Modelling groundwater flow and contaminant transport to a threatened collecting gallery: first assessment of the protection zones and determination of the needed data for a better reliability

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Abstract

Often the modelling approach is considered as a 'final' tool which is used when all the data are already collected in order to integrate all of them in the model. Another approach is to use simulations as an intermediate tool providing informations on the necessary data and investigations to be made in order to reach a better accuracy with regard to the real processes occurring in the aquifer. This methodology has been applied on a particular case study, involving a gallery of about 3 km length, collecting 900 m^3/hour of drinking water in a chalky aquifer.

Results of the simulations provide isochrone lines computed for many different cases. The main benefit is that these results direct very clearly towards further investigations to be made as: shallow geophysical prospecting, drilling of piezometers, pumping and tracer tests....

It is only when all these data will be collected adequately that detailed 2D or 3D simulations of groundwater flow and transport conditions in an heterogeneous aquifer will provide reliable approximations of the protection zones .

I Introduction

Nowadays, regulations about protection and prevention zones around pumping wells are enacted in order to maintain or to restore the quality of groundwater in the vicinity of the drinking water production wells. In practice it is still very difficult to determine on a rigorous and scientific basis the effective zones which are to be protected in each particular case. Moreover, misunderstanding or very inadequate determination of the zones are often due to an insufficient knowledge of the real groundwater conditions, with regard especially to aquifer heterogeneities and complex processes of contaminant transport in a porous and/or fractured medium.

Usually regulations about protection and prevention zones are mainly based on transfer time of contaminants in the saturated part of aquifer. Three kinds of protection zones are defined in Walloon region of Belgium: (a) the water supply zone (zone I) where the water supply installations are lying at the circumference of which a 10 meters radius is added in all directions, (b) the first prevention zone (zone IIa) is defined as the distance in each direction corresponding to a time of pollutant transit of 24 hours in the saturated zone (in karstic areas the zone IIa includes all the preferential points of infiltration, as sinkholes,...), (c) the second prevention zone (zone IIb) is defined as the distance in each direction corresponding to a time of pollutant transit of 50 days, (d) the observation zone (zone III) is the whole alimentation basin of the catchment area. A list of restricted activities is established for each protection zone and "intervention codes" are foreseen in case of accidental spill.

It seems evident that aquifer vulnerability has to be assessed in each studied case; even if this general concept applied to a "universal contaminant" has significant limitations in rigorous scientific terms [1]. In practice, each aquifer system will respond differently to individual contaminants and pollution scenarios [2]. In the case of Belgian regulations, the unsaturated zone is not taken into account, considering that we are on security side with regard to the reality. Only the saturated zone will be treated here, discarding at this stage of the conceptual approach, any processes occurring in the unsaturated zone.

How could we calculate or compute practically perimeters of different zones in each case, considering that the factors that control groundwater flow and transport are mainly influenced by the heterogeneities of the ground?

In this case, contrasted lithologies and fissuration/fracturation may produce important influences close to pumping wells, creating highly contrasted groundwater flow velocities, in function of which the different processes of the contaminant transport may be more or less amplified. Emphasis is given on how an intermediate modelling exercise can provide valuable informations on the main lacking data and their eventual respective influences on the results. On basis of these results, the further investigations to be completed in the studied zone are deduced.

2. Hydrogeological context

The particular site which is taken as an example in this paper is located in the "Hesbaye" aquifer (figure 1), represented by a chalk outcrop of 350 km^2 lying to the North of the River Meuse near Liège. About 60000 m3/day of drinking water 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 has been collected at a regional scale. A Finite Element model of this regional aquifer has been completed [3].

