University of Liège, Belgium - Faculty of Applied Sciences
Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting

Advances in groundwater protection strategy using vulnerability mapping and hydrogeological GIS databases

Thesis presented to the Faculty of Applied Sciences of the University of Liège
for obtaining the title of "Docteur en Sciences Appliquées"

Radu Constantin GOGU

2000

Civil Engineer in Hydraulic Structures at UTCB-Bucharest, Romania
M.Sc. in Water Resources Engineering at UTCB-Bucharest, Romania

Members of the jury:

Prof. A. Monjoie, President , Université de Liège
Prof. A. Dassargues, Thesis director, Université de Liège
Prof. J.P. Donnay, Université de Liège
Prof. V. Hallet, Université "Notre-Dame de la Paix" Namur
Prof. S. Dautrebande, Faculté Universitaire des Sciences Agronomiques de Gembloux
Prof. J. Petch, University of Manchester, United Kingdom
Prof. D. Stematiu, Technical University of Civil Engineering - Bucharest, Romania
Prof. H. Hötzl, University of Karlsruhe, Germany

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Prof. H. Hötzl, University of Karlsruhe, Germany

Părinților mei

(To my parents)

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- Laboratory of Engineering Geology, Hydrogeology, and Geophysical Prospecting (LGIH), University of Liege, Belgium

"There is no road traveller,

The road is made by walking."

Antonio Machado

Preface

The idea of developing this thesis originated in my first research training period in 1995 at the Laboratory of Engineering Geology, Hydrogeology, and Geophysical Prospecting (LGIH), University of Liège. During a discussion, Professor Alain Dassargues showed his interest in supervising a research work, which integrates GIS within hydrogeological studies, and more precisely in the vulnerability of aquifers. Due to various administrative aspects, the effective research work started in June 1997. Many persons have contributed to the realisation of this work and I would like to express my thanks to all of them.

Without Professor Alain Dassargues, the workout of this thesis would simply not have existed. Professor Alain Dassargues initiated this work and played a crucial role in the completion of my PhD research. Thank you!

I am also very grateful to Professor Albéric Monjoie, the Director of the Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting, for allowing me to actively participate in several research projects carried out in his department. I would like to kindly thank him for the specific comments and criticisms on my work, which showed to me several times the essentials of hydrogeological thinking.

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An important part of the effective work concerning the hydrogeological GIS database and the coupling procedures to Groundwater Modelling System (GMS) interface, were designed together with Guy Carabin. Thank you Guy, for the knowledge, skills, and for your entire patience you brought to our collaboration.

It is a pleasure for me to mention Assad Saade, David Gaule, and Yves Arbel for the nice and productive moments we spent in the Beauraing and Néblon regions, during the field work campaigns.

With Valerie Peters and Ingrid Ruthy I had the pleasant opportunity to work within different projects related to my thesis. I am addressing to Valerie Peters particular thanks mainly for providing her experience of hydrochemical problems in the hydrogeological database design. Special thanks go to Ingrid Ruthy for her unhesitant aid in different moments at the end of my work.

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I have to mention also my friend Serge Brouyere. His advises during the numerous discussions, debates, and field work campaigns as well as the hydrogeological references he provided to me several times, considerably improved my hydrogeological knowledge.

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Finally, I would like say *"Mulțumesc !"* to all those who stayed close to me with their hearts and minds during all these years. They know perfectly well that without their love and moral support this thesis could not have been accomplished. I shall not tell their names here, but they have to be sure that I shall never, ever, forget them.

Préface

L'idée de développer cette thèse est née lors de mon premier stage en 1995, aux Laboratoires de Géologie de l'Ingénieur, d'Hydrogéologie et de Prospections Géophysiques (LGIH) de l'Université de Liège. Le Professeur Alain Dassargues s'est montré très intéressé par un travail de recherche intégrant les systèmes d'informations géographiques (SIG) dans des études hydrogéologiques et plus particulièrement dans l'étude de la vulnérabilité des aquifères. Pour des raisons administratives, mon travail n'a pu commencer de manière effective qu'en juin 1997. Plusieurs personnes ont contribué à la réalisation de cette thèse, je voudrais leur témoigner toute ma gratitude.

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Abstract

Key words: groundwater protection, resource, vulnerability, karst aquifer, sensitivity analysis, groundwater management, database, GIS, coupling

Groundwater vulnerability maps are useful for environmental planning and decision-making. They are usually produced by applying vulnerability assessment methods using overlay and index techniques. On the basis of a review of the vulnerability assessment and mapping methods, new research challenges in aquifers vulnerability assessment are identified.

Operations like the parameter quantification, the vulnerability index computing, and the final classification, are affected by an empirical character which of course affects also the final product: the vulnerability map. In consequence, the validity of the resulted vulnerability maps must be evaluated in function of the objectives of the survey and in function of the specific characteristics of each studied zone. Analysing their uncertainty can represent the base for their validation. Uncertainty can be investigated through sensitivity analysis or through comparisons between vulnerability maps created using different methods. Both these strategies are developed in this study and illustrated from applications on practical case studies of vulnerability mapping.

Applying the EPIK parametric method, a vulnerability assessment has been made for a small karstic groundwater system in southern Belgium. The aquifer consists in a karstified limestone of Devonian age. A map of intrinsic vulnerability of the aquifer 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.

Five different methods for assessing the intrinsic vulnerability were tested on a case study for comparison of their results. The test area consists in a slightly karstified basin 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 in drainage galleries. Several campaigns of measurements consisting in morpho-structural observations, shallow geophysics, pumping and tracer tests have provided useful data. The tested methods were: EPIK (Doerfliger and Zwahlen, 1997), DRASTIC (Aller *et al.*,1987), 'German method' (von Hoyer & Söfner, 1998), GOD (Foster, 1987), and ISIS (Civita and De Regibus, 1995). DRASTIC and GOD represent classic approaches in vulnerability assessment. ISIS is a development based on DRASTIC, SINTACS (Civita, 1994), and GOD methods, where more importance is given to the recharge.

EPIK was developed specifically for karstic geological contexts and the 'German method' was developed in Germany for a broad range of geological contexts. Compared results are shown and commented. It seems that despite the fact that the EPIK method can better outline the karstic features, about 92% of the studied area is assessed by this technique as low vulnerable. In contrast, the other four methods are considering extended zones of high or moderate vulnerability. From the analysis, it seems also that reducing the number of considered parameters is not ideal when adaptation to various geological contexts is needed.

Reliability and validity of groundwater analysis strongly depend on the availability of large volumes of high quality data. Putting all data in a coherent and logical structure supported by a computing environment helps ensure a validity and availability, and provides a powerful tool for hydrogeological studies. A *hydrogeological* GIS *database* that offers facilities for groundwater vulnerability analysis and hydrogeological modelling has been designed in Belgium, for the Walloon Region. Data from five river basins, chosen for their contrasted hydrogeological characteristics, are now introduced in the database and a set of applications that have been developed allow now further advances. However the basic concept of the database is represented by the commonly accepted "Georelational model" developed in the 1970s, the database concept presents a distinctive character.

There is a growing interest in the potential for integrating GIS technology and groundwater simulation models. Between the mentioned spatial database schema and the groundwater numerical model interface GMS© (Groundwater Modelling System), a "loose-coupling" tool was created. Following time and spatial queries, the hydrogeological data stored in the database can be easily used within different groundwater numerical models. This development can represent also a solid base for the physical processes integration within the quantification of the vulnerability methods parameters.

The fundamental aim of this work was to help improving the aquifers protection strategy using vulnerability mapping and GIS. The results are offering the theoretical and practical basis for developing a strategy for protecting the groundwater resources.

Résumé

Mots clef : protection des eaux souterraines, ressource, vulnérabilité, aquifère karstique, analyse de sensibilité, gestion des eaux souterraines, base de données, SIG, couplage

Les cartes de *vulnérabilité des eaux souterraines* sont utiles pour la gestion de l'environnement et pour l'aménagement du territoire. En général elles sont produites en appliquant des méthodes d'évaluation de la vulnérabilité en utilisant les techniques de superposition et d'indexation. Sur la base d'un examen des méthodes existantes de cartographie et d'évaluation de la vulnérabilité, de nouveaux défis de recherche sont identifiés.

Des opérations comme la quantification des paramètres, le calcul de l'index de vulnérabilité et la classification finale, sont affectées par un caractère empirique qui, bien entendu, affecte également le produit final: la carte de vulnérabilité. Par conséquent, la validité des cartes de vulnérabilité doit être évaluée en fonction des objectifs de l'étude et en fonction des caractéristiques spécifiques de chaque zone étudiée. L'analyse de leur incertitude peut représenter une base rigoureuse pour leur validation. L'incertitude peut être quantifiée par des analyses de sensibilité ou par des comparaisons entre les cartes de vulnérabilité créées en utilisant différentes méthodes. Les deux stratégies sont développées dans cette recherche et sont illustrées par des applications sur des cas pratiques.

En appliquant la méthode paramétrique EPIK, une évaluation de la vulnérabilité a été réalisée pour un petit bassin aquifère karstique situé dans le sud de la Belgique. L'aquifère est constitué d'un calcaire karstifié du Dévonien. La carte finale de vulnérabilité intrinsèque de l'aquifère montre trois zones de vulnérabilité. Une étude des paramètres et une analyse de sensibilité ont été réalisées afin d'évaluer l'influence d'un seul paramètre sur l'évaluation de la vulnérabilité, en utilisant la méthode EPIK. Cette approche fournit une méthode pour l'évaluation de la vulnérabilité cartographiée et permettant des interprétations plus fiables en ce qui concerne les indices de vulnérabilité pour les ressources en eaux souterraines.

Cinq différentes méthodes pour l'évaluation de la vulnérabilité intrinsèque ont été testées dans le cadre d'un étude de cas afin de comparer leurs résultats. L'aquifère étudié est légèrement karstifiée et située dans la région du Condroz (Belgique). Le bassin couvre environ 65 km^2 et l'aquifère assure une alimentation journalière d'environ 28000 m^3 d'eau, dans des galeries de drainage situées à ses exutoires naturels. Plusieurs campagnes de mesure, qui consistent en observations morphostructurales, prospections géophysiques, essais de pompage et essais de traçage, ont fourni des données très précieuses. Les méthodes testées sont les suivantes: EPIK (Doerfliger et Zwahlen, 1997), DRASTIC (Aller et al., 1987), « La méthode allemande » (von Hoyer & Söfner, 1998), GOD (Foster, 1987), et ISIS (Civita et de Regibus, 1995). DRASTIC et GOD représentent des approches classiques pour l'évaluation de la vulnérabilité. ISIS a été développée à partir des méthodes DRASTIC, SINTACS (Civita, 1994) et GOD, en donnant plus d'importance à la recharge. EPIK a été développée spécialement pour les milieux karstiques et la méthode allemande a été développée pour une large variété des contextes géologiques. Les résultats comparés sont montrés et commentés. Bien que la méthode EPIK peut mettre mieux en évidence les caractéristiques karstiques, environ 92% de la zone étudiée sont caractérisés comme étant peu vulnérables. Par contre, les quatre autres méthodes aboutissent à des zones étendues de vulnérabilité grande ou modérée. Il apparaît également que réduire le nombre des paramètres considérés n'est pas idéal, lorsqu'une adaptation à des contextes géologiques variés est nécessaire.

La fiabilité et la validité des études concernant les eaux souterraines dépendent fortement de l'existence d'un grand nombre de données de bonne qualité. L'organisation de toutes les données dans une structure cohérente et logique, assistée par un outil informatique, aide à assurer l'utilisation adéquate et la disponibilité ultérieure et constitue donc un outil puissant pour les études hydrogéologiques. Une base de donnée hydrogéologique SIG a été conçue en Belgique, pour la Région Wallonne. Elle offre des avantages et facilités pour les analyses de vulnérabilité des eaux souterraines et pour la modélisation hydrogéologique. Les données de cinq bassins hydrologiques, choisis pour leurs caractéristiques hydrogéologiques contrastées, ont été introduites dans la base de données et une série d'applications qui ont été développées permettent maintenant d'autres recherches. Même si le concept de base pour la base de données correspond au « modèle géorelationnel » développé dans les années '70, le concept de la base de donnée présente un caractère spécifique et original.

Un intérêt croissant est montré pour le potentiel d'intégration de la technologie SIG et les modèles de simulation des réservoirs souterrains. Un outil de « couplage souple » a été créé entre le schéma de base de données spatiales et l'interface du logiciel GMS© (Groundwater Modelling System). En suivant des interrogations temporelles et spatiales, les données hydrogéologiques stockées dans la base de données peuvent être facilement utilisées dans différents modèles numériques hydrogéologiques. Ce développement peut aussi représenter une base solide pour la prise en compte des processus physiques dans la quantification des paramètres des méthodes de vulnérabilité.

Le but principal de ce travail a été d'aider par les quelques développements proposés à améliorer la stratégie de protection des aquifères, en complémentarité avec la détermination des zones de protection proprement dites, en utilisant la cartographie de la vulnérabilité et les SIG. Les résultats offrent les bases théoriques et pratiques pour le développement de ce genre de stratégie qui permettra une meilleure protection des ressources en eaux souterraines.

Content

Chapter 1

Introduction

1.1. Perceptions of groundwater vulnerability

Scientists and resource managers recognised the need for effective and efficient methods for protecting groundwater resources from future contamination. They created techniques for predicting which areas are more likely than others to become contaminated as a result of activities at or near the land surface. Recently, more and more countries are starting to develop consistent frameworks for decision making in groundwater protection, following the scientific and legislation advances introduced within the European context (Ward et al. 2000). The general tendency is to apply a groundwater policy that uses risk-based approaches to groundwater protection. Two supporting tools are usually developed: *Source Protection Zones* and *Groundwater Vulnerability Maps*. The first is designed to protect the groundwater supply systems and the second to provide a general indication of potential risks for the aquifers. Both recommend controls and protection measures.

The concept of *groundwater vulnerability* to contamination has however different meanings for different people. Some consider vulnerability as an intrinsic characteristic of soils in relationship to other parts of the natural environment (i.e. topography, geology, climate). Others consider that vulnerability depends on the properties of individual contaminants or contaminant groups, but is independent of specific land-use or management practices. Still others associate vulnerability with a specific set of human activities and the land surface. Some authors have attempted to avoid the term vulnerability altogether and have substituted terms such as sensitivity. Some examples to illustrate the diversity in terminology may create a better idea of what can be meant by vulnerability:

Foster (1987)

Aquifer Pollution Vulnerability - « the intrinsic characteristics which determine the sensitivity of various parts of an aquifer to being adversely affected by an imposed contaminant load »

Ground Water Pollution Risk - « the interaction between the natural vulnerability of the aquifer, and the pollution loading that is, or will be, applied on the subsurface environment as a result of human activity »

Pettyjohn et al. (1991)

Aquifer Vulnerability - « The geology of the physical system determines vulnerability »

Aquifer Sensitivity - « Aquifer sensitivity is related to the potential for contamination. That is, aquifers that have a high degree of vulnerability are in areas of high population density, are considered to be most sensitive... »

U.S. Environmental Protection Agency (1993)

Aquifer Sensitivity - " The relative case with which a contaminant (in this case a pesticide) applied on or near the land surface can migrate to the aquifer of interest. Aquifer sensitivity is a function of the intrinsic characteristics of the geologic materials of interest, any overlaying saturated materials, and the overlaying unsaturated zone. Sensitivity is not dependant on agronomic practices or pesticide characteristics »

Ground Water Vulnerability - « The relative ease with which a contaminant (in this case a pesticide) applied on or near the land surface can migrate to the aquifer of interest under a given set of agronomic management practices, pesticide characteristics and hydrogeologic sensitivity conditions »

U. S. Committee on Techniques for Assessing Groundwater Vulnerability - (National Research Council 1993)

Ground Water Vulnerability to Contamination - « The tendency or likelihood for contaminants to reach a specified position in the ground water system after introduction at some location above the uppermost aquifer. »

« ***Specific Vulnerability***, is used when vulnerability is referenced to a specific contaminant, contaminant class, or human activity. »

« ***Intrinsic Vulnerability***, refers to vulnerability determined without consideration of the attributes and behaviour of particular contaminants. »

Robins et al. (1994)

« ***Aquifer vulnerability*** would thus be a function of the intrinsic properties of the overlaying soil and rock column or unsaturated zone of the aquifer, with the risk of groundwater pollution dependent on the interaction of the natural aquifer vulnerability and the subsurface contaminant load imposed by human activity »

International Association of Hydrogeologists (Vrba and Zaporozec 1994)

« ***Vulnerability*** is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts »

Intrinsic Vulnerability (natural) - is the « vulnerability defined solely as a function of hydrogeological factors - the characteristics of an aquifer and the overlaying soil and geological materials. »

Specific Vulnerability (integrated) - « In addition to intrinsic properties of a groundwater system, some users of vulnerability maps may also wish to include potential human impacts, which may prove detrimental - in space and time - to the present or future uses of the groundwater resource. »

European project COST Action 620 - Vulnerability and risk mapping for the protection of carbonate (karst) aquifers

« ***Intrinsic vulnerability*** is the term used to define the vulnerability of groundwater to contaminants generated by human activities. It takes account of the inherent geological, hydrological and hydrogeological characteristics of an area but is independent of the nature of the contaminants. »

« ***Specific vulnerability*** is the term used to define the vulnerability of groundwater to a particular contaminant or group of contaminants. It takes account of the properties of the contaminants and their relationship with the various components of intrinsic vulnerability. »

1.2. Thesis description

Groundwater vulnerability maps are useful for environmental planning and decision-making. They are usually produced by applying vulnerability assessment methods using overlay and index techniques. A short examination of vulnerability assessment and mapping methods follows in Chapter 2. Because of increased interest in groundwater protection, new aquifer vulnerability concepts and techniques come into view since the last general review made by Vrba and Zaporozec (1994). In consequence, the review presented in the following chapter was considered compulsory for this work.

The currently operations used by the aquifer vulnerability methods as the parameter quantification, the vulnerability index computing, and the final reclassification, indicate an empirical character of the vulnerability assessment procedures. In consequence the validity of the resulted vulnerability maps must be tested. Analysing their uncertainty can represent the base for their validation. Uncertainty can be investigated through sensitivity analysis or through comparisons between vulnerability maps created using different methods. Both these strategies are developed in this study in order to establish a clear understanding of the groundwater vulnerability assessment process. Study cases are illustrated and analysed from applications of vulnerability mapping in Chapter 3 and 4.

Reliability and validity of groundwater studies and in particular for vulnerability assessment, depend strongly on the availability of large volumes of high quality data. Putting all data in a coherent and logical structure supported by a computing environment helps in developing powerful tools used for hydrogeological studies.

A *hydrogeological* GIS *database schema* offering facilities for groundwater modelling as well as for other hydrogeological studies has been designed. Data from five Belgian river basins, chosen for their different hydrogeological characteristics, are now introduced in the database and a set of applications have been developed or are still in progress. This hydrogeological GIS database described in Chapter 5, offers facilities mainly for aquifer vulnerability assessment and hydrogeological numerical modelling.

There is a growing interest in the potential for integrating GIS technology and groundwater simulation models. Between the mentioned spatial database schema and a groundwater numerical model interface, a "loose-coupling" tool was created. A brief description of this tool is done in Chapter 5. Following time and spatial queries, the hydrogeological data stored in the database can be easily used within different groundwater numerical models. This represent a solid base for the physical processes integration within the quantification of the vulnerability methods parameters.

Other hydrogeological studies can also be facilitated such as: water reserves evaluation, hydrogeological maps, hydrogeochemical studies, data verification and validation. Prototypes of a general *hydrogeological map* are developed for the Walloon region of Belgium. However this work is not developing this aspect, further developments for an organisational implementation (water regulator or decision-maker) are possible following a method and a formalism (Pantazis and Donnay 1996).

1.3. Research objectives and assumptions

Research of groundwater flow and contamination transport shown a considerable progress over the last 25 years. Despite this, adequate understanding of these processes is still lacking in many areas. In consequence, there is still a serious limit of the ability to predict with high certainty the effects on groundwater vulnerability of a change in land-management practice of a region.

This study is analysing the *vulnerability of aquifers* and principally of the karstic aquifers. The existing groundwater vulnerability methods are discussed and are tested on a case study, a technique of evaluating the uncertainty of vulnerability mapping is developed and applied on a karstic aquifer, and a hydrogeological GIS database for sustaining the vulnerability assessment is designed and created. These achievements described in the following chapters, were done in order to offer a theoretical and a practical support for a modern and accurate development of the groundwater vulnerability mapping. Previous studies as well as field campaigns assured a good quantity and a certain accuracy of the data used in the study cases.

However Geographical Information Systems (GIS) problems are not specifically developed within this manuscript, the GIS represented the basis for the entire performed research. The two study cases of aquifer vulnerability analysis presented in this paper were done using GIS. The basic GIS theory, assumptions, as well as the different procedures and operations are considered familiar. In consequence, only the aquifer vulnerability aspects are developed.

The hydrogeological database presented in Chapter 5 was developed on the base of an accurate analysis of the commonly used hydrogeological data and data needs as well as the data formats, relationships, and requirements for hydrogeological analysis. Three kinds of thinking are integrated within the proposed schema: the field hydrogeologist, the groundwater numerical modeller, and the GIS operator. The database was designed firstly to answer their immediate needs. Later, were added the requirements of the water regulator. However the basic concept of the database is represented by the commonly accepted "Georelational model" developed in the 1970s, the database concept presents a distinctive character.

For this study the used definitions of aquifer vulnerability are those adopted by the specialists working in the frame of COST 620 Action (European Community, Directorate General XII - Science, Research and Development) on "Vulnerability and risk mapping for the protection of carbonate (karst) aquifers". These definitions outline clearly the notions of intrinsic and specific vulnerability as well as the relationship between them. Also, they are mentioning specifically the examined environments.

"All ground water is vulnerable"

(National Research Council 1993)

Chapter 2

Groundwater vulnerability assessment

2.1. General concepts of groundwater vulnerability assessment

Vulnerability assessment of groundwater, as used in many methods, is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept "that some land areas are more vulnerable to groundwater contamination than others" (Vrba and Zaporozec 1994). Nevertheless mapping the degree of groundwater vulnerability to contaminants, as a function of hydrogeological conditions, shows that effective protection provided by the natural environment may vary drastically from one place to another.

Often, the groundwater contamination level is determined by the natural attenuation processes occurring within the zone located between the pollution source and the aquifer. Various natural physical processes and chemical reactions that operate in the soil, unsaturated, and saturated zones may cause the pollutant to change its physical state and chemical form. These changes may attenuate the degree of pollution or change the nature of the contamination. Especially in soil and the unsaturated zone, some mechanisms may affect the contaminant concentration much more than in the saturated zone.

Chemical processes can be very complex and may work individually or in combination with other processes to provide varying attenuation degrees. These reactions depend on site specific soil and aquifer characteristics as well as on the particular geochemical properties of each pollutant. Although, the importance of these chemical reactions for attenuation of pollution is widely recognised and sometimes modelled, attenuation processes can be partially or completely bypassed depending on geochemical conditions in the aquifer and the infiltration conditions.

Pollution sensitive areas

Pollution sensitive areas can be divided into three groups: naturally vulnerable areas, well-protection zones, and potential problem areas.

Naturally vulnerable areas are more sensitive zones where the soils, subsoil, and bedrock do not provide adequate protection and the potential exists for rapid transfer of pollutants to groundwater. Areas of concern are, for example, the recharge zones of shallow aquifers.

In the vicinity of pumping wells, each pollutant can potentially contaminate the pumped groundwater relatively quickly. In many countries, the methods for delineating well-protection zones are standardised using different criteria, based on the piezometric heads, on the advective transport time, on the advective-dispersion transport time or other parameters.

Overlaying maps of the most vulnerable zones, with maps showing the location of each potential contamination sources or polluting land-use activities, generates the map of potential problem areas (risk maps).

Concepts and methods of vulnerability assessment

Aquifer vulnerability concept involves mainly two particular notions: intrinsic vulnerability and specific vulnerability.

European specialists of the COST Action 620 "Vulnerability and risk mapping for the protection of carbonate (karst) aquifers", agreed that intrinsic vulnerability is a "term used to define the vulnerability of groundwater to contaminants generated by human activities", taking "account of the inherent geological, hydrological and hydrogeological characteristics of an area", but being "independent of the nature of contaminants". On the contrary, specific vulnerability notion is used "to define the vulnerability of groundwater to a particular contaminant or group of contaminants", taking "account of the contaminant properties and their relationship with the various components of intrinsic vulnerability".

The UK National River Authority recognised that a full assessment of aquifer vulnerability and groundwater pollution risk can be achieved only by local studies (Robins et al. 1994). These kinds of methods can reduce the number of areas to be studied in detail by identifying the most vulnerable areas. However, vulnerability assessment is a useful management concept for guiding decisions on groundwater protection tasks. It requires co-operative efforts of policy makers, natural resource managers, technical and scientific experts.

In relation with groundwater protection, three main approaches can be distinguished in the assessment of groundwater vulnerability to contamination:

- Vulnerability assessment considering only the soil and unsaturated zone without taking into account the transport processes within the saturated zone. In this case, the assessment is limited to the relative probability that troublesome concentrations of contaminants reach the saturated zone. Many classical vulnerability methods, are based on this approach : the GOD method (Foster 1987), the Irish approach (Daly and Drew 1999), and the AVI method (Van Stempvoort et al. 1993).

- The approach based on delineation of protection zones for groundwater supply systems, where groundwater flow and contaminant transport processes within the saturated zone are considered to some extent (including dispersion transport as it is done in Walloon Region of Belgium, Derouane and Dassargues 1998).

- An approach, targeting the soil and unsaturated zones as well as the aquifer medium.

Based on these different approaches, various methods of groundwater vulnerability assessment have been developed. They range from sophisticated numerical models simulating the physical, chemical and biological processes occurring in the subsurface, to techniques using weighting factors affecting vulnerability and also to statistical methods. Coupled physically based models considering soil, unsaturated and saturated zones in order to compute contaminant transport time in the system and various empirical vulnerability methods such as DRASTIC (Aller et al. 1987), SINTACS (Civita 1994), EPIK (Doerfliger and Zwahlen 1997).

The current methods used for groundwater vulnerability assessment are most often based on overlay and index techniques. The combination of maps with spatial distributions of specific attribute data (soil, geology, depth to water, etc.) are used to give for each attribute an assigned numerical index or score. They are combined to produce a vulnerability score. Attempts are made to obtain values as quantitative as possible.

2.2. Current trends in vulnerability assessment using overlay and index methods

Overlay and index methods, rely mainly on the quantitative or semi-quantitative compilation and interpretation of mapped data. Starting from the fundamental concept of vulnerability of the U.S. Committee on Techniques for Assessing Ground Water Vulnerability (National Research Council 1993) and from the definitions of the International Association of Hydrogeologists (Vrba and Zaporozec 1994), some general characteristics of these methods must be emphasised:

- Groundwater vulnerability is a relative, non-measurable, dimensionless property.

- The main attributes used for intrinsic vulnerability assessment are recharge value, soil properties and characteristics of unsaturated and saturated zones. Attributes of secondary importance include topography, groundwater/surface water relation, and the nature of the underlying unit of the aquifer.

- Specific vulnerability is mostly assessed in terms of danger for the groundwater system becoming exposed to specific contamination. The most important parameters in specific vulnerability assessment are: contaminant travel time within the unsaturated zone and its residence time inside the aquifer medium, attenuation capability of the soil-rock-groundwater system with respect to the properties of individual contaminants.

- The assessment of groundwater vulnerability is site or area specific.

A summary of some significant methods used for groundwater intrinsic vulnerability assessment can be found in ***Table 2.1.*** The existing methods can be grouped into two basic categories: Hydrogeological Complex and Settings methods and Parametric System Methods.

Hydrogeological Complex and Settings methods (HCS)

This kind of methods implies a qualitative assessment. First, one must decide the hydrogeological, hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Then the entire area is analysed and divided following the criteria established (Albinet and Margat 1970). Generally, a map overlay procedure is used. Large areas with various hydrographical and morphostructural features are best suited for assessment through these methods and thematic maps are produced from medium to large scale.

Parametric System methods

These are the Matrix Systems (MS) and Rating Systems (RS) methods and the Point Count System Models (PCSM) for the groundwater vulnerability assessment. For all parametric system methods the procedure is almost the same. The system definition depends on the selection of those parameters considered to be representative for groundwater vulnerability assessment. Each parameter has a defined natural range divided into discrete hierarchical intervals. To all intervals are assigned specific values reflecting the relative degree of sensitivity to contamination.

Matrix Systems (MS) methods are based on a restricted number of carefully chosen parameters. To obtain a quantified degree of vulnerability, these parameters are combined following a number of strategies developed by different research groups. These research applications are site specific methods developed for local case studies, such as the method selected for the Flemish Region of Belgium (Goossens and Van Damme 1987) and the system used by Severn-Trent Water Authority in some areas of Central England - (Carter et al. 1987).

Rating Systems (RS) methods provide a fixed range of values for any parameter considered to be necessary and adequate to assess the vulnerability. This range is properly and subjectively, divided according to the range of each parameter. The sum of rating points gives the required evaluation for any point or area. The final numerical score is divided into intervals expressing a relative vulnerability degree. The rating systems are based upon the assumption of a generic contaminant. Examples are GOD system (Foster 1987), AVI Method (Van Stempvoort et al. 1993), and the ISIS method (Civita and De Regibus 1995).

Table 2.1 - Main methods for the assessment of groundwater intrinsic vulnerability (*)

METHOD Reference	TYPE	**BASIC PARAMETERS**			**CHARACTERISTICS OF SOILS**													**Observations**
		PRECIPITATION RATE & CHEMICAL COMPOSITION	TOPOGRAFIC SURFACE SLOPE VARIABILITY	STREAM FLOW NETWORK DENSITY	THICKNESS, TEXTURE& MINERALOGY	EFFECTIVE MOISTURE	PERMEABILITY	PSHYCAL & CHEMICAL PROPRETIES	AQUIFER CONNECT TO SURFACE WATER	NET RECHARGE	CHARACT OF THE UNSATURATED ZONE	DEPTH TO WATER	WATER LEVEL CHANGES	HYDROGEOLOGICAL FEATURES	AQUIFER HYDRAULIC CONDUCTIVITY	THICKNESS OF THE AQUIFER	LAND-USE TYPE (**)	
Albinet & Margat (1970) B.R.G.M. (1976)	HCS								•		•	•		•	•			
Vrana (1968) Olmer & Rezac (1974)	HCS										•			•				
Fenge (1976)	RS				•					•	•	•	•	•	•			
Josopait & Schverdtfeger ('79)	HCS									•	•	•		•	•			
Zampetti (1983) Fried (1987)	AR										•	•						
Villumsen et al (1983)	RS				•						•	•	•	•	•			
Haertle (1983)	MS										•	•						
Vrana (1984)	HCS	•			•						•			•				
Subirana Asturias & Casas Ponsanti (1984)	HCS								•		•	•		•	•			
Engelen (1985)	MS								•		•	•		•				
Zaporozec (1985)	RS				•	•	•	•			•	•		•				
Breeuwsma et al (1986)	HCS				•	•	•	•	•	•	•	•			•			
Sotornicova & Vrba (1987)	RS						•					•	•	•				
Ostry et al (1987)	HCS				•			•				•		•				
Ministry Flemish Comm. ('86) Goossens &Van Damme ('87)	MS				•			•				•		•				
Carter et al (1987) Palmer (1988)	MS				•		•	•						•				
Marcolongo & Pretto (1987) Method 1	RS				•				•	•	•							
Marcolongo & Pretto (1987) Method 2	AR					•				•	•	•						
GOD - Foster (1987)	RS										•	•		•				
Schmidt (1987)	RS				•				•		•	•						
Trojan & Perry (1988)	PCSM	•	•				•			•	•	•		•				
Civita et al ('88)	HCS								•		•	•		•	•			
DRASTIC-Aller et al ('87)	PCSM		•		•					•	•	•		•	•			
SEEPAGE - Moore J.S. ('88)	RS		•		•	•	•	•			•	•		•				
SINTACS - Civita (1994)	PCSM		•	•	•				•	•	•	•		•	•		•	
AVI -Van Stempvoort et al (1993)	RS				•		•				•	•						
ISIS (Civita and De Regibus 1995)	PCSM		•		•			•		•	•	•		•		•	•	
German method (von Hoyer and Söfner 1998)	PCSM				•	•		•		•	•	•		•				
EPIK (Doerfliger 1996)	PCSM		•		•				•		•			•			•	Specific to karst aquifers
Hungarian system approach Madl-Szonyi and Fule (1998)	MS							•				•		•	•			Specific to karst aquifers
Irish approach (Daly and Drew 1999)	MS				•				•		•							Specific to karst aquifers
REKS (Malík and Švasta 1998)	RS		•		•			•	•	•	•			•	•			Specific to karst aquifers

Observations: * Readapted and updated from Gogu and Dassargues (2000 a), Vrba and Zaporozec (1994).
** The land use parameter characterise the human activity impact as effect on the runoff coefficients and not as the nature of contaminants

Explanation: **AR** - analogical relations
HCS - hydrogeological complex and settings methods
MS - matrix system methods
RS - rating systems methods
PCSM - point count system model (rating and weighting system)

Point Count System Models (PCSM) or Parameter Weighting and Rating Methods are also a rating parameters system. Additionally, a multiplier identified as a weight is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are added to obtain a final score.

This score provides a relative measure of vulnerability degree of one area compared to other areas and the higher the score, the greater the sensitivity of the area. One of the most difficult aspects of these methods with chosen weighting factors and rating parameters remains distinguishing different classes of vulnerability (high, moderate, low etc.), on basis of the final numerical score. Examples are the DRASTIC method developed by U.S. EPA in 1985 (Aller et al. 1987), SINTACS method (Civita 1994), and the EPIK method used in karst groundwater protection strategy developed by Doerfliger and Zwahlen (1997).

2.3. Principal methods used in groundwater vulnerability assessment

As it can be seen in ***Table 2.1.*** there are many vulnerability methods developed for various hydrogeological settings and conditions. In different countries or regions, specialists have developed their own methodology or applied some imported ones to investigate vulnerability of groundwater. It is of course impossible to say that one method can be better than another one. However there are methods that are more suitable than others for specific hydrogeological conditions and particular objectives. A good example of specific conditions is given by the karstic aquifers. They are characterised by highly heterogeneous structure, ranging from hydraulic conduits where the term hydraulic conductivity is meaningless, to fissures and fractures more or less interconnected. Assessing vulnerability for this kind of aquifers is a complex process. However the necessity to establish and develop methods for assessing vulnerability with a special attention to karst aquifers is obvious because of the rapid and concentrated infiltration that occurs in such systems. Also, the limited filtering and purification of contaminants provided by karst is another important reason for analysing their vulnerability. In karstic aquifers the extension of the "classical" porous media approach, based on the Representative Elementary Volume (REV) concept (Dassargues 1995) and used mainly in defining sources protection zones, is difficult. For all these reasons many aquifer vulnerability assessment methods developed world wide, deal mainly with karst groundwater bodies. In fact the vulnerability of karst aquifer systems has been taken into account by regions where these systems show a significant extension. Some of them give an important consideration to the karst groundwater systems in their methods for assessing vulnerability. Others use less specific methods for these systems or apply only matrices of measures and rules for preservation and protection. In Switzerland and Ireland, where carbonate aquifers represent a considerable percentage of the groundwater reserves, vulnerability assessment methods were developed that analyse the particular aspects of the karst.

2.3.1. Review of accepted vulnerability assessment methods

A general trend in developing aquifer vulnerability methods can be observed in the last years. This follows the need of new and good tools for groundwater resource protection. With a large variety of groundwater vulnerability assessment methods using different parameters (***Table 2.1.***), the choice for one or another is difficult.

The following review identifies some important methods and outline their specific features in order to indicate the theoretical base for the studies presented latter in this paper. Because of the karstic aquifers specificity, some of the vulnerability methods were developed to be applied strictly to these aquifers. In consequence, these methods are considered separately in the next paragraph.

GOD rating system

This method (Foster 1987) has a simple and pragmatic structure. It is an empirical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are considered: the Groundwater occurrence, Overlying lithology, and the Depth to groundwater (in unconfined or confined conditions). The vulnerability index (***Figure 2.1.***) is the result of the values assigned to these three parameters.

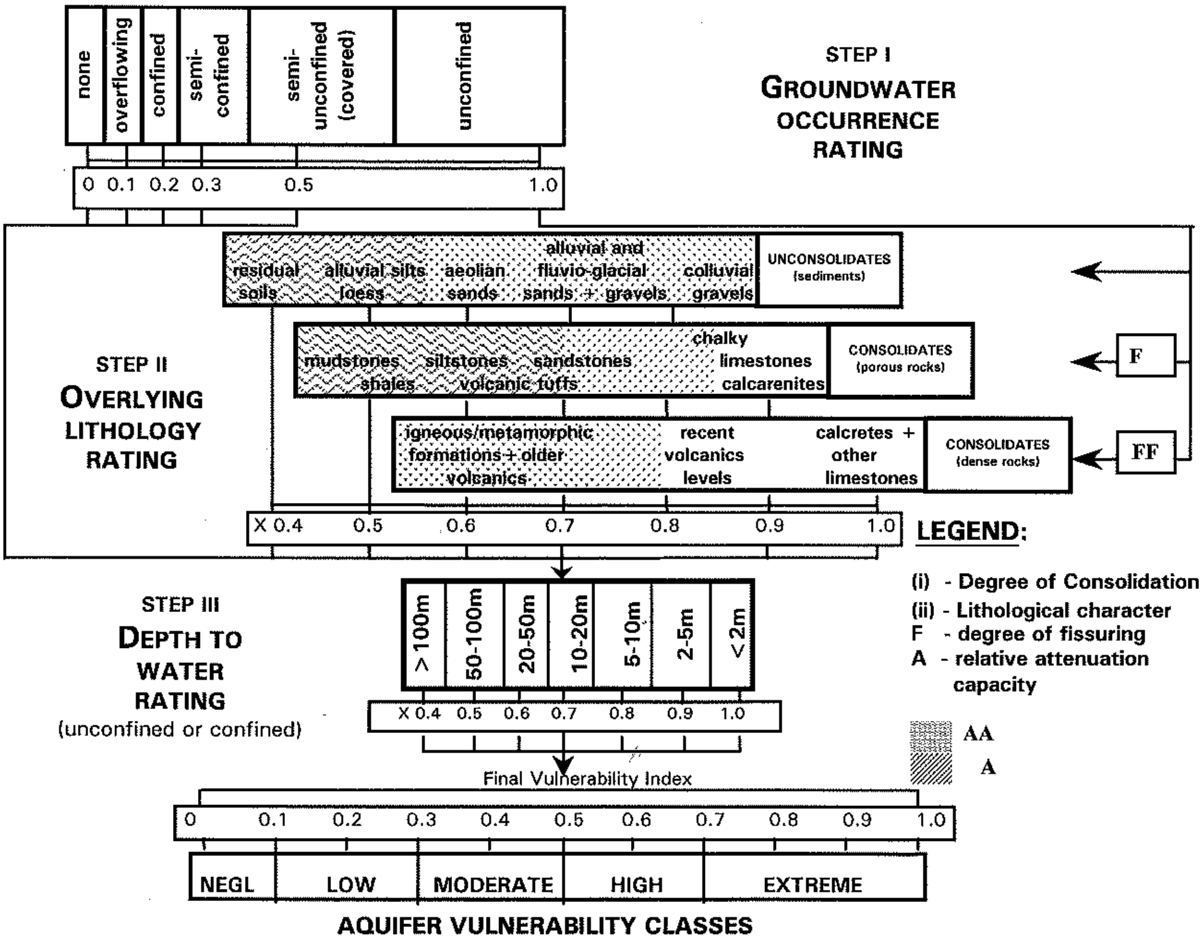


Figure 2.1 - The GOD parameters rating method, from Foster (1987)

Following the GOD flowchart, the area vulnerability index is computed by choosing first the rating of Groundwater Occurrence parameter and then multiplying by the Overlying Lithology rating as well as with the Depth to Water parameter rating. The Overlying Lithology parameter is giving its contribution to the vulnerability index only in the case of unconfined aquifers.

Because the parameters can take values only from 0 to 1, the computation result is usually a value less than the score assigned to each parameter. In the particular case where two parameters have a value equal to 1, the vulnerability score is equal to the score of the third parameter.

DRASTIC point count system model

The U.S. Environmental Protection Agency (EPA) developed DRASTIC (Aller et al. 1987) as a method for assessing groundwater pollution potential. This method considers the following seven parameters: Depth to water, Net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic Conductivity. Each mapped factor is classified either into ranges (for continuous variables) or into significant media types (for thematic data) which have an impact on pollution potential. The typical rating range is from 1 to 10. Weight factors are used for each parameter to balance and enhance their importance. The final vulnerability index (D_i) is a weighted sum of the seven parameters and can be computed using the formula:

$$D_i = \sum_{j=1}^{7} (W_j \times R_j) \qquad (2.1.)$$

D_i = DRASTIC Index for a mapping unit
W_j = Weight factor for parameter j
R_j = Rating for parameter j

DRASTIC provides two weight classifications (***Table 2.2.***), one for normal conditions and the other one for conditions with intense agricultural activity. This last one, called Pesticide DRASTIC index, represent a specific vulnerability assessment approach. In a specific area only one weight classification should be selected for the whole area.

Once DRASTIC indices have been computed, it is possible to identify areas that are more susceptible to groundwater contamination than others. The higher the DRASTIC index the greater the groundwater contamination potential. The DRASTIC index provides only a relative evaluation tool and is not designed to provide absolute answers. Moreover, the values generated by DRASTIC index and Pesticide DRASTIC index are not similar.

To facilitate interpretation, some users have tried to divide the final index into vulnerability classes (Atkinson and Thomlinson 1994, Civita and De Regibus 1995, Corniello et al. 1997, Navulur and Engel 1997).

Table 2.2. - Weight factors for DRASTIC and Pesticide DRASTIC

Parameter	DRASTIC Weight	Pesticide DRASTIC Weight
Depth to Ground Water	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of Vadose Zone	5	4
Hydraulic Conductivity	3	2

SEEPAGE method

The System for Early Evaluation of Pollution potential of Agricultural Groundwater Environments (SEEPAGE) considers various hydrogeologic settings and soil physical properties that affect groundwater vulnerability to pollution potential (Navulur and Engel 1997). It is also a numerical ranking model analysing contamination potential from both concentrated and dispersed sources. The SEEPAGE model considers the following parameters: soil slope, depth to water table, vadose zone material, aquifer material, soil depth, and attenuation potential. Attenuation potential takes into account the texture of surface soils, texture of subsoil, surface layer pH, organic matter content of the surface, soil drainage class and soil permeability.

To each parameter a weight factor ranging from 1 to 50 is assigned, based on its relative significance. A weight factor of 50 is assigned to the most significant parameter affecting the water quality and a weight factor of 1 is assigned for the least significant. These weights are different for concentrated sources and dispersed ones. As with DRASTIC, each parameter can be divided into ranges, but the rate value assigned for each parameter vary from 1 to 50. The ratings of the aquifer media and vadose zone are subjective and can be changed for a particular region. Once the scores for the six parameters are obtained, these are summed to get the SEEPAGE Index Number (SIN). SIN numbers are ordered in four categories of pollution potential: low, moderate, high, and very high. A high or very high SIN category indicates that the site is highly vulnerable.

AVI rating system

This method (Van Stempvoort et al. 1993) estimates the Aquifer Vulnerability Index (AVI) using only two parameters: the thickness of each sedimentary unit above the uppermost aquifer (d); and the estimated hydraulic conductivity of each of these layers (k).

The hydraulic resistance is given by:

$$c = \sum_{i=1}^{n} d_i / k_i \qquad (2.2.)$$

c - the hydraulic resistance given by AVI rating system
n - the numbers of layers
k - estimated hydraulic conductivity of each of the n layers

The c or log(c) value is related to a qualitative Aquifer Vulnerability Index by a relationship table. The authors suggest to calculate c for each well or test hole and then to generate the iso-resistance contour to classify the study area in AVI zones.

SINTACS method

Derived from DRASTIC model, this method has been developed for vulnerability assessment and mapping requirements (medium and large-scale maps) by Italian hydrogeologists (Civita 1994). The SINTACS point count system has a complex structure (***Figure 2.2.***).

A number of weight strings are used in parallel, to define the existing conditions. These parameter values are then rated and divided into intervals. The final results outline six vulnerability classes.

In fact, SINTACS proposed by Civita (1994) uses the same seven parameters as DRASTIC but the rating and weighting procedure is more flexible. It provides four weight classifications but it also allows the creation of new ones. The user encodes the input data as functions of local conditions in each area, and has the possibility of using different classifications depending on circumstances.

SINTACS vulnerability index can be computed as follows:

$$I_v = \sum P_{(1,7)} \times W_{(1,n)} \qquad (2.3.)$$

I_v - vulnerability index by SINTACS method

$P_{(1,7)}$ - the rating of each of the seven parameters used

$W_{(1,n)}$ - the associated weight

n – the number of weight classification arrays

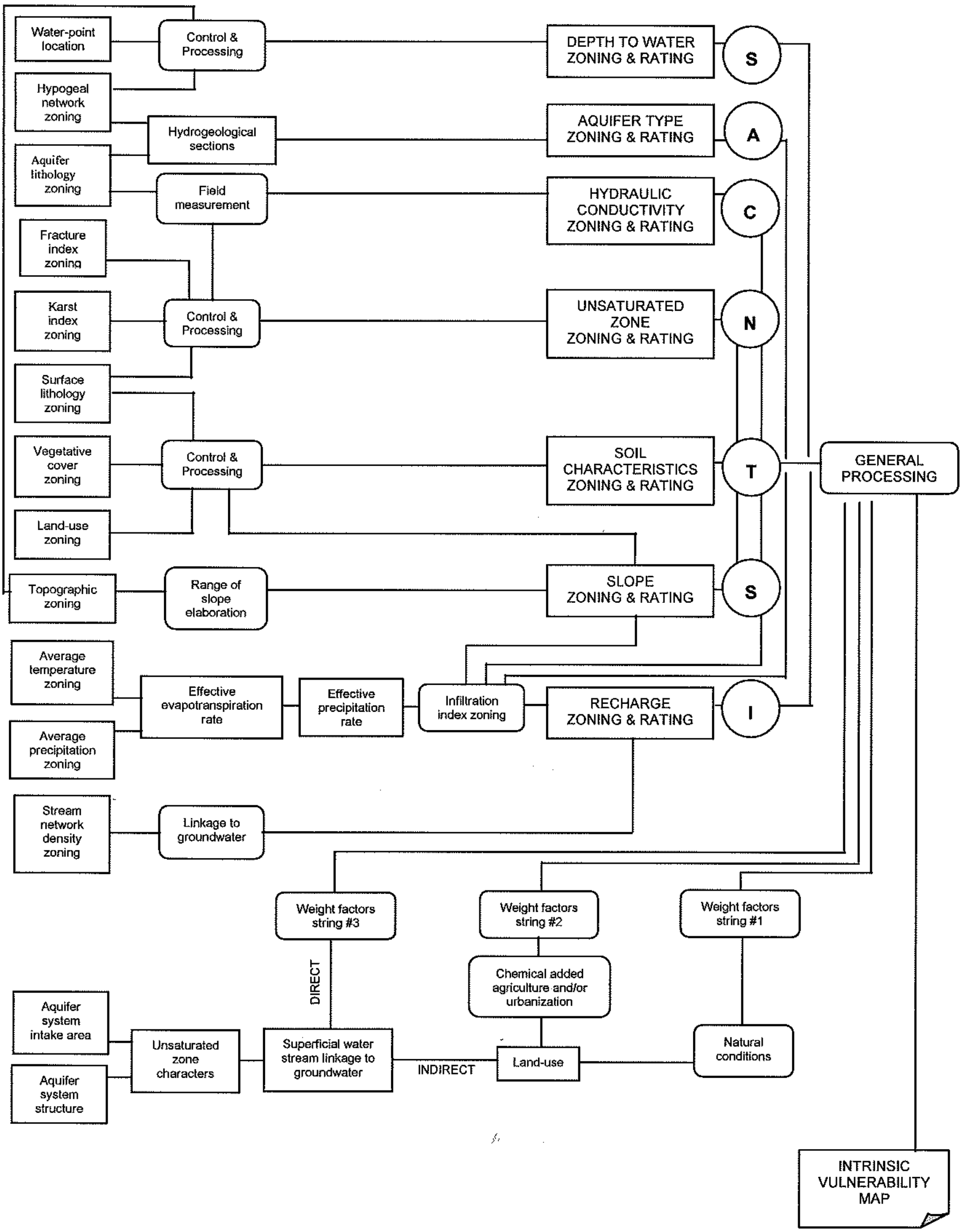


Figure 2.2 - SINTACS method recipe, adapted from Vrba and Zaporozec (1994)

ISIS method

This method is a synthesis of various studies on aquifers intrinsic vulnerability assessment (Civita and De Regibus 1995) and can be classed with the Point Count System Model group of methods. ISIS is a hybrid method, based on the comparative evaluation of the existing hydrogeological situations. It has been developed taking into account the rating and weighting systems of DRASTIC and SINTACS methods and the GOD method for the general structure design. Parameters used by ISIS method are: the annual mean of the net recharge (it's possible to introduce the rainfall value and the mean annual temperature or other related parameters), topography, soil type, soil thickness, lithology of the unsaturated zone, thickness of the unsaturated zone, aquifer media, and aquifer thickness.

The land use parameter, as the human activity impact feature, has been adopted from the SINTACS methodology and quantified. It has been divided in three areal units: areas with normal conditions, strong contaminated agricultural area, strong superficial drained area. This parameter is used as a weighting element for modulating the relative importance of the direct used parameters, as a function of the different land use conditions.

To estimate the vulnerability index I_v, ISIS method is using the following formula:

$$I_v = p_{Inf} \cdot f_{Inf} + p_{Su} \cdot f_{Sus} \cdot f_{Su} + p_{Ins} \cdot f_{Si} \cdot f_{Ins} + p_{Sat} \cdot f_{Ss} \cdot f_{Sat} \qquad (2.4.)$$

where:

p_{Inf} - the rating values for ranges on the net recharge;

f_{Inf} - infiltration coefficient dependent on land use;

p_{Su} - the rating values for the soil media;

f_{Sus} - soil coefficient dependent on land use;

f_{Su} - weighting coefficient dependent on soil thickness;

p_{Ins} - the rating values assigned to the vadose zone;

f_{Si} - weighting coefficient dependent on the unsaturated zone lithology and thickness;

f_{Ins} - vadose zone coefficient dependent on land use;

p_{Sat} - the rating values assigned to aquifer media;

f_{Ss}- weighting coefficient dependent on the aquifer thickness;

f_{Sat} - aquifer coefficient dependent on land use.

