JOURNAL OF ENVIRONMENTAL HYDROLOGY

CONTENTS

REPORTS

APPLIED METHODOLOGY TO DELINEATE PROTECTION ZONES AROUND PUMPING WELLS

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A complete methodology is proposed to accurately compute groundwater protection zones (in each particular case in function of the local hydrogeological conditions of the site), the effective transfer durations of the pollutant in the studied zone, and the spatial distribution of the concentration plume for each injection point. This methodology involves 'in situ' tracer tests to determine transport parameters in a geologically heterogeneous medium. Then a flow-transport numerical model is used and the parameters are calibrated on the measured piezometric levels and the breakthrough curves. Particular attention is given to the simplifying assumptions that are acceptable for each case. The choice of these assumptions can be facilitated using results of laboratory and in situ tests. After calibration of the numerical model under heterogeneous conditions for flow and contaminant transport, simulations can be carried out that provide isochrone lines of contaminant arrival time at the pumping well. For each injection point simulated in the surrounding zone of the well, the plume of pollutant can be modeled providing detailed information about concentration levels reached as a function of time. These results provide the necessary information for a good choice of effective protection zones around the well to comply with the local regulations, taking into account all the local and particular hydrogeological conditions. This methodology is illustrated by a case study located in a chalky aquifer in Belgium.

INTRODUCTION

Nowadays each country or region has established or is establishing regulations for the protection of zones around pumping wells to maintain or to restore the quality of the groundwater in the vicinity of drinking water wells.

Despite the fact that the authorities have often consulted the scientific community for help in the choice of the appropriate general regulations to be prescribed, it is still very difficult in many practical cases to determine on a rigorous and scientific basis the effective zones which are to receive special protection from accidental pollution. Moreover, it appears that even if the regulations exist, they are very often not followed, not applied, or misunderstood due to an insufficient knowledge of the real groundwater conditions, especially aquifer heterogeneities and the complex processes of the transport of a contaminant in a porous and/or fractured medium.

GROUNDWATER PROTECTION REGULATIONS

Usually regulations for protection and prevention zones are based on travel 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 provide a summary of the regulations which have been adopted in Belgium.

Three kinds of protection zones have been defined: a water supply zone, a prevention zone, and an observation zone.

a) **Zone I**, the water supply zone, is defined as an area within a 10 m radius of a water supply installation. This zone has to be owned by the water company.

b) **Zone II**, the prevention zone, is divided in two successive zones.

From the boundary of the Zone I, **Zone IIa** is defined as a distance in each direction corresponding to a time of pollutant travel of 24 hours in the saturated zone. A minimum of 25 meters is required from the boundary of Zone I. In karstic areas, Zone IIa must include all the preferential points of infiltration, such as sinkholes, collapse dolines, and poljes, for which a connection with the water supply capture zone is clearly established (for example by tracer tests).

. From the boundary of Zone IIa, **Zone IIb** is defined as the distance in each direction corresponding to a time of pollutant travel of 50 days. However, in unconfined aquifers, the Zone IIb can be established using a radius of influence of 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.

c) Zone III, the observation zone, is defined as the entire basin contributing to the water supply capture zone.

Permitted activities have been listed for each of these protection zones. In Zone I, nothing is allowed except the normal activity of the water supplier. In Zone IIa, all discharge or storage of hydrocarbons, fertilizers, or any hazardous compounds is strictly forbidden. Class 1 and 2 waste disposal operations, wastewater treatment plants, discharge of used or treated waters, and any disposal of liquid manure or dung-pits are prohibited. Many other activities (from various industrial activities to cycle-tracks) are strictly regulated. In Zone IIb, only the disposal and discharge of hazardous products and hydrocarbons remain forbidden. All other activities listed above are regulated. In Zone III, only the discharge of hydrocarbon compounds is forbidden and other activities are regulated. In each zone, "intervention codes" are provided in case of accidental spills.

It is evident, considering this example of defining protection zones, that for each zone 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).

Of course, attenuation of the contamination can occur in the unsaturated zone, but in this example of regulation it is not taken into account to be on the safe side with regard to reality. This last remark will not be discussed here, as we will treat only the saturated zone.

