

Delineation of groundwater protection zones based on tracer tests and transport modeling in alluvial sediments

J. Derouane · A. Dassargues

Abstract Regulations aiming to protect exploitable groundwater resources were edicted in Belgium a few years ago. Therefore, prevention and protection zones are defined by law and must be determined practically around each pumping well or spring, based on local hydrogeological conditions. The determination of hydrodynamic and hydrodispersive parameters, characterizing the local flow and transport properties of the aquifer, requires pumping and tracing tests. The interpretation of these field experiments, considering the heterogeneity of the geological layers, is performed through the use of numerical FEM simulations of the groundwater flow and pollutant transport conditions in a deterministic framework. After calibration of the model on experimental measurements, multiple simulations with contaminant injections at various points of the modeled domain allow the determination of the transfer time of the pollutant in the studied aquifer whilst taking the updated heterogeneity into account. On the basis of the computed transfer times in the saturated zone, the various prevention and protection areas can be assessed based on provisions of the law.

Key words Groundwater resources · Alluvial aquifer · Protection zones · Tracing test · Numerical model

Introduction

Nowadays, each country or region has promulgated regulations regarding the protection and prevention zones around pumping wells, in order to maintain or to restore the quality of the groundwater in the vicinity of the

drinking water exploitation wells. However, despite the fact that authorities have often consulted the scientific community 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 be especially protected from any accidental pollution.

Groundwater protection regulations

In the Walloon Region of Belgium (Fig. 1), regulations about protection and exploitation of groundwater resources define, according to some criteria, different protection zones inside which some activities are regulated or prohibited (Arrêté de l'Exécutif Régional Wallon 1992). The regulations about 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. Three kinds of 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 lying, at the circumference of which a 10-m radius is added in all the directions. This zone has to be owned by the water company exploiting the well or the spring.

Zones II or *prevention zones* are to be determined as follows: from the external perimeter of *Zone I*, *Zone IIa* is defined by the distance in each direction corresponding to a time of pollutant transit of 24 h in the saturated zone. A minimum of 25 m must be added to the external perimeter of *Zone I*. From the external perimeter of *Zone IIa*, *Zone IIb* is defined by the distance corresponding to a time of pollutant transit of 50 days. However, in an unconfined aquifer, *Zone IIb* can be determined by considering the influence radius of the pumping in each direction with a minimum specified to 100 m in sandy aquifers, 500 m in gravel aquifers and 1000 m in fissured and karstic aquifers.

Zone III or *observation zone* is defined as the whole allimentation basin of the catchment area.

Activities allowed and those prohibited have recently been listed for each of these protection zones. One should discuss at length the scientific basis of such a regulation, but it should be admitted that the approach considering the contaminant transfer time in the saturated part of the aquifer is consistent. Indeed, the basic idea for this criterion is to ensure a delay between an eventual

Received: 27 June 1997 · Accepted: 29 July 1997

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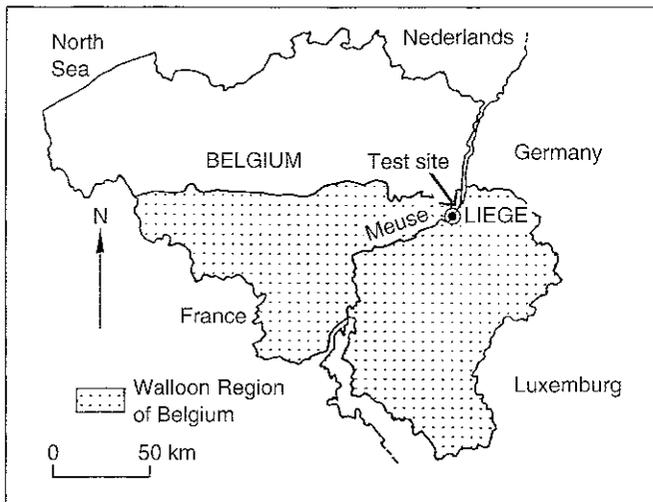


Fig. 1

The Walloon region of Belgium

injection of pollutant and its arrival at the pumping well, allowing one to decide on an appropriate intervention scheme.

However, in practice, the shape and the extension of these protection zones are strongly dependent on the heterogeneity of the geological layers. These heterogeneous conditions affect the groundwater flow properties (permeability, storage coefficient, etc.) as well as the pollutant transport characteristics in the saturated part of the aquifer (effective porosity, longitudinal and transverse dispersivity, molecular diffusivity, retardation factor, etc.). In consequence, only a spatially distributed model coupled to a very comprehensive data set are able to integrate these heterogeneities in the analysis accounting for the spatial variability of the hydrodynamic and hydrodispersive parameters.

Applied methodology performed in an alluvial aquifer

A complete hydrogeological study has been realized in the pumping station site of Vivegnis, located in the alluvial plain of the River Meuse in the north of Liège (Belgium), with the aim of delineating with accuracy the extension of the protection zones IIa and IIb around each pumping well.

In a first step, the methodology consists in determining experimentally the values and the spatial layout for hydrodynamic and hydrodispersive parameters of the alluvial aquifer; these parameters are then used in groundwater flow and contaminant transport equations integrated and solved by a numerical model using the finite element method (FEM).

The numerical model, taking all detected local heterogeneities into account, allows the simulation of groundwater flow and contaminant transport conditions characterizing the saturated part of the studied aquifer, and leads to an accurate delineation of the protection zones (Dassargues 1995).