The final vulnerability index, varying between 24 and 180 is divided in 6 vulnerability classes: Extreme (141 - 180); Very High (124 - 140); High (88 - 123); Medium (64 - 87); Low (44 - 63); Very Low (24 - 43).

The German concept

The German method (von Hoyer and Söfner 1998) is applied for determination of the "protective effectiveness" of the cover above the uppermost aquifer as "protective barrier against groundwater pollution".

The method assess the "protective effectiveness" that is in fact the inverse of vulnerability, as being mainly dependent on the residence time of percolating water in the rock and soil cover. The residence time, as mentioned in the method, is determined from the thickness of the rock and soil cover, the permeability of the rock (lithology) and soil cover (pedological constitution), and the percolation rate.

When assessing the protective effectiveness of the cover above groundwater, the German concept considers separately the soil and the rock together with the superficial deposits below the soil. Both zones are linked by the amount of water which passes the lower boundary of the rooting zone. Due to their fundamentally different hydrogeological properties unconsolidated sediments and solid rocks are assessed on the basis of different criteria.

The main parameters used by this method are: soil (S), percolation rate (W), rock cover below soil (R_u and R_s), thickness of the soil and rock cover above the aquifer (T), the presence of a perched aquifer (Q) as well as the existence of unconfined/confined conditions (HP).

The soil parameter is assessed using the "effective field capacity" that is taken as a measure of the capacity of a soil to store plant available water. The effective field capacity is determined for each individual soil horizon. In Germany its value can generally be found in the pedological mapping handbook. The value of the effective field capacity is then multiplied by the thickness of the soil horizon in decimeters and the results are translated in points. The percolation rate is defined as the amount of water infiltrating the ground per unit time. It is affecting the movement and thus the residence time of the percolating water. R_u and R_s are two factors representing respectively the lithology of the unconsolidated and consolidated rocks. They are translated into points.

For solid rocks, R_s is determined (***Table 2.3***) as a product of the lithology rating and a parameter called "Structure" reflecting the degree of fracturation or kartification.

Table 2.3 - Assessment of consolidated rocks factor R_s = O×F, in the German method (von Hoyer and Söfner 1998)

Rock type	O	Structure	F
claystone, shale, marlstone, siltstone	20	non-jointed slightly jointed	25.0 4.0
sandstone, quartzite, volcanic rock, plutonic rock, metamorphic rock	15	moderately jointed, slightly karstic moderately karstic	1.0 0.5
porous sandstone, porous volcanic rock (e.g. tuff)	10	strongly jointed, fractured or strongly karstic	0.3
conglomerate, breccia, limestone, tufaceous limestone, dolomitic rock, gypsum rock	5	not known	1.0

For determining the overall "protective effectiveness" (P_t) of the soil and rock cover above the topmost aquifer, the protective efficiency of the soil (P_1) and then the protective efficiency of the rock cover (P_2) are calculated as following:

$$P_1 = S \cdot W \tag{2.5.}$$

$$P_2 = W(R_1 \cdot T_1 + R_2 \cdot T_2 + \dots\dots\dots + R_n \cdot T_n) + Q + HP \tag{2.6.}$$

$$P_t = P_1 + P_2 \tag{2.7.}$$

Based on the P_t index, five classes of "protective effectiveness" are distinguished: very high, high, moderate, low, and very low.

2.3.2. Vulnerability assessment methods developed with specific attention to karst (carbonate) aquifers

EPIK method

The EPIK method represents a classic Parameter Weighting and Rating Method 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 diagrammed in ***Figure 2.3.*** In the EPIK method, four parameters are considered: Epikarst (E), Protective cover (P), Infiltration conditions (I), and Karst-network development (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).

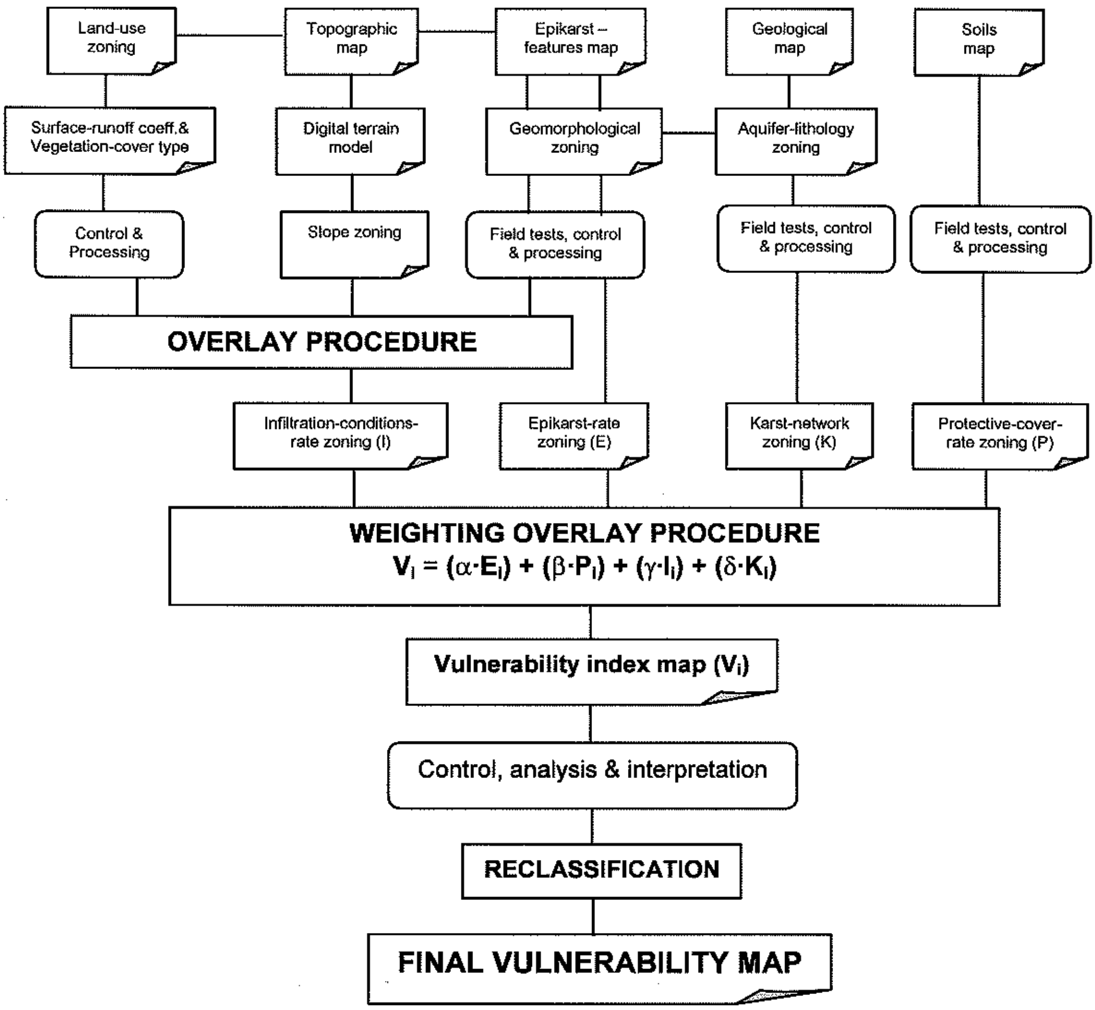


Figure 2.3 - Procedure for applying the EPIK method (Gogu and Dassargues 2000 b)

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 to the karstic network (drained dolines, caves, etc.); E2, for epikarst associated with 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, rocks 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, δ; see ***Figure 2.3.***) 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:

$$V_i = (\alpha \cdot E_i) + (\beta \cdot P_i) + (\gamma \cdot I_i) + (\delta \cdot K_i) \quad (2.8.)$$

where:

V_i = vulnerability index in subarea i (pixel or polygon)

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

Doerfliger and Zwahlen (1997) use the rating values shown in ***Table 2.4.*** 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 kind of karstic systems.

Table 2.4. - Rating values for E, P, I, and K parameters – EPIK method

E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Note: the lower the rating value, the higher the vulnerability

REKS method

Derived from EPIK, this method was developed by Slovakian hydrogeologists (Malík and Švasta 1998) for assessing vulnerability of karstic aquifers. It has been applied for the first time in Muranka Planina Plateau, in Brezovke Karpaty mountains. The site is a karst plateau of 126 km^2, built of Triassic limestones and dolomites.

The parameter I (Infiltration conditions) from EPIK, is replaced by the Rocks parameter (R). This Rocks parameter is represented by a layer that describes the geological situation and its influence on hydrogeology. It represents the characteristics of different lithological types of the unsaturated zone and the link between groundwater and surface water. This parameter depicts in a simplified way, how the various rock types enable feeding of the aquifer from surface water. The authors consider this parameter necessary because of the dominant geological conditions in West Carpathians (scattered karstic hydrogeological structures formed by various nappe units and isolated by non-karstic rock types). Malík and Švasta (1998) are using this R parameter to solve two aspects:

- to depict point infiltration conditions represented by swallowholes or linear feeding of karstic structures by stream losses

- to quantify the unsaturated zone media lithology

For the first aspect the Rocks (R) parameter is divided in three categories depending on point and linear infiltration conditions. In first the category enter buffers areas of 100 m upstream the swallowholes. The watershed areas upstream the swallowholes but outside the 100 m buffer area, represent the second category. In the third category enter the areas corresponding to karst linear feeding by stream discharge (through river bed sediments).

The rating is done as follows:

- buffer areas of 100 m upstream a swallowhole are given a rate value of 15 points

- watershed areas upstream a swallowhole and outside the above mentioned 100 m buffer area are given values of 10 points

- watershed areas upstream the linear sinks have values of 5 points

The quantification of the unsaturated zone lithology was done for a pilot area in Brezovské Karpaty mountains (Malík and Švasta 1998) as following:

- loess sediments, clays, marls, cherts, marly limestones - 1 point

- loess sediments, clays, marls, cherts, marly limestones - 2 points

- dolomites, non-karstified limestones - 3 points

- karstified limestones, karstified gypsum - 4 points

As the method is a rating system, the parameter R is calculated by simple summation between the two rating arrays corresponding to lithology and to water infiltration conditions.

Parameter Epikarst (E) is very similar to Epikarst of the EPIK method. The difference is the use of different rating values. The quantification of the Karst network development (K) parameter is done using the discharge analyses of recession curves or the ratio between the maximum and minimum measured flow rates of springs. The K parameter takes values from one to five. Using a complex procedure, the Soil cover parameter (S) is rated based on two groups of characteristics. The first group associates the texture of the soil and the organic content. The second associates the terrain slope and the tangential curvature. The two results are then correlated and quantified with values from one to five.

This complicated method is not yet very stable. It was tested only in a few sites in the Slovakian mountains. Improvements in parameter quantification are necessary. Initially, the method was designed as a rating system but the authors want now to transform this method in a Point Count System model, by applying weighting factors between parameters.

The Irish approach for vulnerability assessment

Based on the specific features of Irish aquifers, the Irish approach represents a particular matrix system method. In the Irish concept (Daly and Drew 1999), aquifer vulnerability assessment represents the first step in the groundwater protection procedure.

The groundwater protection zones (***Figure 2.4.***) are divided in groundwater resources protection areas and sources protection zones. The groundwater resources protection areas are represented on the groundwater resources protection map. This map is obtained by combining the vulnerability map and the aquifer map. The aquifer map is obtained by a delimitation of aquifers, according to their value as resource, for any region outside the source protection zones. In other words, the aquifers are represented on the aquifer map function of their value as resource.

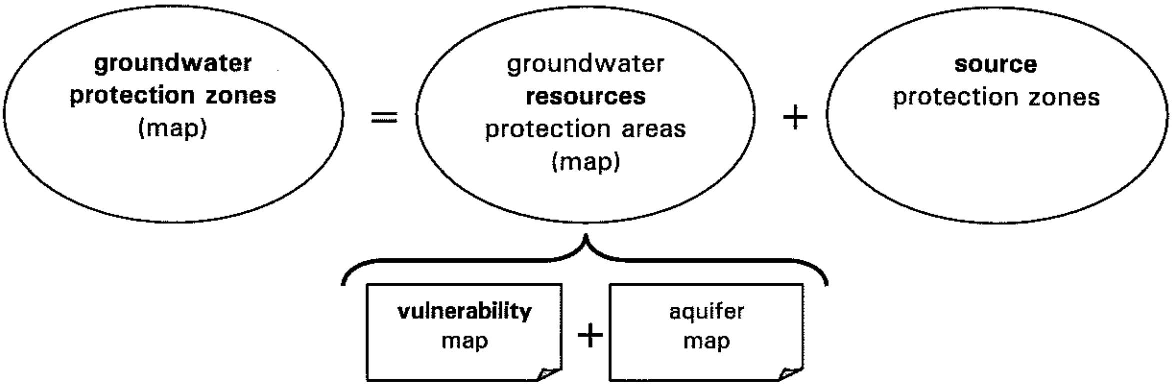


Figure 2.4 - The Irish concept on the groundwater protection

In order to obtain the aquifer map, the resource protection areas are classified on the basis of the value of the resource and the hydrogeological characteristics (permeability, areal extent, and storage capacity) in:

Regionally important aquifers (R) :

- Karstified aquifers (Rk)
- Fissured bedrock aquifers (Rf)
- Extensive sand/gravel (Rg)

Locally important aquifers (L) :

- Sand/gravel (Lg)
- Bedrock which is generally moderately productive (Lm)
- Bedrock which is moderately productive only in local zones(Ll)

Poor aquifers (P) :

- Bedrock which is generally unproductive except for local zones(Pl)
- Bedrock which is generally unproductive (Pu)

The result of integrating the source protection zones and the resource protection areas with the vulnerability rating is given in ***Table 2.5.*** The source protection zones are delineated around each public supply well or spring in an Inner Protection Area (SI) and an Outer Protection Area (SO). The Inner Protection Area is defined by a 100-day travel time within the aquifer from any point below the water table to the source. The Outer Protection Area encompasses the source catchment area or zone of contribution.

Table 2.5. - Matrix of groundwater protection zones – Irish approach (Daly and Drew 1999).

Vulnerability Rating	SOURCE PROTECTION		RESSOURCE PROTECTION						
			Regionally Important		Locally Important		Poor Aquifers		
	Inner	*Outer*	Rk	Rf/Rg	Lm/Lg	Ll	Pl	Pu	
Extreme (E)	Sl/E	SO/E	Rk/E	Rf/E	Lm/E	Ll/E	Pl/E	Pu/E	↓
High (H)	Sl/H	SO/H	Rk/H	Rf/H	Lm/H	Ll/H	Pl/H	Pu/H	↓
Moderate (M)	Sl/M	SO/M	Rk/M	Rf/M	Lm/M	Ll/M	Pl/M	Pu/M	↓
Low (L)	Sl/L	SO/L	Rk/L	Rf/L	Lm/L	Ll/L	Pl/L	Pu/L	↓
	→	→	→	→	→	→	→	→	

Obs. Arrows indicate directions of decreasing risk

In ***Table 2.5.*** it can be observed that the nature of the karst system in this assessment method is included as two-way distinction: Rk = karstic and Rf = fissured - intergranular. In addition to Rk and Rf division a further distinction is made :

- Rk^c = a degree of karstification which inhibits the development of groundwater (large conduits, variable spring flows, unpredictable well yields)

- Rk^d = exploitable karst water (some conduits but more diffuse, more storage more predictable, more consistent spring flows)

This last distinction (Rk^c, Rk^d) is only made on the aquifer maps. On the groundwater protection maps only Rf and Rk are present because is has been considered that the difference between Rk^c and Rk^d aquifers would not affect the groundwater protection responses.

There are some essential factors that are taken into account in the vulnerability assessment process in Ireland. First of all the target is represented by the first groundwater in bedrock and sand/gravel aquifers. The term "bedrock" is considered in the Irish method, as any solid rock exposed at the surface of the earth or overlain by unconsolidated material. The bedrock is not considered to be a significant factor in attenuating pollutants. In consequence an unsaturated zone in bedrock is not taken into account and the reference location in defining vulnerability is the top of the bedrock (and the water table in case of unconfined sand/gravel aquifers). The release point of contaminants into the geological environment is considered to be 1-2 m below ground level and vulnerability is assessed on the basis of the vertical transport of contaminants to the top of the bedrock.

As can it be seen in ***Table 2.6.***, in assessing vulnerability of aquifers the used parameters are the subsoil thickness and permeability and the recharge type (diffuse or point). The karstic features are represented through the recharge type. So, groundwater is classified as extremely vulnerable within 30 m of karstic features (swallowholes, sinking streams, collapse features) and within 10 m on either side of losing streams upflow the area of loss (Daly and Drew 1999).

Table 2.6. - Vulnerability mapping guidelines – Irish approach (Daly and Drew 1999)

Vulnerability Rating	**Hydrogeological Requirements**				
	Subsoil Permeability (Type) and Thickness			**Unsaturated Zone**	**Recharge Type/ karst feature**
	high permeability (sand/gravel)	**moderate permeability** (e.g.: sandy till)	**low permeability** (e.g.: clayey till, clay, peat)	(sand/gravel aquifers only)	
Extreme (E)	0 - 3.0 m	0 - 3.0 m	0 - 3.0 m	0 - 3.0 m	point (< 30m radius)
High (H)	> 3.0 m	3.0 - 10.0 m	3.0 - 5.0 m	> 3.0 m	diffuse
Moderate (M)	N/A	> 10.0 m	5.0 - 10.0 m	N/A	diffuse
Low (L)	N/A	N/A	> 10.0 m	N/A	diffuse

Obs. N/A - not applicable

Hungarian "System approach" assessing method

The purpose of this method was to assess the vulnerability of a regional carbonate aquifer (Madl-Szolnyi and Fule, 1998) in the Keszthely Mountains, Hungary. The method consists in a classical matrix system, created for assessing this particular aquifer. This method regards the upper part of the saturated zone as the reference unit of the assessment. Vulnerability is assessed using three groups of factors:

-factors influencing the potential subsurface input of contaminants: topography, recharge conditions, interactions between surface and groundwater, karst cavities, and faults

- factors influencing the migration of contaminants between the ground surface and the water table: nature and thickness of the soil and of the unsaturated zone

- factors influencing the movement of contaminants in the saturated aquifer: groundwater flow direction, aquifer lithology, and transmissivity

In the matrix of vulnerability assessment, three parameters representing the three groups of factors are utilised. The first group is called by the authors (Madl-Szolnyi and Fule, 1998) "Hydrodynamics and covering". It is made of four sub-parameter maps: Aquifer type (confined/unconfined), soil type, infiltration conditions, and unsaturated zone media. Function of soil physical and chemical properties, in the soil sub-parameter map are delineated five areas: negligible, poor, medium, good, and excellent. In the conditions of infiltration map the linear infiltration, point-source infiltration, as well as areas of intense recharge are distinguished. In the map of the unsaturated zone area, Madl-Szolnyi and Fule (1998) delineated four area types: "karstic outcrops without any covering layer", "aquicludes/aquitards", areas of "karstic outcrops with thin covering", and areas with a "slow downwards migration" (covered water table karst). The four maps are combined and the "Hydrodynamics and covering" parameter map is obtained. It assigns values of I for the most vulnerable conditions, II, III, and IV for the least vulnerable.

The second parameter, transmissivity of the aquifer, is divided in five classes taking rating values from A (the most vulnerable) to E (the least vulnerable). This parameter takes value of A for transmisivities greater than 2000 m^2/day and E for values less than 10 m^2/day. The third parameter is thickness of unsaturated zone. It is rated from 1 (the most vulnerable) to 6 (the least vulnerable). Between 0 and 50 m, the thickness of the unsaturated zone is rated 1 and when it is rated 6 when the thickness is greater than 250 m.

Combining the three maps of parameters using the matrix system (Madl-Szolnyi and Fule, 1998), produces the final vulnerability map showing areas rated from 1 to 14.

2.4. Groundwater vulnerability and GIS

2.4.1. Basic concepts of GIS

A GIS can be defined (Goodchild 1996) as a system for input, storage, manipulation, and output of geographically referenced data. GIS provides a means of representing the real world through integrated layers of constituent spatial information (Corwin 1996). Geographic information can be represented in GIS as objects or fields. The object approach represents the real world through simple objects such as point, lines, and areas. The objects, representing entities, are characterised by geometry, topology, and non-spatial attribute values (Heuvelink 1998).

In hydrogeology some examples of spatial objects are wells, piezometers, boreholes, galleries, and zones of protection. Attribute values of objects could be the number of a well, the ownership, the diameter of a gallery or drain. The field approach represents the real world as fields of attribute data without defining objects, some examples being strata elevation, piezometry head and vulnerability zones. This approach provides attribute values in any locations. In GIS this distinction between objects and fields is often associated with vector data models and raster data models. The vector model represents spatial phenomena through differences in the distribution of properties of points, lines and areas. In this system each layer is an adapted combination of one or more classes of geometrical features. A raster model consists of a rectangular array of cells with values being assigned to each cell. In the raster model, each cell is usually restricted to a single value. In consequence, representing the spatial distribution of a number of parameters or variables requires multiple layers.

In their work environmental specialists need to have available clear representations of the spatial variation of the data. In GIS, there are two ways to solve this problem: field variables ("a variable can be given a single, well defined value at every location") and kernel functions (spatially continuous functions).

For digital representation of the spatial variation characterised by fields, six methods could be distinguished: raster model, grid model (rectangular array of sample points), point model (area irregular distributed sample points), contour model (isolines), polygon model (polygons holding average attribute values), and TIN (triangular irregular network).

Storing and manipulating data through spatial relationships could be done with the GIS packages using the "Georelational" model or the "Geodata base" model. The first consists of linking a relational database to geometrical features. The modelled entities are organised into categories sharing common characteristics (points representing wells, piezometers, or gallery wells). A table represents each category. The different attributes can be found as columns of the table, the rows assuring the data registration. Relationships "one to one" or "one to many" can be established between tables. In the second model, entities are represented as objects with properties, behaviour, and relationships. A real distinction between the two models cannot be done, however the second represent a recent improvement of the first one.

2.4.2. The role of GIS in aquifer vulnerability assessment

The groundwater vulnerability assessment cannot be anymore performed without GIS, because of the large data volumes required by a reliable analysis. GIS technology support aquifer vulnerability assessment in the analysis of spatial and physical relationships of critical environmental elements. It represents a useful tool for creating vulnerability maps and for quick and simple display.

Usually, the vulnerability methods are using only the basic GIS tools. Functions as map overlay, reclassification, and query assist the principal operations of the vulnerability assessment methods. This technology is particularly useful to overlay and index techniques.

The aquifer vulnerability assessment analyses can be rigorously performed using a GIS based database. The operation of parameter quantification can be done easily using various spatial queries. Generating automatically the piezometric heads contour maps and evaluating the error by performing spatial statistics on the piezometric head data (numbers of measures, mean value, standard deviation, etc), leads to reliable assumptions on the depth to groundwater parameter.

For the parameters describing the soil and the geology, comfortable rating procedures can be made using respectively the map of soil and the geological map. The spatial visualisation of the hydrogeological parameters related to the geomorphological features, assist in a better quantification of the aquifer vulnerability parameters. For example for karst aquifers a good assessment of the unsaturated zone lithology or of the aquifer media parameters, can be obtained by overlaying the kastic features map on the following maps: geological map, depth to groundwater map, faults and fractures map, and hydrogeological parameters values (hydraulic conductivity, porosity, etc).

A simplified correlation between various hydrogeologic information with hydrologic data allows a refined assessment of the aquifers vulnerability. Analysing the relation between the river network and the aquifer using and overlaid spatial visualisation, can outline the preferential contamination pathways.

Most of the aquifer vulnerability methods use the topography in terms of slope. This can enter explicitly or within other parameters. A correct slope computing and reclassification can be done only by GIS. Further correlation with the geomorphological features or with the runoff coefficients (usually derived from the land-use map) in order to better quantify the recharge of the aquifer, can be completed accurately using the classical GIS functions.

2.4.3. GIS and hydrogeological data error

The hydrogeological data errors derive from measurements, interpretation or estimation, spatial or temporal analyses, and from mistakes in data entry. Into a GIS, the spatial data are entered often by digitizing a map. The map existing errors are multiplied by the transfer of the source map, to the digital database. Very important are the uncertainties contained by the source map (geology, map of soils, land-use, etc.) as well as those amplified by the GIS operations. The uncertainties related to the maps data representation are also significant. However they are not very suitable to represent the real world situation, for the spatial attributes representation are used polygons. In reality, the mapping units are not homogenous and the boundaries are often gradual. In addition, there are many other sources of errors on the paper maps related to the operations of reproduction, deformation, and generalisation. Data derived by interpolation from point observation contain other types of errors. These last derive from the measurement and interpolation procedures.

In consequence, there is a considerable need of uncertainty analysis developments (Heuvelink 1998) in Geographical Information System (GIS) related to the attribute and positional accuracy, lineage, logical consistency, completeness, and temporal accuracy. However GIS is largely used in the activity of groundwater vulnerability assessment, this paper is evaluating only the procedures and parameters used by the aquifer vulnerability assessment methods.

Vulnerability assessment maps have not conveyed the uncertainty arising from errors in data and assessment methods. With some improvements, GIS are useful in depicting uncertainty on the vulnerability maps. These improvements require the collection of better information on data quality, the development of methods to analyse the error propagation, and the design of techniques for visualising the net uncertainty of individual layers.

2.5. Uncertainty and recommendations in applying aquifer vulnerability assessments

Groundwater vulnerability predictions are made in a relative, not an absolute, sense. In many cases the vulnerability maps are created to obtain a quick assessment of pollution risk, however they could be used as a meaningful tool in the environmental decision-making process. Methods applied to obtain groundwater vulnerability maps have to portray a correct view of site vulnerability and subsequent site-specific investigations are essential in many situations.

In all methods for assessing groundwater vulnerability, uncertainty is inherent. The sources of uncertainty may be model related errors (from an inadequate or incomplete representation of the system and/or processes) as well as data related errors (input data).

Sources of errors in groundwater vulnerability assessment are multiple and the National Research Council (1993) classified them as follows:

A. Errors in obtaining data

1. Accuracy in locating sites
2. Sample collection and handling
3. Laboratory preparation and analysis
4. Interpretation

B. Errors due to natural spatial and temporal variability

1. Random sampling error
2. Bias
3. Regionalization, extrapolation, interpolation
4. Scale effects, changes in variance due to averanging
5. Interpretation

C. Errors in computerisation (digitising) and storage of data

1. Data entry
2. Data age
3. Changes in storage format
4. Errors in programs to access data
5. Use of surrogate data and procedures

6. Adjustment in scale

7. Determining boundaries

8. Changes in representation of data

9. Interpretation

D. Data processing errors

1. Numerical, truncation, and round-off errors

2. Discretization errors

3. Problems in solution convergence

4. Interpretation

E. Modelling and conceptual errors

1. Process representation and coupling

2. Parameter identification

3. Scale effects

4. Interpretation

F. Output and visualisation errors

1. Determination of boundaries

2. Classification into vulnerability categories

3. Interpretation

To limit errors the vulnerability assessment has to be tested and evaluated. The evaluation of a vulnerability assessment must address at least two questions: Can the vulnerability rating assigned to a given subarea considered valid or not ? Are the values assigned to the neighbouring subareas sufficiently different ?

Validation of the vulnerability map can be done only after analysing it's uncertainty. Ways to investigate this uncertainty consists in performing sensitivity analysis (Gogu and Dassargues 2000 b, Napolitano and Fabbri 1996) or comparing vulnerability maps obtained from several methods applied in the same area (Gogu et al. 1996, Corniello et al. 1997).

In the first approach the analysis allows to study the parameter balance in order to eventually reduce or increase the importance of a parameter in the next calculation of the vulnerability index. The second is a useful evaluation technique in order to choose a vulnerability assessment method for a given case study.

2.6. Comparison studies

One of the few comparison studies of vulnerability assessment methods was performed by an Italian research team in the "Piana Campana" region, Southern Italy (Corniello et al. 1997). To assess the vulnerability of the aquifer in this area, four methods were tested: DRASTIC, SINTACS, GOD, and the AVI model. For an operational comparison, specific aspects of vulnerability classes were considered.

Generally, it was shown that the SINTACS method produced "very high vulnerability zones" compared to the other methods in the areas concerned with surface waters and aquifer interactions. This result is strongly influenced by the aquifer identification and by different weight classification series used for the area affected by drainage. A similar result was obtained in a vulnerability assessment study made on the alluvial cone Prahova - Teleajen (Gogu et al. 1996), by applying the SINTACS method together with a matrix system method locally developed by a Romanian research team.

Using the DRASTIC model, the low vulnerability class was wider than within SINTACS. In areas where the degree of vulnerability has modest variations, the GOD method provided stable vulnerability classes. Even with fewer parameters, the vulnerability map generated through AVI method was similar to those obtained from DRASTIC and SINTACS models. Moreover, a statistical comparison of all vulnerability maps showed the greatest similarity between the DRASTIC and SINTACS methods as well as a good correlation between those two and the AVI method.

Civita and De Regibus (1995) performed another significant comparative study of six methods for groundwater vulnerability assessment. To cover different hydrogeologic situations, the study targeted three specific areas in Northern Italy, respectively flat, hilly and mountainous regions. The methods considered were DRASTIC, SINTACS, GOD, the Flemish Method (Goossens and Van Damme 1987), ISIS, and the CNR – GNDCI method based on direct confrontation with hydrogeological predefined situations (Civita 1990). Applying different methods to the same zone and using the same data showed that in contrasted hydrogeologic contexts, the relative simple methods could provide similar results to the complex ones. Having a good precision and flexibility, DRASTIC and SINTACS methods are much more effective in detailed studies. Other methods, such as the Flemish one, were evaluated as not able to be adapted to situations other than those they were designed for.

A sensitivity analysis to evaluate a single parameter influence on the aquifer vulnerability assessment was performed on the same "Piana Campana" region by Napolitano and Fabbri (1996).

Comparing SINTACS and DRASTIC methods, they observed that removing each of the seven parameters one by one, created relevant and significant changes in the vulnerability maps. They concluded that all the seven DRASTIC parameters are important in assessing aquifer vulnerability.

Comparing vulnerability methods using different parameters raises a lot of questions. However it represents the only way to compare their efficiency on a case study.

This can be done mainly by examining the resulted vulnerability maps obtained with each method. A confrontation between them as well as with the initial hydrogeological information is always very interesting. In general, a method providing more contrasted results for a specific area can be assumed to present a higher sensitivity and on thus basis results can be used and interpreted.

2.7. Future challenges in groundwater vulnerability assessment

Hydrogeologists are trying to agree on issues concerning intrinsic and specific vulnerability, on the different models and assessing methods, and on risk mapping and management aspects. Improvement of vulnerability assessment analysis (Gogu and Dassargues 2000 a) provides a number of research challenges:

- to determine circumstances in which properties of the intermediate vadose zone are critical to vulnerability assessment and to develop methods for characterising this zone with more accuracy. A better quantification of physical and chemical processes that are taking place in this zone as well as the relationship with geomorphology, topography, climate, land-cover, aquifer media and constraints will drive to better results of the assessment procedure;

- to develop methods for accounting preferential flow pathways (soil macropores, fissure network, etc.) that can influence severely the vulnerability;

- to gather more information on uncertainty associated with vulnerability assessments and to develop systematic ways to handle and display this aspect;

- to improve the hydrogeological and hydrochemical database structures, and to find ways of introducing them in vulnerability assessments (intrinsic and specific);

- to define more meaningful categories of vulnerability and determine which processes are most important to be incorporated into vulnerability assessment at different spatial scales. For instance, the UK National review on aquifer vulnerability defines the relative vulnerability of aquifers in terms of land zonation, based on the average time taken by infiltrating water to reach the aquifer. The accompanying maps, therefore, have classes of 1 week, 1 year, 20 years, greater than 20 years, plus three other categories ("multizone", "no information" and "no aquifers"). The "multizone" category was designed to overcome the limitation of detail at the used map scale (Robins et al. 1994);

- to create tools for merging data obtained at different spatial and temporal scales into a common scale for vulnerability assessment;

- to seek for useful comparative techniques and procedures to evaluate assessment methods and groundwater quality monitoring data;

- to improve analytical tools in GIS software for effective integration of assessment methods with spatial databases as well as with statistical and process based modelling techniques.

One of the main future challenges of hydrogeology is to establish the conceptual and operational basis for combining vulnerability methods and the results of process based models. This should be achieved, first at the theoretical level and later as a complex expert tool that could merge the data from spatial databases, vulnerability methods, process-based numerical models, and statistical models into an integrated tool. To meet such a challenge, it will be necessary to use numerical models results to quantify the parameters of the vulnerability assessment analysis.

"Uncertainty is inherent in all vulnerability assessments."

(National Research Council 1993)

Chapter 3

Parameter balance study investigation for evaluating the uncertainty of vulnerability maps
Sensitivity analysis applied to a small karstic aquifer

3.1. 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.

A part of 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 sensivity 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).

This method is diagrammed in ***Figure 2.3.*** and summary described in Chapter 2. Then, using a sensitivity analysis of the applied parameters, an evaluation of this vulnerability-mapping method was done.

This analysis represents a technique of investigation for the vulnerability map uncertainty and allows a correct judging of the parameters role in the calculation of the vulnerability index. The results could lead to changes in the parameter estimation within the basic equation of the vulnerability method.

3.2. Intrinsic vulnerability of the aquifer

3.2.1. Hydrogeological framework

The Beauraing study site is an area of 2.5 km^2 in the southern part of the Dinant synclinorium near to the France - Belgium border. Locations are shown in ***Figure 3.1.***

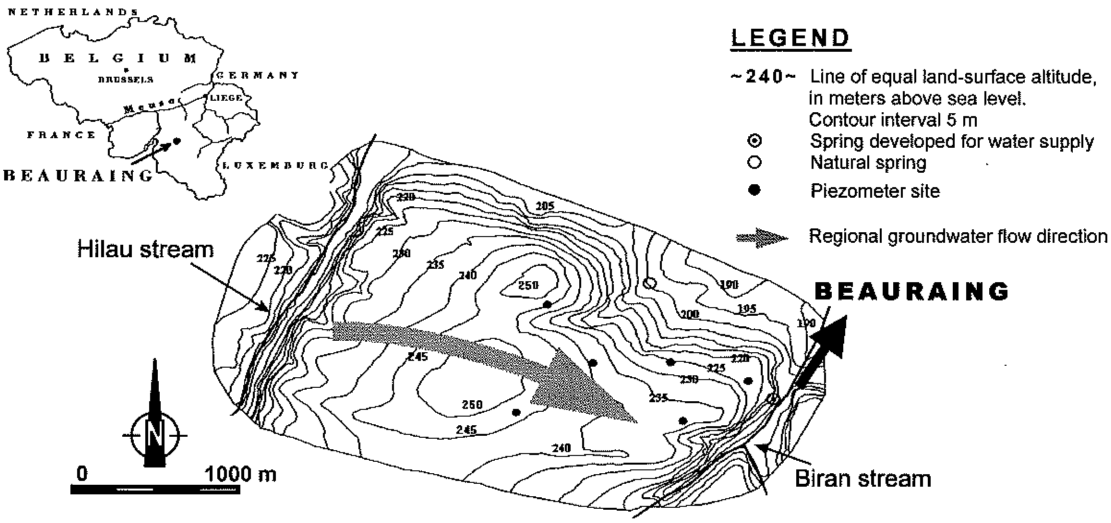


Figure 3.1. - Location of the study area, near Beauraing, Belgium

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 3.2.***

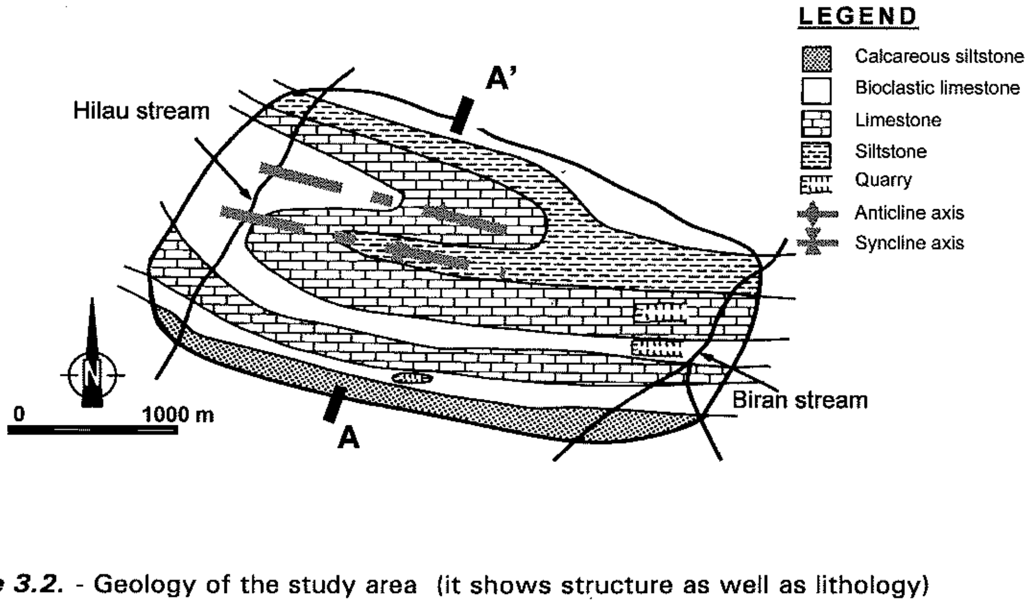


Figure 3.2. - Geology of the study area (it shows structure as well as lithology)

The siltstone bands act as impermeable boundaries for the limestone aquifer. A geological cross-section can be seen in ***Figure 3.3.*** 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 (LGIH 1997 a).

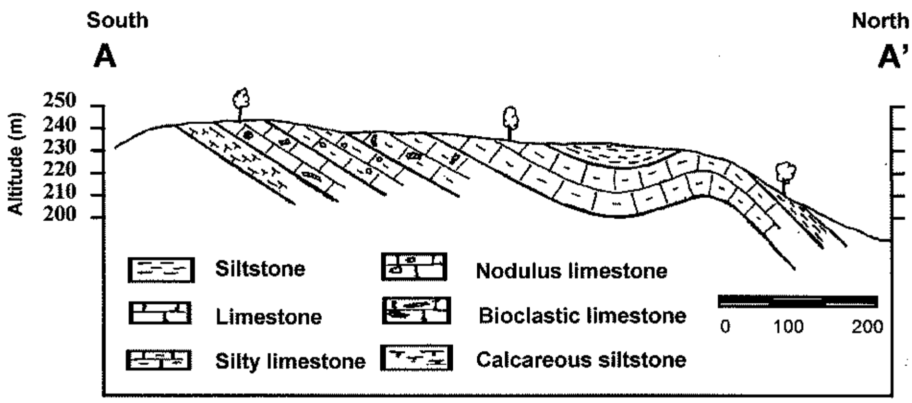


Figure 3.3. – Geological cross-section on the study area

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 from 18-40 m. Regional studies (LGIH 1997 a) 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 m^3/h) 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 m^3/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 (LGIH 1997 a).

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 possible 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.

3.2.2. Map of intrinsic vulnerability

In order to map aquifer intrinsic vulnerability for the study area, a raster-based Geographical Information System software (IDRISI) was used. The *Epikarst* (*E*) parameter was determined using morpho-structural analysis on aerial photos and 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 soils map of 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 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 where 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 (***Figure 3.4.***). A detailed analysis was performed using a raster model with a 16-m^2 cell size. This resolution corresponds to the surface of the smallest morphological element to be mapped. Using the vulnerability index of equation (2.8.), the four parameter maps were overlaid cell by cell to produce a "vulnerability index map". For the study area, calculated values of 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.

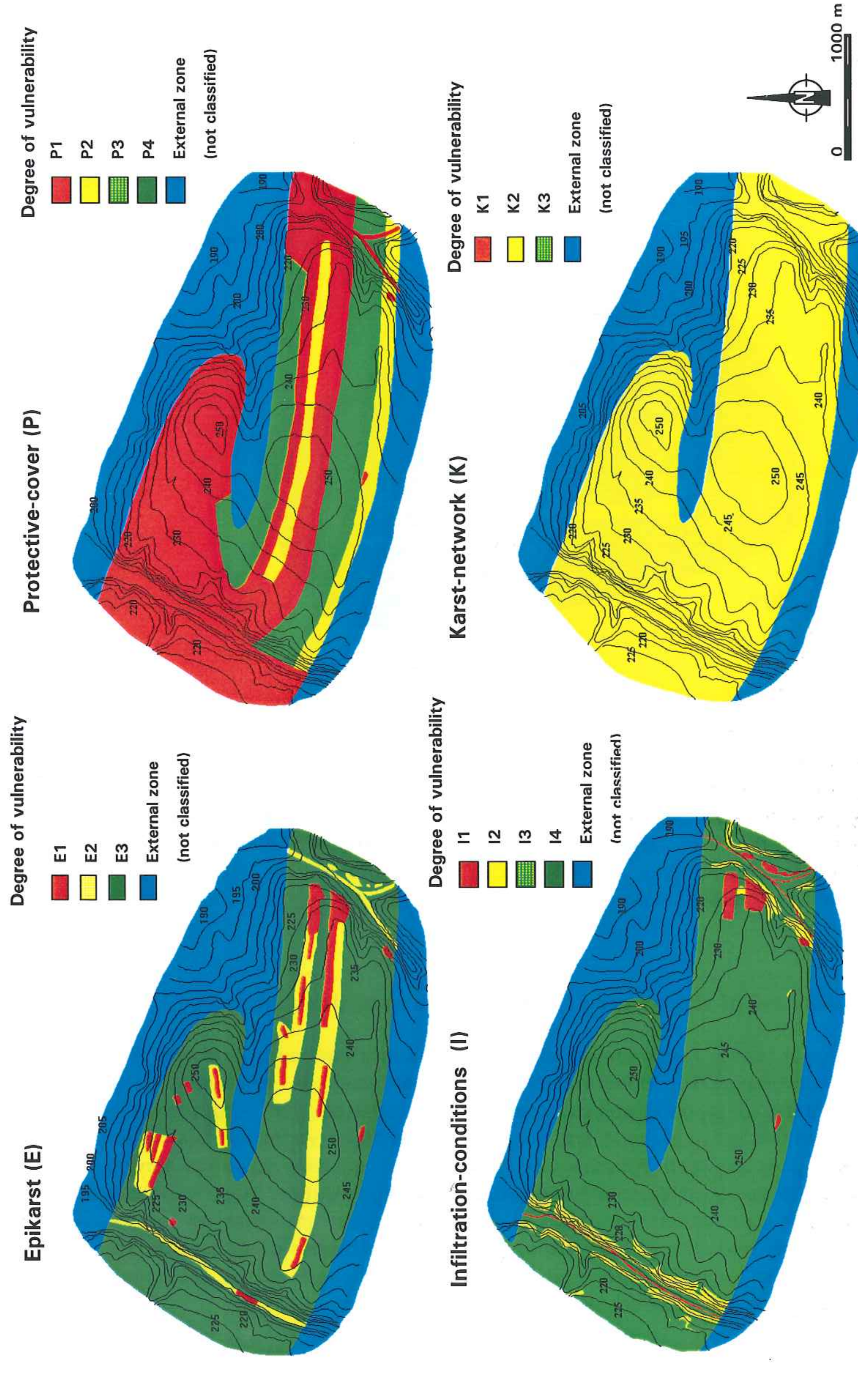


Figure 3.4. - Parameter maps (E, P, I, and K) estimated for the Beauraing study area

The final vulnerability map is shown in ***Figure 3.5.***

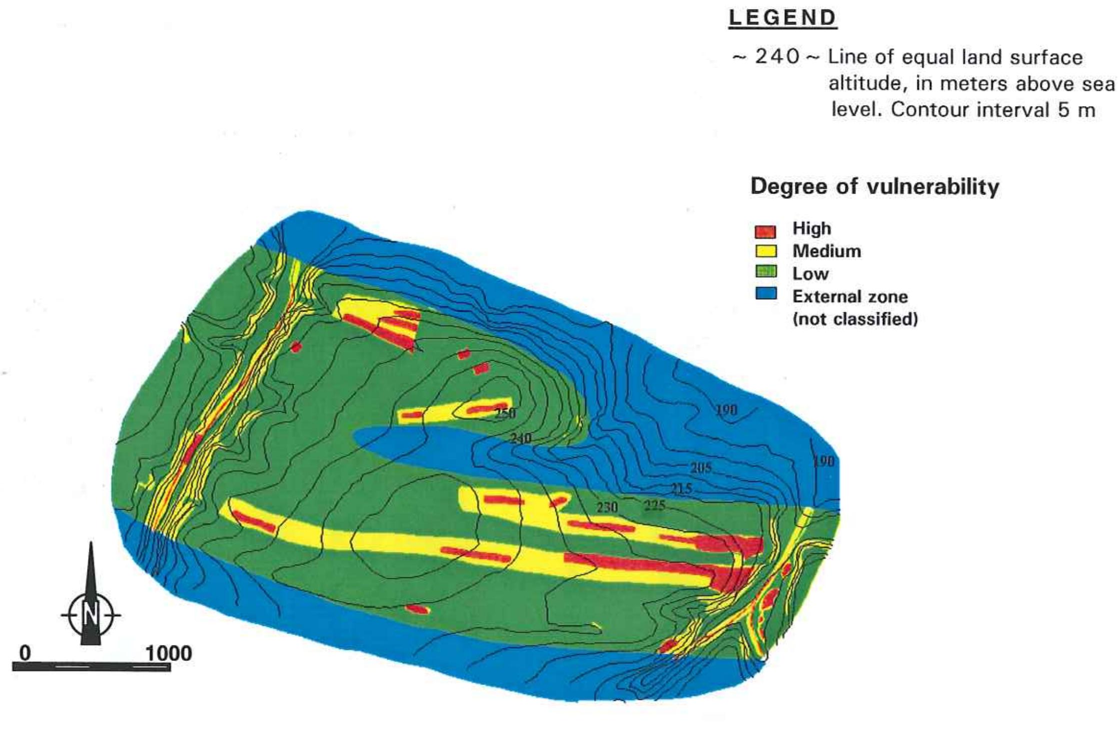


Figure 3.5. - Vulnerability map of the study area Beauraing site, based on the EPIK method

A comparison of the four parameter maps (***Figure 3.4.***) to the final vulnerability map (***Figure 3.5.***) indicates that the *epikarst* parameter (*E*) plays a major role in delineating the high vulnerability zones. The *conditions of infiltration* (*I*) also have a noticeable contribution. Parameters *E* and *I* both play an important role in determining medium vulnerability zones.

3.3. Review of the theory of geographical sensitivity analysis

In general terms, geographical sensitivity analysis concepts (Lodwick et al. 1990) were developed for understanding how perturbations or errors on the input parameters of a geographical analysis can change the output map. Imposing perturbations on the input and computing resultant variations (using an overlay-based operation) can indicate which are more sensitive subareas (group of cells having the same attribute value or polygons) of the output map. It indicates where most attention must be paid in the input data, in order to obtain reliable conclusions from the output maps. This kind of analysis of errors and sensitivities for attribute values associated to subareas mapped units, assumes that the delineation of the subareas is correct.

Mathematical formulation

Two definitions are given, representing concepts used in GIS operations. A *primary map* represents a map of a physical property (i.e. geologic, hydrogeologic, land-use) that is going to be studied. A *rank map* is a map having numerical attributes and represent mathematical relations or measurements of the attributes connected with to one or more maps. In consequence the *rank maps* can be derived from *primary* maps or other *rank maps*. In aquifer vulnerability assessment the rank maps are the *parameter* maps.

For example, in ***Figure 3.6.***, there are two primary maps: the *Depth to water* map and *Aquifer media* map. Data existing on the both maps are captured and encoded, and respective *rank maps* can be generated. In ***Figure 3.6.*** the rank maps are grids, each of them made by 4 cells. The *Aquifer media* map was classified using values that are ranging from 0 to 10. The *Depth to water* map has been rated with classes of 10 m from 0 to 100 m (0 – the depth to water is between 0 and 10 m; 10 – the depth to the water is greater that 100 m).

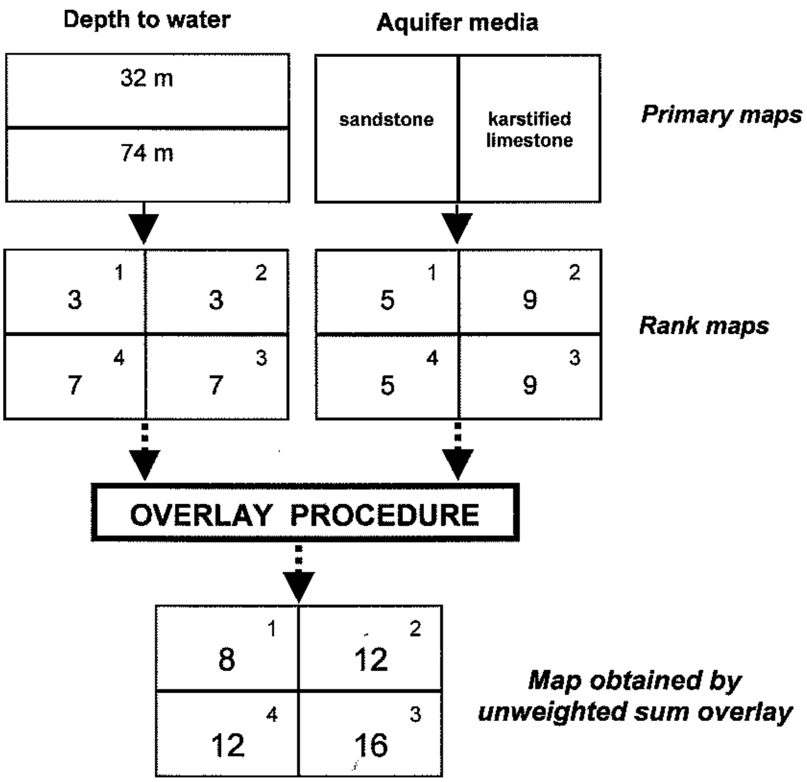


Figure 3.6.- Steps in the examining the sensitivity analysis technique applied for an unweighted sum overlay procedure

The mathematical representation of a geographical analysis that combines and transform attributes of several inputs maps into an output map (in the mentioned case, *unweighted overlay*) can be defined as a function whose domain is a set of vectors of input map attributes and whose range is the resultant attribute:

$$r_c = P\,(\mathbf{a}_{ci}) \tag{3.1.}$$

where:

P – geographical procedure (example: the formula of the vulnerability index V_i)

$\mathbf{a}_{ci} = (a_{c1}, a_{c2}, \ldots, a_{cN})^T$ – the vector of input attributes (example: the parameter maps)

N – the number of input maps corresponding to the c^{th} subarea (group of cells or polygons)

r_c – the resultant attribute of the c^{th} subarea (group of cells or polygons) of the output maps (in the vulnerability assessment represents the vulnerability index V_i)

c – subarea (group of cells or polygons) of the resultant map

Considering the example presented in ***Figure 3.6***, the equation (3.1.) can be rewritten as follows:

resultant map1 map2 weights

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} 8 \\ 12 \\ 16 \\ 12 \end{bmatrix} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{41} \end{bmatrix} \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \\ a_{42} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} 3 & 5 \\ 3 & 9 \\ 7 & 9 \\ 7 & 5 \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{3.2.}$$

As a function, the geographical analysis representing the overlay map can be written as:

$$\mathbf{r} = \mathbf{A} \cdot \mathbf{w} \tag{3.3.}$$

where:

A – the matrix of attributes whose columns correspond to the attribute values of one map and whose rows are the attributes corresponding to one subarea, as in equation 3.2.

