Comparison of aquifer vulnerability assessment techniques. Application to the Néblon river basin (Belgium)

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Abstract Five different methods for assessing intrinsic aquifer vulnerability were tested in a case study and their results compared. The test area was a slightly karstified district in the Condroz region of Belgium. The basin covers about 65 km^2 and the karst aquifer provides a water-supply of about 28,000 m^{3}d^{-1}. The methods tested were: EPIK (Doerfliger et al. 1999), DRASTIC (Aller et al. 1987), 'German method' (von Hoyer and Söfner 1998), GOD (Foster 1987) and ISIS (Civita and De Regibus 1995). The results are compared and critically examined. From the analysis, it seems that reducing the number of parameters is unsatisfactory, due to the variety of geological conditions. The various methods produce very different results at any given site. As only physically-based methods can be checked for their reliability, it is clear that future vulnerability mapping techniques must incorporate such methods.

Keywords Groundwater protection · Vulnerability · Aquifer · GIS · Belgium

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Study outline and hydrogeological context

Up to now, it has not been possible to evaluate vulnerability methods quantitatively . Comparing different vulnerability maps is one way partially to assess the reliability of results. The use of a large number of parameters in vulnerability assessment allows one to describe complex hydrogeological settings. A substantial effort is required to obtain the necessary input data and to ensure an adequate level of accuracy. One way to develop easily applicable methods is to reduce the number of parameters. Unfortunately, due to simplification, methods involving fewer parameters present serious difficulties when used in different geological conditions.

In order to compare their suitability for delineating groundwater vulnerability in the limestone aquifers of the Walloon Region (Belgium), several vulnerability assessment methods have been examined. Five methods were selected for this study: EPIK (Doerfliger et al.1999), DRASTIC (Aller et al. 1987), the German method (von Hoyer and Söfner 1998), GOD (Foster 1987), and ISIS (Civita and De Regibus 1995). DRASTIC and GOD represent classic approaches to vulnerability assessment. ISIS is a method based on DRASTIC, SINTACS (Civita 1994), and GOD, where the authors give more importance to recharge. EPIK and the German method are procedures developed recently in Europe for the geological conditions present respectively in Switzerland and in Germany. The analysis was conducted using the raster data model called GRID within the Arc/Info software package (ESRI 1997).

The test area is located in the Condroz region, about 30 km south of Liège in Belgium (Fig. 1). Geologically, this zone belongs to the eastern part of the Dinant synclinorium. Hydrogeologically, it forms a part of the Néblon river basin. The area includes several villages and the main land uses are agriculture and forestry.

The hydrological basin covers about 65 km^2 and is an important hydrogeological resource. The aquifer is located upgradient from the springs in the Neblon valley. It is exploited by means of drainage galleries to provide water for Liège city and for local water supplies. It yields a daily supply of about 28,000 m^3.

Many previous studies and data collections were performed in the scope of PhD researches (Meus 1993), as well as expertise studies for the local water company. They

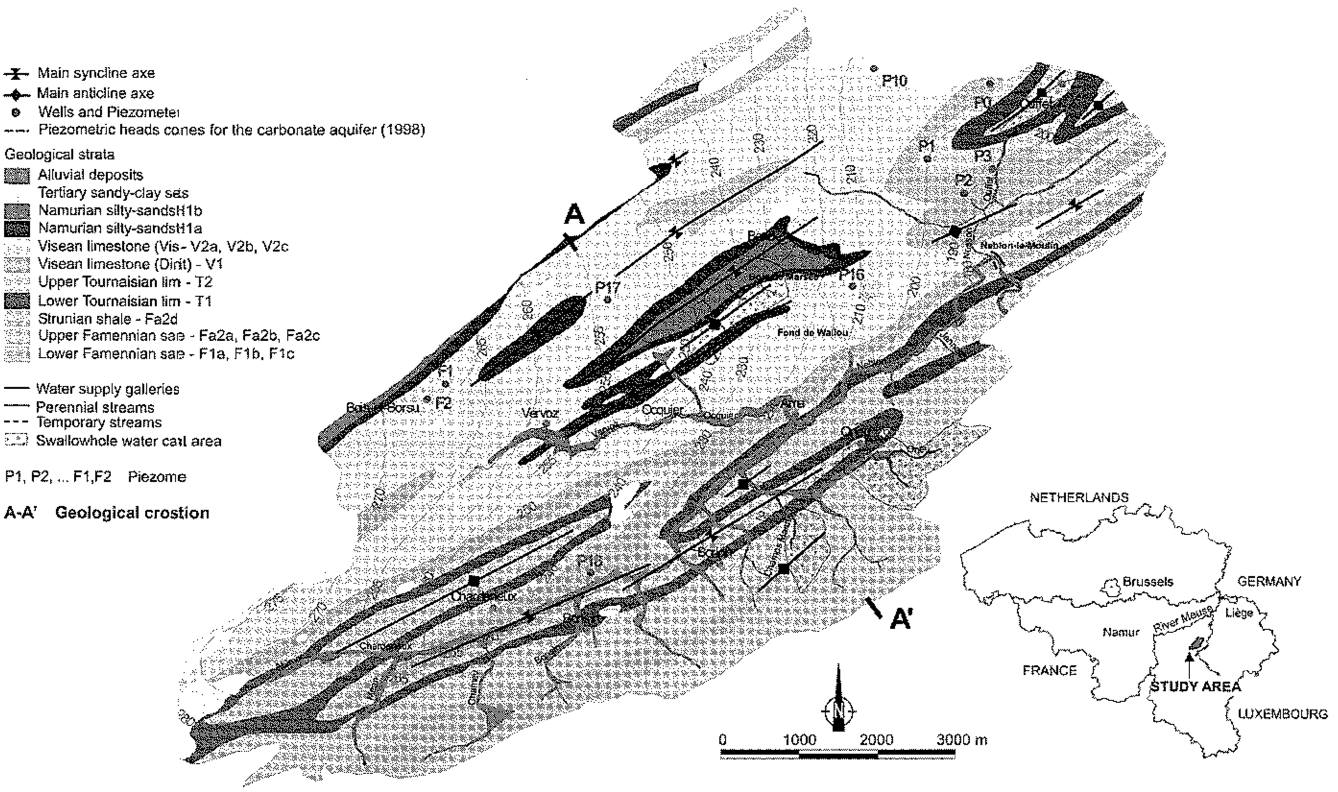

Fig. 1
Location, geology, and hydrogeology of the Néblon river basin, Belgium

have involved morphostructural analysis, geophysical prospecting, pumping and tracer tests, balance studies, hydrogeological mapping (Hallet et al. 2000, unpublished data) and groundwater modeling (Dassargues and Derouane 1997). Nowadays, the whole data set consists of information on the geometry of the geological strata, hydrological and hydrogeological boundaries of the basin, location and characterization of faults, lineaments and fracture zones, evolution of piezometric heads, hydrological water balance, hydrogeochemical analyses, and hydraulic conductivity, storage coefficient, and effective porosity values.

Geomorphology

The Néblon basin is a part of the Devonian-Carboniferous folded formations of the eastern edge of the Dinant synclinorium that crosses Belgium from west to east. The region is called the "Condroz anticlinorium".