Parameters and laws describing groundwater flow and miscible contaminant transport processes in saturated porous medium

Groundwater flow and the contaminant transport processes in a saturated porous medium can be physically described by a series of constitutive laws. Such laws take into account a series of parameters characterizing the studied medium, linked to geometry of the aquifer, its physical characteristics (hydrodynamic and hydrodispersive properties) and the external sink and sources (solicitations). These parameters relate to the representative elementary volume (REV) of the studied medium. Properties are averaged on the basis of such a REV, while considering that the medium is continuous (Bachmat and Bear 1986). In these conditions, the corresponding equations, noted according to Einstein's notation rule, can be succinctly written as follows (Bear and Verruijt 1987). Darcy's law, for an incompressible fluid, is written

$$q_i = -K_{ij} \frac{\partial h}{\partial x_j}, \quad i, j = 1, 2, 3$$

where q_i is Darcy's specific discharge and K is the permeability tensor.

The phase average velocity is expressed by:

$$V_i = \frac{q_i}{n_e}$$

where n_e is the effective porosity ($n_e < n$).

The groundwater flow equation for an unconfined aquifer, reduced to two horizontal dimensions, can be written:

$$\frac{\partial}{\partial x_i} \left(T_{ij} \frac{\partial h}{\partial x_j} \right) + R + Q = S \frac{\partial h}{\partial t}, \quad i, j = 1, 2$$

where $T_{ij} = b K_{ij}$, R = infiltration, Q = flow-rate [pumping (-) or injection (+)], S = storage coefficient, T = transmissivity, b = saturated aquifer thickness.

Miscible contaminant transport equation in a saturated porous medium can be written:

$$b \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - b \cdot V_i \frac{\partial C}{\partial x_i} = b \cdot R_d \cdot \frac{\partial C}{\partial t} + b \cdot R_d \cdot \lambda \cdot C - R \frac{C_0 - C}{n} - Q \frac{C_w - C}{n}$$

Here, D is the hydrodynamic dispersion tensor whose components are:

$$D_{ij} = \alpha_T \cdot V \cdot \delta_{ij} + (\alpha_L - \alpha_T) \frac{V_i \cdot V_j}{V} + D_m \quad \text{where } V = \sqrt{V_i \cdot V_i}$$

The retardation coefficient R_d is given by:

$$R_d = 1 + \beta \frac{(1-n)\rho_s}{n \cdot \rho_l}, \quad \text{where } \beta = K_d \cdot \rho_l$$

with: C = pollutant concentration, R = infiltration, V_i = effective velocity, C_w = injection concentration, α_L = longitudinal dispersivity, Q = injection flow rate, α_T = transversal dispersivity, b = aquifer thickness, Dm = molecular diffusivity, λ = decay constant, n_e = effective porosity, K_d = distribution coefficient, C_0 = concentration of vertical inflow, ρ_l = density of the liquid, n = porosity, ρ_s = density of the porous medium.

Characteristics of the studied aquifer

Geological context, geometry, and piezometry of the aquifer

The pumping site of Vivegnis (Fig. 2) provides drinkable water for part of the city of Liège. The average groundwater discharge of the site is about 8000 m³/day, extracted from four production wells. For the needs of the study, ten piezometers have been drilled, completing the set of boreholes already existing in the area. The lithological information provided by these boreholes, added to data from many penetration tests and from geophysical survey (electric and seismic sounding methods),

leads to an accurate definition of the setting and lithology of the geological layers, the geometrical configuration of the aquifer, its heterogeneity, and the limits of its vertical and lateral extension.

The alluvial plain of the River Meuse is characterized by a fluvial sedimentation composed of gravels mixed in a sandy, silty, or clayey matrix. High spatial variations in the importance and composition of the matrix have been detected in the geophysical results and confirmed by the drilling logs. The lateral as well as vertical heterogeneity of the fluvial deposits reveals the geomorphological evolution of the course of the River Meuse in the studied area (Calement 1964).

The main gravel layer has an average thickness of about 7 m. It is overlain by a 2-m-thick silt layer: this partially saturated layer has a considerable potential for attenuation of pollution from the infiltration of surface water toward the aquifer.

The Primary shale and sandstone bed-rock (Namurian and Westphalian ages of Carboniferous formation) is characteristic of the substratum of the River Meuse valley and its slopes in the north of Liège (Vivegnis site). This formation can be considered as an impervious bottom for the alluvial aquifer (Fig. 3).

The aquifer, unconfined in nearly the whole of the studied area, flows northward with a 0.075% average gradient (outside the area of catchment of the pumping). The aquifer is in equilibrium with the River Meuse, whereas the bottom of the Canal Albert is situated at a superior mark at the aquifer level.

Hydrodynamic and hydrodispersive parameters

The numerical model allowing estimates of the protection zones for the pumping station is based on the resolution of groundwater flow and contaminant transport equations, according to conceptual scheme and work hypotheses which must validly represent reality. Implementation of field experiments is necessary in order to determine values and spatial layout of the hydrogeological parameters intervening in those equations.