ELABORATION OF A RIGOROUS METHODOLOGY

Generally, the question posed is the following: how can we calculate, or compute practically, the boundaries of the different zones defined above, considering that the factors that control groundwater flow and transport are mainly influenced by the heterogeneous nature of the geological setting? All soil and rock masses under consideration in this study are fully saturated. Different lithologies and fissuring and fracturing can occur which have an important influence close to the pumping well. Highly differing groundwater flow velocities and contaminant transport mechanisms can can exist.

It is essential to characterize the hydro-dispersive parameters of an aquifer at a particular field site in order to simulate and to predict movement and spreading of a contaminant plume. For example, from experimental tests and investigations we need to find field-scale dispersivity values, which are often greater than values determined in laboratories. This difference can reach several orders of magnitude. It is usually a consequence of natural heterogeneities that cause irregular flow and transport patterns at the field scale (Gelhar et al., 1992).

Consequently, different investigation methods must be combined with other techniques such as geophysical prospecting, installation of piezometers, aquifer pumping tests, and multi-tracer tests.

The study area is located in the Hesbaye Aquifer, a chalky aquifer in the eastern part of Belgium located near the city of Liège (Figure 1). In the study from which this example is drawn, tracer tests have been conducted at different locations in the Hesbaye Aquifer. The purposes were (1) to examine the transport processes of a fully miscible contaminant in a heterogeneous and fissured chalky aquifer, (2) to determine the values of the transport parameters under these conditions using analytical and numerical simulations of the tracer tests, (3) to compare results with the values obtained at the laboratory scale, and (4) to delineate the prevention and protection zones near planned pumping wells.

With these goals in mind and with regard to the legal constraints described previously, the following methodology has been chosen: (1) characterization of the groundwater flow system in the chalky aquifer, (2) experimental tracer tests, (3) theoretical concepts and the conceptual options chosen for simulations of the field tests, (4) calibration on breakthrough curves and the results of simulations, and (5) conclusions with regards to the delineation of protection zones.

CHARACTERIZATION AND MODELLING OF THE GROUNDWATER FLOW CONDITIONS

The Hesbaye Aquifer is represented by a chalk outcrop of 350 km² lying to the north of the River Meuse near Liège (Figure 1). About 60,000 m³/day of drinking water
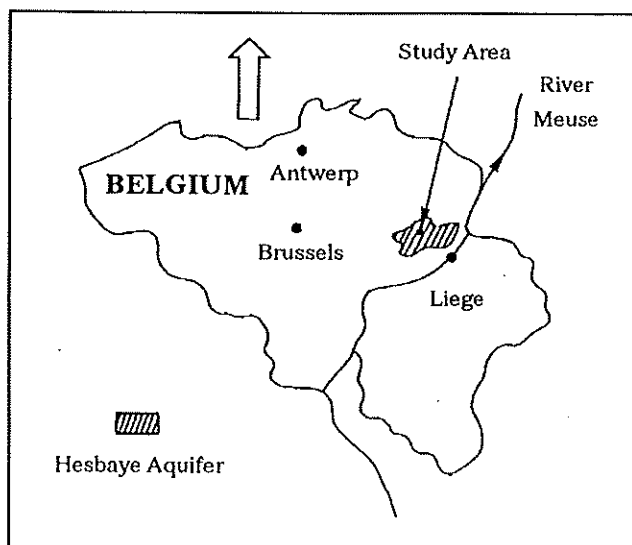

Figure 1. Location of the study area.

are pumped and collected in wells and galleries for Liège and its suburbs. A complete set of data relating to the geology, hydrology, geomorphology, and geophysics of the chalk has been collected at a regional scale. A finite element model of this regional aquifer has been completed previously (Dassargues et al., 1988).

In the local zone around the pumping well where the boundaries of the protection zone are to be determined, the geological sequence can be summarized as follows (from top to bottom): (1) 14 m of Tertiary loess, (2) 7 m of a residual conglomerate, (3) 30 m of Cretaceous fractured chalk, and (4) a layer of hardened calcareous clay that forms the impermeable base of the chalk aquifer.

