ISSN 1018-5593

COST action 65

Karst groundwater protection

Final report

European Commission

Report
EUR 16547 EN

European Commission

COST action 65

Hydrogeological aspects of groundwater protection in karstic areas

Final report

Directorate-General
Science, Research and Development

1995

EUR 16547 EN

CONTENTS

NATIONAL REPORT FOR BELGIUM

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1. INTRODUCTION

During the last few years, the protection of karstified or slightly karstified aquifers has been studied in greater depth than previously. In Belgium the carbonate rocks concerned are the Devonian limestones, the Carboniferous limestones and the Cretaceous chalk. In the framework of the COST ACTION 65 entitled *Hydrogeological Aspects of Groundwater Protection in Karstic Areas*, we had the opportunity to meet European scientific partners working on the same kind of problems. It was a very fruitful experience to compare and exchange scientific information and experiences. However, no additional funding was dedicated to the scientific work itself in the research pilot areas. Thus the content of this National Report on the hydrogeological aspects of karstic groundwater protection in the Belgian research pilot areas, is essentially a synthesis of the results over the last four years from different researchers belonging to two or three teams within the framework of private and/or public research and applied research conventions.

The results from the lower Carboniferous limestones in the Néblon-Anthisnes areas and from the tracer tests performed at many sites (paragraphs 2.1.4 and 2.1.5) in the Carboniferous limestones as well as in the Devonian limestones and in the Cretaceous chalks are taken from research realised by Ph. Meus for his PhD doctorate at the LGIH of the University of Liège (ULG). The aerodynamic study of a "blowing well" in the Carboniferous karstified limestones (paragraph 2.1.6) is the responsability of Prof. Loy at the Catholic University of Leuven (KUL). The methodology and results of the delineation of protection zones in the Cretaceous slightly karstified chalks (paragraph 2.2) are from the research work of P. Biver, Ph. Meus and A. Dassargues at the LGIH of the University of Liège (ULG).

Nowadays, each country or region has promulgated regulations on protection zones around pumping wells in order to maintain or to restore the quality of groundwater in the vicinity of drinking water supply wells. However, despite the fact that the authorities have often consulted the scientific community for assistance in the choice of the appropriate general regulations to be prescribed, it is still very difficult in many cases to determine, on a rigorous and scientific basis, the effective zones which are to be specially protected from any accidental pollution.

The problem is particularly difficult in karstified aquifers where enlarged fissures, fractures and conduits carry the main portion of the groundwater flow. In these conditions, the groundwater network consists mainly of series of conduits and enlarged caves rather than a diffuse seepage porous medium. The permeability and storage conditions are physically very different and thus the transit times of pollutants are affected.

Consequently, it appears that even if the regulations exist, they are very often not followed, not applied or misunderstood, due to insufficient knowledge of the actual groundwater conditions; especially with regard especially to aquifer heterogeneity and the complex processes of the transport of a contaminant in a porous, fractured and/or karstified medium.

1.1. Groundwater protection regulations

Usually regulations relating to protection zones are mainly based on transfer time of the contaminants in the saturated part of the aquifer or in some cases, simply expressed in terms of distances from the pumping well.

As an example, we can provide hereafter a summary of the regulations which has been chosen in our country[1]. Three kinds of protection zones are defined: the "water supply zone", the prevention zones and the observation zone.

- "**zone I**" or "water supply zone" is defined as the zone where the effective water supply installations are located, at the circumference of which a 10 meters radius is added in all the directions. This zone has to be owned by the water company.

- "**zone II**" or prevention zones are divided in two successive zones.

From the external perimeter of zone I, "**zone IIa**" is defined as the distance in each direction corresponding to a time of pollutant transit of 24 hours in the saturated zone. A minimum of 25 meters is required from the external perimeter of zone I. In karstic areas, zone IIa has to include all preferential points of infiltrations (sinkholes, collapse dolines, poljes, ...) for which connection with the water catchment is established (by tracer tests for example). From the external perimeter of zone IIa, "**zone IIb**" is defined as the distance in each direction corresponding to a time of pollutant transit of 50 days. However, in unconfined aquifers, zone IIb can be considered to be the radius of influence of the pumping in each direction with a minimum of 100 meters in sandy aquifers, 500 meters in gravel aquifers and 1000 meters in fissured and karstic aquifers.

- "**zone III**" or observation zone is defined as the total recharge capture area to the borehole.

The permitted and prohibited activities have been listed for each of these protection zones. An important decision is currently being made taken during these days (end of 1994) by the political authorities[2] for prescribing accurately all the controlled activities :

- in zone I, nothing would be allowed except the normal activity of the water supplier.

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[1] As groundwater protection is relevant to regional authorities, the regulations mentioned hereabove relate to the Walloon Region of Belgium. For comparison, in the Flanders Region of Belgium, three protection zones are defined: zone I: 24 hours of pollutant transit; zone II: 60 days with a maximum of 150 m in artesian aquifers and 300 m for all the others; zone III: whole alimentation basin of the catchment area with a maximum of 2000 m for the water table aquifers

[2] authorities of the Walloon Region of Belgium

- in zone IIa, any discharge or storage of hydrocarbons, fertilisers, ...or any dangerous compounds would be strictly forbidden, class 1 and 2 waste disposals, wastewater treatment plants, discharge of used or treated waters and any disposal of liquid manure or dung-pit would be prohibited. Many other activities (from various industrial activities to cycle- tracks !) would be strictly regulated.
- in zone IIb, only the disposal and discharge of dangerous products and hydrocarbons would remain forbidden all the other mentioned activities would be controlled.
- in zone III, only the discharge of hydrocarbon compounds would be forbidden and the other activities controlled.

In each zone, "intervention codes" are foreseen in the case of accidental spillage.

Considering these prevention and protection regulations, it is evident that in each particular zone, the aquifer vulnerability has to be assessed. However, as mentioned by Foster (1993), the vulnerability concept has significant limitations in rigorous scientific terms because 'general vulnerability to a universal contaminant in a typical pollution scenario' has little meaning. In practice, each aquifer system will respond differently to individual contaminants and pollution scenarios (Andersen and Gosk, 1987).

Evidently, attenuation of contamination can occur in the unsaturated zone, but in these regulations it is not taken into account; thus a factor of safety is introduced. This last remark will not be discussed further here, as the following studies essentially only consider the saturated zone. However, in highly karstified aquifers the classical significance of unsaturated and saturated zones is not reliable and in practice not used.

1.2. Specific problems of karstified aquifers

Karst areas and karstified aquifers are generally highly vulnerable to pollution due to the following main characteristics :

- the groundwater network has a hydraulic behaviour closer to conduit hydraulics than to porous medium hydraulics. The flow is very rapid in directions corresponding to the main conduits, with nearly no filtration effect. Consequently, any solute pollutant can travel long distances in a short time.
- the heterogeneity, geometry of conduits, siphons, caves,... is highly variable from one place to another. Additionally, these characteristics depend strongly on the conditions leading to the karst development itself. Confident predictions on contaminant spreading and the probability of pollution are very difficult to make and have to be based on reliable and extensive data.

1.3. Applied methodologies

In this report, we will consider slightly karstified aquifers as well as karstified aquifers. The methodology applied in each particular research area depends strongly of the local degree of karstification.

In the karstic pilot area located in the lower Carboniferous limestones, which are characterised by high groundwater storage in low permeability blocks between channels and catchment galleries collecting diffuse springs (the Néblon and Anthisnes systems), the following approaches were used: geomorphology, geophysical prospecting, hydrochemistry, hydrodynamics and tracer tests.

In highly karstified Carboniferous limestones, an estimation of the volume of underground cavities is being realised from the aerodynamic study of a "blowing well".

For the three sites located in the slightly karstified Cretaceous chalk aquifers, a comprehensive set of methods has been applied involving morphostructural analysis, geophysical prospecting, drilling of piezometers, balance studies, hydrodynamic measurements, piezometric mapping, geochemical methods, pumping tests and multi-tracer tests.

2. PILOT RESEARCH AREAS

2.1. Palaeozoic limestones (by Ph. Meus)

2.1.1. Distribution and main characteristics of the palaeozoic limestones in Belgium

In Belgium, beside the Cretaceous chalks, two other kinds of carbonate rocks outcrop. They are the Devonian and Carboniferous limestones. The distribution of these carbonate rocks is shown on the map of figure 1. The degree of karstification in each zone is dependant upon its geological history and particularly its lithological characteristics. Due to these different rates of karstification, the hydrogeology is also different. One may also take into account the eventual effect of a cover of loose sediments. The final result is that the sensitivity to any change (whether natural or artificial) depends on the aquifer concerned.

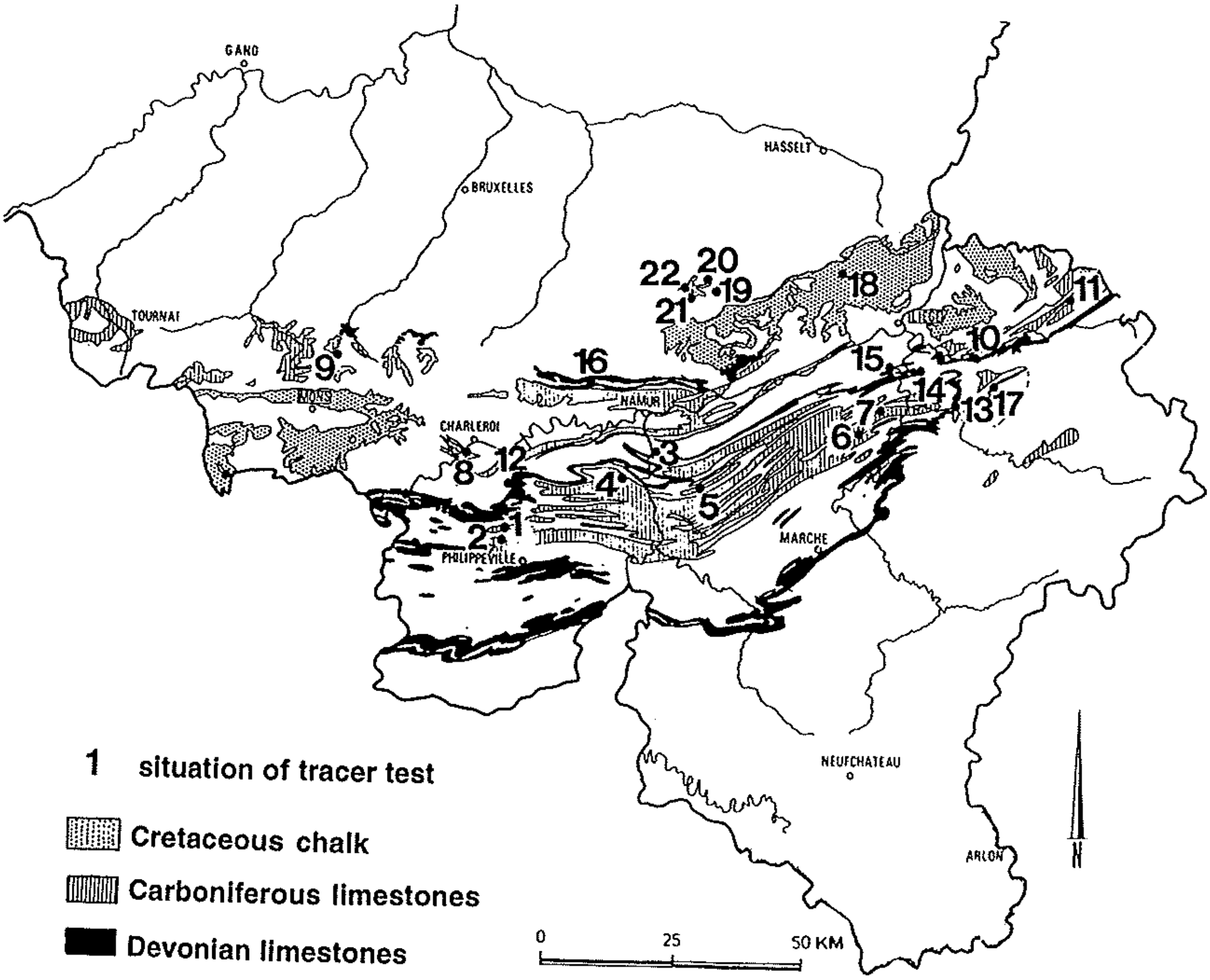

Figure 1.-Map of the carbonate fissured rocks in South Belgium. Situation of the tracer tests. 1 = Fairoule 2 = Yves-Gomezée 3 = Lustin 4 = Bioul 5 = Spontin 6 = Néblon 7 = Anthisnes 8 = Mont-sur-Marchienne 9 = Soignies 10 = Dison 11 = Walhorn 12 = Gerpinnes 13 = Remouchamps 14 = Xhoris 15 = Esneux 16 = Bossière 17 = La Reid 18 = Crisnée 19 = Bertrée 20 = Grand Hallet 21 = Jandrain 22 = Orp.

