



Sensitivity analysis for the EPIK method of vulnerability assessment in a small karstic aquifer, southern Belgium

Radu Constantin Gogu · Alain Dassargues

Abstract Applying the EPIK parametric method, a vulnerability assessment has been made for a small karstic groundwater system in southern Belgium. The aquifer is a karstified limestone of Devonian age. A map of intrinsic vulnerability of the aquifer and of the local water-supply system shows three vulnerability areas. A parameter-balance study and a sensitivity analysis were performed to evaluate the influence of single parameters on aquifer-vulnerability assessment using the EPIK method. This approach provides a methodology for the evaluation of vulnerability mapping and for more reliable interpretation of vulnerability indices for karst groundwater resources.

Résumé Une analyse de la vulnérabilité d'un petit aquifère karstique du sud de la Belgique a été réalisée en appliquant la méthode paramétrique EPIK. L'aquifère est logé dans des calcaires karstifiés du Dévonien. Une carte de la vulnérabilité intrinsèque de l'aquifère et du captage existant montre trois zones de vulnérabilité. Une étude d'évaluation des paramètres et une analyse de sensibilité ont été conduites pour juger l'influence des paramètres sur l'estimation de la vulnérabilité de l'aquifère au moyen de la méthode EPIK. Cette approche fournit une méthodologie pour évaluer la cartographie de la vulnérabilité et pour interpréter d'une façon plus sûre les indices de vulnérabilité des ressources en eau des milieux karstiques.

Resumen Se ha efectuado un estudio de vulnerabilidad de un pequeño acuífero kárstico en el Sur de Bélgica mediante el método paramétrico EPIK. El acuífero consiste en calizas karstificadas del Devónico. El mapa de vulnerabilidad intrínseca del acuífero y del sistema local de abastecimiento indica la existencia de tres áreas vulnerables. Se estudió el balance de los parámetros y se hizo un análisis de sensibilidad para evaluar la influencia de cada parámetro en las valoraciones de vulnerabilidad de acuíferos utilizando el método EPIK. Este enfoque proporciona una metodología para evaluar zonas vulnerables y para obtener interpretaciones más robustas de los índices de vulnerabilidad en relación con los recursos de aguas subterráneas en medios kársticos.

Key words vulnerability · karst · groundwater protection · sensitivity analysis · Belgium

Introduction

Assessing vulnerability of aquifers using overlay and index methods is an empirical procedure, but for karstic aquifers this kind of technique represents one of the only meaningful ways to delineate the zones most vulnerable to groundwater contamination. Some subjectivity is, to some extent, unavoidable in the selection of rating values and weights in the EPIK method (Epikarst, Protective cover, Infiltration conditions, and Karst network development) as in other similar methods, such as DRASTIC (Aller et al. 1987) and SINTACS (Vrba and Zaporozec 1994).

In order to investigate the impact of this subjectivity on the final results, a small karstic aquifer near Beauraing, Belgium, was selected to test the sensitivity of vulnerability to selected values of ratings and weight in the EPIK method. The first step was to prepare a detailed vulnerability map according to the EPIK technique (Doerfliger and Zwahlen 1997). Then, using a sensitivity analysis of the applied parameters, an evaluation of this vulnerability-mapping method was done. The analysis allows one to study the parameter balance in the vulnerability method, in order to reduce or increase the importance of a parameter in the calculation of the vulnerability index.

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The results could lead to changes in the parameter estimation within the basic equation of the vulnerability method.

Intrinsic Vulnerability of the Aquifer

Hydrogeological Framework

The Beauraing study site is an area of 2.5 km² in the southern part of the Dinant synclinorium near the France–Belgium border. Location is shown in *Figure 1*. The main karstic aquifer is composed of Devonian limestone. These limestone deposits are bounded to the north and south by Frasnian and Eifelian siltstone bands; the rocks are folded into an anticline–syncline structure with a WNW-trending axis. The geology is shown in *Figure 2*. The siltstone bands act as impermeable boundaries for the limestone aquifer. Consequently, the study area was confined to the karstic aquifer. Four joint systems have been identified. One of them is orthogonal to the strike of the main strata, two others are at 45° angles, and the fourth one trends NE (Gontier et al. 1997).

The aquifer is unconfined and water supply is provided to the small city of Beauraing by pumping from one of the natural caves of the aquifer. In order to study the protection zones around the water-supply system, six piezometers with depths of 65–80 m were drilled in 1994–1995. The measured potentiometric levels indicate that the depth to the water table ranges