Morphostructural analysis based on aerial photographs revealed lineaments which appear to correspond to the main fracture axis in the chalk. Moreover, the results of local geophysical prospecting clearly showed some zones with lower apparent resistivity corresponding to more fissured zones in the chalk (Figure 2). Later in the modelling process we will take into account these initial data on local heterogeneities of the aquifer.

Initial values for local hydrodynamic parameters of groundwater flow have been obtained from aquifer pumping tests interpreted using classical analytical methods

that assume homogeneous and isotropic conditions for the porous medium. The initial estimation gives 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. The storage coefficient is 1×10^{-3}, indicating that the aquifer is semi-confined locally.

A local two-dimensional finite-element horizontal flow model allowed accurate calibration to natural conditions (natural gradient of the piezometric heads) and to pumping test results (drawdowns of the piezometric heads), taking into account the detailed local heterogeneity of the chalky formation near the well. These identified heterogeneities are related to the more fissured zones detected by boreholes and geophysical methods. Figure 3 shows the detailed modeled piezometric maps for natural and pumping conditions.

EXPERIMENTAL PROCEDURE OF THE TRACER TEST METHODOLOGY

This methodology was chosen in order to allow an accurate *a posteriori* simulation by numerical modelling, especially for control of the input function. Details about the methodology of these tracer tests can be found in the work of Meus (1993).
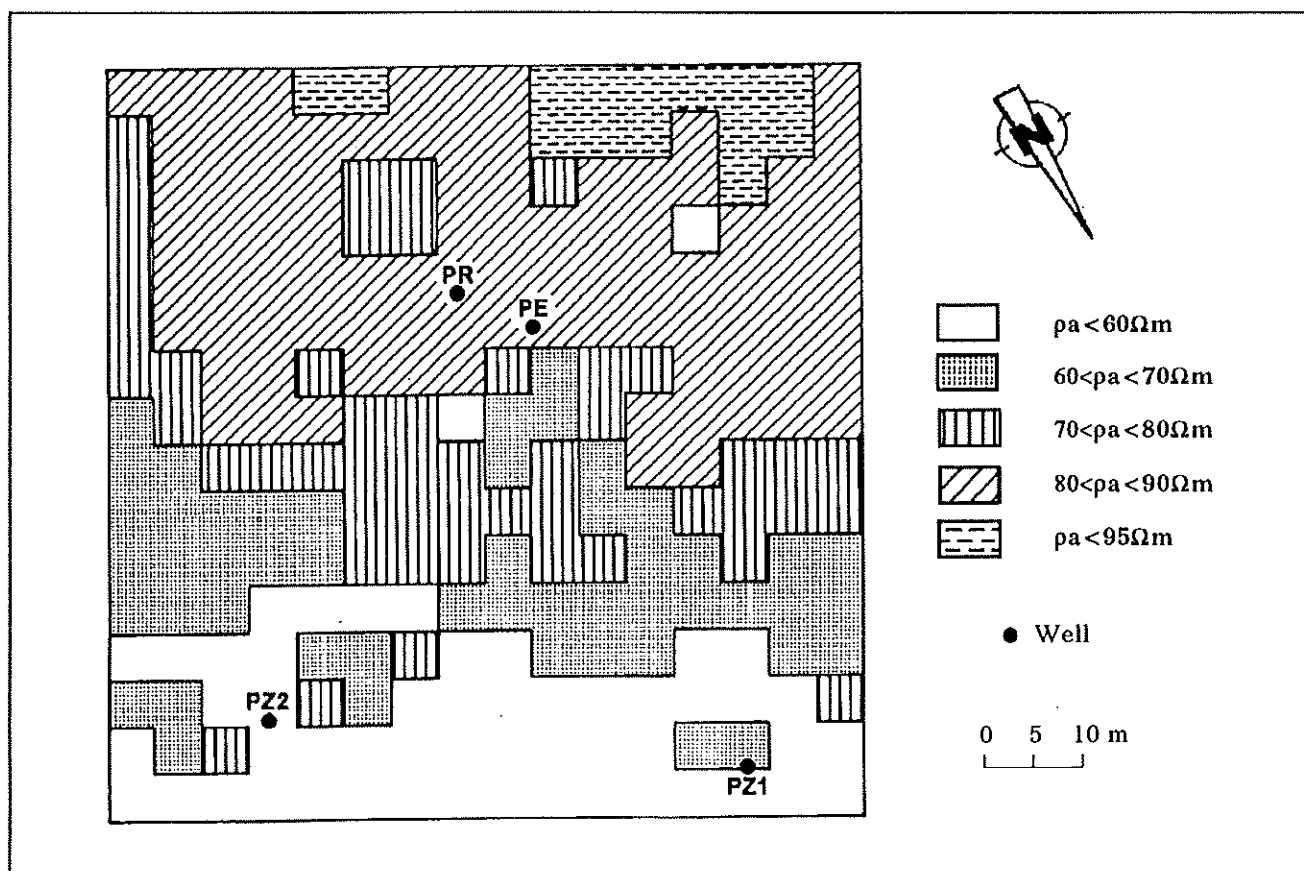

