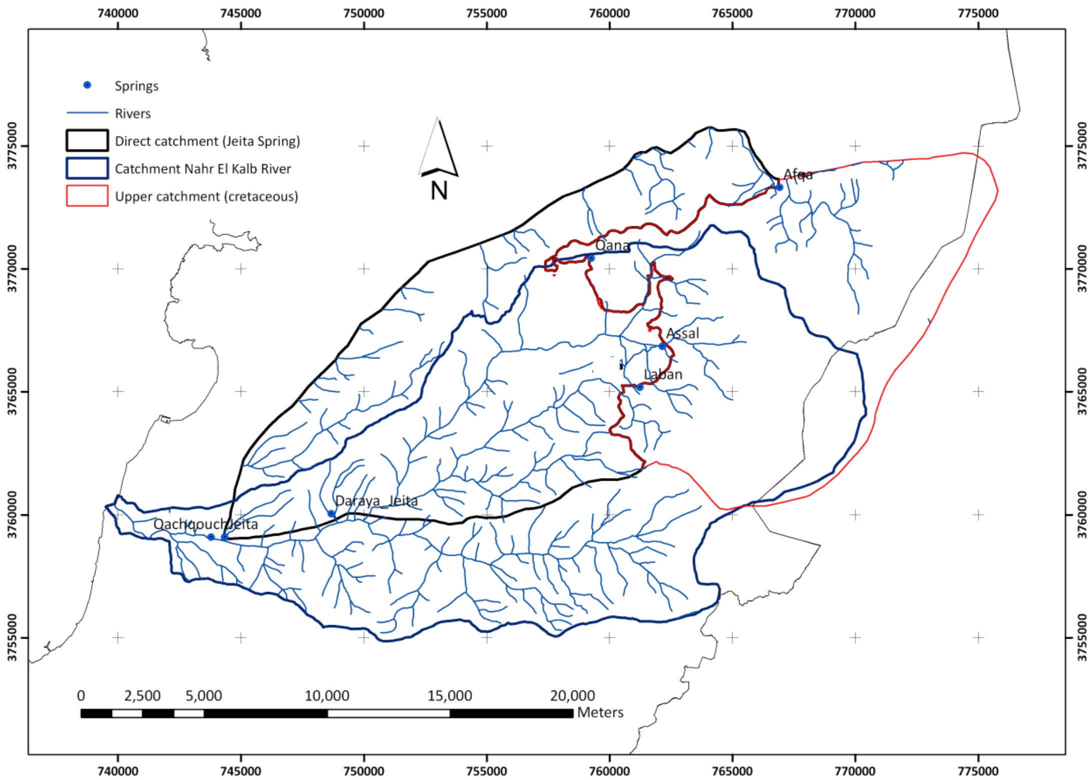

Figure 1 **Division of the study area into two main groundwater catchments**

2.3 REQUIRED DATA

The assessment of the vulnerability of a spring or a water catchment requires a robust investigation of the factors affecting vulnerability. Since the term vulnerability in this section refers to intrinsic groundwater vulnerability, therefore data are related only to the inherent geological and hydrogeological characteristics of the catchment, mainly to surface features and catchment parameters, including climatic data, land use land cover, soil, topography, lithology, karst features, and depth to groundwater. This section provides an overview of the major investigated layers used in the vulnerability assessment (Table 1).

Table 1 **Layers (type and reference) required for the vulnerability mapping (COP and EPIK)**

Shapefile/layer	Reference	Type of data	Vulnerability method
Precipitation	FAO/UNDP (1973)	-	COP
Topography/Slope	Digital Elevation Model (DEM) provided by BGR	DEM Raster	COP- EPIK
Land use/ Land cover	Shapefile provided by BGR	Polygon	COP- EPIK
Soil (texture and thickness)	Shapefile provided by BGR	Polygon	COP- EPIK
Geology	Shapefile provided by BGR	Polygon	COP- EPIK
Karst features	Shapefile provided by BGR	Points	COP- EPIK

Shapefile/layer	Reference	Type of data	Vulnerability method
Depth to GW	Estimated	-	COP

The shapefiles were processed with ARC GIS (version 9.3), using various tools, like **Analyst tool** (buffering, clipping etc...), **3-D Analyst tool** for the creation of TINs, contours and other attributes related to topography (e.g., slope) or raster functions e.g., to reclassify values of raster into classes as required by the respective method, and **conversion tools** to transform shapefiles into raster for mathematical calculations and overlay of various layers. This section briefly summarizes the type of data, their acquisition, and their processing into adequate shapefiles used in the generation of the vulnerability maps. The UTM (Universal Transverse Mercator; Zone 36N) map projection was adopted for the entire database. The different layers were first reproduced as shapefiles (vector) and were then converted into a 110 m cell unit grid that represents the cell size of the DEM.

- Topography (Slope)

A Digital Elevation Model (DEM) gridded with a cell size of 110 m was provided by BGR. This grid size was used for the final generated vulnerability maps. A slope map was generated using the spatial analyst in ARCGIS.

- Precipitation

A precipitation map developed by FAO/UNDP (1973) was adopted to delineate the amount of precipitation according to varying altitude on the investigated catchments.

- Land use and land cover

This shapefile was provided by BGR and includes information about land use and land cover in the study area. The different crops, vegetation patterns and urban settlements are identified in the attribute table (Figure 2).

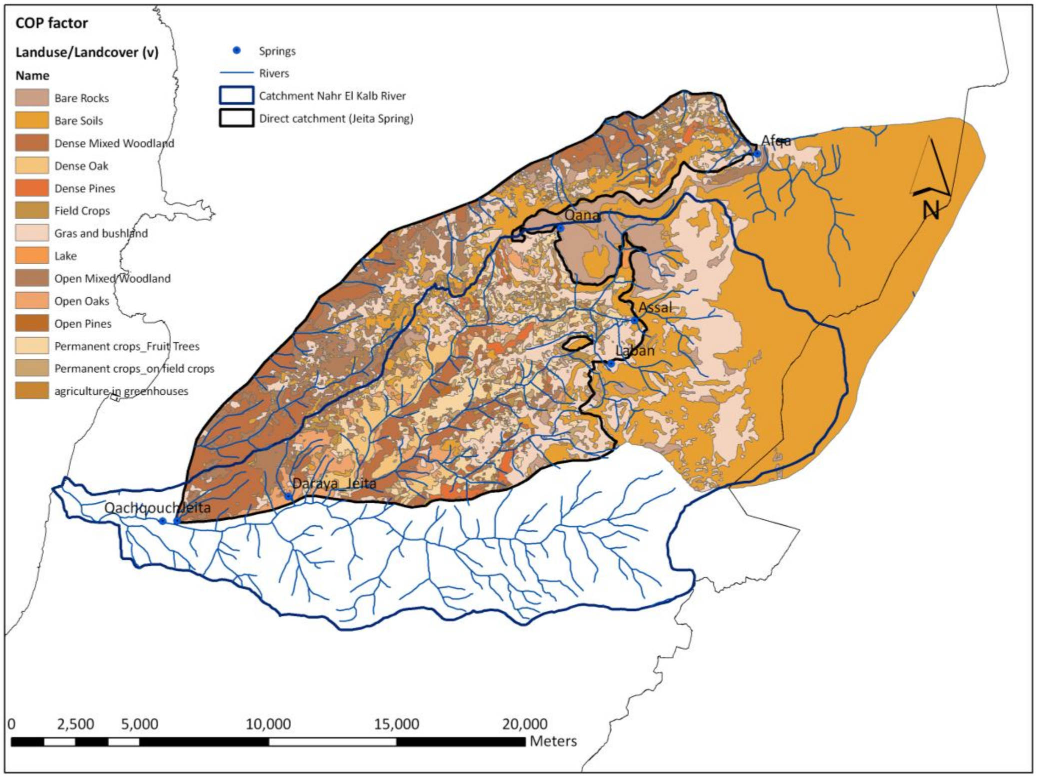

Figure 2 Land use and land cover map (BGR, 2011)

- Soil (thickness and Texture)

A soil shapefile (polygon) was provided by BGR. The map included information about the texture and the thickness.

- Geologic map

A geologic map was prepared (Hahne et al., 2011) by BGR and provided for the purpose of this study.

- karst features

A mapping of the karst features including dolines and sinkholes was conducted by BGR (Abi Rizk and Margane, 2011) and provided for the purpose of this study.

- Depth to groundwater

The depth to groundwater is the thickness of the unsaturated zone, therefore it is to be inferred from the water level contours available for the area; however, such maps are currently not available. The groundwater level was extrapolated tentatively from the groundwater level in the Jeita cave over the lower catchment. The depth to UZ was calculated by subtracting the water level from the topography (DEM). However, this approach portrays significant uncertainties, as it is only a very rough estimate given the available information.

3 APPLICATION OF COP IN THE STUDY AREA

3.1 CONCEPT

The COP method is the acronym of three main factors used to assess the vulnerability of an aquifer C, O, and P. This method assesses on one hand, the capacity of the overlying layers, namely soil and unsaturated zone to attenuate the contaminant (layer O). On the other hand, since karst aquifers are characterized by a diffuse and a concentrated infiltration, the C factor defines the importance of the infiltration processes, while the P factor underlines the role of climatic conditions namely precipitation in the definition of vulnerability (Vias et al., 2006). The COP method is summarized in Figure 3.

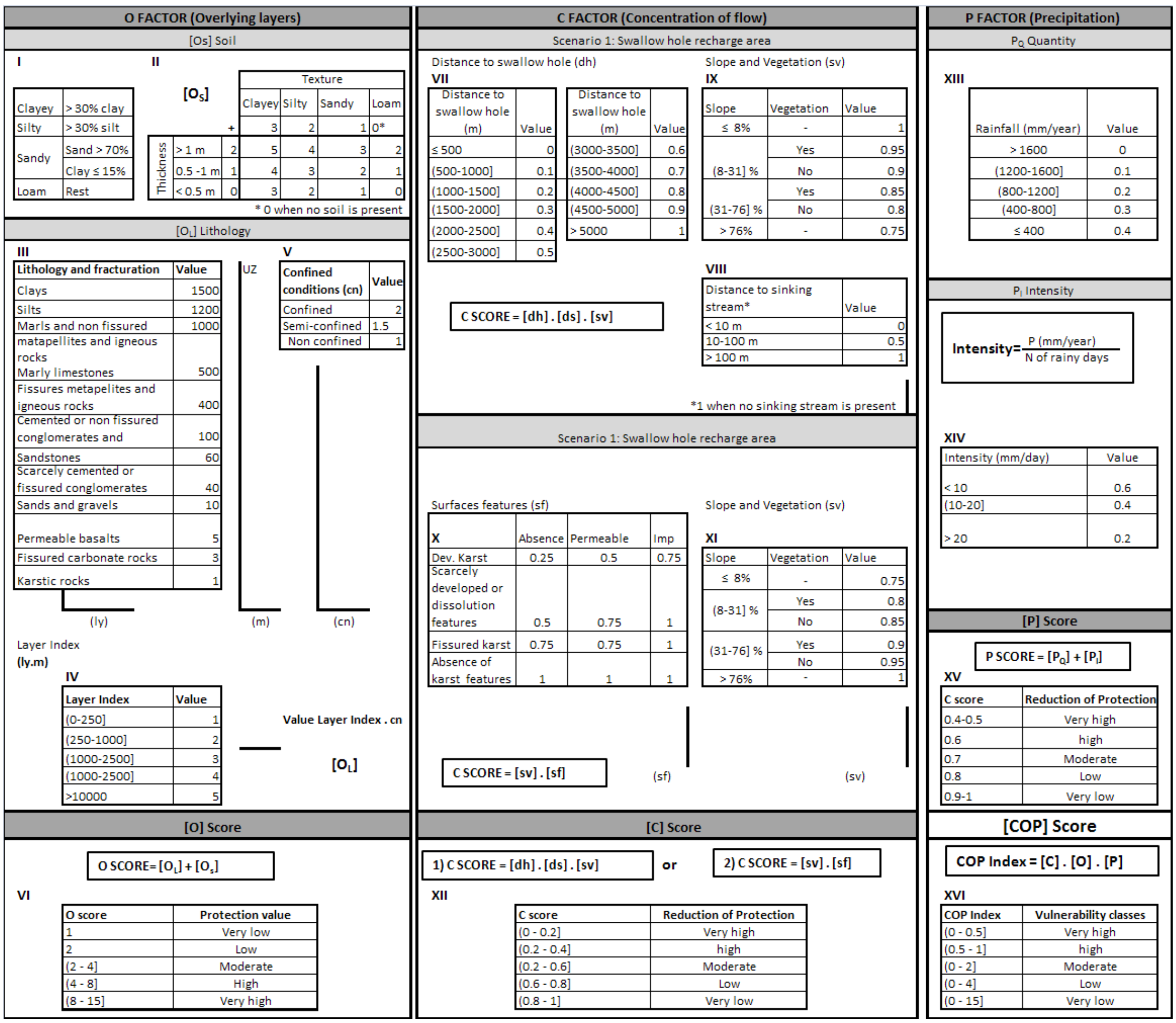

Figure 3 Main factors playing a role in the definition of the COP map (modified from Vias et al., 2006)