The Condroz region typically has alternating anticlinal crests of shales and sandstones (Upper Devonian or Famennian) and calcareous synclinal depressions (Lower Carboniferous or Dinantian), that contain several carbonate aquifers, locally connected through sandstone layers.

The Hoyoux, the Néblon and the Ourthe are the main rivers of the region (Meus 1993). The river network cuts the relief and the tributary streams of the Néblon flow transversely following the general east-west geological structure. Most of these streams have their sources in the southern part of the water catchment area, in the Famennian sandstone. Due to karstification, several streams end in swallow holes at the following locations: Oneu, Bois de Marsée, and Champs Manhay (Fig. 1). Several temporary and losing streams as well as five areas of diffuse losses are also present.

Hydrogeology

General description

The Néblon basin aquifers are located in Tournaisian and Visean limestone, in Famennian fractured sandstone, and in Namurian silty-sandstone.

The main aquifer of the basin is composed of Tournaisian and Visean limestone. The aquifer is highly fissured, locally showing distinctive karst features. In this karst limestone, the Hastiere formation of the Lower Tournaisian includes shale intercalations and consequently has lower hydraulic conductivity values. The Ivorian (Upper Tournaisian) and the Visean limestone can be considered as forming a single hydrogeological unit (Hallet et al. 2000, unpublished data). The Visean is generally purer limestone than the Tournaisian and is easily karstified.

The Néblon river is considered as draining the main aquifer. The natural outflows of the aquifer were the diffuse discharges, point sources along the Neblon river and the springs of Neblon-le-Moulin. These springs are exploited via four collecting galleries by the CILE Water Company, abstracting 25,000 and 30,000 m^{3}day^{-1}. The galleries are parallel to the axis of the Neblon valley and located upgradient of the natural outlets of the hydrogeological basin on both sides of the Néblon river. The main gallery ("Principale") located on the left side of the river provides about 50% of the water-supply.

The Famennian sandstone is another exploitable aquifer. This aquifer has a large storage capacity principally in the weathered zones and in the strongly fissured/fractured zones. The connection with the limestone aquifer (Fig. 1) is mainly by several springs rising upgradient of the separating Strunian shale band or possibly through fissured zones.

The silty-sandstone Namurian formations of the Bois-et-Borsu and Bende synclines act like small perched aquifers. These aquifers have a limited storage capacity. The Namurian groundwater is exploited for agricultural purposes by a few local wells with yields of several cubic meters per day. It is believed that a shale belt provides an impervious layer in the Namurian synclines at depth. A connection with the limestone aquifer can only result by overflowing this shale belt or through the existing faults (Fig. 1).

Karstic features

Several karstic features are present in the Neblon basin, the most significant being dry valleys, swallow holes, resurgences and dolines. The high discharge springs of Neblon-le Moulin indicate the presence of a karstic conduit. Three large swallow holes have been identified: Bois de Marsée, Bende, and Oneu (Fig. 1).

Tracers injected in the swallowhole of Bois de Marsee, have been recovered in two of the collecting galleries ("Communale" and "Principale" galleries). This clearly indicates a network of karst conduits (Meus 1993). In the "Communale gallery", the tracers' arrival times were less than 50 h or had a velocity of about 73 m hr^{-1}. Such velocities confirm that some zones are affected by a high degree of karstification where Darcy's law does not apply.

Several dry valleys can be seen in the area. The largest one is the Fond de Bende, located to the east of the village of Bende. During rainy periods the bottom of this dry valley becomes a tributary stream of the Nesson. Two other dry valleys joining the Nesson stream are the Himbe ravine in the North-East and the Ouffet ravine in the North. Starting from the Bois de Marsée, a dry valley called the Fond de Walou (it has several names: Fond de Marsée, Fond de Sartre, and Fond de Walou) joins the Néblon between Ama village and the Jenneret stream. Another dry valley runs parallel to the Fond de Wallou. This latter starts some 1,000 m SE of the Fond de Wallou, and also ends in the Néblon river. A small swallow hole is present in the upper part of this dry valley but is not included in the karst atlas of De Boyer et al. (1996).

Extended karstic cavities are unknown in this region. Only a few poorly developed karst caves occur along the Néblon cliffs as well as a small doline located south of Ouffet.

Hydrogeological parameters

Several pumping tests were performed in existing wells in the karstic aquifer. Data interpretation indicated transmissivity values between 10^{-3}–10^{-5} m^2s^{-1} (Dassargues and Derouane 1997). In the entire catchment area, the effective porosity was estimated between 1.5–2%. This global estimate is based on interpretation of annual groundwater storage variations (Dassargues and Derouane 1997).

A longitudinal dispersivity of 15 m was deduced from the tracer tests performed in the Bois de Marsée swallow hole (Meus 1993). This value was obtained by modeling the tracer test results using an analytical formula assuming a single drain. No additional data were obtained from the tracing tests performed in the wells.

There is no data available for hydraulic conductivity in the Famennian aquifer in the Néblon basin. However, several pumping tests were performed in these Famennian sandstones in the Condroz region. These tests performed in similar neighboring aquifers, indicate hydraulic conductivity values between 1.4×10^{-4}–5.5×10^{-6} m s^{-1}. This value was also seen to decrease with depth.

An initial numerical model approach was performed (Dassargues and Derouane 1997) in order to try to describe globally the aquifer behavior for the groundwater flow and solute transport. The resulting parameter values are shown in Table 1.

Table 1
Hydrodynamic and hydrodispersive parameter values used in the regional 2D and 1D numerical models

Carbonate rock aquifer (Tournaisian and Visean)		
Transmissivity	Mean value	10^{-3}–10^{-4} $m^2 s^{-1}$
	Fractures	10^{-2}
	Karstic conduits	>>>(Darcy's law not valid)
	Rock mass	$<10^{-5}$
Effective porosity	Mean value	1–2%
Longitudinal dispersivity	Mean value	max. 30 m
	Karstic conduits	max. 100 m
Transverse dispersivity	Mean value	1 to 5 m
Molecular diffusivity	Mean value	10^{-9} $m^2 s^{-1}$
Sandstone aquifer (Famenian)		
Transmissivity ($m^2 s^{-1}$)	Mean value	10^{-4}–10^{-5} $m^2 s^{-1}$
Effective porosity	Mean value	10%
Longitudinal dispersivity	Mean value	10 m
Transverse dispersivity	Mean value	1 m
Molecular diffusivity	Mean value	10^{-9} $m^2 s^{-1}$
Strunian shale		
Transmissivity	Value	10^{-6} $m^2 s^{-1}$

Conceptual scheme required for the vulnerability assessment of the aquifer

This vulnerability study examined the aquifer within the Néblon hydrological basin that feeds the groundwater supply galleries.