Palaeozoic aquifers provide more than 30 % (i.e. more than 200 Millions of m^3/y) of the water supply in Belgium. In some places (in the area near Tournai), they are overexploited. They have also been widely studied because of their competition with other economic activities (quarries, waste disposal, tourism,...).

The main karstic phenomena are encountered in the Devonian limestones (Givetian and Frasnian) and to a lesser extent in the Carboniferous limestones.

In the synclinorium of Dinant (Fig. 2), karsts are usually called in French "karsts barrés" with a intensive karstification. The Carboniferous karsts occupy the centre of the synclinorium while the border is made of narrow Devonian karstic bands. These two formations are also found to the east, in the synclinorium of La Vesdre and in the geological window of Theux.

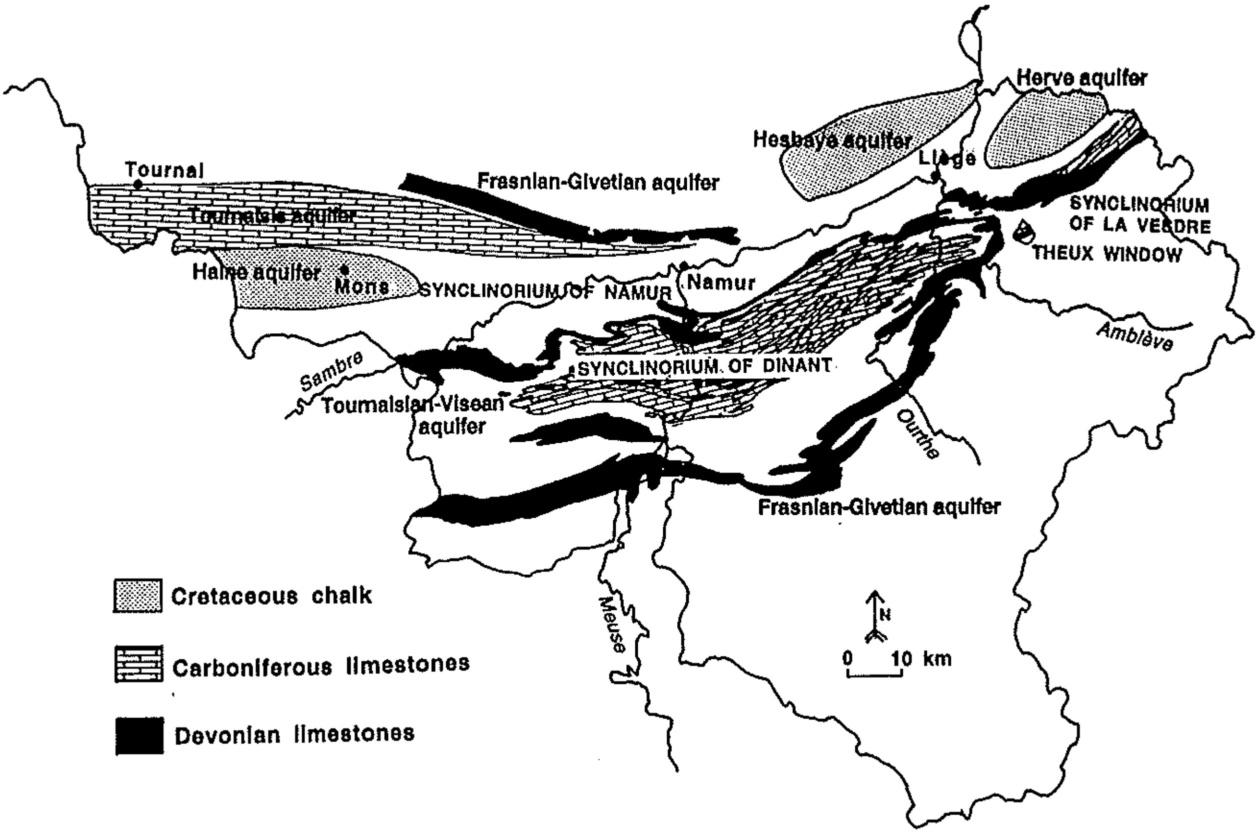

Figure 2.-Distribution of the main carbonate aquifers of South Belgium.

In the synclinorium of Namur, the limestones are less folded. They thus form more continuous aquifers. One may distinguish two main aquifers on the northern flank of this synclinorium: one in the Devonian limestones (Frasnian-Givetian) and one in the Carboniferous limestones (near Tournai). Unlike the aquifers in the Dinant synclinorium, these aquifers are sometimes confined or covered by thick tertiary and/or quaternary deposits.

2.1.2. Consequences for resource potential and management of the karst

From an economic point of view, the Carboniferous aquifers are more valuable than the Devonian aquifers. The transit times in the former are longer and the reserves are less vulnerable. For this reason, almost all of the production water from the Palaeozoic limestones is taken from the Carboniferous aquifers. The wells in the aquifer of the northern flank of the Namur synclinorium provide more than 110 Millions m3/y, i.e. 40 Millions less than its estimated potential resources. Nevertheless, some areas of this aquifer are overexploited, due to an inadequate distribution of the pumping sites.

The aquifers in the Dinant synclinorium provide more than 80 Millions m3/y. Catchment galleries are more frequent in this case, thus avoiding any overexploitation. The greatest volumes come from the Modave (16 Millions m3/y) and the Néblon (8 Millions m3/y) galleries.

Great quantities of water are extracted from the dewatering of quarries. These volumes could potentially compensate local deficits but the Belgian regulations prevent this because dewatering water is considered as waste water.

From a protection point of view, it is extremely difficult to predict the distribution of the main conduits in the Carboniferous karst. For this reason, determination of protection zones around catchment wells or galleries is conditioned by the availability of data on the local hydrogeological conditions.

2.1.3. Study area and main approaches

As mentioned above, the first pilot area is the Néblon-Anthisnes aquifer consisting of two contiguous karstic systems in the eastern part of the synclinorium of Dinant. The situation is shown on figure 1. The Anthisnes basin is drained towards the Ourthe valley while the Néblon river drains the south-western part of the aquifer. In the Anthisnes basin, the main outlet is a huge karstic spring whose specific discharge is 10.42 l/s/km^2. In the Néblon basin, groundwater flows towards three galleries which collect more than 400 l/s.

Additionally, artificial tracing has been applied to the following sites (Fig. 1): (a) in the Carboniferous limestones of the Dinant synclinorium (Fairoule, Yves-Gomezée, Lustin, Bioul, Spontin, Néblon, Anthisnes), (b) in the Carboniferous limestones of the Namur synclinorium (Mont-sur-Marchienne, Soignies), (c) in the Carboniferous and Devonian limestones of the Vesdre synclinorium (Dison, Walhorn), (d) in the Devonian limestones of the Dinant synclinorium (Gerpinnes, Remouchamps, Xhoris, Esneux), (e) in the Devonian limestones of the Namur synclinorium (Bossière), (f) in the Devonian limestones of the Theux window (La Reid), (d) in the Cretaceous chalks of Hesbaye (Crisnée, Bertrée, Grand Hallet, Jandrain, Orp).

2.1.4. The Néblon-Anthisnes pilot basins

Two approaches have been used to compare these basins: a structural approach using geophysical prospecting and a functional approach using the natural (hydrodynamic and hydrochemical) and artificial (tracer tests) responses of the aquifer. In this kind of system, the determination of the structure can not explain completely the functioning. The two approaches are in fact complementary. Some differences in the degree of karstification have been found. The Anthisnes basin is more karstified than the Néblon. The former contains fewer reserves and is more sensitive to contamination. The difference between the two basins is probably due to their respective geological and geormorphological evolution.

These facts are obvious from the hydrodynamic behaviour of the springs. The table 1 summarizes the main characteristics of both basins, compared with those of a Devonian system in the same region.

	Néblon	Anthisnes	Remouchamps
Surface (km^2)	66	26	27
Lithology	Carboniferous	Carboniferous	Devonian
Qmax/Qmin	1,2	3,9	90-160
Specific discharge (l/s/km^2)	8,4	10,4	42
Recession coeff. (j^{-1})	0,0004	0,003-0,01	0,02-0,09
Mean transit time	several years	160-400 d	48 d
k	>1	0,45	0,13
i	no peak	0,8	0,3-0,6
Regulation time	-	53 d	21 d
Response time	-	2 d	1,5 d

Table 1.-Main characteristics of the pilot basins

The study of the hydrographs and piezometric curves are particularly useful in order to get some parameters characterising the inertia or "memory effect" of the systems. Those parameters are related to the degree of karstification. The reserves have been estimated as comprising between 100 mm in the Anthisnes basin and 1400 mm in the Néblon. As a consequence, the mean transit time is longer than one year for the Néblon while it is only a few months for Anthisnes. The shape of the hydrographs has given two parameters k (depending on the reserves) and i (depending on the infiltration) used in the Mangin classification.

Correlation and spectral analysis have shown the time of regulation is about 50 days for both basins while the time of response corresponding to the direct infiltration through karstic channels is only 2 days in the Anthisnes basin while it is more than 100 days in the Néblon. The correlation analysis of the piezometric data gives an insight to the problem of infiltration through the unsaturated zone and on the effect of the poorly permeable loess covering the karst and filling the channels (palaeokarst). Indeed, those formations act indeed as an epikarst. The informations gathered by the pumping tests in the boreholes has not led to any useful conclusion. The scale effect and the distribution of the conduits seem to be critical in this case.

Tracer tests have confirmed that the Néblon basin is less karstified. In the Anthisnes basin, velocities range from 73 to 277 m/h. These velocities are strongly influenced by the occurrence of flood events. Several configurations of tracer experiments have been used, i.e. tracing from sinkholes to boreholes or the contrary. These configurations are useful to understand the exchanges between the conduits and the fissures containing the reserves. By applying analytical solutions, it was possible to compare the dispersivities in time and space and also estimate the volumes of the reserves where diffusion occurs place (immobile water). The dispersivities range from 20 to 100 m.

2.1.5. Transport properties of karst: application of tracer tests

Every configuration used to conduct the tracer tests has been adapted according to the hydrogeological conditions. Five situations were tested with varying input and output: from sinkhole to spring, from borehole to spring, from sinkhole to borehole, between two boreholes or in a single borehole. Tracing between boreholes is more suitable for homogeneous aquifers without any known outlet. Only the radially convergent method has been used.

The choice of the tracer depends on the kind of permeability and the minimal size of the opened joints. For strongly karstified aquifers such as the Devonian and the Carboniferous limestones, any tracer may be used. Immobile water effects are becoming more important in chalks. Generally, the adsorption effects may also be neglected. Twelve tracers have been injected and recovered with success: NaCl, KI, KNO_3, LiCl, $SrCl_2.6H_2O$, uranine, naphtionate, rhodamine B, sulforhodamine B, rhodamine WT, fluorescent microspheres and bacteriophages.

Three kinds of curve have been computed in order to compare the individual tracer tests: simple breakthrough curves, normalized breakthrough curves and residence time distributions (RTDs). This made it possible to define the influence of a few parameters such as the structure of the aquifer (fissured or karstified), the characteristics of the tracer (conservative or not), the discharge and flow velocity, the thickness of the unsaturated zone, the distance of the injection point from the karstic drains, the gradient, the contact with clays...