3.1.1 C Factor

The C factor is the *flow concentration* map and represents the types of infiltration occurring on the catchment. Karst systems are characterized by a duality of infiltration, where infiltration can occur diffusively on the entire catchment and/or concentrated in sinkholes or dolines (fast flow pathways). In the COP method, the catchment is divided into two main zones. The first zone (Scenario 1) includes the recharge area of karst features namely dolines or sinkholes. The second zone (Scenario 2) consists of the rest of the area, where no surface karst features were identified. The C factor for Scenario 1 consists of the multiplication of three main factors (Equation1; distance to swallow hole (dh), vegetation and slope (sv) and distance to sinking stream (ds)).

$$C = dh.ds.sv$$ Equation 1

$$C = sf.sv$$ Equation 2

3.1.1.1 Slope and vegetation (sv)

The slope and vegetation play an important role in vulnerability. A higher slope indicates a higher surface runoff, and consequently a more localized recharge. On the other hand, dense vegetation decreases the likelihood for surface runoff therefore the vulnerability decreases with vegetation. Therefore the groundwater vulnerability of an area is reduced with an increasing C factor, in other terms with decreasing slope and increasing vegetation.

3.1.2 O Factor

The O factor represents the overlying layers, namely the soil cover (O_S) overlying the bedrock/ lithology (O_L).

3.1.2.1 O_S factor

The O_s factor represents the soil, i.e. the texture and thickness of the soil cover. The thicker the soil cover, the higher the likelihood of contaminant attenuation. Furthermore, fine soil textures (i.e., clay) have lower hydraulic conductivity, and are therefore characterized by higher transit times. Additionally, due to their sorption capacity for ionic species, they are more likely to attenuate some types of contaminants (ionic or charged species). The O_S factor increases with increasing thickness and fining soil texture denoting a low vulnerability.

3.1.2.2 O_L factor

The O_L factor is representative of the unsaturated zone. It defines the layers directly overlying the aquifer. It consists one the one hand of the type of lithology, the confinement of the aquifer, and the thickness of the unsaturated zone. It is calculated according to the following equation, where the product of ly and m is calculated separately, reclassified and multiplied by the degree of confinement. The lower the value of the product of ly and m the lower is the protection value, i.e., the higher is the vulnerability.

$$O_L = [ly.m].cn$$

Values representative for each type of lithology are given to the various types of rocks outcropping in the catchment area. The higher the value, the lower the vulnerability (e.g., karstic rocks are given a value of 1, whereas clays a value of 1500.

3.1.3 P Factor

The P Factor represents the climatic conditions in the catchment. It is the sum of two sub factors (P_Q and P_I) defining the amount and intensity of yearly precipitation respectively. P_q represents the amount of precipitation, it ranges between 0.20 and 0.40. P_I reflects the intensity of precipitation, in other terms the ratio of precipitation amount and number of rainy days. This factor ranges between 0.2 and 0.6. The P factor considers that the higher the precipitation i.e., the likelihood for recharge and the higher the intensity during precipitation events, the more vulnerable the investigated area.

3.2 VULNERABILITY MAPPING

3.2.1 Lower catchment

3.2.1.1 C Factor

- **Slope and vegetation (sv)**

The slope is extracted with ARCGIS from the Digital Elevation Model (DEM) in percent, and reclassified into 4 categories (≤8%, 8<S<31, 31<S<76, and >76; Figure 4), which were assigned weights accordingly. Based on the land use / land cover maps provided by the BGR, land use was divided into two main types, mainly “no vegetation” (including bare soils and rocks, grassland or low sparse vegetation) and “vegetation”.

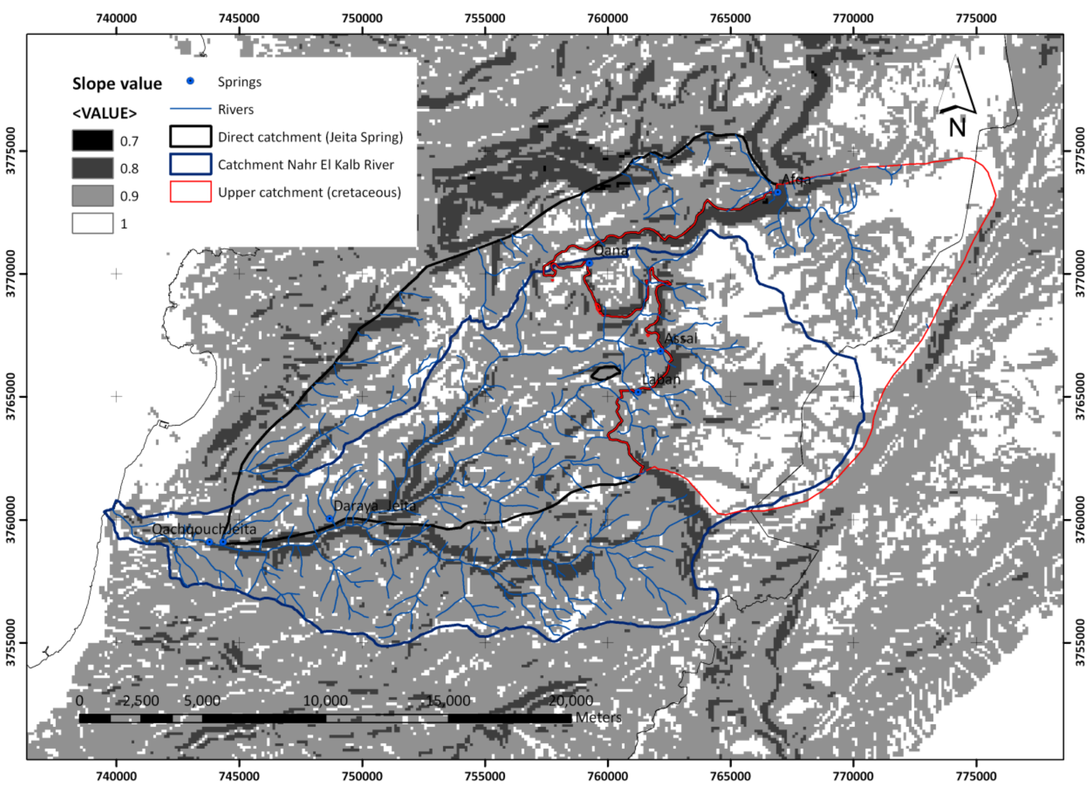

Figure 4 **Slope distribution in the lower catchment**

Slopes and type of vegetation were assigned values as per Table 2. The final map resulting from the multiplication of slope and vegetation indices is shown in Figure 5.

Table 2 **Classification of slope and vegetation in the lower catchment and calculation of the factor sv**

Slope	Value (s)	Vegetation	Value (v)	s+v (sv)	Reclassification sv
≤8%	1	Yes	0.05	1.05	1
	1	No	0	1	
8<S<31	0.9	Yes	0.05	0.95	0.95
	0.9	No	0	0.9	0.9
31<S<76	0.8	Yes	0.05	0.85	0.85
	0.8	No	0	0.8	0.8
>76	0.7	Yes	0.05	0.75	0.75
	0.7	No	0	0.7	

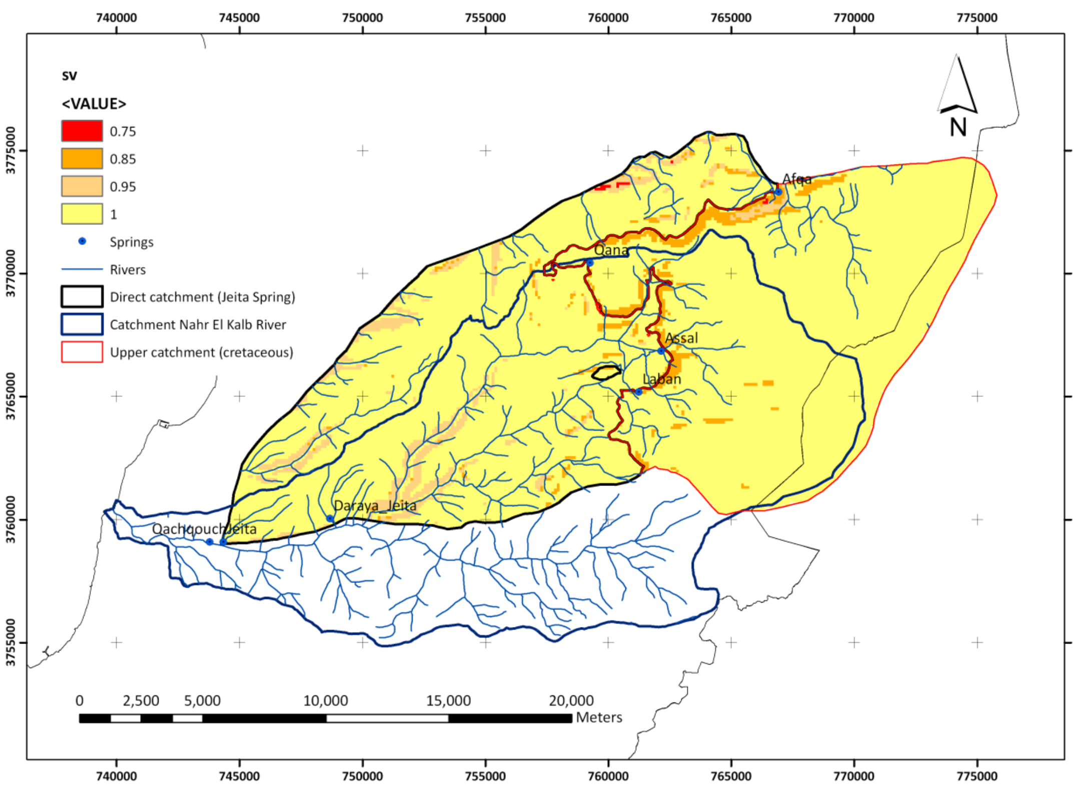

Figure 5 **Map showing the map resulting from the multiplication of the slope and vegetation (sv)**

- **Swallow hole recharge area (dh)**

The distance to swallow holes consists of a series of buffer zones located at determined distances from fast recharge karst features (such as dolines). The locations of the dolines were provided by BGR (Abi Rizk and Margane, 2011). The recharge areas of dolines consist of the buffer around each identified doline. It is assumed that the area located around to a doline is characterized by a high vulnerability. A series of increasing Buffers (500 m each) using the Arc Tool Box was created around each doline. Each buffer was attributed a respective factor (dh; Figure 6). Scenario 2 is considered to include the area located outside the buffer zone extending 5000 m from the dolines. The final C factor is illustrated in Figure 7.