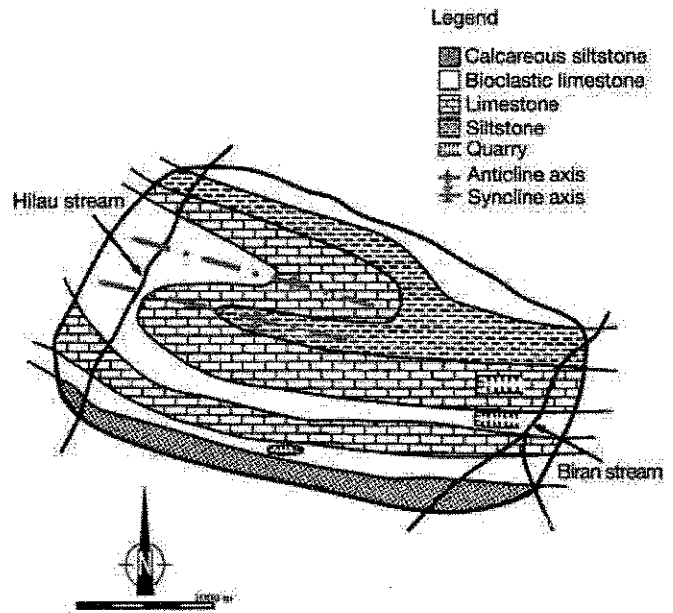
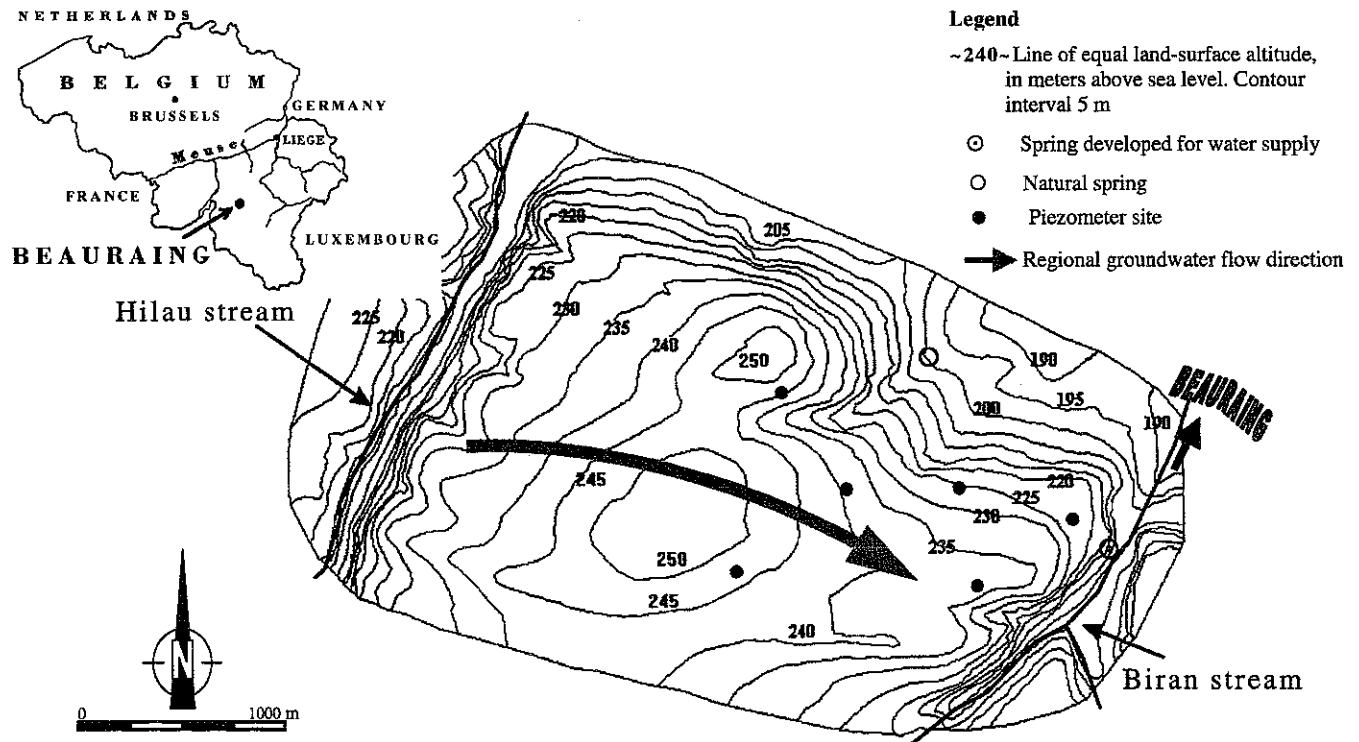


Figure 2 Geology of study area

from 18–40 m. Regional studies (Gontier et al. 1997) indicate that the general groundwater flow direction is from west to east. In the study area, groundwater flows from the area of the Hilau stream to the Biran stream, as confirmed by measured losses of water in the Hilau stream. The aquifer has two discrete natural groundwater outlets. The principal one is in a natural cavern in the eastern part of the area. This outlet has been developed to collect groundwater (25–40 m³/h)

Figure 1 Location of study area, near Beauraing, Belgium



for water supply. The second one is a small natural spring in the northern part of the area, on the lithological transition from limestone to siltstone; flow rate is $1 \text{ m}^3/\text{h}$.

Karstic Features

The limestone aquifer is overlain by a thin (less than 0.8 m) soil cover and has several external features of karstification (epikarst). At the western boundary of the study area, five swallow holes and a small cave occur in the course of the Hilau stream. Several aligned dolines were mapped in the study area. Geophysical investigations include geoelectrical sounding and profiling and local seismic sounding. The geophysical data helped delineate the local geological structure, assess thickness of the overlying soil cover, and accurately delineate the position of the limestone-siltstone contact (Gontier et al. 1997).