Hydrodynamic parameters

The major hydrodynamic parameters, characterizing 2D groundwater flow in the heterogeneous porous medium, are transmissivity and storage coefficient. These paramet-

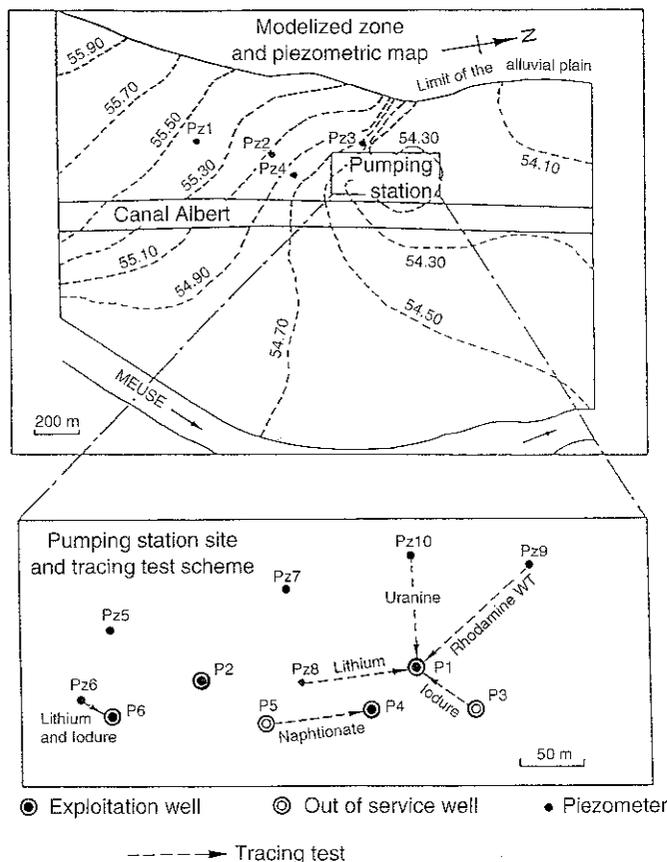


Fig. 2
Location of the studied area, modeled zone, and piezometric map

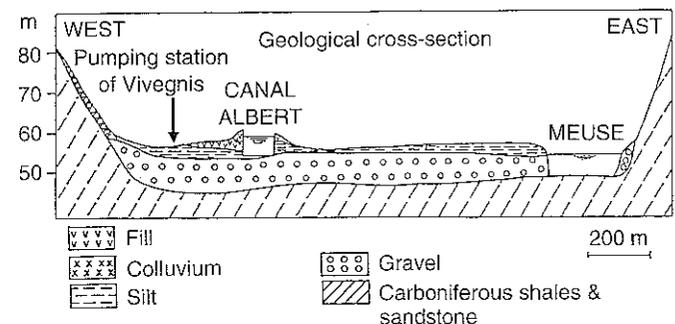


Fig. 3
West-east geological cross section

ers can be locally estimated by the interpretation of several pumping tests completed in each production well and piezometer. A first interpretation is made following the classical analytical solutions of Theis (transient conditions) and Dupuit (steady-state conditions), considering a water table aquifer and an homogeneous and isotropic porous medium (Castany 1982). As results, calculated transmissivity values range from 1.10^{-4} to 2.10^{-1} m²/s, with an average value of 3.10^{-2} m²/s. Transmissivity values lower than 5.10^{-3} m²/s are found corresponding to zones where the clay content is higher. Conversely, transmissivity values higher than 8.10^{-2} m²/s should locally correspond to clean and well-sorted gravel zones.

An averaged storage coefficient of 0.10 has been analytically estimated using the Theis solution. The aquifer being unconfined, this value can be used as a first approximation for the effective porosity of the porous medium. An averaged radius of influence for the production wells is estimated, on the basis of Dupuit solution in steady-state conditions, at 500 m, with extreme values ranging from 230–810 m. In transient conditions, a value of 440 m has been calculated. One should keep in mind that only a first approximation of the hydrodynamic parameters can be obtained from those pumping test interpretations, given the strong assumptions under which the Theis and Dupuit expressions are valid.

Hydrodispersive parameters

Major hydrodispersive parameters characterizing the miscible pollutant transport processes are, for this case-study, effective porosity, longitudinal and transversal dispersivities, and molecular diffusivity. Acquisition of these data requires tracing tests.

A set of radial convergent and multi-tracer tests were performed using piezometers located near the pumping wells, in order to study at the field-scale the behavior of a miscible pollutant moving along in the saturated zone of the gravel aquifer. Five tracers (LiCl, KI, Uranine, Rhodamine WT, Naphtionate) were used to simulate the evolution of a contaminant in the porous medium from different injection piezometers.

The tracer nature is here considered as having no important influence on the recorded breakthrough curve. As mentioned by Käss (1994), lithium chloride is suitable for tracer experiments because of its low sorptivity, high water solubility and its generally low background. The determination of concentrations in iodide (I⁻) is theoretically not affected by adsorption as it is an anion. Uranine or sodium fluorescein is an excellent dye for any tracer tests. The sorption properties of rhodamine WT have been discussed by many authors (Di Fazio and Vurro 1994, Käss 1994, Shiau and others 1992, Sabatini and Austin 1991). Due to increasing limitations in relation with the concern of environmental protection, the choice between tracers was becoming very limited. So that, at the present stage of the study, and considering that the aquifer consists mainly of well-sorted gravels, we take the assumption that the little sorption characteristic of the rhodamine WT (Käss 1994) can be neglected here. Sodi-

um naphtionate which is a low blue-violet fluorescent tracer is considered so far as not sorptive (Käss 1994). As the wells are producing continuously drinkable water, we had the permanent constraint of complying with regulations regarding the quality of drinkable water extracted from pumping wells during the tests. The standards have to be complied in regard to visibility, toxicity, taste criteria, and so on. (Parriaux and others 1988). In view of this, local preliminary numerical simulations using simplistic models have been computed before effective tracer injections. Based on estimated "a priori" values chosen for hydrodispersive parameters, rough simulations are made with the aim of estimating beforehand the probable behavior of the tracers (transfer times, modal concentrations, etc.). This preliminary and preventive stage has allowed to estimate the ideal mass of tracer to be injected in each piezometer or well, in order to optimize the tracer-test experimentation.