Some RTDs are shown in figure 3 with enlarged horizontal and contracted vertical scales in the upper part. From the great diversity of shapes, the heterogeneity is obvious. That is one good reason why the delineation of protection zones would be a very hazardous task without a thorough knowledge of the local hydrogeological conditions and also a good control of the tracing conditions. The tests have to be repeated in different hydrological conditions.

In natural flow, the maximum velocities were between 1.2 and 327 m/h. The modal velocities ranged between 0.4 and 225 m/h. In radial convergent flow, the modal velocities are between 1 and 9.2 m/h for the limestones and between 1 and 48 m/h for the chalks. Figure 4 shows the breakthrough curve of a tracer test with naphtionate in the chalky aquifer. The distance from the injection borehole to the spring is 350 m. The maximum velocity is 13 m/h and the modal velocity 3.8 m/h. This example indicates that preferential conduits may also be present in the chalk and that the assumption of a homogeneous medium in a mathematical model for chalk may also be a risk without a better knowledge of the structure.

Dispersivities and effective porosities have been calculated using two analytical models: (a) advection-dispersion in a uniform one-dimensional, uniform two-dimensional or radial convergent flow, (b) advection-dispersion in a conduit with diffusion in immobile water.

The greater the degree of fissuring, the higher the dispersivities. In the limestones, the longitudinal dispersivities range between 15 and 100 m for tracing from sinkholes to spring and between 10 and 92 m for tracing involving boreholes. For comparison, in the chalks (see paragraph 2.2), the dispersivities do not exceed 14 m. The variation of transport properties as a function of the structure of an aquifer appears clearly when the dispersivities are plotted against the effective velocities (see general conclusions).

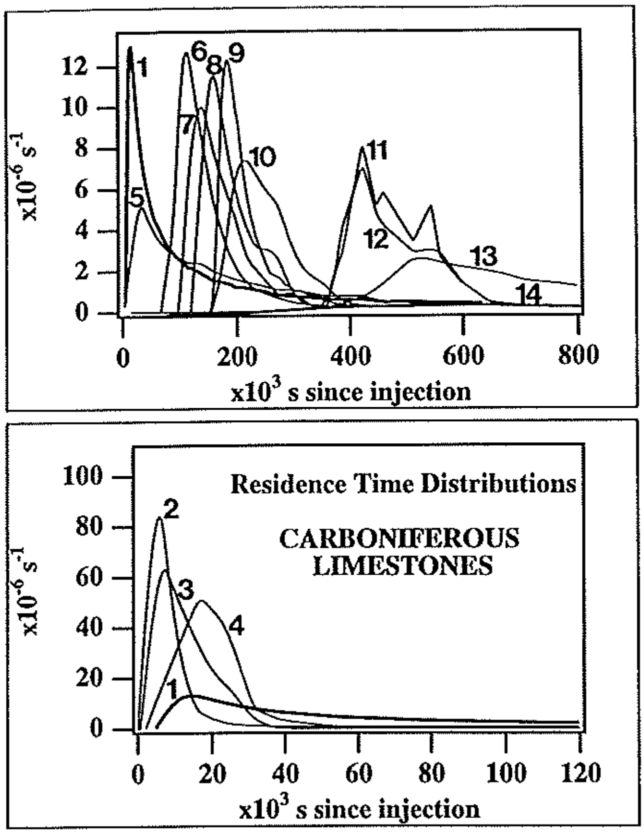

Figure 3.-Residence time distributions for tracer tests in the Carboniferous limestones. 1 = lithium-Spontin-7/1/91 2 = microspheres-Spontin-7/1/91 3 = uranine-Spontin-7/1/91 4 = bacteriophages-Spontin-6/3/90 5 = lithium-Mt-sur-Marchienne-16/12/91 6 = uranine-Crossée-10/12/88 7 = rhodamineB-Anthisnes-29/3/89 8 = naphtionate-Crossée-29/3/89 9 = lithium-Marsée-27/12/91 10 = uranine-Vien-29/3/89 11 = microspheres-Crossée-15/8/90 12 = uranine-Crossée-15/8/90 13 = naphtionate-Spontin-15/1/92 14 = uranine-Mt-sur-Marchienne-16/12/91.

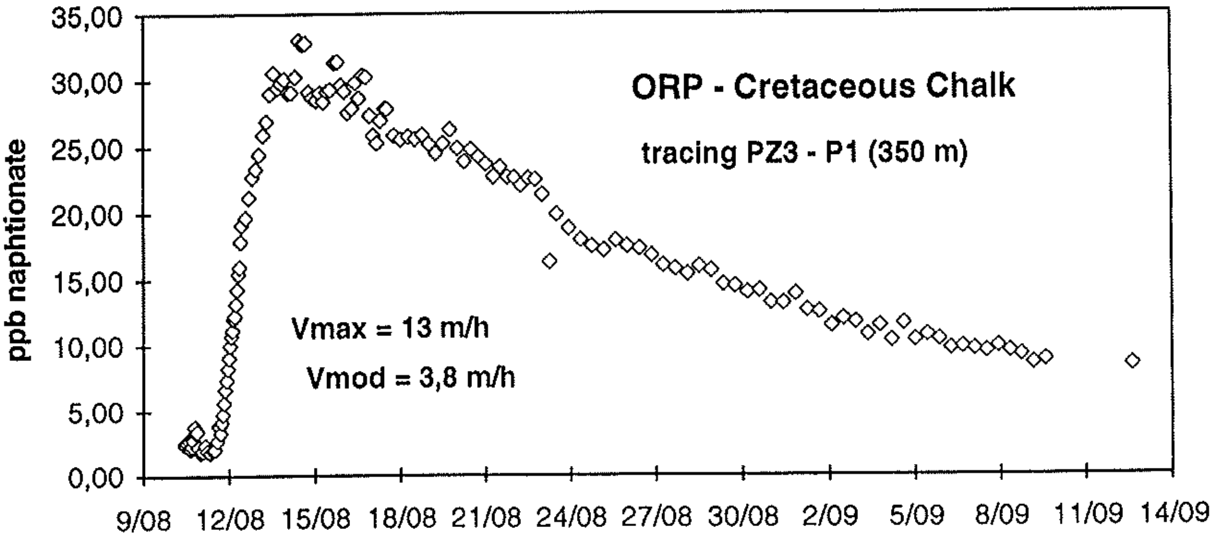

Figure 4.-Breakthrough curve at the well P1 of the naphtionate injected in the borehole PZ3 at 350 m in the Cretaceous chalk of Orp. Vmax = velocity for the first arrival Vmod = modal velocity corresponding to the peak.

2.1.6. Aerodynamic study of a "blowing well" in the Carboniferous karst (by Prof. W. Loy)

The phenomenon of air movement is common knowledge in the speleology. This phenomenon is less familiar in boreholes. The only documented case of a "Blowing well" known to us is mentioned by Prof. de Vries (1982) in " Anderhalve Eeuw Hydrologisch Onderzoek in Nederland" page 54: "...the relation between changes in hydrostatic levels and atmospheric pressure is the result of compression, and expansion, of enclosed air in, and above, the groundwater (King, 1899). This vision, which will be partially correct, is undoubtedly inspired by the phenomenon of "blowing wells". This phenomenon is observed in situations where air, or other gasses, are compressed between the enclosing layer, and the groundwater. Reduction of atmospheric pressure results in the escape of these gasses through wells or springs. Through siphon-action it can be accompanied by the rise of the hydrostatic groundwater levels. In our country, this phenomenon can be seen in southern Limburg". We were verbally informed by Prof.Zwaelen of the existence of another "blowing well" located in Switzerland (in the flysh formations).

The well D1, situated in Ramegnies-Chin (south-west of Belgium), has sucked air in and blown it out periodically over several years. It was drilled in 1949 by the SNDE (Société Nationale de Distribution d'Eau), and is archived under number 111E565 (map Pecq) by the Geological Survey of Belgium.

In this well, an impermeable layer composed of Turian marl (chalk) occurs under alluvials of the Scheldt. This layer protects the aquifer of Visean dolomite, which is partially dry pumped. The aquifer is formed in a karst of Wealden origin (Lower Cretaceous). Traces of the Wealdien formation are preserved in fissures and karstic cavities of the Visean formation. The morphology of the karstic spaces are unknown although this is of great importance for determining the flow direction, the infiltration of pollutants, and the possible formation of sinkholes.

The measurements, carried out by VITO (Flemish Institute for Technical Research), took place from December 9th until December 15th of 1993. This period was chosen because of the big fluctuations in atmospheric pressure which were meteorologically expected for this time of year. Simultaneously with the decrease of pressure over the measuring flange, variations in atmospheric pressure, the temperature of the airstream in the well and the groundwater level were recorded. These measurements were analysed by F. Massen (Diekirch-Luxembourg) as follows:

- Analyses of the data through calculating the incoming, and outgoing, volumes and the statistical variations.
- Modelling the stream flow following the variations of atmospheric pressure and the difference of air density inside, and outside the well.
- The approximate calculation of the total cavity volume is based upon two methods:
    - .Spectral analysis of the flow variations.
    - .Application of the "law of gasses" during the period which corresponds with a constant barometric pressure. The modulation is based upon the resonance formula of Helmholtz for semicircular spaces.

This analysis tries to make an estimate of the volume of underground cavities, which are in contact with the well. The paper on this subject is planned for the beginning of 1995.

2.1.7. Perspectives on the protection of water supply in karstic areas

The study of the different pilot areas in the karstified limestones of Belgium, especially the tracer tests, shows us that we must be very careful when delineating protection zones based on the simple assumption of a continuous homogeneous medium. Usually the presence of enlarged conduits, often hidden under unconsolidated sediments, may cause a false understanding concerning recharge paths to a well or a spring used for water supply.

Moreover, in Belgium, the interactions between water exploitation and other land activities make the situation crucial and require effective coordination between all interested parties.

We can conclude with the following sentence which is not very exaggerated: for good management of karstic aquifers every fragment has to be put "under a microscope".

2.2. Cretaceous chalk (by P. Biver , Ph. Meus and A. Dassargues)

2.2.1. Introduction

The Chalk in Belgium was deposited mainly during Cretaceous times (Dassargues & Monjoie, 1993). The formation is found in the northern part of the country, but it outcrops in only two areas : near Mons in the south-west and near Liege in the east (Fig. 5). An important hydrogeological basin occurs in the area near the city of Mons in the south-west. In the east, the chalk outcrops out in the Hesbaye and Herve areas but towards the north, in the Campine area, the thickness of the Tertiary and Quaternary cover gradually increases. In the north-east of Belgium, the chalk is characterized by regular horizontal or sub-horizontal layers dipping slightly towards the north (Dassargues & Monjoie, 1993). The chalk aquifers provide about 20 per cent of the total volume of groundwater used for industrial and drinking purposes in Belgium. The main pumping zones are the outcrop areas.

In the study from which this example is drawn, tracer tests were conducted at different locations of the same aquifer: the 'Hesbaye aquifer' located near the city of Liège. The purposes were (1) to examine the transport processes of a full-miscible contaminant in such a heterogeneous, fissured and slightly karstified chalky aquifer; (2) to determine the values of the transport parameters in such conditions using analytical and numerical simulations of tracer tests; (3) to compare the results with some of the values obtained at laboratory scale; (4) to assess the prevention and protection zones to be delineated at the proposed locations of future production wells.

With these goals in mind and with regard to the legal prescriptions described above, the following methodology was chosen and will be briefly described for a particular site taken as an example (the site of Crisnée figure 5) : (1) characterisation of the groundwater flow system in this chalky aquifer; (2) the experimental procedure of tracer tests; (3) theoretical concepts and the conceptual options chosen for the simulation of field tests; (4) calibration to breakthrough curves and the results of the simulations; (5) conclusions with regards to the assessment of protection zones.