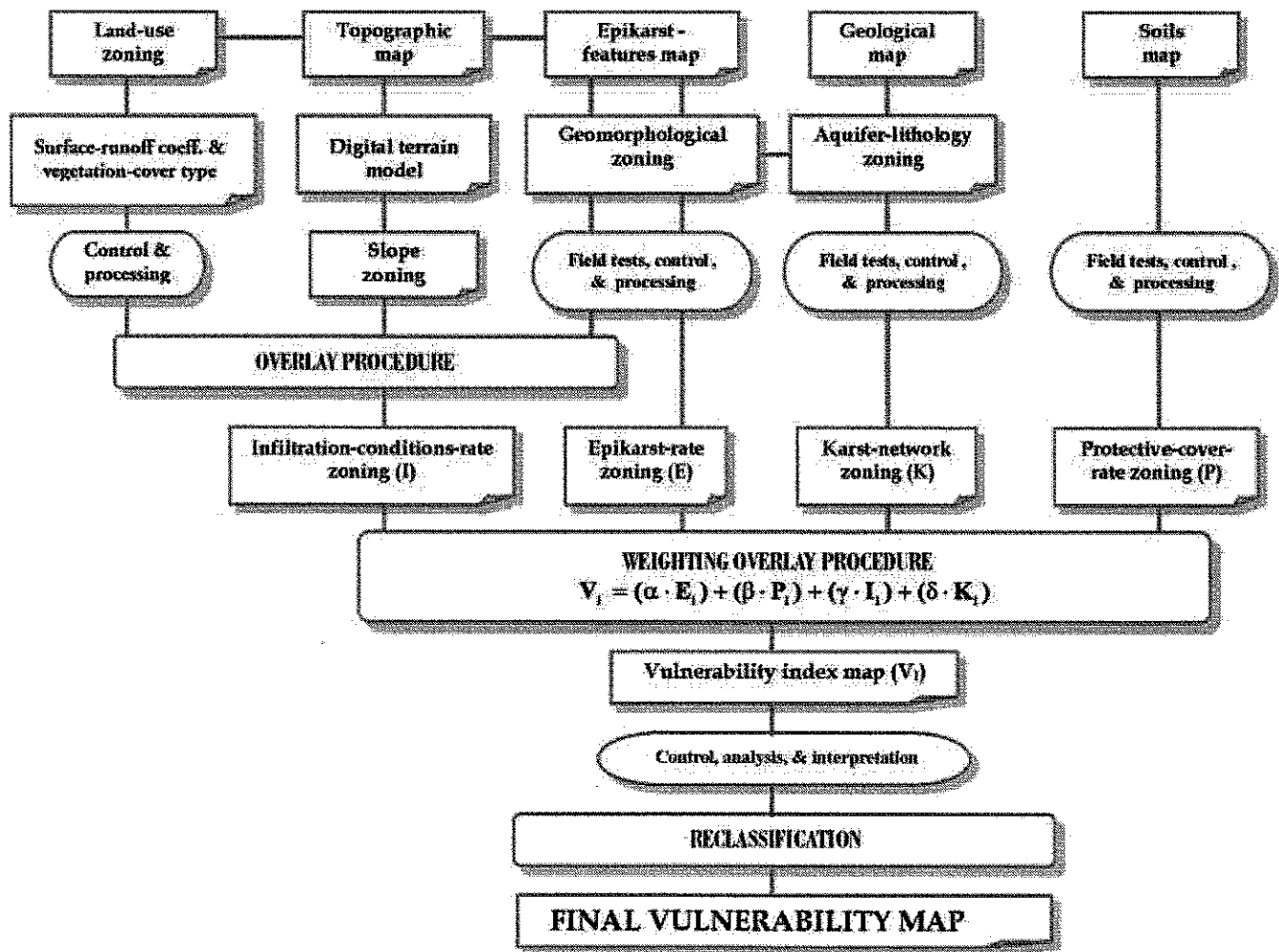
Several tracer tests were conducted, in which injections were made in observation wells and in a swallow hole in the course of the Biran stream, and the possi-

ble arrivals of the tracers were monitored at the outlets. Results indicate that the possible karstic conduits are not directly connected to the two natural groundwater outlets. Therefore, based on the EPIK classification scheme proposed by Doerfliger and Zwahlen (1997), the karst network of these Devonian limestones is characterised as having a medium-poor degree of development.

The EPIK Method

The EPIK method represents an original "parameter weighting and rating method" (Vrba and Zaporozec 1994) developed for outlining and classifying the intrinsic vulnerability of groundwater in karst aquifers to contamination (Doerfliger and Zwahlen 1997). In contrast to other groundwater vulnerability methods, this one uses specific karstic-system features, assuming that a network of connected joints and conduits divides more compact zones of limestone. The method is based on observed geological, geomorphological, and hydrogeological features. The procedure is shown in Figure 3. In the EPIK method, four parameters are considered: epikarst (E), protective cover (P), infiltration conditions (I), and karst-network development

Figure 3 Procedure for applying the EPIK method



(K). These criteria correspond to four characteristics that affect water-flow and transport conditions through the karstic system. A value is assigned to each parameter in one of three (or four) classes that characterise the anticipated impact of this parameter on vulnerability to contamination. For details about values assigned to the parameters in the EPIK method, see Doerfliger and Zwahlen (1997).