$\mathbf{w} = (1,1)^T$ - the vector representing the weights (as the overlay procedure is unweighted, the weights are equal to 1)

Following equation 3.1., the *geographical sensitivity analysis* is the study of the variations in r_c caused by variations or errors in the vector of input attributes $\mathbf{a}_c$ and modalities of measuring these variations.

In consequence, the geographical sensitivity analysis is using imposed variations on the input attribute vector $\mathbf{a}_c$ in order to determine the corresponding resultant r_c using the function or the set of instructions *P*.

Geographical suitability analysis

The notion of *geographical suitability analysis* will be described, in order to understand its need in vulnerability assessment. The following notations are necessary:

N – the number of primary or rank maps used in the analysis

$C(N)$ – the number of subareas (polygons or groups of cells) having the same attribute value after the overlay operation between the N maps

a_{cn} – the attribute from rank map $1 \leq n \leq N$ contained in the c^{th} subarea $1 \leq c \leq C(N)$ of the intersected overaly map

$A = (a_{cn})$ - the $C(N) \times N$ matrix of attributes corresponding to the $C(N)$ subareas of the N maps

w_n – the weighting given to the n^{th} rank map

A *geographical suitability analysis* generates attributes for the c^{th} subarea of the resultant (attribute) map as a mathematical function of $\mathbf{w} = (w_1, \ldots, w_N)^T$ representing weights and $\mathbf{a}_c = (a_{c1}, a_{c2}, \ldots, a_{cN})^T$ representing input attributes, in the following way:

$$r_c = \begin{cases} P(a_{c1}, \ldots, a_{cN}, w_1, \ldots, w_N) \\ P(\mathrm{a_c}, \mathrm{w}) \end{cases} \qquad (3.4.)$$

and

$$\mathbf{r} = (r_1, r_2, \ldots, r_{C(N)})^T = P(\mathbf{A}, \mathbf{w}) \qquad (3.5.)$$

Using geographical sensitivity analysis, the *weighted sum of intersection overlay* could be studied from a more general perspective of equation 3.5.

The weighted sum overlay is represented by:

$$r_c = P(a_c, w) = \Sigma_n a_{cn} \cdot w_n, \quad \text{for } 1 \leq c \leq C(N) \qquad (3.6.)$$

Equation 3.6. identifies *overlay suitability* and the associated map is called *overlay* map. It is assumed that for equation 3.6. the attributes are interval or ratio data types, since multiplication is involved.

Continuing the example presented ***Figure 3.6.***, it can be considered that that a vulnerability assessment method implies only two parameters: *Depth to water* map and *Aquifer media* map. As described above, the grid based *rank* maps are generated. The weighting system is controlled by the w_n in equation 3.6.

Applying an unweighted sum overlay (the equation 3.6. with $w_1 = w_2 = 1$) to the rank maps, the resultant overlay suitability map (*Map obtained by unweighted sum overlay*) is obtained.

The cells values of the resulted map are written in ***Figure 3.6***. If the depth to water of the bottom cell from the *Depth to water* map is 75 m instead of 74 m (a 1% difference), its value on the corresponding *rank map* would be a rating of 8 (if rounding 7.5 to 8). The effect of this error in the suitability analyse equation (3.6.) is that cells 3 and 4 of the overlay operation take values 17 and 13 instead of 16 and 12. This means a 6.25% difference for the cell 3 and a 8.33% difference for cell 4. In conclusion, it can be said that cell 3 is more sensitive to errors than cell 4.

Measures of geographical sensitivity

Numerous defined types of *sensitivities* related to geographical operations can be found in the literature. However, sensitivities more directly related to the suitability analyses are *metric sensitivities* and *weight sensitivities. Metric sensitivities* are the variations that arise when different functions in equation (3.1.) are used in the determination of the suitability (vulnerability index determination) analysis. *Weight sensitivities* are variations that occur with respect to perturbations of weight associated with overlay suitability. The *weight sensitivities* are divided in *layer sensitivities* and *scale sensitivities. Layer sensitivities* are variations in the resultant map that are due to removing any one or a group of maps in a suitability analysis. This corresponds to taking weight perturbations that are equal in magnitude but the negative of ones given for the maps that are to be removed. For *N* maps, there are $2^N - 2$ possible ways to perform the analysis. *Scale sensitivities* are variations that arise from different scale ranges, used in rating schemes for rank maps (if setting rating $w_1 = 2$, this corresponds to a perturbation of 100%, that is equivalent to making the rank scale for the depth to water map to take values between 0 and 20 instead of a 0 to 10 interval).

Starting from these ideas, Lodwick et al. (1990) define several measures of geographical sensitivity that concern the variations over the entire set of subareas *C(N). Map removal sensitivity measures* and *attribute sensitivity measures* are those used in the sensitivity analysis performed for the EPIK method on the Beauraing aquifer.

3.4. Parameter sensitivity analysis

3.4.1. 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.

The general flow-chart of the procedure is presented in ***Figure 3.7.***

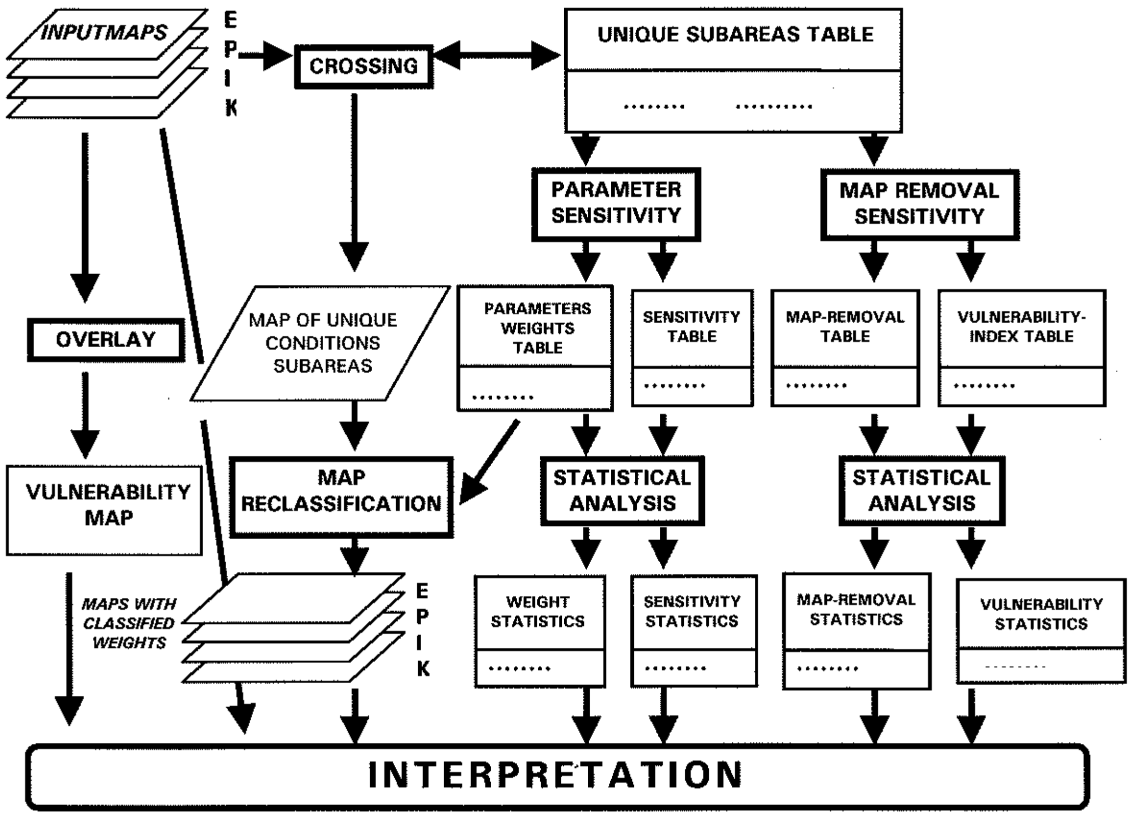


Figure 3.7. – Procedure for applying sensitivity analysis (Gogu and Dassargues 2000 b)

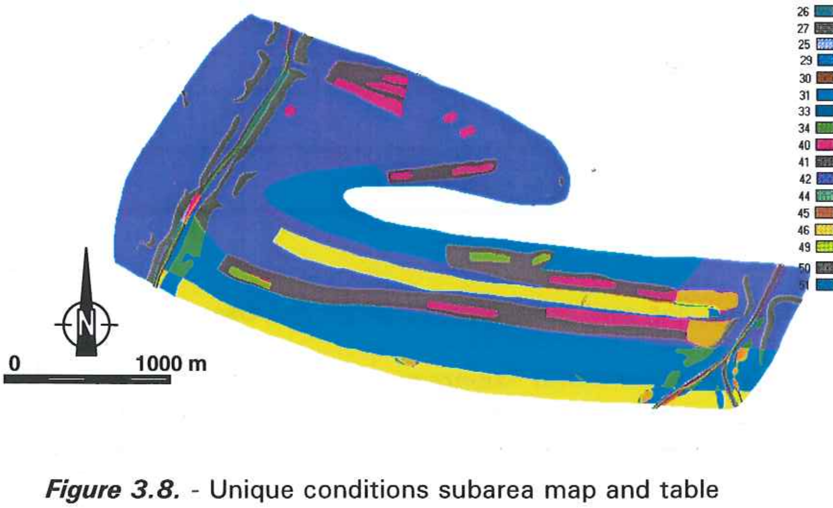
After determination of unique condition subareas, "map-removal" sensitivity and "single-parameter" sensitivity analyses were performed, as described below. The sensitivity analysis results were then processed to obtain tables with statistics. The statistical values are further mapped and discussed.

3.4.2. 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 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 then 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. The resulted "unique conditions subareas" map and table are illustrated in ***Figure 3.8.***



	E	P	I	K	Vul.
12	1	1	1	2	11
13	3	1	1	2	17
14	4	1	1	2	20
16	1	2	1	2	12
17	3	2	1	2	18
18	4	2	1	2	21
20	3	3	1	2	19
21	4	3	1	2	22
26	1	1	2	2	14
27	3	1	2	2	20
25	4	1	2	2	23
29	1	2	2	2	15
30	3	2	2	2	21
31	4	2	2	2	24
33	3	3	2	2	22
34	4	3	2	2	25
40	1	1	3	2	17
41	3	1	3	2	23
42	4	1	3	2	26
44	1	2	3	2	18
45	3	2	3	2	24
46	4	2	3	2	27
49	1	3	3	2	19
50	3	3	3	2	25
51	4	3	3	2	28

Figure 3.8. - Unique conditions subarea map and table

3.4.3. 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 (***Table 3.1.***) indicate that the relative influence on the final vulnerability index is: **E > I > K > P**

Table 3.1. – Statistic balance on the effect of one parameter map removal

Parameter	Average – Parameter value (rating and weight)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
V_i	20.00 (P= 0)	4.65	21.00	11.00	28.00
$V_i - E/f$	15.95	3.57	16.00	10.67	21.33
$V_i - P/f$	24.05	6.24	25.33	13.33	33.33
$V_i - I/f$	18.87	5.19	20.00	10.67	25.33
$V_i - K/f$	21.54	6.20	22.00	9.33	32.00

$\overline{V_i} = 20.00$ (Calculated average of vulnerability index), f = 4/3 (re-scaling factor)

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

$$S_{Xi} = \left| \frac{V_i}{N} - \frac{V_{Xi}}{n} \right| \qquad (3.7.)$$

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 expression (2.8.) 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 (4 maps)

n = number of maps used in perturbed suitability (3 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 3.2.***, 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.

Table 3.2. - Statistics on sensitivity to the 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

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

$$VX_i = \frac{V_i - V_{Xi}}{V_i} \cdot 100 \qquad 1 \le i \le 22 \qquad (3.8.)$$

where:

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

V_i = vulnerability index computed using expression (2.8.) 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 (***Table 3.3.***) is positive for parameters E (*VE*) and I (*VI*) and negative for P (*VP*) and K (*VK*). Because the whole analysed area is 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).

Table 3.3. - Statistics on variation index

Parameter	Average–Parameter value (rating and weight)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
VE	18.66	18.25	23.81	-12.28	46.67
VP	-19.87	6.19	-20.63	-28.21	-2.56
VI	6.42	14.95	3.90	-15.15	37.25
VK	-5.21	7.74	-7.30	-14.29	15.15

3.4.4. 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:

$$W_{Xi} = \frac{X_{Ri} \cdot X_{wi}}{V_i} \cdot 100 \qquad (3.9.)$$

where:

X_{Ri} *and* X_{wi} = are, respectively, the rating values and the weights for the parameter *X* assigned in the subarea *i*

V_i = is the vulnerability index as computed in expression (2.8.) 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 condition subareas was reclassified according to the attribute values of effective weight for each parameter. Statistical results of effective weights are shown in ***Table 3.4.***

Table 3.4. - 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

Then, the effective weights expressed in percentage were mapped according to classes defined every 5%. The effective weights maps are illustrated in ***Figure 3.9.***

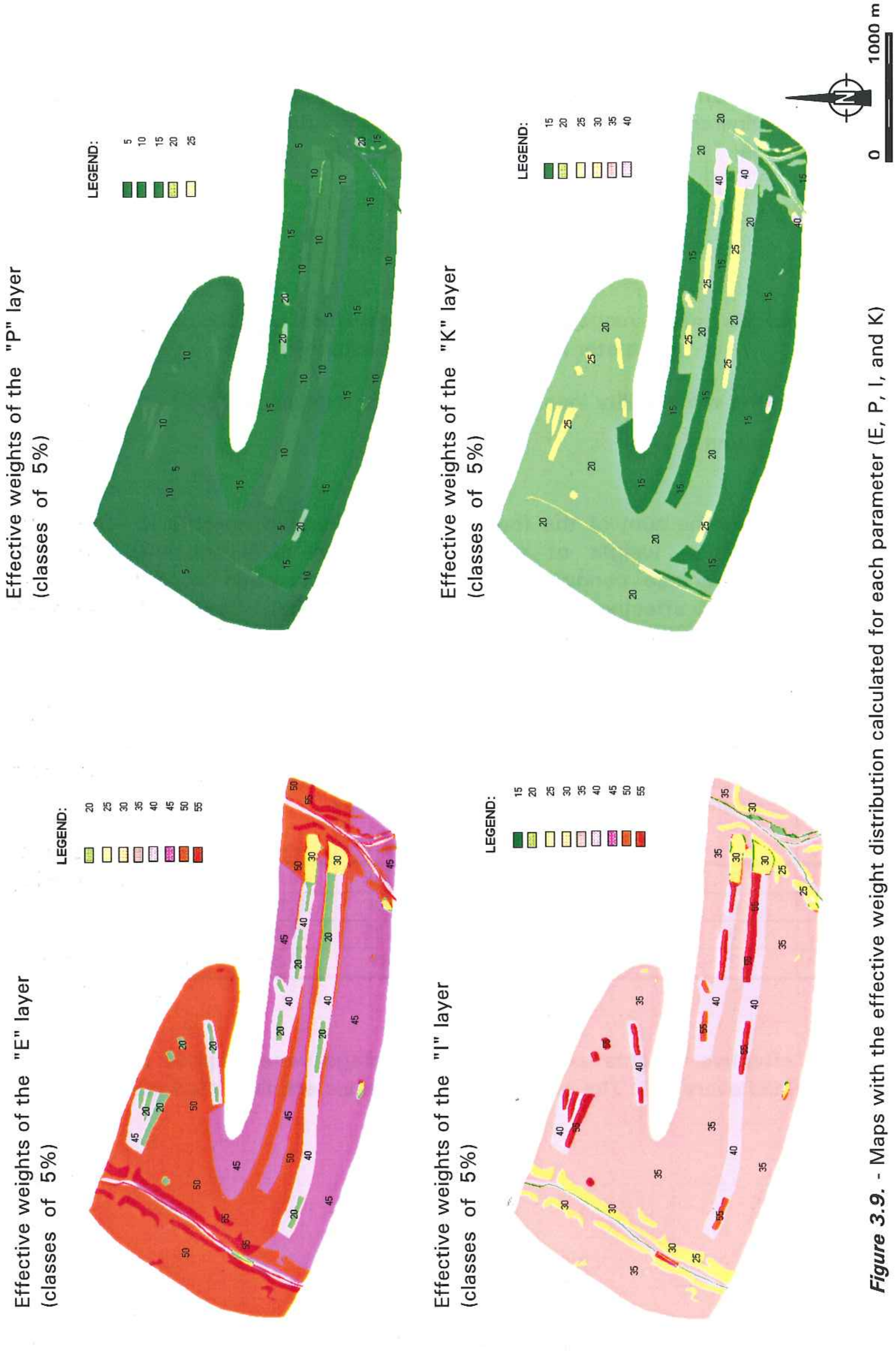


Figure 3.9. - Maps with the effective weight distribution calculated for each parameter (E, P, I, and K)

3.4.5. 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* illustrated on ***Figure 3.4.***), the final vulnerability map (***Figure 3.5.***), and the maps representing the effective weights (***Figure 3.9.***) used in each subarea.

Statistical analysis of the sensitivity of the effective-weight parameters shown in ***Table 3.4.***, indicates that the *Epikars*t 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 (***Figure 3.9.***) shows that all the effective-weight maps are strongly dependent on the value of the *Epikarst* parameter. Also, significant variations of the effective weight distribution exist, depending on values of I and P parameters. 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 ratings and on the theoretical weights chosen in equation 2.8. 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 equation 2.8. can be considered in order to reduce or increase the importance of a parameter in the vulnerability index determination.

3.5. Conclusions

The 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 (equation 2.8.) 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.

"The obvious may be obscured and the subtle indistinguishable."

(National Research Council 1993)

Chapter 4

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

4.1. Study frame and hydrogeologic context

Vulnerability methods can be evaluated by comparing vulnerability map outputs. The use of a large number of parameters in vulnerability assessment allows one to describe complex hydrogeological settings. This usually requires a substantial effort in getting the input data. In order to reduce error propagation, these data must have a certain level of accuracy. For developing easily applicable methods, one solution is 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 vulnerability in the limestone aquifers of the Walloon Region (Belgium), several vulnerability assessment methods have been considered. Five methods were selected for this study: EPIK (Doerfliger and Zwahlen 1997), DRASTIC (Aller et al. 1987), German method (von Hoyer and Söfner 1998), GOD (Foster 1987), and ISIS (Civita and 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 German method are new procedures developed in Europe for geologic 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 is situated in 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 (***Figure 4.1.***). The area includes several villages: Ouffet, Bende, Ama, Oneu, Ocquier, and Bonsin.

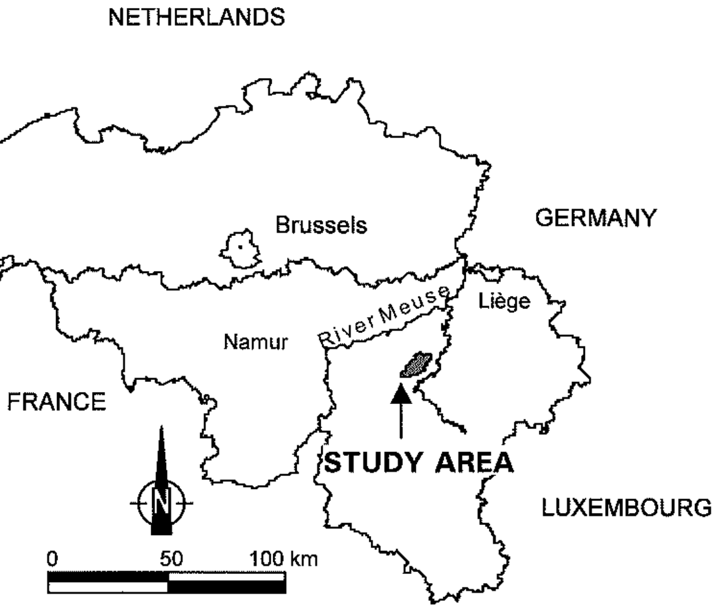


Figure 4.1. - Location of the Néblon river basin, Belgium

The hydrologic basin covers about 65 km^2 and represents an important hydrogeological potential. The aquifer is exploited for supplying water for Liège city and for the 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 modelling, have been performed in the scope of different scientific reports. Several MSc thesis and a PhD thesis contributed also to the study of this aquifer. This already collected information played an important role in choosing this site. Chronologically, this area was the target of several studies to analyse the groundwater reservoir structure (CILE, LGIH, INIEX 1986 and 1989; and LGIH 1995 b), to investigate the karstic aquifer hydrodynamics (Meus 1993), as well as to delineate a first guess for protection zones around the water supply system through numerical modelling (Dassargues and Derouane 1997). A prototype study (LGIH 2000) of a hydrogeological map (Modave-Clavier) was undertaken recently, on this area. All these studies allowed a vast synthesis concerning the nature and the geometry of the geological strata, the hydrological and hydrogeological limits of the basin, faults, lineaments and fractured zones, the piezometric heads evolution, the hydrological water balance, hydrogeochemical analyses, and the determination of groundwater media physical parameters (hydraulic conductivity, storage coefficient, effective porosity, and others).

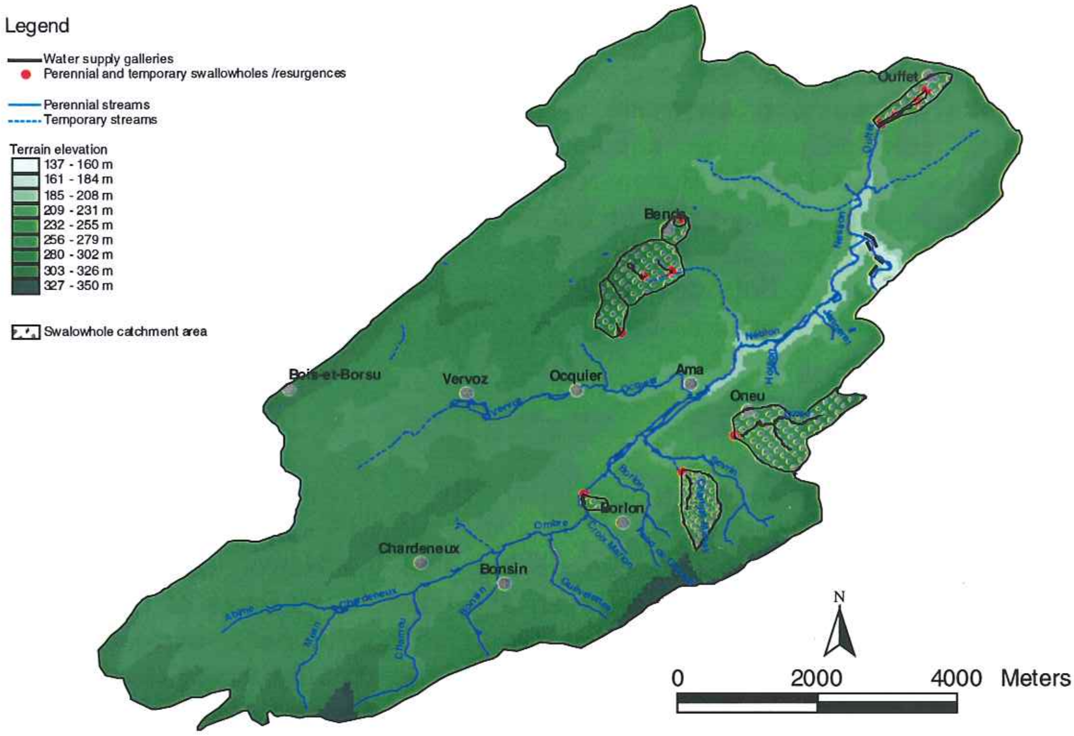


Figure 4.2. - Topography and hydrological network of the Néblon basin

4.2. Geomorphology

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

The Condroz region is characterised by a typical alternation of shales and sandstone anticline crest (Upper Devonian or Famennian) and calcareous syncline depressions (Lower Carboniferous or Dinantian), that support several carbonate aquifers locally interconnected through sandstone layers. The study area is part of a region comprising several synclines and river basins (Monjoie 1984). The main rivers of the region (Meus 1993) are Hoyoux in the North, Néblon in the South and West, and Ourthe in the East.

The relief in the Néblon basin is cut by a well developed river network (***Figure 4.2.***). The tributary streams of the Néblon river are flowing transversely to the general west-east geological structure (***Figure 4.3.***). Most of these streams have their sources in the southern part of the water catchment area, in the Famennian sandstone. Browsing downstream this part of the water catchment area, the following streams can be encountered: l'Abîme, Méan, Charneu, Bonsin, Guévelettes, Croix Marion, Borlon and Fond de Gonwé, Sevrin, Ocquier, Houjon, and Jenneret. The northern part of the Néblon basin is bringing only two streams: Ouffet and Nesson. Due to karstification, several streams are ending in swallowholes: Oneu, Bois de Marsée, and Champs Manhay. Several temporary and losing streams as well as other five diffuse losses can be encountered in the area (***Figure 4.2.***).

4.3. Geology and structural frame

The geological formations that can be found in the Néblon basin are made of terrigenous detrital facies of Famennian age, carbonated rocks of Carboniferous, and terrigenous detrital sediments of Namurian age. 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. The geological structure of the region is characterised by a succession of anticline and syncline folds whose axes are oriented approximately northeast-southwest (***Figure 4.3.***).

The lithological description of the different formations refers to the geological maps of Modave – Clavier 157 (1902) and Hamoir – Ferrières 158 (1902). The lithostratigraphy of the area (LGIH 2000) can be seen in the ***Table 4.1.***

Primary formations

The geological formations of the Lower and the Upper Famennian ages have a Condroz characteristic facies (LGIH 2000). The Lower Famennian consists in mainly purplish siltstone with claystone intercalation - Fa1b (minimum 100 m of thickness) and siltstone with sandstone layers - Fa1c (of about 150 m of thickness). The Upper Famennian consists on four distinct formations:

Souverain-Pré - Fa2a (± 100 m thickness) made of sandstone, siltstone, sandy-limestone, nodule siltstone, and shale;

Monfort - Fa2b (± 150 m thickness) having the bottom made of stratified sandstone and the top of massive sandstone;

Evieux - Fa2c (± 150 m thickness) made of sandstone, sandy-limestone, nodule siltstone, and shale;

Comblain-au-Pont - Fa2d, an alternation of limestone and shale; the Strunian stage is represented by the upper part (15 - 20 m thickness) of this formation;

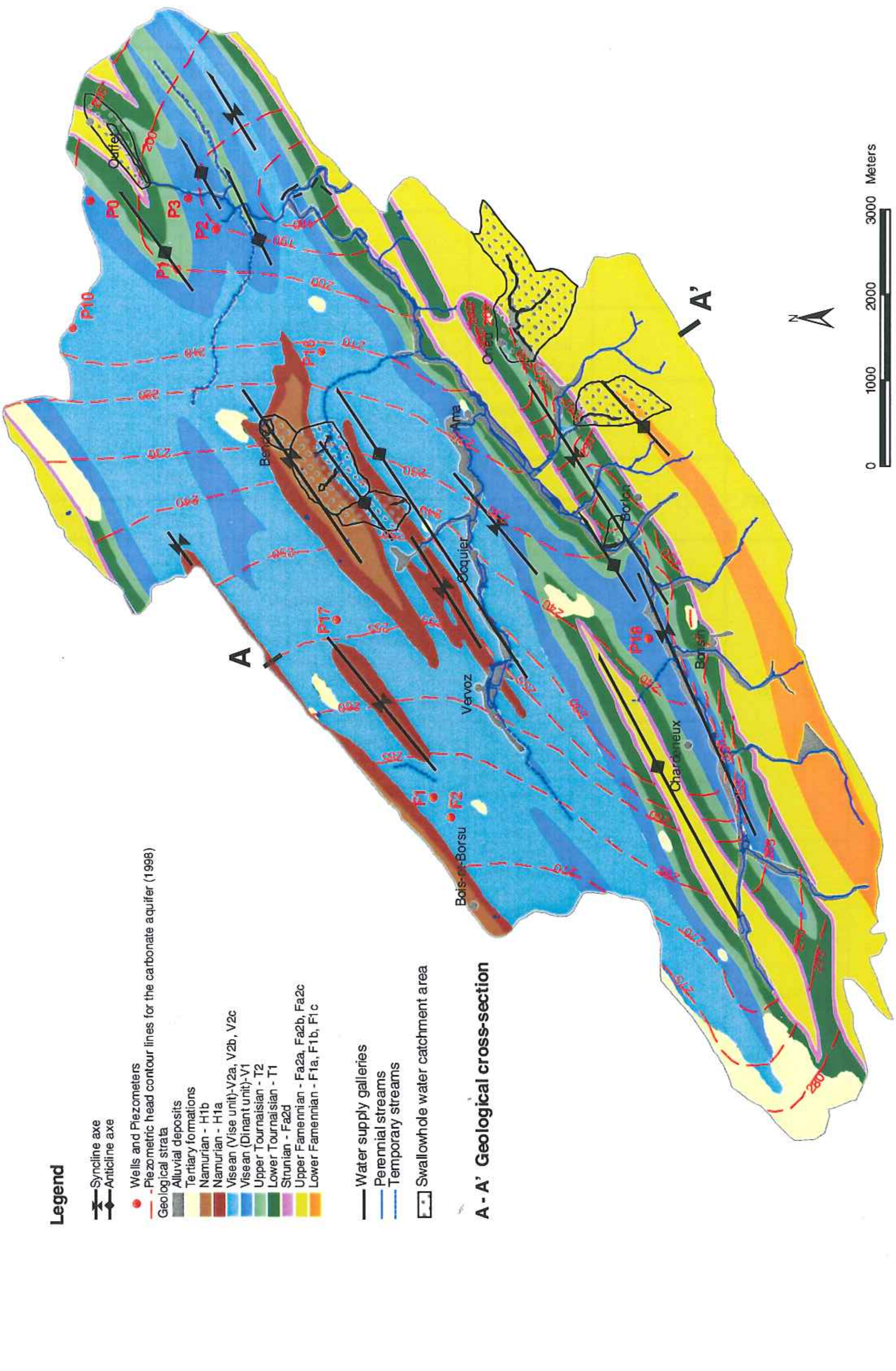


Figure 4.3. - Geology and hydrogeology of the study area

Table 4.1. - Lithology and stratigraphy of the Néblon region

Era	System	Serie	Stage	Formation (new name)	Lithology (description in the map of 1902)	Abbreviation geological map N°157 (1902)	Approximative thickness (m)
CENOZOIC	QUATERNARY	HOLOCENE			alterate silt, scree, tuff, modern alluvia	ale, e, tf, alm	several meters
		PLEISTOCENE	MOSEEN		silt of high plateau	q1n	several meters
	PALAEOGENE	OLIGOCENE		Upper continental deposits	Plastic clay, sandstone, pudding stone, quartzite gravel pockets	Ona, Ong, Onp, Onx	variable
				Lower marine deposits	quartzite sands	Om	variable
PALEOZOIC	CARBONIFEROUS	NAMURIAN			sandstone, micaceous sandstone, shale, lean coal	H1b	
				Formation of Souvré	siliceous sandstone, siliceous shale	H1a	10 to 20
		VISEAN	WARNANTIAN	Formation of Anhée	sequential dark limestone	V2c	40
				Formation of la Bonne	lightly to dark limestone	V2c	50
			LIVIAN	Formation of Grands-Malades	breccia limestone and of stromatolite limestone	V2b	50
				Formation of Lives	sequential dark limestone	V2b	80
			MOLINIACIAN	Formation of Neffe	massive oölithical limestone	V2a	40 to 50
				Formations of Terwagne and of Ourthe breccia	dolomized crinoidal black-blue limestone	V1b	75
		TOURNAISIAN	IVORIAN	Formations of Flémalle and of Avins	top: dolomized oölithical limestone dolomized, base:crinoidal limestone	V1b	80
				Formation of Martinrive	black limestone with chert usually dolomized	V1a	50
				Encrinite of Ourthe	crinoidal limestone	T2b	40
				Formation of Yvoir	limestone with black chert	T2a	60
			HASTARIAN	Formation of Landelies	crinoidal limestone	T1ch T1c	40
				Formation of Pont d'Arcole	dark shale	T1b	10
				Formation of Hastière	crinoidal limestone with narrow siltstone layers	T1a	20
	DEVONIAN	UPPER	STRUNIAN	Formation of Comblain-au-Pont	alternation of limestone and shale	Fa2d	40 to 50
			FAMENIAN	Formation of Evieux	sandstone, sandy-limestone, nodule siltstone, and shale	Fa2c	150
				Formation of Monfort	bottom: massive stratified sandstone, top: massive sandstone	Fa2b	150
				Formation of Souverain-Pré	sandstone, siltstone, sandy-limestone, nodule siltstone, and shale	Fa2a	100
				Formation of Esneux	silty stratified micaceous sandstone	Fa1c	150
				Formation of Famenne	shale and micaceous sandstone	Fa1b	> 100

The Lower Tournaisian (T1) consists in a marine carbonated facies overlaying on a limestone-sandstone alternation (LGIH 2000). Defined recently as Hastarian level, it is composed of the following formations:

Hastière - T1a (± 20 m thickness) made of crinoidal limestone with intercalation of siltstone thin layers;

Pont d'Arcole - T1b (± 10 m thickness) made of dark-brown shale;

Landelies - T1c (± 40 m thickness) made of crinoidal limestone;

The Upper Tournaisian (T2), defined as Ivorian stage is composed of the following formations:

Yvoir - T2a (± 60 m thickness) made of limestone with black cherts and sporadic crinoids;

Ourthe - T2b (± 40 m thickness) made of crinoidal limestone;

Martinrive - V1a (± 50 m thickness) made of black limestone with cherts ;

Flémalle and Avins - V2a made of crinoidal limestone at the base and dolomitized oölithical limestone on top (± 65 m thickness of crinoidal limestone and ± 15 m thickness of oölithical limestone);

Following the edited geological map (Modave – Clavier 157, 1902 and Hamoir – Ferrières 158, 1902), the carbonate formations of Visean age are divided in two units:

Dinant unit - V1, made of the black limestone of Dinant (with black cherts, often dolomized) and by a black-blue crinoidal dolomitized limestone;

Visé unit - V2, composed of a gray limestone with crystalline grains and a compact oölithical limestone (V2a), a very compact black-grey limestone (V2b), and a limestone with anthracite layers (V2c);

The present classification divide the Visean age in three stages: Moliniacian (Terwagne and Ourthe - consisting of ± 75 m of dolomitized crinoidal black-blue limestone and Neffe -consisting of ± 40-50 m of massive oölithical limestone), Livian (Lives formation consisting of ± 80 m sequential dark limestone and Grand Malade formation consisting of ± 50 m breccia limestone and of stromatolite limestone), and Warnantien (Bonne formations made of ± 50 m lightly to dark limestone and Anhée formations made of ± 40 m sequential dark limestone).

The Lower Namurian is characterised by a silty-sandstone facies of paralic type, rich in carbon (LGIH 2000). Two facies can be distinguished:

- deposits of siliceous sandstone, siliceous shale, organic claystone, and coal (H1a) having a thickness of about 10 - 20 m;

- deposits of feldspatic and psamitic sandstone, shale, and lean coal (H1b).

Tertiary and Quaternary formations

The Tertiary deposits filling the paleokarst are quite heterogeneous. These are composed by fine and spangled quartzite sands, gravel pockets, and plastic clay. In the valleys are observed Quaternary deposits.

4.3.1. Tectonic frame

The numerous folds generally created a relief with topographic crests right on the anticline axis of the Famennian sandstone. The depressions correspond mostly to the syncline axis of the Tournaisian and Visean limestone. Locally the Namurian formations form the core of several synclines, providing an "inverse" relief (i.e. a hill at the centre of the syncline). A schematic North - South geological cross-section is shown in ***Figure 4.4.***

The region is intensively faulted (***Figure 4.5.***) and the main structural features can be divided in three major groups:

- thrust longitudinal faults and fractures, orientated East-West (parallel to the stratification): fault of Ouffet, the fault that put into contact the Dinantian limestone and the Famennian sandstone at Néblon-le-Moulin;

- transverse faults, NNW-SSE to N-S oriented, mainly perpendicular to fold axis. These faults and fractures generating probably an anisotropy effect for hydraulic conductivity, are thought to drain the groundwater fluxes towards the collecting galleries. Several lineaments and geophysical studies provided data on the location of these faults (CILE, LGIH, INIEX 1986, Di Clemente and Laurent 1986, Dreze 1997);

- oblique faults or fractures, oriented generally NE-SW. They are thought as having a minor influence on the groundwater flow (Meus 1993, Dassargues and Derouane 1997).

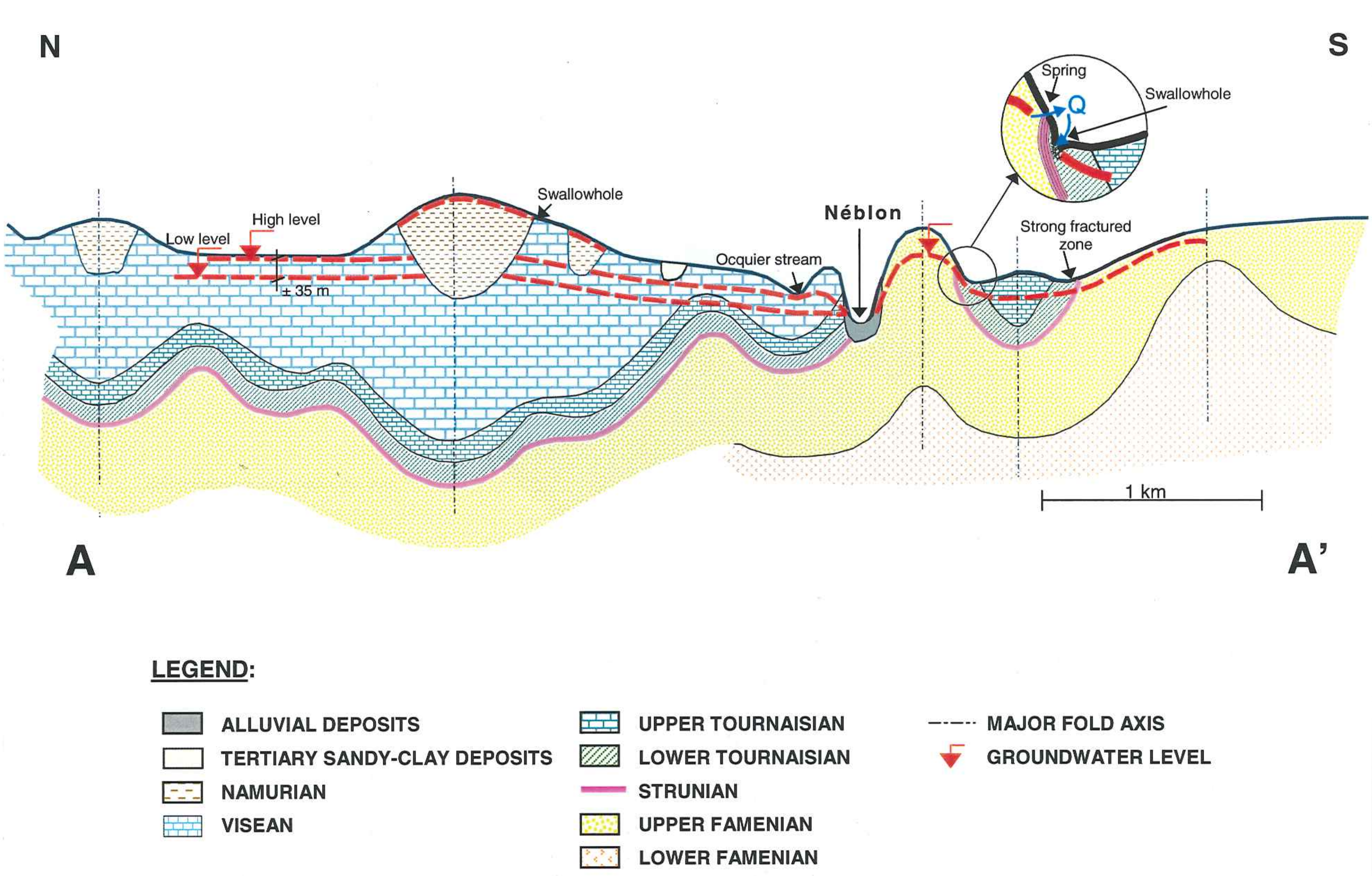


Figure 4.4. - Schematic North-South geological and hydrogeological cross-section of the Néblon river basin

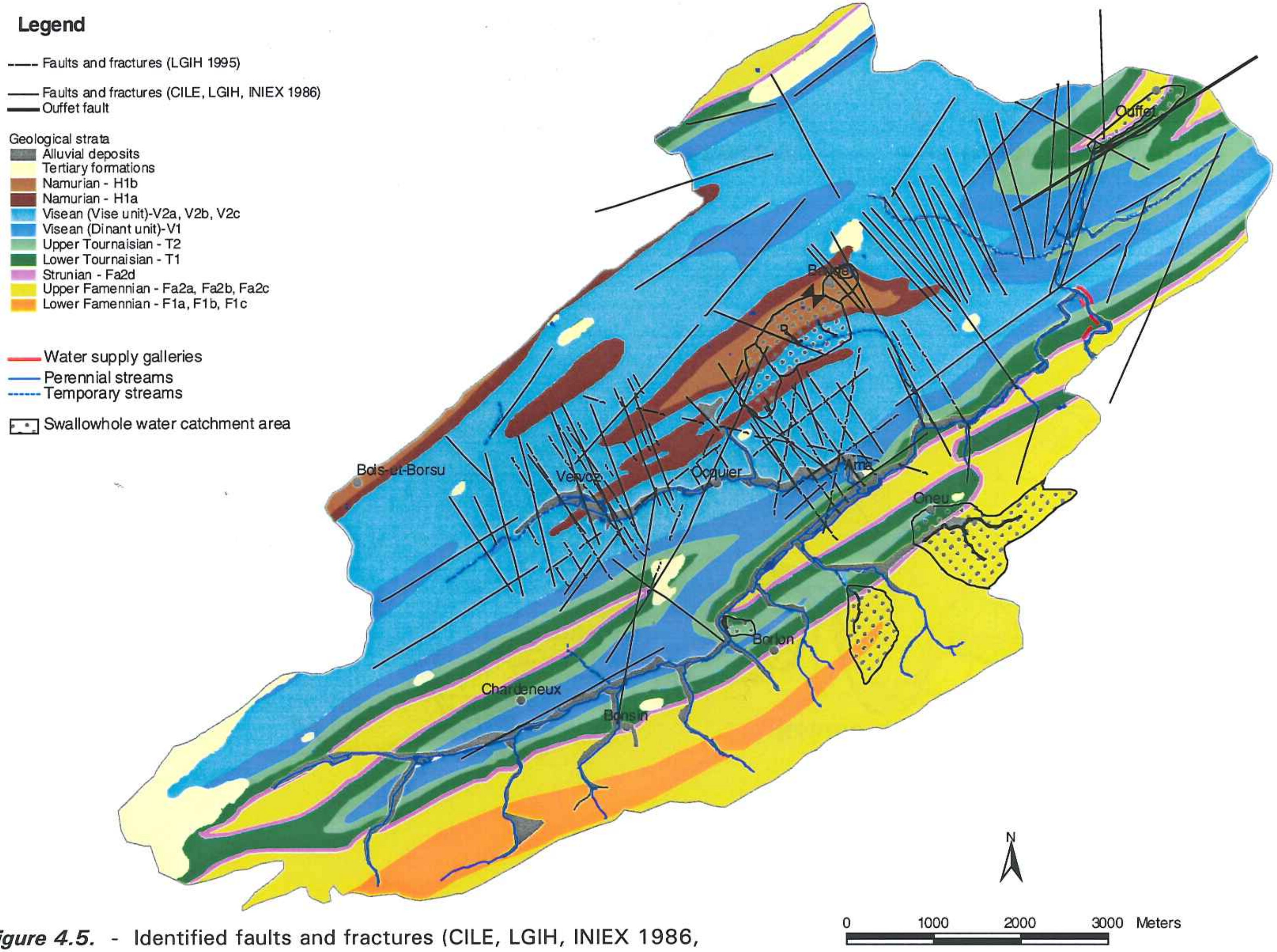


Figure 4.5. - Identified faults and fractures (CILE, LGIH, INIEX 1986, Di Clemente and Laurent 1986, Dreze 1997, Meus 1993, LGIH 1995 b)

4.4. Hydrogeology

General description

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. In this karstified limestone, the Hastiere formation of the Lower Tournaisian includes shale intercalations and consequently is affected by lower hydraulic conductivity values. The Ivorian (Upper Tournaisian) and the Visean limestone can be considered a single hydrogeological unit (LGIH 2000). The Visean is generally made of more pure limestone than the Tournaisian, and can be karstified easier.

The Néblon river is generally draining the main aquifer. The natural outflows of the aquifer are the diffuse discharges and point sources along the Neblon river and the springs of Neblon-le-Moulin. These last are exploited via four collecting galleries by the CILE Water Company. They provides a daily yield between 25.000 and 30.000 m^3. The galleries are located in the natural outlets of the hydrogeological basin on the both sides of the Néblon river. The main gallery (Principale) located on the left side of the river is providing about 50% of the water-supply.

The Famennian sandstone represents an other exploitable aquifer. It is located in the rock weathered zones that could be also strongly fissured in depth. This aquifer have a small storage capacity (LGIH 1989 and LGIH 2000). The connection with the limestone aquifer (***Figure 4.4.***) is done predominantly by several springs 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 act like small perched aquifers. These aquifers have a very weak storage capacity. The Namurian groundwater is exploited for agricultural purposes by a few local wells with production yields of about several cubic meters per day (LGIH 2000). It is supposed that a shale belt insure the watertightness of the Namurian synclinals depths. The connection with the limestone aquifer is done mainly by overflowing this shale belt or it could be presumed through the existing faults (***Figure 4.4.***).

Karstic features

Several karstic features can be identified in the Neblon basin, the most significant being the dry valleys, the swallowholes and the resurgences, the sinkholes (dolines). The high flow-rates springs of Neblon-le-Moulin is presumed to be the effect of a karstic conduit. On ***Figure 4.2.*** are marked the area swallowholes and diffuses losses. Among them, three major swallowholes were identified: Bois de Marsée, Bende, and Oneu.

Tracers injected in the swallowhole of Bois de Marsee, have been recovered in two of the collecting galleries called Communale and Principale. This clearly indicates a karstic conduit (Meus 1993). For the Communale gallery, 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 a high degree of karstification where the Darcy's law is likely out of validity.

Several dry valleys can be observed in the area (***Figure 4.2.***). The most extended one is Fond de Bende, located at east of the Bende village. During rainy periods the bottom part of this dry valley becomes one of the Nesson's tributary streams. Two other dry valleys reaching the Nesson stream are Himbe ravine in North-East and Ouffet ravine in North. Starting from the Bois de Marsée, a dry valley called Fond de Walou (it has several names: Fond de Marsée, Fond de Sartre, and Fond de Walou) is reaching Néblon between Ama village and Jenneret stream. Another dry valley, recently observed presents a parallel direction to Fond de Wallou. This last starts at about 1000 m SE from Fond de Wallou, and also ends in the Néblon river. Its precise position is marked on the epikarst parameter map of the EPIK method (***Figure 4.10.***). In the upper part of this last observed dry valley was noticed a small swallowhole (***Figure 4.2.***). This last swallowhole is not mentioned in the karst atlas of De Boyer et al. (1996).

In this region are not mentioned extended karstic cavities. Only a very few undeveloped karstic caves are noticed along the Néblon cliffs as well as a small sinkhole South of Ouffet.

Hydrogeological parameters

For the karstic aquifer several pumping tests were performed in the existing wells. Data interpretation indicated transmissivity values between 10^{-3} and 10^{-5} m^2s^{-1} (LGIH 1995 a, Dassargues and Derouane 1997). Hydraulic conductivity values were calculated on the basis of pumping tests results (Gaule 1998) in Pz 16 (***Figure 4.6.***) and in F1 and F2. Results are respectively 1.2×10^{-6} m/s for Pz16 and 1.09×10^{-6} m/s and 5×10^{-6} m/s for F1 and F2.

For the entire catchment area a global value of for the effective porosity was estimated between 1.5-2 %. This global estimation is based on the interpretation of annual groundwater storage variations (Dassargues and Derouane 1997).

A longitudinal dispersivity could be estimated at 15 m (Meus 1993) for the presumed karstic conduit, starting from the tracer tests performed in the Bois de Marsée swallowhole. This value was obtained by modelling the tracer test results by an analytical formula (unique drain). As no significant results were registered from tracing tests performed in the wells, additional data could not be obtained.

There is no available value of hydraulic conductivity for the Famennian aquifer in the Néblon basin. However, several pumping tests were performed in the Famennian sandstone of Condroz region. These tests performed in similar neighbouring aquifers (LGIH 1997 b), indicate a hydraulic conductivity value between 1.4×10^{-4} - 5.5×10^{-6} m/s. A decreasing of this value with the considered depth was also observed.