Figure 2. Map of the apparent electric resistivity in the study area, showing that the chalk is more fractured in the Pz1-Pz2 zone than in the PE-PR zone.
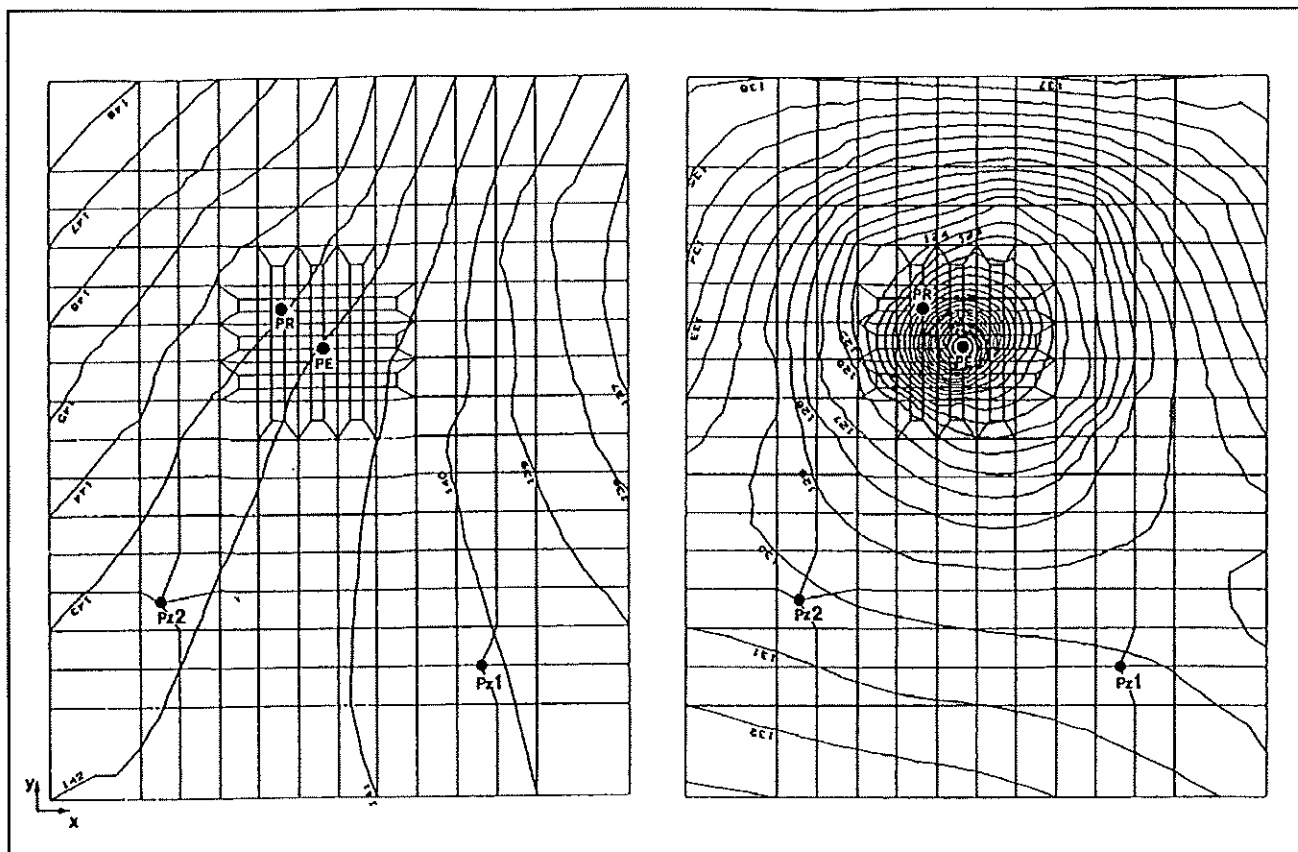
Figure 3. Modeled piezometric maps in natural (left), and in pumping (right) conditions (after Biver, 1993).