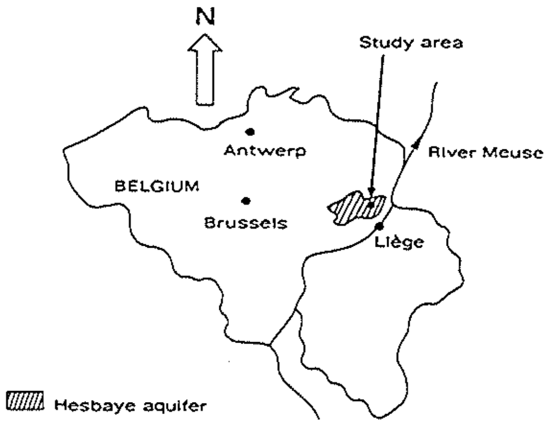


Figure 1 : Location map of "Hesbaye" aquifer and of the particular investigated site.

In the studied site, water is produced by pumping from the free waters of a draining subhorizontal gallery located near the bottom of the chalky aquifer. In the zone around the pumping point, where the perimeters of the protection zones are to be determined, the geological sequence may be summarised as follow (from top to bottom): (1) 7-15 m of Tertiary loess; (2) 10 m of a residual conglomerate; (3) 40 m of Cretaceous chalk, fractured in some places; (4) a layer of hardened calcareous clay that forms the base of the chalk aquifer.

The morphostructural analysis using aerial photographs reveals two main lineaments. One of them, oriented NE-SW corresponds to a main fault (figure 2) well-known in this region. This fault has been active in the chalk, so that high values of hydraulic conductivity and porosity can be assumed along this more fractured axis. The second morphostructural lineament, oriented approximately N-S, corresponds to a 'dry valley', usually considered as preferential groundwater drainage axis and characterized by more altered and karstified chalks. In the modelling process, these important morphostructural informations will be taken into account, introducing local heterogeneities in the aquifer.

Piezometric measurements are available in the concerned aquifer since 1951 and many regional piezometric maps have been drawn. For the 1951-1994 period, the lowest and highest piezometric conditions have been measured respectively in 1951 and in 1966 (figure 2). The averaged gradient of the water table is about 1 %, directed northwards. A strong influence of the NE-SW fault is observed on the piezometric levels. Even if the general piezometric conditions of the aquifer are known, no data are available near the gallery so that the influence of the pumping in the collecting gallery is unknown.

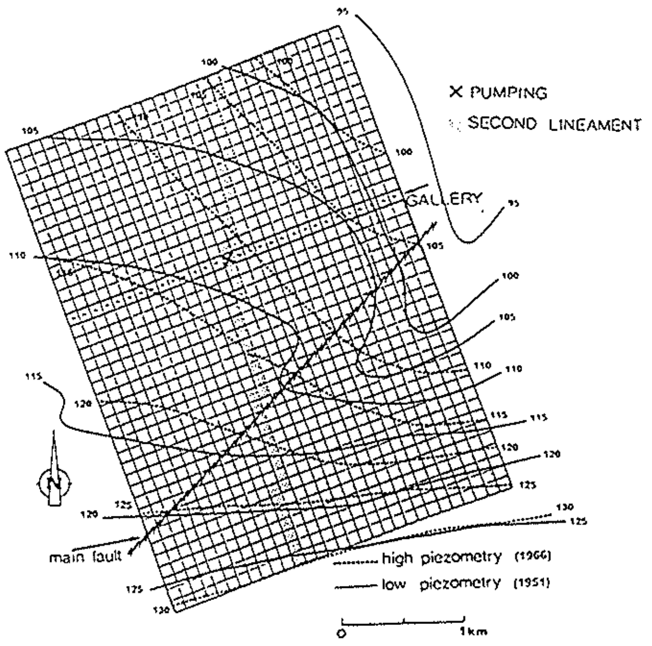


Figure 2 : Morphostructural and measured piezomeric maps, discretization of the finite difference model

3. Simulations

The numerical simulation described below is the first step in an iterative process [9] consisting of model simulations steps and site characterisation steps. At this stage, a very simple conceptual model is chosen and the results of the simulations will provide informations on its validity and on the necessary data to reduce the uncertainty of the results. For the modelling approach, all the coefficients or parameters are considered at a macroscopic scale with the Representative Elementary Volume (REV) theory, associated to the continuum approach and the porous medium concept.