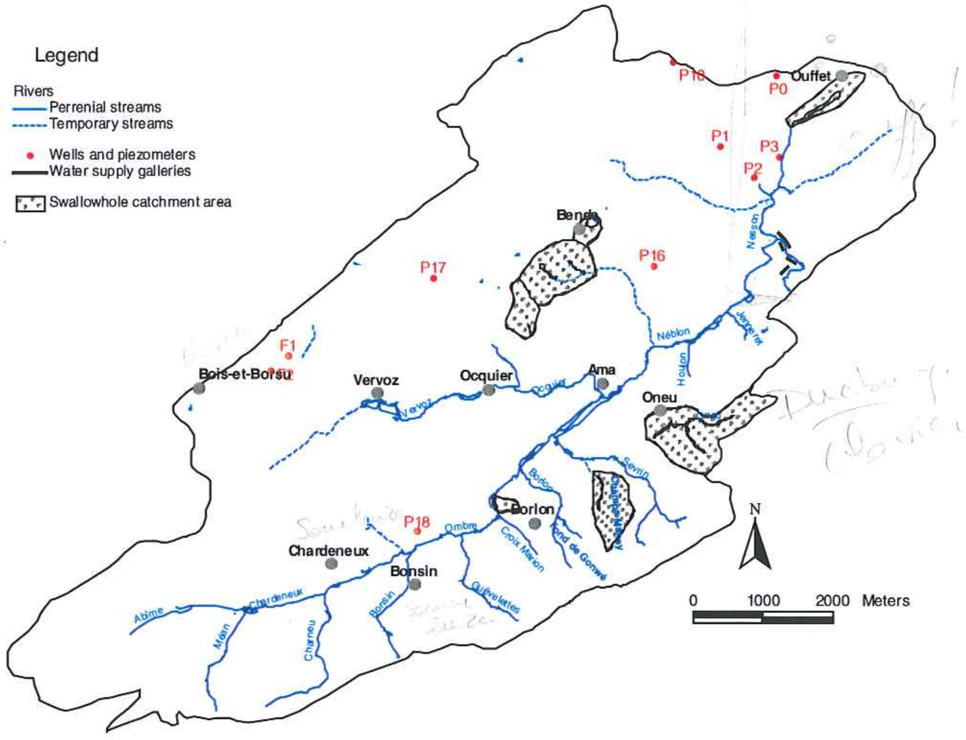


Figure 4.6. - Wells and piezometers within Néblon basin

A first numerical model approach has been performed (LGIH 1995 a, Dassargues and Derouane 1997) in order to try to describe globally the aquifer behaviour for the flow and solute transport. The resulted parameters values are indicated in the ***Tabel 4.2.***

Table 4.2. - Hydrodynamic and hydrodispersive parameter values used in the regional 2D and 1D numerical models (Dassargues and Derouane 1997)

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

Interesting results of river/aquifer interaction were obtained by studying the flow-rates along the Néblon river (Gaule 1998). Measures (***Table 4.3.***) highlighted an increase of about 25% of the Néblon flow-rate between A and B gauging stations (***Figure 4.7.***). This river flow-rate increase can be explained by a groundwater contribution onto the Fond de Wallou dry valley. Downstream, between the gauging stations B and C (***Figure 4.7.***) was registered a flow-rate loss of about 10%. The loss indicates an infiltration penetrating the Lower Tournaisian rock mass in the Jenneret meander. Between C and D the flow-rate increases of about 30%. This cannot be explained only by the contribution of the Nesson stream. However this increase can be justified by associating the groundwater feed onto the Fond de Bende dry valley and onto the Himbe ravine. Following this reasoning, the karst conduit (Meus 1993) starting from the Bois de Marsée swallowhole is supposed to continue under the Fond de Wallou dry valley and to reach the Néblon river bed in a karstic or high fractured zone. This last hypothesis is consolidated by the geophysical studies outlining several faults in the Fond de Bende dry valley (***Figure 4.7.***).

Table 4.3. - Flow-rates measurements on the Néblon river: A, B, C, and D gauging stations (1998 field work campaign)

	GAUGING STATIONS			
Date	**A** (upstream Wallou) (m^3/h)	**B** (downhill Wallou) (m^3/h)	**C** (upstream pond) (m^3/h)	**D** (downhill pond) (m^3/h)
12/07/1998	519	968	882	1159
20/07/1998	380	480	424	593
31/07/1998	374	456	398	579
10/08/1998			722	873
12/08/1998			305	508

4.5. The aquifer conceptual scheme required for the vulnerability assessment

The vulnerability study analyses the aquifer located within the limits of the Néblon hydrologic basin that feeds the groundwater supply galleries.

The hydrogeological limits of the Néblon basin show spatial and temporal variations. In the Southern part, an impervious boundary made by shale is forming the Famennian anticline of Borlon. The northern and eastern limits are mainly situated in the Visean limestone. These limits are often considered as corresponding to the crest of the respective hydrological basins of the Hoyoux and Anthisnes, however in reality the hydrogeological limit is not corresponding to the hydrologic one. This theoretical equivalence between these two limits does not exclude in reality the groundwater transfers. The eastern limit with the neighbouring basins, is represented by a geological, hydrogeological, and topographical complex boundary. In west, the hydrogeological limit is usually designated the same as the hydrological one. A possible extension of the hydrogeological basin to the west is indicated by water-balance studies (LGIH 1995 b). The studies show a flow excess in summer for the Ocquier river that could be explained by a groundwater feed from the western neighbouring basin.

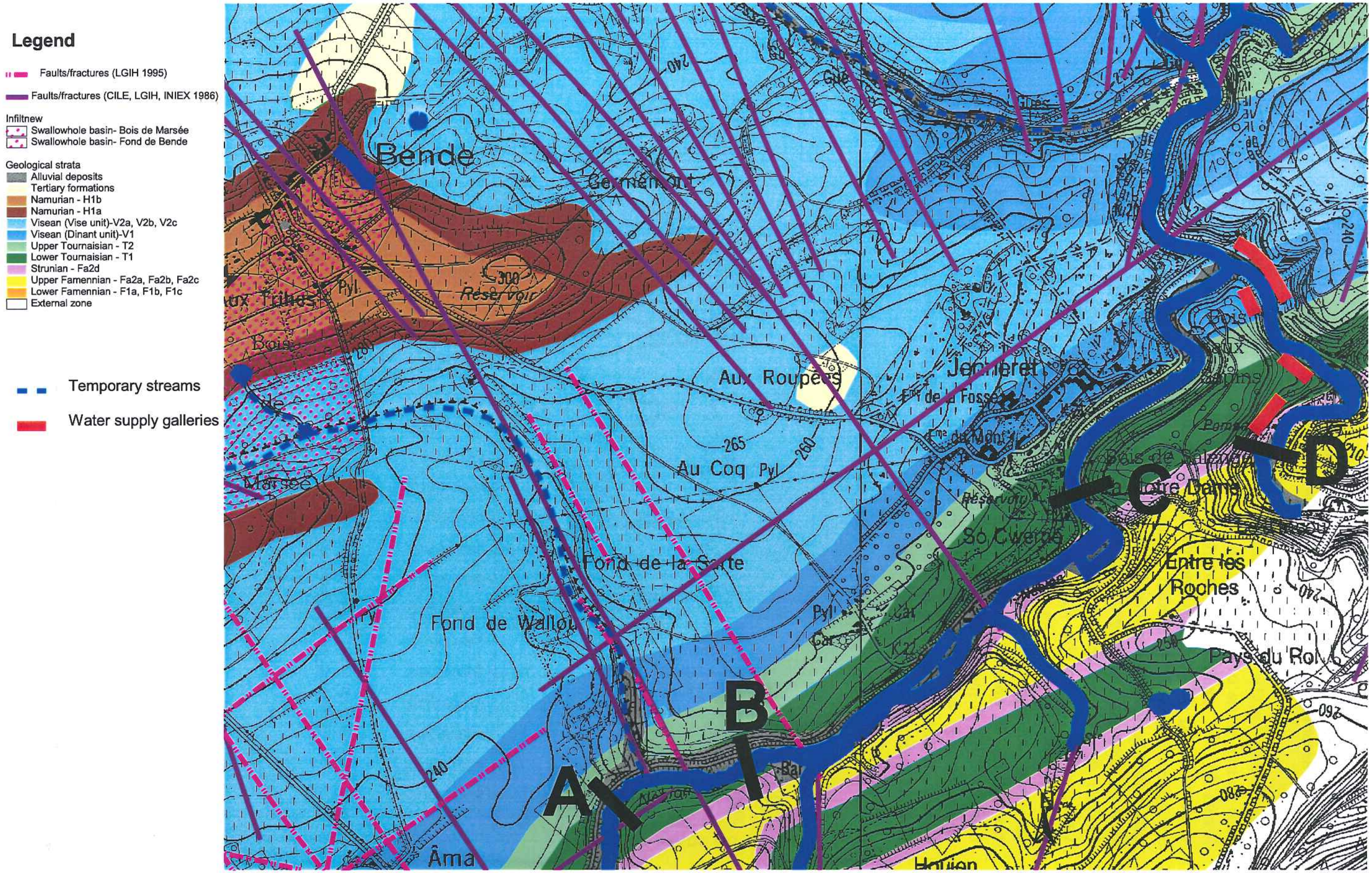


Figure 4.7. - Faults and fractures in different Fond de Wallou dry valley and Gauging stations (A, B, C, and D) on the Néblon river for 1998 field works campaign

The Néblon karstic system is considered as moderately karstified, corresponding to a young stage of karstification. The low frequency of checking the goundwater levels in the existing piezometers (***Figure 4.6.***) does not allow a complete understanding of the aquifer behaviour (LGIH 2000). However, considerable variations of the hydraulic heads were observed. ***Figure 4.8.*** gives the groundwater level variations in two piezometers. The groundwater levels have in P16 a seasonal variation. This well is located on the left side of the Fond de Wallou dry valley, in the fissured limestone. P18 shows a groundwater level variation similar to the river water level (238 m). This variation is completely different than in P16. As P18 is located at about 200 m from the river, in this zone we can suppose a good groundwater communication between the river and the aquifer. In general, the seasonal groundwater levels fluctuations are between 5 and 40 m. A piezometric head map (LGIH 2000) portraying a groundwater low levels period, was designed for 1998 (***Figure 4.3.***). This piezometric head map clearly indicates a general groundwater flow to East. A stronger depression in the Néblon river valley is also shown.

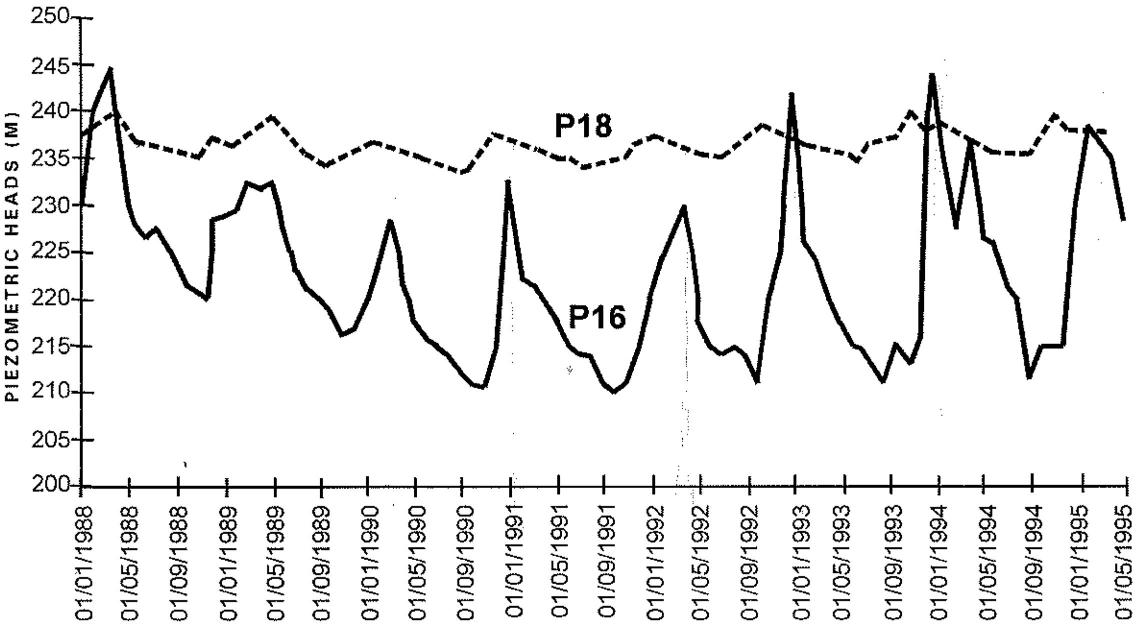
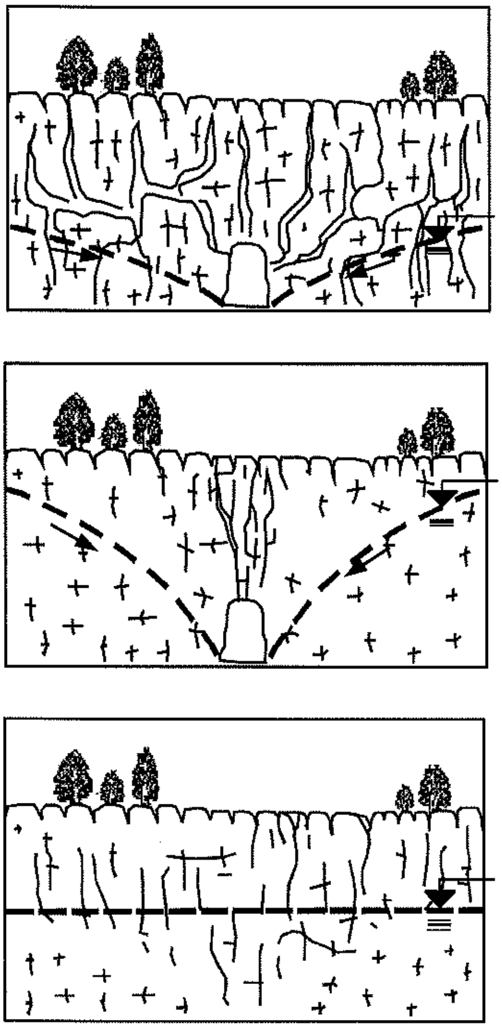


Figure 4.8. - Water level variations observed in the piezometers P16 and P18 (Dassargues et Derouane 1997)

Using the classification provided by Dodge (1983) the conceptual model for the karst aquifer, used in this vulnerability analysis (***Figure 4.9.***), presents well defined karstic conduits with a limited extension of karstification.



a) Very karstified aquifer showing a strong karstification of the rock mass

b) Karstified aquifer showing a limited karstification of the rock mass

c) Aquifer showing a light karstification with an uniform repartition, without major conduit

Figure 4.9. - Classification of karstic aquifers from Causse Comtal (modified after Dodge 1983)

The link between the karst aquifer and the Fammenian sandstone aquifer is supposed to be limited. Meanwhile the Namurian aquifers can be considered isolated, 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 (LGIH 1995 a). This phenomena, predominant in the alluvial plain, prompts the hypothesis of water-supply galleries contamination by the river. Di Clemente and Laurent (1986), 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 (***Figure 4.2.***) and the drained groundwater in galleries. These observations point out possible links between the Néblon river and the galleries.

Some of the stream basins crossing the Famennian sandstone present recession coefficients similar to the stream basins crossing the limestone. This indicates a good storage capacity for the sandstone aquifer and of course an important effective porosity. The Borlon stream crosses the Fammenian sandstone (sands of alteration) as well as the Visean limestone. Borlon and Fond de Gonwé streams present high recession coefficients (Di Clemente and Laurent 1986). The values of 12.7×10^{-2} d^{-1} for Borlon and 23.65×10^{-2} d^{-1} for Fond de Gonwé indicate the presence of a high porosity aquifer. Similar situations are found for the Champ Manhay stream and for the Sevrin stream. The recession coefficient is about 20.6×10^{-2} d^{-1} for Champ Manhay stream. The downhill sector of Sevrin stream, crossing the Visean limestone, has recession coefficients of 8.6×10^{-2} d^{-1} and 3.1×10^{-2} d^{-1}. The upstream part of the same stream has coefficients of 7.1×10^{-2} d^{-1} and 2.3×10^{-2} d^{-1}. For the Jenneret stream basin a stock value of 19,000 m^3 (23 mm) was calculated by Di Clemente and Laurent (1986). This high value, if compared to other Fammenian aquifers, can be explained by a tectonic disrupt created by the possible extension of the faults found in the limestone. For the Oneu swallowhole basin a value of 13.3×10^{-2} d^{-1} was calculated. This value supposes an influence of a very porous zone (sand of alteration) or of a strong fissured sandstone.

The depth of the Namurian synclines made of shale and sandstone is not known. Often they are considered as allowing deep groundwater communication in the underlying limestone aquifer (***Figure 4.4.***). This hypothesis is confirmed by water-balance results, showing an excess for the Ama and Vervoz streams basins (Di Clemente and Laurent 1986, Dassargues and Derouane 1997).

4.6. Quantification of the vulnerability assessment methods parameters

The study was conducted on the area of 64.70 km^2 determined for the Néblon hydrologic basin. For the five applied methods the quantification of the parameters was done in parallel, in order to provide accuracy in the analysis. As hydrogeological parameters can be to some extend interdependent, the 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 judgement of the data sources, (3) a correlation between the hydrogeological parameters, and finally (4) the hydrogeological interpretation of each method parameter.

4.6.1. Short overview on technical aspects in vulnerability analysis

A brief description of the most important steps in the vulnerability parameter estimation is necessary. However, in this description all the GIS terms definitions (DeMers 1997), the types of geographical modelling and their achievement, the aspects of data capturing, the used GIS functions, procedures, operations, spatial manipulation issues and errors are considered as well known.

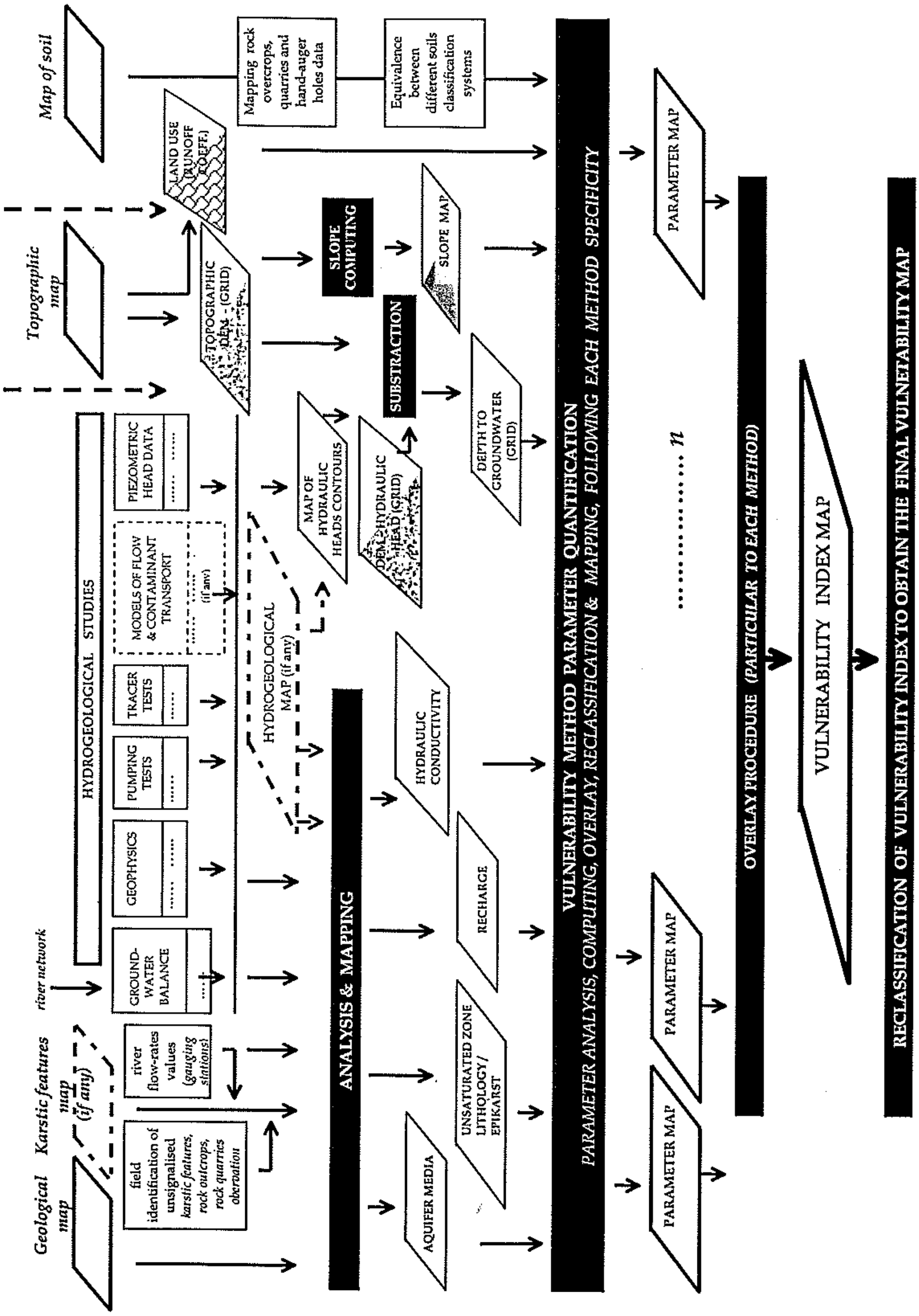


Figure 4.10. - Main steps in groundwater vulnerability assessment for Néblon aquifer

Aquifer vulnerability assessment is based, as it is illustrated in ***Figure 4.10***, on different data sources. In our case study the data comes from: the geological map (Modave – Clavier 157 /1902, Hamoir – Ferrières 158 /1902), the map of karstic features (De Boyer et al. 1996), a prototype of the hydrogeological map (LGIH 2000), various local and regional hydrogeological studies, topographic map (Hamoir 49/5, Clavier 48/8, Modave 48/7, Maffe (54/3) , Grandhan 54/4), map of soil (Maps of soils in Belgium, see References), the digital numerical model of Belgium (source: National Geographical Institute of Belgium), and the land use map (source: National Geographical Institute of Belgium). Also these data were completed by a campaign of field tests (Gaule 1998) consisting in: collecting data by geophysical prospecting (electrical sounding and profiling, seismic soundings), piezometric head 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, the rock quarries, and the new karstic features (not mentioned before).

Information and data coming from the various studies (***Figure 4.10.***) and from the geological map, the map of karstic features, and the hydrogeological map, served as basement analysis for outlining the aquifer media, the unsaturated zone lithology, epikarst, the hydraulic conductivity, and the recharge of the aquifer.

The digital numerical model (DTM) of the region was the base for the slope computing needed for some of the applied methods. A hydraulic head contour map was created using the piezometric head values of the existing hydrogeological map (LGIH 2000) and completed with data obtained in the field measurements campaign of 1998. This hydraulic head map was used to generate a grid map of hydraulic head. Further, by subtraction of this piezometric head grid from the DTM, is created the map of depth to water table for the karstic aquifer.

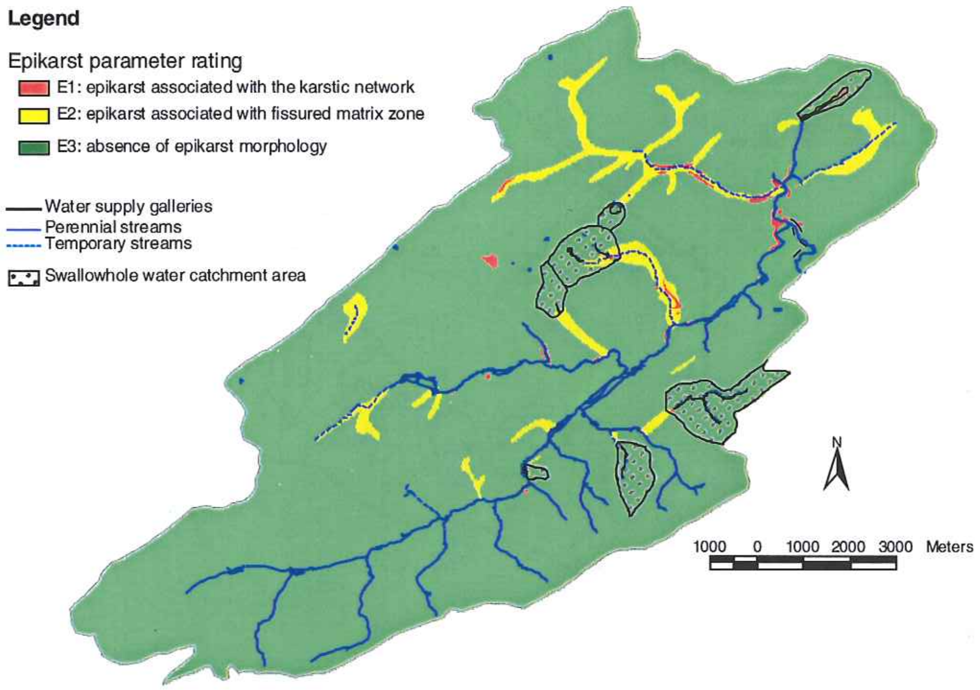
The existing map of soils represented the base for obtaining the map of soil parameters. Additional information concerning soil thickness, rock outcrops and quarries, was obtained in a field work campaign (Gaule 1998).

The map representing the land-use in terms of runoff coefficients was derived from the land use map provided by the National Geographical Institute of Belgium (1997).

4.6.2. Parameters for the EPIK method

Describing only epikarst features, the Epikast parameter (E) is specific to this method. As mentioned before, it can take three possible ratings: E1, E2, and E3. The Atlas of the Walloon karst (De Boyer et al. 1996), the aerial photos, and the region topographical maps (Hamoir, Clavier, Modave, Maffe, and Grandhan scale 1:10,000) were used in the first step for estimation of the E values. Also data coming from previous studies and field campaigns, completed the parameter rating process. The resulted Epikarst map (***Figure 4.11.***) show a quite uniform E3 value on the basin area. Related to the high karstification zones, the dry valleys are clearly marked. They are taking the value E2. E1 is given to areas where epikarst is linked directly to the karst network. This last value was chosen for the three swallowholes and for the other five diffuse losses, and also for the outcrops situated along the Néblon river, Fond-de-Bende, Fond-de-Wallou, and for the few existing sinkholes.

Figure 4.11. - The *Epikarst* (E) parameter map - EPIK



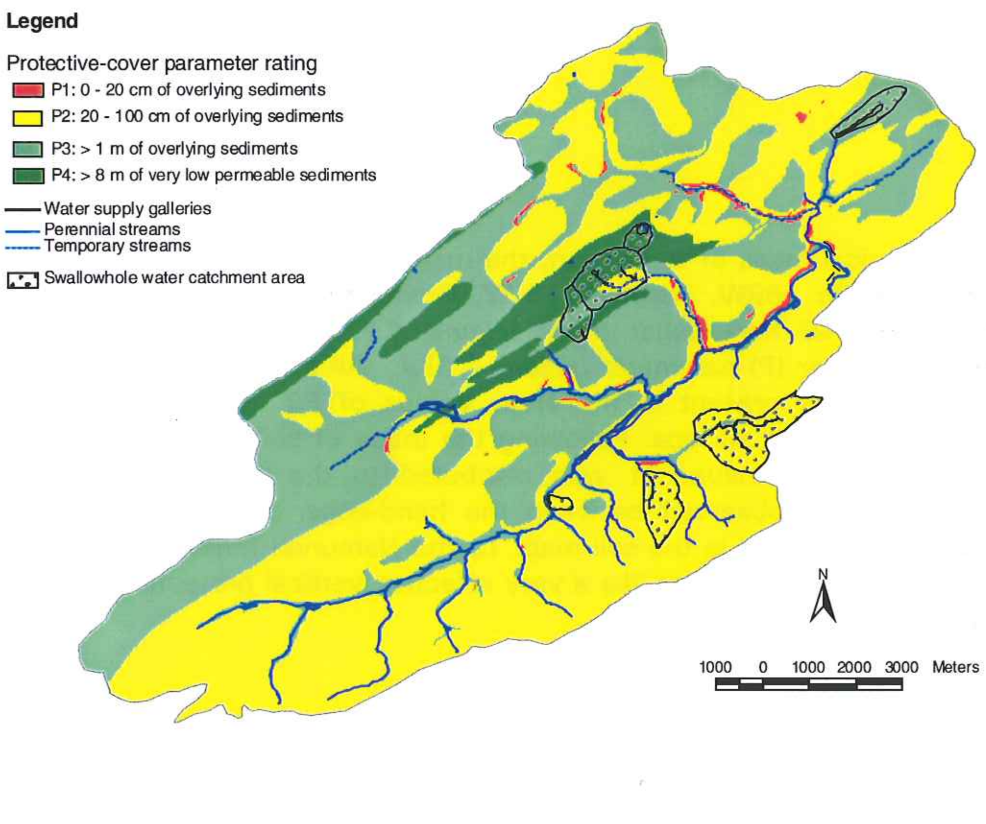


Figure 4.13. - The *Protective cover* (P) parameter map - EPIK

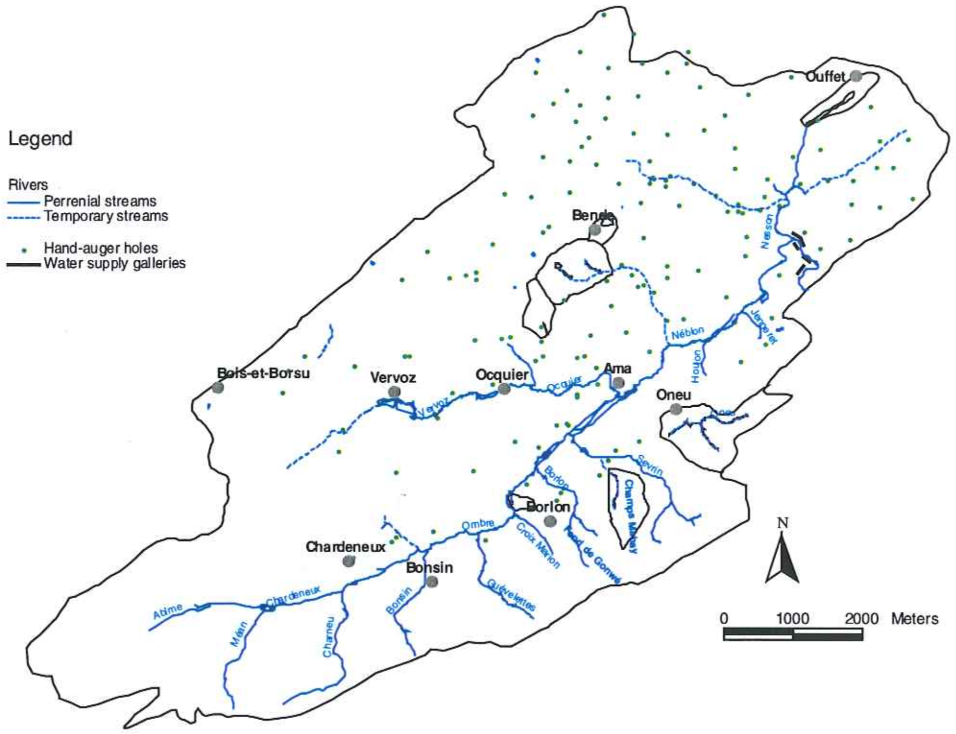


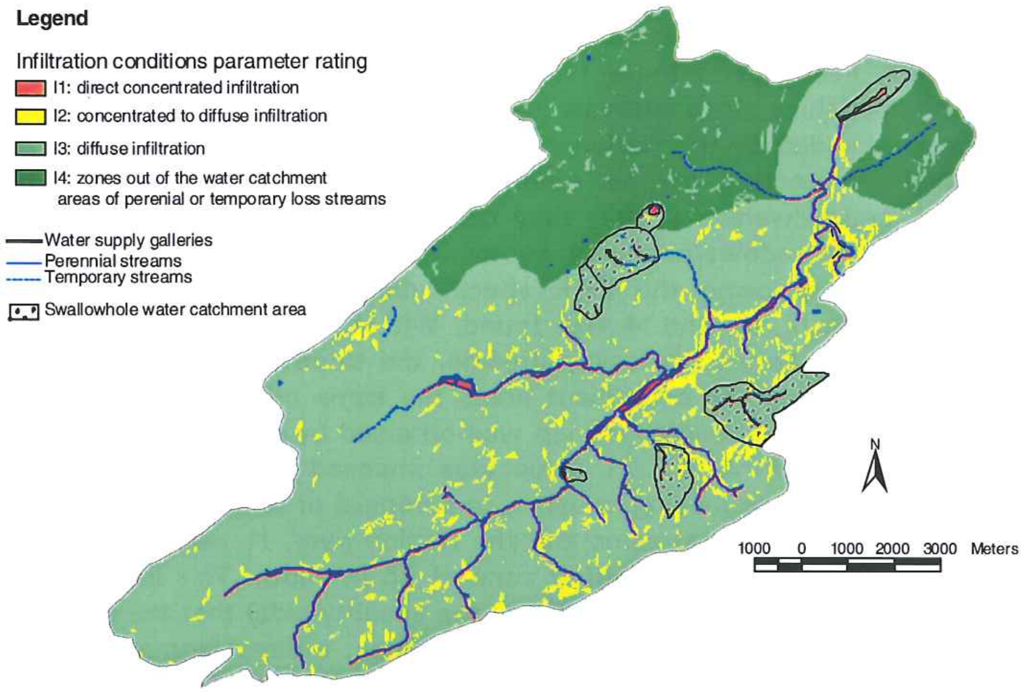
Figure 4.12. - Relative position of the 140 hand-auger holes used to complete the soil thickness data (1998 work campaign)

The geological maps of the region, the maps of soils scale 1:20,000 (Modave 157 W, Maffe 168W, Hamoir 158 W, Grandhan 168E), the boreholes logs, and about 140 hand-auger holes (***Figure 4.12.***) helped in quantifying the Protective cover (P) parameter (***Figure 4.13.***). All the four values designed by the method are present in the area. Values of P2 and P3 show a similar distribution on the surface. Following the maps of soil, to the alluvial valleys was given a P2 value. P1 was attributed to the rock outcrops. A good correlation was observed between the hand-auger holes data and the soil thickness mentioned in the soil map. To the Namurian formations was given a P4 value because they act like a very effective vertical protection for the main aquifer.

For delineating the I2, I3, and I4 values of the Infiltration conditions (I), the analysis started from the existing digital elevation model of Belgium made of 30x30 m square cells. In the analysed area two zones were identified as belonging or not to the catchment area of a stream or to the catchment area of a swallowhole. For each of these two categories a slope zoning was performed, considering the three slope intervals (0-10%, 10-25%, and > 25%). The land use raster map provided by the National Geographic Institute of Belgium (1997) was reclassified in function of the runoff coefficients, in two zones. Following Doerfliger and Zwahlen (1997) they can mainly correspond to cultivated and non-cultivated (meadows/pastures) sectors. Correlating this last map with the slope zoning map using the EPIK specifications, a map showing the areas corresponding to I2, I3, and I4 was found. Within the water catchment areas of the perennial and temporary losing streams, the slope criteria outlined I2 and I3 zones; in the rest of the catchment areas the same criteria delimited I3 and I4 zones. The Infiltration conditions map was obtained by overlaying the I1 value on this last map (***Figure 4.14.***). I1 value was imposed to areas corresponding to swallowholes and their feeding streams, to perennial or temporary streams, and to the Néblon river. For the streams and the Néblon river, I1 was assigned on both parts of the stream axe, on a buffer zone of 25 m width. This last decision was based on the pessimistic assumption (out the security side) that the river can be in contact with the aquifer in different zones and so, a direct contamination of the aquifer by the river could occur.

The Karst network (K) parameter map (***Figure 4.15.***) shows three distinct areas. The most part of the carbonate aquifer was assessed with K2. The decision is based on the results from geophysical studies (CILE, LGIH, INIEX 1986 and LGIH 1995 b) that have shown a great number of existing faults and fractures (***Figure 4.5.***). The same value of K2 is prescribed to the carbonate aquifer located under the Namurian formations. There, the karstic aquifer is supposed to be continuous. The geomorphology analysis and tracer tests results (Meus 1993) lead to the value of K1 on the supposed extensions of the karstic conduits. The supposed very karstified zones derived from the presence of swallowholes and from the dry valleys were rated with K1 (Doerfliger 1996). K3 value is assigned to the fissured sandstone aquifer as well as to the Tertiary sandy-clay deposits.

Figure 4.14. - The *Infiltration conditions* (I) parameter map - EPIK



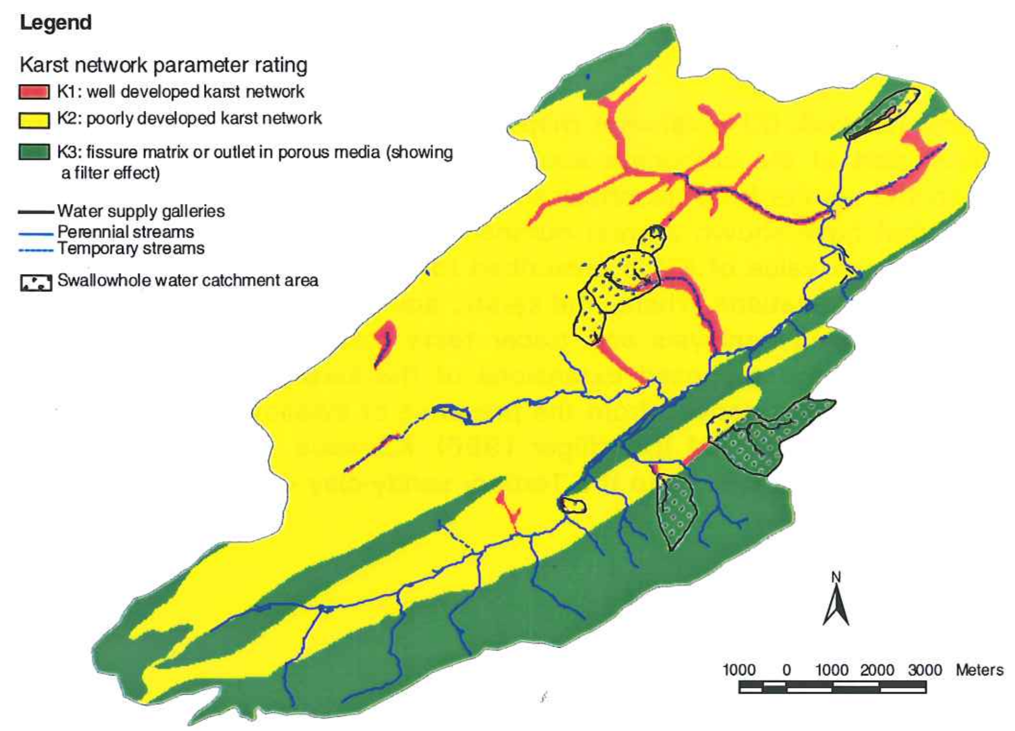


Figure 4.15. - The *Karst network* (K) parameter map - EPIK

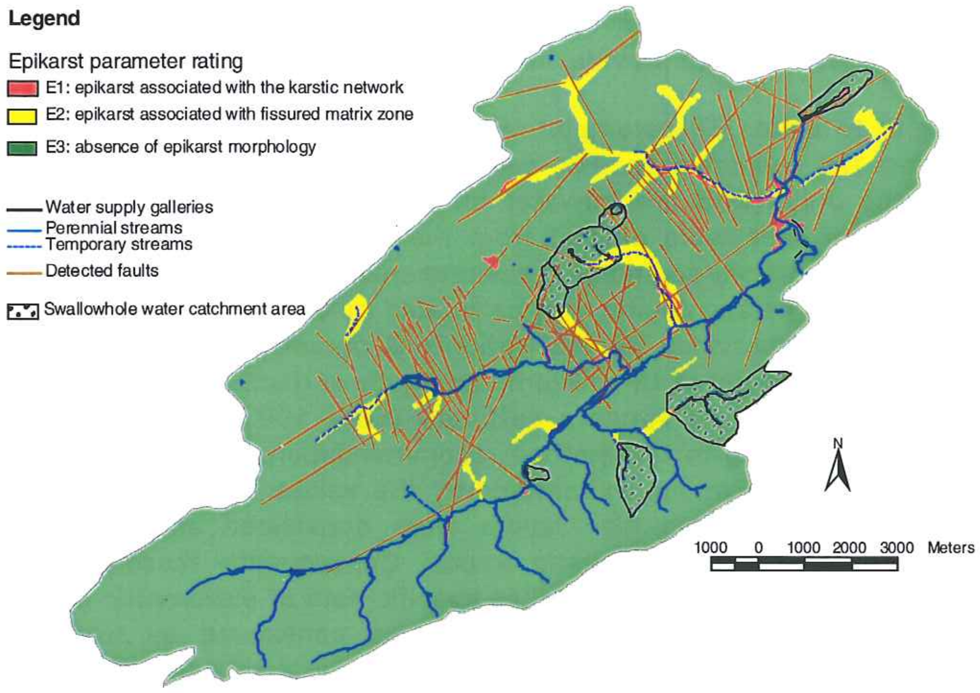


Figure 4.16. - *Epikarst* parameter in relationship with detected faults – EPIK

Geophysical prospecting could be better used to evaluate the epikarst morphology. Fractures and faults (***Figure 4.16.***) detected by geophysics were introduced in the Epikarst (E) parameter. For each fault and fracture a 5 m buffer zone (on each side) was generated. A value of E2 was chosen for them. This chosen value is related to the assumption that the faults and fractures acts as preferential flow paths. Maybe some of these faults could be major discontinuities or actual karstic conduits and so, a E1 value may be more appropriate for them. Unfortunately, more information concerning the real limit, dips, fissure geometry, relative roughness or filling is lacking, so that the value of E1 was considered too high.

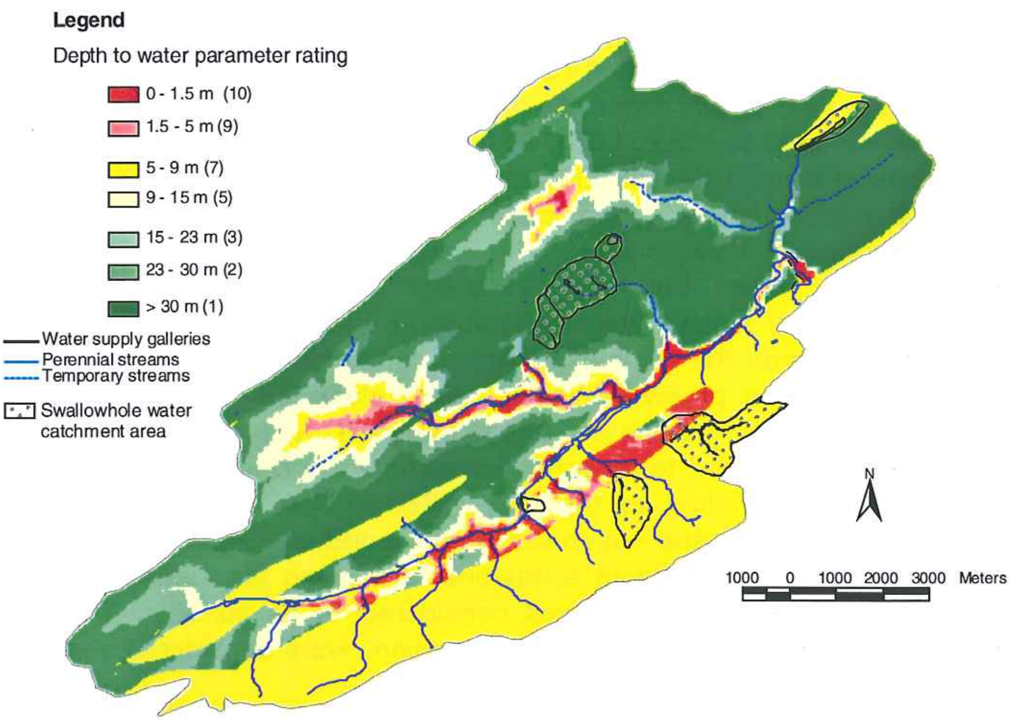
4.6.3. Parameters for the DRASTIC method

As described before, DRASTIC method is a general vulnerability assessment tool and not specific to karstic environment (Gogu and Dassargues 2000 a). However, this method was used to provide solutions also for karstic aquifers.

The Depth to water (D) parameter (***Figure 4.17.***) is considered very important in estimating the vulnerability. For calculating this parameter for Néblon karstic aquifer, the July 1998 groundwater reference level was used. The piezometric heads contour lines were derived from the Modave-Clavier hydrogeological map (LGIH 2000) and from additional measurements near the border zones. The depth to water for the karstic aquifer was calculated by extracting from the region digital elevation model (provided by the National Geographic Institute of Belgium), the digital elevation model of the piezometric heads surface. This operation was done within GRID module of Arc/Info software (ESRI 1997). The resulted grid was reclassified according to the method recommendation. To areas corresponding to the Namurian and Famennian formations, the values of the Depth to water (D) were imposed. The Namurian layers were considered as assuring a perfect protection for the underlain karstic aquifer. Consequently these areas took value of 1. For the Famennian sandstone, as specific data of piezometric heads were not available, the aquifer piezometric level was considered as having variations between 5 and 9 meters (LGIH 1989).

The Recharge (R) parameter (***Figure 4.18.***) was approximated as having a uniform distribution on the entire aquifer area. Exception is made in the zones corresponding to Namurian formations: considering that the groundwater recharge of the main aquifer is null below the Namurian formations, a value of 0 was assigned. The rest of the catchment area took the value of 8. It corresponds to a groundwater recharge interval of 188 - 255 mm/year. The assimilation is based on the recharge value of 210 mm/year, calculated within the groundwater numerical modelling study (LGIH 1995 a). Actually, this consideration represent a rough approximation.

Figure 4.17. *- Depth to water* (D) parameter map - DRASTIC



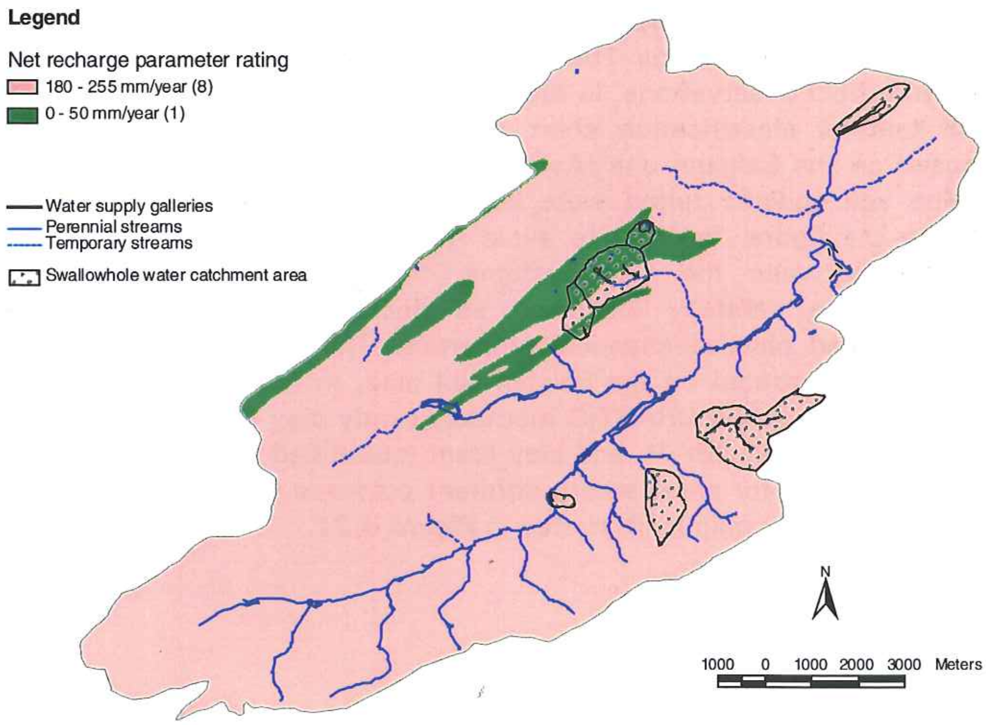
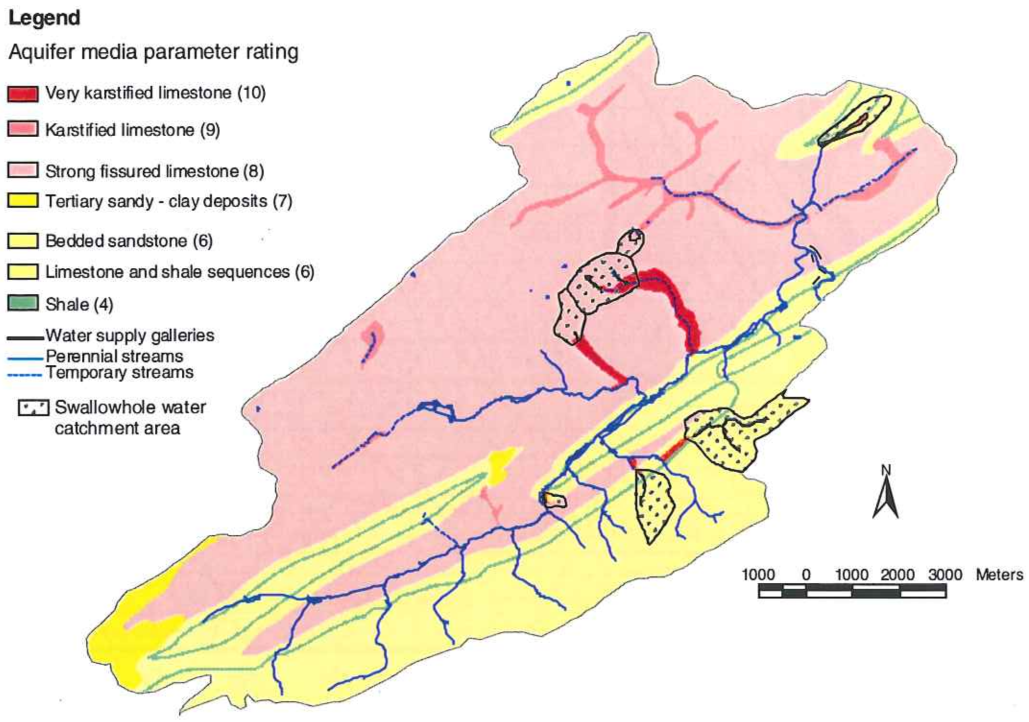


Figure 4.18. *- Net Recharge* (R) parameter map - DRASTIC

Aquifer media (A) parameter map (***Figure 4.19.***) is based on: the geological map of the region (Modave-Clavier 157, 1902 and Hamoir-Ferrières 158, 1902), the Modave-Clavier prototype hydrogeological map (LGIH 2000), the karst atlas of the Walloon region (De Boyer et al. 1996), the existing hydrogeological studies, and complementary field observations. Seven different zones can be seen on the map. The geophysical studies (CILE, LGIH, INIEX 1986 and LGIH 1995 b) pointed out a strong fractured zone in the Visean and in the Upper Tournaisian. In consequence a value of 8 was allocated. A clear distinction was made between the areas with different degrees of karstification. The method allowed to separate the very karstified zones from the less karstified ones. In consequence, areas corresponding to dry valleys were estimated as keeping a relative low degree of karstification and took the value of 9. Areas corresponding to possible extensions of the losing streams or swallowholes, were classified with a high degree of karstification. For them, a value of 10 was assigned. As mentioned previously, the karstic aquifer is supposed to be continuous under the Namurian formations. Most of the areas corresponding to the Lower Tournaisian took a value of 6. The exception was done for the supposed karstic conduits derived from the known swallowholes. To the Famennian sandstone was given the same value of 6. For the Strunian shale a value of 4 was considered to be suitable. Those Tertiary sandy-clay deposits that shown a large extension, were considered also very deep and took a value of 7.

