Intrinsic vulnerability maps of a karstic aquifer as obtained by five different assessment techniques: comparison and comments

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Abstract

Five different existing methods for assessing intrinsic vulnerability were tested on a case study for comparison of their results. The test area consists in a slighly karstified area located in the Condroz region (Belgium). The basin covers about 65 km^2 and the karstic aquifer provides a daily water-supply of about 28000 m^3. Several campaigns of measurements consisting in morpho-structural observations, shallow geophysics, pumping and tracer tests have provided useful data. Compared results are commented. However applying these different existing vulnerability methods in one study-site, gives quite different results, showing the need for more physically-based methods. To be more reliable, vulnerability mapping techniques must be adapted in the future. The Working Group 1 of the COST620 Action is acting in this direction for intrinsic vulnerability mapping, checking that each parameter of the proposed general approach is given a value having a physical consistency with regards to transfer time, physical attenuation and effective recharge.

Résumé

Cinq méthodes différentes d'évaluation de la vulnérabilité intrinsèque ont été testées sur un cas d'étude, afin de comparer leurs résultats. L'aquifère étudié est légèrement karstifié et est situé dans la région du Condroz (Belgique). Le bassin couvre environ 65 km^2 et l'aquifère assure une alimentation d'eau journalière d'environ 28000 m^3 d'eau. Plusieurs campagnes de mesure, impliquant des observations morphostructurales, des prospections géophysiques, des essais de pompage et de traçage, ont fourni des données très précieuses. Les résultats comparés sont montrés et commentés. Cependant, l'application des ces différentes méthodes a conduit à des résultats fort contrastés, montrant par conséquent le besoin de développer des méthodes plus physiquement significatives. De nouvelles techniques plus fiables doivent être mises en œuvre. Le Groupe de Travail 1 de l'Action COST620 agit dans ce sens pour la vulnérabilité intrinsèque en cherchant, pour la nouvelle approche générale proposée, des paramètres ayant une signification physique par rapport au temps de transfert, à l'atténuation physique et la recharge effective.

1. Introduction

Vulnerability methods can be evaluated by comparing vulnerability map outputs. The use of a large number of parameters in vulnerability assessment requires a substantial effort in getting the input data. For developing easily applicable methods, it is often proposed to reduce the number of parameters. Unfortunately the methods using fewer parameters present serious difficulties for adaptation to different geological contexts. In order to evaluate their capacity for delineating groundwater intrinsic vulnerability in limestone aquifers, several vulnerability assessment methods have been considered. Five methods were selected for this study: EPIK (DOERFLIGER *et al.* 1999), DRASTIC (ALLER *et al.* 1987), the 'German method' (VON HOYER & SÖFNER 1998), GOD (FOSTER 1987), and ISIS (CIVITA & DE REGIBUS 1995). DRASTIC and GOD represent classic approaches in vulnerability assessment. ISIS is a development based on DRASTIC, SINTACS (CIVITA 1994), and GOD, where the authors give more importance to the recharge effect. EPIK and the 'German method' are recent procedures developed in Europe for geological contexts existing respectively in Switzerland and in Germany. The analysis was conducted using the raster data model called GRID within Arc/Info software package (ESRI 1997).

The chosen test area is located in the Condroz region (Belgium). Geologically it belongs to the eastern part of the synclinorium of Dinant. It represents a part of the Néblon river basin and is situated at about 30 km South of Liège (Fig. 1). This aquifer is exploited for supplying water for Liège and for surrounded villages. It provides a daily yield of about 28.000 m^3. Because of its high hydrogeological potential and its geological heterogeneity, this aquifer has been the subject of previous investigations. Several campaigns of data collection consisting in geomorphological observations, geophysics, pumping and tracer tests as well as their interpretation and processing, have been perfomed in the scope of different scientific reports. A data-base was built concerning nature and geometry of the geological strata, hydrological and hydrogeological limits of the basin, faults, lineaments and fractured zones, piezometric heads evolution, hydrological water balance, hydrogeochemical analyses, and groundwater media hydrodynamic parameters (hydraulic conductivity, storage coefficient, effective porosity, and others). This already collected information played an important role in choosing this site for testing the existing methods for intrinsic vulnerability mapping.