2.2.2. Regional and local groundwater flow systems

The Hesbaye aquifer is represented by a chalk outcrop of 350 km^2 situated to the North of the River Meuse near Liège (Fig. 5). By means of collecting galleries and pumping wells it provides about 60000 m3/day of drinking water for Liège and its suburbs. Recently, a comprehensive set of data relating to the geology, hydrology, geomorphology and geophysics has been collected. A three-dimensional finite element model of the regional flow in the aquifer has been developed by the University of Liège (Dassargues et al., 1988) to forecast changes in the heights of the water level and to provide additional interpretation about the main drainage axes in the aquifer (Dassargues, 1991). The geological sequence may be summarised as follow: (1) recent alluvial and colluvial deposits, up to 5 m thick; (2) Quaternary and Tertiary sands and loess, 2-20 m thick; (3) residual conglomerate, 2-15 m thick; (4) Maastrichtian Chalk locally referred to as 'Upper Chalk'. It has been exposed to weathering and hence it is fractured, 10-15 m thick; (5) thin (less than 1 m) layer of hardened Upper Campanian Chalk (or 'hardground'); (6) Campanian Chalk, compact massive white chalk, referred to as 'Lower Chalk', with many fracture zones providing preferred flow routes for groundwater; 20-40 m thick; (7) 'Smectite de Herve', a layer of hardened calcareous clay of Campanian age, about 10 m thick, that forms the impermeable base of the chalk aquifer.

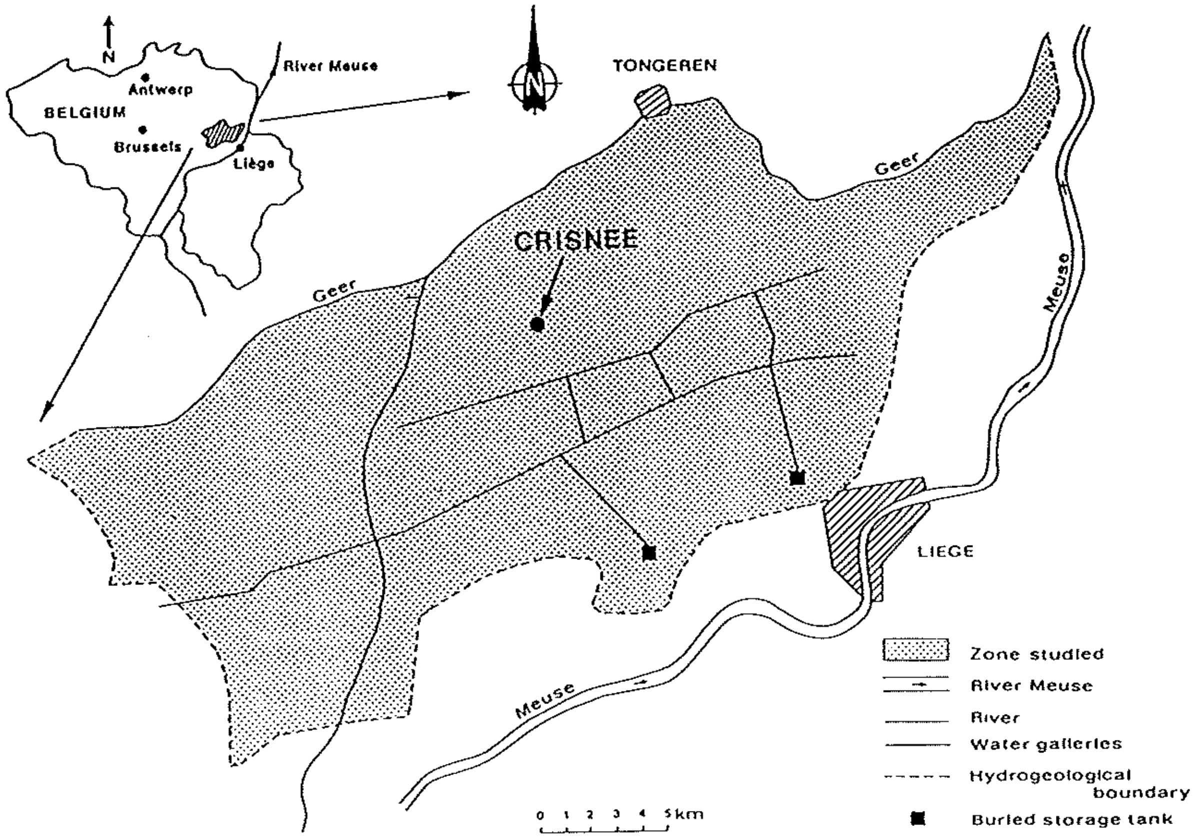

Figure 5.-Location of the site of Crisnée in the 'Hesbaye aquifer' near the city of Liège in Belgium.

The main drainage axes of the aquifer are below dry valleys in the chalk, and are characterized by high hydraulic conductivities due to the presence of fractures and karstic features (Fig. 6). .Values for the hydrodynamic parameters of the groundwater flow have been obtained initially from pumping tests and then carefully calibrated in the model. For the hydraulic conductivity of the chalk layers, values between 1.10^{-5} and 1.10^{-3} m/s were determined and for the effective porosity assimilated to the storage coefficient (water table conditions) values from 1.10^{-2} to 1.10^{-1} deduced. The complex geometry of the layers and the full heterogeneity with regard to the parameters, depending on the degree of fissuring, are taken into account to some extent by a full 3D finite element mesh allowing for the different limits and sub-limits of the layers. The Representative Elementary Volume (REV) theory and conceptual approach was chosen to deduce the parameters to introduce in each finite element of the 3D mesh. The model was calibrated against historical data from 1951 until 1993. A "post-audit" analysis of the results provided by this model was completed recently (Dassargues, 1994).

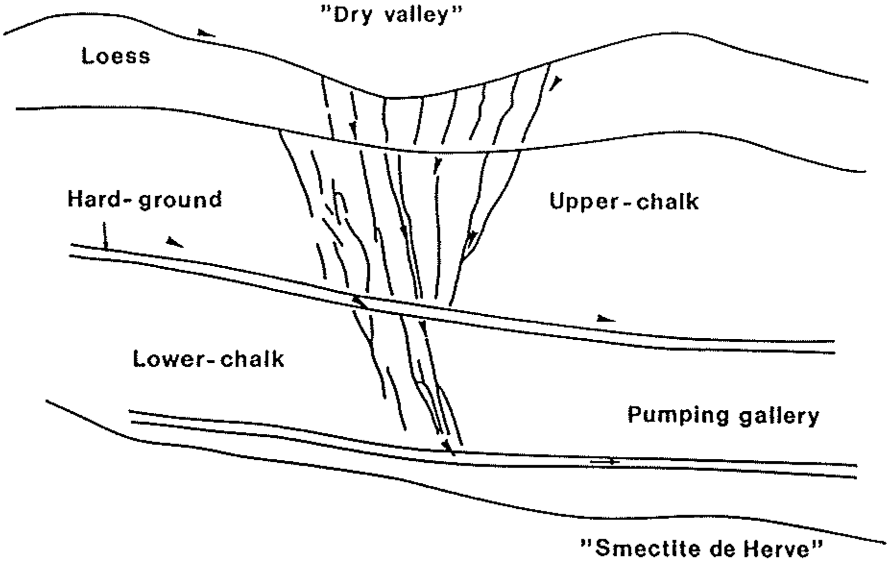

Figure 6.-Dry valley corresponding to a main groundwater drainage axis through the fractured/karstified chalk.

Tracer tests have been conducted at different locations in this aquifer. At each location, a complete local investigation was completed which included among other techniques: morphostructural analysis, geophysics, drilling of piezometers and pumping tests.

The morphostructural analysis using aerial pictures revealed lineaments which could correspond to main fracture axes in the chalk. Moreover, the results of the local geophysical prospecting clearly showed in each case some zones having lower apparent resistivity corresponding to more fissured zones in the chalk (Fig. 7). This information on the local heterogeneity of the aquifer was taken into account in the modelling process.

First local hydrodynamic values for the parameters of the groundwater flow were obtained from pumping tests interpreted with classical analytical methods assuming homogeneous and isotropic conditions for the porous medium. For the chosen example (the site of Crisnée), the first estimation provided values between 7.6 10^{-4} m/s (PE) and 2.1 10^{-3} m/s (Pz1) for the hydraulic conductivity of the lower chalk layer, and a value of 1 10^{-3} for the storage coefficient (showing locally semi-confined conditions).

A local 2D horizontal flow model using the Finite Element Method (FEM) allowed accurate calibration to natural conditions (natural gradient of the piezometric heads) and to the pumping test results (drawdowns of the piezometric heads), taking into account the detailed local heterogeneity of the chalk formation near the well. The recognised heterogeneities are of course related to the more fissured and slightly karstified zones detected by morphostructural analysis, boreholes and geophysical prospecting.

Figure 8 shows the corresponding computed piezometric maps and the Darcy's specific discharge maps for natural and pumping conditions at the site of Crisnée. It can be seen (Fig. 8b) that the computed fluxes are greater in the north-east zone where the chalk is more fissured as had been previously detected by geophysical investigations.

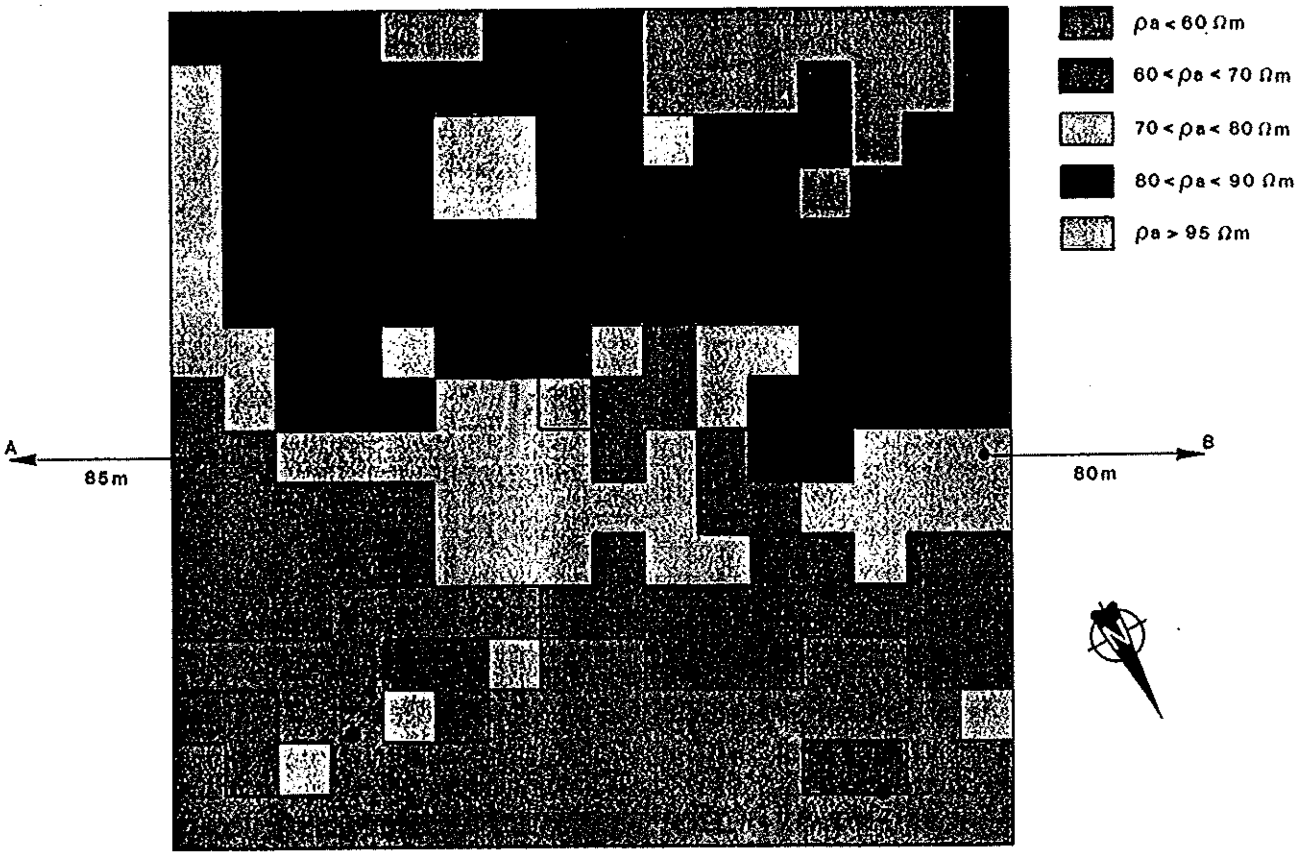

Figure 7.-In one of the tested areas (site of Crisnée), the map of the apparent electric resistivity shows that the chalk would be more fractured in the Pz1-Pz2 zone than in the PE-PR zone.