Epikarst is defined as "an intensively karstified and highly permeable near-surface zone" (Tripet et al. 1997). The epikarst parameter has three classes: E1, for epikarst associated with the karstic network (drained dolines, caves, etc.); E2, for epikarst associated with the fissured matrix zone (dry valleys, alignment of dolines, etc.); and E3, for the absence of epikarst morphology. Doerfliger and Zwahlen (1997) include in the protective cover parameter (P) the soil and other overburden deposits, such as Quaternary deposits (glacial till, silt, loess, rock debris, etc.), and other non-karst layers (for example, clay and sandstone). Values are assigned to the protective-cover parameter (P1, P2, P3, P4) principally on the basis of the thickness of the overlying sediments.

The infiltration parameter (I) is the most complex parameter to be estimated. I1 is assigned to zones, such as swallow holes, where direct concentrated infiltration is possible. I2 and I3 are assigned values by taking into account three slope ranges (0–10%, 10–25%, and >25%) as well as the surface-runoff coefficients and the vegetation-cover type. Contrary to other parametric methods, here vulnerability increases with increasing slope, on the assumption that surface runoff is directed toward karstified infiltration points. This feature is characteristic for well-developed karstic systems.

The karst network parameter (K) is assigned one of three possible values: K1, for areas presenting a well-developed karstic network; K2, for areas presenting a poorly developed karstic network; and K3, for karstic aquifers having an outlet in porous media or showing fissure-matrix intercalations.

Weighting factors (α , β , γ , and δ ; see Figure 3) are used for each parameter to balance their importance in the calculation of a vulnerability index, V_i . This vulnerability index, called "the protection factor" (Doerfliger and Zwahlen 1997), is calculated as:

$$V_i = (\alpha \cdot E_i) + (\beta \cdot P_i) + (\gamma \cdot I_i) + (\delta \cdot K_i) \quad (1)$$

where:

V_i = vulnerability index in subarea i

E_i = rating value for the "epikarst" parameter

P_i = rating value for the "protective cover" parameter

I_i = rating value for the "infiltration conditions" parameter

K_i = rating value for the "karst network development" parameter

α , β , γ , and δ = the weighting factors corresponding to E, P, I, and K parameters.

Table 1 Rating values for E, P, I, and K parameters (Note: the lower the rating value, the higher the vulnerability)

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

Doerfliger and Zwahlen (1997) use the rating values shown in Table 1 for E, P, I, and K parameters and the following weighting factors: $\alpha=3$, $\beta=1$, $\gamma=3$, and $\delta=2$. The final vulnerability index (V_i) ranges from 9–34, and different intrinsic vulnerability categories could be distinguished. For karstic systems of the Swiss Jura mountains, Doerfliger and Zwahlen (1997) recommend four categories of vulnerability: high (9–19), medium (20–25), low (26–34), and very low, where at least 8 m exists of a soil-protective cover that consists of sedimentary detrital deposits with very low hydraulic conductivity. These categories can be modified to fit other kinds of karstic systems.

Map of Intrinsic Vulnerability

In order to map aquifer intrinsic vulnerability for the study area, a raster-based geographical information system (GIS) software (IDRISI) was used. The epikarst (E) parameter was determined using morphostructural analysis on aerial photos and a topographical map (scale 1:10,000) and through geomorphological field surveying. Values of soil protective cover (P) were determined using a detailed local map of the soil-cover thickness. This last was developed from data obtained from the published *Map of the Soils in Belgium* (Avril et al. 1984) and integrated results from boreholes, piezometers, seismic soundings, and from 35 hand-auger short holes executed for this purpose. A map of classified slopes was prepared by slope-computing and slope-classification operations using a digital elevation model (DEM) of the region (1:10,000). The infiltration parameter map indicated a rating value I1 in zones with possible direct infiltration. An overlay operation between the map of classified slope and the land-use map was carried out to delineate zones with I2 or I3 rating values. The data from tracer tests show that this site is not characterised by a highly developed karst network. Therefore, a K2 rating was assigned to the entire area for the karst network parameter (K). The zones of old quarries were considered separately. They were considered as a geomorphological attribute and assigned appropriate E and I parameters. The rating value of extreme vulnerability was given to these zones of old quarry works.

All four parameters were mapped on the E, P, I, and K maps, shown in Figure 4. A detailed analysis was performed using a raster model with a 16-m² cell size. This resolution corresponds to the surface of the smallest morphological element to be mapped. Using the vulnerability index of Eq. (1), the four parameter