2. Study area

Geomorphology and Geology

The Néblon basin is a part of the Devonian-Carboniferous folded formations of the south-eastern edge of the Dinant synclinorium that crosses Belgium from West to East.

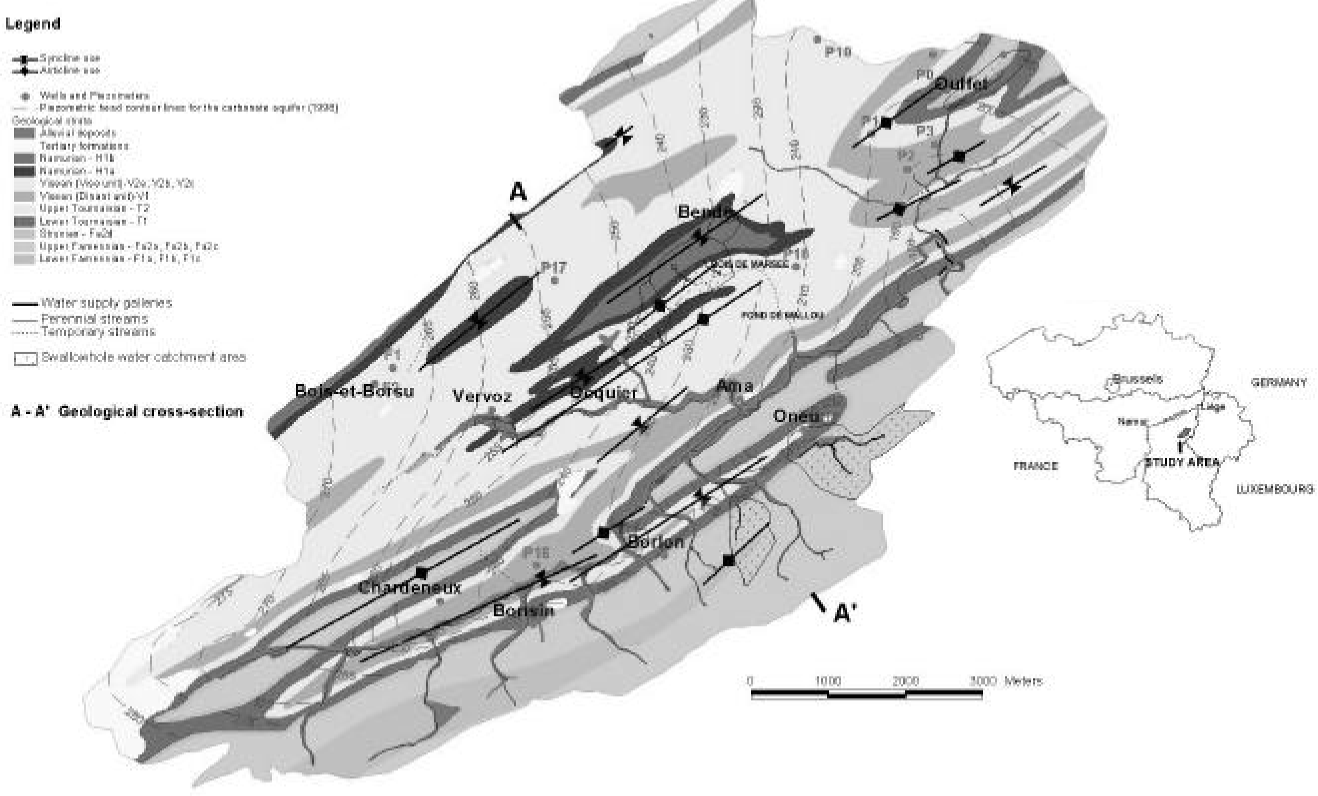

Fig. 1 Location, geology and hydrogeology of the study area

Typical alternation of shales and sandstone anticline crest (Upper Devonian or Famennian) and calcareous syncline depressions (Lower Carboniferous or Dinantian) are found. They contain several carbonate aquifers locally interconnected through sandstone layers. The relief in the Néblon basin is cut by a well developed river network. The tributary streams of the Néblon river are flowing transversely to the general West-East geological structure (Fig. 1). 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 are ending in swallowholes. Several temporary and losing streams as well as other diffuse losses can be observed in the area. Locally, ancient paleokarst was filled by Tertiary sandy-clay sediments. Generally, the region is covered by a loess formation with about 2 to 4 m of thickness.