Soil media (S) rating was based mainly on the map of soil scale 1:20,000 (Modave 157 W, Maffe 168W, Hamoir 158 W, Grandhan 168E) and completed with data coming from field observations. In order to match the DRASTIC soil classification, the soil textural classification chart (Aller et al. 1987) valid in U.S.A. was superposed on the Belgium one (Avril et al. 1984). The result is drawn in ***Figure 4.20.*** The soil specific terms were kept in the original language (English and French) on the figure, in order to avoid misunderstandings. To perform a good equivalence between the two systems, the units of the soil cartographic description were carefully examined as thickness, texture and mineralogy, permeability, and physical/chemical properties. The analysis allowed to regroup the soil units, illustrated on the Belgian soil map, in four categories: sandy loam (quantified with 6 in the DRASTIC method), sandy clay loam (quantified with 5), silty loam (quantified with 4), and clay loam (quantified with 3). The rating value of 10 was imposed for areas where different outcrops were noticed. The resulted Soil media parameter map is illustrated in ***Figure 4.21.***

Figure 4.19. *- Aquifer media* (A) parameter map - DRASTIC



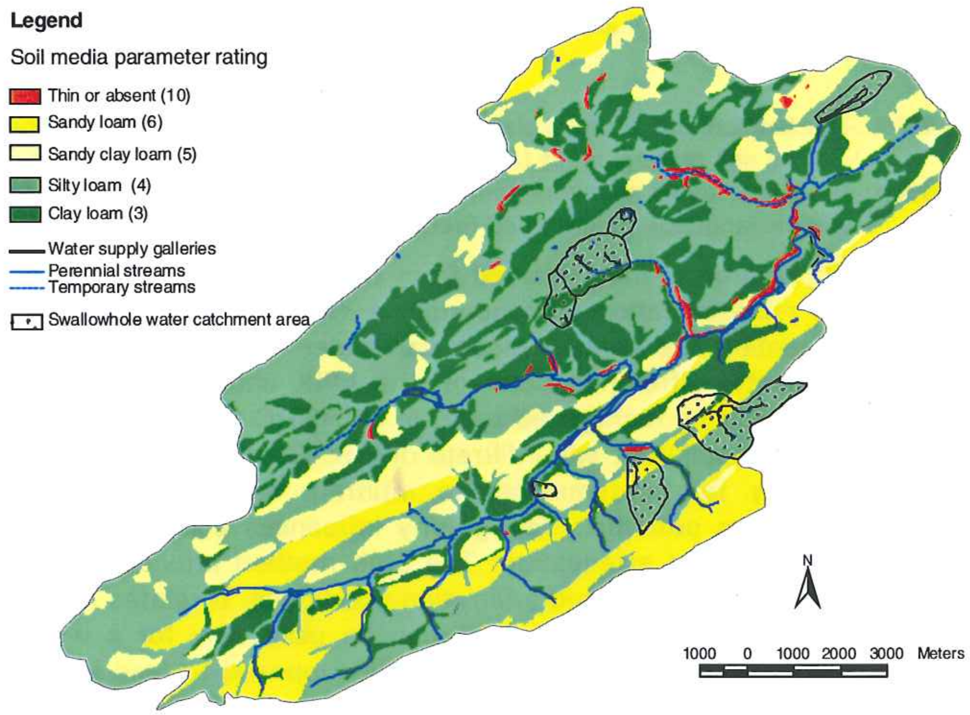


Figure 4.21. *- Soil media* (S) parameter map - DRASTIC

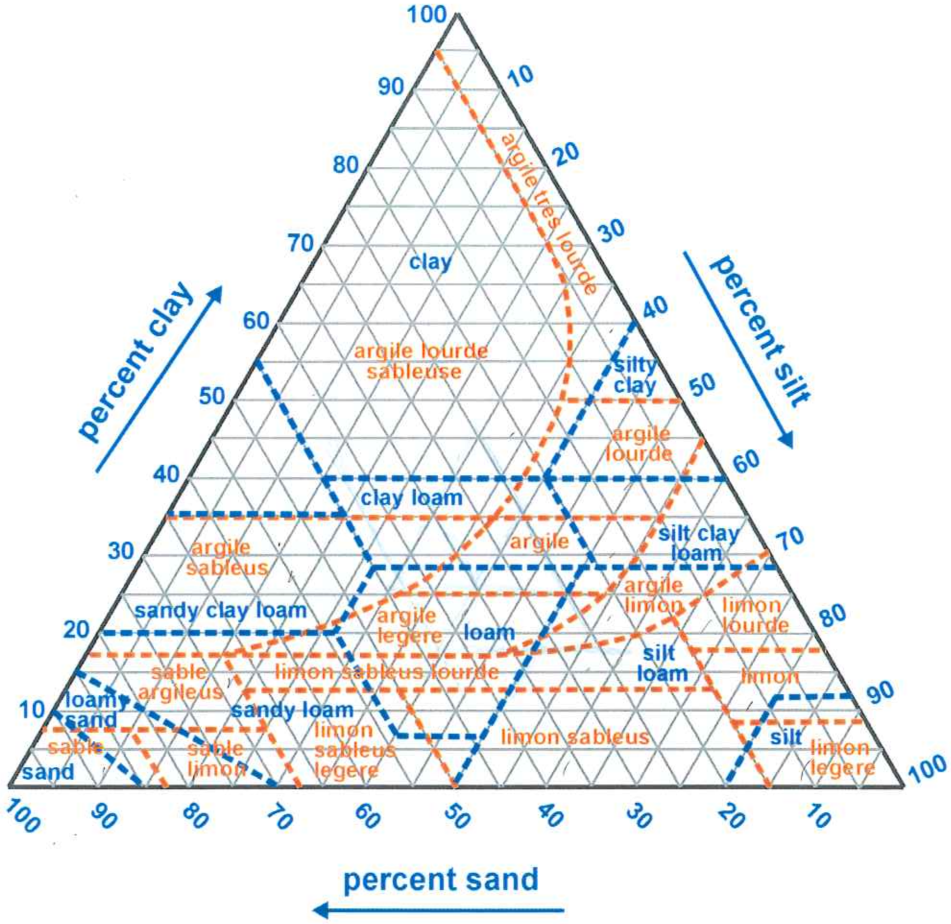
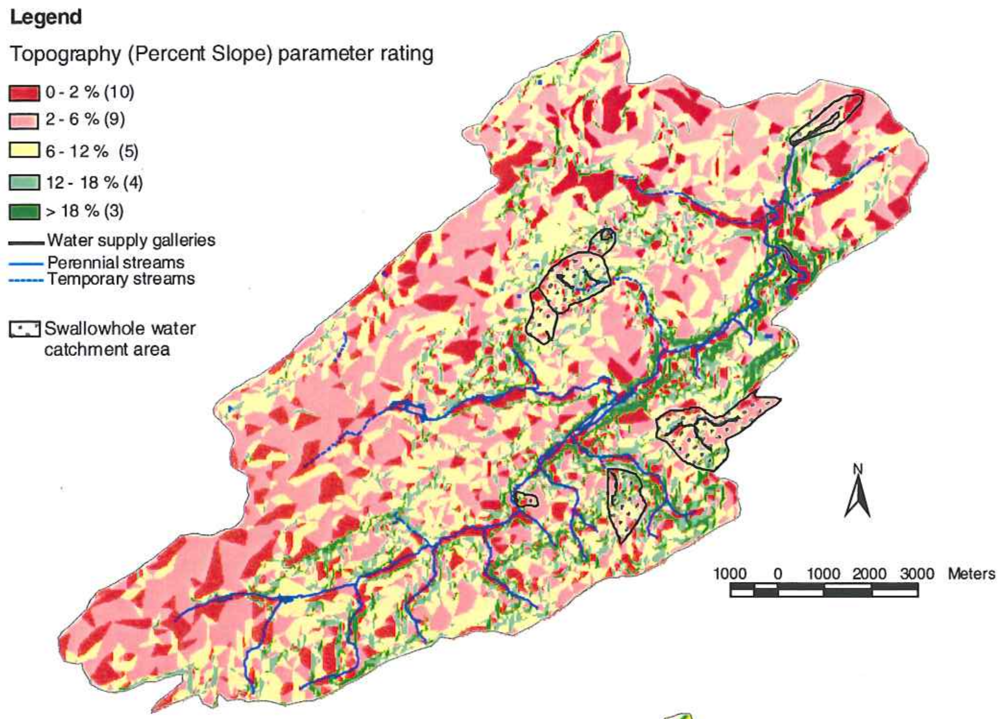


Figure 4.20. -The Belgium soil textural classification chart (Avril et al. 1984) superimposed on the soil textural chart (Aller et al. 1987) valid in U.S.A.

Observation: In order to avoid misunderstandings the soil specific terms were kept in the original language (English and French).

Topography (T) parameter map resulted from the digital elevation model by slope calculation and reclassification in concordance with the DRASTIC methodology. The map representing the percent slope parameter rating is illustrated in ***Figure 4.22***. A fundamental difference between the EPIK and DRASTIC concepts for classifying slopes can be highlighted here. In DRASTIC the slope helps to assess the likelihood that a pollutant will infiltrate or not. Gently slopes which provide a greater opportunity for contaminants to infiltrate are associated with higher groundwater pollution potential. Topography influences soil development having an effect on contaminant attenuation. The EPIK method provides a very specific karst concept about the slope and infiltration conditions. It relates a steeper slope to a higher degree of vulnerability. This can be used only for a well-developed karstic morphology where the existing runoff is supposed to feed karstic features (perennial or temporary loss streams, swallowholes, sinkholes). The arguments of EPIK method is that the surface runoff is directed to karstified infiltration points. However, this EPIK assumption is fragile when open valleys and fissure matrix hydrogeological conditions can be found. In this last case, it is more reasonable to consider that gentle slopes are facilitating vertical infiltration.

Figure 4.22. - *Topography* (T) parameter map - DRASTIC



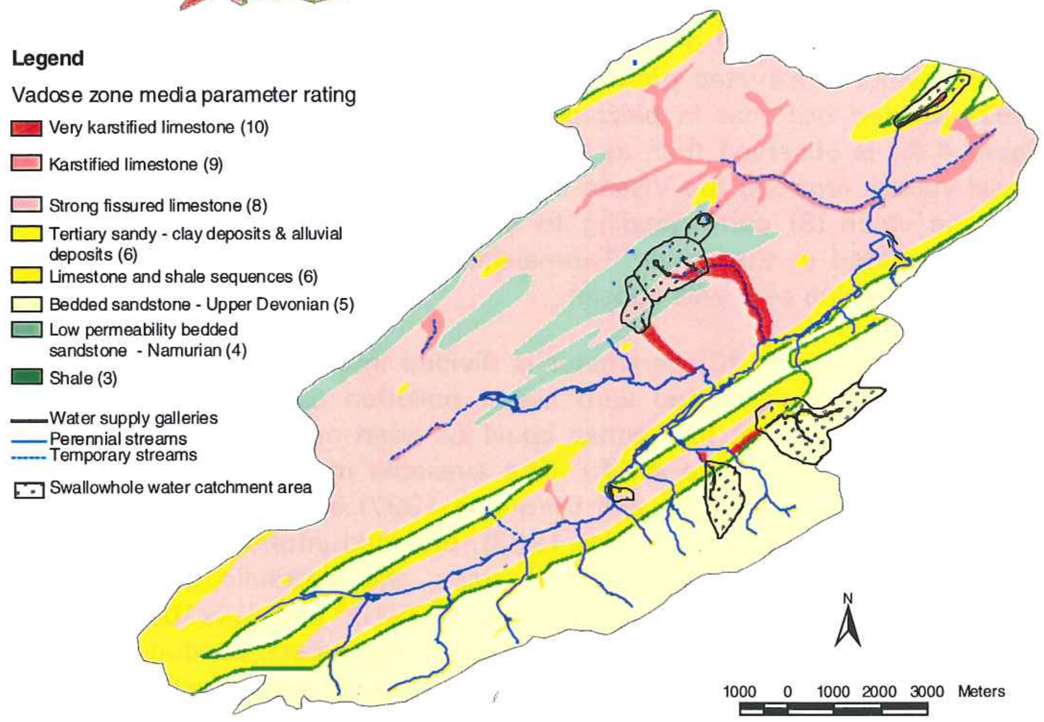


Figure 4.23. - *Vadose zone media* (I) parameter map - DRASTIC

The Vadose zone (I) is defined by Aller et al. (1987) as "that zone above the water table which is unsaturated or discontinuously saturated" and where "biodegradation, neutralisation, mechanical filtration, chemical reaction, volatilisation, dispersion" are the processes that occurs. Also, this media controls the path and the routing affecting the attenuation time and the quantity of the contaminant. The Vadose zone media (I) parameter quantification (***Figure 4.23.***) is based on the geological map of the region, the existing prototype of the hydrogeological map (LGIH 2000), the karst atlas of the Walloon region (De Boyer et al. 1996), the existing hydrogeological studies, and the field recognition results. The information was considered on the basis on the material below the soil horizon and above the groundwater table. For the Visean and the Upper Tournaisian parts outside the supposed karstic conduits, a value of 8 was chosen. This decision is related to the rating method and to the existing geophysical and hydrogeological data. Sectors as dry valleys and other parts showing a light karstification took the value of 9. A value of 10 was assigned to areas corresponding to the supposed groundwater conduits derived from losing streams and swallowholes. The value of 6 was taken by the Lower Tournaisian. The Namurian formations took a value of 4, meanwhile the Strunian shale a value of 3. To Famennian sandstone a value of 5 was assigned. All the Tertiary sandy-clay deposits referenced on the geological map took a value of 6. The alluvial valleys were considered as being in contact with the aquifer. Reasons sustaining this hypothesis were highlighted by Di Clemente and Laurent (1986) and by Dassargues and Derouane (1997). The recession coefficient of the Abîme stream found equal to 1.9×10^{-2} d^{-1}, is interpreted with the existence of an important aquifer having an elevated porosity due to fissuration. Dassargues and Derouane (1997) pointed out that in piezometer P18 (***Figure 4.6.***) the same water level (***Figure 4.8.***) is observed than as the river level (238 m). In consequence, to the alluvial valleys crossing the Visean and the Upper Tournaisian limestone are given the same value (8) corresponding to strong fissured limestone. For the alluvial deposits located in the Lower Tournaisian and those located in the Famennian sandstone, a value of 6 was chosen.

Hydraulic conductivity (C) parameter is divided into ranges where high hydraulic conductivities are associated with higher pollution potential. In concordance to DRASTIC classification, four zones could be seen on the Hydraulic conductivity (C) parameter map (***Figure 4.24.***). The available maps and the hydrogeological numerical model (Dassargues and Derouane 1997) added to several pumping and tracer tests (Meus 1993 and Gaule 1998), provided information used in designing this parameter. Except the karstified areas, the hydraulic conductivity of the limestone aquifer was considered between 4.7×10^{-5} and 1.4×10^{-4} m/s. The same interval was chosen for the sandstone aquifer. The karstic conduits and the lightly karstic zones could be differentiated with rates of respectively 10 and 8. The Strunian shale formations being much more impermeable, were included in the interval of 4.7×10^{-7} and 4.7×10^{-5} m/s.

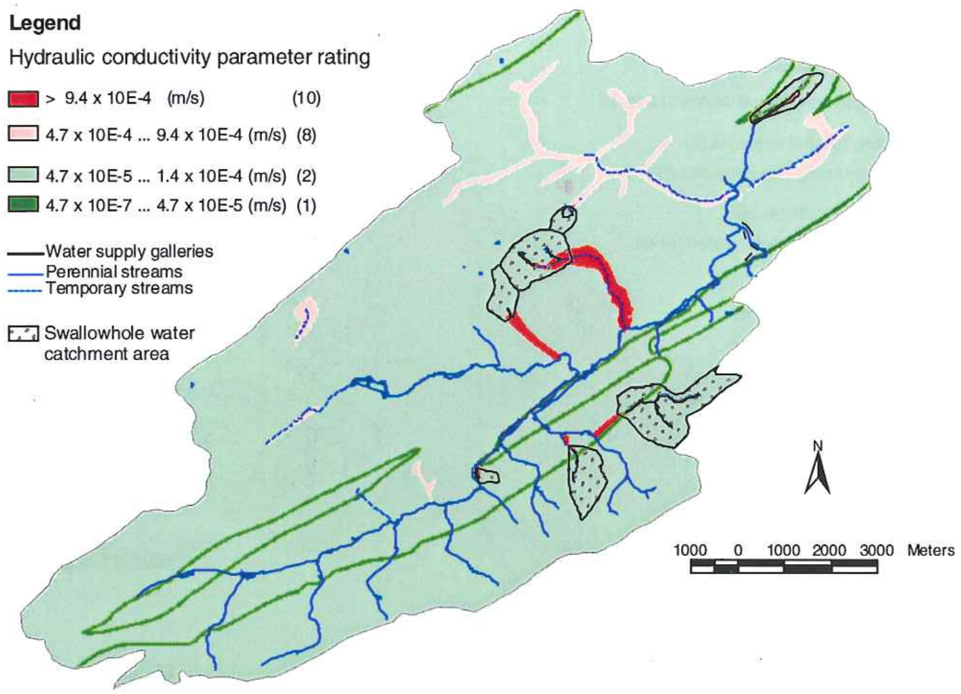
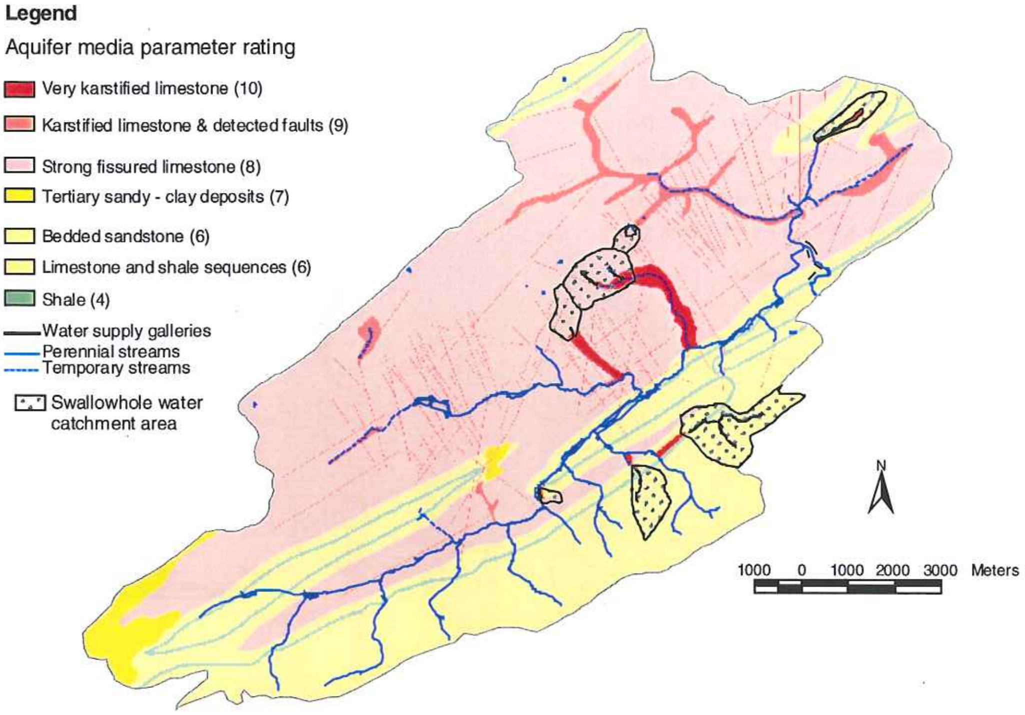


Figure 4.24. - *Hydraulic conductivity* (C) parameter map – DRASTIC

As done for the EPIK method, the detected fractures and faults were introduced in the parameter maps. This operation was done for the Aquifer media (***Figure 4.25.***), Vadose zone (***Figure 4.26.***), and Hydraulic conductivity (***Figure 4.27.***). On each of these parameter maps, for each fault and fracture a 5 m buffer zone was produced. These zones were rated for each parameter map with values corresponding to very strong fissured zones.

Figure 4.25. - *Aquifer media* parameter map considering the effect of the detected faults - DRASTIC



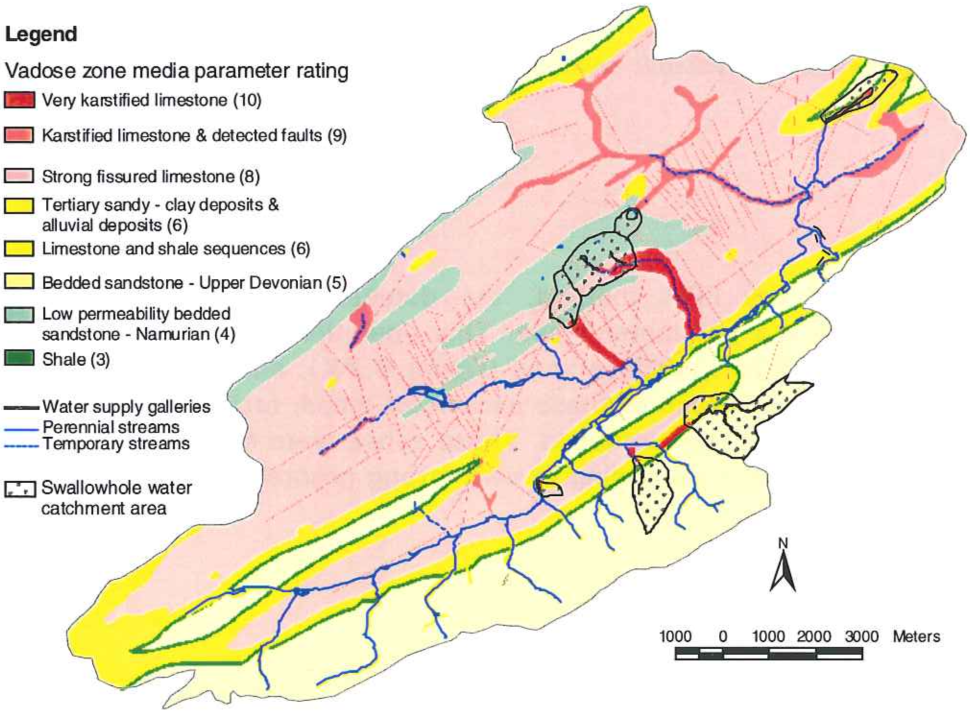


Figure 4.26. - *Vadose zone media* parameter map considering the effect of the detected faults - DRASTIC

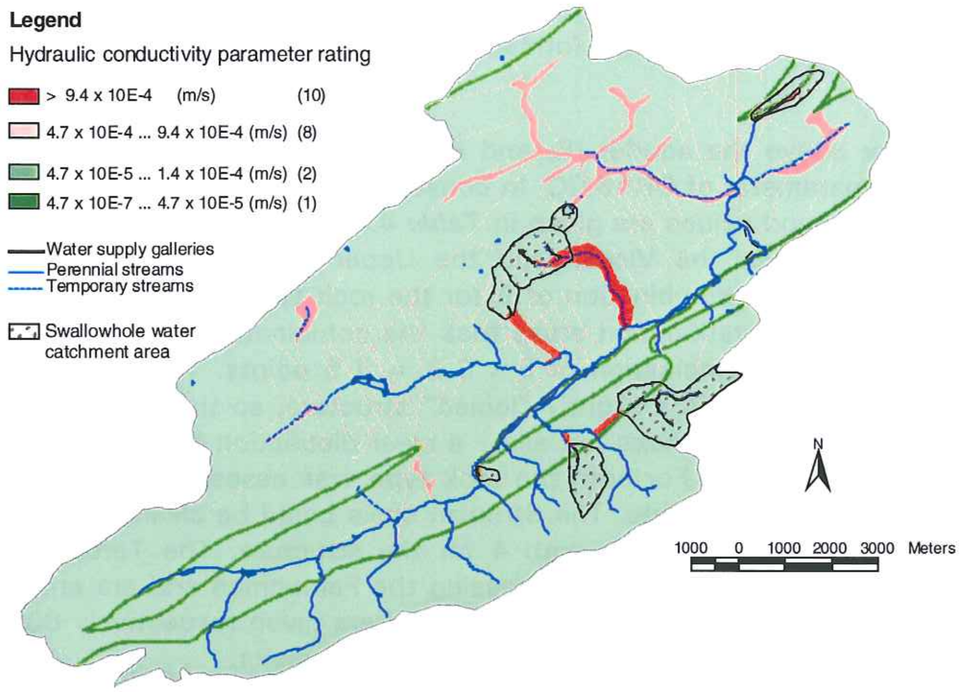


Figure 4.27. - *Hydraulic conductivity parameter map* considering the effect of the detected faults - DRASTIC

4.6.4. Parameter for the German method

This method is a rating system developed for a broad range of hydrogeological contexts in Germany. As karst occupies only 6.5% of the total surface of the country, the special characteristics of karstic morphology are listed but they have not received a specific attention.

The *Soil* (S) parameter is quantified taking into account the effective field capacity [mm/dm]. The effective field capacity was determined using standard tables, found in the pedological mapping handbook generally available in Germany, for the following types of soils: sandy loams (medium and strongly sandy), silty loam, clayey loam (slightly and medium clayey), sandy clayey loam and medium silty clay. Then the effective field capacity was multiplied by the thickness of the soil horizon. According to the methodology presented by von Hoyer and Söfner (1998), the resulted *Soil* parameter was almost constant on the entire study domain. Except the rock outcrops, values of 250 points were estimated. The rock outcrops took 10 points.

The *Percolation rate* (W) parameter was similarly quantified as the *Net recharge* (R) of the DRASTIC method. Consequently, the *Percolation rate* (W) parameter takes only two different values. The groundwater recharge of the main aquifer is also considered null below the Namurian formations. For the rest of the basin was introduced the value of 210 mm/year. These values are 1.75 for the areas corresponding to the Namurian formations and 1.25 for the rest of the catchment area.

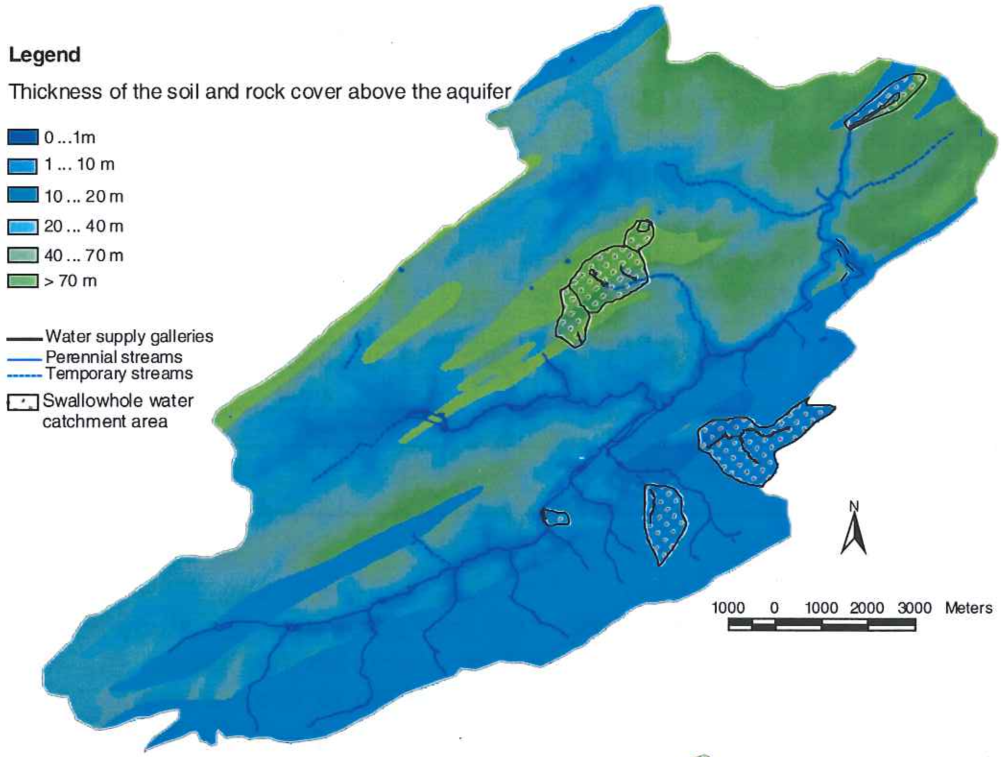
Rock cover above the aquifer (R_u and R_s) is the equivalent of the *Vadose zone material* (I) parameter of DRASTIC. In consequence the analysis was conducted in the same way and values are given in ***Table 4.4.*** The parameter map is illustrated in ***Figure 4.28.*** For the Visean and the Upper Tournaisian parts, outside the karstified sectors, a combination of 5 for the rock type and 1.0 for the structure was given. Light karstification areas took the combination of 5 × 0.5 and strong karstified zones a combination of 5 × 0.3 = 1.5 points. The Lower Tournaisian was assessed as having a slightly "joined" structure, so the given points are 5 × 4.0 = 20. The method does not allow a clear distinction between Namurian and Famennian formations. For both the rock type was assessed with 15 points and their structure with 4 points. The Strunian shale could be clearly distinguished by the combination of 15 points with 4 for the structure. The Tertiary sandy-clay deposits and the alluvial deposits crossing the Famennian and are entering in the class of unconsolidated rocks (R_u). To them were given respectively 60 points for the Tertiary deposits and 120 points for alluvial deposits.

The German method is also taking into account the thickness of the unsaturated zone: the parameter is called *Thickness of the soil rock above the aquifer* (T). It acts ***(Figure 4.29)*** as a direct multiplier for each different geological strata of the unsaturated zone. This multiplier represents the thickness value of the unsaturated zone (in meters). For the karstic aquifer and the Tertiary sandy-clay deposits, the parameter map is represented in ***Figure 4.29.*** It was determined in the same way as in DRASTIC, without the final reclassification. For the Famennian zones a mean value of 7m (LGIH 1997 b) was chosen. For the Namurian formations the thickness exceeds probably 70 m. In these case 500 additional points are given.

Table 4.4. - Ratings used for *Rock cover* above the aquifer (R_u and R_s) - German method

Rock type	Unconsolidated rock	Consolidated rock		Total points
		Rock type rating (O)	Structure (F)	
Very karstified limestone		5	0.3	1.5
Karstified limestone		5	0.5	2.5
Strong fissured limestone		5	1.0	5.0
Limestone and shale sequences		5	4.	20.0
Bedded sandstone – Upper Devonian		15	4.	60.0
Low permeability sandstone - Namurian		15	4.	60.0
Tertiary sandy-clay deposits	60			60.0
Shale		20	4	80.0
Alluvial deposits -slightly clayey loam	120			120.0

Figure 4.29. - *Thickness of the soil and rock cover above the aquifer* (T)
German method



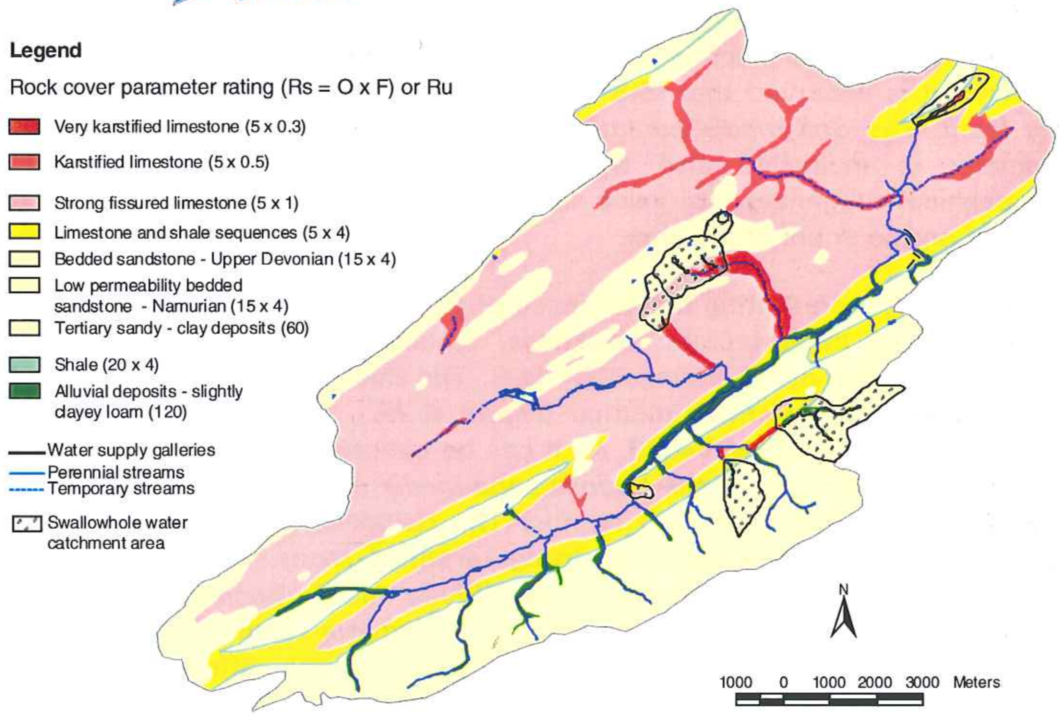


Figure 4.28. - *Rock cover, above the aquifer (Ru* and *Rs)* parameter map
German method

4.6.5. Parameters for the ISIS method

In this method the *Land use* is playing an important role through weighting (multiplying) each parameter. Multipliers take different values according to each parameter. The land use raster map was reclassified for each ISIS parameter, function of different criteria. The *Land use* type map is presented in ***Figure 4.30.*** For seeing the influence on each ISIS parameter, the *Land use* type map has to be correlated with the recommended coefficients written in ***Table 4.5.***

Table 4.5. - Recommended coefficients for the parameter weighting function of *Land use* - ISIS method

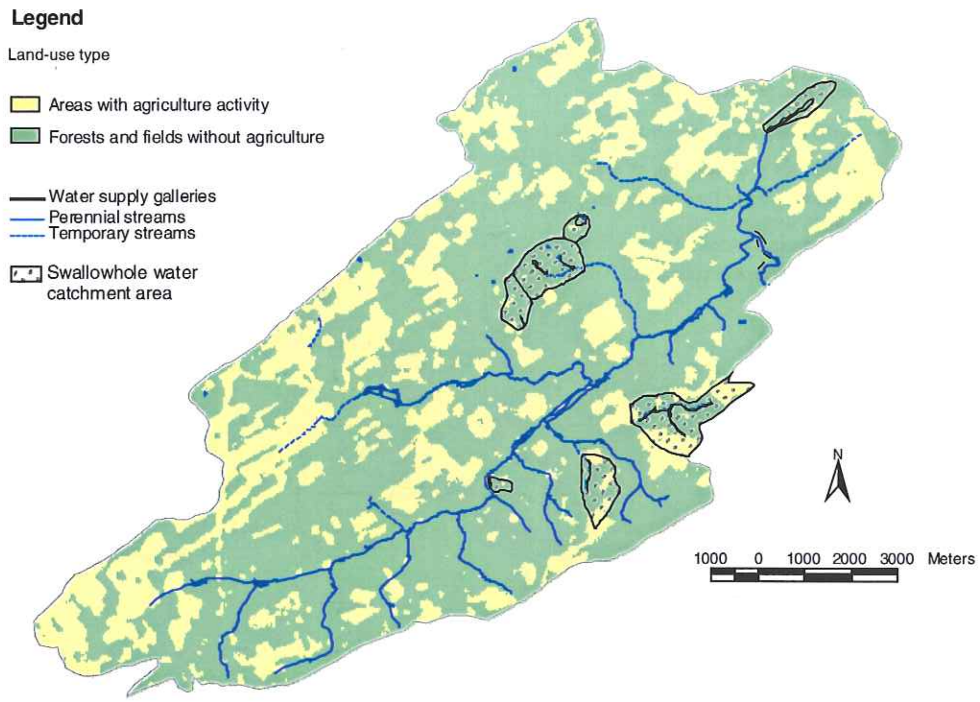
Conditions	Recharge	Soil	Unsaturated zone	Saturated zone
Normal	4	2	5	3
Intense agriculture	5	5	4	3

For mapping the *Effectiveness infiltration* (p_{inf}) parameter, the study area was divided in two zones. In zones corresponding to Namurian formations the recharge was considered 0 mm/year and the value of 1 is given to this parameter. The rest of the area is characterised with a value of 8, corresponding to 210 mm/year.

As the method was inspired from DRASTIC, a similar soil classification is used. However, it is observed that ISIS is rating with the same value a Silty loam and a Clay loam. The *Soil media parameter map* (p_{su}) can be seen in ***Figure 4.31.*** This parameter is multiplied also by a correction factor which depends of the topographical roughness. Its value corresponds to hilly regions (f_{su} = 0.9) and is constant on the entire study area.

The parameter representing the influence of the *Unsaturated zone* is established as a combination of three factors: thickness, lithology (p_{ins}), and a multiplying factor proportional to the media permeability (*cK*). The thickness of the unsaturated zone is the same as in the German method (***Figure 4.29.***). The other two parameters are shown in ***Figures 4.32.*** and ***4.33.*** As it can be observed in ***Figure 4.32.***, the lithology (p_{ins}) is taken analogous to the *Vadose zone media* parameter of DRASTIC. There are only small differences between ratings. The carbonate rock is divided in fissured, high fissured, light karstified, and strong karstified zones. The rating value for high fissured zones and lightly karstified zones (Civita and De Regibus 1995) is the same. For the permeability of the medium (*cK*), the parameter values representing the rating for high fissured zones and lightly karstified zones are different. Visean and the Upper Tournaisian zones are considered highly fissured and take a combination of 8 for lithology with 1000 for permeability multiplying factor (*cK*). Highly karstified zones were rated with a combination of 10 for lithology and 10,000 for *cK*. For dry valleys a combination of 8 for lithology with 10,000 for *cK* was chosen. The Lower Tournaisian was evaluated with 5 for lithology and *cK* = 100. For Namurian formations and Famennian sandstone a combination of 5 for lithology and 100 for *cK* was prescribed. To the Strunian shale as a very low permeable rock, was given 2 for lithology and 100 for *cK*. The Tertiary sandy-clay and the alluvial valleys were quantified with 4 for lithology and 100 for *cK*.

Figure 4.30. – *Land-use* type map - ISIS



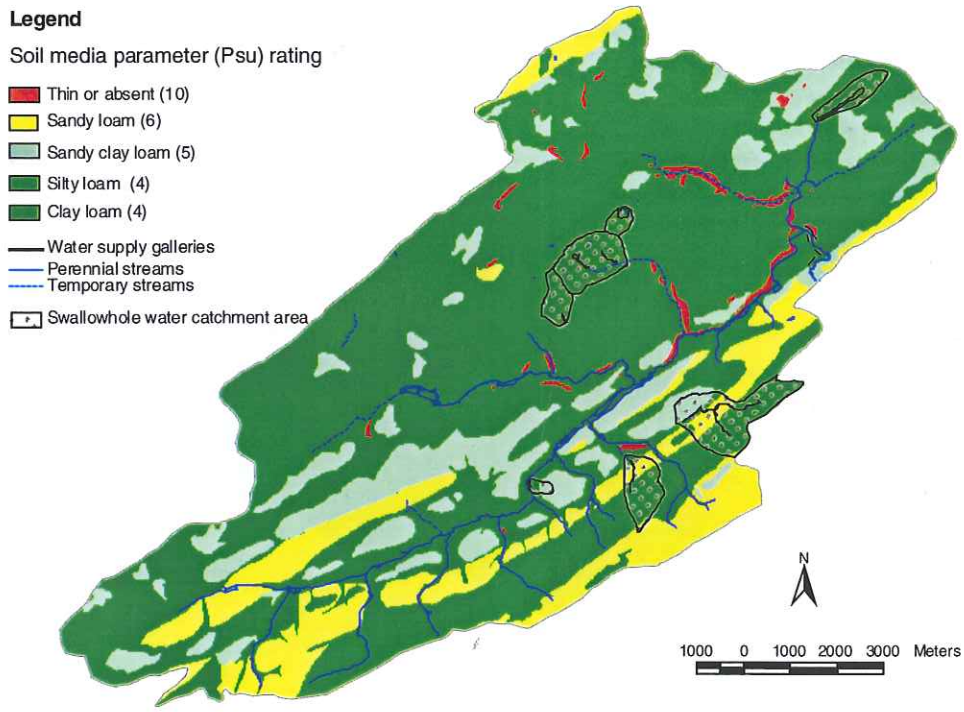
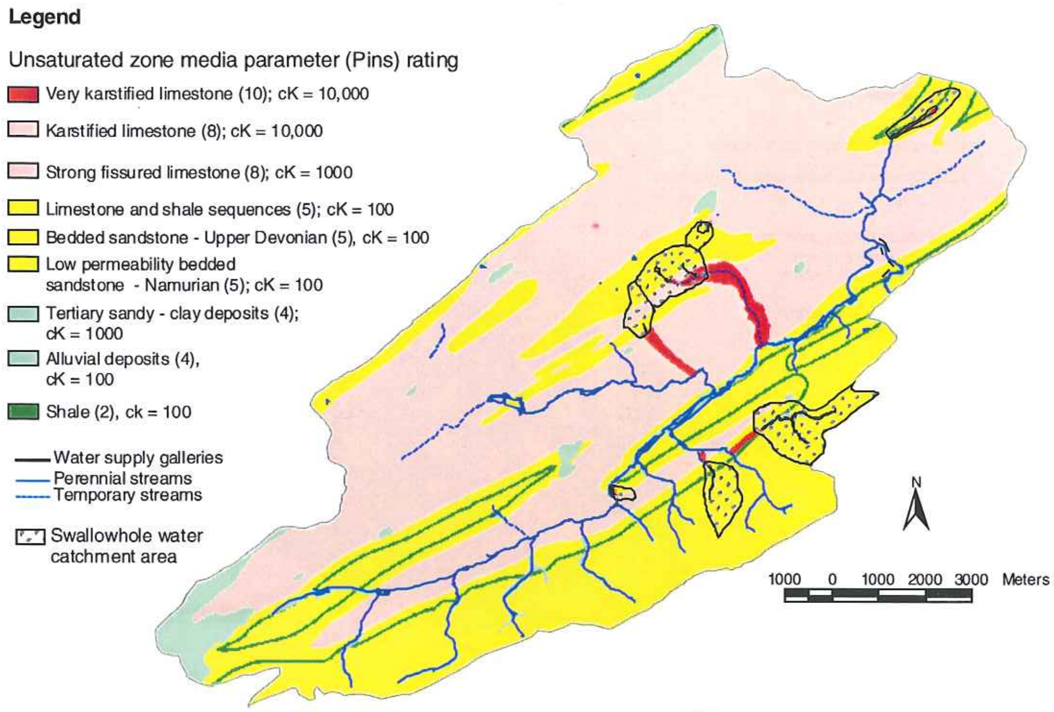


Figure 4.31. - *Soil media* parameter (Psu) map – ISIS

Figure 4.32. - *Unsaturated zone media* parameter (Pins) map - ISIS



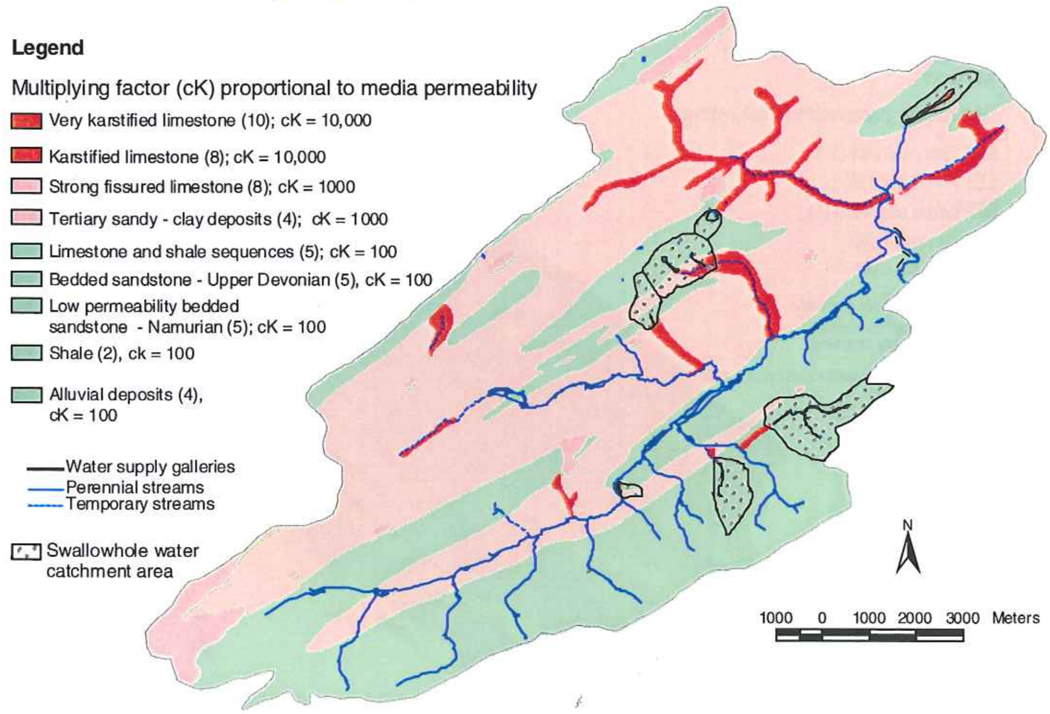


Figure 4.33. - Map of the *multiplying factor* proportional to the *media permeability* (cK) - ISIS

For the *Unsaturated zone* parameter, the proposed method fails. A multiplying factor (f_{Si}) is calculated by equation 4.1. The mentioned formula can be used as far as the unsaturated zone thickness has a value smaller than *cK*. On the contrary, when the thickness value is equal or higher than the *cK* value, the term is zero or negative. This fact is interpreted as a problem, because in the published method (Civita and De Regibus 1995) the f_{Si} has to take values between 0 and 1. If a negative value appears the term acts in the sense of decreasing the vulnerability index.

$$f_{Si} = (1 - \textit{unsaturated zone thickness}/cK) \qquad (4.1)$$

The *Aquifer media* (p_{sat}) parameter map is shown in ***Figure 4.34.*** This parameter is similar to the DRASTIC *Aquifer media* parameter. The difference is that dry valleys could not be differentiated of the rest of the fissured carbonate aquifer. As multiplying factor related to the aquifer thickness (f_{ss}), the value of 1 was selected. This value corresponds to strong uncertainties about the aquifer thickness data.

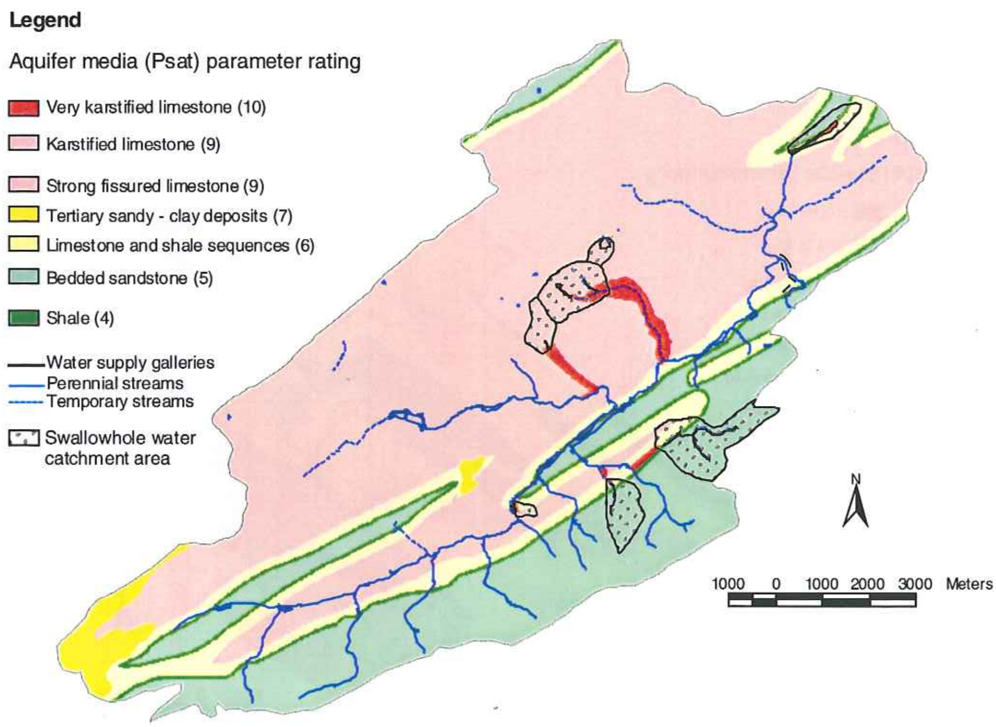


Figure 4.34. - *Aquifer media* parameter (Psat) map - ISIS

4.6.6. Parameters for the GOD method

Like other general methods for assessing vulnerability, GOD considers karst aquifers as having a high or an extreme vulnerability. However, this method is not focusing the specific particularities of karstic aquifers. As it can be seen in the GOD flowchart (***Figure 2.1.***), the *Groundwater occurrence* is the first parameter that is taken into account. According to the aquifer conceptual scheme, the parts of the main aquifer below the Namurian formations were estimated as confined zones. The rest of the aquifer is considered unconfined. This is shown in ***Figure 4.35.***

The *Overlying lithology* is mapped in ***Figure 4.36***. According to the method, only five distinct values could be defined for this parameter. The limestone aquifer was divided in three parts: karstified limestone (1.), highly fissured limestone (0.9), and limestone with shale sequences (0.8). To Namurian formations, Fammenian sandstone, as well as crossing alluvial valleys were given the same value (0.7). For the Strunian shale a value of 0.6 was assigned.