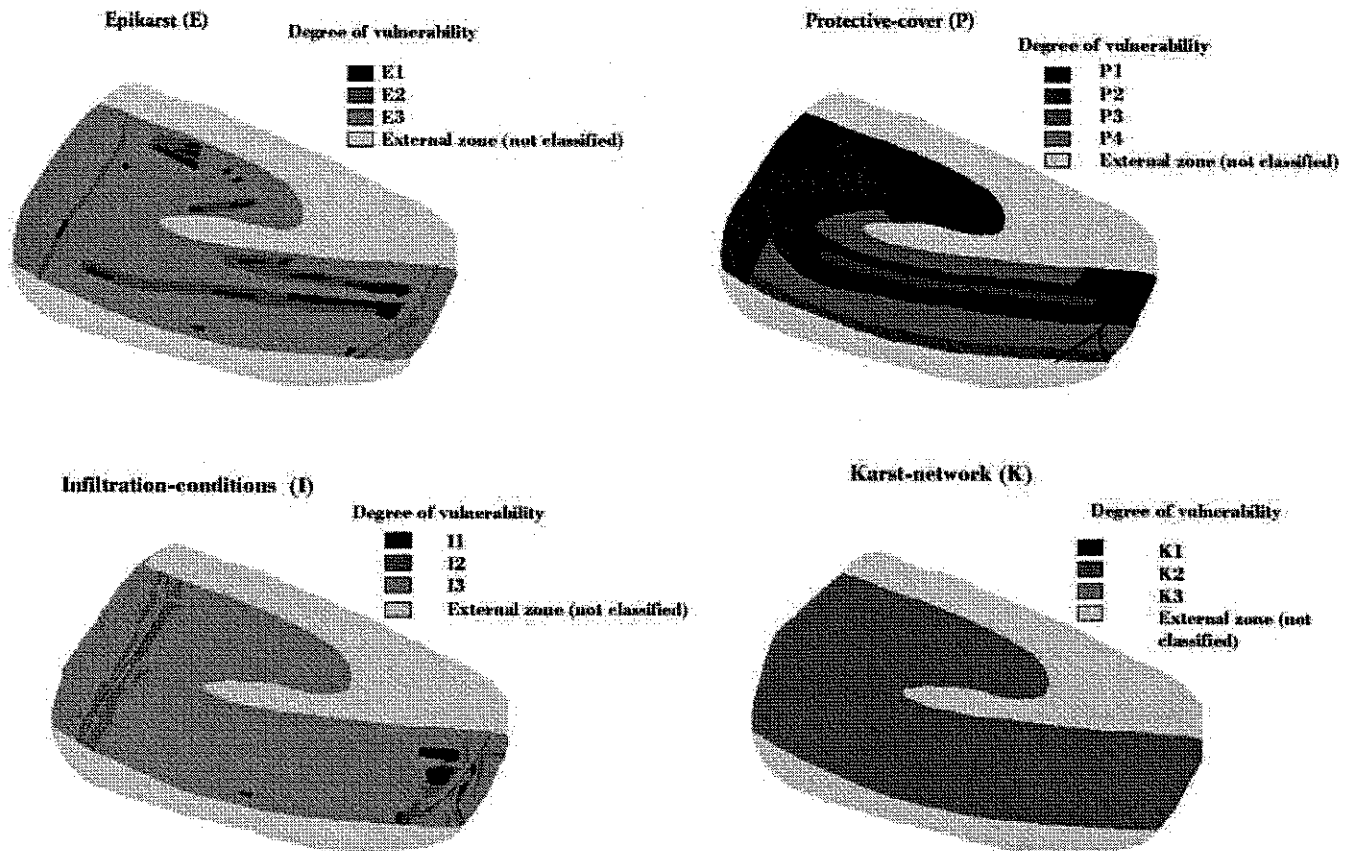


Figure 4 Parameter maps (*E*, *P*, *I*, and *K*) estimated for the Beauraing study area

maps were overlaid cell by cell to produce a “vulnerability index map.” For the study area, calculated values of the vulnerability index range from 11–28 and were classified in three vulnerability classes: high, medium, and low. No zones were classified in the very low category. The final vulnerability map is shown in *Figure 5*.

A comparison of the four parameter maps (*Figure 4*) with the final vulnerability map (*Figure 5*) indicates that the epikarst parameter (*E*) plays a major role in delineating the high-vulnerability zones. The conditions of infiltration (*I*) also make a noticeable contribution. Parameters *E* and *I* both play an important role in determining medium-vulnerability zones.

Parameter Sensitivity

Method

As in all other parametric techniques, subjectivity is inevitable in the selection of rating values and weights related to the EPIK parameters, and this subjectivity can strongly affect the final vulnerability map. Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to

each parameter and helps the analyst to judge the significance of subjective elements.

An analysis, based on the concept of “unique condition subareas,” was performed to study the sensitivity of each parameter in operations between map layers. Similar analyses have been applied in the assessment of aquifer vulnerability using DRASTIC and SINTACS methods (Napolitano and Fabbri 1996).

The general flow-chart of the procedure is presented in *Figure 6*. After determination of unique condition subareas, “map-removal” sensitivity and “single-parameter” sensitivity analyses were performed, as described below. The sensitivity-analysis results were then processed to obtain tables with statistics.

Unique Condition Subareas

A “unique condition subarea” consists of one or more zones (consisting of cells) where a unique combination of *E*, *P*, *I*, and *K* rating values of the four layers is used to compute the vulnerability index. In this study, the weights were not taken into consideration because they are constant for each parameter.