Hydrogeology and karstic features

The Néblon basin aquifers are located in the Tournaisian and Visean limestone, in the Famennian fractured sandstone, and in the Namurian silty-sandstone. The main aquifer of the basin is made of the Tournaisian and Visean limestone. The aquifer is highly fissured, presenting locally clear signs of karstification. The Visean is generally made of purer limestone than the Tournaisian, and it is easily karstified.

The Néblon river is generally draining the main aquifer. The natural outflows of the aquifer are diffuse discharges and point sources along the Néblon river. They are exploited by the CILE Water Company via four collecting galleries. The galleries are located in order to drain the natural outlets of the hydrogeological basin on the both sides of the Néblon river.

The Famennian sandstone represents another exploitable aquifer mainly in the weathered zones but also in strongly fissured zones. Connection with the limestone aquifer (Fig. 2) is done predominantly by several spring raising upstream the Strunian shale band or probably through presumed strong fissured zones.

The silty-sandstone Namurian formations of Bois-et-Borsu and Bende synclinals (Fig. 1) act like small perched aquifers. These aquifers have a very weak storage capacity, and are exploited only for agricultural purposes by few local wells with production. It is supposed that the shale of the lower Namurian insures a relative imperviousness of the Namurian synclinals in depth.

Several karstic features can be identified in the Neblon basin, the most significant being dry valleys, swallowholes and resurgences, sinkholes (dolines). The high flow-rates recorded at the springs is presumed to indicate that karstic conduits are active. On Fig. 1, swallowholes and diffuses losses are located. Among them, three major swallowholes were identified: Bois de Marsée, Bende, and Oneu. Tracers injected in the swallowhole of Bois de Marsée, have been recovered in two of the galleries. This clearly indicates very quick flow in karstic conduits (MEUS 1993). The tracers times arrivals were lower than 50 h. That corresponds to a velocity of 73 $m \times h^{-1}$. Such velocities confirm that some particular zones are affected by karstification. Several dry valleys can be observed in the area (Fig. 1). Only very few undeveloped karstic caves are noticed along the Néblon cliffs as well as a small sinkhole South of Ouffet. During rainy periods the bottom parts of these dry valleys become small tributary streams.

The hydrogeological limits of the Néblon basin show spatial and temporal variations. In the southern part, an impervious boundary can be considered in the Famennian shale. The northern and eastern limits are mainly situated in the Visean limestone, where hydrogeological limits are not corresponding to hydrological ones. Also in the western part, groundwater transfers from the West are indicated by water-balance studies.

The few goundwater level measurements do not allow a complete understanding of the aquifer behaviour. However, considerable variations of the hydraulic heads were observed. (5 to 40 m). A piezometric map portraying a groundwater low levels period, was designed for 1998 (Fig. 1). This piezometric map clearly indicates a general groundwater flow to the East. A stronger depression in the Néblon river valley is also shown.