The hydrogeological boundaries of the Néblon basin show spatial and temporal variations in some zones. In the southern part, shale forms the impervious boundary of the Borlon Famennian anticline. The northern and eastern boundaries are mainly situated in Visean limestone. These

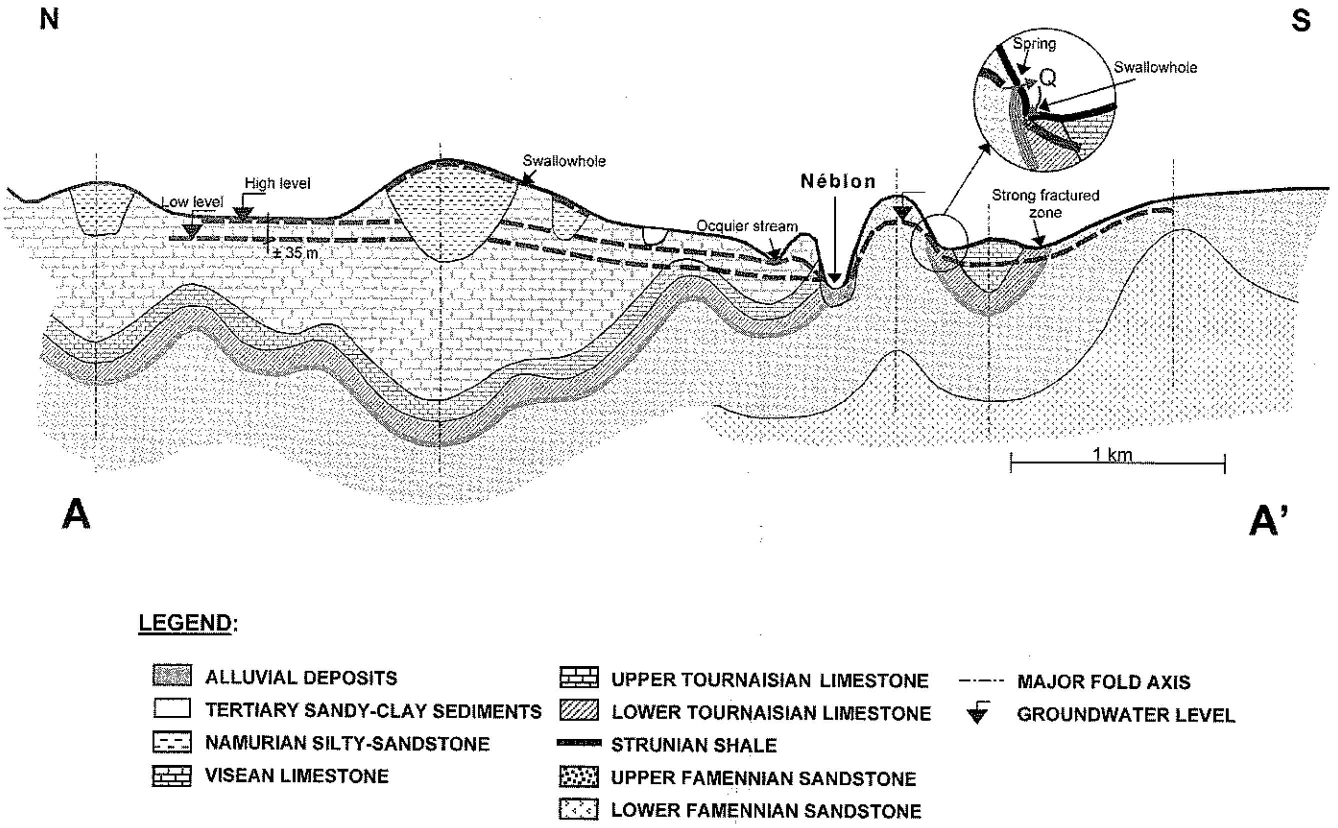

Fig. 2
Schematic north-south geological and hydrogeological cross-section of the Néblon River basin

boundaries are often considered as corresponding to the crest of the respective hydrological basins of Hoyoux and Anthisnes, however the hydrogeological and hydrological boundaries do not coincide. The choice of these boundaries does not rule out groundwater transfers. The eastern boundary with the neighboring basins is complex. To the west, the hydrogeological boundary is often considered as the same as the hydrological one. However a possible extension of the hydrogeological basin to the west is indicated by water-balance studies, which show a high summer base flow in the Ocquier river. This could be explained by a groundwater discharge from the neighboring western basin.

The Néblon karst system is moderately karstified, corresponding to a young stage of karstification. The few measurements of groundwater levels in the existing piezometers do not permit a full understanding of the aquifer. However, considerable variations in the hydraulic heads have been observed. A piezometric head map of low groundwater levels in 1998 (Fig. 1) was prepared by Hallet et al. (2000, unpublished data). This piezometric map clearly shows a general groundwater flow to the East with a lower piezometric level in the Néblon river valley as groundwater levels are observed nearly in equilibrium with the river water levels.

The conceptual model for the karst aquifer, used in this vulnerability analysis, has well defined karst conduits with a limited extension of karstification.

The link between the karst aquifer and the Famennian sandstone aquifer is believed to be limited. The Namurian aquifers can be considered as isolated. A good groundwater connection can be seen between the Tertiary sandy-clayey deposits filling the paleokarst pockets and the limestone aquifer.

A clear relationship between the karstic aquifer and the surface river network was pointed out. There is inflow to the aquifer through various sections of the river bed. This raises the possibility of contamination of the supply galleries by the river, especially in the alluvial plain. Di Clemente and Laurent (1986, unpublished data), observed an identical chemical composition of groundwater as well as a similar temporal variation of the groundwater chemical and physical parameters (conductivity, pH, and ionic content) between the Vervoz springs feeding the Ocquier stream (Fig. 1) and the water in the galleries. These observations point to possible links between the Néblon river and the galleries.

Recession coefficients calculated for some of the stream basins crossing the Famennian sandstone present values similar to those calculated for the stream basins crossing the limestone. This indicates a generally good storage capacity in the sandstone aquifer and of course an important effective porosity.

The depth of the Namurian synclines is not known. Often they are considered as allowing a deep groundwater connection in the underlying limestone aquifer (Fig. 2). This hypothesis is supported by water-balance results, showing an excess for the Ama and Vervoz streams basins (Dassargues and Derouane 1997).