Starting from the four parameter maps (*E*, *P*, *I*, and *K*), all possible combinations of rating values are recorded in one resulting map and in one exhaustive table. In practice, this stage is performed using the GIS “crossing” function. This function performs two operations: cross-tabulation and cross-classification. In the first operation, the existing values of one of the

Figure 5 Vulnerability map of the Beauraing study area, based on the EPIK method

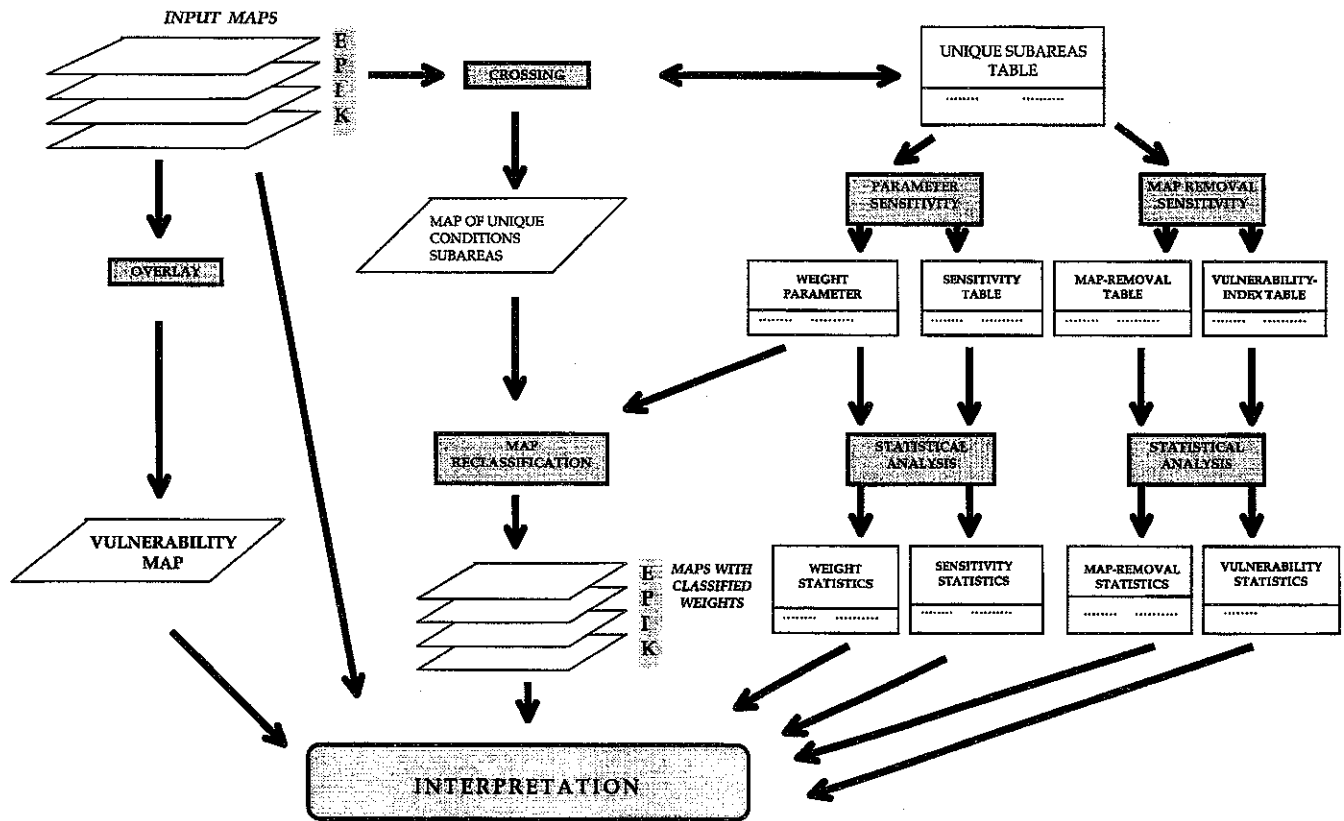
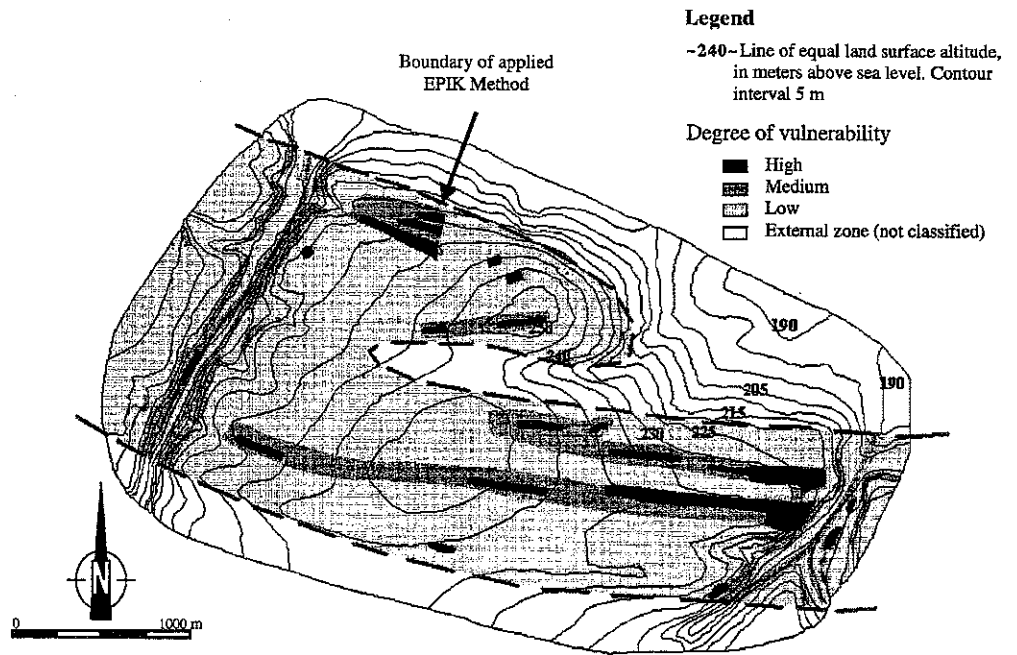