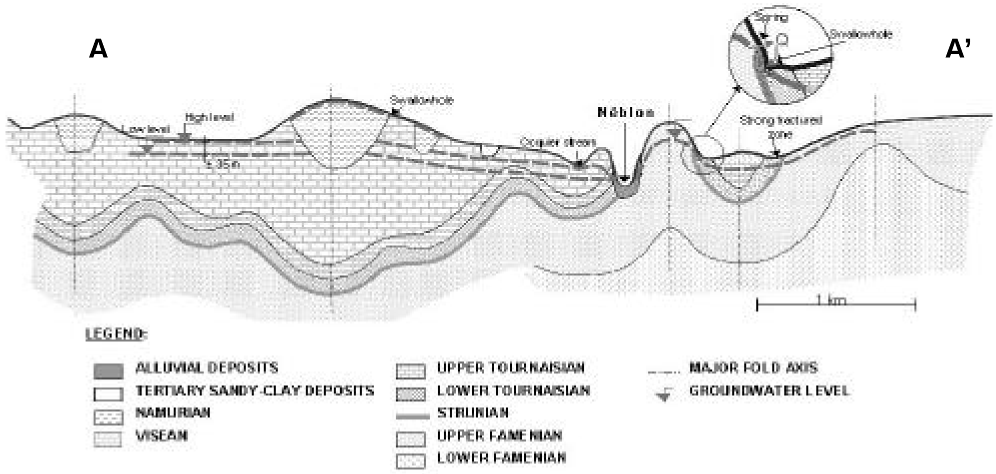

Fig. 2 Schematic geological and hydrogeological cross-section

The karstified aquifer and the Tertiary deposits filling the paleokarst pockets are supposed to keep a good groundwater communication. A clear relationship between the karstic aquifer and the surface river network was pointed out. In different river sectors, the water feeds the aquifer through the river bed. These observations pointed out the danger of water-supply galleries contamination by the river. DI CLEMENTE & LAURENT (1986), observed an identical chemical composition of groundwater and similar temporal variation of groundwater conductivity, pH, and ionic content at the Vervoz springs feeding the Ocquier stream and in the galleries. These observations pointed out possible links between the Néblon river and the galleries. The depth of the Namurian synclines made of shale and sandstone is not known. They are considered as allowing deep groundwater communication within the underlying limestone aquifer (Fig. 2) as confirmed by water-balance results (DI CLEMENTE & LAURENT 1986, DASSARGUES & DEROUANE 1997).

3. Methodology

The study was conducted in an area of 64.70 km^2 (Fig. 1). For the five applied methods, quantification of the parameters was done in parallel, in order to be consistent for further analysis. Evaluation of the vulnerability methods parameters was done by considering possible relationship between them. The needed data processing steps for obtaining reliable results were the followings: (1) a careful analysis of the existing raw and treated data, (2) a quality control of the data, (3) a study of possible correlations between the hydrogeological parameters, and finally the (4) hydrogeological interpretation of each parameter of each method.

Short overview on technical aspects in vulnerability analysis

It is not beyond the scope of this paper to describe GIS terms definitions (DE MERS 1997), types of geographical modelling and their achievement, aspects of data capturing, used GIS functions, procedures, operations, spatial manipulation issues and possible errors.

The tested methods for mapping intrinsic vulnerability are mentioned in the introduction paragraph.

Mostly, data come from the geological map of Belgium, the map of karstic features (DE BOYER *et al.* 1996), a prototype of the hydrogeological map (HALLET *et al.* 2000), various local and regional hydrogeological studies, topographic map of Belgium, soils map of Belgium, the digital numerical model of Belgium and the land use map (source: National Geographical Institute of Belgium). These data were then completed by a campaign of field tests consisting in: geophysical prospecting (electrical sounding and profiling, seismic soundings), piezometric measurements, pumping tests, tracer tests, field observation (geomorphology, rock quarries, springs), river flow-rates data (gauging stations), short auger holes interpretation, identifying and mapping the rock outcrops, rock quarries, and new karstic features (not mentioned before). The digital numerical model (DTM) of the region was used for slope computations needed for some of the methods. The piezometric map of the existing hydrogeological map (HALLET *et al.* 2000) was completed with data obtained in the more recent field measurement campaign. Then, by subtraction, a map of 'depth to water table' for the karstic aquifer was drawn.

The existing map of soils represented the basic information for obtaining the map of soil parameters. Additional information concerning soil thickness, rock outcrops and quarries, was obtained during an extensive field work campaign.

4. Results

Analysing and comparing results from such different methods can be performed in different ways. As each method has its own system for defining and regrouping final classes of vulnerability, a first way for comparing results consists in taking the point of view of a 'blind' user of the methods. According to the classification system prescribed in each of the methods, results are found in terms of high, moderate and low vulnerability zones. Then, the user can check, for example, if high vulnerability zones are mapped in the same areas and if there are some large discrepancies between results from one method to the others. If a more quantified comparison is to be made, a regrouping in three common classes is needed: let's propose high, moderate and low vulnerability. Respective percentages of high, moderate and low vulnerability zones found by each method can be compared from one map to another. This direct approach will be applied here below.