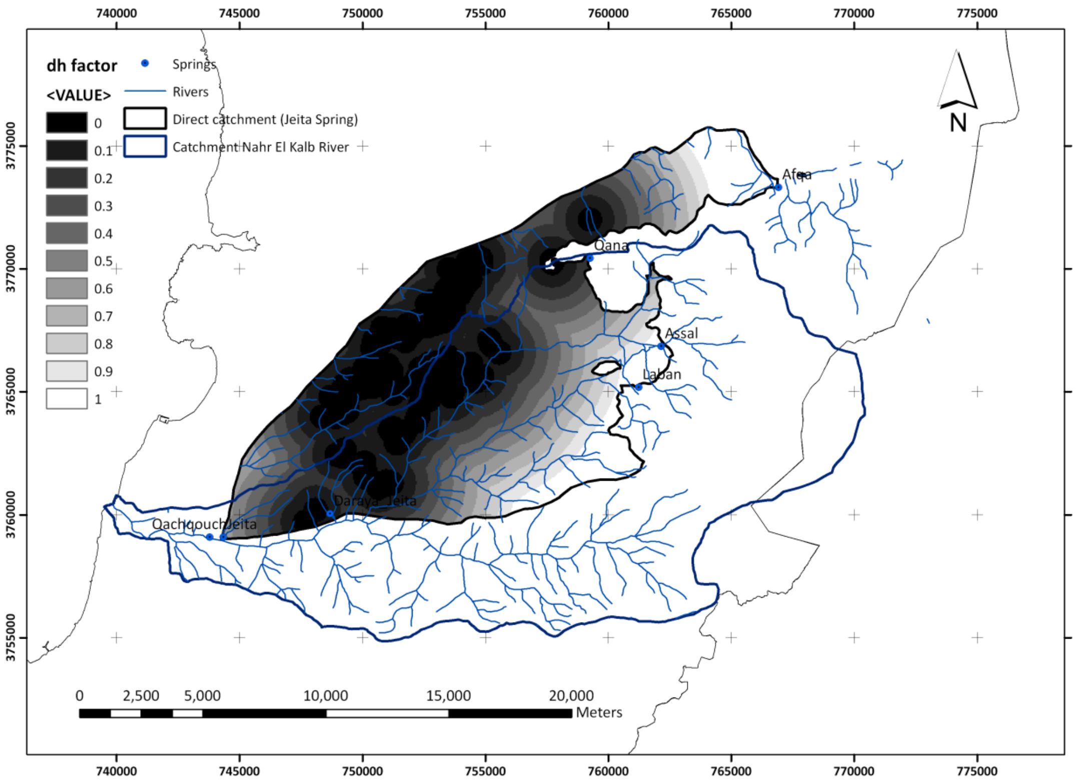

Figure 6 **Series of multi-ring increasing buffers of 500 m intervals around dolines and sinkholes in the lower catchment**

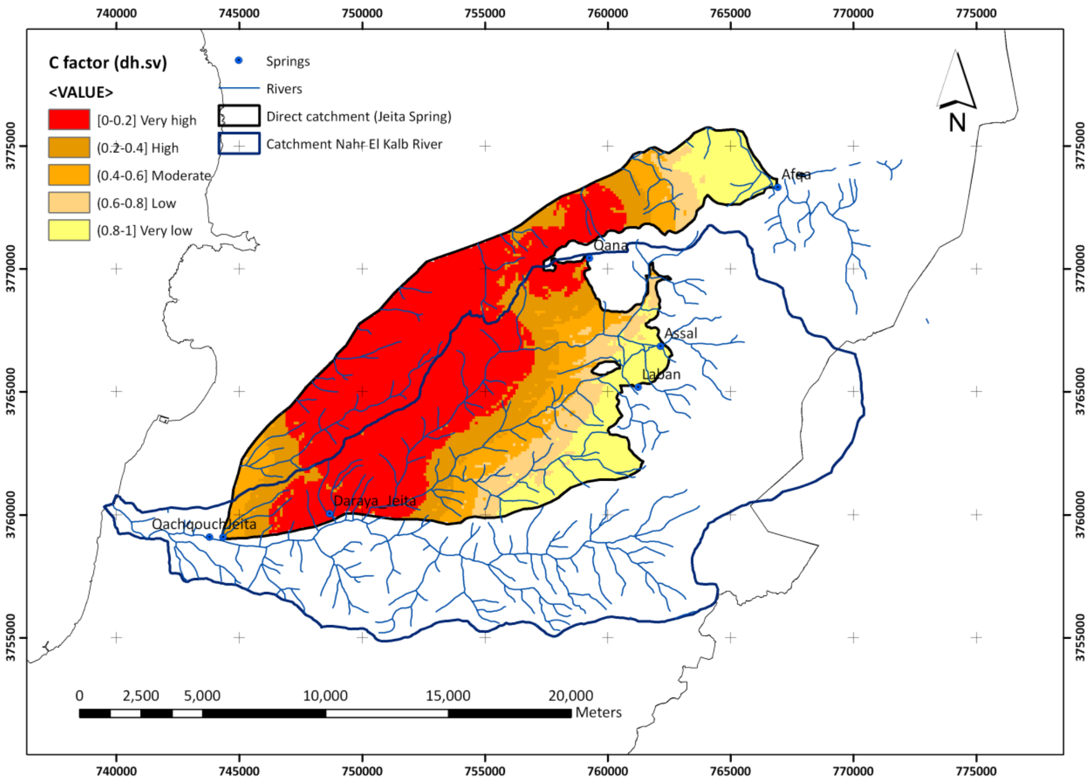

Figure 7 Map for C factor in the lower catchment

3.2.1.2 *O Factor*

- Os factor

The Os factor map was developed based on the soil map. Four main categories of Os factor are prevailing in the study area, the factor "3" is mainly attributed to the lower catchment area on the Jurassic aquifer, where most of the soil has a thickness that exceeds 1 meter and is classified as loam. Most of the Os factor map was interpolated based on lithology and the 166 samples collected from various formations over the catchment (BGR).

- O_L factor

The O_L factor is the product of the layer index and the degree of confinement (cn). The layer index is the product of the type of lithology and fracturing (ly) and the thickness of the unsaturated zone. Each formation was assigned a value for *ly* and *cn* as in Table 3. The confinement conditions are identified for each aquifer, notably the main aquifer, depending on the impervious properties of overlying and underlying layers. The depth to groundwater is mainly representative of the thickness of the unsaturated zone under static conditions.

Figure 8 shows the final O factor map resulting from the summation of both O_L and Os factors.

Table 3 Values attributed to the lithologies outcropping on the investigated catchment (ly refers to the type of lithology and cn refers to the degree of confinement as per the COP method)

Type of lithology	Nomenclature	Age	Value_cn	Value_ly
Limestones, highly karstified	J4	Jurassic	1.5 (J5 basalts)	1
Fissured fractured limestones	C2b, J6	Cretaceous, Jurassic	1.5 (C3 basalts/marls)	3
	J7, C2a	Cretaceous, Jurassic	1 (non confined)	3
Sandstones	C1	Cretaceous	1.5 (C1 basalts)	60
Marly limestones	C3	Cretaceous	1 (non confined)	500
Basalts	J5	Jurassic	1 (non confined)	1000

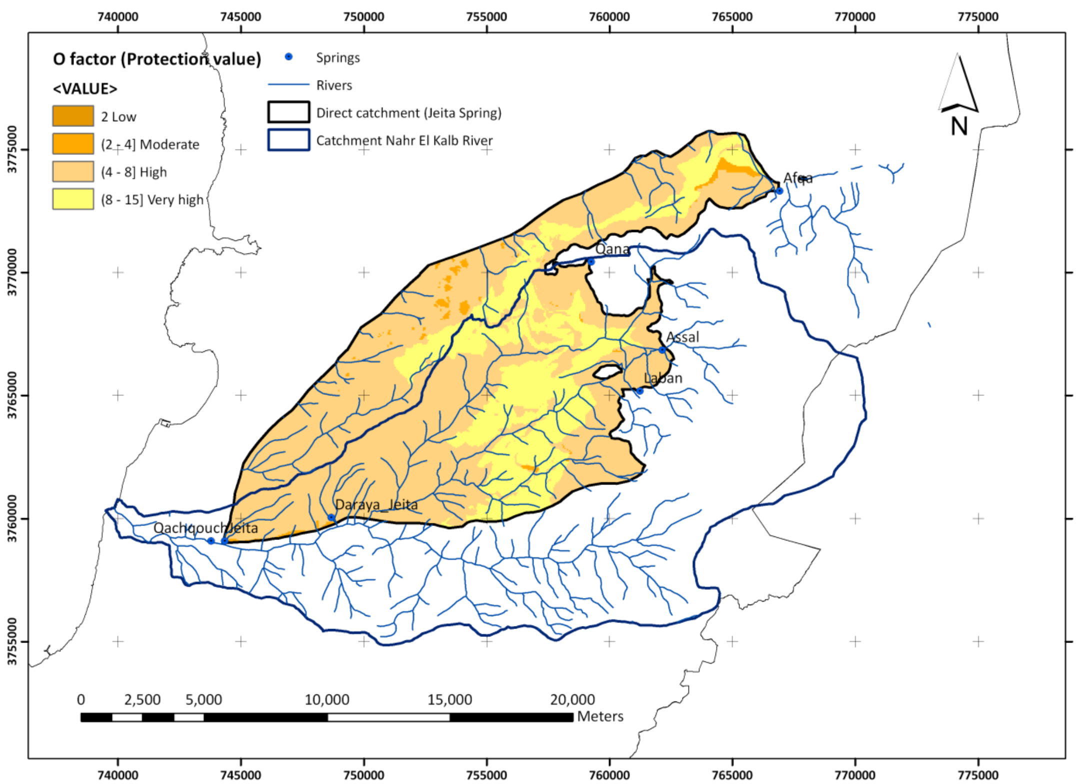

Figure 8 Map for O factor in the lower catchment

3.2.1.3 P Factor

The P Factor represents the climatic conditions in the catchment. It is the sum of two sub-factors (P_Q and P_I) defining the amount and intensity of yearly precipitation respectively.

- Precipitation Quantity P_Q

The Precipitation map (Section 2: FAO/UNDP, 1973) can be reclassified, where intervals are attributed values as per the following:

Rainfall (mm per year) (for a wet year)	Value
>1600	0.4
1200-1600	0.3
800-1200	0.2
400-800	0.3
≤400	0.4

- Precipitation Intensity P_I

The precipitation intensity is the ratio of the amount of precipitation to the number of rainy days (for a wet year: P_I/ number of rainy days; Figure 3). The number of rainy days in Lebanon ranges for a wet year at around 80 days per year, based on the analysis of precipitation data for the Beirut (Beirut International Airport AIB) or the years 1999-2010 .

Table 4 Numbers of rainy days (1999-2010); comparison of Pi ranges for different elevations

Hydrological year	Total (mm/year)	number of rainy days	Precipitation range (P_I values) 400	800	1200	1600
1999-2000	742	70	5.71	11.43	17.14	22.86
2000-2001	618	66	6.06	12.12	18.18	24.24
2001-2002	786	86	4.65	9.30	13.95	18.60
2002-2003	1080	81	4.94	9.88	14.81	19.75
2003-2004	526	47	8.51	17.02	25.53	34.04
2004-2005	691	57	7.02	14.04	21.05	28.07
2005-2006	742	67	5.97	11.94	17.91	23.88
2006-2007	746	62	6.45	12.90	19.35	25.81
2007-2008	436	42	9.52	19.05	28.57	38.10
2008-2009	866	82	4.88	9.76	14.63	19.51
2009-2010	960	78	5.13	10.26	15.38	20.51
Average (AVE)	744.8		6.26	12.52	18.78	25.03
Value of precipitation for a wet year= (0.15+AVE)+ AVE=856 mm (in red)						
Number of rainy days for a wet year= about 80 days						

A wet year is a year where the precipitation is 0.15 higher than the average yearly value. The value of 80 days was adopted all over the catchment because of the lack of data, therefore by dividing the amount of precipitation by the number of rainy days (estimated at 80 days), a precipitation intensity contour map could also be generated (Figure 9). The summation of P_Q and P_I generates the P score as shown in Figure 10.