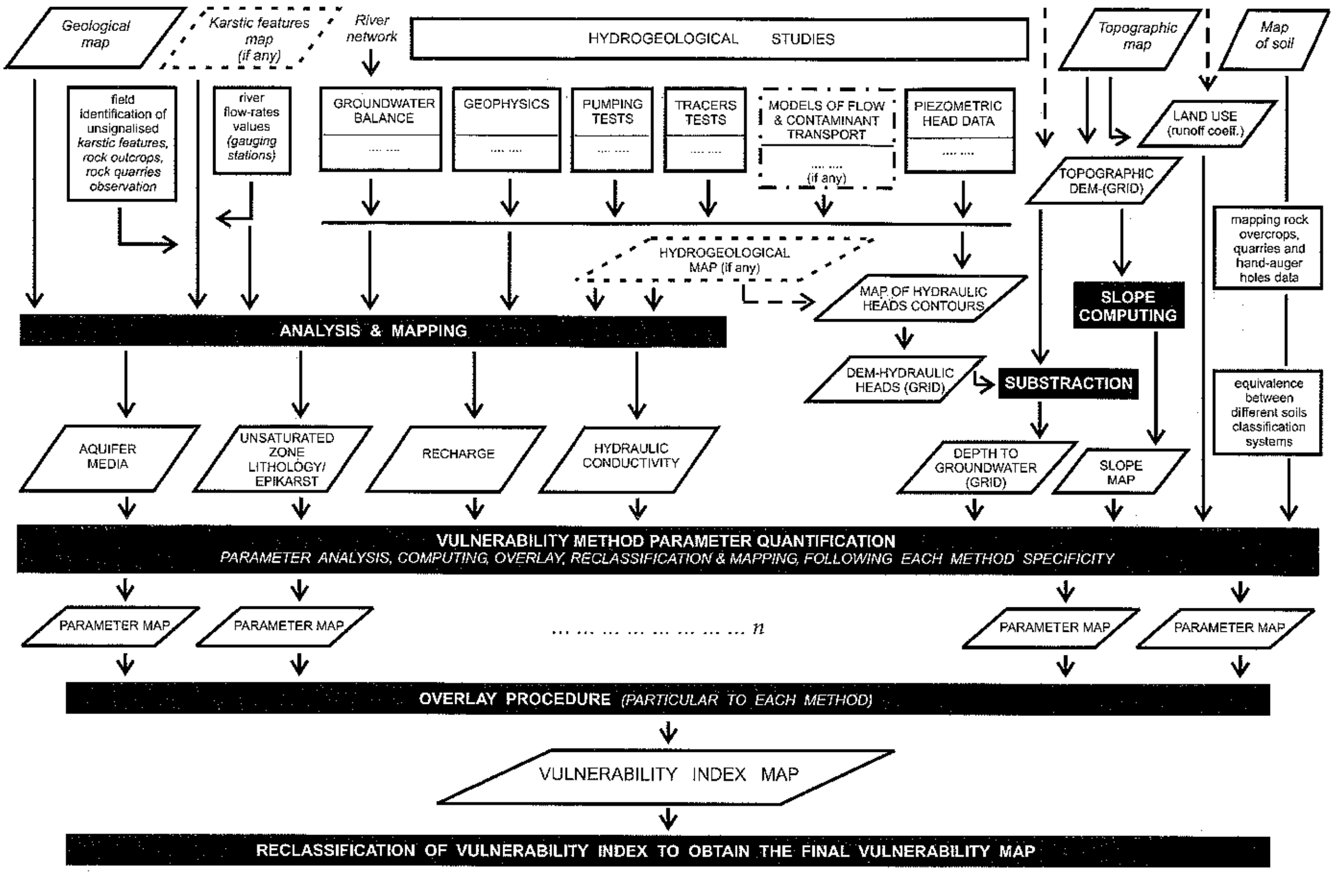

Fig. 3
Main steps in groundwater vulnerability assessment for Néblon aquifer

Overview on the quantification of the parameters used by the vulnerability-assessment methods

The study was conducted on the area of 64.70 km^2 calculated for the Néblon hydrological basin. The quantification of the parameters was done in parallel for the five applied methods. As hydrogeological parameters can be to some extent interdependent, evaluation of the different vulnerability parameters needed by each method was done by considering the possible relationship between them.

The necessary steps for obtaining reliable results were the following: (1) a careful analysis of the existing raw and treated data, (2) an evaluation of the data sources, (3) a correlation between hydrogeological parameters, and finally (4) an hydrogeological interpretation of each method parameter.

A brief description of the most important steps in vulnerability parameter estimation is needed. However, in this paper all the GIS terms and definitions (DeMers 1997), the types of geographical modeling, the means of obtaining data, the GIS functions, operational procedures, spatial manipulation issues and errors are considered as known.

Aquifer vulnerability assessment is based on different data sources as is shown in Fig. 3. In this case study the data comes from: geological maps, maps of karst features (De Boyer et al. 1996), hydrogeological maps (Hallet et al. 2000, unpublished data), various local and regional hydrogeological studies, topographical maps, soil maps, the digital numerical model of Belgium, and land-use maps. These data were augmented by a series of field tests: geophysical investigations (electrical sounding and profiling, seismic soundings), piezometric head measurements, pumping tests, tracer tests, field observations (geomorphology, quarries, springs), river flow-rate measurements (gauging stations), short auger hole interpretation, identification and mapping of rock outcrops, quarries, and newly discovered karst features.

Information and data coming from the various studies (Fig. 3) and from the geological maps, the maps of karst features, and the hydrogeological maps, provided a basic outline of the aquifer, the unsaturated zone lithology, the epikarst zone, the hydraulic conductivity, and the recharge of the aquifer.

The digital elevation model (DEM) of the region formed the basis for the calculation of the slopes needed for some of the methods. A hydraulic head contour map was created using piezometric head values from the existing hydrogeological map (Hallet et al. 2000, unpublished data) and augmented with data obtained from the 1998 field measurements. This hydraulic head map was used to generate a GIS grid layer of information of hydraulic heads. Subtraction of the piezometric head grid from the DEM, produced the GIS grid layer of "depth to water table" for the aquifer.

The existing soils map was the data source for the soil parameters map. Additional information on soil thickness, rock outcrops and quarries, was obtained in the field. The map representing the runoff coefficients corresponding to land-use was derived from the land-use map of the National Geographical Institute of Belgium.

Vulnerability analysis results

Description of the vulnerability maps

Following the procedures of each vulnerability method, the quantified parameter maps were overlaid and six different final vulnerability maps were produced. These maps are respectively Figs. 4, 5, 6, 7, 8, and 9 for the EPIK, DRASTIC, modified DRASTIC, "German Method", ISIS and GOD methods. Table 2 gives by percentage the portion of the total area mapped in each vulnerability class for each method.

The EPIK vulnerability map (Fig. 4) shows three vulnerability classes. Moderate vulnerability covers about 91.5% of the examined area and high vulnerability 7.8%. The concentrated or diffuse swallow holes and the losing streams feeding the swallow holes are characterized by a very high degree of vulnerability (0.7%). Fissured outcrops are also in the same category. The river Néblon, where it is in contact with the aquifer, its tributary streams crossing the limestone or the sandstone, and the few mapped dolines are placed in the high vulnerability class. Likewise are dry valleys, the Néblon gorges, and other small areas of steep slopes. The effect of weighting and rating results in parameter E exerting the main influence on the final vulnerability map (Gogu and Dassargues 2000b). Vulnerability can be overestimated for some outcropping epikarst features. Highly fractured natural outcrops are given the same vulnerability rating as artificial outcrops (quarries, road or railway cuttings). However, the non-fissured outcrops or those having no direct contact with the aquifer may be much less vulnerable than the zones between dolines or dry valleys.

The original DRASTIC method published by Aller et al. (1987) does not provide vulnerability classification ranges, but allows the user to interpret the vulnerability index using their own field knowledge and hydrogeological experience. In the literature two distinct classification ranges are found. The commonly used vulnerability index classification (Civita and De Regibus 1995, Corniello et al. 1997) produced the vulnerability map shown in Fig. 5. This classification system defines five classes of vulnerability: very high vulnerability (vulnerability index >199), high vulnerability (160–199), moderate vulnerability (120–159), low vulnerability (80–119), and very low vulnerability (<79). As can be seen on the map, moderate vulnerability is by far the largest zone with about 73% of the area including most of the fissured limestone and the Famennian sandstone. The stream zones occurring on the Namurian and feeding the swallow holes are not shown as more vulnerable than the adjacent zones. However, in general the main karst features are accurately outlined by this method.