However, knowing that intrinsic vulnerability is only a relative concept, this last approach can be judged statistically and mathematically inconsistent. Another way for comparing results would consist in redefining the final vulnerability classes taking into account that the values of the vulnerability index follow in each study area a normal statistical law. Then defining percentiles, vulnerability classes can be found: taking a percentile 33, would lead, for example, to the definition of the three vulnerability classes (low, moderate, high). However, even if this last method is more statistically consistent for comparing results in one study area, from the hydrogeological point of view it is difficult to accept that a same zone will be given another final vulnerability depending if it was included within a map or another.

Comparison between intrinsic vulnerability maps

As previously mentioned, a classical comparison is made here below, applying as a 'blind' user the methods as prescribed by authors.

For the classic DRASTIC method, the zones of very high and high vulnerability cover about 5 % of the study area (Fig. 3). According to EPIK, the zones of high and very high vulnerability covers 8.5 %. The very high and high vulnerability zones for the other three methods, correspond to more than a half of the study area.

A general similarity between GOD, ISIS, and the German method can be observed. The German method is outlining the most extended zones with high and very high vulnerable areas (high 48 % and very high 34 %). The ISIS method provides 63 % of high vulnerable areas.

In general the limestone aquifer is characterized as high or very high vulnerable. Only in the DRASTIC method it takes moderate vulnerability. In the German method and in the GOD method vulnerability maps, the difference between high and very high vulnerability is largely influenced by the depth to groundwater table. Furthermore, these two methods use the depth to groundwater table as a direct multiplier for the other parameters. The ISIS method is using differently (than the other methods) the depth to groundwater table parameter. Unfortunately this procedure, used by ISIS, is smoothing the vulnerability index results. It clearly appears that in DRASTIC vulnerability map, the introduction of depth to the groundwater table creates the distinction between the moderate vulnerability and the high vulnerability (Fig. 3) zones.

Karst features are not always pointed out as high or very high vulnerable zones. For example for the GOD method, the small diffuse swallowhole of Bende and the swallowholes and resurgences located near Ouffet are considered respectively as low and moderate vulnerable. The streams feeding the swallowholes are considered as high vulnerable zones by EPIK, by the German method, and by GOD. ISIS and DRASTIC methods consider these zones partly high vulnerable, partly moderate vulnerable. Except ISIS, the dry valleys and the sinkholes were characterised by all methods as being more vulnerable than the rest of the limestone.

Temporary streams are springing from the Namurian terrains and are feeding directly swallowholes when arriving in limestones (Fig. 1). EPIK is the only method that consider these temporary small stream-basins as moderate vulnerable zones. The other four methods consider them as low vulnerable zones. These methods are not outlining specifically, the karstic environment. This delicate issue is derived from the vulnerability concept scheme used by these four methods: only vertical permeability is considered. In consequence these methods are neglecting the potential contamination that comes by the streams and bypassing the soil and the unsaturated zone.

A similar problem is observed for the small Vervoz lake, that overlies the limestone as well as the Namurian formations. All the methods except EPIK, consider as low vulnerable the part corresponding to the Namurian formations and as high or very high vulnerable the parts of the lake lying on the limestone.

The Lower Tournaisian is mostly characterised with a moderate or high vulnerability. The Strunian bands appear with a moderate or low vulnerability.

A particularity of the ISIS method is the use of the land-use parameter as a multiplier factor for all other parameters.

Regrouped classes of vulnerability

For comparison, regrouping the classes of vulnerability was done for each vulnerability map, outlining three main categories: high (including the high, very high, and extreme vulnerability), moderate vulnerability (the same class for all five methods), and low vulnerability (including low and very