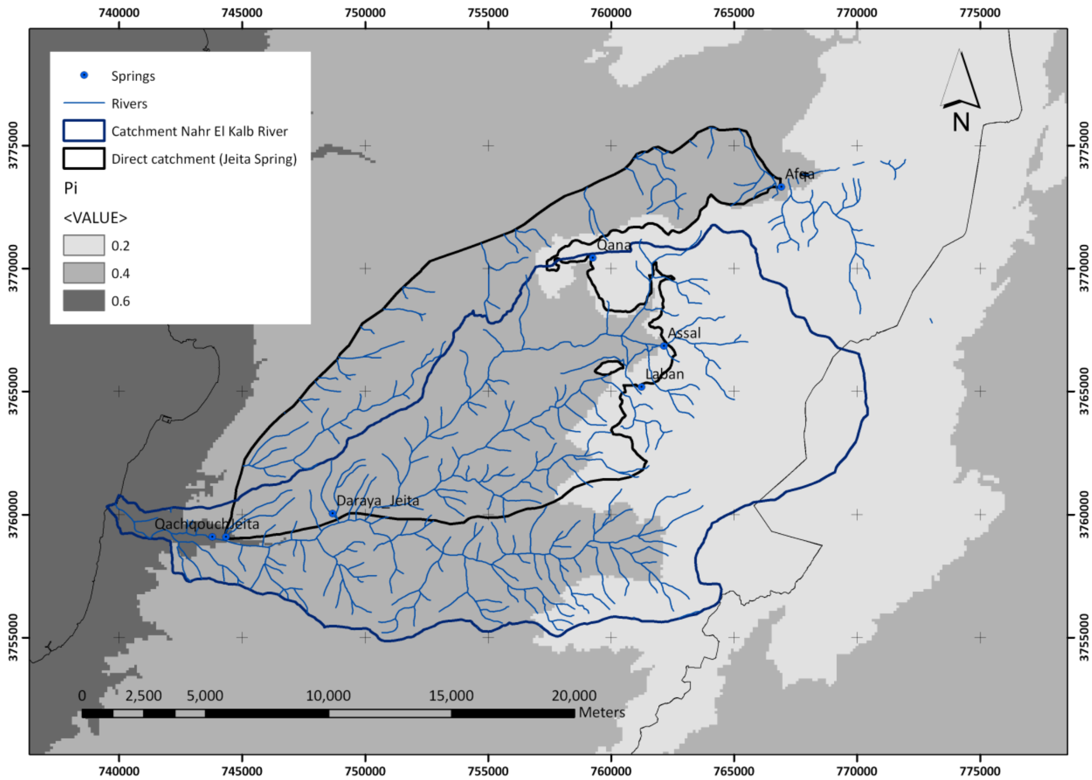

Figure 9 **P_I factor outlining the intensity of precipitation in the investigated areas**

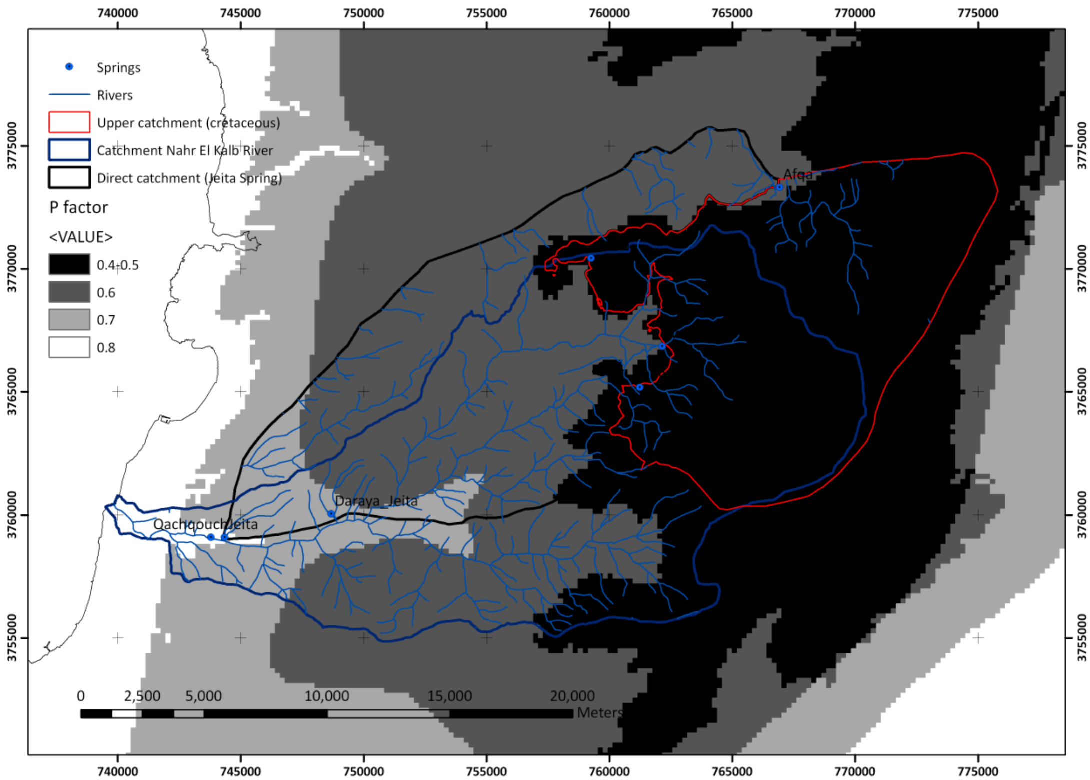

Figure 10 **P factor map resulting from the summation from P_I and P_Q**

3.2.2 Upper catchment

The upper catchment consists mainly of Cretaceous formations. The COP layers were generated following the same procedure used in the lower catchment as follows:

- O factor:
  - The O_s factor is generated based on the soil map provided by BGR, where most of the area is attributed a value of 0 (absence of soil);
  - The O_L factor is attributed a value of 1.5 as the lithology and the confinement conditions are homogeneous over the entire area (1, for karstified rocks and 1.5 semi confined). The unsaturated zone was assumed to have a thickness of about 250 m.
- C factor
  - *dh* layer: A multi-ring buffering of 500 m incremental distance was performed around dolines identified in the upper catchment. Each buffer ring was attributed a value varying between 0 and 1, 0 being the closest to the doline center.
  - *Vegetation and slope:* See section 3.2.1
- P factor
  - See section 3.2.1

3.3 COP INDEX

The multiplication of the three maps for each score, namely C, O, and P yields as per the following equation the resulting COP factor for the lower catchment. The final map is reclassified according to the vulnerability classes as per the COP method (Figure 11).

$$COP = C.O.P$$

Five different vulnerability classes ranging from very low to very high are identified on the COP map. The C factor seems to highly influence the final COP map, mainly because the area located within a 500-m distance from the dolines has a weighting value of 0, which highly affects multiplication with vegetation and slope and the two other factors (O or P) as well and reduces their weight to zero.

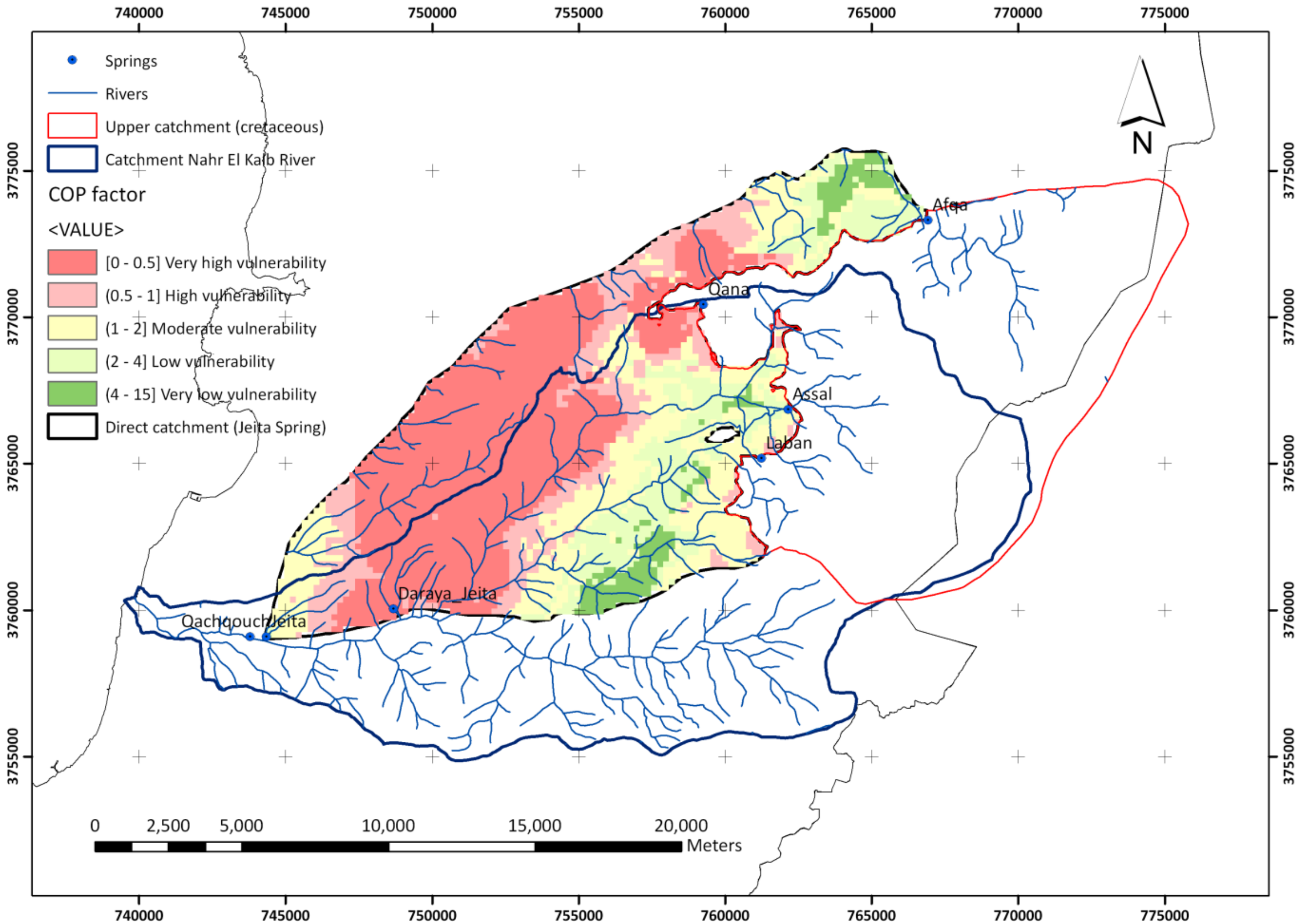

Figure 11 COP map showing the extent of vulnerability in the lower catchment

3.3.1 Results: Lower catchment

The highly vulnerable area consists of a relatively significant portion of the total investigated area, i.e., about 36% including the villages of Faitroun, Raifoun, Qlaiaat and Ballouneh, and partially the villages of Aajaltoun, Daraya, Deir Chamra and Beit el Mehdi. The high and moderate vulnerable areas extend to greater buffers around dolines and sinkholes and cover an area of about 51 km^2 (32% of total area). The areas with low and very low vulnerability mainly include the non-karstic formations located upstream in the catchment and cover the rest of the area, i.e., 31%.

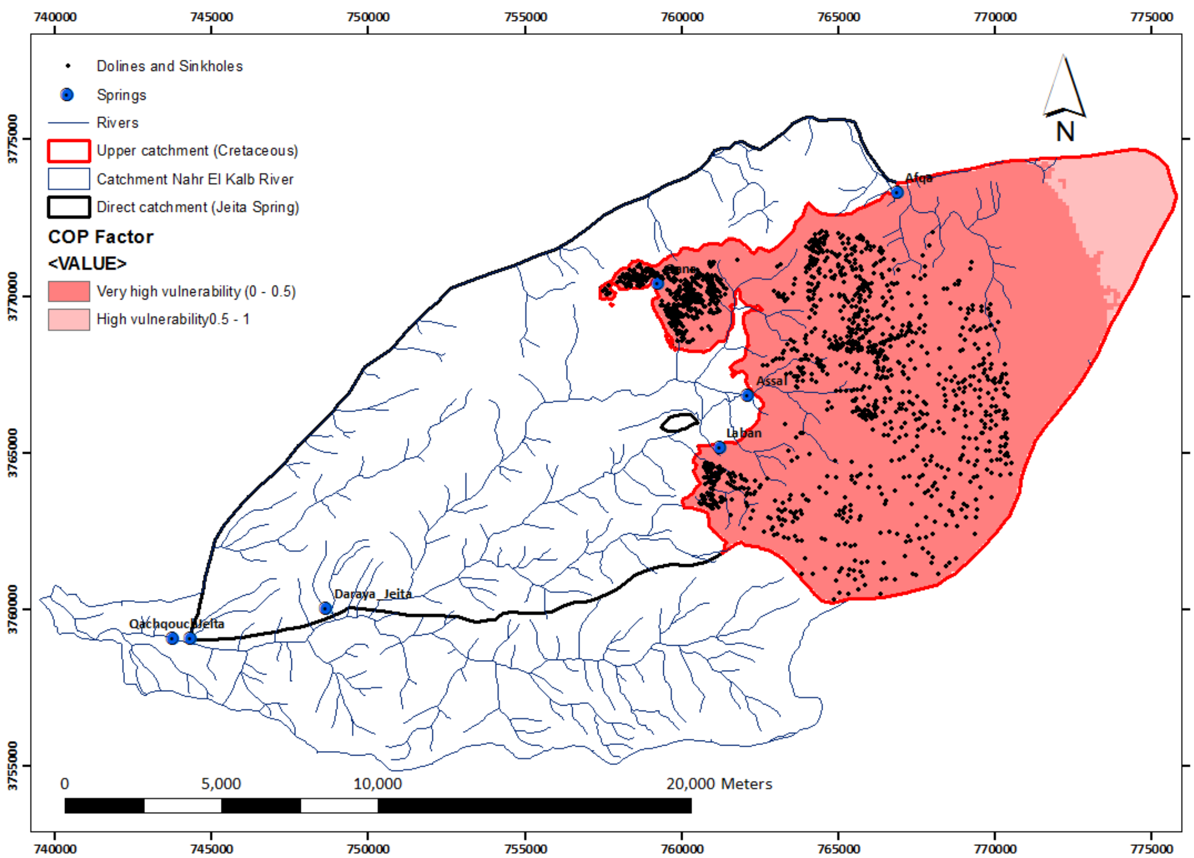

Figure 12 **COP map showing the extent of vulnerability in the upper catchment**

3.3.2 Results: Upper catchment

Most of the upper catchment area is characterized by a very high vulnerability (Figure 12), especially because of the density of the dolines, the karstic nature of the formation which decrease drastically the C and O values. Additionally precipitation is relatively high, however mostly under the form of snow. The vulnerability decreases in areas located about 3.5 km upstream from the highest doline cluster, it corresponds to the areas attributed a *dh* value equal or greater than 0.7. The vegetation and slope play a very minor role in the vulnerability calculation.