Figure 6 Procedure for applying sensitivity analysis. (Modified after Napolitano and Fabbri 1996)

four raster images (one for each parameter) are compared with those of a second parameter, and a tabulation with the number of cells in each combination is registered. In effect, cross-classification is as a multiple

overlay showing all combinations of the logical "AND" operation. The result is a new image that shows the locations of all combinations of the parameters' rating values.

The study area was divided into 145,935 cells. The concept of unique conditions subareas was used to avoid problems in handling such a large number of pixels. The unique condition subareas were obtained

by crossing the four layers, two at a time. The calculation procedure was conducted using IDRISI macro-language as well as EXCELL macros. Applying this method, 25 subareas were obtained. Due to the digitising data process, inevitable residual slivers consisting of areas smaller than 6 pixels occurred. Three such small subareas were not considered in the analysis. This procedure reduced the computation time as well as the analytical complexity.

Map-Removal Sensitivity

The first stage of this analysis was to compute the vulnerability values using three maps instead of four (i.e., removing one map). For each subarea, four vulnerability indexes were calculated using combinations of three of the four parameters. For comparability, the output values were re-scaled by a factor 4/3. Comparing the new index with the initial one provides a direct measure of the influence of the missing parameter. Results indicate that the relative influence on the final vulnerability index is $E > I > K > P$.

Lodwik et al. (1990) define a map-removal sensitivity measure that represents the sensitivity associated with removing one or more maps. This measure can be expressed as:

$$S_{Xi} = \left| \frac{V_i}{N} - \frac{V_{Xi}}{n} \right| \quad (2)$$

where:

S_{Xi} = sensitivity (for the i^{th} unique condition subarea) associated with the removal of one map (of parameter X)

V_i = vulnerability index computed using Eq. (1) on the i^{th} subarea

V_{Xi} = vulnerability index of the i^{th} subarea without considering parameter X (E, P, I, or K)

N = number of maps used in primary suitability (four maps)

n = number of maps used in perturbed suitability (three maps).

In each subarea, this measure reflects the variability of each parameter but not the contribution of the weighting factors. For each subarea, four values of sensitivity associated with the removal of one parameter were computed.

On the entire domain, the statistical parameters, shown in Table 2, confirm the greater sensitivity of parameter E and show that the average sensitivity of parameter P is greater than that of parameter I. The role of P becomes significant when the entire analysed area is examined. The sensitivity of the parameter K is indeed the lowest, because it was kept constant throughout the entire domain.

In order to assess the magnitude of the variation created by removal of one parameter, the variation index VX was computed as:

Table 2 Statistics on sensitivity to removal of one parameter

Parameter	Average	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
S_E	1.21	0.75	1.29	0.00	2.33
S_P	1.03	0.42	1.08	0.08	1.83
S_I	0.62	0.46	0.67	0.00	1.58
S_K	0.44	0.27	0.42	0.08	1.00

$$VX_i = \frac{V_i - V_{Xi}}{V_i} \cdot 100 \quad 1 \leq i \leq 22 \quad (3)$$

where:

VX = variation index of the removal parameter X (E, P, I, or K)

V_i = vulnerability index computed using Eq. (1) in the i^{th} subarea

V_{Xi} = vulnerability index of the i^{th} subarea without considering parameter X (E, P, I, or K).

This variation index measures the effect of the removal of each parameter. Its value can be positive or negative, depending on the vulnerability index. A positive value means that removal of the parameter reduces the vulnerability index, thereby increasing the calculated vulnerability. A negative value means that removal of the parameter increases the vulnerability index, thereby reducing the calculated vulnerability. Here, this variation index directly depends on the weighting system.

For the studied domain, the averaged variation index is positive for parameters E (VE) and I (VI) and negative for P (VP) and K (VK). Because the whole analysed area was examined, it is concluded that the removal of parameters E and I decreases the vulnerability index (calculated vulnerability is increased) and the removal of P and K increases the vulnerability index (calculated vulnerability is decreased).

Effective Weighting Factors

Each parameter contributes with an effective weight (Napolitano and Fabbri 1996) to the final vulnerability index. This effective weight (W_{Xi}) can be calculated for each subarea as:

$$W_{Xi} = \frac{X_{Ri} \cdot X_{Wi}}{V_i} \cdot 100 \quad (4)$$

where X_{Ri} and X_{Wi} are, respectively, the rating values and the weights for the parameter X assigned in the subarea i , and V_i is the vulnerability index as computed in Eq. (1) in the subarea i . For each subarea, the sum of the four parameter effective weights is 100%.