After 18 hours of stabilized pumping in PE, injections were carried out in Pz1 with uranine and in Pz2 with lithium chloride (LiCl).

The injections can be considered as instantaneous at the level of the aquifer by using an injection tube coupled with water injection above and below. It is a converging radial flow tracer test and the monitoring equipment allowed only a two-dimensional analysis of the concentrations. Under these conditions we are working with what is usually called depth-averaged (mixed vertically) concentrations. As Gelhar et al. (1992) have pointed out, we will underestimate the tracer concentration and, as a result, the longitudinal dispersivity is likely to be overestimated.

The recorded breakthrough curves in the pumping well PE, shown in Figure 4, indicate that the restitution of the lithium from Pz2 and of uranine from Pz1 are quite different in time.

In a first interpretation, this fact can be explained by the different piezometric gradients between Pz1-PE and Pz2-PE. The heterogeneity of the aquifer (which corresponds to an heterogeneous field of transmissivities in the calibration of the flow model) leads to different flow conditions around the pumping well. As a matter of fact the results of the transport processes in this aquifer are quite dependent on these flow conditions.

THEORETICAL CONCEPTS FOR THE NUMERICAL SIMULATION

Deterministic finite element models have been used for groundwater flow and transport simulations. As low concentrations of miscible tracers are concerned, we assume that flow and transport simulations can be uncoupled: no density or viscosity effects interacting on flow are taken into account.

In fact, the transport parameters of the advection-dispersion equation are investigated assuming that the representative elementary volume (REV) concept can be used. The parameters are deduced from accurate calibration computations to the observed breakthrough curves, using numerical finite element simulations.

The Hesbaye Aquifer is a double porosity and a double permeability medium. The permeability coefficients relative to the porosity of the pores have been estimated on basis of laboratory tests (Biver, 1991) to be 1×10^{-8} m/s. On the contrary, the global permeability coefficients 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 deterministic system of classical advection-diffusion equations (applied to an equivalent porous medium) considering that the pore water can be qualified as immobile water (Bear and Verruijt, 1987, Biver and 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. The transport equations can be simplified to obtain a system including two mass balance equations: one for 'mobile' water, the other for 'immobile' water, with a transfer constant, α_d^*, representing globally (and averaged on the REV) all the interactions between 'mobile' and 'immobile' water. For more details on the equations used in the model see Biver et al. (1994).

The classical finite element method, using the Bubnov-Galerkin schema, is not efficient to solve the advection-diffusion equation. If this method is used some strong numerical dispersion or spurious fluctuations are found. In fact, there is a fundamental difficulty in the solution of this transport equation because of the simultaneity of the advection and dispersion processes: they contribute to the total mass transport of the solute very differently. As mentioned above, convection is a transport along streamlines of the flow and dispersion is a transport by spreading both along and between these characteristic lines.

Mathematically, this means that we have hyperbolic terms representing the convection/advection in the same equation with parabolic terms for dispersion. The integration of this kind of equation is a problem that no numerical method has yet fully overcome (Yeh, 1993).

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 involving often 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 code and are now being tested in the SUFT code (see Note at end of this paper).

CALIBRATION OF THE NUMERICAL MODEL TO OBTAIN THE HETEROGENEOUS HYDRODISPERSIVE PARAMETER OF THE AQUIFER

The discretized finite element meshes are shown in Figure 5 for the transport simulation of lithium from Pz2 and of uranine from Pz1. The transport parameters to calibrate are: a_L, a_T, α_d^*, n_e, and θ_{im} which are respectively, the longitudinal and transverse dispersivity, the 'immobile' effect coefficient, the effective porosity, and the proportion of 'immobile' water.