Tracers have been injected (instantaneous injections) in six different piezometers and wells. Distances between the injection points and the pumping wells range from 27 to 115 m. Water sampling in each of the three production wells in normal pumping conditions, followed by chemical analysis giving the tracer concentrations for each time-step, provided a set of seven experimental breakthrough curves (tracer concentration in the pumping well versus time) (Fig. 4).

The interpretation of the tracer-test results is often done by taking advantage of analytical solutions (Sauty and Kinzelbach 1987; Moench 1995). Here, the quantitative and detailed interpretation of each measured breakthrough curve, by calibration of a detailed 2D numerical model considering a heterogeneous porous medium, will lead to the determination of values and spatial distribution for the major hydrodispersive parameters (basically, effective porosity and longitudinal dispersivity) characterizing the gravel aquifer. Conductivity measurements (for saline tracers) and regular chemical analyses on samples, taken at regular time-steps after injection and at different levels of depth in each injection borehole, were performed to verify the "instantaneous" character of the injection and to quantify the penetration of tracers into the aquifer.

External sink/source term (solicitations)

Averaged flow-rate of the pumping station is approximately 8000 m³/day. During the pumping and tracing-test period, it was pumped equally from three wells (P1, P4, P6), each of them pumping 115 m³/h in assumed steady-state conditions. Calibration of the groundwater flow and transport model is achieved in these particular conditions. However, in the normal production situation, a fourth well (P2) is also used. The protection zones IIa and IIb will be determined in this configuration, with a uniform spreading of the cumulated maximum flow-rate of the station between the four wells. The average recharging infiltration over the whole studied area is estimated at 250 mm/year, and an additional local infiltration of 3000 mm/year was prescribed along Canal Albert

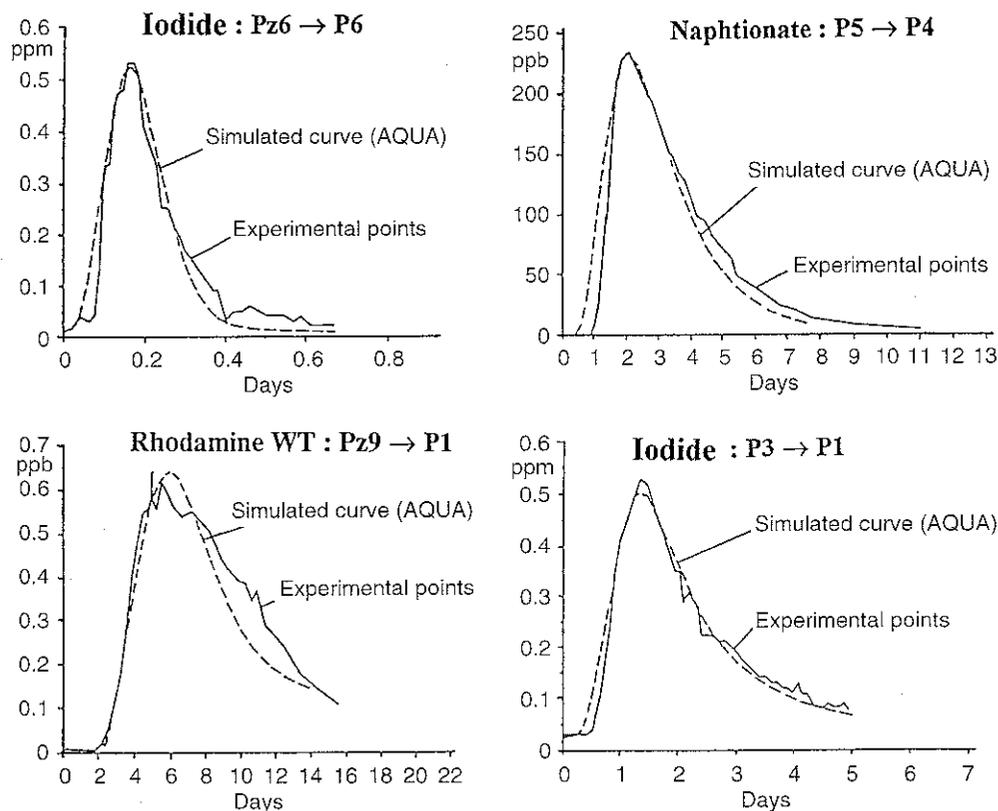


Fig. 4
Measured and computed
breakthrough curves
(calibration of transport
model)

(due to water losses from its bottom) (Dassargues and Lox 1991, Dassargues 1992). These values are introduced into groundwater flow and contaminant transport models.