2.2.3. Experimental procedures and tracer test methodology

The methodology is chosen in order to allow an accurate "a posteriori" simulation by numerical modelling, especially concerning the control of the input function. Details about the methodology of these tracer tests can be found in the PhD thesis of Meus (1993). The injections can be considered as instantaneous at the level of the tested aquifer by using an injection tube coupled with water injection above and below (Fig. 9). It was a converging radial flow tracer test and the monitoring equipment allowed only a two-dimensional analysis of the concentrations (Biver & Meus, 1992). In these conditions we are working with what is usually called depth-averaged (mixed vertically) concentrations and as a result, the tracer concentration will be underestimated and the longitudinal dispersivity will be probably overestimated (Gelhar et al., 1992).

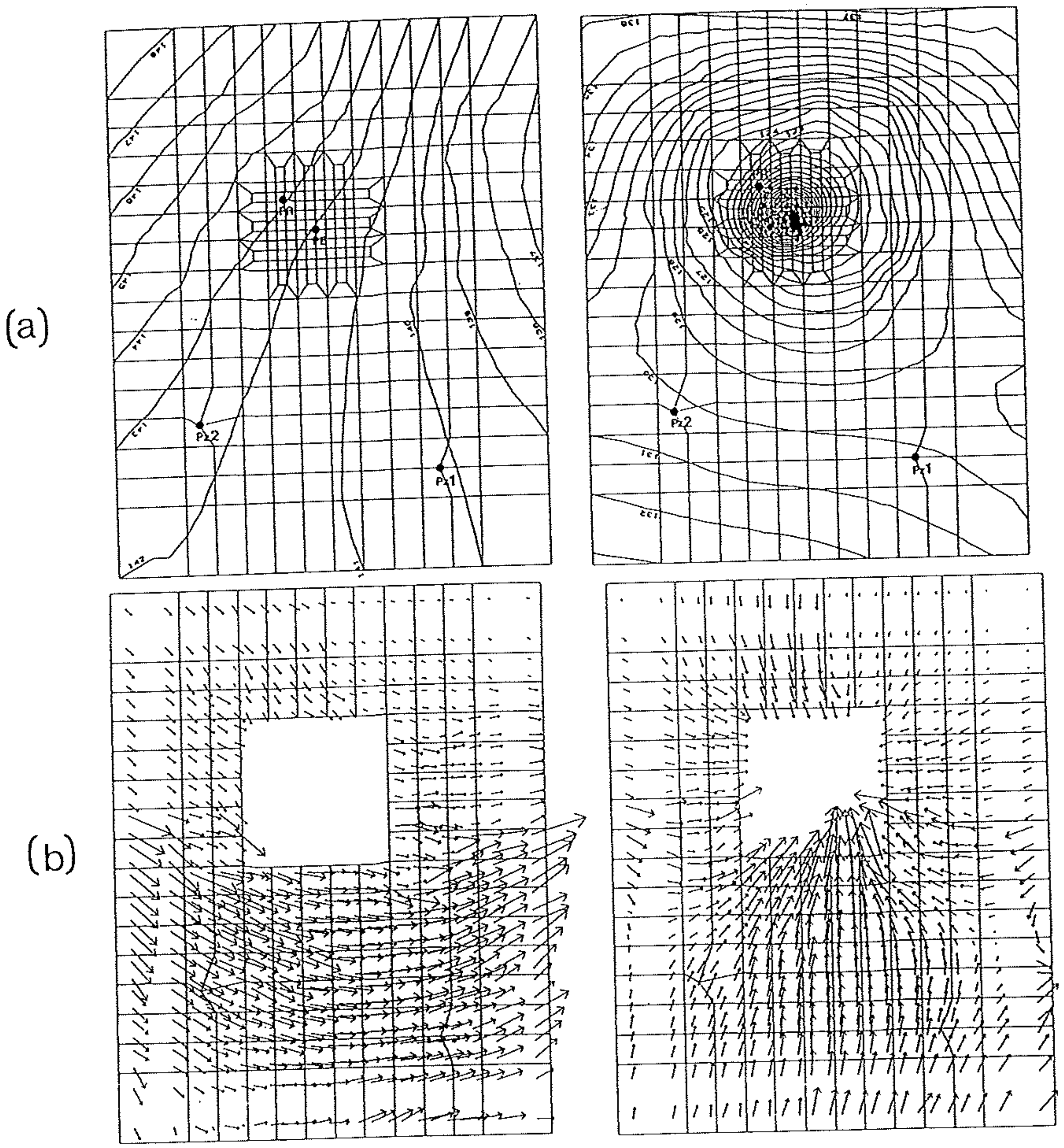

Figure 8.-(a) Computed piezometric maps in natural (left) and in pumping (right) conditions; (b) Computed vectors of the specific discharge (Darcy's law), in natural (left) and in pumping (right) conditions.

As the aim of the tracer test is mainly to simulate pollutant transport in the aquifer, it would be convenient to inject tracers presenting similarities of molecular size and behaviour in the aquifer with the potential pollutants of interest. Otherwise, the following considerations are involved in the choice of tracer: the kind of aquifer, the available analytical equipment, the distance between injection and pumping, the geochemical properties of the groundwater, the background levels, the eventual toxicity, the price,etc. Among fluorescent tracers, uranine (sodium fluorescein), rhodamine B and WT, and naphtionate are used. Among salt tracers, NaI, NaCl (for short distances), KI, LiCl or KCl are chosen. For the example described at figures 7 and 8, after 18 hours of stabilised pumping in PE, injections were carried out in Pz1 with uranine and in Pz2 with lithium chloride (LiCl). The recorded breakthrough curves in the pumping well PE (Fig. 10) showed that the restitution of the lithium from Pz2 and of uranine from Pz1 were quite different in time.

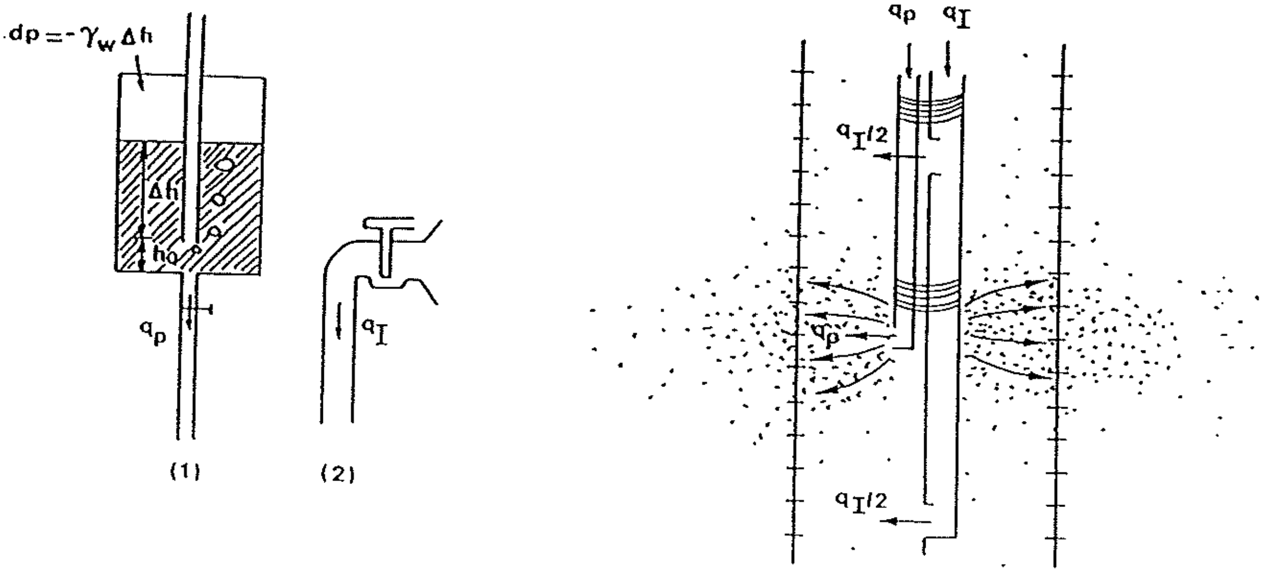

Figure 9.-Injection tube coupled with water injection above and below.

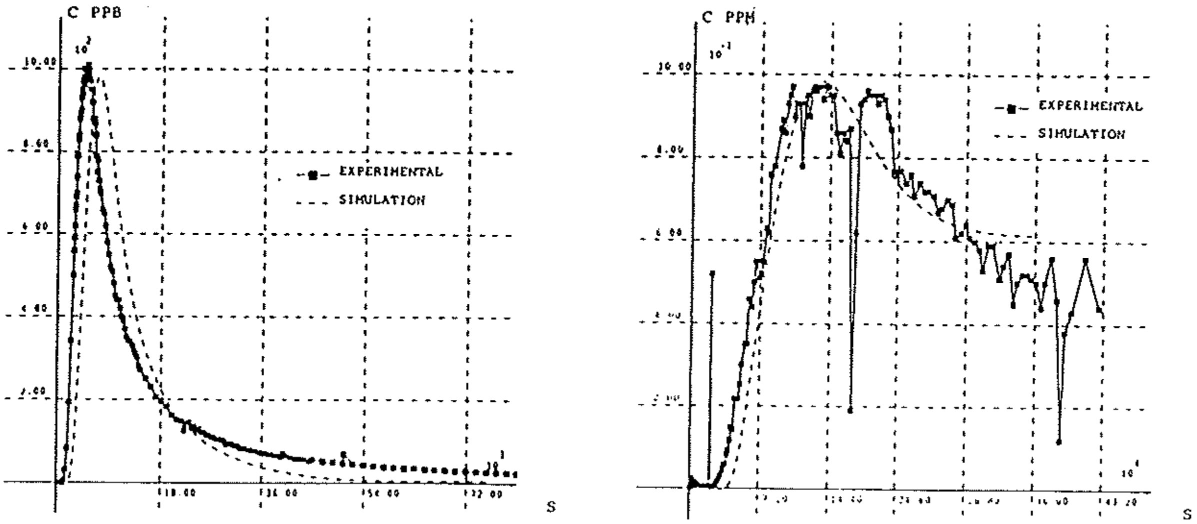

Figure 10.-Experimental and calibrated breakthrough curves in PE.
(a) for lithium (b) for uranine (after Biver,1993)

In a first interpretation, this fact can be explained by the different piezometric gradients between Pz1-PR and Pz2-PR. The heterogeneity of the aquifer (which corresponds to a heterogeneous field of transmissivities in the calibration of the flow model) leads to different flow conditions around the pumping well and the results of the transport processes in this aquifer are quite dependent of these flow conditions. These differences in the flow conditions (Fig. 8) when pumping in PE can also explain the quite different observed breakthrough curves and also the lower mass recovery factor found for uranine.

2.2.4. Concepts of the numerical simulation

The classical approach when dealing with numerical models used to solve local or regional groundwater flow and transport situations, is to consider the aquifer as a continuous porous medium. Moreoften, it is practically realised using the concept of Representative Elementary Volume (REV) described very clearly by many authors.