Following the chart presented in ***Figure 2.1.***, the *Depth to water* is the last parameter to be evaluated. The delineated areas are illustrated in ***Figure 4.37.***

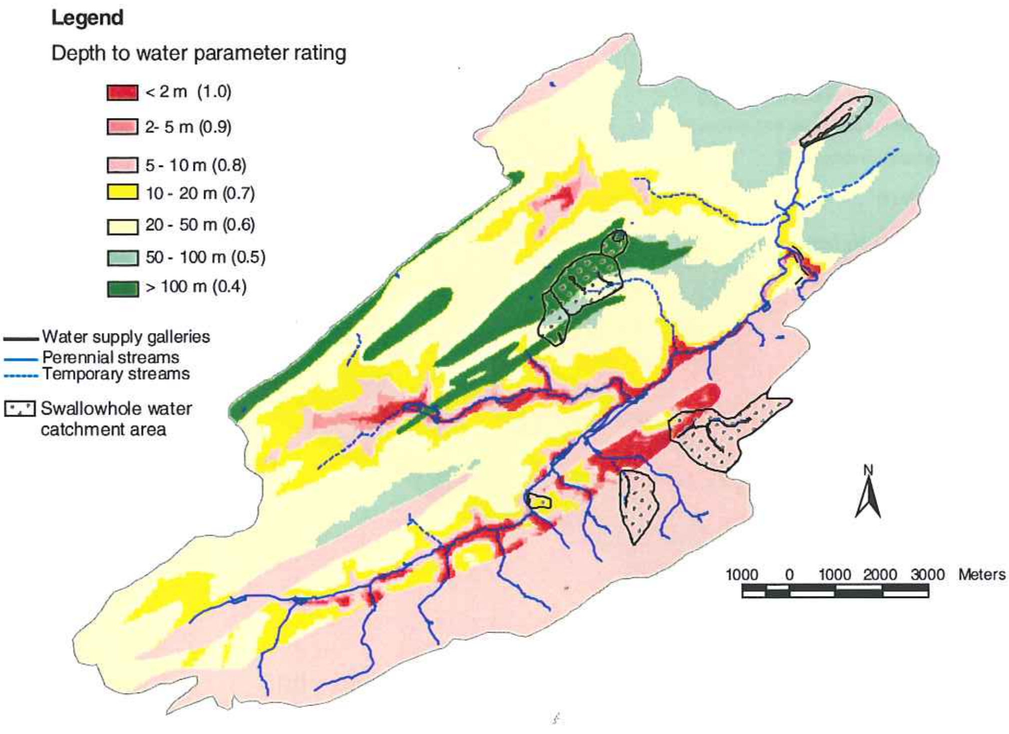
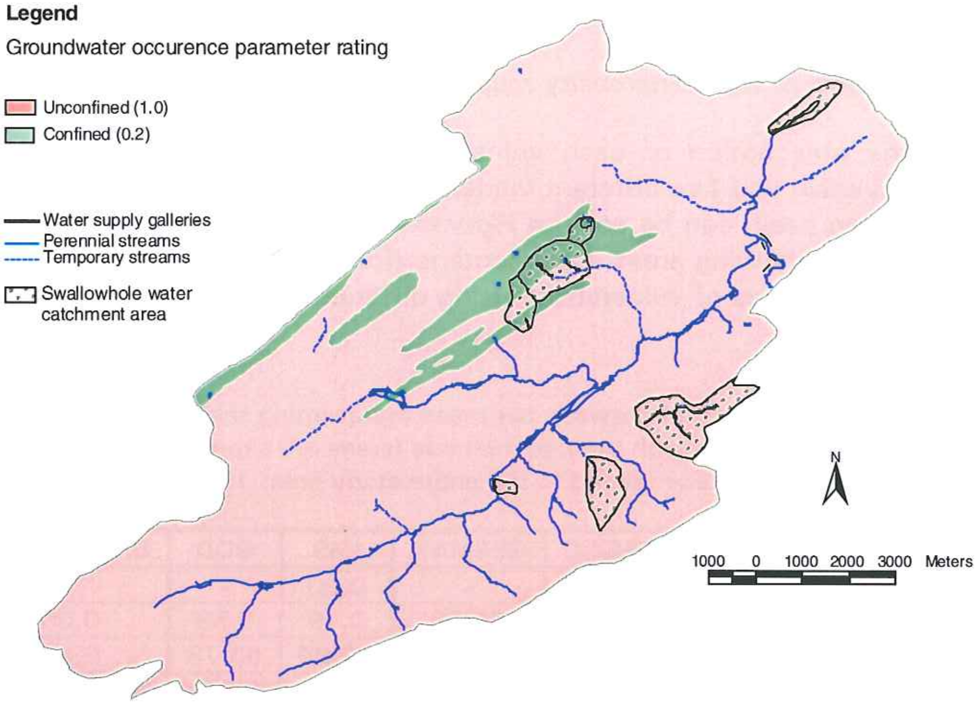


Figure 4.37. - *Depth to water* parameter map - GOD

Figure 4.35. - *Groundwater occurrence* parameter map - GOD



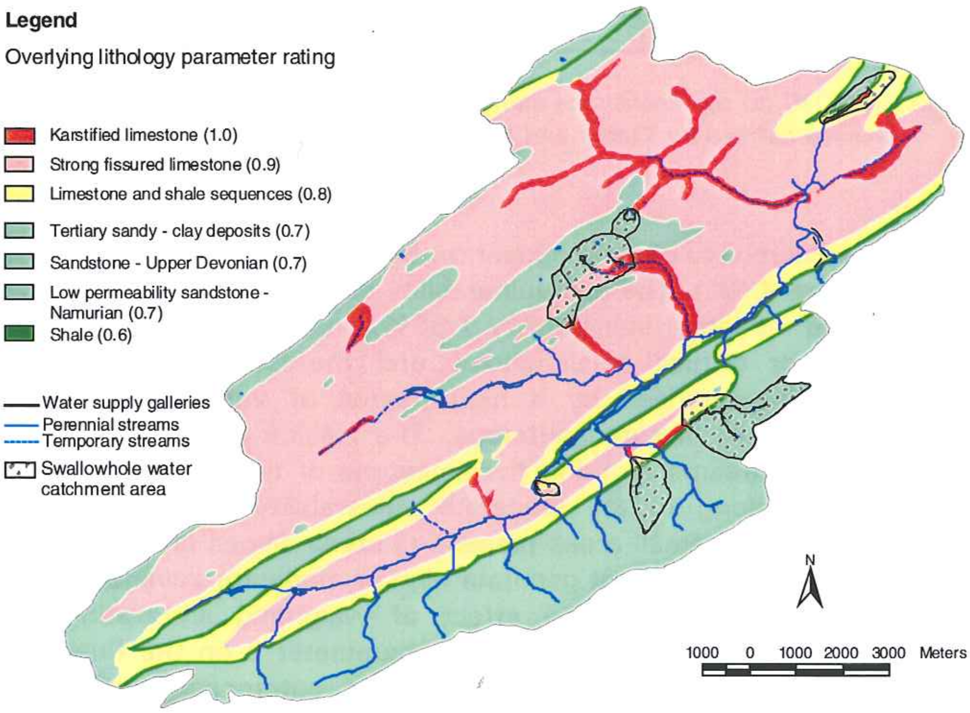


Figure 4.36. - *Overlying lithology* parameter map - GOD

4.7. Vulnerability analysis results

4.7.1. Description of the vulnerability maps

Following the prescription of each vulnerability method, the quantified parameter maps were overlaid and five different vulnerability maps were produced. The resulted maps for Néblon basin can be seen in ***Figures 4.38., 4.39., 4.41., 4.42.***, and ***4.43.*** The ***Table 4.6.*** is showing areas in percentage (for the analysed zone of 64.69 km^2), for the different classes of vulnerability using different methods.

Table 4.6. - 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% represent 64.70 km^2)

	EPIK	DRASTIC	GERMAN	ISIS	GOD	DRASTIC (b)
extreme	-	-	-	0.00	-	-
very high	-	0.16	34.28	0.19	9.53	0.00
high	0.66	5.01	48.29	***62.90***	63.73	0.59
moderate	7.81	73.04	7.56	29.11	20.49	14.83
low	***91.52***	15.63	3.61	2.69	0.00	84.57
very low	-	6.15	6.25	5.11	6.25	-

Obs.: DRASTIC (b) represents the same method DRASTIC where the vulnerability classes defined by Kumar and Engel (1997) were used.

The three main vulnerability classes appear on the final vulnerability map obtained by **EPIK** method (***Figure 4.38.***). The low vulnerability class occupy about 91.52% of the examined area, the moderate vulnerability 7.81%, and the high vulnerability 0.66%. The concentrated or diffuse swallowholes and the losing streams feeding the swallowholes are characterised by a high degree of vulnerability. In the same category appear also the fissured outcrops. The Néblon river in contact with the aquifer, its tributary streams crossing the limestone or the sandstone, and the few mapped sinkholes, belong to the moderate vulnerability class. Also dry valleys, Néblon gorges, and other small areas presenting steep slopes are taken in the same category. The slope criteria did not generate high or moderate vulnerable zones in the swallowholes catchment areas. The effect of weighting and rating (Gogu and Dassargues 2000 b) is strongly imposing the parameter E on the final vulnerability map (***Figure 4.11.*** and ***Figure 4.38.***). For some outcropping epikarst features, vulnerability can be overestimated. To the highly fractured natural outcrops are given the same vulnerability degree as to the artificial outcrops (quarries and along roads or railways). However, the non fissured outcrops or those who do not have a direct contact with the aquifer may be much less vulnerable than the zones between dolines or dry valleys (characterised with E2).

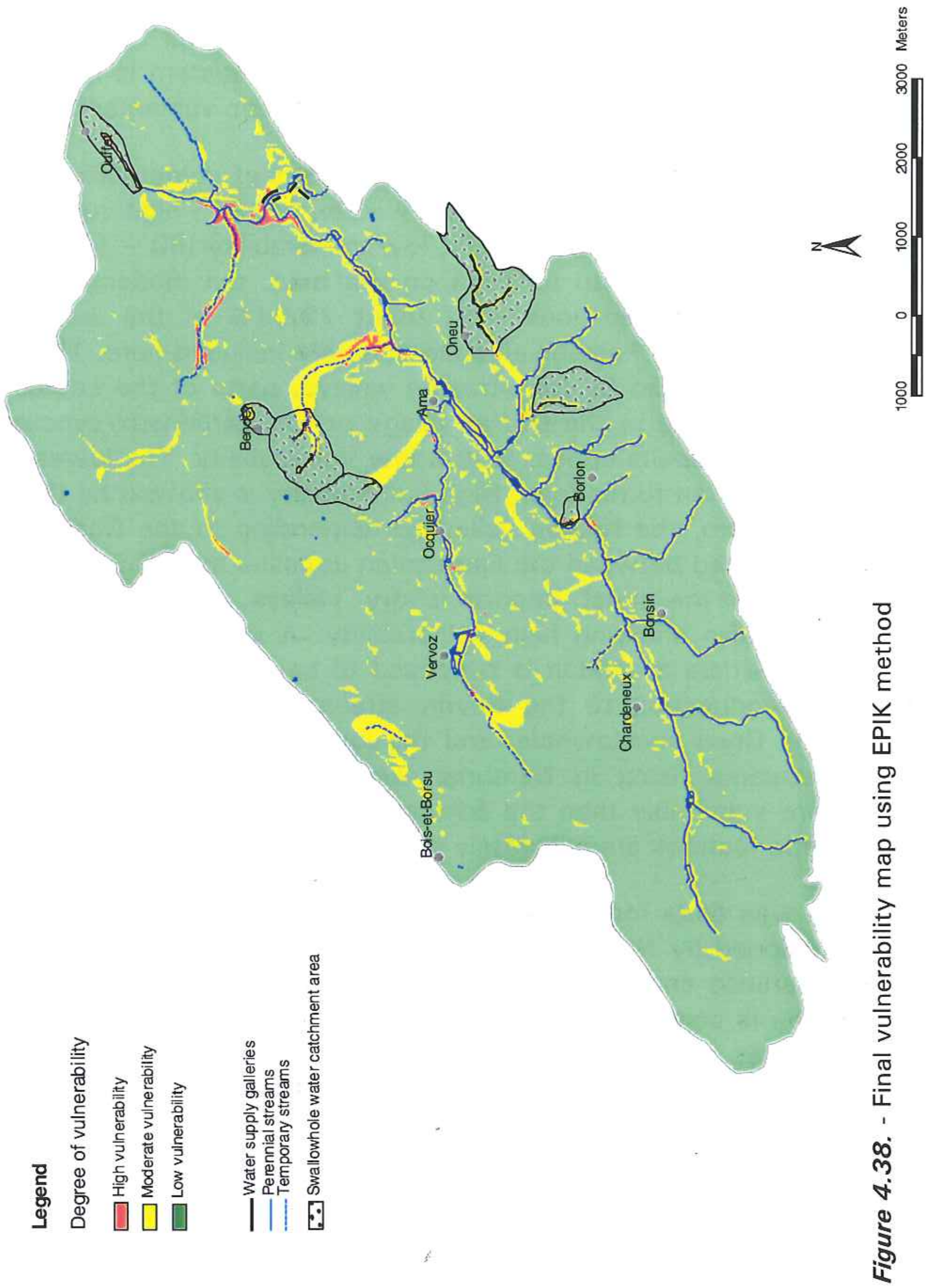


Figure 4.38. - Final vulnerability map using EPIK method

The initial **DRASTIC** method published by Aller et al. (1987) is not providing vulnerability classification ranges, but allows the user to interpret the vulnerability index using its field knowledge and hydrogeologic experience. In the literature two distinct classification ranges are defined. The commonly used classification of vulnerability index (Atkinson and Thomlinson 1994, Civita and De Regibus 1995, Corniello et al. 1997) conducted to the vulnerability map illustrated in ***Figure 4.39.*** Navulur and Engel (1997) modified this classification in order to increase the effect of the land use and fertiliser usage. Actually, this last system is leading to specific vulnerability assessments for pesticide and not to intrinsic vulnerability.

The common classification system define five classes of vulnerability (***Figure 4.39.***): very high vulnerability (DRASTIC vulnerability index > 199), high vulnerability (160 – 199), moderate vulnerability (120 – 159), low vulnerability (80 – 119), and very low vulnerability (< 79). As it can be seen on the map, the moderate vulnerability is distinctly the most extended zone with about 73.04% of the area. Most of the fissured limestone and the Famennian sandstone are included here. The thin Strunian shale bands locally crossed by the streams valleys, parts of the Lower Tournaisian limestone (as those close to the Ouffet village or to Chardeneux synclinal), and the Tertiary sandy-clay deposits appear with a low vulnerability. The lowest vulnerability is given to the Namurian formations. High vulnerability is showed by the entire valley of the Ocquier stream, the Néblon valley corresponding to the Chardeneux stream, the small valley located between the Famennian anticline axis of Borlon and the Oneu village, as well as the most important dry valleys. Very locally, the mapped swallowholes are also showing high vulnerability. A very high vulnerability can be found for a zone where a conduit is supposed to be present in relation with a small swallowhole in connection to the Sevrin stream, a supposed karstic conduit in relation with the Oneu swallowhole, and the lower part of the Fond de Wallou dry valleys. The streams rising in Namurian and feeding the swallowholes are not considered more vulnerable than the adjacent zones. However, in general the most significant karstic features are accurately outlined by this method.

A second map was done for the DRASTIC method with the use of the vulnerability categories mentioned by Navulur and Engel (1997). This step was made only for a quantitative reference and not considered as a valid result in the analysis (because this classification is particular to the specific vulnerability assessment). The authors defined four classes of vulnerability (***Figure 4.40.***): very high vulnerability (DRASTIC vulnerability index > 230), high vulnerability (181 – 230), moderate vulnerability (141 – 180), and low vulnerability (1 – 140). In the ***Table 4.6.***, the areas corresponding to this classification are placed in the DRASTIC (b) column.

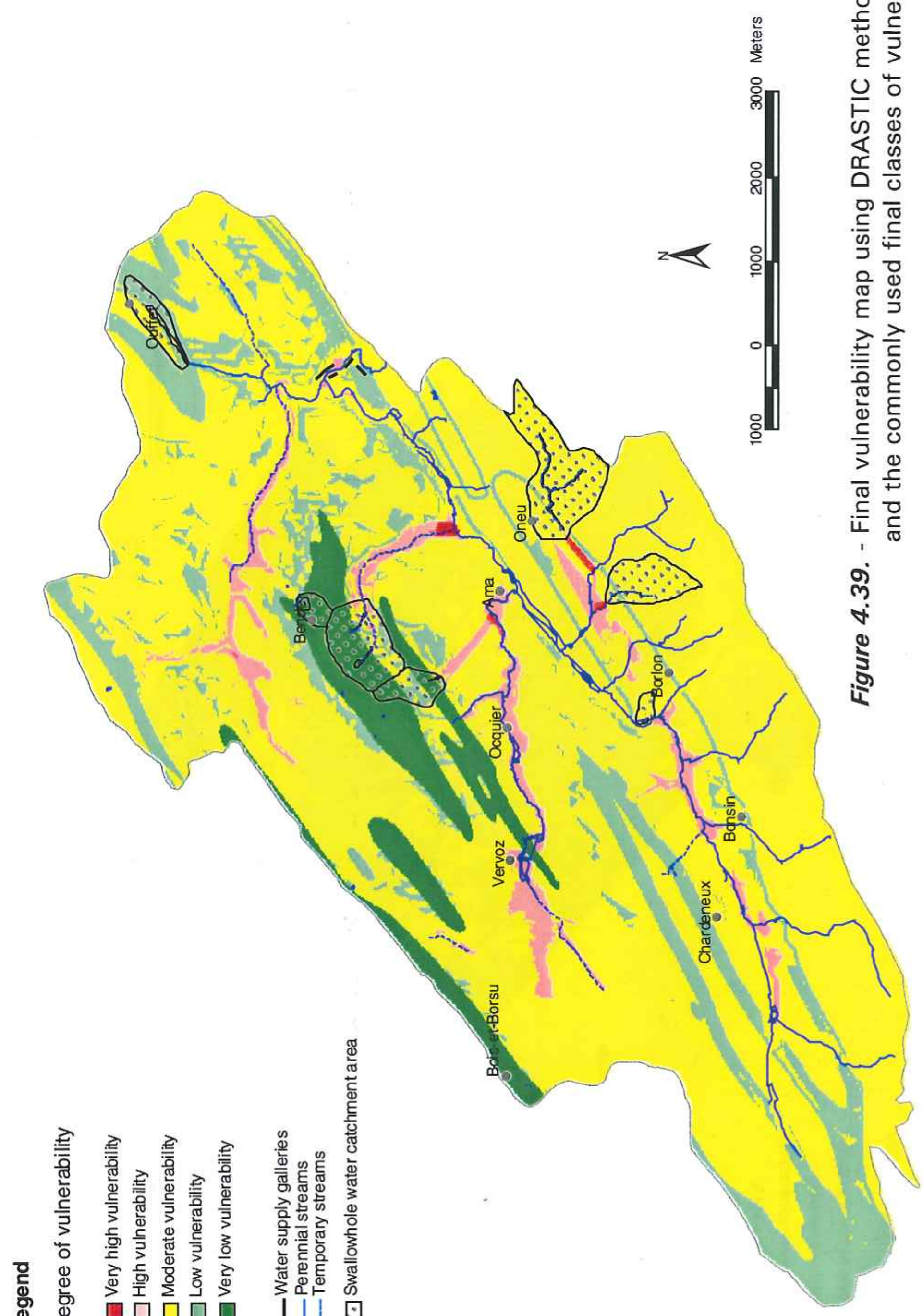


Figure 4.39. - Final vulnerability map using DRASTIC method and the commonly used final classes of vulnerability

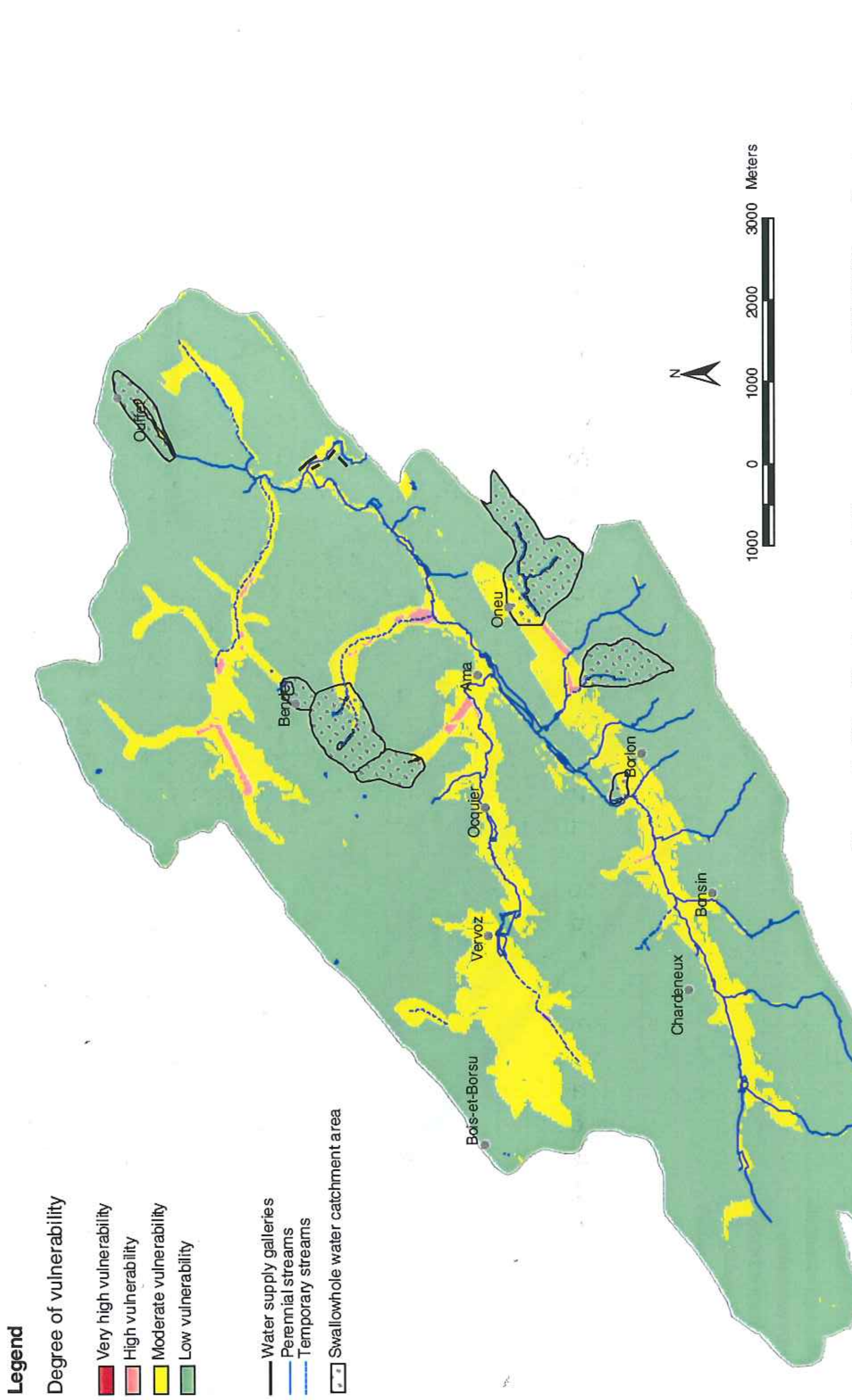


Figure 4.40. - Final vulnerability map using DRASTIC method and classes of vulnerability defined by Kumar and Engel (1997)

The **German method**, as almost all parametric systems, is providing its classes of vulnerability. The results are illustrated in ***Figure 4.41.*** According this method, 48.29% of the basin area is high vulnerable and 34.28% is very high vulnerable. These classes of vulnerability are including the entire limestone aquifer as well as the Famennian aquifer. The moderate vulnerability is very limited (7.56%) and is corresponding to the Strunian bands, to parts of the Lower Tournaisian bands, and to the alluvial valleys crossing the Famennian. Low vulnerability is given to the Tertiary sandy-clay formations and to small sectors corresponding to the Lower Tournaisian and to the Strunian. A very low vulnerability is given to the Namurian formations. The karstic features are apparently correctly assessed, most of them being considered as very high vulnerable zones.

Six vulnerability categories are designed for **ISIS** (***Figure 4.42.***). The extremely vulnerable category cannot be found in the area and the very high vulnerability is strongly limited to some outcrops (Fond de Wallou and a quarry located in the North), the high vulnerability is given to 62.90% of the analysed area. The moderate vulnerability (about 29.11%) is mainly observed for the Fameninan standstone and for the Lower Tournaisian. The low vulnerability appears for the Strunian bands. The very low vulnerability class is shown only by the Namurian formations. The role played by the land-use in terms of runoff is clearly marked in the low vulnerability areas of the Namurian formations. This can be observed by comparing the Land use map shown in ***Figure 4.30.*** with ***Figure 4.42.*** Also this effect can be seen on the high vulnerability zones in the sandstone as well as in the Lower Tournaisian limestone. Karstic features are generally assessed with a high vulnerability but very few of them are contrasted with the surrounding zones.

The result of the **GOD** method application is shown in ***Figure 4.43.*** There is no zone with the low vulnerability category and the very low is observed for the Namurian formations. Most of the study area is assessed as having a high vulnerability (63.73%). The very high vulnerability can be distinguished in 9.53% of the study area. In terms of vulnerability the Fammenian aquifer cannot be differentiated from the most part of the limestone. To the karstic features are generally given a high vulnerability. The moderate vulnerability occupy about 20.49% of the study area. It includes the Tertiary sandy-clay deposits and parts of the carbonate aquifer having a thicker unsaturated zone. The method is not accurate for assessing karstic features: the area of Ouffet swallowhole is showing a moderate vulnerability, when the area corresponding to the diffuse swallowhole of Bende is characterised by a very low degree of vulnerability.

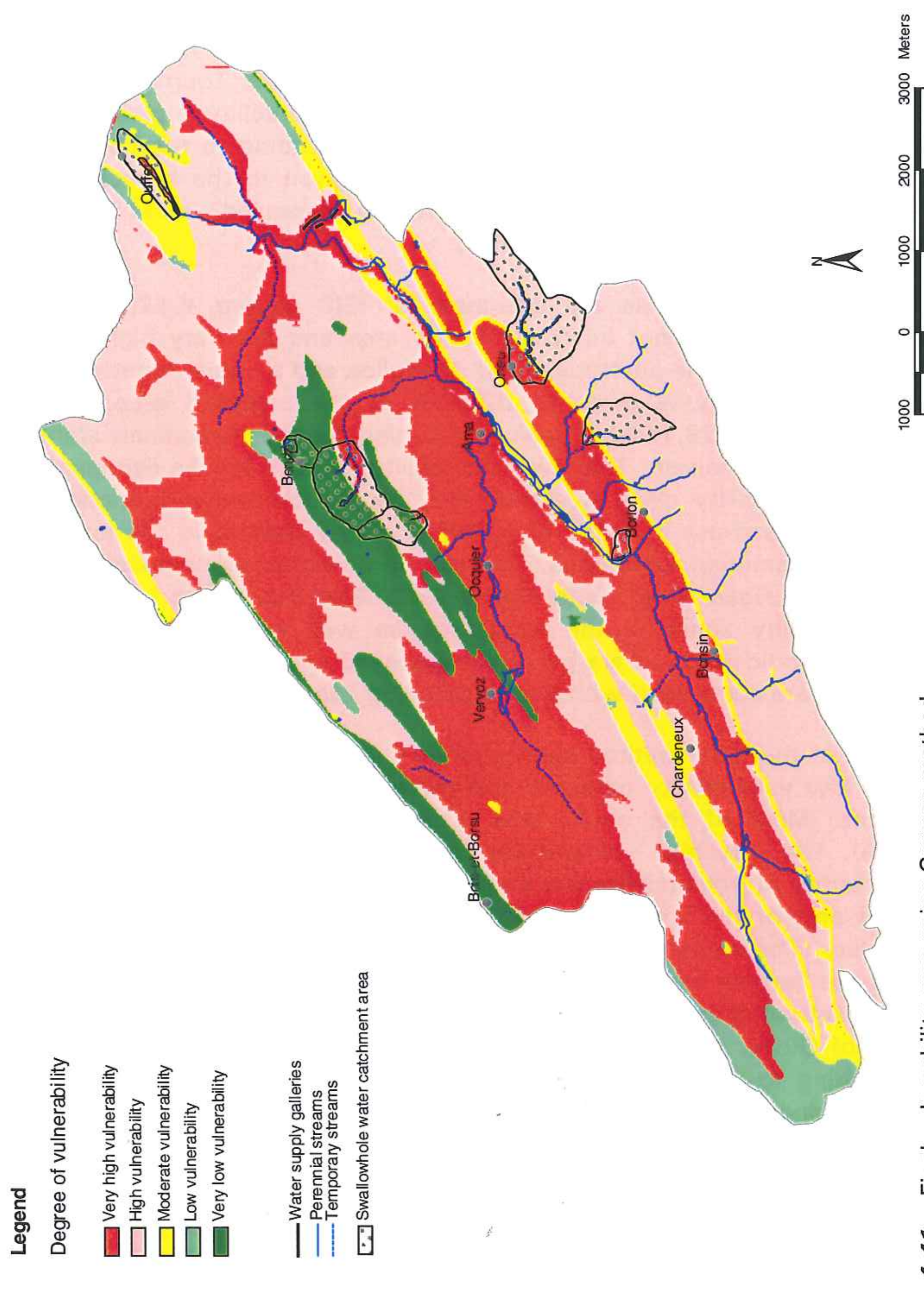


Figure 4.41. - Final vulnerability map using German method

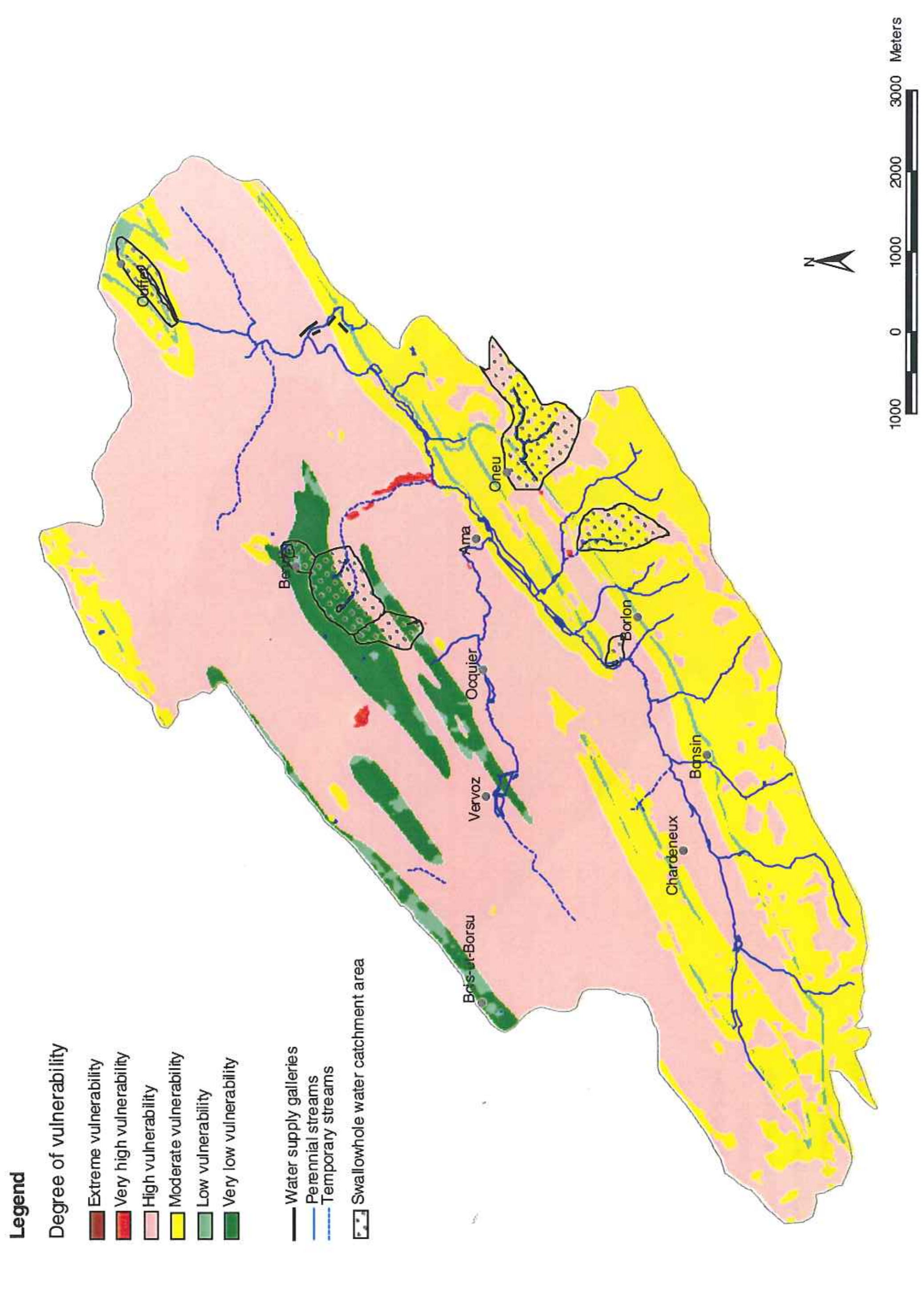


Figure 4.42. - Final vulnerability map using ISIS method

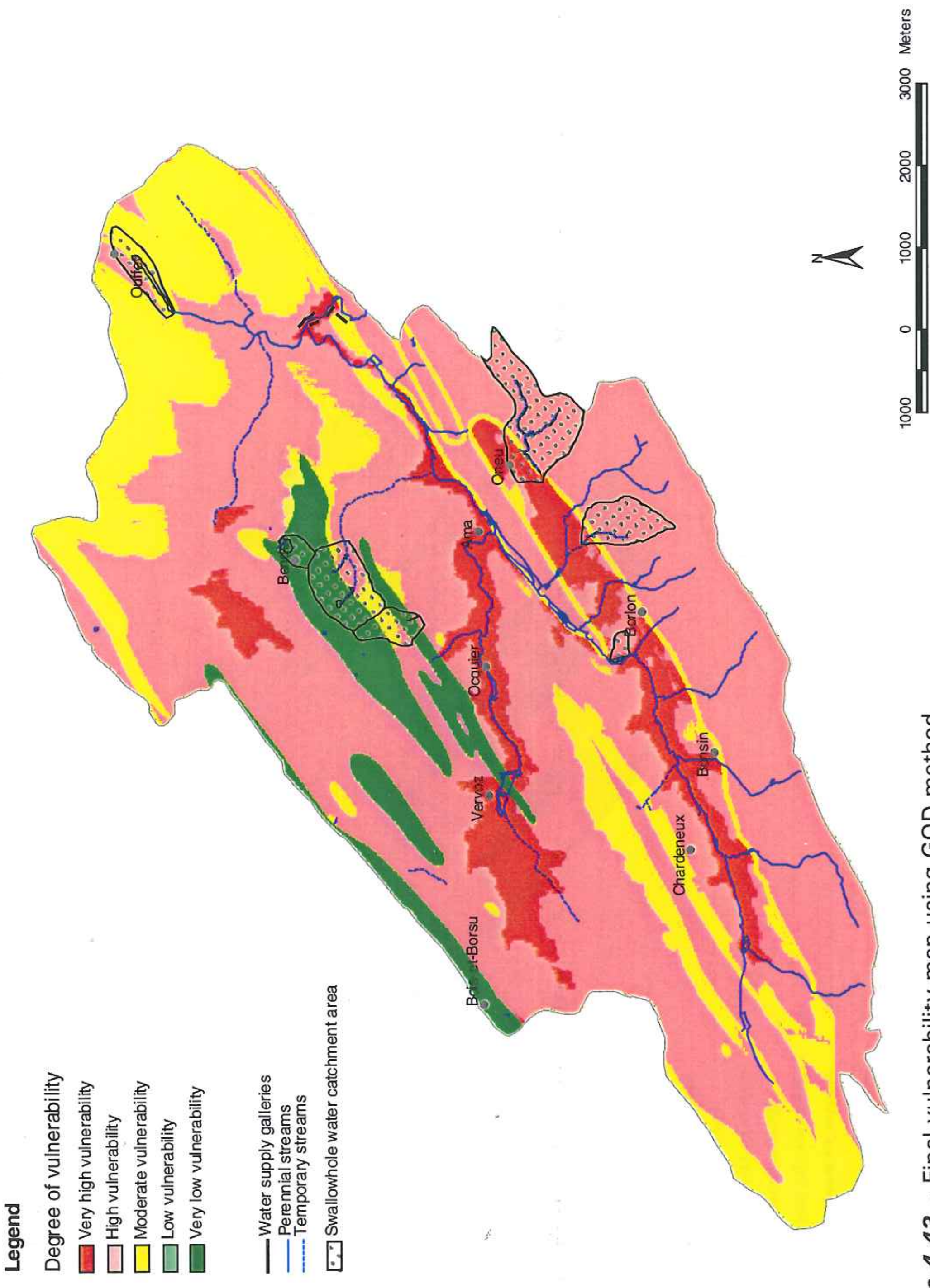


Figure 4.43. - Final vulnerability map using GOD method

4.7.2. Comparison between vulnerability maps

For the classic DRASTIC method, the zones of very high and high vulnerability cover about 5.17% of the study area. According to EPIK, the zones of high vulnerability covers only 0.66%. The very high and high vulnerability zones for the other three methods, correspond to more than a half of the study area (***Table 4.6.***). With the EPIK method, most of the territory is considered with a low vulnerability (91.52%): this is coming from the fact that this method was designed only for karstified limestones.

Comparing the vulnerability maps, it can be observed a general similarity between GOD, ISIS, and the German method (***Figures 4.43.***, ***4.42.***, and ***4.41.***). Important differences are observed for EPIK (***Figure 4.38.***) and DRASTIC (***Figure 4.39.***) results. The German method is outlining the most extended zones with high and very high vulnerable areas (high 48.29% and very high 34.28%). The ISIS method provides 62.90% of high vulnerable areas.

In general the limestone aquifer is characterised 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. This procedure also increases the vulnerability. 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 (***Figure 4.39.***) 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.

Figure 4.3. shows the temporary streams springing from Namurian and feeding directly the swallowholes. EPIK is the only method that consider these temporary streams 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 bypass the soil and the unsaturated zone.

A similar problem is observed for the Vervoz lake that overlies the limestone as well as the Namurian formations (***Figure 4.3.***). 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. The result can be easily observed on the resulted vulnerability map looking to the vulnerability class given to the Famennian sandstone, to the Namurian formations, to the Lower Tournaisian, and to the Strunian bands.

By comparing the vulnerability maps obtained by EPIK (***Figure 4.38.***), DRASTIC (***Figure 4.39.***) and on ***Figure 4.40.*** by DRASTIC b (Navulur and Engel 1997), appears that DRASTIC b map can be seen as a step between DRASTIC and EPIK, in the vulnerability index reclassification. Performing further reclassifications of the vulnerability index, was obtained a higher similitude between DRASTIC and EPIK maps. In consequence DRASTIC and EPIK seems to underline mainly the same hydrogeologic and geomorphologic features, even if they have different basis.

4.7.3. Regrouped classes of vulnerability

A different kind of interpretation can be made by regrouping the classes of vulnerability. This 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 low vulnerability). The results are shown in ***Plate 4.1.***, ***Figure 4.38.*** and ***Table 4.7.*** To facilitate the comparison, the results were diagrammed in ***Figure 4.48.***

All the five methods designated the areas corresponding to the Namurian formations as low vulnerable. The German method shows the most extended area of high vulnerability with 82.57%. The DRASTIC results are more equilibrated with 73.04% of the territory with a moderate vulnerability and 21.78% with a low vulnerability.

For this basin, these regrouped classes of vulnerability indicate three main trends in the vulnerability assessment: (a) the German method, the GOD method, and the ISIS method consider the study area as being dominant high vulnerable; (b) for the DRASTIC method the moderate vulnerability dominates with 73.04%; (c) the EPIK method attributes a low vulnerability to about 91.52% of the study area. These results show a very high discrepancy between the methods.

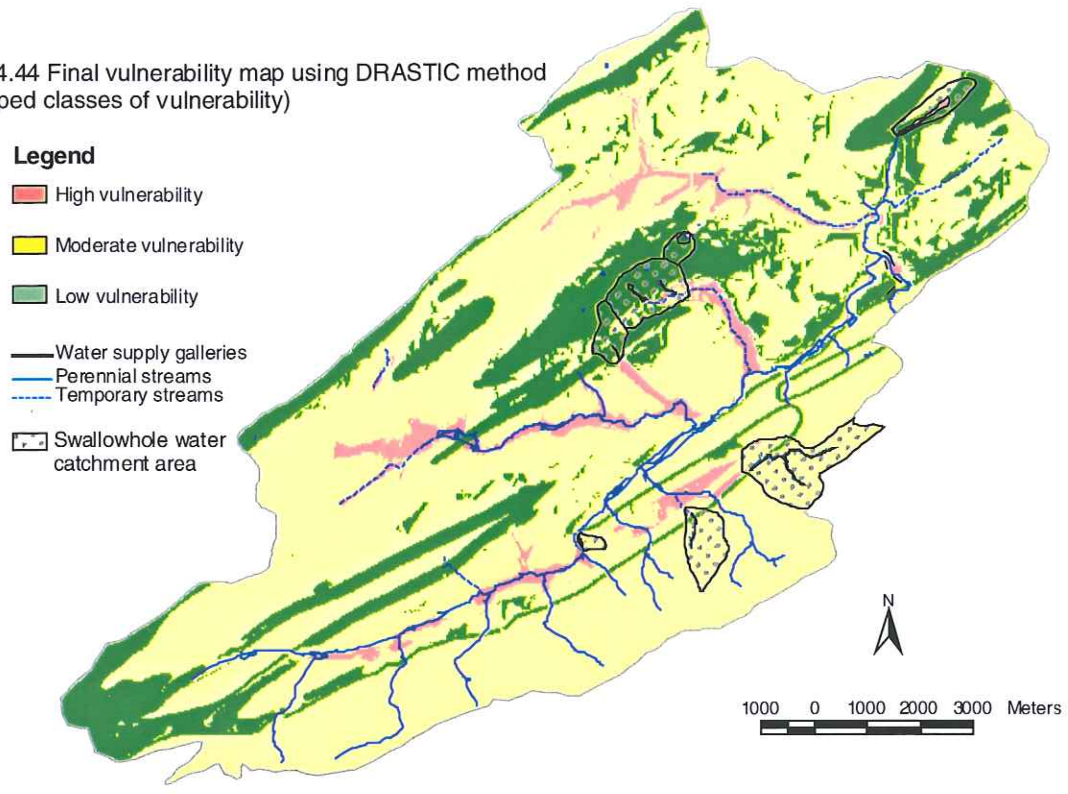


Figure 4.44 Final vulnerability map using DRASTIC method (regrouped classes of vulnerability)

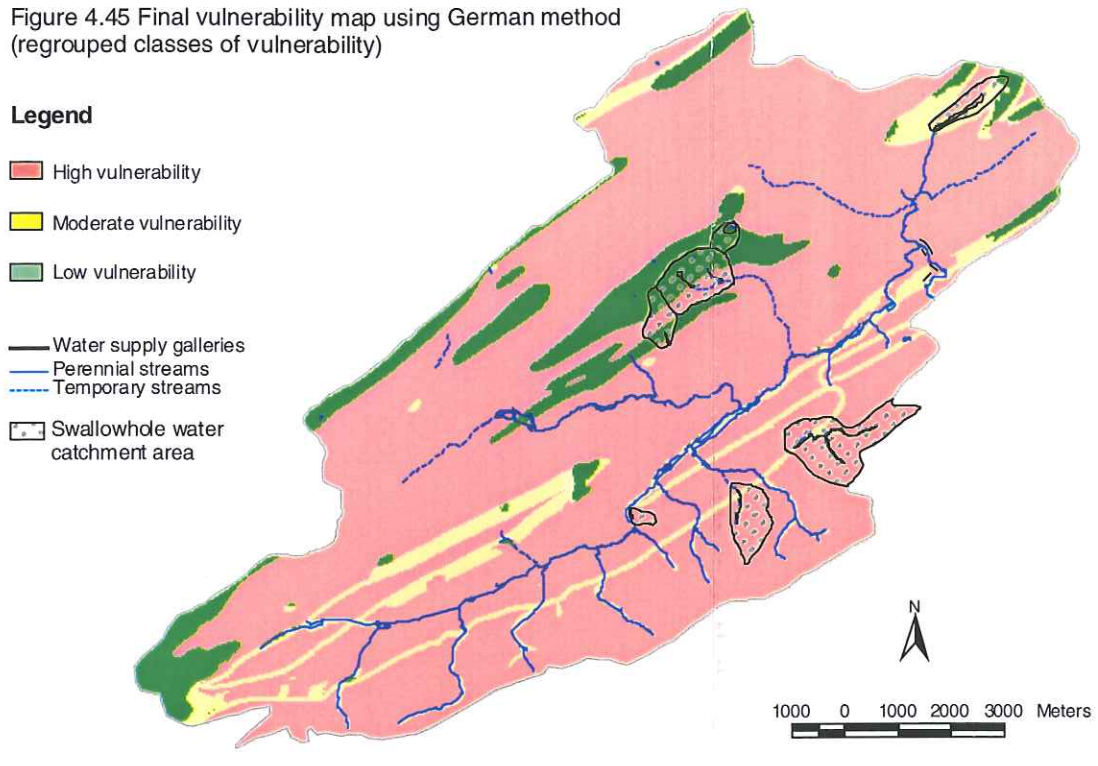


Figure 4.45 Final vulnerability map using German method (regrouped classes of vulnerability)

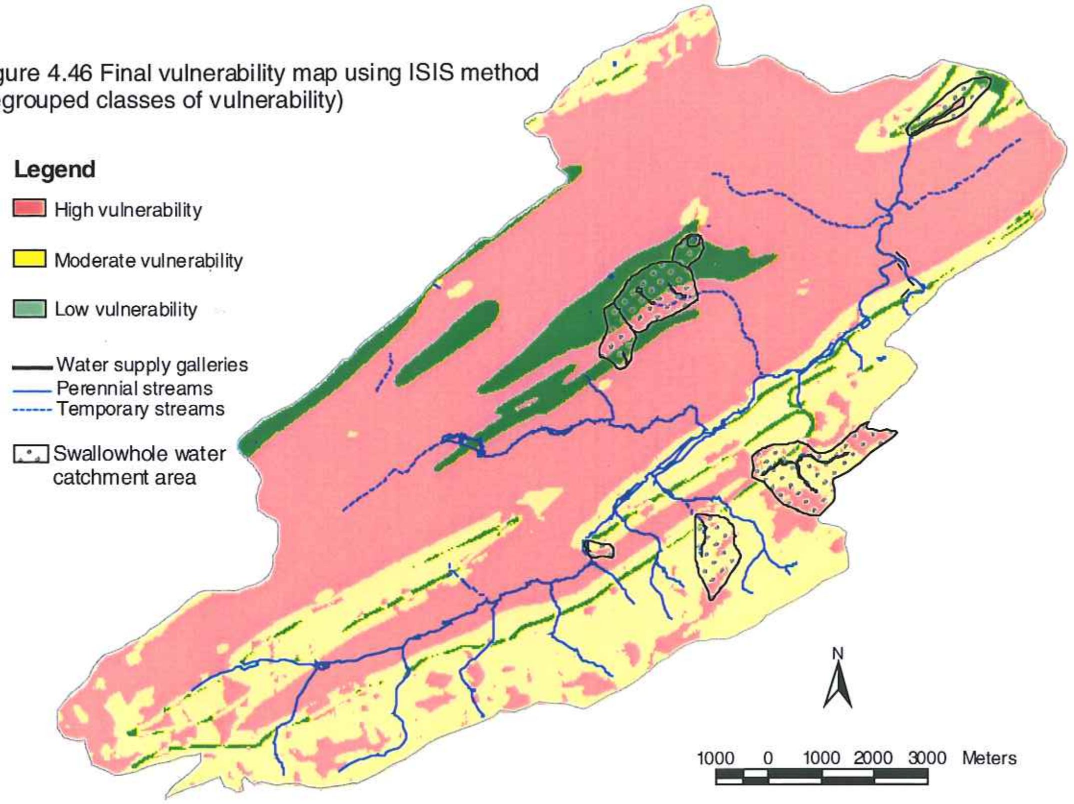


Figure 4.46 Final vulnerability map using ISIS method (regrouped classes of vulnerability)

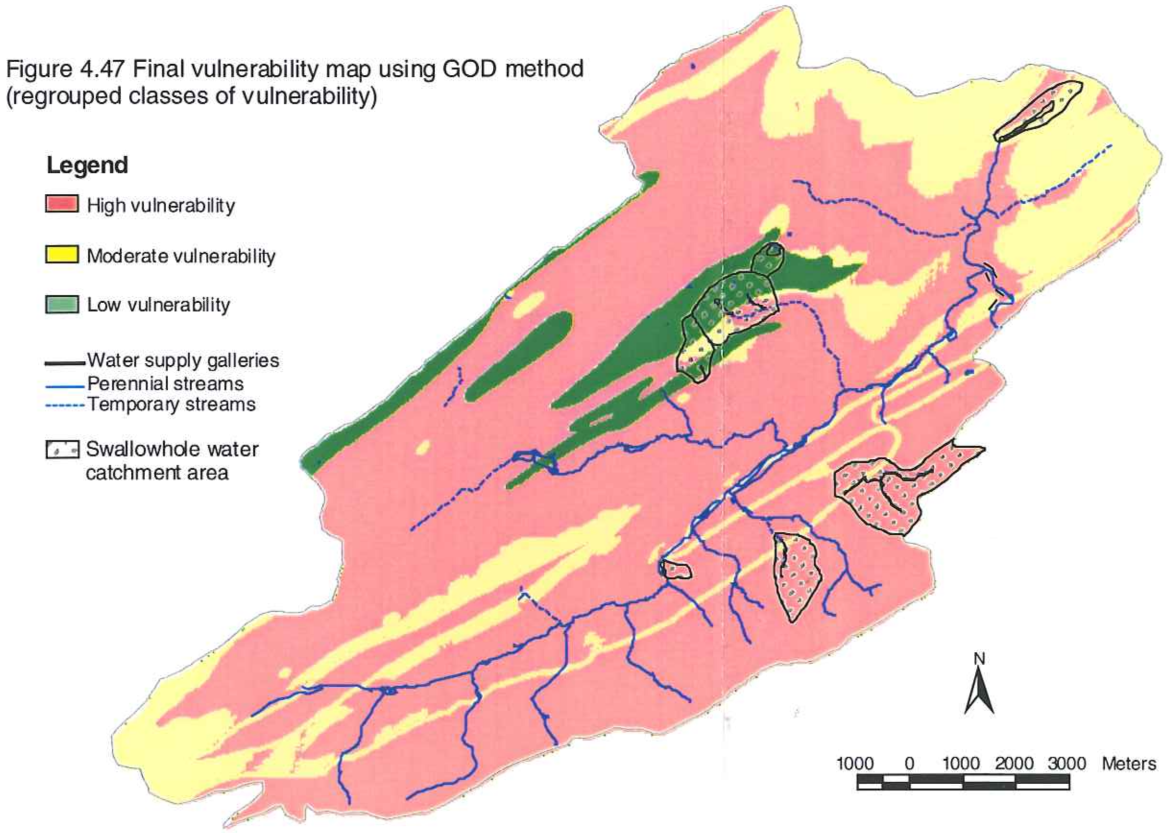


Figure 4.47 Final vulnerability map using GOD method (regrouped classes of vulnerability)

Plate 4.1. - Comparison between the vulnerability maps obtained by applying DRASTIC, German method, ISIS, and GOD (regrouped classes of vulnerability)

Table 4.7. - Comparison between the areas representing the regrouped vulnerability classes, obtained with the five methods (areas are expressed as percentage related to the entire study area; 100% represent 64.70 km^2)

	EPIK	**DRASTIC**	**GERMAN**	**ISIS**	**GOD**	**DRASTIC (b)**
high	0.66	5.17	***82.57***	63.09	73.26	0.59
moderate	7.81	73.04	7.56	29.11	20.49	14.83
low	***91.52***	21.78	9.86	7.80	6.25	84.57

Obs.: DRASTIC (b) represents the same method DRASTIC where the vulnerability classes defined by Kumar and Engel (1997) were used.