Simulations and results

Numerical method, boundary conditions and discretization

Building up a numerical model requires the integration of all data collected during previous stages of the study, the logical assessment of missing data, and the provision of a global solution showing all the trends of the aquifer concerning groundwater flow and contaminant transport in saturated porous medium. After calibration of the model, simulations using fitted parameters will lead to the delineation of probable extension of the protection zones to be considered for the pumping site, taking into account aquifer geometry and heterogeneity, local values of the hydrogeological parameters, and external sink/source values (solicitations of the system).

As already seen, the porous medium is considered as a continuum whose properties are globalized at a scale corresponding to a representative elementary volume (REV) (Bear and Verruijt 1987). The considered laws are macroscopic, requiring determination of the coefficients at this scale.

The model has been realized using the software AQUA

2D. This program, developed by Vatnaskil Consulting Engineers (Reykjavik, Iceland), allows the resolution – in two spatial dimensions – of groundwater flow and miscible pollutant transport equations, by a finite element code using the streamline upwind petrov-galerkin method (SUPG), associated to a “fully implicit” time integration (Yu and Heinrich 1986).

The modeled zone (Derouane, unpublished data) covers a surface of about 4 km², limited by the River Meuse on the eastern side and by the limit of the alluvial plain extension on the western side. The zone is crossed, from south to north, by the Albert Canal (Fig. 2).

The area is discretized in 3000 triangular finite elements whose side lengths range from 200 m to less than 2 m. A finer mesh is essential for the experimentation and pumping zone inside which we want to simulate with accuracy the contaminant transport process. It is badly needed in order to limit numerical oscillations that may appear within the framework of the chosen numerical resolution method. As expected, confirmed by measured breakthrough curves, hydrodispersive properties of the studied porous medium are characterized by quite low dispersivities. Therefore, the advective/convective component can be considered as dominant. For the chosen integration scheme, one might consider that the numerical solution is acceptable (with weak oscillations) when the local Peclet number expressing the advection/dispersion ratio is kept under a value of 10 (Biver, unpublished data). The Peclet number, in one direction, can be written:

$$Pe = \frac{V \cdot \Delta L}{D} = \frac{V \cdot \Delta L}{\alpha_L \cdot V} = \frac{\Delta L}{\alpha_L},$$

where ΔL is the characteristic length of the mesh.

For this case study, a locally refined mesh may not always be sufficient to satisfy this condition, and introduction of an upstream weighting factor (SUPG method) often turns out to be necessary.

Calibration

The first stage of the model consists in fitting the groundwater flow and transport parameters, in order to reproduce correctly by numerical simulation the experimental measurements collected during pumping and tracing tests. The previous assessed spatial distribution of the permeability values, as deduced from pumping test results, has greatly reduced the choice in the different ways to obtain an acceptable calibration of the groundwater flow model. At the end of the fitting simulations, the measured piezometric levels are accurately restored by the model. The boundary conditions of the model are carried over the measured radius of influence of the pumping wells: prescribed piezometric heads were imposed along each side of the modelled area (Dirichlet conditions).

Concerning the calibration of the contaminant transport model, advection, hydrodynamic dispersion and molecular diffusion were considered to characterize the behavior and the evolution of the pollutant plume in the saturated zone of the porous medium. For each simulated injection, the contaminant transport simulations allow us to obtain computed breakthrough curves. The shape and the characteristics of each computed curve are function of the chosen values for hydrodispersive parameters (effective porosity, longitudinal and transversal dispersivity coefficients, effective molecular diffusion coefficient) characterizing transport processes. The fitting of each calculated breakthrough curve to the corresponding experimental curve obtained by tracer tests leads to the accurate determination of local values and spatial layout of the hydrodispersive parameters characterizing the porous medium in the studied area. The main results are shown in Table 1 and Fig. 4.

Two problems arose during calibration of the transport model. Firstly, an implicit integration scheme always leads to the appearance of a certain numerical dispersion. This phenomenon may generate an underestimation of the calibrated dispersivity coefficients. Moreover, in spite of a strong refining of the local mesh for each transport simulation, the use of decentralized spatial weight functions proved to be necessary to limit numerical oscillations. Indeed, the density of nodes is limited by the sensible raise in computation time and occupation of memory space, which does not always allow me to maintain the Peclet number below a reasonable value.

The second problem is that during calibration of the computed breakthrough curves, it is sometimes difficult to adjust the model on late arrivals of pollutant observed on experimental curves. The asymmetrical appearance presented by each curve cannot be adjusted in its entirety by the model if only advection, hydrodynamic dispersion, and molecular diffusion processes are considered (Fig. 5a).

A possible interpretation of these results was to attribute the late arrivals of pollutant to the influence of undetected zones characterized by lower permeability coefficients. A part of the tracer migrates in those locally less permeable zones and is strongly delayed when comparing to the averaged advective/convective route. The well-known sedimentation processes which lead to River Meuse alluvial deposits justifies fully that heterogeneity should be taken into account, not only laterally but also on a vertical basis (granulo-classifying sequence). At this stage of the study, the limited data do not allow a reliable interpretation of heterogeneity in the vertical direction; this has been done later by Dassargues and others (1997). Introduction of local heterogeneities with contrasted values of permeability into the 2D model leads to conclusive results (Fig. 5b). Of course, besides heterogeneity, the long tailing of some of the breakthrough curves can be explained also by such other processes as adsorption/desorption and perhaps immobile water effect (Biver and others 1995).