A second map was prepared employing the DRASTIC method with the use of vulnerability categories suggested by Navulur and Engel (1997, unpublished data). This was done only for a quantitative reference and not considered as a valid result in the analysis (this classification is confined to the specific vulnerability assessment of pesticides). The authors define four vulnerability classes (Fig. 6) : very

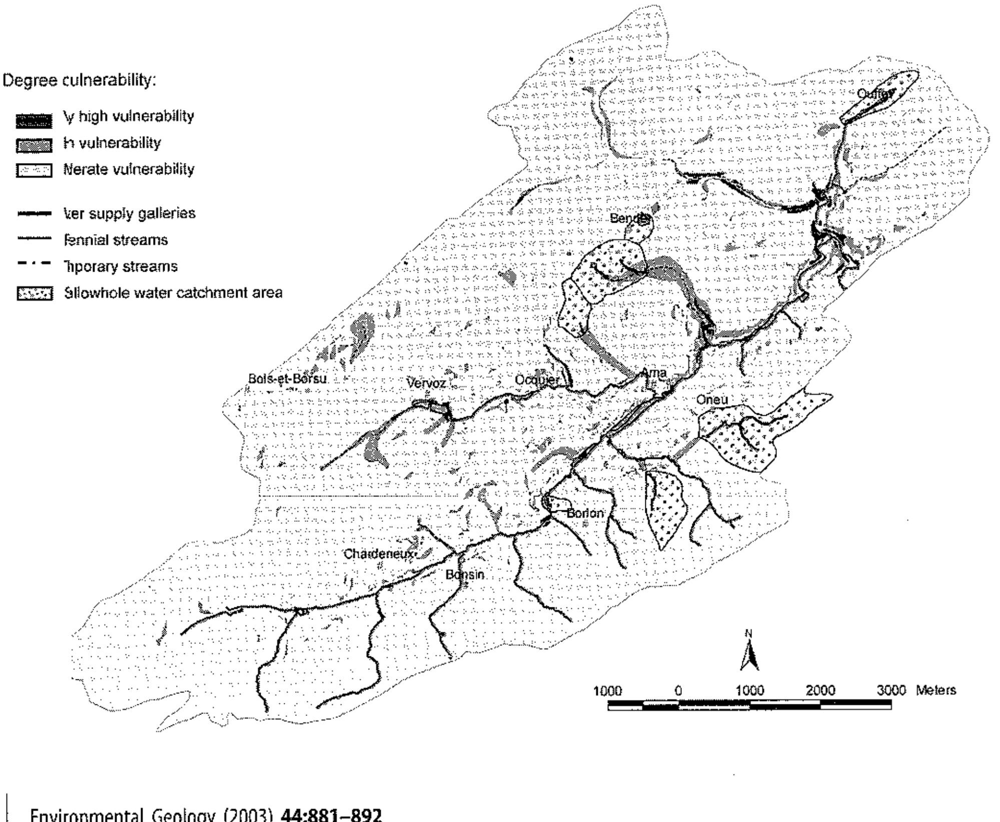

Fig. 4
Final vulnerability map using EPIK method

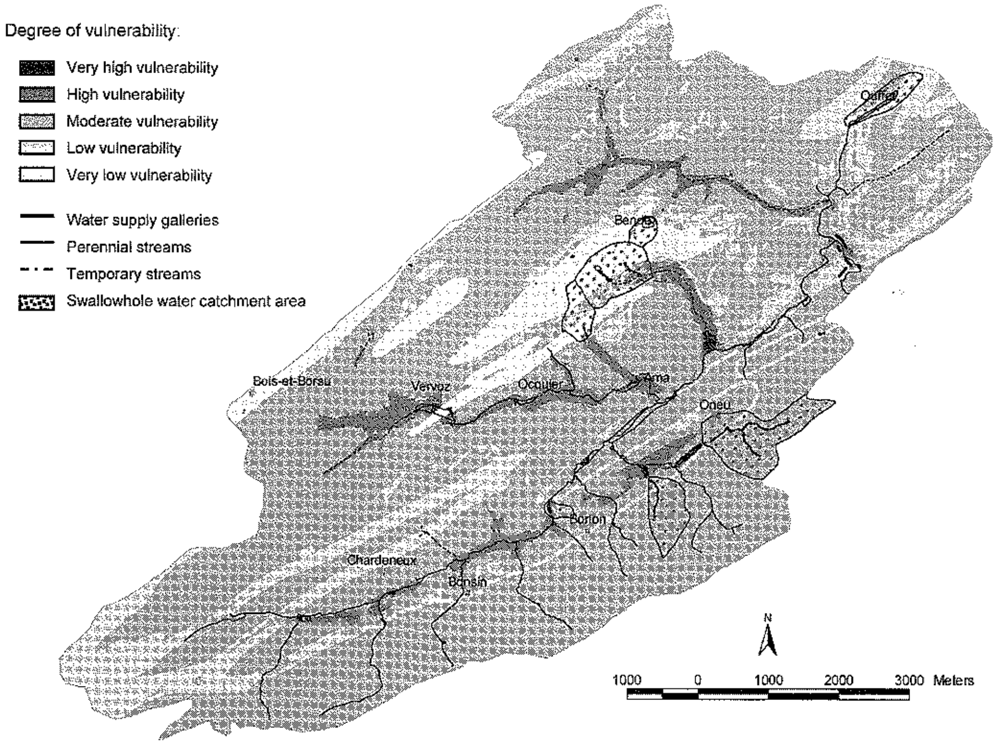

Fig. 5
Final vulnerability map using DRASTIC method and the commonly used final classes of vulnerability