The simulations are done using the ASM software developed by Kinzelbach and Rausch [10] for two-dimensional groundwater flow and transport. The classical flow equation is solved using a node-centred finite difference method and the solute transport is simulated by the random-walk method. Heterogeneities in the aquifer can be taken into account with respect to flow conditions (hydraulic conductivity and storage coefficient) but not for solute transport parameters (homogeneous values of dispersivities, effective porosity and effective diffusion coefficient). The program handles both steady-state and transient flow conditions. The equations system can be solved using either the IADI method or the conjugate-gradient method. For computation of pathlines and isochrones, two different schemes of velocity interpolation (schemes by Prickett and by Pollock) are available [10].

3.1 Discretization, boundary conditions and data of the simulations

The studied zone (3000 m x 4000 m), is discretized with 1200 finite difference (100 m x 100 m) cells (figure 2). Prescribed piezometric heads are introduced on the lateral boundaries. They are relative to the extreme conditions of 1951 and 1966 (introduced separately). The bottom levels of the aquifer are introduced with detail including the shift due to the NE-SW main fault.

The maximum total discharge of groundwater is 900 m^3/h. The gallery is conceptually represented by a line of cells where a high hydraulic conductivity is introduced: 0.1 m/s. To prescribe the total discharge, three cases are considered: (a) a uniform distribution along the total length of the gallery (no influence of the pumping point), (b) 50 % of pumping prescribed on two cells adjacent to the pumping point, the rest being uniformly distributed, (c) 50 % of pumping prescribed at the pumping point, the rest being uniformly distributed. The real pumping conditions occurring in this system, composed of a draining gallery and a pumping out of the gallery, are unknown (measured piezometric levels near and above this gallery would be very helpful for a better understanding of the real pumping conditions).

Values for the local parameters of the groundwater flow have been obtained from other studies realised in the area: hydraulic conductivity of the chalk ranges from 8.10^{-6} to 4.10^{-3} m/s and storage coefficient from 0.01 to 0.12, depending strongly on the fissuration degree [4,5]. Tracer tests have been completed in the same aquifer [6,7], providing local values of the main transport parameters. The parameters values which are used for the simulations are those inducing the fastest contaminant transport (table 1). The adsorption-desorption and immobile water effect [8] are neglected. The transport parameters are not changed from a simulation to another.

Simulations are completed considering the second lineament or not. If it is considered, a local hydraulic conductivity value of 1.10^{-3} m/s is chosen (as in the zone of the main NE-SW fault).

As the piezometric gradient is directed northwards, simulation of upstream and downstream pollutant injections have been completed.

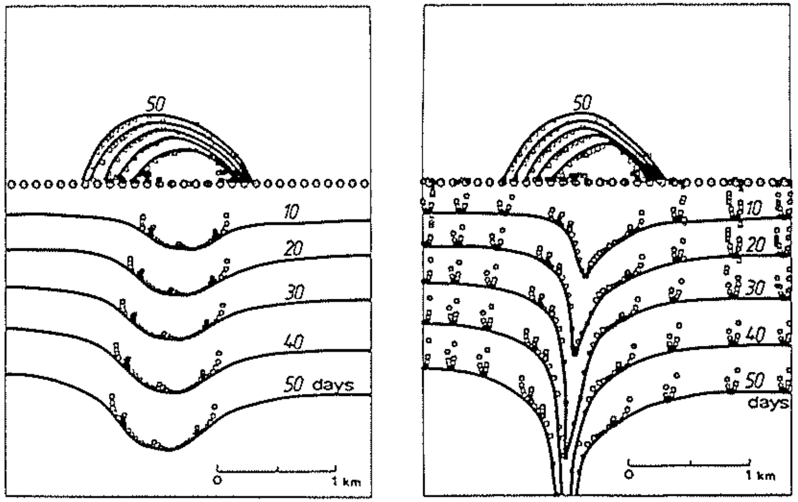
Table 1. Flow and transport parameters used for the simulations