Figure 6 illustrates, for four different travel times (including the modal one), the simulated spatial distribution of the Rhodamine WT plume, spreading from the injection well (Pz9) toward the pumping well (P1).

Table 1

Hydrodispersive parameters obtained by calibration of the model

injection well	pumping well	distance (m)	tracer	n_e (effective porosity) (%)	α_L (long. dispersivity) (m)	α_T (trans. dispersivity) (m)	D_m (molecular diffusion) (m^2/s)
PZ6	P6	26.85	KI	4.80	0.01	0.003	10^{-9}
P3	P1	49.35	KI	7.20	0.01	0.003	10^{-9}
P5	P4	77.50	Naphthionate	5.63	0.95	0.220	10^{-9}
PZ10	P1	90.62	Uranine	5.90	0.04	0.010	10^{-9}
PZ9	P1	115.25	Rhodamine WT	4.70	0.60	0.200	10^{-9}
PZ8	P1	87.50	LiCl	8.20	0.90	0.250	10^{-9}

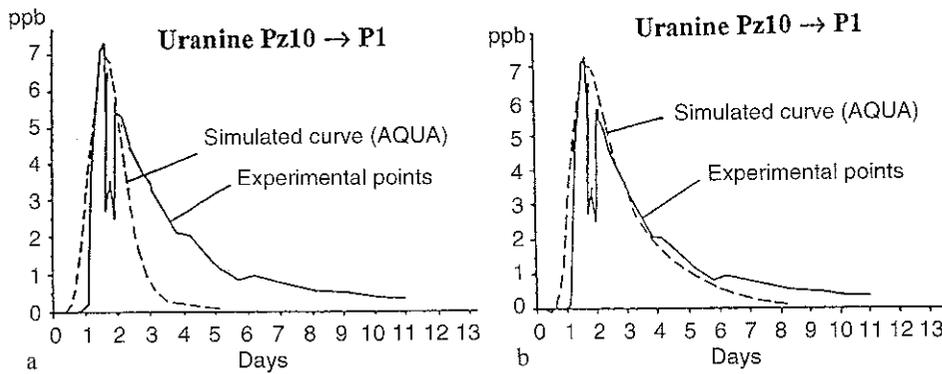


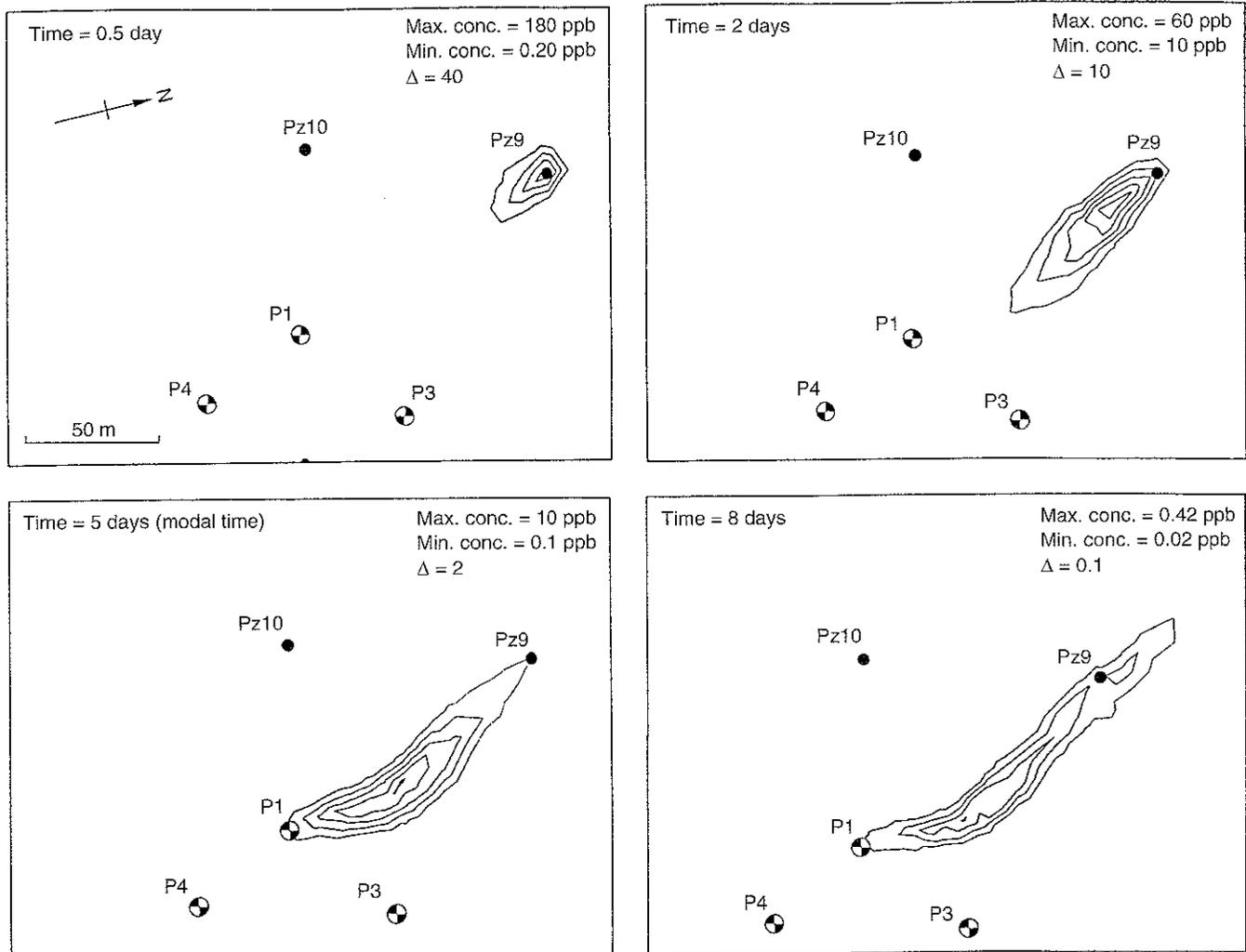
Fig. 5
Fitting of breakthrough curve a without and b with introduction of local heterogeneities into the model (illustrated by Uranine tracing test performed from Pz10 towards P1)