4 APPLICATION OF EPIK IN THE STUDY AREA

4.1 CONCEPT

The EPIK method is one of the methods developed especially for karst aquifers. It is used to assess the intrinsic vulnerability of a karst catchment. Four attributes are of main importance in this method, mainly Epikarst (E) Protective cover (P), Infiltration condition (I), and Karst network (K). A summation of these four weighted attributes yields a protection factor (F) to be assigned to each cell on the investigated catchment.

The method consists of analyzing 4 main parameters individually producing four maps and then performing a spatial analysis by combining the four parameter layers based on a weighted additive equation (Raster Calculator). The product of this method is a color-coded map representing areas of relative vulnerability to groundwater contamination from the surface, which also represent protection zones (SAEFL, 2000)

EPIK is a point count system method developed in Switzerland (Doerfliger et al., 1999). It relies as specified above on four attributes

EPIK is an acronym defining the four parameters analyzed in the method:

- Epikarst (E)

Epikarst refers to the highly kastified zone located beneath the soil cover. It is mainly representative of the water storage. Protective cover: protection of the soil and unconsolidated sediments. Epikarst is classified into three (3) categories.

- Protective cover (P)

Protective cover defined mainly by the thickness of the soil cover, or other non-karstic geological formations overlying the main aquifer. The thicker the protective cover the more significant is the protection, i.e., the higher the P value. P is divided into four main categories, varying from 1 to 4.

- Infiltration (I)

Infiltration refers to the type of recharge or infiltration, whether it is diffused or concentrated. In karst systems, areas with diffuse concentration are generally considered less vulnerable than areas with concentrated infiltration, e.g., sinking streams, etc. This attribute is divided into four categories.

- Karst network (K)

This parameter refers to the degree of karstification of a karst formation. It is mainly defined based on surface features and the presence of a karst network in the underground. Karst network is divided into three categories.

As already mentioned, each above parameter is subdivided into categories defining the type and degree of its development and scored on a scale of 1 to 3 or 1 to 4 as summarized in Table 5. The summation (Raster calculator) of the four layers using the value attribute yields a Protection Factor (F) for the different areas of the studied area according to the following formula:

$$F = 3\mathbf{E} + 2\mathbf{P} + 1\mathbf{I} + 3\mathbf{K}$$

The weights before each parameter are a function of the importance of the parameter and its relation with the others. Ranges of Protection Factor values are ultimately grouped to represent four different vulnerability levels associated with the catchment protection zones. The final output of the vulnerability assessment is thus a map showing protection zones for corresponding levels of vulnerability. Such zones are associated with restrictive activities (Doerfliger and Zwahlen, 1998).

Table 5 Evaluation of E, P, I, and K Parameters (modified from Doerfliger and Zwahlen, 1998)

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 on limestone formations or on detrital formations with very high hydraulic conductivity*	**B.** Soil resting on > 20 cm of low hydraulic conductivity geological formations**
Protective cover absent	P1	1	0 - 20 cm of soil	-
	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				
Concentrated infiltration	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	

Status	Code	Score	Description
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 decimeter to meter sized conduits with little fill and well interconnected
Poorly developed karstic network	K2	2	Poorly developed karstic network with poorly interconnected or infilled drains or conduits, or conduits of decimeter 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 6 Protection Factor and Vulnerability Zones

Protection Factor	Vulnerability Level
$9 < F \leq 19$	Very High Vulnerability
$20 < F \leq 25$	High Vulnerability
$26 < F \leq 34$	Moderate Vulnerability
> 25 with the presence of both P_4 and $I_{3,4}$	Low Vulnerability
-	Outside catchment

4.2 VULNERABILITY MAPPING

4.2.1 *Lower catchment*

The following sections describe the methodology used to derive each parameter.

4.2.1.1 Epikarst

Three main categories (E1, E2, and E3) were delineated according to the dolines and sinkholes mapped in the study area. The characterization of epikarst in the EPIK method is highly subjective, as it considers the rims of the dolines as being highly vulnerable and the area between the dolines as less vulnerable. However, it does not account for the effective recharge area of the doline. The recharge areas located within 50 m around a doline is generally specified as being highly vulnerable (Dunne 2003a), therefore attributed in this case a value of E1. A buffer of a random value of 500 m around the doline was assigned a value E2, whereas the rest of the catchment was attributed the value E3 (Figure 13). Table 7 illustrates the classification rationale of the Epikarst in the study area.

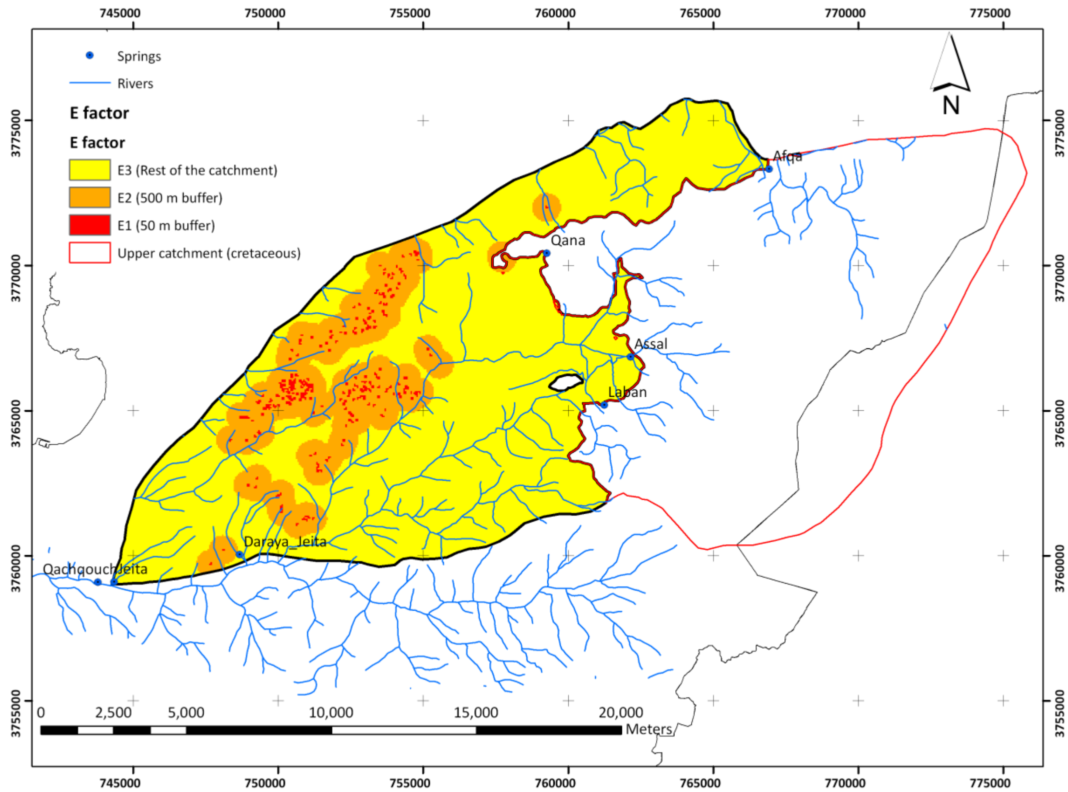

Figure 13 **Epikarst Layer of the lower catchment**

Table 7 **Epikarst rating for the lower Jeita catchment**

Epikarst Category	Score	Rationale
E1	1	The area surrounding the dolines and sinkholes (50 m diameter buffer)
E2	2	500 m buffer around dolines and sinkholes
E3	3	Rest of the catchment

4.2.1.2 Protective Cover

This layer represents the soil cover (Figure 14). It is divided into two main groups: soil resting directly on limestone formations and soil resting directly on non karstic formations. It is estimated to range between 20 and 100 cm. This layer was provided by BGR based on interpolation of soil analysis and field validation. Table 8 summarizes the classification of the protective cover in the Lower Jeita catchment.

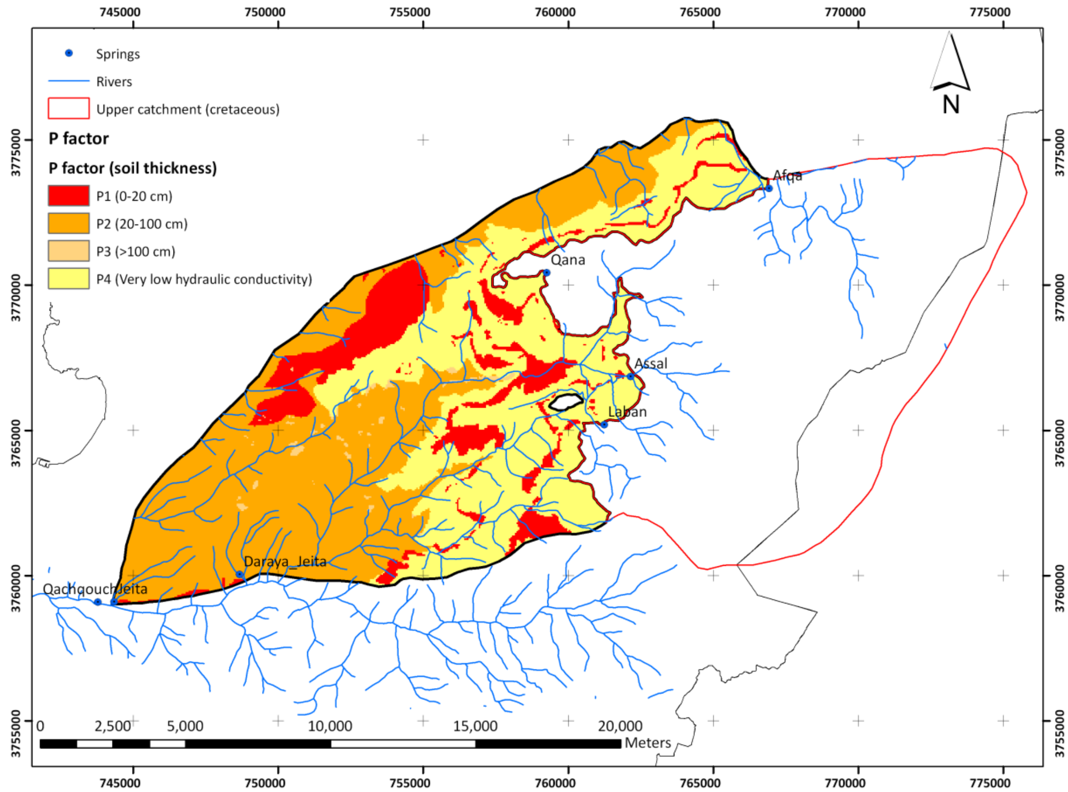

Figure 14 Protective cover layer of the lower catchment

Table 8 Protective cover rating for Jeita lower catchment

Protective Cover category	Score	Rationale
P1	1	Areas having no soil cover or cover less than 20 centimeters
P2	2	Areas consisting mainly of soil cover ranging between 20 to 100 centimeters in thickness
P3	3	Areas where soil cover exceeds 100 cm
P4	4	Soil resting on more than 6 m of low hydraulic conductivity formations, which in this case are the marly limestone and basaltic formations

4.2.1.3 Infiltration condition

No evidence of perennial streams supplying swallow holes was reported to date. Additionally the area is considered a surface water catchment therefore the I1 and I4 were not assigned to any location in the studied area. Values 2 and 3 were attributed respectively according to slope and land use. The higher the slope, the higher the likelihood of concentrated recharge, therefore the lower the value of I (Table 9). The higher values for I are at steep slopes of ephemeral water courses. Meadows were considered areas where vegetation is less than 50%.