After calibration, five different 'materials' are distinguished in the modeled zone on basis of the values of their transport parameters (Table 1).

The two dimensional spatial distribution of both tracers in the 'mobile' water reflects two different behaviors due mainly to the heterogeneity of the aquifer.

The modeled plume of injected lithium has a regular shape with a long ridge, due to the fact that the migration velocity of the tracer decreases strongly when passing successively to the zone with lower fracturing (lower permeability coefficient).
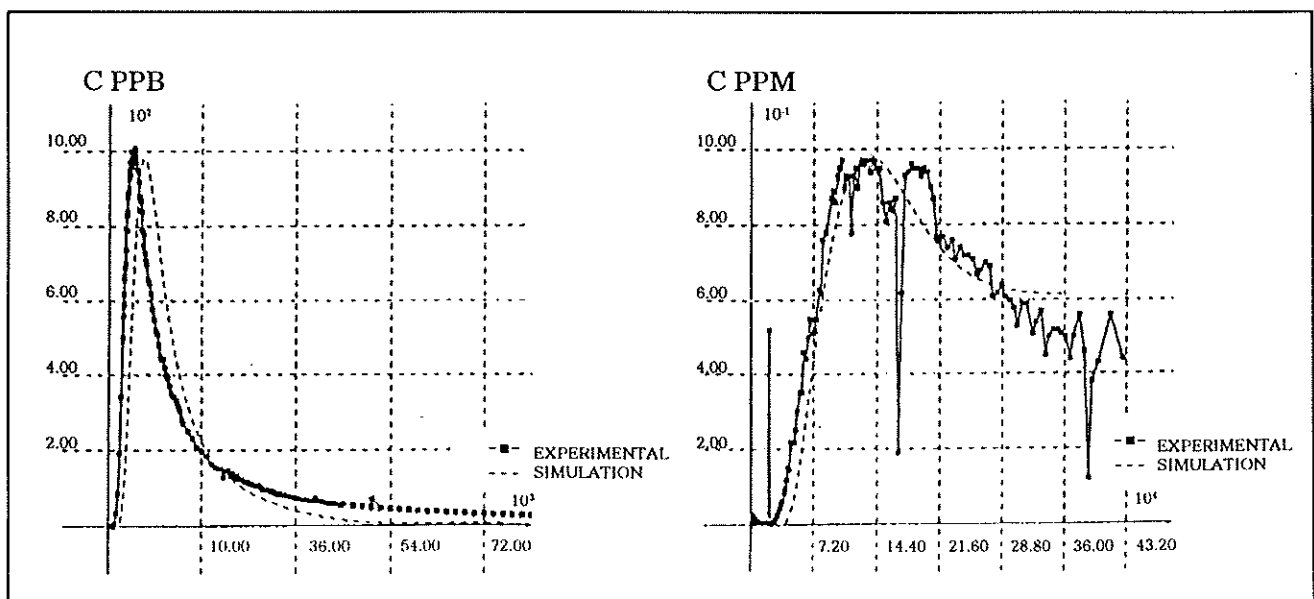