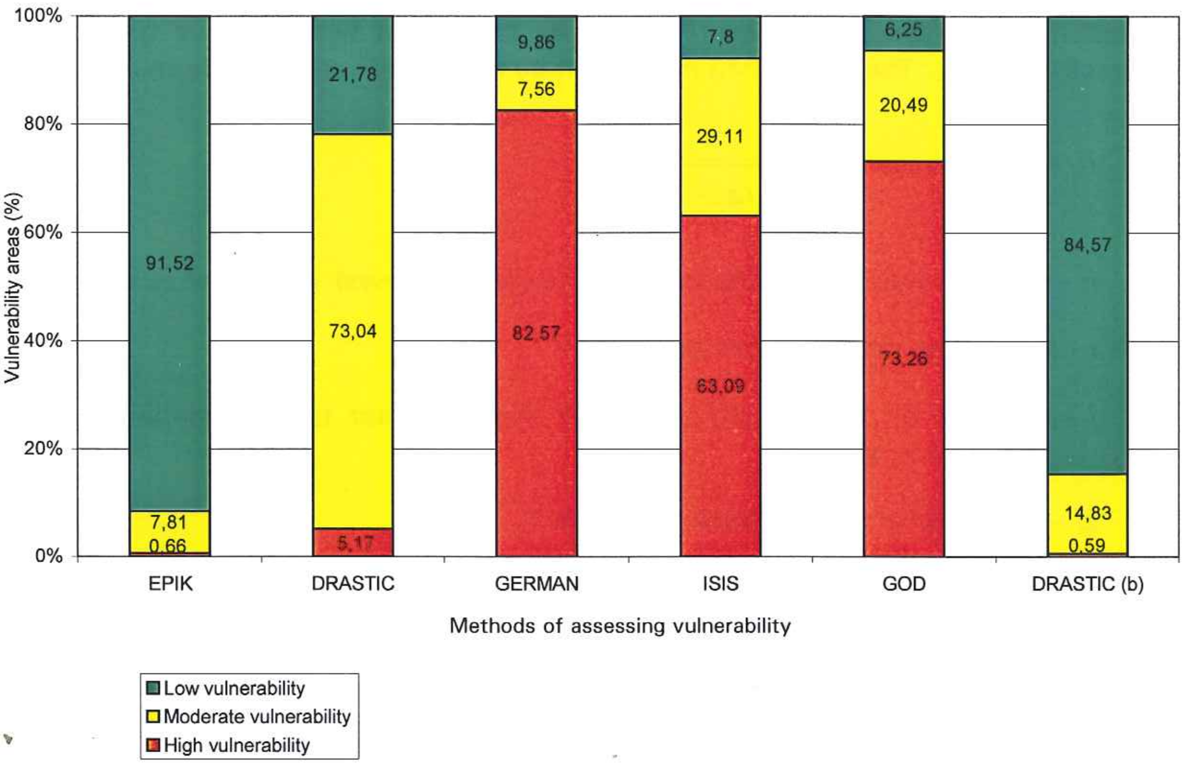


Figure 4.48. - Comparison between the regrouped classes of vulnerability defined by the applied methods

4.7.4. Statistical analysis on vulnerability maps

The resulted vulnerability maps can also be analysed by spatial statistics. On the maps of ***Plate 4.1.*** and ***Figure 4.38.*** was performed a correlation analysis (Engel et al. 1996).

The spatial autocorrelation is a measure of objects similarity within an area. An object can have at least two types of descriptive elements: non-spatial attributes (as soil type, land use code, slope), and spatial attributes (as the x, y location in a specified coordinate system). The spatial autocorrelation gives the relationship between the difference of the aspatial (non-spatial) attributes of objects with the distance between the objects. For example two objects which are close together having also very similar aspatial descriptors, are highly spatially autocorrelated. Two objects close together having also very different aspatial descriptors, are not very spatially autocorrelated. Hence, a negative spatial autocorrelation exists when objects that are close together have very different aspatial attributes. In our case, the aspatial descriptor is the vulnerability class (low, moderate, or high). This notion of correlation can be used to measure the cross correlation between two grids (two vulnerability maps). The correlation index can be computed using the formula 4.2.

$$C_{ij} = \sum_{k=1}^{n} \frac{c_{ij}}{\sqrt{\sum_{k=1}^{n}(z_i - z_m)^2} \cdot \sqrt{\sum_{k=1}^{n}(z_j - z_m)^2}} \qquad (4.2)$$

n - the total number of cells in a grid: (number of rows) × (number of columns)

i - any cell on the first input grid

j - any cell on the second input grid that is offset from *i* location by the specified x, y offset

z_i – the value of the attribute of the cell *i*

z_j – the value of the attribute of the cell *j*

z_m – the mean value of the cell attribute

c_{ij} – the similarities of *i* and *j* attributes: $(z_i - z_m) \cdot (z_j - z_m)$

The resulting correlation index have values from -1 to 1. If the two grids are highly cross correlated the index will equal one. If the two grids are independent the index is zero and if there is a strong negative correlation the output value will equal -1.

The highest correlation index was found between the vulnerability grids of the German method and the GOD method. This correlation index value is 0.785. Between the German method and the ISIS method the correlation index value is 0.642. The lowest correlation indexes resulted between the vulnerability grids of the EPIK method and the ISIS method (0.006) as well as between the EPIK and the GOD method (0.021).

Simple statistical operations between the vulnerability maps (***Figures 4.38., 4.39., 4.41., 4.42.***, and ***4.43.***) were also performed. The following statistical measures were considered significant: the maximum (the highest vulnerability degree), the minimum (the lowest vulnerability degree), the median (the median degree of vulnerability), and the majority (the majority of maps showing the same vulnerability degree). These measures were computed for each cell and the results are illustrated in ***Plate 4.2.***

In ***Figure 4.50.*** of ***Plate 4.2.*** is illustrated the majority of the vulnerability classes for each cell. The map outlines that three of the five methods determined 41.35% of the study area as high vulnerable. This corresponds mostly to the limestone aquifer. Apart, a very high vulnerability is attributed to 3.80 % of the area. This very high vulnerability is mainly determined by the depth to the groundwater table. The alluvial valleys crossing the Famennian sandstone are considered as keeping a moderate degree of vulnerability. In the majority of the methods the tertiary sandy-clay pockets have a low vulnerability and the Namurian formations have a very low vulnerability. In 36.08% of the territory, the vulnerability degree is not clearly defined: it refers mainly to the Famennian sandstone.

The median value (***Figure 4.49.***) indicates a high vulnerability in most of the limestone aquifer (50.87% of the study area). A very high vulnerability is shown on only 0.17% of the area. The moderate vulnerability is observed for 37.93%. It can be found mainly for the Famennian sandstone, for the Lower Tournaisian bands, as well as for the NE part of the limestone aquifer (due to the depth to the groundwater table).

The statistic Highest and Lowest vulnerability were determined also. Except for the Namurian formations, the map showing the Lowest vulnerability (***Figure 4.52.***) redraws the EPIK vulnerability map. It could be seen that the alluvial valleys take a moderate vulnerability. On ***Figure 4.51.*** is drawn the Highest vulnerability. As it can be observed, the Extreme vulnerability is not present: this degree of vulnerability is not significant for this area.

4.7.5. Refining parameters values using results of geophysical studies

For epikarst and in general for the unsaturated zone of limestone aquifers, the geophysical interpretation can conduct to reliable results (Müller and Turberg 1998). As mentioned before, an extension of EPIK and DRASTIC was done to include this type of data.

In this work the geophysical data played an important role in evaluating the various parameters of the presented methods, however the modification for EPIK and DRASTIC methods was by increasing the vulnerability in the detected zones of faults and fractures. The results for the EPIK method are illustrated in ***Figure 4.54.*** and for the DRASTIC method in ***Figure 4.53.*** For EPIK this procedure increased the moderate vulnerability zones with 1.2% and the high vulnerability zones with 0.74%. For DRASTIC this approach increased the high vulnerable area with 0.46% and the moderate vulnerable area with 0.20%. These percentages are not so significant in terms of enlarging the vulnerable areas in the study zone. Furthermore, this approach may be considered useless if the uncertainty degree of the hydrogeological characteristics for the detected faults or fractures (geometry, depth, hydraulic conductivity, material and degree of filling) is high. In consequence, their use can be done at a small scale and in relation with other measurements of the hydrogeologic characteristics.

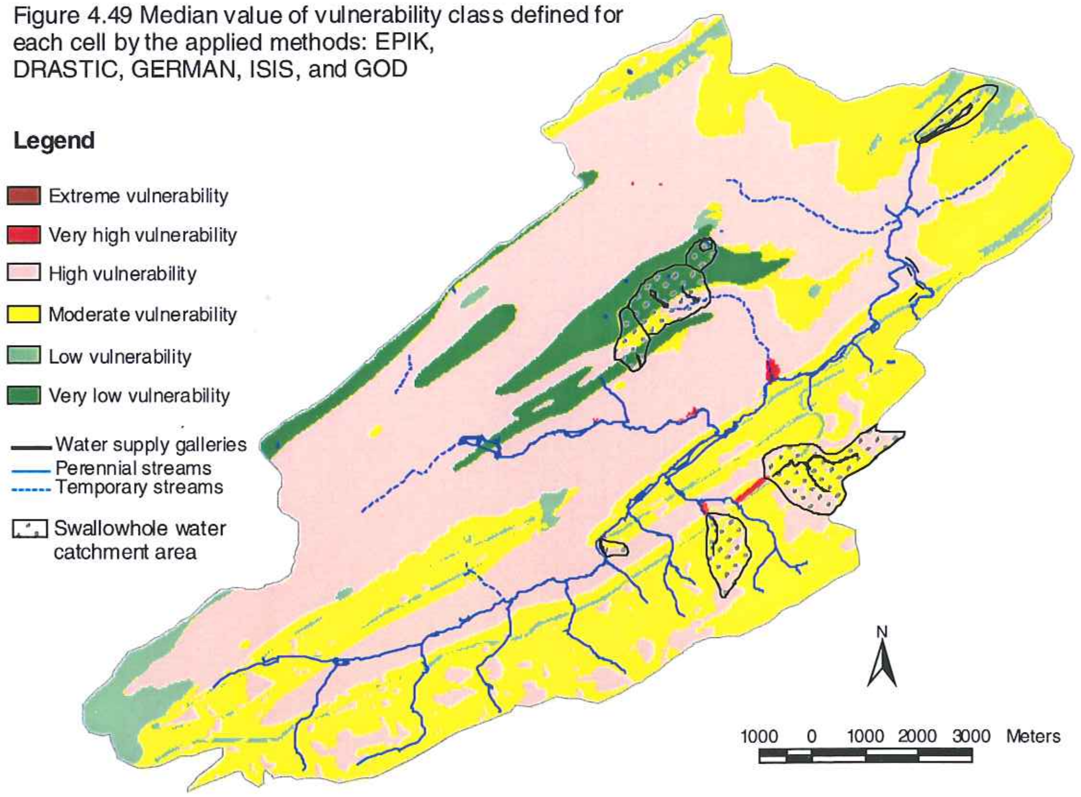


Figure 4.49 Median value of vulnerability class defined for each cell by the applied methods: EPIK, DRASTIC, GERMAN, ISIS, and GOD

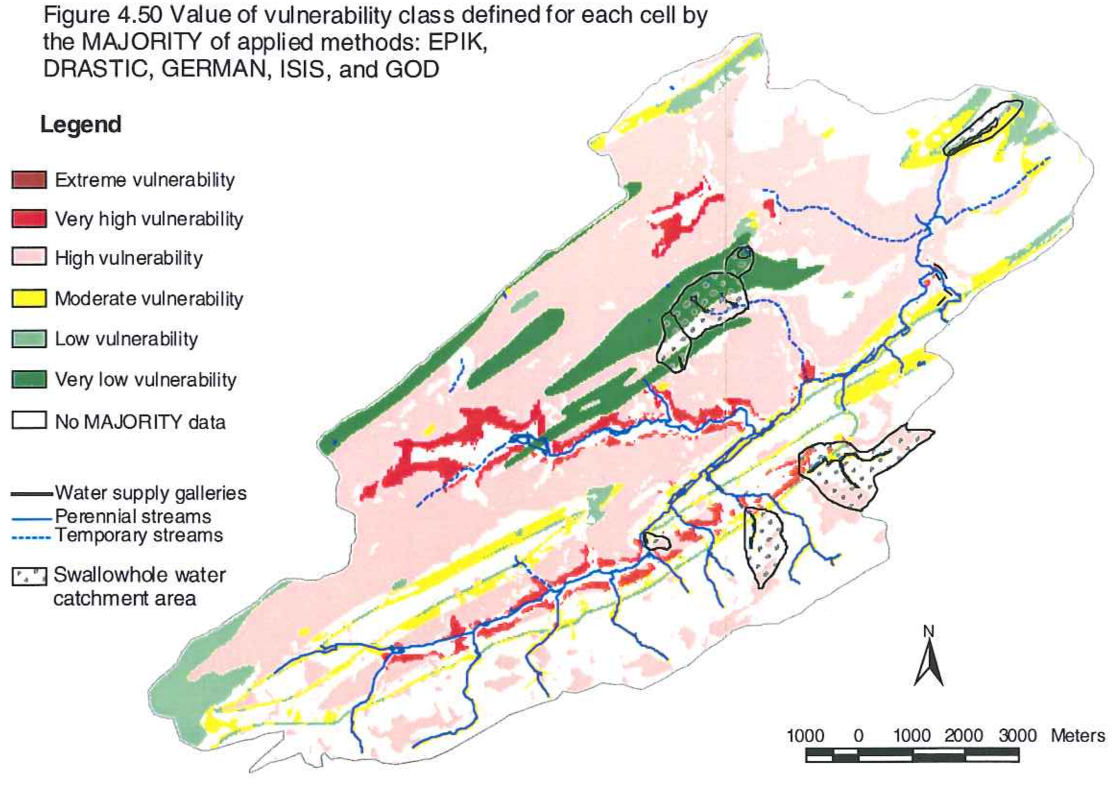


Figure 4.50 Value of vulnerability class defined for each cell by the MAJORITY of applied methods: EPIK, DRASTIC, GERMAN, ISIS, and GOD

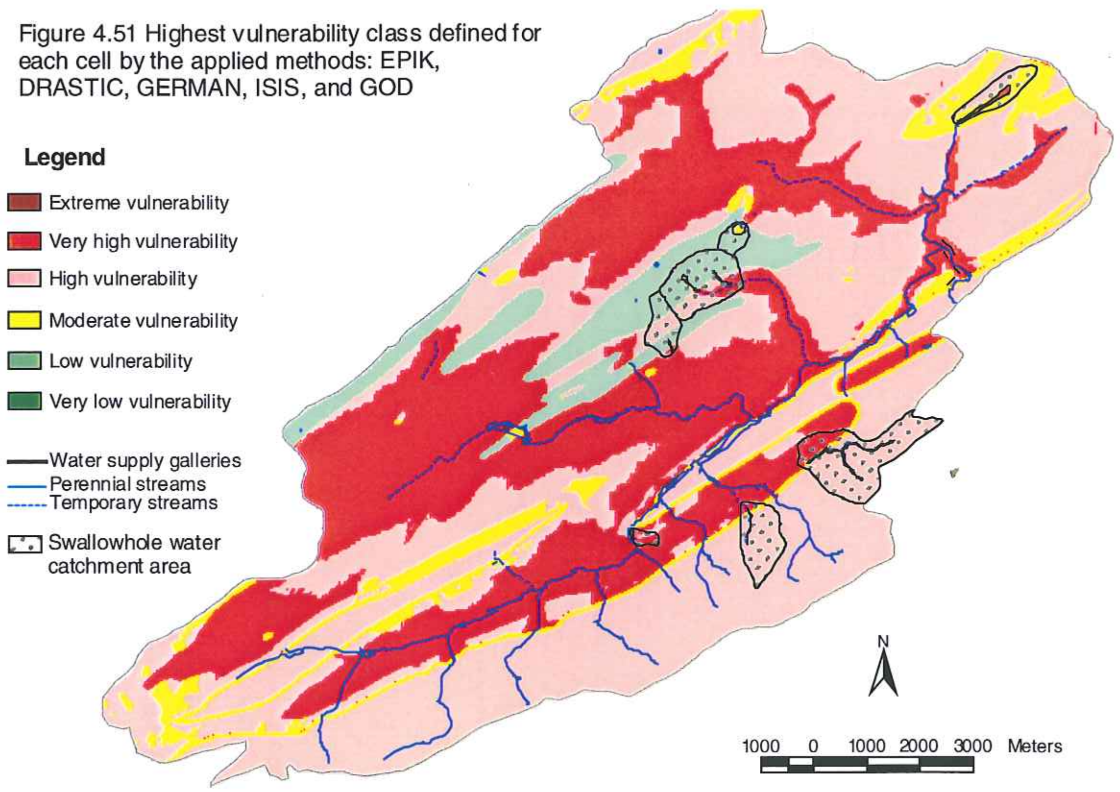


Figure 4.51 Highest vulnerability class defined for each cell by the applied methods: EPIK, DRASTIC, GERMAN, ISIS, and GOD

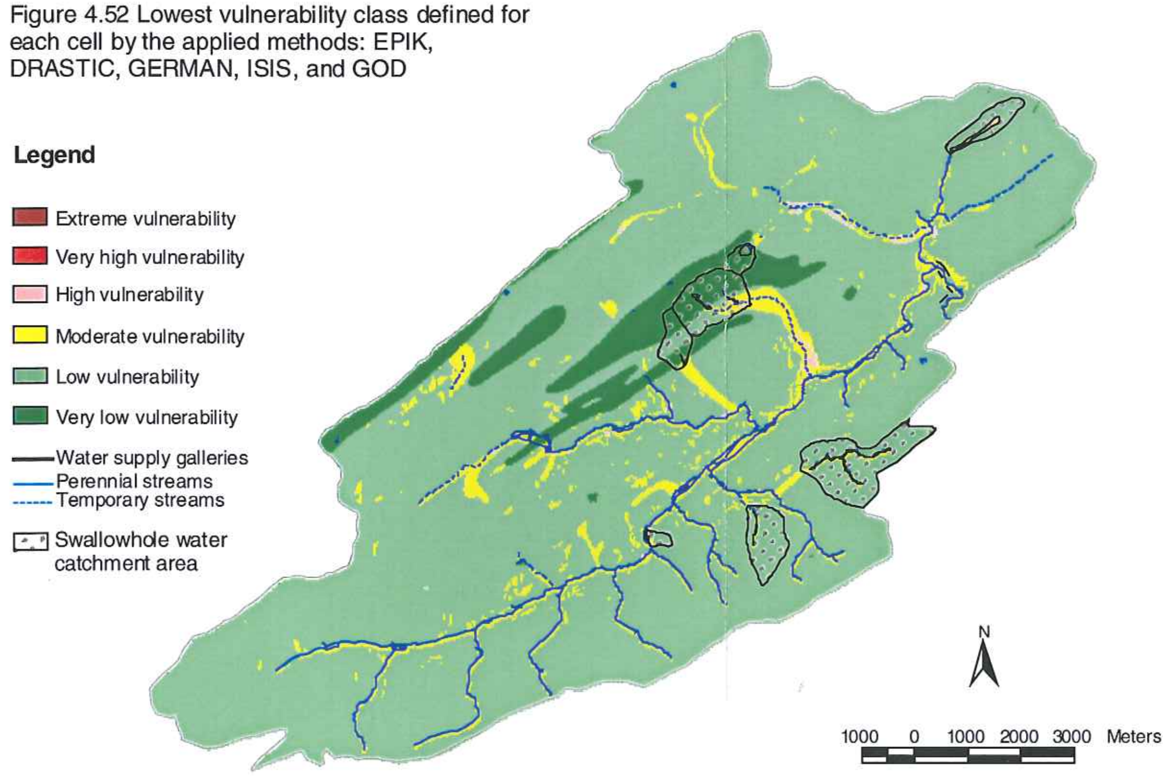
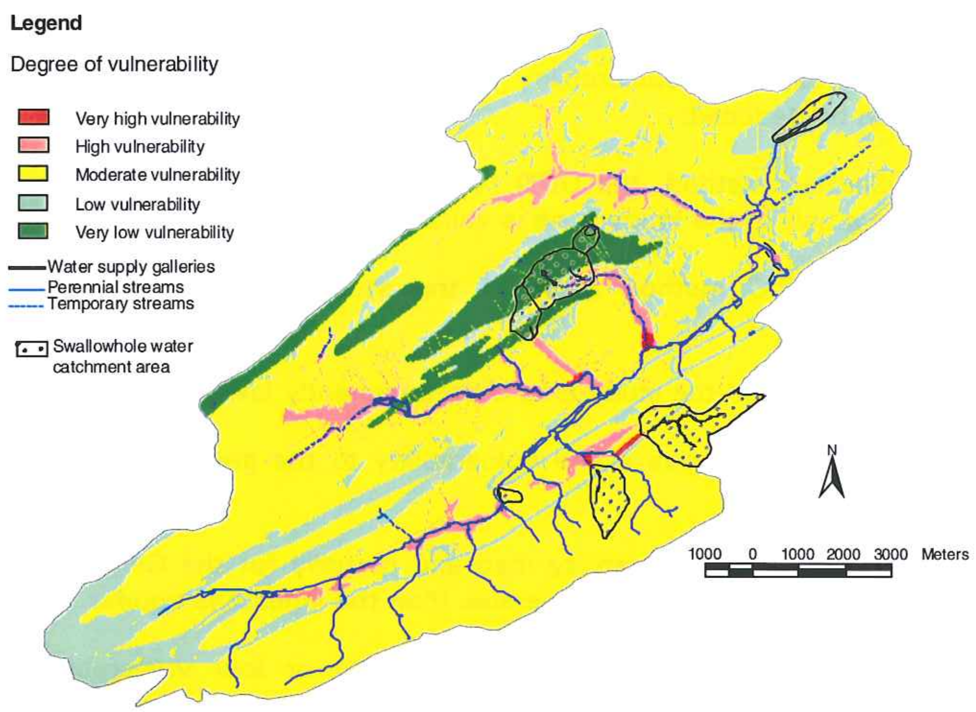


Figure 4.52 Lowest vulnerability class defined for each cell by the applied methods: EPIK, DRASTIC, GERMAN, ISIS, and GOD

Plate 4.2. - Statistical results on the vulnerability maps obtained using: EPIK, DRASTIC, German method, ISIS, and GOD

Figure 4.53. - The effect of detected faults on the DRASTIC vulnerability map



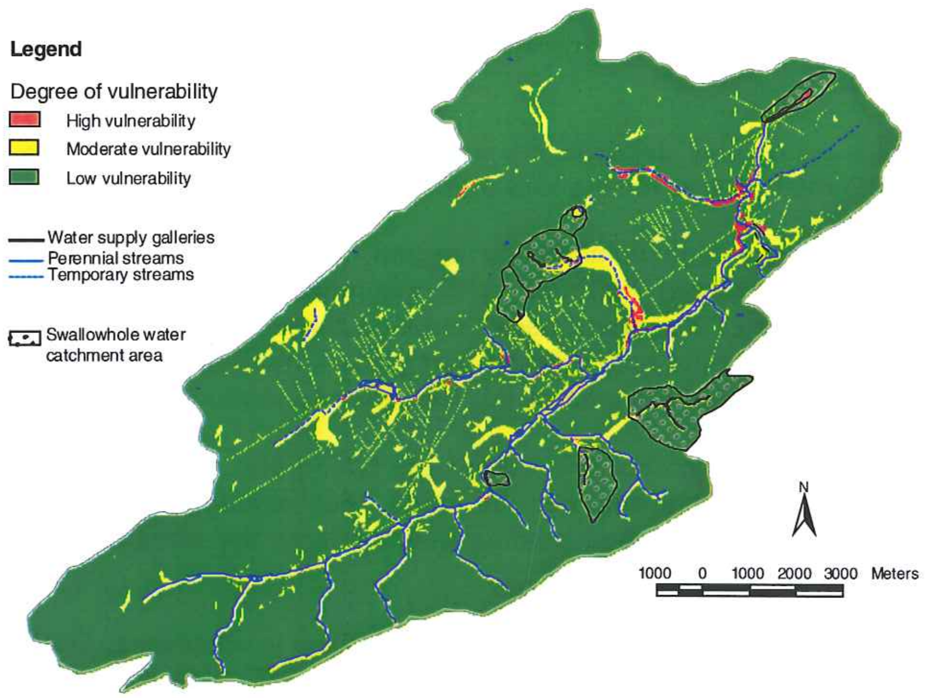


Figure 4.54. - The effect of detected faults on the EPIK vulnerability map

4.8. Conclusions

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

(a) For the German method, the GOD method, and the ISIS method (***Table** 4.7.*), more than a half of the study zone is vulnerable.

(b) For the DRASTIC method most of the study area is moderate vulnerable (73.04%).

(c) For the EPIK method the study area is predominantly low vulnerable (91.52%).

(d) All the five methods give a low vulnerability to the areas corresponding to the Namurian formations.

(e) Except for the GOD vulnerability map and partially for the German method, the Fammenian sandstone is less vulnerable than the limestone aquifer.

(f) The Strunian bands are considered moderate or low vulnerable for all the methods.

(g) The Lower Tournaisisan is mostly assessed with a moderate or a high vulnerability.

(h) The tertiary sandy-clay deposits are assessed as low vulnerable with exception for the GOD method and for the ISIS method.

Suiting a high or very high vulnerability degree, the karstic features are properly evaluated by the presented methods with exception for GOD and in a smaller measure for ISIS. The EPIK method better outlined these karstic features than all the other four methods. It is the only method that gives a moderate class of vulnerability to the small streams within the area of the Namurian formations.

Because almost all the vulnerability methods are taking into account only the vertical permeability, inaccurate choices can be done. For example, most of them are neglecting possible contamination coming directly from the streams and bypassing the soil and the unsaturated zone.

The EPIK method has good strengths as well as serious weaknesses. 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. It is valid only within the drainage basins of karstic features. Another concern is that the EPIK method lead to results where most of the study area (91.52%) has a low vulnerability. The four other methods characterised the Néblon aquifer as being mostly high or moderate vulnerable. The difference comes from 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 to delineate land areas that are more vulnerable than others (Vrba and Zaporozec 1994, Gogu and Dassargues 2000 a) is a relative concept, ignoring other lithogical and hydrogeological conditions lead to less contrasts.

Comparison between the vulnerability maps obtained with the two classification systems of DRASTIC and with EPIK, shows that these methods outline the same hydrogeologic and geomorphologic characteristics. Nevertheless, it demonstrates the DRASTIC capacity of fairly outlining the karst morphology. These conclusions should open new research in the procedures of the parameter quantification and weighting. 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.

Developments are needed to better differentiate the fissure matrix from compact rock masses and from the major discontinuities or karstic conduits. Information coming from geophysical prospecting should help more to delineate and to infer faults limits, dips, geometry, relative roughness, and filling.

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.

The choice among vulnerability methods remains a subjective decision of the hydrogeologist. Additionally, all the methods are to some extend to somehow 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 all the existing studies related to geology, hydrogeology, hydrology, soil, topography, climate, and land-use.

Chapter 5

Hydrogeological spatial databases, support for vulnerability assessment and groundwater numerical modelling

5.1. Introduction

In recent years the use of the Geographical Information Systems (GIS) has grown quickly in groundwater management and research. GIS are now widely used to create digital geographic databases, to manipulate and prepare data as input for various model parameters and to display model output. These functions allow primarily overlay or index operations but new GIS functions, that are available or under development, could further support the requirements of process-based approaches. Actually, groundwater studies cannot be anymore performed without Geographical Information Systems.

A GIS managed hydrogeological database in order to support data used in vulnerability assessments techniques and numerical modelling for groundwater flow and contaminant transport studies have been developed here.

The database has the hydrogeological specificity of the Walloon region (Belgium) environment. The design of the coupling between the database and process-based numerical models was also performed. Subsequent projects have dealt with the preparation of groundwater quality maps and hydrogeological maps.

Work with hydrogeological data and the study of several commercial hydrogeological database schemas (like ERMA, Intergraph 1995) have lead to the conclusion to design the schema of a new hydrogeological spatial database. There is a need for an advanced structure to be used for different environmental studies and consulting activities as well as research and modelling. Design has to address: (i) data management, processing and analysis as well as hydrogeological map production; (ii) numerical modelling as well as overlay and index techniques used in aquifer vulnerability assessment; (iii) support for water authorities' decision making process.

5.2. GIS and hydrogeology

5.2.1. Data and databases representation

Data and information required by hydrogeological studies are complex. Information concerning geology, hydrology, geomorphology, soil, climate, land use, topography, and man made features (anthropogenic) need to be analysed and combined. Data are collected from existing databases, maps as well as through new field measurements.

Use of point automatic collecting systems for some of the physical and chemical parameters is more and more used. Remote sensing techniques to assess parameters related to soil, unsaturated zone, geomorphology, and climate, are increasingly used. Some of the techniques for hydrogeological parameters measurement (sampling, monitoring of piezometric heads and flow rates, geophysical techniques) show a continuous progress. All these data need to be managed and this can be done in databases and particularly in GIS databases.

Storing data implies data analysis, conceptual data model design, and data representation. In hydrogeology, because of a limited number of sample locations, point attribute data need also to be processed by applying adequate kinds of interpolation or modelling algorithms. The derived data also have to be managed.

5.2.2. Assembling groundwater models and GIS

Geographic data processing can be seen as a subfield of data processing in general. There is a clear distinction between *geographical data processing* and *process-based modelling*. In order to create a digital version of the real geographic form or pattern, geographical features and attributes have to be modelled. For understanding and prediction behaviour, process-based modelling are using the equations describing the physical or biochemical processes which are to be simulated. Between these two forms of modelling useful relationships can be established.

Most of GIS can easily accomplish overlay and index operations, but cannot perform the process-based groundwater modelling functions related to groundwater flow and transport processes. However coupling a GIS to "process-based" models can provide an efficient tool for processing, storing, manipulating, and displaying hydrogeological data. Even if the use of GIS does not enhance the applicability of the process-based models, it can reduce drastically the time needed for data preparation and presentation.

The process-based models used in hydrogeology include the simulation of steady or transient state groundwater flow, advection, hydrodynamic dispersion, adsorption, desorption, retardation, and multi-component chemical reaction. Very often, exchanges with the unsaturated zone and with rivers are also addressed. In these models, the equations based on the physical processes are solved.

Modelling groundwater flow and contaminant transport in aquifers represent a spatial and temporal problem that requires the integration of deterministic process-based models with GIS. In order to model the physical and chemical processes in the aquifer, each model parameter or variable is represented on a three or four dimensional (x, y, z, and time) information layer. Due to the heterogeneity of aquifers, representing the spatial distribution of the parameters and variables, involved in the constitutive laws describing the simulated processes, creates a huge data volume. Managing this data can be done only through GIS.

Data used in groundwater modelling can be divided into four categories: (i) the aquifer system *stress-factors*, (ii) the aquifer system and strata *geometry*, (iii) the *hydrogeological parameters* of the simulated process, (iv) the main *measured variables*.

Stress-factors for groundwater flow can be: effective recharge, pumping volumes, water surface flow exchanges, etc. In contaminant transport modelling, the input and output contaminant mass flows can be mentioned. These *stress-factors* are imposed to the model through the "boundary" conditions or "source/sink" terms.

A good aquifer system *geometry* can be determined using geological information (maps and cross-sections), topographical maps, contour maps of the upper and lower limits for the aquifer strata and aquitards.

Initial guess for the distributed values and spatial distributions of the *hydrogeological parameters* (hydraulic conductivity, storage coefficient, dispersivity, etc.) have to be done using raw data and interpretation. Of course, the interpretation is based on the good knowledge of the aquifer geology and hydrogeology. Maps and vertical cross-sections representing the *hydrogeological parameter values* spatial variation are used. For a flow problem the main *measured variable* is the piezometric head and for a contaminant transport problem, the contaminant concentration. These consist of point values measured at different time periods in the entire aquifer. They are required for model calibration and validation.

In describing how links can be organised between models and GIS, three techniques could be used: *loose coupling*, *tight coupling,* and *embedded coupling*.

Loose coupling is defined when the GIS and the model represent distinct software packages and the data transfer is made through input/output model pre-defined files. The GIS software is used to pre-process and post-process the spatial data. An advantage of this solution is that the coupled software packages are independent systems, facilitating potential future changes in an independent manner.

In *tight coupling* an export of data to the model from GIS is performed, but the GIS tools can interactively access input model subroutines. In this case, the data exchange is fully automatic. An example of this coupling is the Groundwater

Modeller link (Steyaert and Goodchild 1994) between ERMA Spatial database schema (supported by Modular GIS Environment, Intergraph 1995) and MODFLOW, MODPATH, MT3D finite difference software packages.

When a model is created using the GIS programming language or when a simple GIS is assimilated by a complex modelling system, *embedded coupling* is used. *Tight coupling* as well as *embedded coupling* involves a significant investment in programming and data management that is not always justified. Also, this could be constraining when changes are required.

5.3. Application of GIS data processing for groundwater numerical modelling

A good opportunity for developing the hydrogeological database was given by the study of the climate changes impact on the hydrological cycle at the basin scale, within the Belgian research project "Integrated modelling of the hydrological cycle in relation to global climate change" (CG/DD/08). The modelled system involves the simulation of quantitative interactions between river, soil, and groundwater. Three different process-based models are coupled to simulate the water flow in each of the three media: soil, river, and groundwater (***Figure 5.1.***). The groundwater models are using finite element or finite difference software.

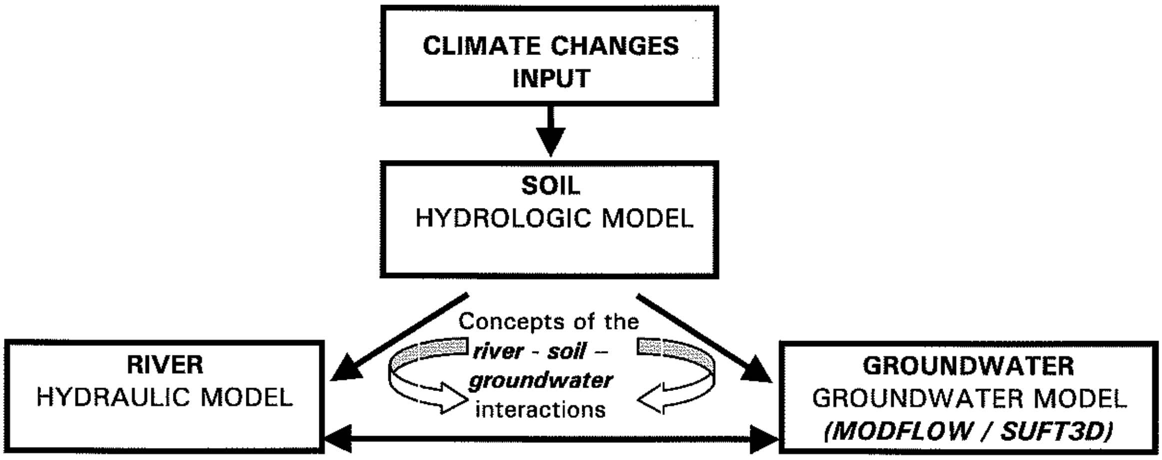


Figure 5.1 - The general frame of integrating the hydrogeological database, as support for study the impact of the climate changes in the hydrological cycle at the "small" basins scale

For application, five hydrogeological basins were chosen (***Figure 5.2.***) for their contrasted hydrogeological characteristics: Gette (sands and chalk), Geer (chalk), Hoyoux (limestones and sandstones), Orneaux (sands and limestones), Ourthe (fissured shale bedrock).

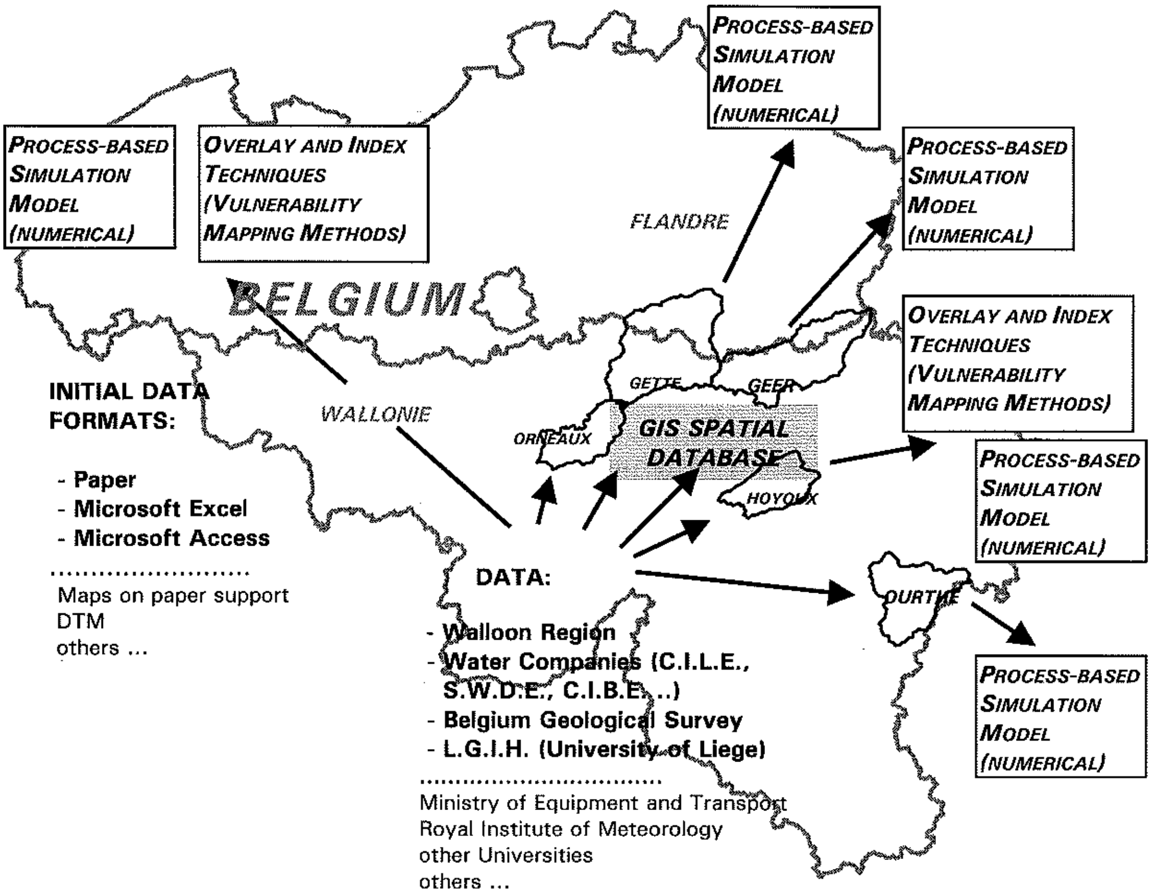


Figure 5.2 - Applications of the hydrogeological database and analysed hydrogeological basins location (Geer, Gette, Hoyoux-Neblon, Orneaux, Ourthe)

5.3.1. An advanced approach for managing hydrogeological data: the HYGES database schema

Accepting that every field hydrogeologist, modeller, or regulator must have strength in data management, the purpose of developing the hydrogeological database concept (called HYGES) was to integrate main data and information the hydrogeologist needs. The objectives for the final database were: (i) to provide an organised schema for capturing, storing, editing, and displaying geographically referenced hydrological data and information, (ii) to process and analyse spatial distributed data, (iii) to properly support aquifer vulnerability assessments, (iv) to easily provide values for numerical models parameters and variables, (v) to create hydrogeological maps.

Existing and required data types have been examined in order to design the database schema. Parameters and information were reclassified and regrouped several times. Many hydrogeological parameters and relationships were analysed in order to be placed in the database. Maximum information, minimum data redundancy, reducing storage capacity, and optimum in retrieving data for analysis were the constraints that defined the final schema. Data integration limits were imposed because of different restrictions concerning the hardware and software storage capacity, limitations in current activities and in available information.

Technical aspects in the HYGES database construction

An important consideration in database construction is data analysis. Accurate studies of all types of data and data formats are extremely important before designing a database.

The data collection operation showed that hydrological and hydrogeological data come from very different sources: water regulators, water companies, environmental agencies, geological services, research offices, and many others. In this case the main data providers were Ministry of Walloon region, Walloon Society for Water Distribution (SWDE), Water supply Company of Liege (CILE), Water supply Company of Brussels (CIBE), Belgian Geological Survey, Laboratory of Engineering Geology, Hydrogeology, and Geophysical Prospecting (LGIH), and others. These distinct sources showed strong dissimilarities in data type, in quality and in quantity as well as in storage media. All the data were analysed for import to a single system. Data that could appear redundant had to be specified in the database schema to avoid loss of information. Such decisions were based on: (i) exploitation schedules, (ii) data registration formats, (iii) uncertainty of existing data (measures and registration), and (iv) insufficiency in data registration system.

Depending on the accepted conceptual model (basic assumptions) and needs, additional data could appear. Also data that were not explicit or sufficient, needed to be flagged or supplied with fields of information or even entire tables. An example was the case where flow rate registrations related to several wells were available, without distinguishing the exploitation schedule of each well. There, a field containing wells sharing the same flow rate value had to be specified.

Data formats were also an important issue because the pre-treatment of data consists of hours of encoding or of writing import/export codes. So, data coming from paper sources as tables, maps, singular data, as well as different spreadsheets and data existing in databases having distinct schemas were analysed in order to create a unitary database system.

After structuring the spatial database schema (see the ***Annex***), hydrological and hydrogeological data coming from Ministry of Walloon region, SWDE, CILE, and elsewhere, were introduced into a GIS project using Arc/Info (ESRI) with Access (Microsoft). This solution was chosen after analysing the software platforms used by different hydrological and hydrogeological research teams, Belgian regulators, water companies and authorities, in order to ensure compatibility in future data exchange operation.

In the first step, the information has been collected for the following hydrogeological entities: wells and wells systems, piezometers, drains, water supply galleries, quarries and mines exploited for water. For this features the following characteristics were mainly introduced: location in Belgian Lambert coordinates, address, altitudes, depth, local aquifer information and owners. Almost 30 years (1947 – 1999) of time dependent data have been encoded: piezometric heads, annual and monthly exploitation flow rates. Quality data represented by 147 water quality parameters determined on 2316 groundwater samples are now registered in the database. The information is completed with digital geological maps (geology, strata elevation), land-use maps, zones of hydrogeological protection and others.

The HYGES database schema description

Data and information being specific to geomorphologic, geologic, and hydrological conditions have been divided in two parts: primary and secondary data. The complete database schema is attached in the ***Annex.***

Primary data section (***Figure 5.3.***) contains layers of general environmental information (such as topography, geological maps, maps of soils), hydrological and hydrogeological raw data or data undergoing an initial minor pre-treatment as well as information related to hydrogeological investigation and exploitation means (wells, piezometers, drains, mines, quarries) and land use maps. Secondary data consist of derived primary data after being treated in different ways (maps of piezometric head, hydraulic conductivity maps, vulnerability maps, etc.).

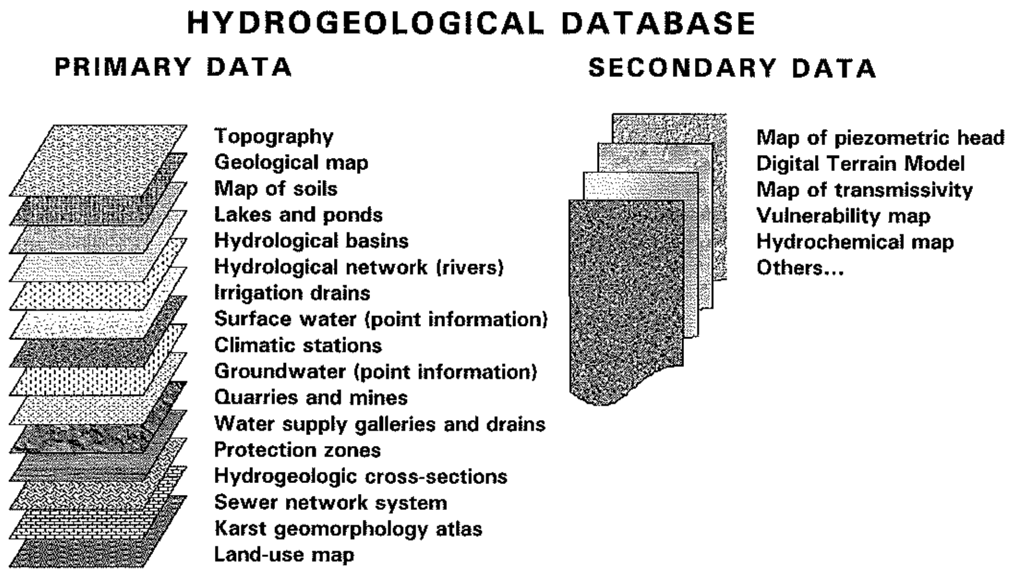


Figure 5.3. - The general database schema, dividing the required hydrogeological information into "Primary data" and "Secondary data"

The primary database composition is shown in ***Figure 5.4***.

Information has been divided into several groups of layers:

- Topography
- Geological Map
- Map of Soils
- Surface water tables (lakes, ponds)
- Hydrological basins
- Hydrological network
- Irrigation drains
- Surface water points
- Climatic stations
- Groundwater points
- Quarries and Mines
- Water supply galleries and drains
- Protection Zones
- Hydrogeologic cross-sections
- Sewer network system
- Karst (carbonate rocks) geomorphology atlas
- Land-use plan

As described in ***Figure 5.4.***, one or several layers compose each information group. The number of layers, the name of each layer, the represented entities, the format or geometric characteristic, and the characteristics of the database link are specified in the same figure.

Topography is represented by contour isolines. Because of the available encoded data, the "Geological map" and the "Map of soils" are polygon layers and simple attributes are attached directly to them. The same approach has been applied for the "Karst geomorphology atlas", "Land use plan", and "Sewer network system".

The "Hydrogeologic cross-sections" are represented by line features. They have attached Computer Aided Design (CAD) drawings or scanned images showing the cross-sections.

Point information has been classified into two main layers depending on the relative position to the ground surface: "Surface water points" and "Groundwater points".

N°	Groups of layers	Number of layers	Name of layer (coverage)	Characteristics represented	Geometry	Item - ID INFO File	Main table DBMS	Link column RDBMS	Structure and Format
1	TOPOGRAPHY	1	TOPO	*Land elevation – contour isolines*	*ARC*	TOPO-ID	-	-	*INFO*
2	GEOLOGICAL MAP	1	GEOL	*Geological formations*	*POLYGON*	-	-	-	*INFO*
3	MAP OF SOILS	1	SOILS	*Soils*	*POLYGON*	-	-	-	*INFO*
4	SURFACE WATER-TABLES	1	HYDRO	*Surface waters (lakes,ponds)*	*POLYGON*	HYDRO-ID	HYDRO	NUMBER	*INFO +ACCESS*
5	HYDROLOGICAL BASINS	1	BASIN	*Hydrological basin*	*POLYGON*	BASIN-ID	BASIN	NUMBER	*INFO +ACCESS*
6	HYDROLOGICAL NETWORK	1	RIVER	*Rivers, Interactions - aquifers*	*ARC*	RIVER-ID	RIVER	NUMBER	*INFO +ACCESS*
7	IRRIGATION DRAINS	1	DRAIN	*Irrigation drains (Unexploited)*	*ARC*	DRAIN-ID	DRAIN	NUMBER	*INFO+ACCESS*
8	SURFACE WATER *(POINT)*	1	GAUGING	*Quantitative measurement sections*	*POINT*	SURFACE-ID	SURFACE	NUMBER	*INFO +ACCESS*
			QUALITY	*Qualitative measurement sections*	*POINT*				
			SPRING	*Springs*	*POINT*				
			EXPS	*Exploited springs*	*POINT*				
			SWR	*Swallowholes and resurgences*	*POINT*				
			UDRAIN	*Irrigation drains (Unexploited)*	*POINT*				
9	CLIMATIC STATIONS	1	CLIMATE	*Climatic measurement stations*	*POINT*	CLIMATE-ID	CLIMATE	NUMBER	*INFO +ACCESS*
10	GROUNDWATER *(POINT)*	1	WELLS	*Wells, Piezometers*	*POINT*	GRWATER-ID	GROUNDWATER	NUMBER	*INFO +ACCESS*
			GALLERY	*Water supply galleries and drains*	*POINT*				
			CMH	*Quarries, mines – hydrogeological information*	*POINT*				
			UMP	*Unknown points of measurement*	*POINT*				
			BORH	*Geological boreholes (drilling)*	*POINT*				
11	QUARRIES AND MINES	1	CM	*Quarries, mines – description*	*POLYGON*	CM-ID	CM	NUMBER	*INFO +ACCESS*
12	WATER-SUPPLY GALLERIES AND DRAINS	1		*Water supply galleries and drains*	*ARC*	GALLERY-ID	GALLERY	NUMBER	*INFO + ACCESS*
13	PROTECTION ZONES	1	PZONES	*Protection zones*	*POLYGON*	ZONES-ID	ZONES	NUMBER	*INFO +ACCESS*
14	HYDROGEOLOGIC CROSS-SECTIONS	1	SECTION	*Hydrogeologic cross-sections*	*ARC*	SECT-ID			*INFO*
15	SEWER NETWORK SYSTEM	1	SEW	*Sewer network system*	*ARC*	SEW-ID	-	-	*INFO*
16	KARST ATLAS	1	KARST	*Karst geomorphology*	-	-	-	-	*INFO*
17	LAND-USE MAP (3 layers)	1	SIT	*Topographical map*	-	-	-	-	*Topo raster map*
		1	COM	*Communes*	*POLYGON*	-	-	-	*INFO*
		1	PROV	*Provinces*	*POLYGON*	-	-	-	*INFO*

Figure 5.4. - Primary hydrogeological database layers

"Surface water points" information layer

The information layer "Surface water points" contains: rivers gauging information, water quality sampling data, irrigation drains point data, springs, exploited springs, and swallowhole and resurgence hydrogeologic characteristics.