Figure 15 shows the Infiltration (I Factor) of the investigated area calculated based on slope variation and vegetation cover.

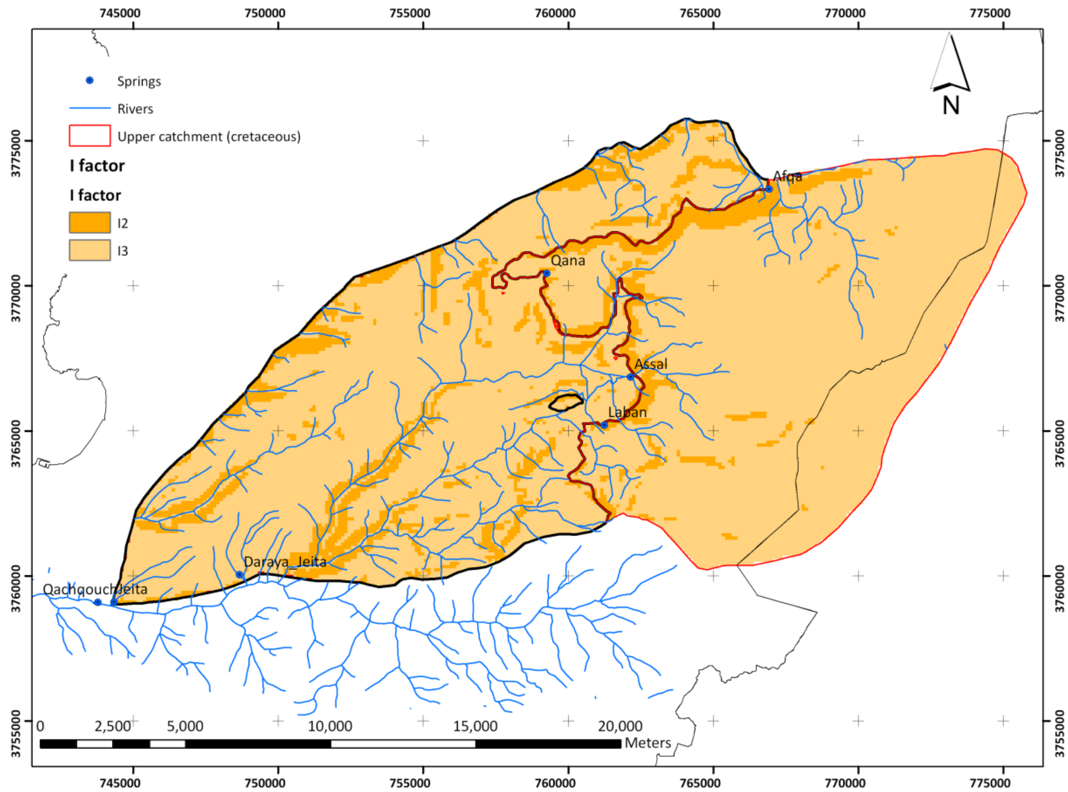

Figure 15 Infiltration condition layer of the lower catchment

Table 9 Infiltration rating for the lower catchment

Infiltration Category	Score	Rationale
I1	1	not existent
I2	2	Steep slopes of surface water sub-basins where slopes are greater than 25%
I3	3	Slopes in surface water sub basins where slopes are less than 10% for cultivated areas and less than 25 % for meadows
I4	4	not existent

4.2.1.4 Karst Network

The karst network was defined over the entire area according to

Table 10. The K factor map is represented in Figure 16.

Table 10 Karst ranking for the lower catchment

Karst Category	Score	Rationale
K1	1	Jurassic Limestone (J4)
K2	2	Poorly developed karstic network (Limestone J6 and C2b)
K3	3	Fissured non karst aquifers (other formations)

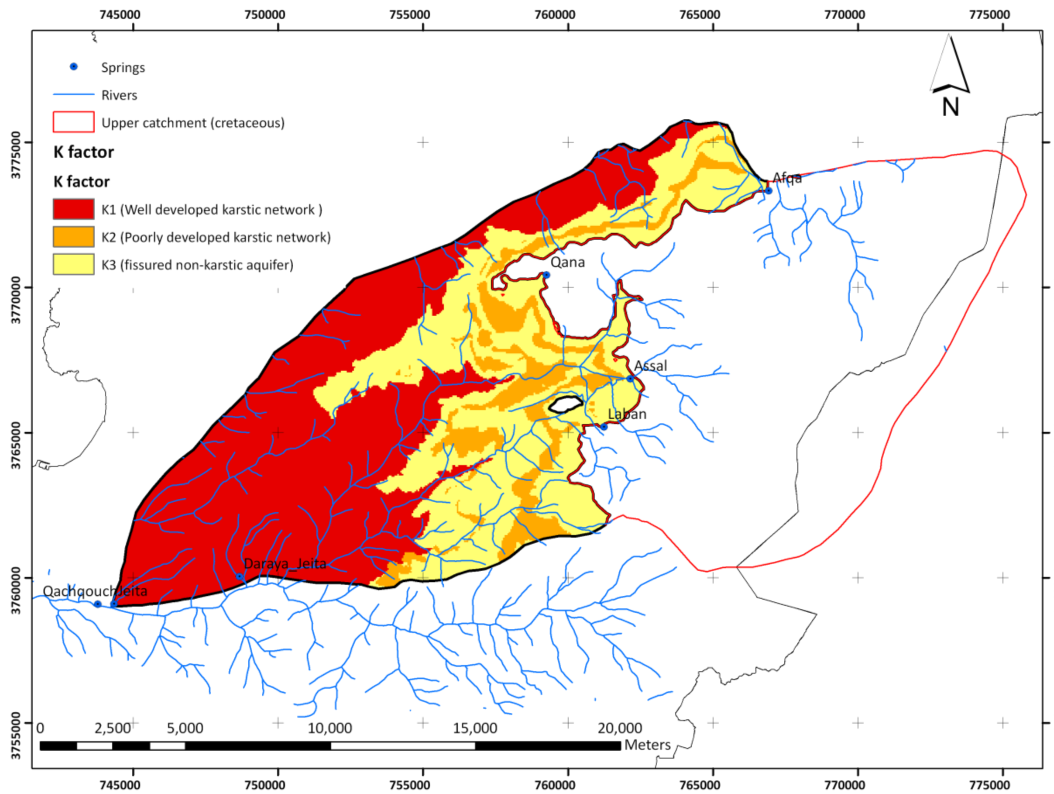

Figure 16 Karst network layer of the lower catchment

4.2.2 Upper catchment

The vulnerability mapping of the upper catchment was done according to the same methodology adopted in the lower catchment as follows:

- Epikarst: E1 and E2 were assigned to areas located respectively within a buffer of 50 m and 500 m from mapped dolines and sinkholes, whereas E3 was attributed to the rest of the area.
- Protective cover: given that the area is characterized by less than 20 cm of soil cover, the entire area was assigned the value P1. However the latter depends highly on the degree of accuracy in soil mapping.
- Infiltration conditions were developed based on slope and vegetation, most of the area is characterized by slopes less than 10%, the few water course catchments have slopes greater

than 25%. Therefore the infiltration factor varies between 3 and 4, where water course catchments with slopes greater than 25% are considered I3, and the rest of area I4.

- The degree of karstification is based on the outcropping formation, which is in this case the limestone of Cenomanian age. Most of the springs of the upper catchment present important multi branch cave systems developed in this formation, especially the Afqa spring, therefore the entire lithology was assigned in this case a factor K1.

Table 11 Scores assigned on the upper catchment and range of final Protection Factor (F)

EPIK	Score	Value range	Weighting coefficient	Value and weighting coefficient Range
Epikarst	E1 E2 E3	1-3	3	3-9
Protective cover	P1	1	2	2
Infiltration conditions	I3 I4	3-4	1	3-4
Karstification	K1	1	3	3
Protection factor	F			11-18 (Very high vulnerability)

4.3 EPIK FACTOR

After completing the individual layers as shapefiles, all the layers were converted into raster with a 50 m grid. Nevertheless, the final raster calculation was done on the basis of the DEM grid size. Each factor was attributed a weighting factor as per the EPIK equation, and a summation of the four layers yielded the final F factor map, where each area is attributed a number varying between 9 and 34.

4.3.1 Results: Lower catchment

The protection factors varied between 10 and 29 and were reclassified into 4 categories according to Table 6. One map was therefore established representing simultaneously both a vulnerability assessment map as shown in Figure 17. This further highlights the high vulnerability of the Jeita Lower catchment. The very high vulnerability zone corresponding to the most vulnerable areas consists mainly of the area buffering the dolines; while the area close to the spring is regarded mostly as highly vulnerable area. The moderately vulnerable area barely exists, mainly because most of the remaining area has a protection factor greater than 25 and is characterized by I3 and P4 factors for Infiltration and Protective cover respectively, therefore is rather attributed low vulnerability.

The areas characterized by a high vulnerability consists of about 29% of the total area and include partially or completely the villages of Faitroun, Qlaiaat, Ballouneh, Aajaltoun and Raifoun. The vulnerable area covers a more significant portion of the total catchment, about 38%. Areas with moderate vulnerability are not present on the study area as those area have a diffuse infiltration coefficient, slopes smaller than 10% (I3) and soil cover lying on low conductivity formations (P4), therefore those areas are regarded as having a low vulnerability and covers about 33% of the total study area.

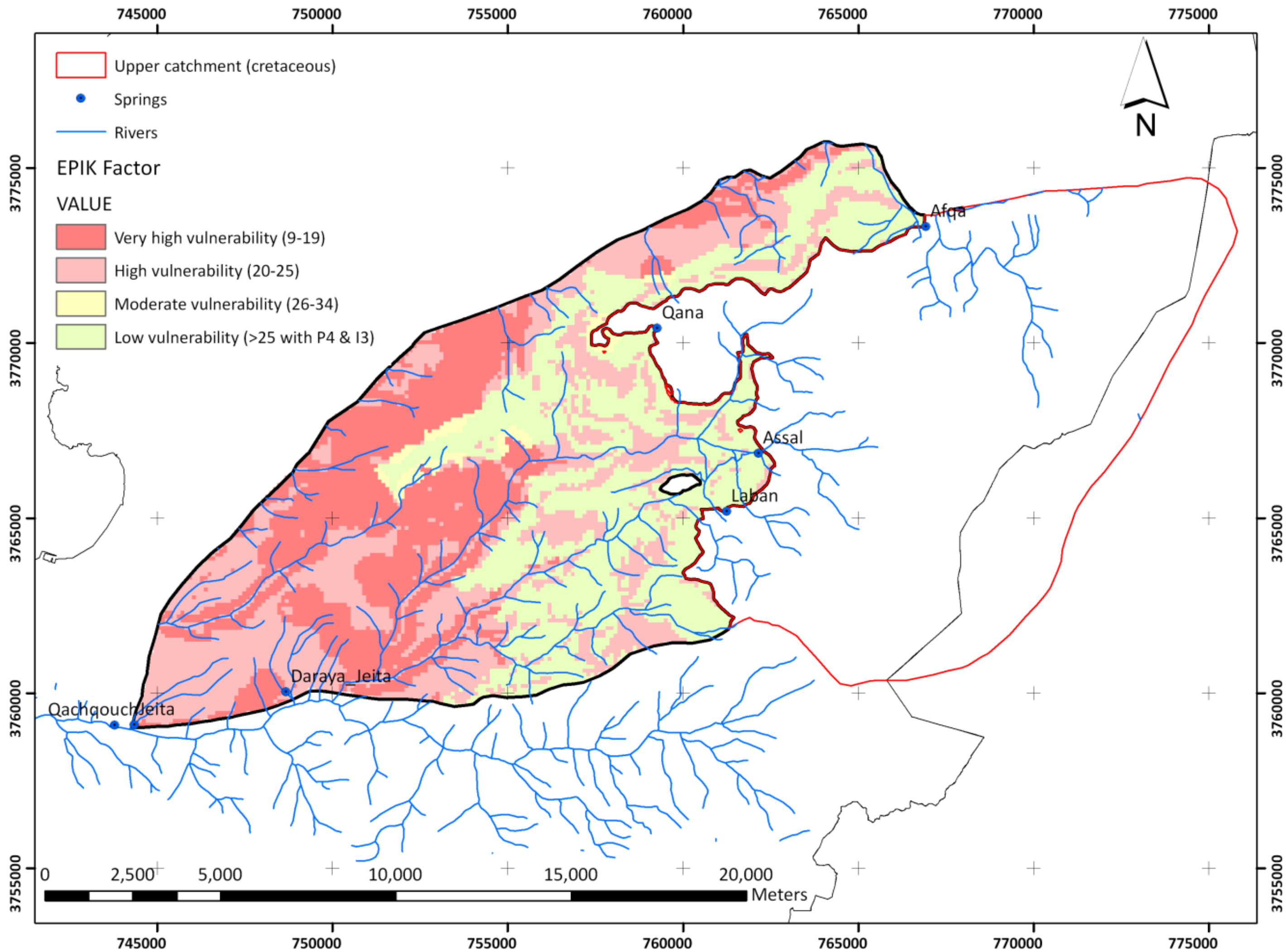

Figure 17 **EPIK Groundwater vulnerability assessment map for the lower catchment area**