In the fissured media and "a fortiori" in the karstified media, the main difficulty consists in finding a good adequation between the highly heterogeneous reality and the REV concept. The parameters describing the characteristics of the aquifer (permeability coefficient, effective porosity, dispersivities,...) chosen with "equivalent" or averaged values on the REV, do not describe with accuracy the reality of the aquifer as they represent globally the behaviour of the different zones of this aquifer. The lack of precision in the representation of the reality depends strongly on the scale at which the problem is considered. It is evident that this "averaging procedure" of the aquifer properties on a volume of aquifer (sometimes very large), is much less accurate than a localised study of the problem.

In the case of a fissured and slightly karstified aquifer, this approach has been used to simulate flow and solute transport problem at a local scale around pumping wells. Determinist finite element models have been used for groundwater flow and transport simulations. As low concentrations of miscible tracers are concerned, we can assume that flow and transport simulations can be uncoupled: no density or viscosity effects interacting on flow are taken into account.

The parameters in each REV are deduced from accurate calibration computations on the observed breakthrough curves. Due to the fissuring and the slight karstification, the 'Hesbaye aquifer' is considered as a double porosity and a double permeability medium. The permeability coefficient relating to the porosity of the pores has been estimated on the basis of laboratory tests (Biver, 1991) at 1.10^{-8} m/s. The global permeability coefficients, however, vary between 1.10^{-5} and 1.10^{-3} m/s, as mentioned previously.

It is possible to describe the transport of a solute contaminant with a determinist system of classical advection-diffusion equations (applied to an equivalent porous medium) by assuming that the pore water can be qualified as 'immobile' water (Fig. 11) compared to the 'mobile' water in the fissures and karstified conduits (Bear & Verruijt, 1987, Biver & Dassargues, 1993).

Adsorption, reactive processes and degradation are very low in this fissured and porous chalky aquifer (Biver, 1993), and their effects on the transport of the solute can be neglected. Thus the transport equations can be simplified to obtain a system including two mass balance equations: one for 'mobile' water, the second for 'immobile' water with a transfer constant α_d^* representing globally (and averaged on the R.E.V.) all the interactions between 'mobile' and 'immobile' water. For more details on the equations implemented in the model see Biver et al. (1994).

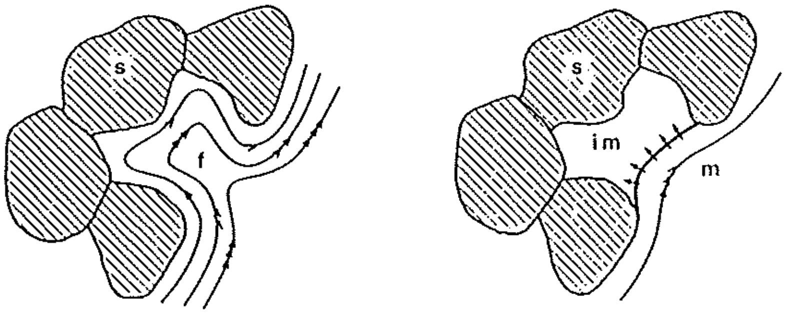

Figure 11.-Conceptual representation of 'immobile' water (im) as a distinct phase.

The numerical methods which are used for solving the transport equations may be classified into three categories: (1) Eulerian methods where an Eulerian form of the equation is solved at the nodes of a fixed grid, requiring the simultaneous solution of hyperbolic and parabolic operators; (2) Lagrangian methods where a Lagrangian form of the equation is solved in grids moving with the fluid, avoiding the explicit treatment of hyperbolic terms but often involving a set of points (moving grid) which becomes gradually very distorted during the motion; and the computation of partial derivatives is then very complicated; (3) Eulerian-Lagrangian methods where one tries to combine the best aspects of the two other categories. The methods (1) and (3) have been introduced by Biver (1993) in the LAGAMINE[3] code and are now being tested in the SUFT[4] code.

2.2.5. Model calibration providing hydrodispersive parameters in heterogeneous conditions

As an example, the discretized finite element meshes for the site of Crisnée are presented in figure 12 for the transport simulation of lithium from Pz2 and uranine from Pz1. Each material number denotes a different combination of transport parameters a_L, a_T, α_d^*, n_e and θ_{im} , for the longitudinal and transversal dispersivity, the 'immobile' effect coefficient, the effective porosity and the proportion of 'immobile' water. After calibration, five different 'materials' were distinguished in the zone on the basis of the values of their transport parameters (table 2).

Transport parameters	material 1	material 2 Li$^+$ - Uranine	material 3 Li$^+$ - Uranine	material 4 Li$^+$ - Uranine	material 5 Li$^+$ - Uranine
a_T (m)	0.05	0.25 - 0.32	0.32 - 0.50	0.50 - 0.70	0.65 - 0.95
a_L (m)	0.5	2.50 - 3.20	3.20 - 5.00	5.00 - 7.00	6.50 - 9.50
α_d^* (s^{-1})	1.10^{-7}	1.2 - 3.7 10^{-7}	2.5 - 6.7 10^{-7}	5.0 - 7.9 10^{-7}	6. - 15. 10^{-7}
n_e (%)	0.3	0.5 - 1.5	1.0 - 2.7	1.5 - 5.3	2.0 -11.3
θ_{im} (%)	8.0	10.0 - 19.0	13.0 -24.0	18.0 - 31.0	20.0 - 42.0

Table 2.-Calibrated transport parameters for the lithium (between Pz2 and PE) and for the uranine (between Pz1 and PE).

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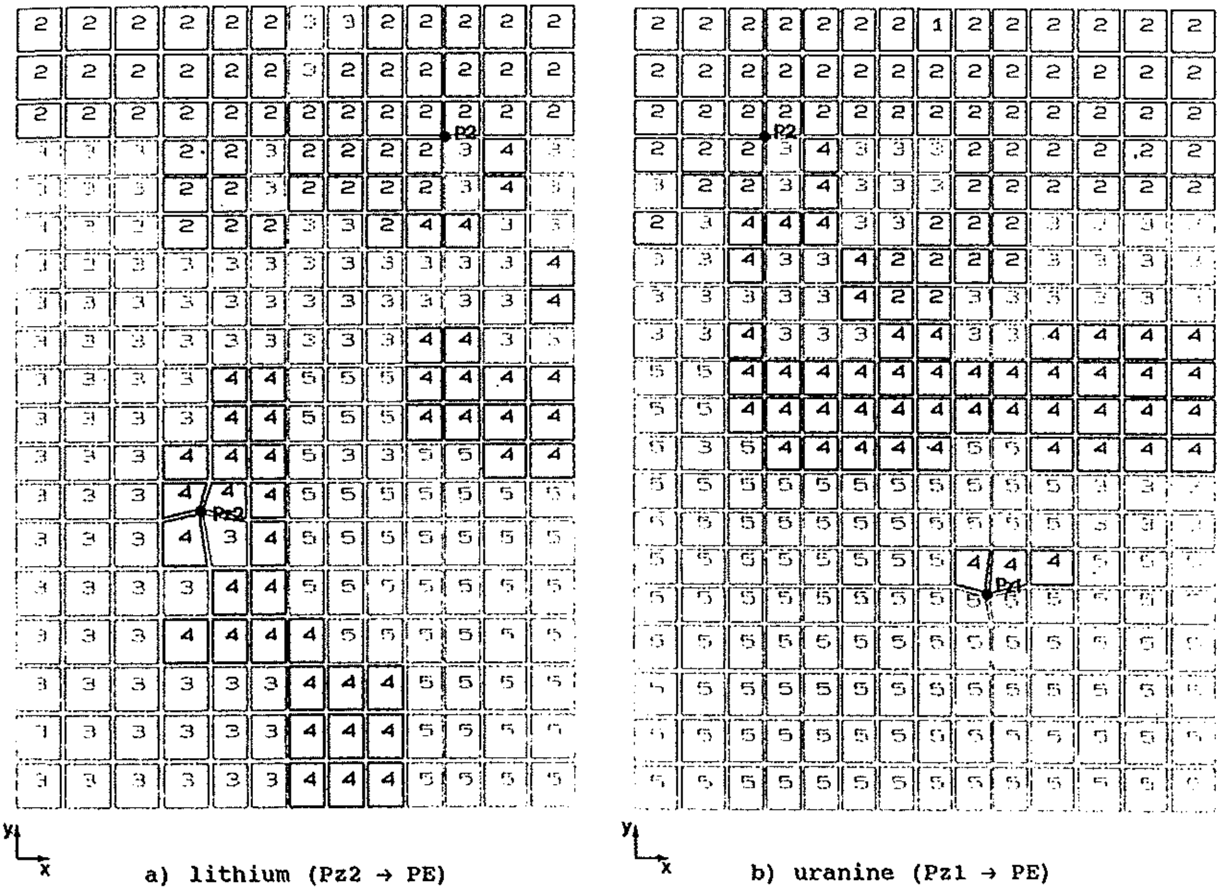
[3] The LAGAMINE code has been developed at the Civil Engineering Department of the University of Liège (M.S.M. Dpt) in collaboration with the Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting of the same University (L.G.I.H.) for the hydrogeological aspects.

[4] Saturated Unsaturated Flow and Transport code (SUFT) is being developed by S. Brouyere and A. Dassargues at the L.G.I.H. Dpt of the University of Liège.



a) lithium (Pz2 → PE)

b) uranine (Pz1 → PE)

Figure 12.-Finite element meshes and 'materials' of the discretizations for lithium and uranine tracer tests transport simulations (after Biver, 1993).

The 2D spatial distribution of both tracers in the mobile water reflects two different behaviours (Fig. 13) due mainly to the heterogeneity of the aquifer. The computed plume of injected lithium (Fig. 13a) has a regular shape with a long ridge, due to the fact that the migration velocity of the tracer decreases strongly when passing in the zone with a lower degree of fracturing (lower permeability coefficient). The computed plume of injected uranine (Fig. 13b) is wider and is spreading in two main directions. One of them corresponds to a fissure axis between Pz1 and PE, the second direction corresponds to the regional groundwater flow. When looking at the immobile water concentrations, one can remark (Fig. 14) that the high concentrations in tracers are simulated in each case as staying in a zone very close to the injection piezometer.

Figure 15 shows the total transport fluxes of tracer mass. Comparing the computed fluxes to the Darcy's fluxes of figure 8, we can deduce that they are mainly dominated by the convection process.

Comparing maps of 'mobile' and 'immobile' water concentrations, it can be seen that a large amount of tracer is provisionally captured in the 'immobile' water near the injection piezometer. In the breakthrough curves (Fig. 10) it induces a long tail in the curve as the pollutant is slowly restored from the 'immobile' water into the 'mobile' water.