The attribute schema of this layer (***Figure 5.5***.) contains several related tables. *Surface* is the main table where using a relation "one to one", the schema is linked to the geographical location of the point in the GIS software. The linkage is done through the unique item called "Number". The relationships "one to one" and "one to many" between the *Surface* table and the derived tables are defined using the same item. The *Water levels* and *Description (Gauging station)* tables contain river cross-sections characteristics. *Geology* and *Aquifer* are tables needed to describe the environmental conditions of springs, exploited springs, surface drains (irrigation), and karst features. The *Type (Swallowhole/Ressurgence)* table is specific to the karst features.

As it could be seen in the ***Figure 5.5***., six tables of flow rates data have been introduced. Two of them, *Overflowing flow-rate* and *Overflowing flow-rate data* are available only for the exploited springs. Specific data for the exploited springs are also stored in *Hydraulic equipment* and *Authorisation* tables. Water quality data for all the six entities represented in this layer are described using *Samples* and *Parameters* tables.

The "Groundwater points" attribute schema

The "Groundwater points" layer is registered in the database with a more extended attribute schema. This layer regroups the following entities: wells, traditional hand-dug wells and simple piezometers, galleries and gallery wells, rock quarries and mines hydrogeologic point information, and boreholes. The main table linked to the layer points is *Underground*. The relationships between tables are made using the unique layer item also called "Number".

As can be seen in ***Figure 5.6***., the table *Underground* contains information concerning the geographical position (coordinates, address), type of represented entity (well, traditional well, borehole, gallery well, piezometer....), name (or official names), system of codes (used by several regulators in order to identify the entity), and some technical characteristics related to the represented entity (such as date of execution, type of exploitation, depth, kind of a protection zone belong to, and others).

Data containing the lithology and stratigraphy can be found in the *Geology* table. Each stratum a borehole is penetrating is described here by a "one to many" relationship. Other information related to the borehole and geological parameters (considering that each well or piezometer is initially a borehole) can be found in the tables: *Borehole diameter*, *Borehole execution*, *Borehole treatment*, *Borehole samples*, and *Reference*. Information related to the tests conducted in the boreholes (well logging ...) are stored in the table *Tests*.

Data related to wells technical characteristics and equipment are in the tables: *Hydraulic equipment* and *Equipment*. The table *Equipment* is used to store information relating to the completion of wells.

Aquifer table is used to store information that describes the penetration of aquifer strata by wells. The code of the aquifer (placed in a Dictionary of terms), the punctual confined/unconfined conditions as well the location of the screens are stored here.

The piezometric head values are stored in *Piezometry* table. Seven tables representing diverse kinds of flow rates measurements are present. Two of them contain specific data for galleries and drains (***Figure 5.6.***).

Information that identifies the analysed groundwater quality samples and describes the results, is stored in two tables (*Samples* and *Parameters)*. Because for each analysed sample several parameters could be identified, a "one to many" relationship is established. The link is made using a unique point item called Sample-ID. The *Samples* table contains the sample code, the sampling date, the sampling method, the value of the flow rate when the sample was taken, the water treatment technique, and the aquifer stratum code where the sample has been taken. The *Parameters* table contains the name of each measured parameter (Dictionary of terms) and it's respective value, the date the analysis was done, the analysis type, and it's limit of detection. Also the name of the laboratory and its coordinates are introduced here in a dictionary of terms.

Hydrogeological tests information is stored in the table *Quantitative data* (information related to quantitative tests made in a well) and in the *Tracer tests* table (an inventory and references of the performed tracer tests). Representative values of hydraulic conductivity (m/s), transmissivity (m^2/s), and porosity (%) parameters associated to a bibliographic reference are also stored here.

A table containing the authorised volumes of exploited water for each well (approved by regulators) completes the schema. The *Authorisation* table represents a good reference for the environmental impact studies and other different hydrogeologic investigations.

"Climatic stations" were represented as a separate layer of points having also an attached attribute schema. More simple attribute schemas are developed also for "Hydrological network" (line), "Surface water-tables" (polygon), "Irrigation drains" (line), "Quarries and Mines" (polygon), "Water-supply galleries and drains" (line), and "Protection zones" (polygon).

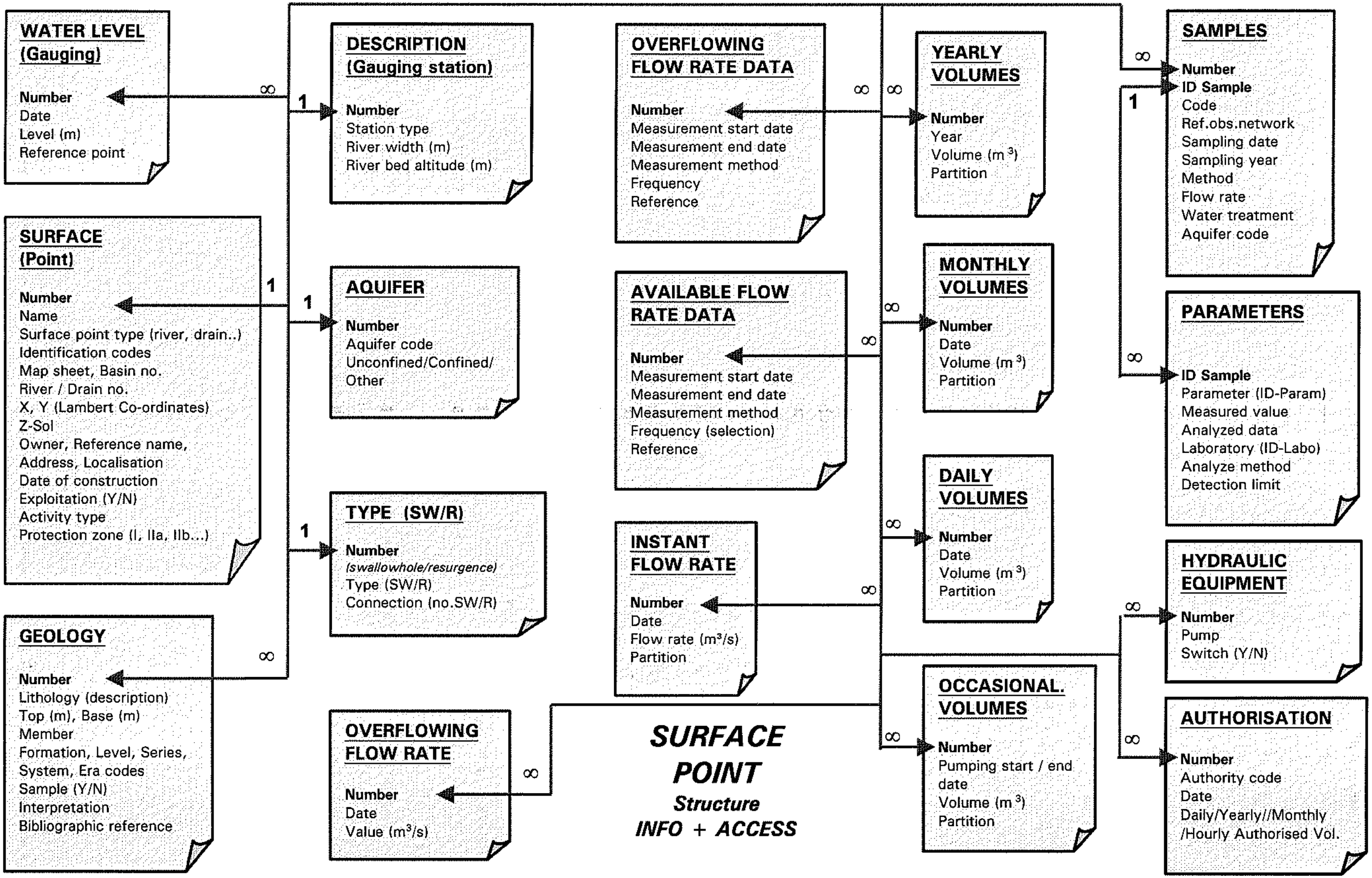


Figure 5.5. - Attribute data schema *simplified version* for "Surface water points" layer (rivers gauging information, water quality sampling, irrigation drains point data, springs, exploited springs, swallowholes and resurgences hydrogeologic characteristics)

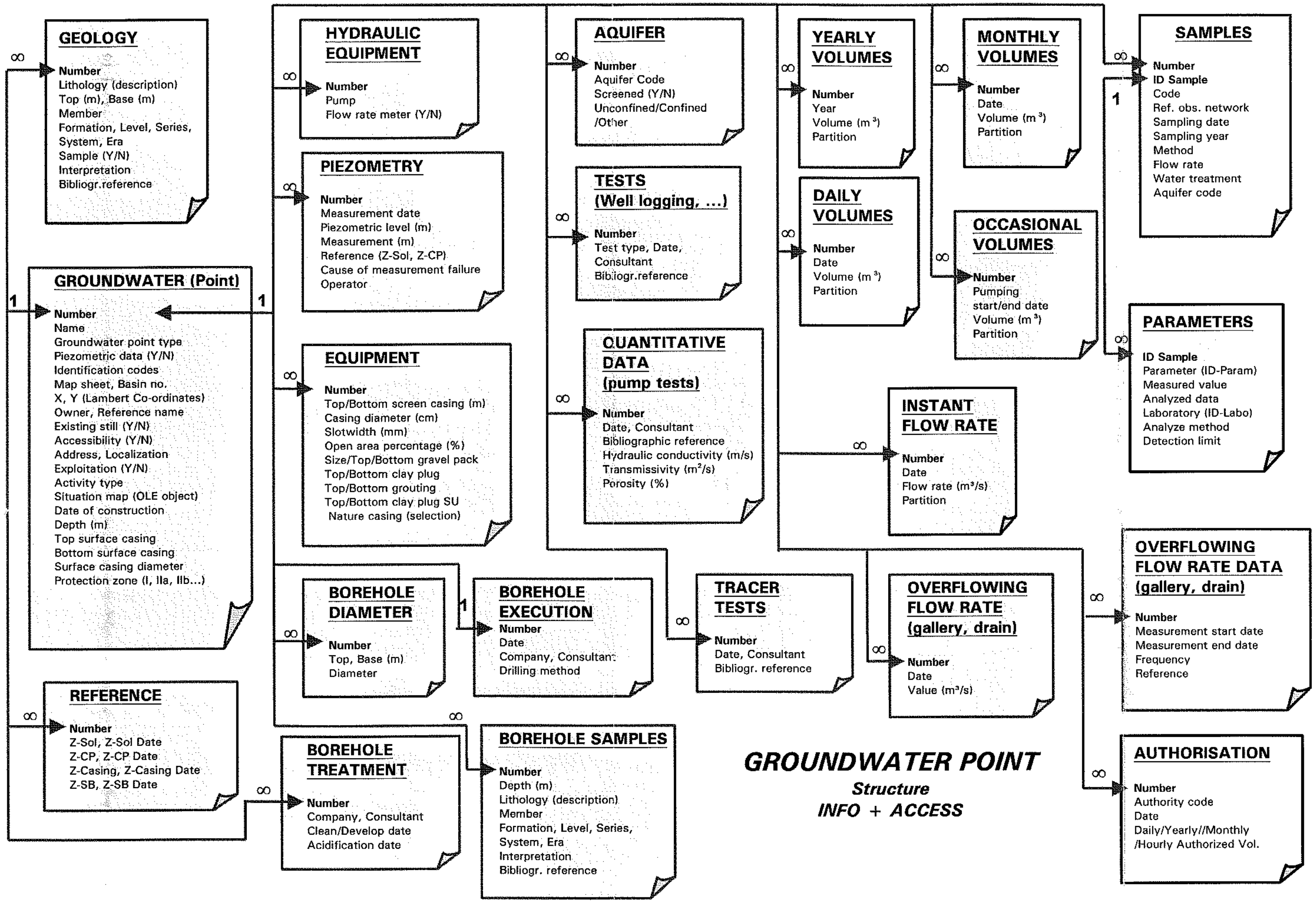


Figure 5.6. - Attribute data schema *simplified version* for "Groundwater points" layer (wells, traditional wells and simple piezometers, galleries and gallery wells, rock quarries and mines hydrogeologic punctual information, and boreholes).

5.3.2. Spatial analysis of hydrogeological data using GIS

Powerful spatial analysis could be done once the database was established. Maps representing database attribute queries (time and space dependent parameter values) could be created. Simple statistics related to hydrogeological entities can be displayed on the screen or printed on paper support maps. Geostatistic procedures (i.e. kriging) complete the analysis. A small part of the tools needed to achieve the objectives are already implemented in the base software package but most of them need good knowledge of GIS techniques, database philosophy, and targeted programming using specific programming languages.

In our case, spatial query procedures having a user-friendly interface were written in AML (Arc Macro Language) and SQL (Standard Query Language). These new query tools were designed to complete and combine the existing GIS package functions. Now, maps displaying the maximum, the minimum, or the mean of the piezometrical levels for a required period of time, can be automatically displayed by choosing the required dates (***Figure 5.7.***). Also, the number of piezometric measurement points and the associated standard deviation could be shown. Well flow rates exploiting schedule can be displayed in the same way on graphics or maps. At the same time, new layers or new maps resulting from combination of any existing layer of information can be generated.

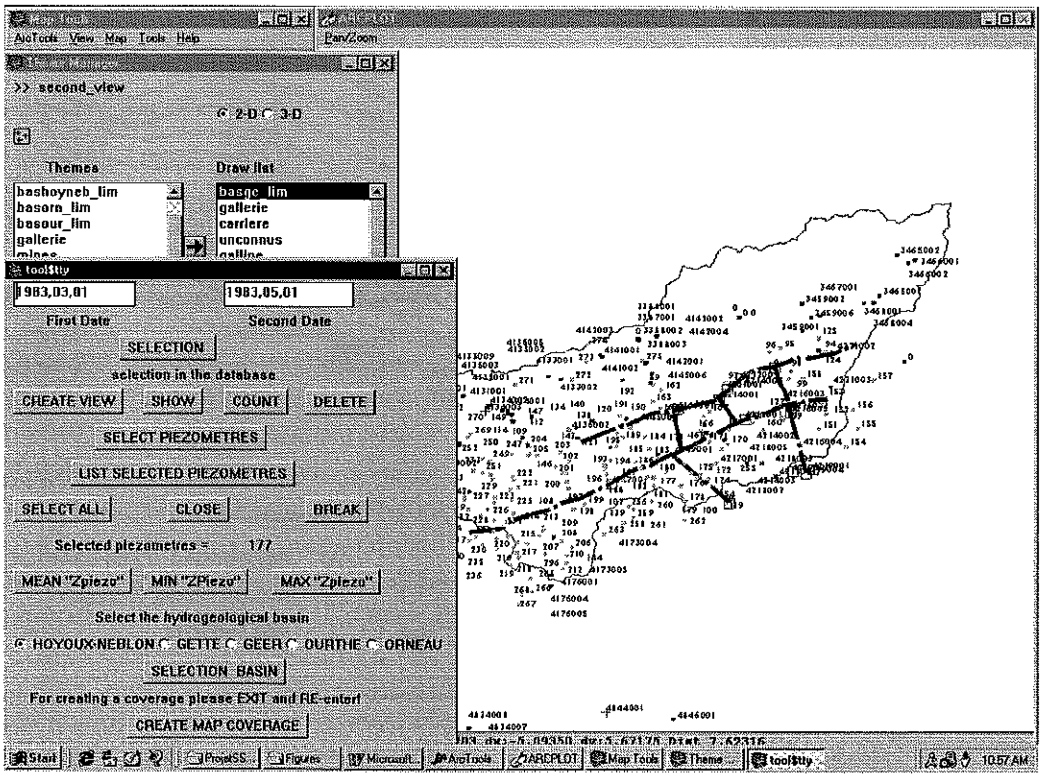


Figure 5.7. - A spatial database query menu for piezometric heads. The piezometric values can be retrieved using time and space criteria. Primary data statistics on the selected data (maximum, minimum, or mean as well as standard deviation) can be derived and spatial visualised, by simple "clicking" on buttons.

Using a chosen interpolation procedure, results obtained by different queries can be treated further. Obtaining maps of piezometric heads for a chosen time interval is one possibility. Spatial interpolation can be done by using the existing software tools or by programming new ones. Arc/Info contains several reliable tools for interpolation. The vector format layer information has to be rasterised to apply these tools. So, the information layer has to be transformed into a uniform cell based grid where each cell has assigned the attribute information. For increasing the accuracy of interpolated results, the cell size has to be chosen depending on data spatial distribution and accuracy. In our case, for obtaining contour lines of piezometric heads the cell size was selected taking into account the spatial distribution of the point information in the hydrological basin, the basin area, the distance between point hydrogeological entities (wells, piezometers, etc.), and the computing time. The interpolation method uses an iterative finite difference interpolation technique. It is optimised to have the computational efficiency of 'local' interpolation methods such as inverse distance weighted interpolation (ESRI 1997). Contour maps of piezometric heads can be generated (***Figure 5.8.***) using the optimised grid of interpolated piezometric levels.

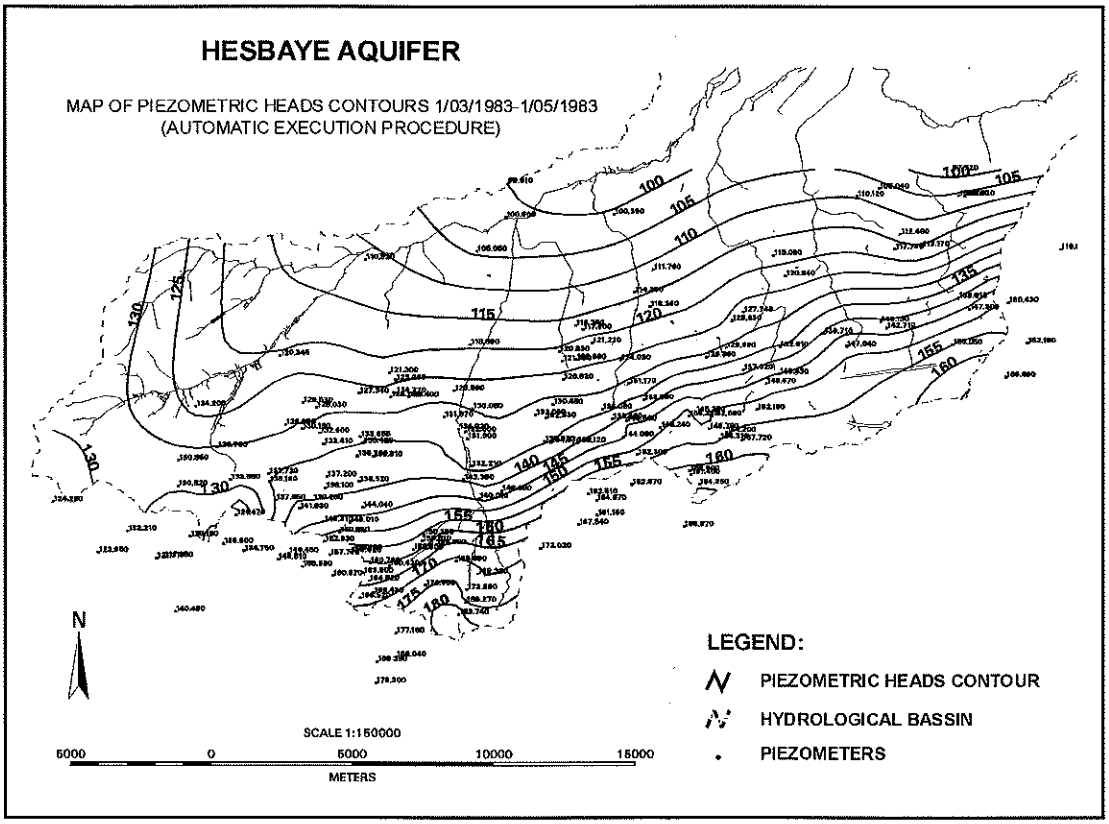


Figure 5.8. - A result of the generating procedure for obtaining contour maps of piezometric heads

5.3.3. Particular aspects of groundwater numerical modelling

Groundwater Modelling System (GMS) is a powerful pre-processor and post-processor (Engineering Computer Graphics Laboratory 1998) that can be used for various groundwater numerical modelling operations. For simulating the groundwater flow in the concerned hydrogeological basins, numerical models were created using this package with the SUFT3D (Carabin and Dassargues 1999) finite element software and the MODFLOW (McDonald and Harbaugh 1988) finite difference software.

For the used GMS version (version 2.1) the hydrogeological attribute data can be directly introduced or they can be imported from a specific format file. The need for importing data in GMS exists in all the groundwater flow modelling steps: *conceptual model* design, *model* construction and, *calibration*.

The boundaries, constraints, stresses, and other features defining the *conceptual model* are created using the so called "feature objects" represented by points, arcs, and polygons. Points are used to define pumping wells and piezometers, arcs to define boundaries, rivers, drains and polygons to define different material zones as well as water surfaces (lakes).

For 3D modelling, TINs (Triangular Irregular Network) are used to represent the ground surface and the theoretical surfaces between geological strata limits. These "feature objects" can be imported in GMS from GIS packages.

Starting from the defined *conceptual model*, the *model* can be build within GMS using automatic tools. Depending on the chosen model (finite element or finite difference) the way of using these tools is different.

For finite difference models, serried attributes can be given to all "feature objects": pumping rates and stress layers for wells, prescribed total heads for boundaries and lakes, elevations and conductances for rivers and drains, hydrogeological properties of each stratum, and the recharge rates for the defined areas. These data are distributed on different coverages. The finite difference grid is automatically constructed to fit the conceptual model and the data are transposed from the conceptual model to the grid cells.

For the mesh of the finite element models only the material properties can be imported. GMS uses the "feature objects" defining the conceptual model to generate a 2D mesh (***Figure 5.9.***). The procedure follows the geometric constraints (refinements can be required around points and element sides corresponding to arc edges). The 3D mesh is built using the 2D mesh and TINs.

Model *calibration* is the process of modifying the input parameter values until the model output matches an observed data set. In groundwater modelling, the observed data being the point values of the piezometric head, a set of "observation points" can be imported in GMS allowing further statistic treatment.

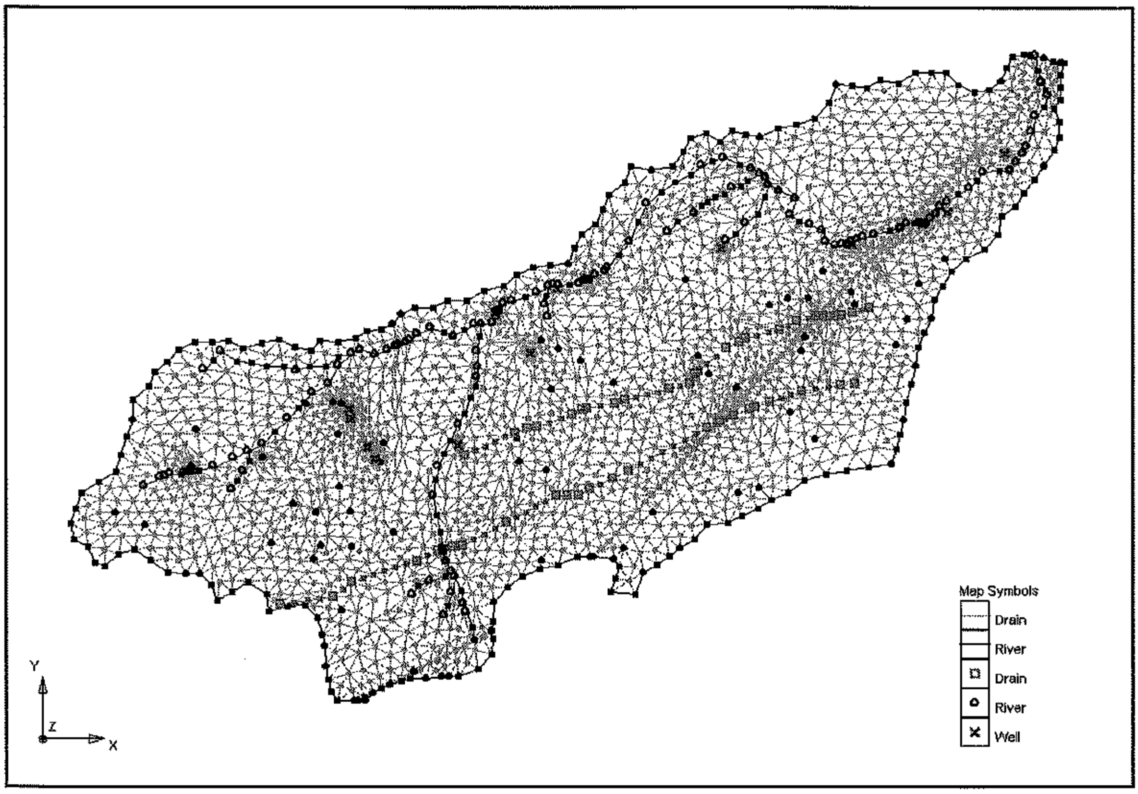


Figure 5.9. - A 2D finite elements mesh generated using "Feature objects"

5.3.4. Coupling HYGES to the Groundwater Modelling System (GMS) interface

GMS contain several tools for exchanging data with GIS packages, but a real coupling tool has not been provided yet. Arc/Info can interchange geometric data (point, arc, and polygon) with GMS through the existing "Generate/Ungenerate" functions. Attribute data cannot be automatically exchanged but GMS is continuously being improved to meet users requirements. Enlarging the GMS software capacities through programming could theoretically solve this issue, but in practice this depends on the entire spatial data schema (geometric features layers and attribute data) or even on the database structure.

In order to solve the coupling aspect, different programs were developed to automatically use the attributes of wells, rivers, and drains in GMS for the mesh of the finite element models. They are making the attribute data transfer between Arc/Info and GMS software through "feature objects" and "observation points". The codes were created using Arc Macro Language (AML) and Standard Query Language (SQL). These programs represent a coupling tool between the GIS package and the groundwater modelling software. This tool allows maintenance of the coupled software packages as independent systems, facilitating any future changes in the spatial database schema or in any particular module of the software.

An user-friendly interface (***Figure 5.10.***) manages the data query and transfer for the "loose coupling" tool. By introducing several query characteristics (spatial or time dependent) for flow rates or piezometric values, a readable GMS file is easily created. Further, GMS handles this file for attributing values (flow rates, piezometric values, statistical parameters) to each location point of the model discretisation.

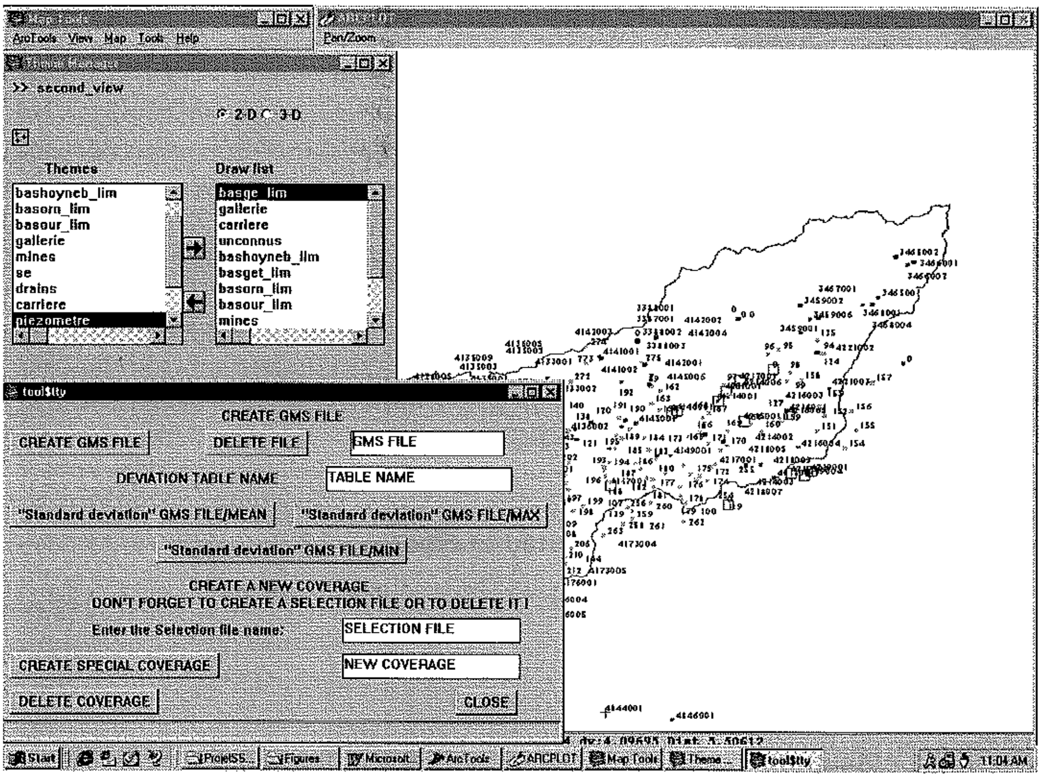


Figure 5.10. - Interface menu for creating readable Groundwater Modelling System (GMS) files and new layers of processed information

5.4. The hydrogeological database schema within a GIS structure

The presented schema can satisfy the hydrogeologist immediate needs in term of research and various environmental studies. However, hydrogeologists must be warned that a complete GIS structure is more that a database schema.

The schema implementation within a complex GIS structure supposes another design step related to concepts and formalisms (Pantazis and Donnay 1996). A GIS structure has a life and a development cycle (Donnay 2000). First of all, "GIS development is a process of technological innovation and requires management attention appropriate to this type of activity very dependent on proper management participation and supervision" (New York State Archives and Records Administration 1997).

Even if this complex direction was not beyond the objectives of the present work the main tasks that must be completed to have a successful organisational GIS, are mentioned. As stated by the above mentioned institution these are:

- Needs Assessment
- Conceptual Design of the GIS
- Survey of Available Data
- Survey of GIS Hardware and Software
- Detailed Database Planning and Design
- Database Construction
- Pilot Study and Benchmark Test
- Acquisition of GIS Hardware and Software
- GIS System Integration
- GIS Application Development
- GIS Use and Maintenance.

These steps are related as it is illustrated in ***Figure 5.11***.

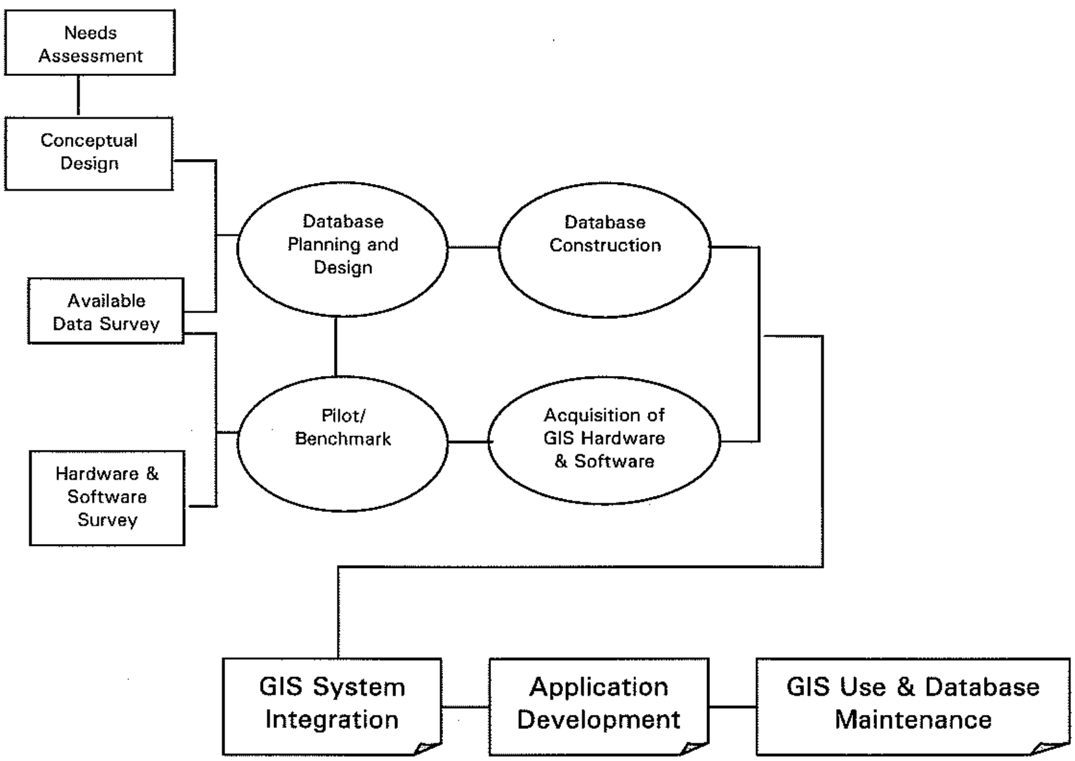


Figure 5.11. - Relationships between main steps of a GIS development process

5.5. Some conclusions and further developments

This hydrogeological GIS database offers facilities for hydrogeological modelling as well as for other hydrogeological studies.

Data verification and validation is essential. Using an advanced database supported by GIS, this operation could be done in a simple way. Possible piezometric data anomalies could be observed directly on the generated piezometric head maps. *Automatic data treatment* is required before input to the numerical model. Because of the huge work in the preparation of the data used in the process-based models, the GIS database is essential.

Global view on the hydrogeological data can be obtained using the generated maps. Piezometric heads maps, maps of exploited flow rates, maps of statistical data, show very clearly the data distribution and allow a clear view of conditions of the aquifer behaviour and stress factors. *Maps of aquifer parameters* can be generated. They can be created starting from existing point data using statistical procedures (geostatistics) supported by the GIS software. These maps are needed to start the calibration procedure of any groundwater model. Potential sites for groundwater exploitation can be detected using these maps. The vertical variability of the hydrogeologic parameters (hydraulic conductivity, porosity) that have a great influence on the aquifer exploitation conditions, also can be analysed.

Correlations between groundwater hydrochemical parameters, aquifer depth, lithology and the landuse can be done using the recorded data and statistical procedures already implemented in the GIS software. *Aquifer vulnerability studies can be performed* using the existing spatial database. New procedures for physically significant quantification of the parameters can be developed using this hydrogeologic database. From this point of view, coupling GIS to process-based numerical models with applications in groundwater phenomena as well as in the unsaturated zone will represent one of the most interesting steps in the hydrogeological research for the near future.

At present the database schema is implemented in Laboratory of Engineering Geology, Hydrogeology, and Geophysical Prospecting of the University of Liege. The software support is Arc/Info (ESRI) in connection to Access (Microsoft). The schema could be applied to other GIS and Relational Database Management Systems (RDBMS) that allow connections. However the authors consider that this schema fully satisfies the requirements, this database still has limitations which were mentioned in the previous chapters. Changes, updates, or further developments of the schema could be done in a simple way. At the same time the database was designed so that its flexibility makes the data retrieval process easy. Also, it has to be mentioned that the spatial database was conceived as a modular schema. Users that are using only a RDBMS in the absence of a GIS tool can handle the attribute data.

Starting from this schema, new developments are already going on. One of them consists in designing hydrogeological maps. A pilot project was set up and prototypes of the first hydrogeological maps for the Walloon region have been already dressed.

Chapter 6

Summary and conclusions

Nowadays, many countries develop new regulations and decision-making frameworks concerning groundwater protection. These are based mainly on two concepts: protection of the groundwater source and of the groundwater resource. In practice these are supported by the Source Protection Zones and the Groundwater Vulnerability Maps. This work has attempt to contribute in improving the assessment of the groundwater vulnerability as well as to find some solutions to ameliorate the completion of this activity.

Conceptual basis as well as the current research trends in groundwater vulnerability assessment are reviewed. This thesis develops three aspects in aquifers vulnerability assessment: (a) a technique of determining the uncertainty associated with the vulnerability assessment of limestone aquifers is developed and applied; (b) tests are performed on the efficiency of five vulnerability assessment methods on a case study of a limestone aquifer; (c) analyses and proposals for supporting aquifers vulnerability assessment are deduced; they are mainly dependent on the design of hydrogeological databases and their use.

Parameter sensitivity analysis is identified as one of the ways of analysing the uncertainty of aquifer vulnerability maps. This approach provides a methodology for evaluation of vulnerability mapping and for more reliable interpretation of vulnerability indices. Following this technique it was observed that in the Point Count System Models, the effective weights for each parameter in each subarea (polygon or goup of cells) are not equal to the theoretical weights. Furthermore, the effective weights are strongly related to the value of the single parameter in the context of values chosen for the other parameters. This "numerical" influence is the result of the combined influence of the theoretical weights and the relative uniformity of the chosen values for the other parameters. Because there is a increasing tendency of using the Point Count System Models, it has to be underlined that the effective-weights analysis technique is very useful when the user wishes to revise the weights in the equation for computing the vulnerability index.

The efficiency of groundwater vulnerability assessment is estimated by comparing different vulnerability methods. The Néblon aquifer was chosen as case study for the amount of existing information concerning its hydrogeological potential and its geological heterogeneity.

Five methods were considered representative to test their capacity of delineating vulnerability areas for the Néblon aquifer: EPIK, DRASTIC, German method, GOD, and ISIS.

Some general conclusions are deduced:

- The DRASTIC method is able to provide contrasted results. This method can be considered as presenting a high sensitivity, so that the vulnerability maps can be easily used and interpreted. By applying a careful quantification of the DRASTIC parameters, reliable results can be obtained for karstic aquifers. Developed 15 years ago when tools like geophysics, tracer tests, and GIS were not so available for parameters quantification, the DRASTIC method seems very efficient. Criticisms made by various authors, related mainly to the number of used parameters, seem not to be justified. Each designed parameter has its own significance in providing reliable results for a large range of hydrogeologic and geomorphologic situations. In karstic aquifers, the vulnerability assessment can be successfully performed using the DRASTIC method. However the karstic features like swallowholes, losing streams, sinkholes must receive a particular attention. Of course, some improvements of this method have to be considered in the future. These are mainly related to the parameters quantification (i.e. recharge) and to the possible developments of the field data collection techniques (geophysical prospections, tracer tests).

- The German method and the GOD method assessed the karstic aquifer as very vulnerable. The German method was good at delineating the karstic features but is creating overpredicted highly vulnerable areas. ISIS is a hybrid method and cannot be considered valuable for the Néblon case study.

- The EPIK method delimited correctly the karstic features but the rest of the study area appeared as being of low vulnerability. This is coming from the method incapacity of analysing other aquifers than the karstic ones. The EPIK method criteria make its only suitable for highly karstified regions or for water catchment areas of the karstic features such as swallowholes, sinkholes, and losing streams.

- Analysing only aquifers that are lithologically very similar can lead to considerable inaccuracy. This is the case for the EPIK method that can provide answers only for karstic aquifers. Furthermore, the chosen methods must be examined through applications on several aquifers characterised by different lithologies and behaviours.

Vulnerability methods have to be used as screening tools. They cannot replace professional expertise and the field work. Extended studies of hydrogeological features and aquifer behaviour must set the baseline for the parameter rating operations.

Vulnerability studies must integrate all the possible information related to geology, hydrogeology, hydrology, soil, topography, meteorology, and land-use. Almost all the methods use a general methodology and they do not impose severe restrictions on parameter quantification.

For groundwater studies, three main distinct applications (***Figure 6.1.***) of GIS can be recognised: (1) the management of hydrogeological data and general hydrogeological analysis (2) aquifer vulnerability assessment (based on overlay and index methods), (3) database support for process-based numerical modelling. Each of them must be based on a hydrogeological GIS database. The first two applications represent the extension in hydrogeology of classical GIS technology. The last one consists mainly of developing interactions between GIS and dynamic models used in groundwater studies. The third main issue of this paper was to improve the hydrogeological and hydrochemical databases concepts for the vulnerability assessment activity. It identified the need for improving GIS analytical tools for an effective integration between vulnerabiliy methods, spatial attribute databases, and numerical modelling. With this purpose a hydrogeological GIS database schema was designed based on the hydrogeological specificity of the Walloon region (Belgium) environment. The database is presented in Chapter 5 and the entire schema is attached in the Annex.

This database was created to support data used in vulnerability assessments techniques as well as studies using numerical modelling for groundwater flow and contaminant transport. For this last aspect, a loose coupling tool managed by a "user friendly" interface was developed. This tool consists of a set of computer programs, allowing also the creation of maps derived from the database attribute queries and the statistic results of hydrogeological parameters.

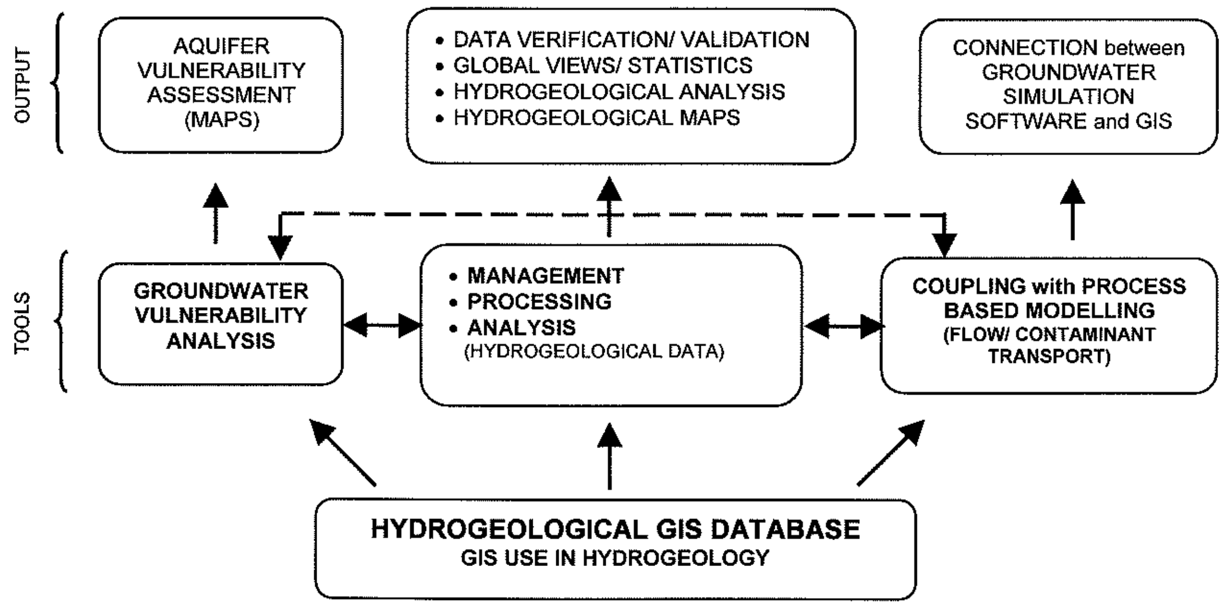


Figure 6.1. – Principal applications of GIS in hydrogeology

Applying vulnerability mapping as part of the groundwater protection strategy

This study provides a framework for applying the groundwater vulnerability studies at a regional scale.

This has to be understood in terms of:

- parameter rating operation has to be done using extended studies on aquifer behaviour and on hydrogeological features;
- estimation of the efficiency of the groundwater vulnerability assessment can be done only by comparing the results of distinct vulnerability methods on the same case study. A good choice for a specific aquifer, can consists in adopting the method that provides reliable contrasted results (higher sensitivity);
- validation of the vulnerability map has to be done after analysing its uncertainty by an adequate technique as shown in this work.

The main phases for implementation of a vulnerability assessment program at a regional scale are:

I. Establish a classification system for groundwater resources on the basis of the value of the resource (potential) and the hydrogeological characteristics (permeability, areal extent, and storage capacity)

II. Perform pilot studies on 2 or 3 representative aquifers with distinct hydrogeological characteristics and behaviours (porous media, fissured matrix, and karstic systems).

  - Identifying and applying several representative vulnerability methods for the study cases
  - Analysing the results by comparisons and statistics

III. Choose the vulnerability method that is best adapted and that present a high sensitivity for the study cases

IV. Evaluate the uncertainty in the preferred method of vulnerability assessment in relation to the all study cases

  - Analysing and discussing the results, parameters checking, and vulnerability index interpretation

V. Establish the vulnerability index classification system for a reliable and usable vulnerability zones delineation

VI. Choosing the regional planning for the vulnerability maps production and the basic options like: choice of scales, data to be drawn, formats, etc.

Final ideas

Aquifers vulnerability assessment is beginning to find its place within a European groundwater protection strategy. Increasing numbers of people are starting to understand that it is not enough to protect only the most important groundwater sources of the water supply systems. Groundwater has to be protected wherever it exists and this can be done only by resource vulnerability mapping in complementary with rigorous delineation of source protection zones. This work tried to outline some of the most sensible aspects in groundwater vulnerability assessment, to test some aquifer vulnerability methods and to analyse them, and than to offer a support for aquifer vulnerability mapping design.

Starting from a theoretical and a practical background for developing aquifer vulnerability assessment using GIS, this work identifies the main applications of GIS in hydrogeology, defines the main phases for a regional scale program implementation of vulnerability assessment, and represents a base for sustaining future research in groundwater resource protection.

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List of figures and plates

List of tables

Annex

HYGES

Hydrogeological Spatial Database

not available

Advances in groundwater protection strategy using vulnerability mapping and hydrogeological GIS databases

by

Radu Constantin GOGU

University of Liège, Laboratory of Engineering Geology, Hydrogeology, and Geophysical Prospecting (LGIH), Belgium

Key words: groundwater protection, resource, vulnerability, karst aquifer, sensitivity analysis, groundwater management, database, GIS, coupling

Groundwater vulnerability maps are useful for environmental planing and decision making. They are usually produced by applying vulnerability assessment methods using overlay and index techniques. On the basis of a review of the vulnerability assessment and mapping methods, new research challenges in aquifers vulnerability assessment are identified.

Operations like the parameter quantification, the vulnerability index computing, and the final classification, are affected by an empirical character which of course affects also the final product: the vulnerability map. In consequence, the validity of the resulted vulnerability maps must be evaluated in function of the objectives of the survey and in function of the specific characteristics of each studied zone. Analysing their uncertainty can represent the base for their validation. Uncertainty can be investigated through sensitivity analysis or through comparisons between vulnerability maps created using different methods. Both these strategies are developed in this study and illustrated from applications on practical case studies of vulnerability mapping.

Applying the EPIK parametric method, a vulnerability assessment has been made for a small karstic groundwater system in southern Belgium. The aquifer consists in a karstified limestone of Devonian age. A map of intrinsic vulnerability of the aquifer 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.

Five different methods for assessing the intrinsic vulnerability were tested on a case study for comparison of their results. The test area consists in a slightly 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 in drainage galleries. Several campaigns of measurements consisting in morpho-structural observations, shallow geophysics, pumping and tracer tests have provided useful data. The tested methods were: EPIK (Doerfliger and Zwahlen, 1997), DRASTIC (Aller *et al.*,1987), 'German method' (von Hoyer & Söfner, 1998), GOD (Foster, 1987), and ISIS (Civita and De Regibus, 1995). DRASTIC and GOD represent classic approaches in vulnerability assessment. ISIS is a development based on DRASTIC, SINTACS (Civita, 1994), and GOD methods, where more importance is given to the recharge. EPIK was developed specifically for karstic geological contexts and the 'German method' was developed in Germany for a broad range of geological contexts. Compared results are shown and commented. It seems that despite the fact that the EPIK method can better outline the karstic features, about 92% of the studied area is assessed by this technique as low vulnerable. In contrast, the other four methods are considering extended zones of high or moderate vulnerability. From the analysis, it seems also that reducing the number of considered parameters is not ideal when adaptation to various geological contexts is needed.

Reliability and validity of groundwater analysis strongly depend on the availability of large volumes of high quality data. Putting all data in a coherent and logical structure supported by a computing environment helps ensure a validity and availability, and provides a powerful tool for hydrogeological studies. A *hydrogeological* GIS *database* that offers facilities for groundwater vulnerability analysis and hydrogeological modelling has been designed in Belgium, for the Walloon Region. Data from five river basins, chosen for their contrasted hydrogeological characteristics, are now introduced in the database and a set of applications have been developed allow now further advances. However the basic concept of the database is represented by the commonly accepted "Georelational model" developed in the 1970s, the database concept presents a distinctive character.

There is a growing interest in the potential for integrating GIS technology and groundwater simulation models. Between the mentioned spatial database schema and the groundwater numerical model interface GMS© (Groundwater Modelling System), a "loose-coupling" tool was created. Following time and spatial queries, the hydrogeological data stored in the database can be easily used within different groundwater numerical models. This development can represent also a solid base for the physical processes integration within the quantification of the vulnerability methods parameters.

The fundamental aim of this work was to help to some extent improving the aquifers protection strategy using vulnerability mapping and GIS. The results are offering the theoretical and practical basis for developing a strategy for protecting the groundwater resources.