Transport process	Coefficient	Values
Convection	K (m/s)	1.10^{-3} to 1.10^{-4}
	Effective porosity	0.01 to 0.08
Dispersion	aL (m)	9.5
	aT (m)	0.95
Adsorption-desorption	Retardation	1
Diffusion	D_m (m^2/s)	$9\ 10^{-9}$
Pollutant mass injected	(kg/d)	100

3.2 First estimations of protection zones

The computations of the 24 hour and 50 days isochrone lines corresponding respectively to the protection zones IIa and IIb have been completed for low and high piezometric conditions. All the simulations are achieved varying (1) the way of prescribing the discharge, (2) hydraulic conductivity values (from 1.10^{-4} to 5.10^{-4} m/s), (3) effective porosity values (from 0.01 to 0.08), and (4) with and without the second lineament (K= 1.10^{-3} m/s).

The table 2 provides a summary of the main results obtained. The results concerning the 50 days isochrone are shown in different conditions in figures 3 and 4, considering only the convective component of the transport.



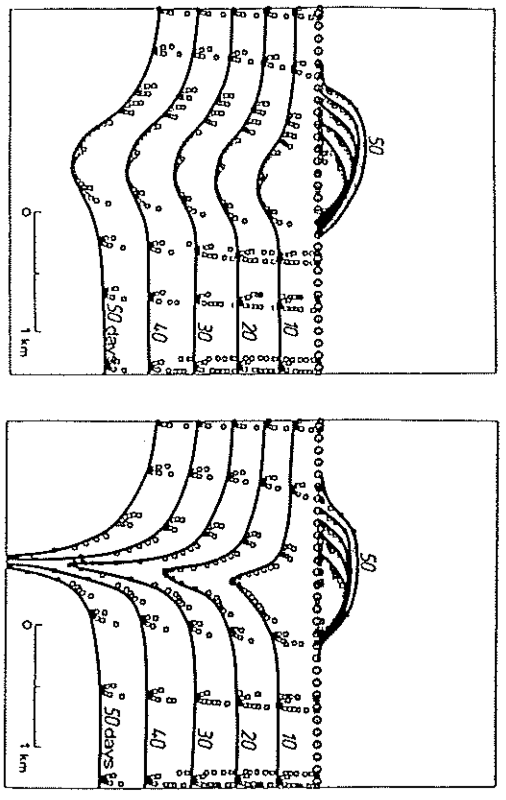
(a)

(b)

Figure 3 : Results of the simulations n°4 (a) and n°10 (b) where the second lineament is taken into account, in low piezometric conditions.

Table 2. Computed maximum distance from the gallery and pumping for zone IIa (24 hours) and zone IIb (50 days)
(the first arrival of contaminant is considered taking into account convection, dispersion and diffusion)

Simulation	Aquifer heterogeneity	Pumping	Permeability m/s	Effective porosity %	Zone IIa (max. distance) Downstream(m)	Zone IIa (max. distance) Upstream(m)	Zone IIb (max. distance) Downstream(m)	Zone IIb (max. distance) Upstream(m)
Low piezo conditions								
n°1	without 2nd lin.	uniform	5.10^{-4}	0.01	(<50)	180	90	2400
n°2	without 2nd lin.	uniform	1.10^{-4}	0.01	no convergence		no convergence	
n°3	without 2nd lin.	uniform	5.10^{-4}	0.08	(<50)	100	(<50)	400
n°4	without 2nd lin.	50 % in 2	5.10^{-4}	0.01	160	210	600	> 2500
n°5	without 2nd lin.	pts	1.10^{-4}	0.01	no convergence		no convergence	
n°6	without 2nd lin.	50 % in 2	5.10^{-4}	0.01	170	240	700	> 2500
n°7	without 2nd lin.	pts	5.10^{-4}	0.03	130	170	450	1100
n°8	without 2nd lin.	50 % in 1 pt	1.10^{-4}	0.01	no convergence		no convergence	
n°9	with 2nd lineament	50 % in 1 pt	5.10^{-4}	0.01	(<50)	220	60	> 2500
n°10	with 2nd lineament	50 % in 1 pt	5.10^{-4}	0.01	180	260	600	> 3500
n°11	with 2nd lineament	uniform	5.10^{-4}	0.01	180	300	650	> 3500
		50 % in 2						
High piezo		pts						
conditions		50 % in 1 pt						
n°12	without 2nd lin.		5.10^{-4}	0.01	150	210	500	> 2500
n°13	without 2nd lin.		5.10^{-4}	0.01	170	230	550	> 2500
n°14	with 2nd lineament		5.10^{-4}	0.01	160	250	450	> 3500
n°15	with 2nd lineament	50 % in 2 pts 50 % in 1 pt 50 % in 2 pts 50 % in 1 pt	5.10^{-4}	0.01	170	270	450	> 3500