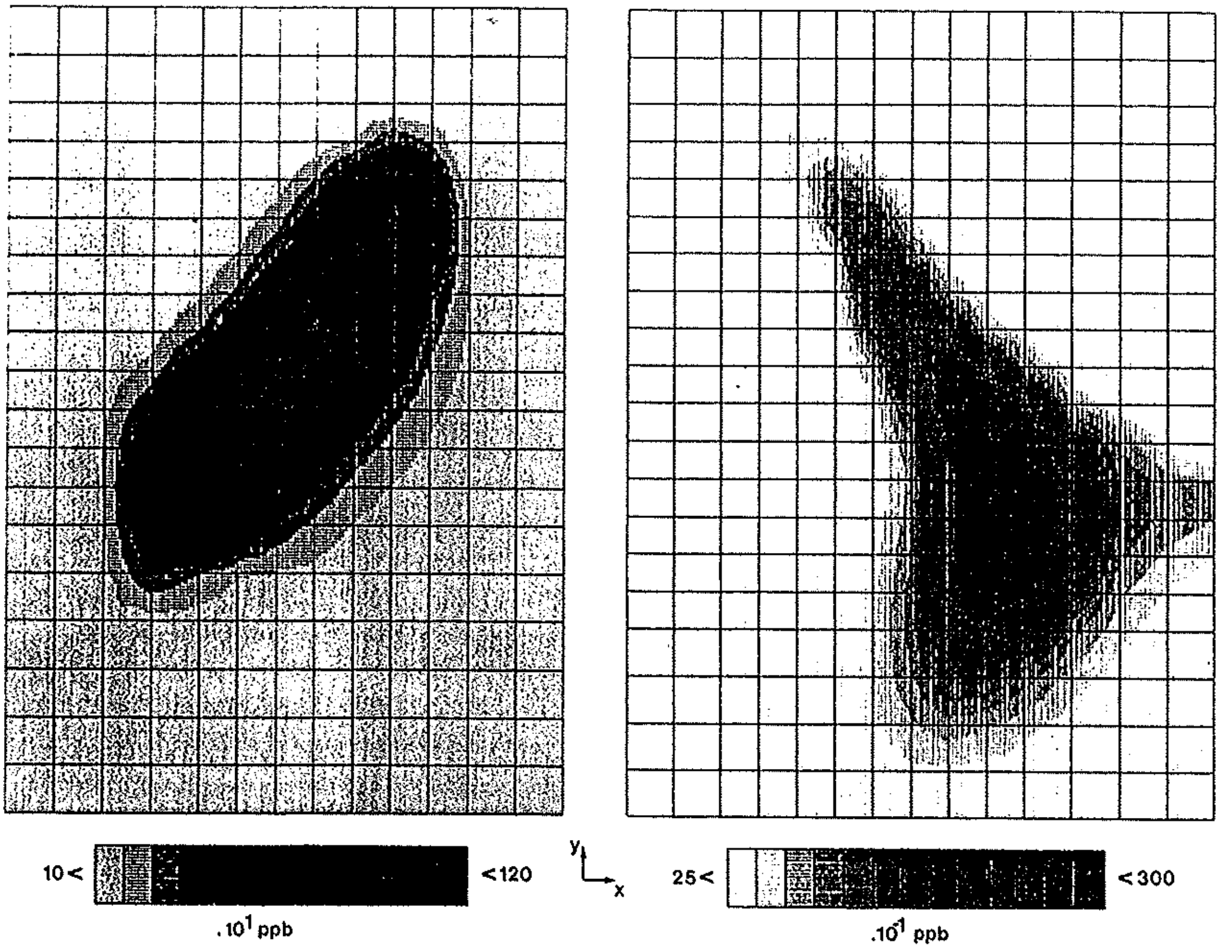


Figure 13.-Computed concentrations in the 'mobile' water (a) for the lithium after 12 hours $\Delta C_m = 100ppb$ *(b) for the uranine after 100 hours* $\Delta C_m = 2.5ppb$. *(after Biver, 1993)*

2.2.6. Computation of pollutant spreading

Once the numerical model has been calibrated on pumping tests and tracer breakthrough curves, the flow results, transport coefficients, and discretization are retained to infer aquifer behaviour in some predictive simulations.

As an example, at the Crisnée site a soluble pollutant injected at a rate of 1.2 kg/hour for a period of 5 hours, was simulated at 20 separate locations in the immediate area around the borehole. An injection flow rate of 0.25 m3/hour was considered. The concentration of the spill is being 10 g/l. With the simulation based on the piezometric map represented in figure 8a, the isochrone lines corresponding to the arrival, at the pumping well, of the very first significant concentrations (i.e. 10 mgr/l or 10 ppm) can be calculated. The result is obtained by interpolating the values for the simulated injections (Fig. 16). These contour lines are more objective than those which could be obtained by particle tracking. They reflect the three main components of transport in the chalky aquifer of Hesbaye (convection, dispersion, and immobile water effect). After a quick look, one can see that the zone which is preferentially affected by the pollution around the well is in the direction of piezometer PR. However this zone does not correspond to the known fractured area. This is due to the regional flow of the aquifer which inhibits the pumping flow in this area and which increases it near piezometer PR. For the same reason, one part of the aquifer is totally unaffected by this particular pollution event.

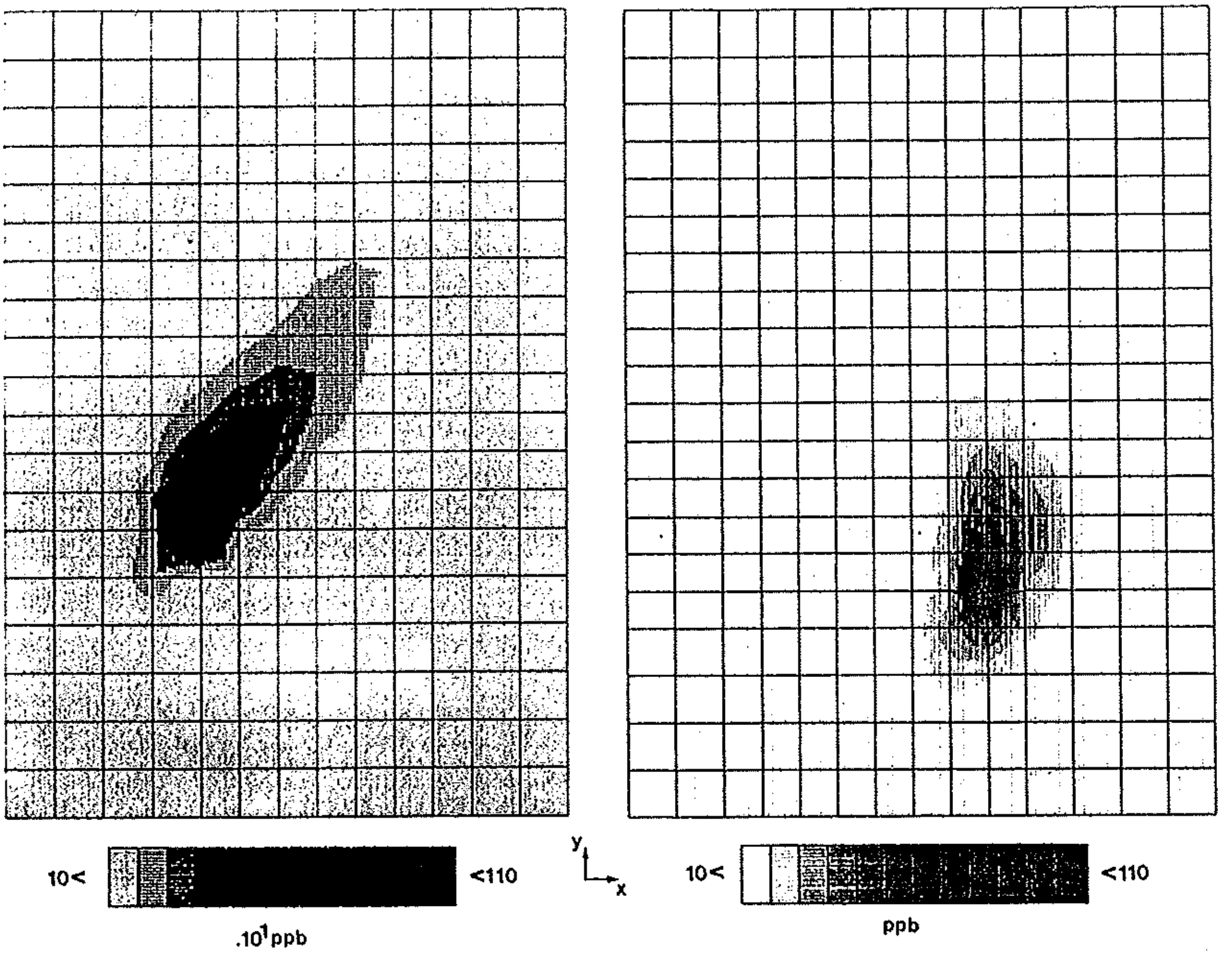


Figure 14.-Computed concentrations in the 'immobile' water (a) for the lithium after 12 hours $\Delta C_{im} = 100 ppb$ *(b) for the uranine after 100 hours* $\Delta C_{im} = 10 ppb$. *(after Biver et al., 1994)*

If we examine in detail the results for 3 injection points (Fig. 17 a, b, and c,), we can understand that, on the basis of the breakthrough curves, it is possible to generate a great number of isochrones associated with different criteria. For instance, if our concentration limit is raised to 50 mg/l, the safe zone will be greater (including the area represented by injection i_1). This kind of sensitivity analysis is not possible with the particle tracking method. Moreover, by drawing the isoconcentration curves, an appreciation of the pollution spreading can be achieved; it is even possible to define, from those results, the limits of the polluted zone and its evolution in time.

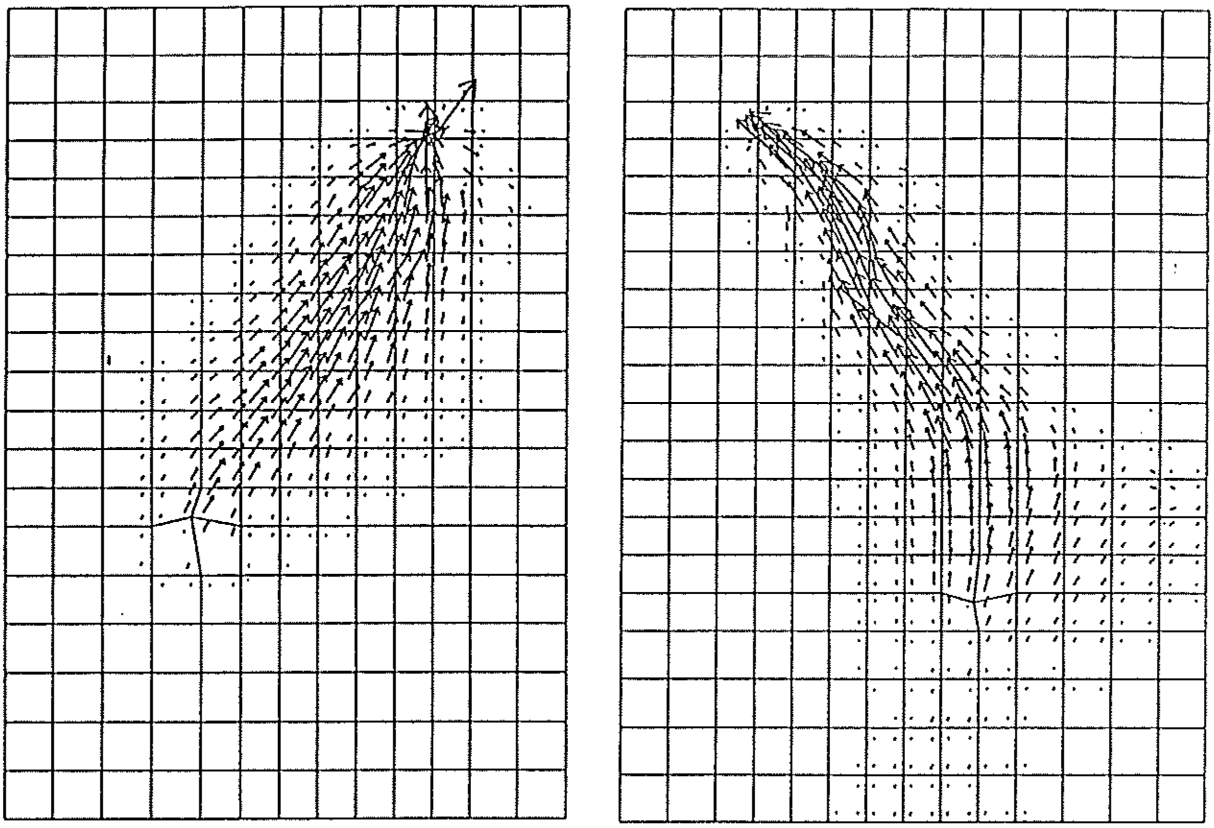


Figure 15.-Computed total transport mass fluxes (a) for the lithium after 12 hours ($f_{\max} = 8.8\ 10^{-8} kg / m^2 / s$) (b) for the uranine after 100 hours ($f_{\max} = 1.1\ 10^{-8} kg / m^2 / s$) (after Biver et al., 1994)