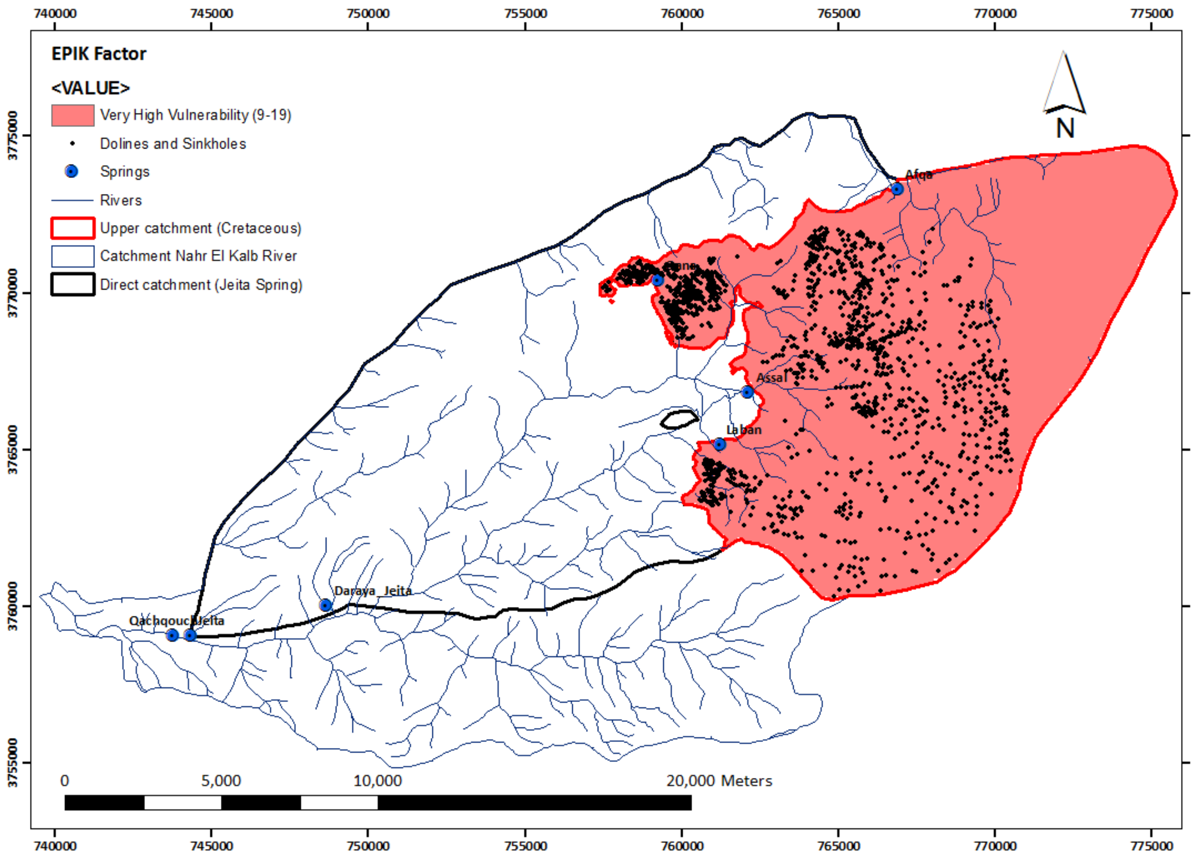

Figure 18 **EPIK Groundwater vulnerability assessment map for the upper catchment area**

4.3.2 Results: Upper catchment

As shown in Figure 18, most of the area is regarded as very highly vulnerable. The vulnerability factor varies mainly between 11 and 18. This is mainly owed to the density of the dolines. Additionally the layer P and K are the same all over the upper catchment and are very low. The Infiltration factor variation plays no role in varying the degree of vulnerability.

5 DISCUSSION

5.1 COMPARISON OF THE TWO METHODS

The two maps generated using the COP and EPIK methods delineate highly vulnerable to low vulnerable areas, which present relatively significant risks in term of groundwater pollution. The areas delineated should be accounted for when implementing strategies for sustainable groundwater protection. Some discrepancies are to be noted in the two maps, as the delineated areas do not always coincide.

The tracer experiments performed in the study area show that, mean velocities in the tested areas (mixed media; unsaturated and saturated zones) range between 40-45 m/h in the unsaturated zone and 67 to 200 m/h in both saturated and unsaturated zones. Additionally, transit times vary between 3 to 10 days under the experiment flow conditions (intermediate to low flow periods; Doummar et al., 2010, Doummar et al., 2011). Pathways characterized by transit times between 3 to 10 days are considered of very high vulnerability (Jeannin, P.-Y et al, 2001). On both EPIK and COP maps, the tracer test injection point sources locations are depicted under very high vulnerability. Other tracer tests on high vulnerable or medium vulnerable locations as portrayed by the EPIK and COP maps were not performed to date; therefore transit times cannot be attributed for these areas (Figure 19 and Figure 20).

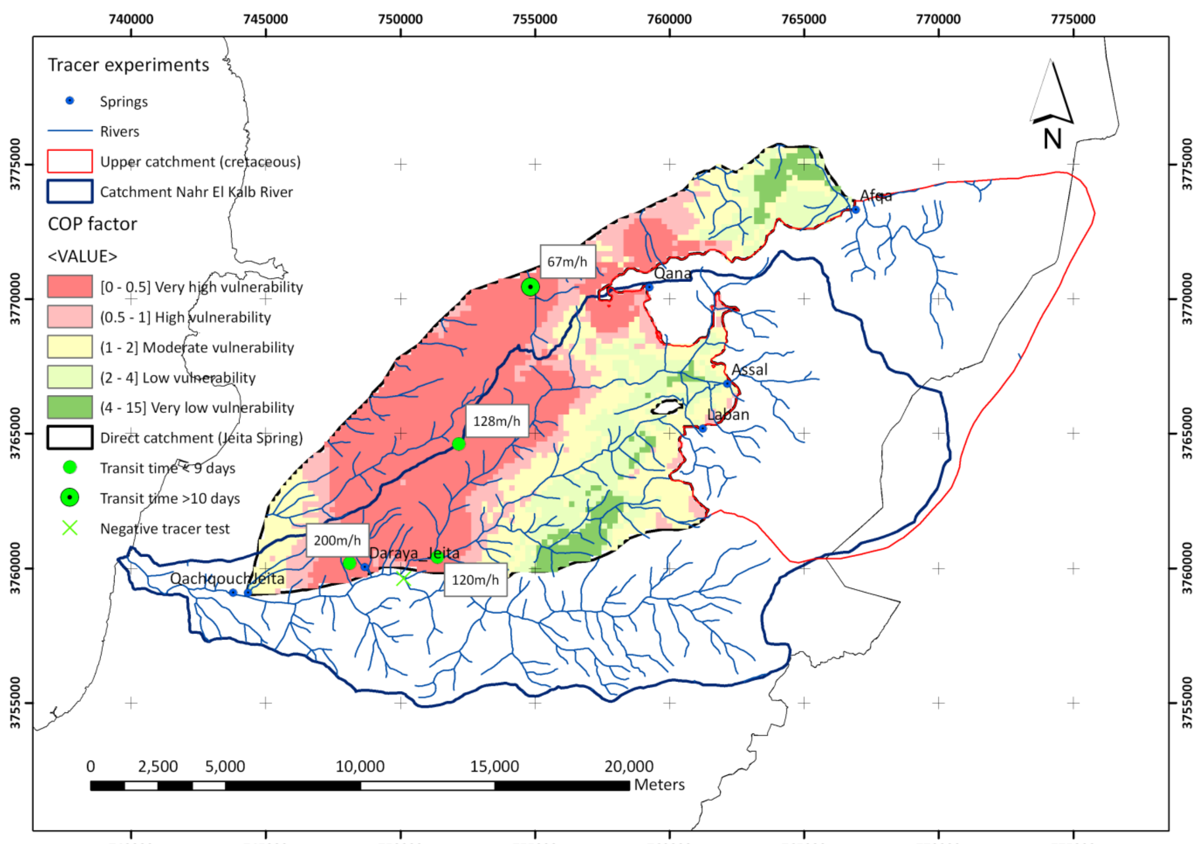

Figure 19 **Comparison of tracer test data with the generated vulnerability map (COP)**

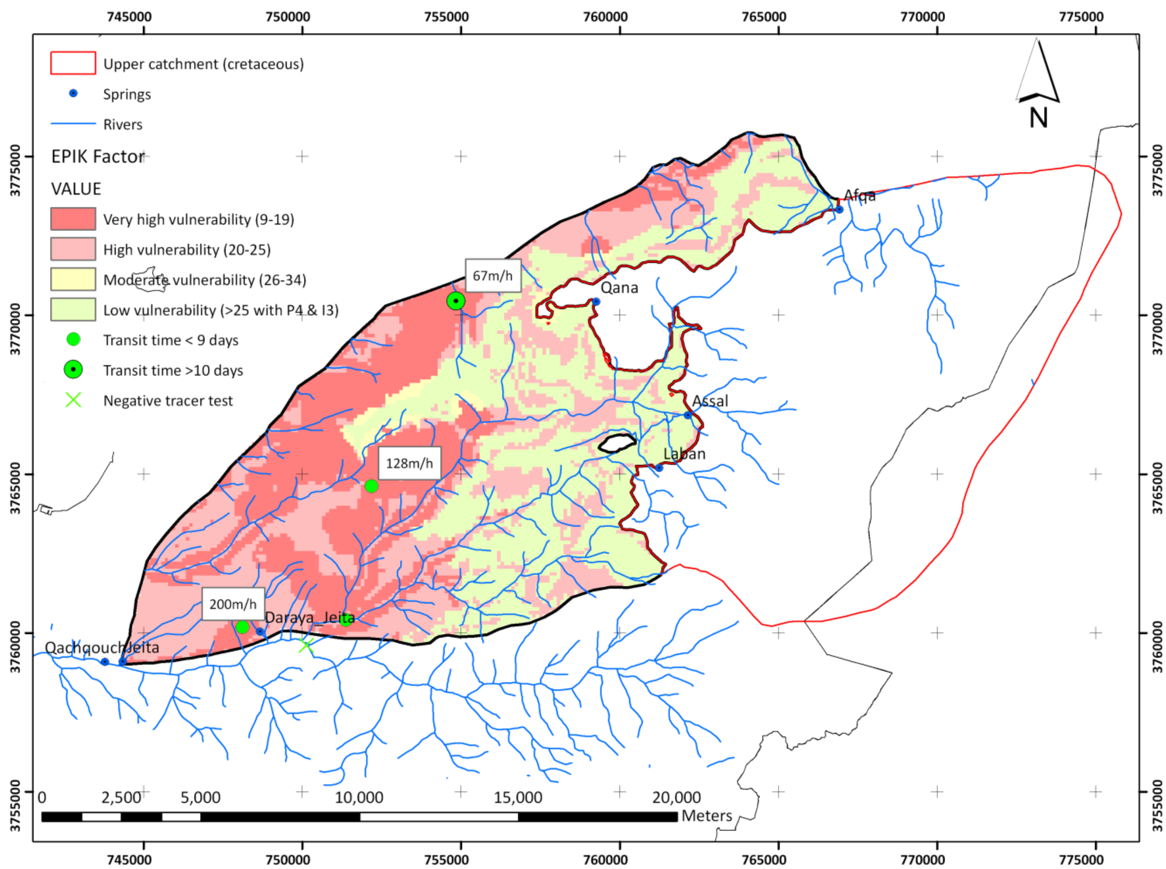

Figure 20 **Comparison of tracer test data with the generated vulnerability map (EPIK)**

The highly vulnerable areas are more or less delineated in the same locations in EPIK and COP. In the COP factor map, the highly vulnerable areas covers almost an entire stretch mostly consisting of a buffer around the dolines and sinkholes, whereas, EPIK is a little bit more selective as delineation of protection zones around dolines is more subjective. The COP methods identifies two classes of high and moderate vulnerability, whereas the EPIK method regards those areas as being highly vulnerable, especially that moderate vulnerability is absent in the EPIK map. The COP methods differentiates between two classes of low vulnerability (low and very low), whereas EPIK considers those same areas as being relatively of low vulnerability. These areas consist of formations having low hydraulic conductivities. The different vulnerability classes are shown in Table 12 and Figure 21.