Figure 3. Experimental and calibrated breakthrough curves in PE. (a) for lithium, (b) for uranine. (after Biver, 1993).
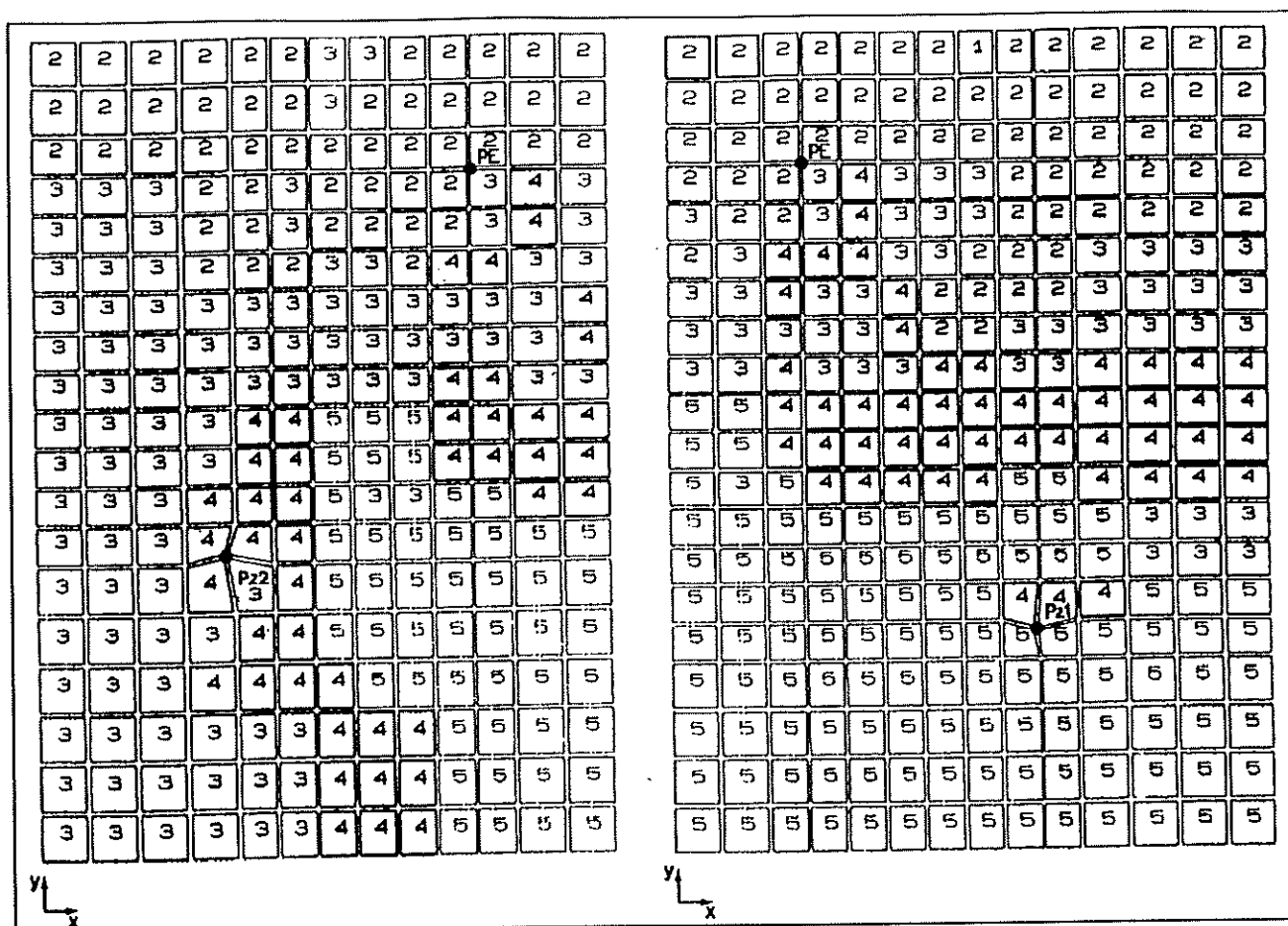
Figure 5. Finite element meshes and 'materials' of the discretizations for lithium and uranine tracer test transport simulations (after Biver, 1993).

The modeled plume of injected uranine is wide and is spreading in two main directions (Figure 6(a)). One direction corresponds to a fissured axis between Pz1 and PE, the other direction corresponds to the regional groundwater flow. Looking at the 'immobile' water concentrations one can see that, according to the simula-

tion, the high tracer concentration stays in a zone very close to the injection piezometer (Figure 6 (b)).

The plume of injected lithium was also computed and a more regular shape with a long ridge has been found. This fact is due to the strong decrease of the migration

Table 1. Calibrated transport parameters for lithium (between Pz2 and PE) and for uranine (between Pz1 and PE)

Transport Parameters	Material 1	Material 2		Material 3		Material 4		Material 5	
		Li^+	Uranine	Li^+	Uranine	Li^+	Uranine	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})	1x10^{-7}	1.20	3.7x10^{-7}	2.50	6.7x10^{-7}	5.00	7.9x10^{-7}	6.00	15.0x10^{-7}
n_e(%)	0.3	0.50	1.5	1.00	2.70	1.50	5.30	2.00	11.3
θ_{im}(%)	8.0	10.0	19.0	13.0	24.0	18.0	31.0	20.0	42.0

The SUFT (Saturated Unsaturated Flow and Transport) code is being developed at the LGIH at the University of Liège.