(a) (b)

Figure 4 : Results of the simulations n°12 (a) and n°14 (b) where the second lineament is taken into account, in high piezometric conditions.

4. Interpretation of the results

In the worst conditions, the maximum distances for the boundary of zone IIa (24 hours) are 160-180 m downwards and 210-300 m upwards from the gallery. For the boundary of the zone IIb (50 days), the maximum distances are 450-700 m downwards and more than 2500 or even 3500 m upwards. These worst conditions correspond to the cases where: (1) a high value of hydraulic conductivity (5.10^{-4} m/s) is used with a low value of effective porosity (0.01), (2) the second lineament is taken into account with K = 1.10^{-3} m/s and n_e = 0.05, (3) the pumping conditions are conceptually represented by 50 % of a concentrated pumping in one point, the rest being distributed uniformly along the gallery. When the hydraulic conductivity is 1.10^{-4} m/s, no convergence is reached.

5. Necessary data and further investigations

The results shown in table 2 demonstrate that a large variation of the perimeter extent of protection zones is computed depending clearly of the chosen parameters. The main factors influencing results are: (1) the values of effective porosity (see simulations n°6 and n°7), (2) the way of representing the pumping, (3) the presence or not of a second zone affected by higher hydraulic conductivity (2nd lineament). Of course, all the other flow and transport parameters can also influence results.

In function of these observations, further investigations should include: (1) a shallow geophysical campaign including, for example, electrical sounding, electromagnetic profiling and refraction seismic, to localise fractured zones in the chalk, (2) drilling of piezometers, (3) a multi-tracer test with injection of tracers in piezometers (located at different distances from the gallery and the pumping point), with sampling in the gallery and at the pumping.

Using these new data, another step of the iterative process for studying the flow and transport conditions in that zone could start. A more complete model should be calibrated accurately on the measured breakthrough curves obtained from tracer test. That way, more reliable results should provide 24 hours and 50 days isochrone lines taking into account: (1) the flow and transport conditions in the saturated chalk, (2) the way of pumping, (3) the eventual heterogeneity of the aquifer.

6. Conclusions

As geological media are heterogeneous, due to various layering, faulting, and fracturing features, it is very difficult to get sufficient and reliable data to make possible the adequate representation of a particular geological domain in a numerical model. In front of this difficulty, and in order to decrease the uncertainty of the model results, one of the approach consists of adopting a kind of iterative process between site characterisation and conceptual model development [9]. This coupled approach involves site measurements, modelling studies, and revision of each of these operations during the iterative process.

For the case exposed here, a first data set is available from previous regional and local studies and the first step of numerical modelling is exposed. The results and their uncertainty show clearly the kind of data to acquire for the next step of the analysis. The integration of additional data in a new model corresponding to a more realistic conceptual approach will allow to decrease the uncertainty. The calculation of isochrone lines for solute contaminant transport to a gallery or to a pumping point, should be as accurate as possible, given the economical and societal consequences of erroneous delimitation of the protection zones.

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