Delineation of the protection zones IIa and IIb with the model

At the conclusion of the groundwater flow and pollutant transport calibrations, the model can be considered as the best representation of reality at the current investigation stage. Having in mind all the afore-mentioned hypotheses, it is a powerful tool of aquifer management. It can be used for prediction purposes, through the study of potential situations resulting from various solicitations: influence of an increase in pumping rate, evaluation of

critical flow-rates, intervention means to implement in case of local pollutions (optimization of recovery wells, pumping rate, duration of operations, analysis of resident times and transfer velocity of the pollutant, etc.). Moreover, a good assessment of protection zones IIa and IIb around each production well can be provided by the

Fig. 6
Computed spatial distribution of the Rhodamine WT plume



model. For this last purpose, computations considering the maximum pumping rate are performed (as opposed to average pumping rate, for example), in order to ensure security.

The calibrated numerical model integrates all the fitted values allocated to hydrogeological parameters. The effective velocity field of the contaminant can then be considered as reliable in the experimentation area. Indeed, for each tracer test, hydrodispersive parameters were calibrated only in the subarea. Nevertheless, for delineation of protection zone IIb (corresponding to a transfer time of 50 days), more important volumes of porous medium are concerned as longer pollutant transit distances are to be considered.

A problem of representative scale arises (Jensen and others 1993) and, in the current state of the study, we have chosen to upscale the values of transport parameters on basis of the geological knowledge about the site. We have extrapolated the effective velocity field and the transport parameters to the whole modeled area using all available information from 'hard data' (direct measurements) and 'soft data' (interpretations from geological evidence). Ideally, long-lasting tracer tests should be realized from piezometers situated at longer distances from pumping wells (Gelhar and others 1992).

For computation of the 50 days isochrone, delineating Zone IIb, the extrapolated value for effective porosity has been set to 0.06. The hydrodynamic dispersion and the molecular diffusion turning out to be very weak in this case, the outline of Zone IIb has been drawn considering only the dominant convective process for isochrone calculation. The main purpose of this statement is to avoid large numerical oscillations, as described before. The computed 50-day isochrone line is shown in Fig. 7 (contour a).

Calculation of the 24-h isochrone, delineating Zone IIa around each pumping well, has been performed with the same statement as Zone IIb. The computed 24-h isochrone line is shown in Fig. 8 (contour a). The effective porosity value has been set to the minimal value deduced from tracer tests (0.047) in order to be sure to compute the shorter transfer time of pollutant in the saturated zone.

Implementation of long-lasting tracer tests should be considered, as far as it could help to solve the problem of upscaling the transport parameters while estimating the Zone IIb perimeter.

An additional improvement could be to account for dispersion when calculating the distances delineating protection zones. In this way, the first arrivals of pollutant should be slightly accelerated due to the effect of longitudinal dispersion added to the purely convective arrivals. In this case-study, as hydrogeological conditions can clearly be considered as convective dominant, this stage would turn out to be laborious – as regards the generated numerical oscillations (Peclet number) – and would probably not be justified. Few simulations made in these conditions show weak difference with results presented here. This would not be the same for other cases correspond-

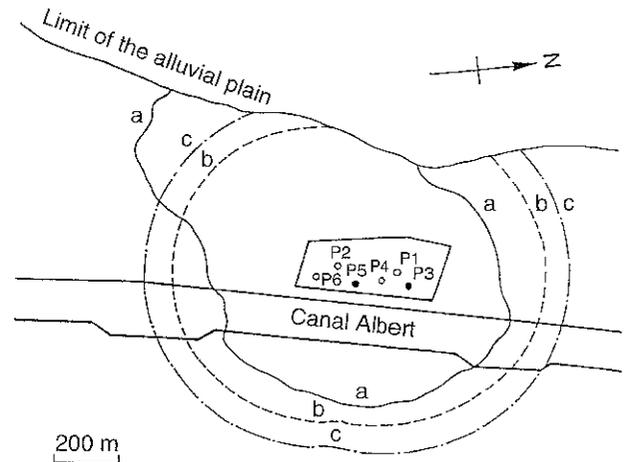


Fig. 7

Delineation of prevention Zone IIb, according to three different criteria. (a) Computed 50 days isochrone (performed by AQUA model), (b) effective radius of influence of the pumping station, (c) fixed distance criteria: radius = 500 m

ing to more dispersive hydrogeological contexts. For those cases, calculations taking dispersion into account are certainly needed when estimating protection-zone perimeters. However, in this last case, delineation of protection perimeters should require that (1) the concentration level of the pollutant to be considered as a first arrival of pollutant be defined by law (ideally in function of the toxicity of each component) and (2) the injected mass of pollutant to be considered in the computation be specified.