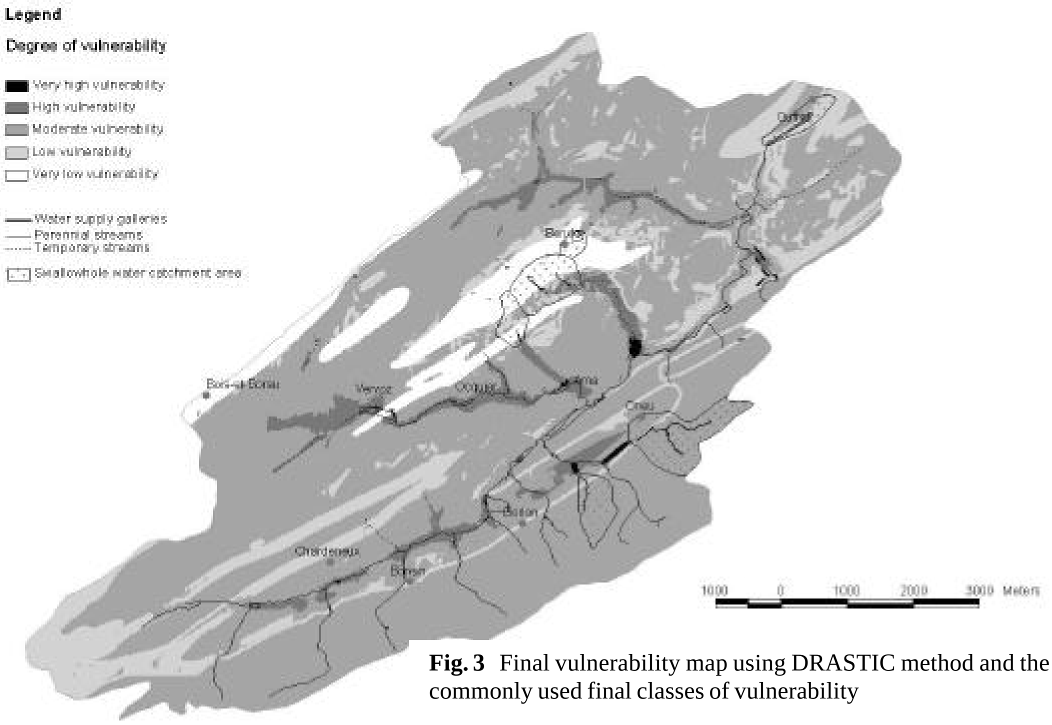

Fig. 3 Final vulnerability map using DRASTIC method and the commonly used final classes of vulnerability

low vulnerability). Results are shown in Fig. 4.

All the five methods designated areas corresponding to the Namurian formations as low vulnerable. The German method shows the most extended area of high vulnerability, with 83 %. The DRASTIC results are more balanced with 73 % of the area with a moderate vulnerability and 22 % with a low vulnerability.

For this basin, these regrouped classes of vulnerability indicate two main trends in the vulnerability assessment: (a) the German method, the GOD method, and the ISIS method consider the study area as being dominantly high vulnerable; (b) the DRASTIC method and the EPIK method moderate vulnerable 73 % and 92 %. These results show a high discrepancy between the methods.

5. Conclusions

Describing the results of vulnerability assessment using the five methods, some comments can be deduced:

(a) according to the German, GOD, and ISIS methods (Fig. 4), more than a half of the study zone is vulnerable.
(b) according to the DRASTIC and EPIK methods most of the study area is moderate vulnerable.
(c) all the five methods give a low vulnerability to the areas corresponding to the Namurian formations.
(d) except for the GOD vulnerability map and partially for the German method, the Famenian sandstone is less vulnerable than the limestone aquifer.
(e) the Strunian bands are considered moderate or low vulnerable for all the methods.
(f) the Lower Tournaisian is mostly assessed with a moderate or a high vulnerability.
(g) the Tertiary sandy-clay deposits are generally assessed as low vulnerable except for the GOD and ISIS methods.

Suiting a high or very high vulnerability degree, the karstified zones are apparently properly evaluated by the presented methods with exception for GOD and in a smaller measure for ISIS. The EPIK method better outlined the karstic features than the other four methods.

All the vulnerability methods are taking into account directly or indirectly the vertical permeability. However, most of them are neglecting possible contamination coming directly from the streams and bypassing the soil and the unsaturated zone.

In the EPIK method, the assumption consisting in relating a steeper slope to a higher degree of vulnerability is not realistic when open valleys and fissure matrix are predominant. On the contrary, it is valid within drainage basins of karstic features. Another concern is the fact that the relative high vulnerability of karstic systems is not related to other types of aquifers in the EPIK method. As the fundamental concept of vulnerability is a relative concept (VRBA & ZAPOROZEC 1994, GOGU & DASSARGUES 2000), ignoring other lithogical and hydrogeological conditions lead to less contrasted results than awaited.