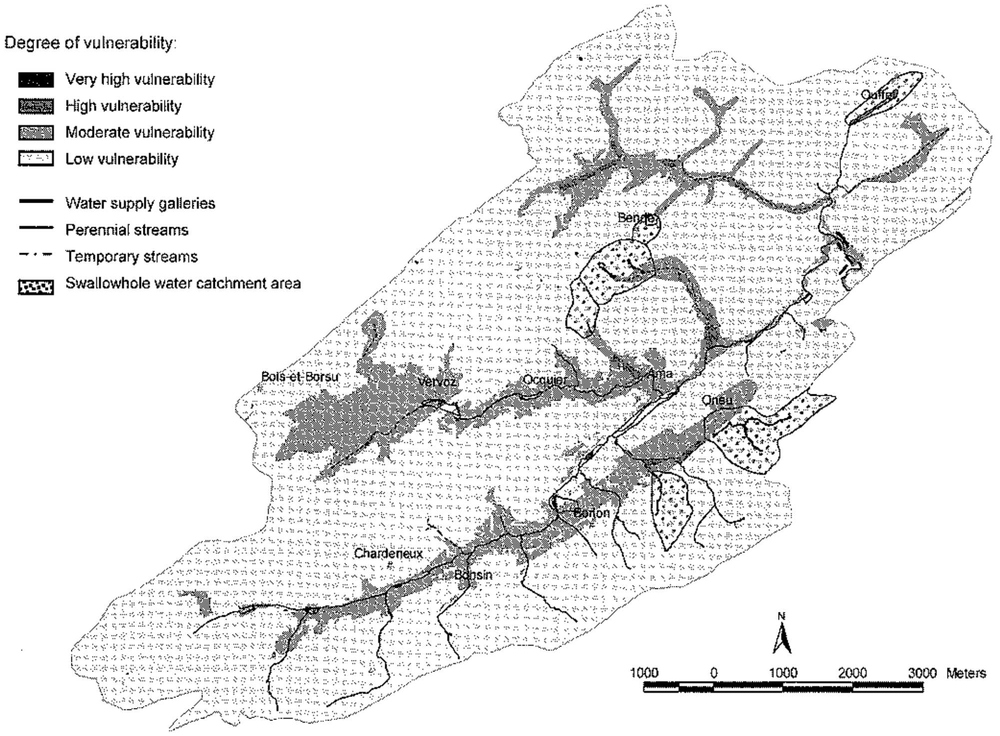

Fig. 6
Final vulnerability map using DRASTIC method and classes of vulnerability defined by Navulur and Engel (1997, unpublished data)—DRASTIC b

high vulnerability (DRASTIC vulnerability index >230), high vulnerability (181–230), moderate vulnerability (141–180), and low vulnerability (1–140). In Table 2, areas corresponding to this classification are placed in the DRASTIC (b) column.

The German method, as with most of the parametric systems, provides its own classes of vulnerability, as shown in Fig. 7. This method shows 48.3% of the basin with high vulnerability and 34.3% with very high vulnerability. These classes of vulnerability include the entire limestone aquifer as well as the Famennian aquifer. Moderate vulnerability makes up just 7.6% of the studied area corresponding to the Strunian bands, to parts of the Lower Tournaisian bands, and to the alluvial valleys crossing the Famennian. Low vulnerability is assigned to the Tertiary sandy-clay formations and to small sectors corresponding to the

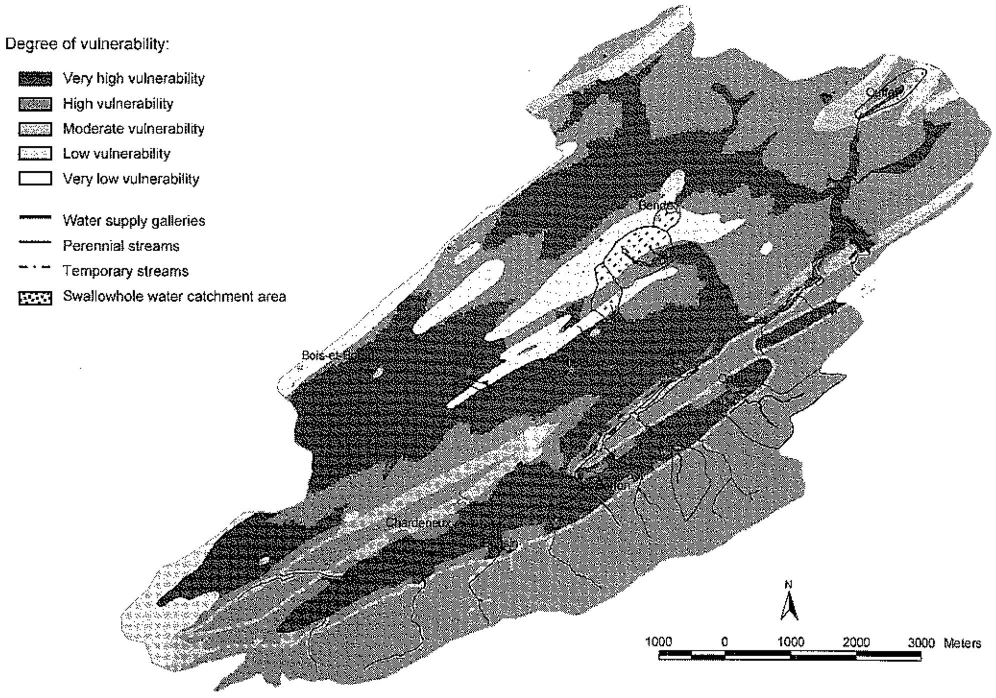

Fig. 7
Final vulnerability map using German method

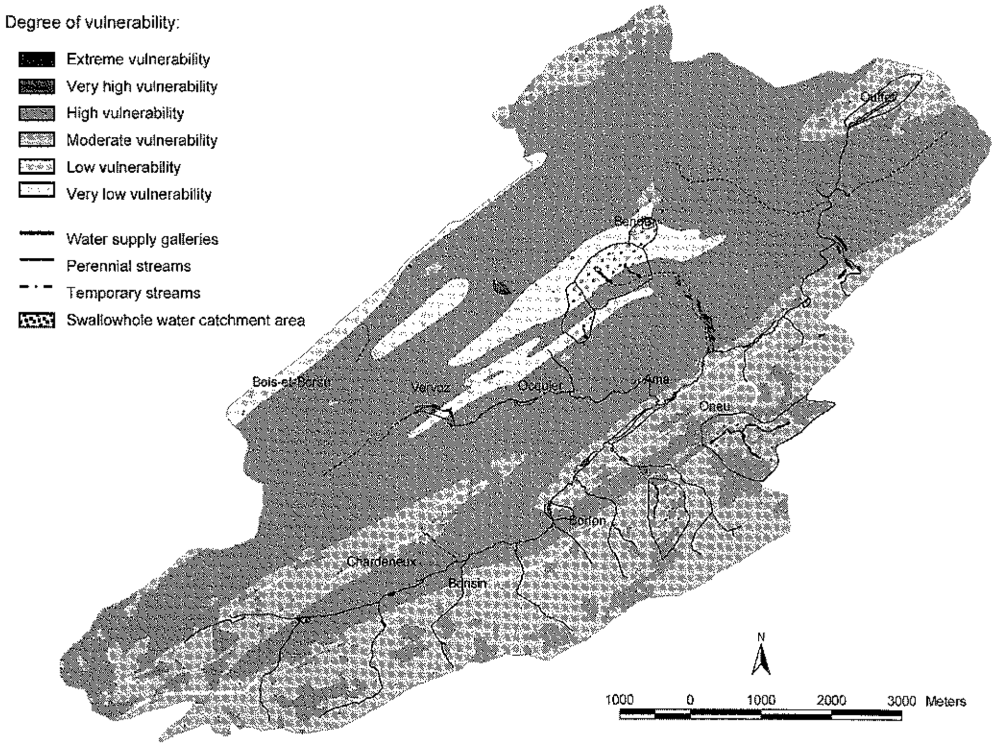

Fig. 8
Final vulnerability map using ISIS method

Lower Tournaisian and to the Strunian. Very low vulnerability is confined to the Namurian districts. The karst features are apparently correctly assessed, most of them being shown as very high vulnerability zones.