To obtain the effective weight of each parameter in each subarea, the map representing the unique con-

Table 3 Statistical analysis of effective weight

Parameter	Theoretical weight	Theoretical weight (%)	Average effective weight (%)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
E	3	33.33	39.00	13.69	42.86	15.79	60.00
P	1	11.11	10.10	4.64	9.52	3.85	23.08
I	3	33.33	29.82	11.21	27.92	13.64	52.94
K	2	22.22	21.09	5.81	19.52	14.29	36.36

dition subareas was reclassified according to the attribute values of effective weight for each parameter. Then, the effective weights expressed in percentage were mapped according to classes defined every 5%. The procedure is shown in *Figure 6*.

Discussion

Interpretation of the results is based on analysis, comparisons, and statistical computation of the input maps relative to each parameter (E, P, I, and K), the final vulnerability map, and the maps representing the effective weights used in each subarea. Statistical analysis of the sensitivity of the effective-weight parameters, shown in *Table 3*, indicates that the epikarst parameter (E) dominates the vulnerability index with an average weight of 39.00% against the theoretical weight of 33.33%. The real weight of parameter I (29.82%) is smaller than the theoretical one (33.33%). Comparison of the maps prepared for each individual parameter with the maps of effective weight shows that all the effective-weight maps are strongly dependent on the value of the epikarst parameter. Also, significant variations in the effective weight distribution exist, depending on the values of parameters I and P. High effective weights are attached to parameter I, corresponding to high-vulnerability and medium-vulnerability areas. These areas are strongly conditioned by the parameter E values. The presence of a thick soil protection layer (P3) reduces the weight attached to parameter I. For the E2 and E3 areas, respectively, effective weights of E are quite strong. They become stronger for slopes greater than 25%, corresponding to I2 areas.

These effective weights depend on the variability of each parameter rating and on the theoretical weights chosen in Eq. (1). If the same rating value is chosen for one of the parameters over the entire area, its effective weight will vary as a function of the rating values of the other parameters. Therefore, for each case study it is desirable to know the effective weights that result from the theoretical ones.

However, there is no need to go further by using the effective weights in place of the theoretical ones. On the basis of the presented analysis, changes of the weights in Eq. (1) can be considered in order to reduce or increase the importance of a parameter in the vulnerability index determination.

Conclusions

Sensitivity analysis helps to validate and evaluate the consistency of the analytical results and is the basis for a correct evaluation of the vulnerability maps. The methodology that is presented should be developed and applied to each vulnerability case study in order to make hydrogeologists more aware of the subjective element of vulnerability assessment. In this way, vulnerability-assessment parametric methods can be judged more effectively. Using sensitivity analysis, a more efficient interpretation of the vulnerability index can be achieved.

In the presented case study, the effective weights for each parameter in each subarea are not equal to the theoretical weights (assigned by the EPIK method). In fact, the effective weights are strongly related to the value of the single parameter in the context of values chosen for the other parameters. For the study site in particular, the parameter E has a strong influence on the vulnerability. This influence is the result of the combined influence of the theoretical weights [Eq. (1)] and the relative uniformity of the chosen values for the other parameters. The effective-weights analysis is very useful when the user of the vulnerability-assessment method wishes to revise the weights in the chosen equation for computing the vulnerability index.

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References

- Aller L, Bennet T, Lehr HJ, Petty JR, Hackett G (1987) DRAS-TIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. RS Kerr Environmental Research Laboratory, US Environmental Protection Agency, Washington, DC, Report EPA-600/2-87-035, 622 pp
- Avril P, Tavernier R, Hanotiaux G (1984) Map of the soils in Belgium. Beauraing 184 E. Cartographic Centre of Southern Belgium, Géembloux Faculty of Agronomic Sciences, Institute for Encouraging the Scientific Research in Industry and Agriculture, Belgium
- Doerfliger N, Zwahlen F (1997) EPIK: a new method for outlining of protection areas in karstic environment. In: Günay G, Jonshon AI (eds) Int Symp on Karst Waters and Environmental Impacts, Antalya, Turkey, 1997. Balkema, Rotterdam, pp 117-123
- Gontier P, Hallet V, Monjoie A (1997) Study for protection zones delineation of the Beauraing-Tamizon water supply system. Intermediary report made for Walloon Water Company, Laboratoires de Géologie de l'Ingénieur, d'Hydrogéologie et de Prospection Géophysique, University of Liege, Belgium, 28 pp
- Lodwik WA, Monson W, Svoboda L (1990) Attribute error and sensitivity analysis of map operations in geographical information systems - suitability analysis. *Int J Geog Info Syst* 4:413-428
- Napolitano P, Fabbri AG (1996) Single parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: Kovar K, Nachtnebel HP (eds) *Proc HydroGIS: Application of Geographic Information Systems in Hydrology and Water Resources Management*. IAHS Publ 235, pp 559-566
- Tripet JP, Doerfliger N, Zwahlen F (1997) Vulnerability mapping in karst areas and its uses in Switzerland. *Hydrogéologie* 3:51-57
- Vrba J, Zaporozec A (1994) Guidebook on mapping ground-water vulnerability. In: *International contributions to hydrology*, vol 16. Heinz Heise, Hannover, 131 pp