These conclusions should open new research directions in the procedures of the parameter quantification and weighting. It shows clearly the need for more flexible and more physically-based methods. To be more reliable, the vulnerability mapping techniques must be adapted in the future. The Working Group 1 of the COST620 Action is acting in this direction for intrinsic vulnerability mapping, checking that each parameter of the proposed approach is given a value having a physical consistency with regards to three main physical observations: transfer time, physical attenuation and effective recharge (DALY *et al.*, 2001).

For example, the recharge of the aquifer seems to be one of the most significant parameters in vulnerability assessment. In all the five methods this parameter is explicitly or implicitly taken into account. Results in vulnerability assessment can be influenced and improved if the recharge parameter becomes a spatially variable data and if a 'concentration of flow' factor is distinguished (DALY *et al.*, 2001).

Too many classes of vulnerability are physically useless: it is the case of the *extreme vulnerability* class defined within the ISIS method. In this study, even if a karstic aquifer was analysed, the *extreme vulnerability* class is not present. In consequence, defining four classes of vulnerability appears to be a more reasonable choice. It fully satisfies the needs and the resulted maps are easily understood and manipulated.

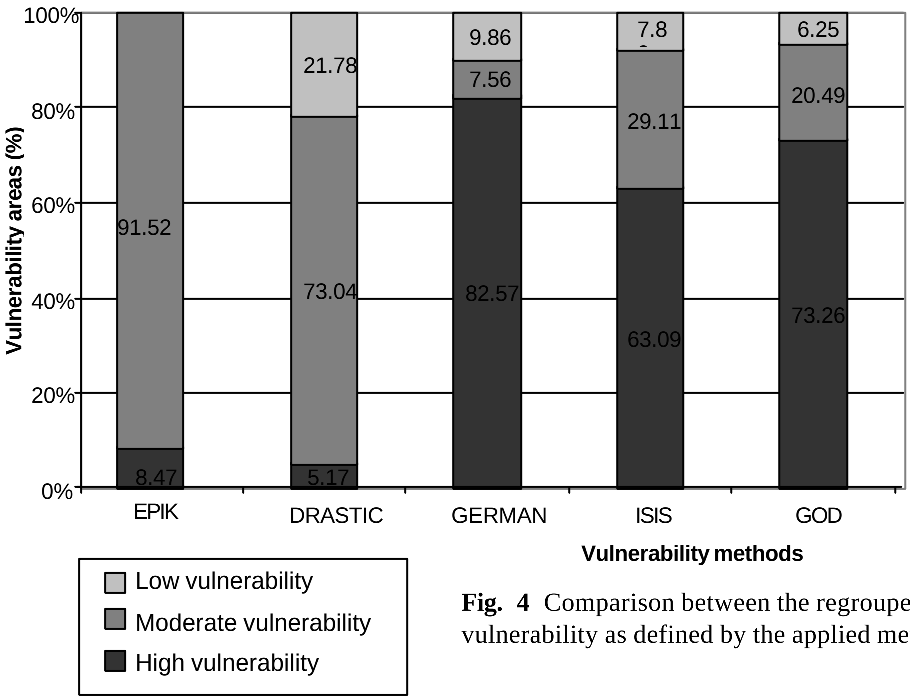

Fig. 4 Comparison between the regrouped classes of vulnerability as defined by the applied methods

Until now, the choice among vulnerability methods remained a subjective decision of the hydrogeologist. Additionally, all the methods are to some extent flexible in the process of parameter quantification. As underlined by ALLER *et al.* (1987), the vulnerability methods has to be used as screening tools. They cannot replace the professional expertise and field works needed for more quantified answers. The choice of parameter rating must be based on extended studies of the hydrogeological conditions. The so-called vulnerability "rapid assessments" performed by untrained operators may conduct to serious errors. The only way to reflect the reality in the aquifers vulnerability results is to merge adequately all the existing studies related to geology, hydrogeology, hydrology, soil topography, climate, and land-use.

Further, each existing method should be evaluated with respect to the physical meaning included implicitely in the definition of the intrinsic vulnerability. According to BROUYÈRE, *et al.* (2001, these Proceedings) three main criteria are underlying the intrinsic vulnerability concept: transfer time of the pollutant to reach the 'target' (groundwater resource in general or the concerned sources or springs), duration of the contamination, and the involved pollutant mass linked to physical attenuation in the medium.

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