Results obtained by other methods

For this case-study, even if it could be improved, the numerical model constitutes the most appropriate tool for delineation of protection zones. It allows calculation of the isochrone lines, integrating a complete set of hydrogeological field data in the best possible way. The collection of additional data, particularly data from long-lasting tracer tests, should lead to improved reliability of the results.

However, it seems that it is not the current authorities' intention, for many reasons (financial above all), directly to apply such a complete and elaborated methodology to each pumping station in the country. For that reason, regulations about protection and exploitation of groundwater resources also propose a definition of protection zones IIa and IIb based on less reliable criteria: fixed distances (contours c in Figs. 7 and 8), transit time calculated by empirical or analytical formulations based mainly on Darcy's law, distance corresponding to the radius of influence of the well (Zone IIb), and so on (Huysgens 1990).

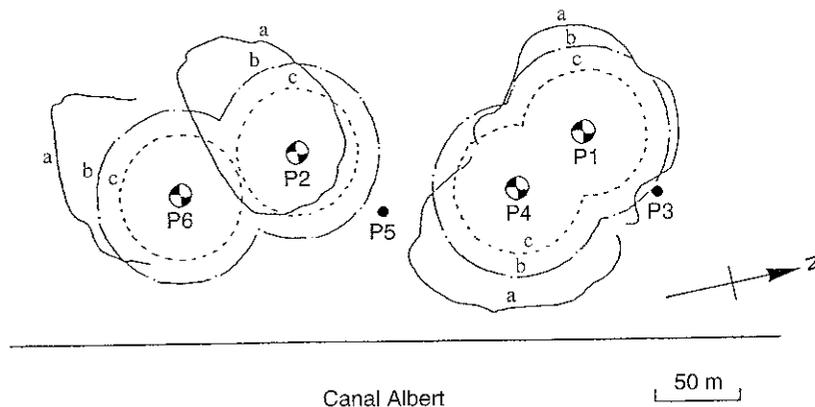


Fig. 8

Delineation of prevention Zone IIa, according to three different criteria. (a) Computed 24-h isochrone (performed by AQUA model), (b) 24-h isochrone estimated by approximative formulation based on Darcy's law (radial converging flow). (c) fixed distance criteria: radius = 25 m

For comparison purposes, we have calculated the delineation of the protection zones IIa and IIb, based on this last second-order criteria. The delineation of Zone IIb can be based on estimation of the effective radius of influence of the concerned pumping well. The most accurate formulation in this case is based on interpretation of pumping tests in transient conditions (Theis).

$$R^* = 1.5 \sqrt{\frac{T \cdot t}{S}} = 220 \text{ m}$$

where R^* = fictitious radius of influence (m), T = average transmissivity (m^2/s), t = pumping time from the start of the pumping test until equilibrium (s), S = storage coefficient.

In practice, we consider that the effective radius of influence R is equivalent to $2R^*$ for an unconfined aquifer. The external circular perimeter of Zone IIb can then be estimated by: $R = 2R^* = 440 \text{ m}$ (contour b in Fig. 7).

For Zone IIa, given that local flow conditions around each pumping well can be considered as "radially convergent" up to a distance greater than about 50 m from each well (keeping in mind that the pumping rate for each well is around $120 \text{ m}^3/\text{h}$), the 24-h isochrone can be calculated by an approximative formulation based on Darcy's law, valid under the assumption of a radial converging flow in isotropic and homogeneous porous medium:

$$R = \sqrt{\frac{t \cdot Q}{\pi \cdot e \cdot n_e}}$$

where R = distance (m) from the well corresponding to transit time t , t = transit time (s), Q = pumping rate (m^3/s), n_e = effective porosity, e = aquifer thickness (m).

In our case, when $t = 24 \text{ h}$, R represents the external circular perimeter of Zone IIa and can be calculated to 47 m (contour b in Fig. 8).

Conclusions

Tracing tests completed in the alluvial plain of the River Meuse near Liège, and interpretation completed by calibration of a numerical model, clearly showed two main

observations: the behavior of a pollutant contamination is essentially convective in the saturated zone of the gravel aquifer, but can be strongly affected by local heterogeneities influencing the groundwater flow field and the evolution of a pollutant plume.

The fitted longitudinal dispersivity values are quite weak, always lower than 1 m, while the average effective porosity is about 0.06. This last parameter certainly constitutes the most influencing factor for transit time of pollutant in this aquifer, given that advection is the dominant process. The 2D macro dispersion is replaced here by distinguishing a detailed 2D distribution of the permeability values. In this hydrogeological context, the distances delineating protection zones by the transfer-time criterion can be estimated considering only the effective velocity field linked to the advection process.

Tracer tests and interpretation of results based on a model integrating all measured data lead to an estimation of those distances while taking heterogeneity of the porous medium into account. That point confers on this methodology an evident advantage in comparison with other methods based (for example) on approximative formulations, and thus justifies fully the consented investments.

Acknowledgements The authors wish to thank the "Société Wallonne des Distributions d'Eau (SWDE)" for financing operations related to this study, and for logistic support.

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