ACKNOWLEDGMENTS

REFERENCES

Andersen, L.J. and Gosk, E., 1987, Application of Vulnerability Maps, in Vulnerability of Soil and Groundwater to Pollutants, *Proc. RIvM Int. Conf.*, 321-332, Noorwijk, The Netherlands.

Bear, J. and Veruijt, A., 1987, *Modelling groundwater flow and pollution*, 415p., Reidel Publ. Company.

Biver, P., 1991, Modelling transport in a double porosity medium: an alternative approach, *Proc. of the first Int. Conf. on Water Pollution: modelling, measuring and prediction*, Comp. Mechanics Publ., Elsevier, pp. 43-57.

Biver, P., 1993, *Etude phénoménologique et numérique de la propagation de polluants miscibles dans un milieu à porosité multiple (application au transport des nitrates dans l'aquifère crayeux du Crétacé de Hesbaye)*, Ph.D. Thesis, Applied Sciences Faculty of the University of Liege, Belgium.

Biver, P. and Meus, Ph, 1992, The use of tracer tests to identify and quantify the transport processes in an heterogeneous aquifer, *Proc. of the 6th Int. Symp. on Water Tracing*, pp. 407-421, Balkema.

Biver, P. and Dassargues A., 1993, Contribution to the simulation of nitrates transport in a double-porosity aquifer, *Proc. of Int. Conf. on Groundwater Quality Management*, Tallinn, IAHS publication, September 1993 (to press).

Charlier, R., Radu, J.P., and Dassargues, A., 1988, Numerical simulation of transient unconfined seepage problems, *Proc. of the Int. Conf. on Computer Methods and Water Resources*, Vol. 1, Groundwater and aquifer modelling, pp. 143-155, Rabat, Springer-Verlag.

Dassargues, A., Radu, J.P., and Charlier, R., 1988, Finite elements modelling of a large water table aquifer in transient conditions, *Advances in Water Resources*, 11, no.2, pp.58-66.

Dassargues, A., 1991, *Paramétrisation et simulation des réservoirs souterrains: discrétisation du domaine, préparation statistique des données, couplages et non-linéarités des paramètres*, Ph.D. Thesis, Applied Sciences Faculty of the University of Liege, Belgium.

Dassargues, A., and Monjoie, A., 1993, Chalk as an aquifer in Belgium, in *Hydrogeology of the Chalk of North-West Europe*, Chapter 8, pp. 153-169, edited by Downing, R.A., Price, M. and Jones, G.P., Oxford Science Publications.

Foster, S.S.D., 1993, The Chalk aquifer - its vulnerability to pollution, in The Hydrogeology of the Chalk of North-West Europe, Ed. by Downing, R.A. and Jones, G.P., pp. 93-112.

Gelhar, L.W., Welty, C., and Rehfeldt, K.R., 1992, A critical review of data on field-scale dispersion in aquifers, *Water Resources Research*, 28, pp. 1955-1974.

Meus, Ph., 1993, *Hydrogéologie d'un aquifère karstique dans les calcaires carbonifères; apport des traçages à la connaissance des milieux fissurés et karstiques*, Ph.D. Thesis, Sciences Faculty of the University of Liege, Belgium.

Yeh, G.T., 1990, A Lagrangian-Eulerian method with zoomable hidden fine mesh approach to solving advection-dispersion equations, *Water Resources Research*, 26, pp. 1133-1144.

Yeh, G.T., 1993, Application of hybrid Lagrangian-Eulerian finite element approach to contaminant transport, Lecture material for the course: Modelling of flow and contaminants in the subsoil, IGWMC-IHE Delft, 24p.

Yu, C.C. and Heinrich, J.C., 1987, Petrov-Galerkin methods for the multidimensional time dependent convective-diffusion equations, *Int. J. for Numerical Methods in Engineering*, 24, pp. 2201-2215.

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