The ISIS method (Fig. 8) has six vulnerability categories. The extreme vulnerability category was not found in the area and very high vulnerability is limited to a few outcrops (Fond de Wallou and a rock-quarry located in the North). High vulnerability is assigned to 62.9% of the study area. Moderate vulnerability (about 29.1%) is mainly found in the Fameninan standstone and the Lower Tournaisian areas. Low vulnerability occurs along the Strunian bands. Very low vulnerability is confined only to the districts underlain by the Namurian. The role played by runoff coefficients corresponding to land-use can be clearly seen in the low vulnerability Namurian districts as well as the high vulnerability zones in the sandstone and in the Lower Tournaisian limestone. Karst features are

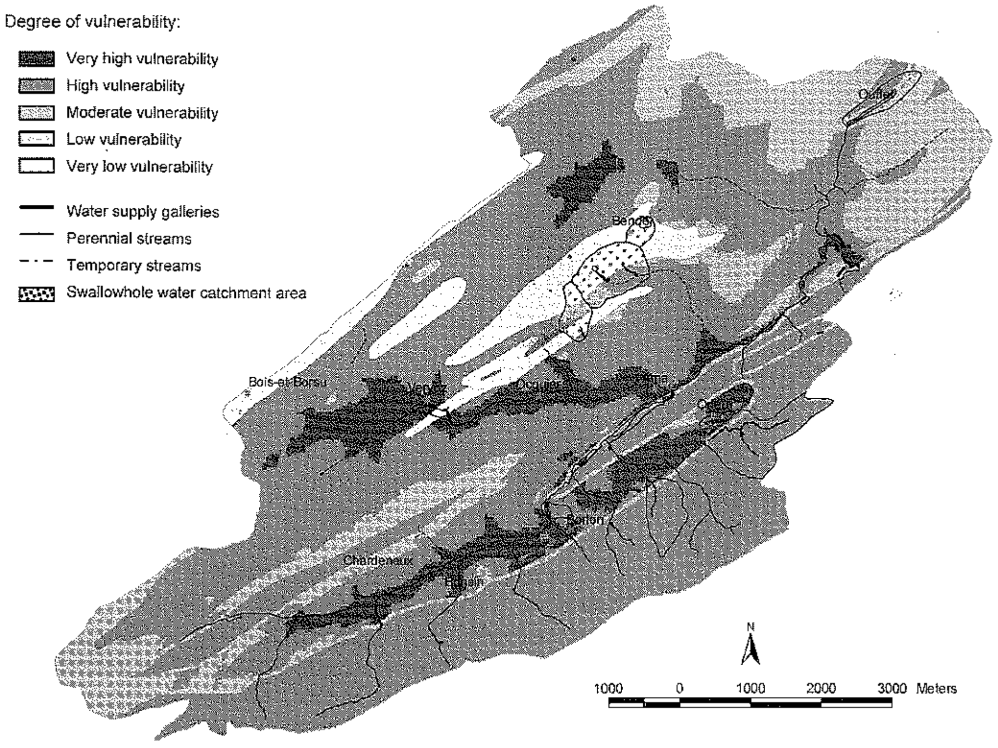

Fig. 9
Final vulnerability map using GOD method

Table 2
Comparison between the areas representing the vulnerability classes, obtained with the five methods (areas are expressed as percentage related to the entire study area; 100% represents 64.7 km^2)

	EPIK	DRASTIC	GERMAN	ISIS	GOD	DRASTIC (b)
Extreme	–	–	–	0.0	–	–
Very high	0.7	0.2	34.3	0.2	9.5	0.0
High	7.8	5.0	48.3	62.9	63.7	0.6
Moderate	91.5	73.0	7.6	29.1	20.5	14.8
Low	–	15.6	3.6	2.7	0.0	84.6
Very low	–	6.2	6.2	5.1	6.3	–

generally assessed with high vulnerability but very few of them show a contrast with the surrounding zones.

The results using the GOD method are shown in Fig. 9. There is no low vulnerability and very low vulnerability is shown for the Namurian districts . Most of the study area is assessed as having high vulnerability (63.7%). Very high vulnerability is assigned to 9.5% of the study area. The Famennian aquifer cannot usually be distinguished from most of the limestone. The karst features are generally assigned high vulnerability. Moderate vulnerability covers about 20.5% of the study area. It includes the Tertiary sandy-clay deposits and those parts of the carbonate aquifer with a thick unsaturated zone. The method does not accurately show karst features: the area of the Ouffet swallow hole is shown with moderate vulnerability, while the diffuse swallow hole of Bende is assigned very low vulnerability.

Comparison between vulnerability maps

Classic DRASTIC has the zones of very high and high vulnerability covering 5.2% of the study area. EPIK has the zones of high and very high vulnerability covering 8.5%. The very high and high vulnerability zones for the other three methods make up more than a half of the study area (Table 2). EPIK rates most of the area with moderate vulnerability (91.5%). This is because EPIK was designed only for karstified limestones.

A general similarity can be seen between GOD, ISIS, and the German method (Figs. 9, 8, and 7). Important differences can be observed for EPIK (Fig. 4) and DRASTIC (Fig. 5) results. The German method produces the largest high and very high vulnerability zones (high 48.3% and very high 34.3%). ISIS shows 62.9% of the area with high vulnerability.

All the methods except DRASTIC and EPIK classify the limestone aquifer with high or very high vulnerability. DRASTIC and EPIK assess it with moderate vulnerability The difference between high and very high vulnerability in the German method and the GOD method vulnerability maps is largely influenced by the depth to the water table. Furthermore, these two methods use the depth to water table as a direct multiplier for the other parameters. This procedure also increases the vulnerability rating. The ISIS method uses the depth to water table parameter differently and unfortunately smoothes out the vulnerability index results. It is evident that in the DRASTIC vulnerability

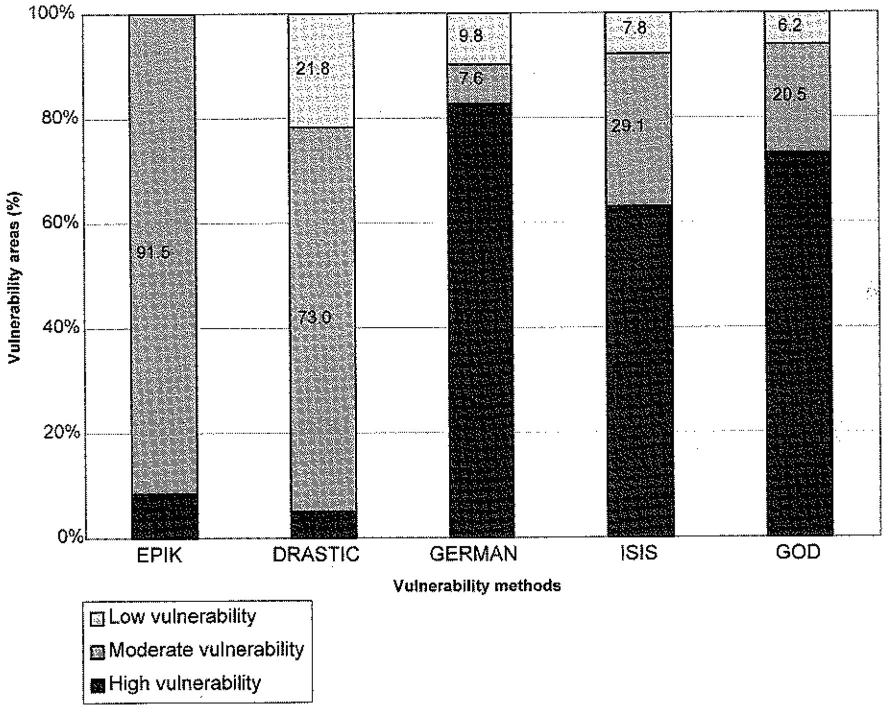

Fig. 10
Comparison between the regrouped classes of vulnerability defined by the applied methods

map, the depth to the water table determines whether an area is classed as moderate vulnerability or high vulnerability (Fig. 5).