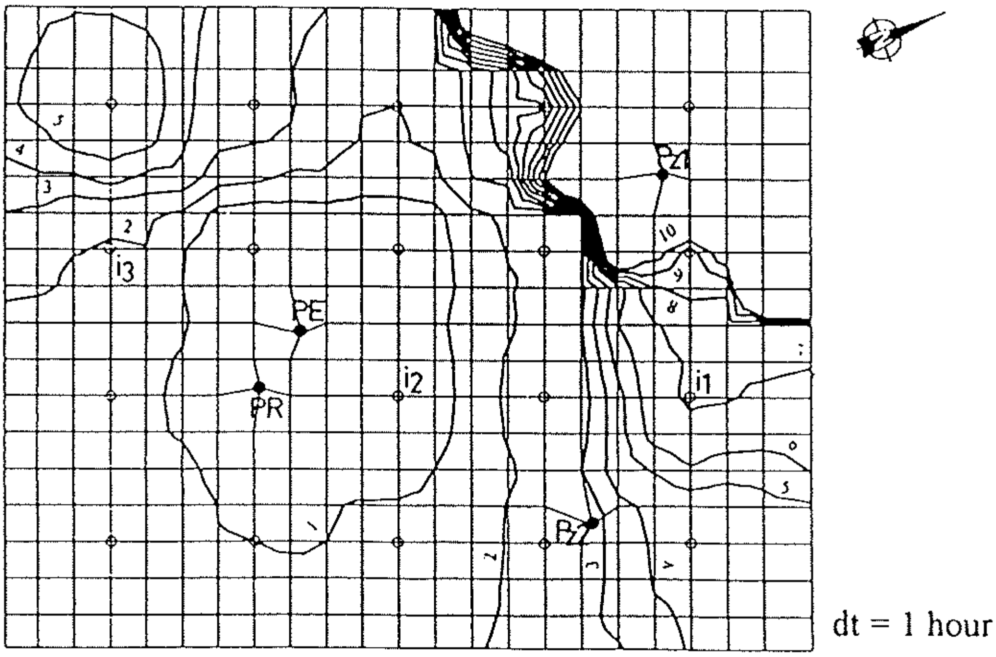


Figure 16.-Isochrone lines for a concentration of 10 mg/l at the pumping well (injection of 10 gr/l during 5 hours at a rate of 0,25 m³/h). (after Biver & Dassargues, 1994)

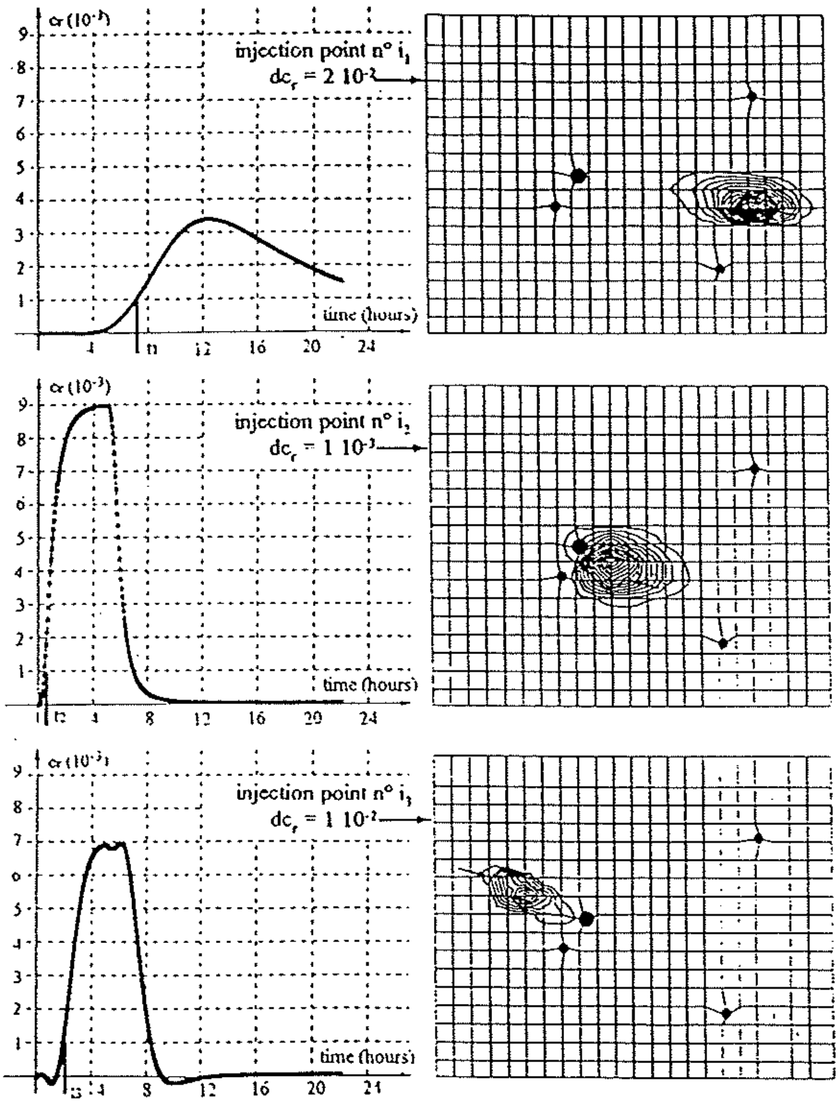


Figure 17 : Detailed results of three simulated injections. (a) Breakthrough curves in the pumping well. (b) Isoconcentration lines after 1 hour after the end of the injection. (after Biver & Dassargues, 1994)

2.2.7. Synthesis of results

From tracer tests results combined with morphostructural, geological, geophysical and hydrogeological investigations, first conclusions have been made on the heterogeneous nature (due essentially to local fracturations and slight karstification) of this double porosity aquifer in the Cretaceous chalks of Belgium.

Numerical simulations using adapted Finite Element methods have been used in preference to analytical solutions in order to include the maximum of available informations in the model. The spatial heterogeneity of the aquifer has been taken into account for both flow and transport simulations. Additionally, the double porosity/permeability effect is included in the simulated interactions between 'mobile' and 'immobile' water. In this way, we try to have a better representation of the very rapid flow and transport processes in the fractures and the karstified zones in the same time that we represent a kind of 'more diffusive process' in the matrix of the chalk.

As the scale of investigation is of the same order than those of the planned protection zones, the transport parameters are deduced from the calibration on the experimental breakthrough curves. It is reasonable to assume that we can use them for the assessment of protection zones around the pumping well. However, these coefficients can not be used at the regional scale as it is evident that a strong scale effect can be predicted in this kind of aquifer.

In order to establish isochrones which are usually used in the definition of the protection zones, some repetitive simulations of injections at different nodes of the discretized mesh were carried out; the different breakthrough curves at the pumping well (for each injection) and maps of concentrations at specific times were obtained. It was then possible to draw the isochrones for the protection zones taking into account the heterogeneity and the double porosity characteristics of the aquifer.

As a synthesis, table 3 presents the values derived for hydrodynamic and transport parameters on the basis of the values obtained from the 3 test sites belonging to the same regional aquifer. These studies are currently continuing in other sites and the results will be available during 1995.

Transport process	parameter	values
convection	K (m/s)	0.25 - 3.5 10-4
	n_e (%)	0;5- 12.0
dispersion	a_L (m)	0.5 - 14.0
	a_T (m)	0.12 - 3.0
immobile water effect	α_d^* (s^{-1})	0.1 - 1.6 10-6
	θ_{im} (%) $= n_{im}$	10.0 - 40.0

Table 3.-Transport parameters in the Cretaceous slightly karstified chalk of the Hesbaye aquifer.

3. GENERAL CONCLUSIONS

The protection of karstified or slightly karstified aquifers has been studied in greater depth than previously. In Belgium, the concerned carbonate rocks are the Devonian and Carboniferous limestones, and the Cretaceous chalks.

In the limestones, the problem is particularly difficult when the degree of karstification is high. In these conditions, it is very difficult to know accurately the real conditions of groundwater flow and pollutant transport.

The aim of these studies was mainly to provide an improved knowledge of the hydrogeological conditions occuring in these calcareous formations and, in this manner, be able to assess important interpretations of the vulnerability of the aquifers and the means of protecting them.

In the Chalk, which are often only slightly karstified, it is theoretically easier to quantify the hydrodynamic parameters which can be used in heterogeneous groundwater and solute transport models. However, when these parameters are deduced from the detailed interpretation and simulation of experimental pumping and tracer tests, the heterogeneous conditions are sometimes not so easy to represent in models. The application of a methodology including morphostructural geology, applied geophysics, hydrology, pumping tests, tracing tests, flow and transport modelling,... leads to the determination of protection zones according to the definitions prescribed in the region concerned.

In terms of pollutant transport, higher dispersivities are recorded when the formations are more fissured. In the limestones, the longitudinal dispersivities range between 15 and 100 m from tracing tests from sinkholes to spring and between 10 and 92 m from tracing tests involving boreholes. For comparison, in the Chalk, the longitudinal dispersivities have been measured as not exceeding 14 m. The variation of the transport properties as a function of the structure of an aquifer appears clearly when the dispersivities are plotted against the effective velocities (Fig. 18).

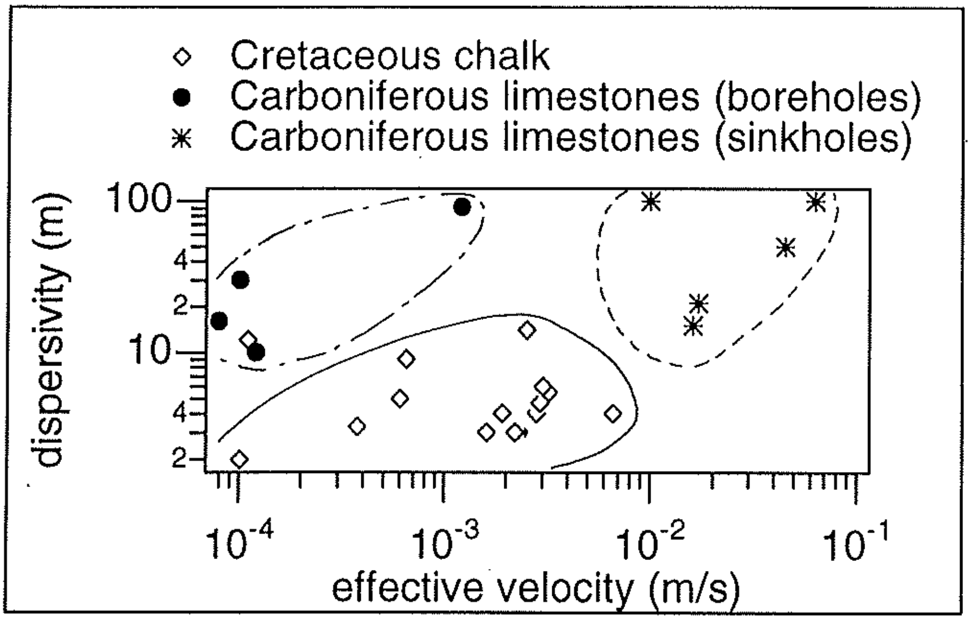


Figure 18.-Diagram dispersivity-effective velocity for the tracer tests in the carbonate aquifers (Cretaceous chalks and Carboniferous limestones). Each group is well separated from the others and reflects its own fissure distribution.

The results of the studies in the different pilot areas in the karstified limestones and in the slightly karstified chalks of Belgium, indicates that we must be very careful when delineating protection zones. Of course it can not be realised using the simple (but usual) assumption of a continuous homogeneous medium. The presence of enlarged conduits, often hidden under unconsolidated sediments, may cause a false understanding concerning the real groundwater flow and pollutant transport conditions. In Belgium, the interactions between water exploitation and other land activities make the situation crucial and requires effective coordination between all interested parties.

ACKNOWLEDGEMENTS

The research about the modelling approach in the chalk groundwater reservoirs was supported by the Scientific Policy Services of the French speaking community of Belgium.

In the framework of a partnership, IBM Belgium S.A. provided hardware support to the L.G.I.H. of the University of Liège, thanks to this support, the SUFT program is being developed on a IBM Risc 6000 environment.

Thanks are also due to the "Société Wallonne de Distribution d'Eau" which funded or supported some of the tracer tests.

Many thanks to Brian Adams of the British Geological Survey for the english language corrections.

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