Table 12 **Vulnerability classes and associated areas for COP and EPIK**

	EPIK			COP		
Vulnerability	**Value**	**Count**	**Area (km²)**	**Value**	**Count**	**Area (km²)**
Very high	9-19	3797	46.17	0-0.5	4859	59.10
High	20-25	5099	62.01	(0.5-1	1820	22.13
Moderate	26-34	0	0	(1-2	2412	29.33
Low	>25 with P4 and I3	4407	53.60	(2-4	2444	29.72
Very low	rest of the catchment			(4-15	1683	20.46
Total		13303	161.78		13218	160.74

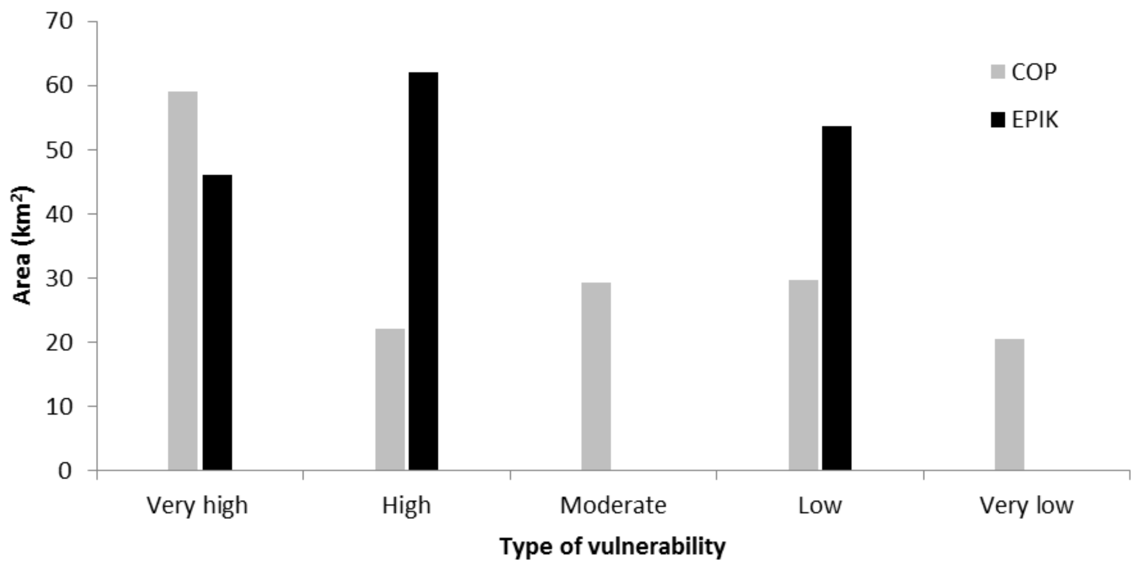

Figure 21 Areas assigned different types of vulnerability in both COP and EPIK methods

The vulnerability of the upper area is not reliable because the entire area is classified as highly vulnerable. In this case, protection measures are difficult to reinforce. Further investigations of recharge processes (especially rapid recharge) and effect of snow have to be accounted for to define the vulnerability of this area.

5.2 IMPORTANCE OF PARAMETERS IN THE VULNERABILITY ASSESSMENT

5.2.1 COP

Soil texture and thickness highly influence the Overlying Layers (O factor), consequently the final protection value. Therefore a detailed soil map with a high resolution (consistent with the adopted grid cell used to generate the final generated map, 110 m) portraying texture and thickness of soil in various locations is primordial for an accurate assessment of the Os factor. The thickness of unsaturated zone plays a major role in defining the O_L factor especially in karstic and fissured carbonate rocks. Therefore the assessment of the latter in critical areas is very important for the definition of the O_L factor, especially when the thickness of the unsaturated zone is less than 100 m.

The main controlling layer in the C factor is the *dh* (doline and sinkhole) layer, because the areas located within 500 m from the doline are attributed a value of 0, which is able to cancel both O and P factor in the final calculations. Therefore it is very important to understand the mechanisms of rapid infiltration in the dolines and sinkholes delineated in the study area and the extent of their recharge areas. P factor plays a role only in the case of moderate to low vulnerability, whereas in the cases where C and O factors are very low, the precipitation factor (P) plays a negligible role.

5.2.2 EPIK

The main factors affecting the Protection factor (F) are the epikarst and degree of karstification, given that they have a weighing coefficient of 3. Therefore buffer distances around dolines and karst features are still to be investigated to ensure that the E factor is well defined, especially when buffer distances from literature are adopted to delineate the E factor. The degree of karstification (K) was based on the lithology because little is known about karst development in the underground. This factor should be delineated based on the degree of fracturing and the potential presence of karst networks. The protective cover plays an important role in the EPIK factor however, given the weighting coefficient (2), it has a lower influence than other factors like Epikarst and degree of Karstification. The infiltration conditions in other words the variation of slope influences the boundary of the vulnerability zoning, however it plays a minor role especially that the weighting coefficient is only 1. A summary of the important parameters that play a major role in the protection factor in both COP and EPIK methods is shown in Table 13.

Table 13 Parameters influencing the protection factor in the COP and EPIK methods

Method	Parameter		Range where parameter plays a role	Effect on final factors and Index
COP (Range of Protection factor 0-15)				
O factor	Soil	Texture	0-3	+/- 1 (Os)
		Thickness	0-2	+/- 1 (Os)
	Lithology	Thickness of unsaturated zone	0-400	+/- 1 (Ly.m)
		Degree of fracturation	1-3	+/- 1-3 (Ly)
C factor	dh	Infiltration conditions in dolines	0	0 in 500 m buffer
		Presence of sinking stream		0 in < 10 m buffer from the sinking stream
EPIK (Range of Protection factor 9-34)				
Epikarst	E	Buffer distance to dolines and recharge areas	1-2	+/- 3-6
Karstification	K	Degree of fracturing	1-2	+/- 3-6
Protective cover	P	Soil thickness (resolution)	1-3	+/- 2-6

5.3 DELINEATION OF PROTECTION ZONES

There are very few outdated local guidelines or laws for groundwater protection zones in Lebanon, the only laws are very old and do not account for the hydrological characteristics of a catchment. Since EPIK was adopted in this study to delineate protection zones, Swiss guidelines developed for karst areas on the basis of the EPIK method, can be adopted to assess different potential activities on the lower catchment (LC) and propose restrictions that should be reinforced in zones of high vulnerability.

The delineated protection zones in EPIK follow the same restrictions as those of the groundwater protection zones defined in the Federal Authority for the Protection of the Environment document in Switzerland (SAEFL, 1977, 1982, 2003). This document clearly states that extremely few activities are acceptable in the S1 protection zone. No constructions whatsoever are acceptable in the S1 zones except for those related to catchment works for water sources. In S2 as well, no constructions of any kind are acceptable except for those that do not produce wastewater, do not handle polluting substances, and even without fuel for heating purposes.

No wastewater installations of any kind (e.g. sewerage pipes), Roads, or tracks, dumps of any kind, and quarrying activities are acceptable in S1 zones. Activities are limited to exceptional circumstances for S2 zones. In S3 zones, the installations should not accommodate domestic and industrial wastewater containing substances with potential adverse impacts on groundwater. No storage of liquids or solids that might have an adverse effect on groundwater are allowed in any of S1 or S2 zones and are highly regulated and in many cases forbidden in S3 zones. No dumps of any kind are acceptable in all of the three zones except for inert material with no adverse impacts on infiltrated water such as clean construction waste (rocks, bricks, wood, etc.). No warehouses of any kind are acceptable in S1 zones and are restricted to non-soluble solids for S2 and S3 that do not implicate the use of substances with adverse impacts on groundwater.

No quarrying activities are acceptable in the three zones except in specific cases in S3. Cemeteries are not acceptable in any of the three zones. Table 14 presents a summary of the restrictions associated with the protection zones.

Table 14 **Restrictions associated with protection factors (EPIK), vulnerability levels and groundwater protection zones (SAEFL, 2000)**

Protection zone	Protection Factor	Vulnerability Level
S1	$9 < F \leq 19$	Very High Vulnerability
S2	$20 < F \leq 25$	High Vulnerability
S3	$26 < F \leq 34$	Moderate Vulnerability
Rest of catchment area	> 25 with the presence of both P_4 and $I_{3,4}$	Low Vulnerability
Exterior Zone	-	Outside catchment

Protection Zone	Some Restrictions
S1	• No construction except for water resources catchment works • No camping sites • No parking sites for caravans and mobile homes • No wastewater installations of any kind • No storage of fuel for heating purposes • No transport infrastructure of any kind (e.g. roads, railroads, railway stations, etc) • No storage of potentially polluting substances • No warehouses of any kind • No dumps except for highly regulated clean and inert construction waste • No quarrying
S2	• No wastewater generating constructions • No camping sites • No parking sites for caravans and mobile homes • No wastewater installations of any kind allowed except in highly regulated exceptional circumstances • No storage of fuel for heating purposes • No storage of potentially polluting substances • Warehouses restricted to non-soluble solids with no potential adverse impacts on groundwater • No dumps except for highly regulated clean and inert construction waste • No quarrying
S3	• No wastewater installations with potential adverse impacts on groundwater • Highly regulated storage and handling of potentially polluting substances • Warehouses restricted to non-soluble solids with no potential adverse impacts on groundwater • No dumps except for highly regulated clean and inert construction waste • No quarrying except in exceptional circumstances
Rest of Catchment	• No restrictions specific to the protection of groundwater
Exterior Zone	• No restrictions specific to the protection of groundwater

6 CONCLUSIONS AND RECOMMENDATIONS

The vulnerability mapping allowed generating two vulnerability maps according to two methods developed especially for karst areas (EPIK and COP). The maps provide a classification of the extent of vulnerability of each parcel located in the study area. Those maps are primordial to secure a sustainable groundwater resources management and ensure the preservation of water quality, given the importance of the Jeita Spring.

Given that the two maps are showing a few discrepancies in terms of delineation and classification of different zones, it is important to mention the various limitations of the available data and their influence on the mapping exercise, and provide recommendations for additional investigations to refine the above study.

It is recommended to investigate thoroughly the following factors to achieve a better refinement of the vulnerability maps, given that the application of vulnerability maps have a major influence on land expropriation and land use patterns. The area located directly above the trace of the Jeita cave should also be thoroughly investigated (Detailed mapping of karst features and soil thickness) especially that mean velocities within the cave are considered significant; therefore contaminants could be conveyed to the spring in relatively low transit time.

- COP
  - A better assessment of the variation of the thickness of the unsaturated zone in the lower and upper catchments
  - A higher resolution mapping of the soil texture and thickness over the entire area especially in areas of concentrated high infiltration, assessment of soil cover in river beds and degree of infiltration, especially in the presence of sinking streams if any.
  - A differentiation between karstic rocks and fissured carbonate rocks on the basis of degree of fracturing and karst features.
  - A more accurate estimation of precipitation/recharge (number of rainy days and precipitation gradient change) and effect of snow and delayed infiltration especially in the upper catchment
- EPIK
  - A higher resolution mapping of the soil thickness
  - Investigate distances to dolines and catchment areas of dolines
  - Assess the degree of karstification based on degree of fracturing rather than adopting one value for the entire formation

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