Karst features are not always shown with high or very high vulnerability. For example in the GOD method, the small diffuse swallow hole at Bende and the swallow holes and resurgences located near Ouffet are assigned respectively low and moderate vulnerability. The streams feeding the swallow holes are classed as high vulnerability zones by EPIK, the German method, and by GOD. ISIS and DRASTIC rate these zones, partly as high vulnerability and partly as moderate vulnerability. The dry valleys and the dolines are shown by all the methods except ISIS, as being more vulnerable than the rest of the limestone.

The Lower Tournaisian is mostly assigned moderate or high vulnerability and the Strunian bands are shown with moderate or low vulnerability.

A feature of the ISIS method is the use of the parameter representing the runoff coefficients corresponding to land-use as a multiplier factor for all the other parameters. This can be easily seen on the resulting vulnerability map in the vulnerability class given to the Famennian sandstone, the Namurian, the Lower Tournaisian, and the Strunian bands.

Comparing the vulnerability maps obtained by EPIK (Fig. 4), DRASTIC (Fig. 5) and DRASTIC modified by Navulur and Engel (1997, unpublished data) in Fig. 6, shows that DRASTIC b can be considered as a step between DRASTIC and EPIK, in the vulnerability index reclassification. Further reclassification of the vulnerability index, results in an even greater similarity between DRASTIC and EPIK. Thus DRASTIC and EPIK seem to mainly stress the same hydrogeological and geomorphological features, even if the two approaches are different.

Regrouped classes of vulnerability

A different kind of interpretation can be obtained by regrouping the vulnerability classes. This was done for each vulnerability map, creating three main categories: high (including high, very high, and extreme vulnerability), moderate vulnerability (the same class for all five methods), and low vulnerability (including low and very low vulnerability). To facilitate the comparison, the results are shown in Fig. 10.

All five methods class the Namurian districts as low vulnerability. The German method shows the most extensive area of high vulnerability, with 82.6%. The DRASTIC results show little variation in vulnerability classes in the study area with 73.0% of the area with moderate vulnerability and 21.8% with low vulnerability.

For this basin, these regrouped classes of vulnerability indicate two main trends in vulnerability assessment: (a) the German method, the GOD method, and the ISIS method rate the study area as having mainly high vulnerability; (b) The EPIK and the DRASTIC methods show the study area with largely moderate vulnerability of 91.5% and 73.0% respectively. These results show a major disagreement between the different methods.

Conclusions

Some conclusions can now be drawn based on the results of the vulnerability assessment using the five methods:

1. The German method, the GOD method, and the ISIS method (Fig. 10) indicate more than half of the study zone has high vulnerability.
2. the DRASTIC and the EPIK methods show most of the study area with moderate vulnerability.

3. Namurian districts are assessed with low vulnerability, except in the case of EPIK.
4. The Famennian sandstone is shown as less vulnerable than the limestone aquifer except for the GOD method and in part the German method.
5. The Strunian bands are considered to have moderate or low vulnerability by all the methods.
6. The Lower Tournaisian is mostly assessed with moderate or high vulnerability.
7. The Tertiary sandy-clay deposits are assessed as having moderate vulnerability, with the exception of DRASTIC and the German method.

Karst features are correctly shown with high or very high vulnerability by all the methods except for GOD and to a lesser extent ISIS. EPIK is the best method at assessing karst features and is the only one that classifies the small streams within the Namurian district as having high vulnerability.

Most of these vulnerability methods only take into account vertical permeability, so inaccurate assessments can arise. For example, most methods ignore possible contamination coming directly from streams and bypassing the soil and the unsaturated zone.

The EPIK method has important strengths as well as serious weaknesses. The assumption of relating a steeper slope to a higher degree of vulnerability is not realistic when open valleys and fissured matrix predominate. It is valid only in karst drainage basins. Another problem is that EPIK produces results whereby most of the study area (91.5%) has moderate vulnerability. This is because the relatively high vulnerability of karst systems does not relate to other types of aquifers in EPIK. As the basic concept of vulnerability *to delineate land areas that are more vulnerable than others* (Vrba and Zaporozec 1994; Gogu and Dassargues 2000a) is a relative concept, ignoring other lithological and hydrogeological conditions reduces contrasts.

A Comparison between the DRASTIC and EPIK vulnerability maps shows that the two methods stress the same hydrogeological and geomorphological characteristics. However, it demonstrates the DRASTIC capacity of satisfactorily outlining karst morphology. These conclusions indicate the need for new research into procedures of parameter quantification and weighting. For example, the recharge of an aquifer seems to be one of the most important parameters in vulnerability assessment. All five methods explicitly or implicitly take this parameter into account. Results in vulnerability assessment can be significantly influenced and improved if the recharge parameter becomes a spatially variable datum.

Progress is needed to better differentiate fissure matrix from compact rock and from major discontinuities or karst conduits. Information from geophysical investigations should help to better delineate and to infer fault boundaries, dips, geometry, relative roughness, and filling.

Too many classes of vulnerability are not of practical value: as for example the *extreme vulnerability* class in the ISIS method. In this study, the *extreme vulnerability* class was not used even in the case of a karst aquifer. Thus, defining four classes of vulnerability appears to be a more sensible choice. It fully meets the needs and the resulting maps are more easily understood and utilised.

The choice of vulnerability method remains a subjective decision for the hydrogeologist. Besides, all the methods are to some extent flexible with regard to parameter quantification. As stressed by Aller et al. (1987), vulnerability methods are screening tools. They must not replace the professional expertise and field studies needed for more quantified answers. The choice of parameter rating should be based on prolonged studies of the hydrogeological conditions. The so called vulnerability "rapid assessments" performed by unqualified persons and using very large pixels for calculating their assessment can lead to serious errors. The only way to accurately depict aquifer vulnerability is to combine at an appropriate scale (ideally 1:25,000) all the relevant data on geology, hydrogeology, hydrology, soil, topography, climate, and land-use.

Subsequent to the attempt to find a uniform "European Approach" for vulnerability mapping in karst systems (Daly et al. 2001), new ways forward are now being discussed. These try to eliminate the inadequacies in the existing vulnerability methods, by taking a more physical approach to the concept of vulnerability. An applied definition is being drawn up from what currently underpins the concept of groundwater contamination. For intrinsic vulnerability, three factors describing contamination by a conservative contaminant are defined: contaminant transfer time, contamination duration, and the level of concentration reached by the contaminant (Brouyère et al. 2001). Clearly new methodologies more consistent with the physics of flow and contaminant transport represent the only way forward. Developing these new concepts in order to obtain a good and lasting method represents the next serious challenge in groundwater vulnerability assessment. Moreover it seems the only way to obtain vulnerability maps that can be validated.

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