Location of protection zones along production galleries: an example of methodology

V. HALLET, T. NZALI, C. RENTIER AND A. DASSARGUES

Laboratory of Engineering Geology, Geophysical prospecting and Hydrogeology
University of Liège, Building B19, 4000 Sart Tilman, Belgium

Abstract The Hesbaye aquifer, consisting of chalk formations, is located in the north-eastern part of Belgium. It provides about 60000 m^3 d^{-1} of potable groundwater for Liege and its suburbs. This aquifer is developed by gravity or pumping, from 45 km of galleries. Despite a protective cover of 5 to 20 meters of superficial loess deposits, groundwater quality is threatened by human activities consisting in intensive agriculture and, in the south-eastern part, industrial activities. In the Walloon Region of Belgium, protection zones around galleries or well fields are defined on the basis of pollutant transfer time in the saturated part of an aquifer. "Zone IIa" and "zone IIb" areas are respectively limited by isochrone lines corresponding to an advection-dispersion travel time of 24 hours and 50 days. To delineate the "zone IIa" along the Hesbaye galleries, five sites were selected. On each site, four to five new wells were drilled. Drilling sites were located according to geomorphologic studies and geophysical investigations. Pumping and tracing tests were performed and interpreted using deterministic flow and transport groundwater models. Then, geophysical data and geomorphologic observations were used to extrapolate results from these five sites to other areas. This has lead to "zone IIa " extensions varying from 1560 m to 30

m according to chalk weathering or fracturing, but also to the regional groundwater flow direction and gradient.

1. INTRODUCTION

In the Walloon Region of Belgium, regulations about protection and exploitation of groundwater resources define different protection zones inside of which some activities are regulated or prohibited. Delimitation of protection zones is mainly based on solute transfer time in the saturated part of an aquifer. Four kinds of zones are defined: (a) "Zone I" as an additional distance of 10 m in all directions from the water supply installations; (b) "Zone IIa" as the area located between Zone I and the distance in all directions corresponding to a pollutant transit time of 24 h in the saturated part of the aquifer; (c) "Zone IIb" as the distance in all directions corresponding to a pollutant transit time of 50 days; (d) "Zone III" as the whole alimentation basin.

In practice, the shape and extension of these protection zones are strongly dependent on the heterogeneity of the aquifer formation and the regional ground water flow gradient. In consequence, only spatially distributed models coupled with a very comprehensive data set are able to integrate the spatial variability of the hydrodynamic and hydrodispersive parameters. For the delineation of the protection zone extensions around a production spot (well, gallery or spring), the following steps of investigations were performed: (a) a complete regional hydrogeological study (involving geological, geomorphologic and piezometric surveys, hydrogeological data inventory, ...); (b) geophysical prospecting (among others electric soundings and profilings) in the aim of locating geological heterogeneities as lithological changes, fault axis, weathering zones, ...; (c) drilling of 4 to 5 observation wells to confirm the geology of the area and to draw piezometric maps; (d) pumping tests in each available well to estimate aquifer hydrodynamic parameters using the classical analytical equations; (e) multi-tracer tests performed between all observation wells and the production spot to have a comprehensive approach of the transport phenomena and, using analytical formula, a first estimation of hydrodispersive parameters; (f) modelling of the groundwater flow conditions with calibration on all the measured piezometric maps with and without pumping, (g) modelling the transport of a dissolved contaminant with calibration on all the measured breakthrough curves, (h) simulations of contaminant injections from different places, using the calibrated hydrodispersive parameters and the experimentally determined values of solicitations (pumping rates, aquifer recharge, ...) in order to compute the contaminant arrival time, (h) delineation of the protection zones on basis of the computed times in respect of the local regulations. This complete methodology is entirely applied in a deterministic framework (Dassargues *et al.,* 1996).

As not only advection is concerned but also dispersion, isochrone lines of the calculated transfer times must be simulated considering an injection mass of pollutant taken here conventionally equal to 5000 kg. The computed transfer time is considered for a detected concentration of 10 ppb at the production spot. In practice, for the 1 day protection zone, about 50 simulations are needed to get a sufficiently wide range of computed transfer times from various injection points, in order to be able to infer the isochrone lines.

Presently, the main water supply companies of Belgium are generally applying this methodology. If it can be easily applicable for production wells, springs or short collecting galleries, it must be adapted for protection zones that have to be delineated along few tens kilometres of collecting galleries.

2. HYDROGEOLOGICAL CONTEXT OF THE STUDIED AREA

The Hesbaye aquifer is located in the north-eastern part of Belgium. It consists of a wide plateau of 350 km² delimited by three rivers : the Meuse at the South and the East, the Geer at the North and the Mehaigne at the West (Fig. 1). The plateau altitude ranges from 206 m at the SW to 80 m at NE. The active river network is limited to two rivers: the Geer, ESE-WNW oriented, that is the outlet of the aquifer and the Yerne that has a N-S orientation. Moreover, lots of N-S oriented dry valleys, are observed all over the region. They are generally considered as located over fractured or weathered zones in the chalk aquifer characterised by high hydraulic conductivities, inducing abnormal drawdown of the piezometric surfaces. The geological sequence may be summarised as follow from top to bottom (Dassargues & Monjoie, 1993) (Fig. 2): (a) recent alluvial and colluvial deposits, up to 5 m thick; (b) Quaternary and Tertiary sands and loess: 2 to 20 m thick; (c) residual conglomerate, 2 to 9 m thick; (d) weathered and fractured Maastrichtian chalk, 10 to 15 m thick; (e) thin (about 1 m) hardened layer of Campanian chalk (hardground); (f) compact Campanian chalk locally fractured, 20 to 40 m thick; (g) Smectite de Herve which is a calcareous clay layer of 2 to 10 m thick; it is considered as the aquifer impermeable base of the chalk aquifer.

3. COLLECTING GALLERIES

The first galleries were dug in the early twentieth century by the CILE (Compagnie Intercommunale Liégeoise des Eaux). They consist of 45 km of collecting galleries and 11 km of connecting aqueducts. The galleries are driven in the lower chalk and are about 1.5 m wide and 2.0 m high. Aqueducts have the same dimension, but they are not designed for drainage of groundwater; moreover they are often located above the water table. The collecting galleries are subdivided into two networks : the southern network, located at a depth of 40 m, which feed by gravity, two big water tanks (Hollogne and Ans reservoirs) and the northern network, at a depth of 60 m, in which water could be pumped from three stations (Kemexhe, “Puits regulateur” and Juprelle) for supplying the southern network via three aqueducts. In addition, groundwater is locally pumped out of the galleries at Jeneffe, Waroux and Xendremael, to supply small local water tanks. Due to the wide extent of the galleries, the methodology as described here above was applied only in five selected spots where drilling, pumping, tracer tests and modelling were performed. Results are then be used for extension along the whole galleries network. The chosen spots are the pumping stations of Jeneffe and Waroux for the southern galleries and of Kemexhe, “Puits régulateur” and Juprelle for the northern galleries (Fig. 1).

4. TRACERS TEST RESULTS

At each pumping station, 5 piezometers were drilled to carry out pumping and tracer tests. Drilling locations were selected according to electrical sounding and profiling results. Piezometers were generally drilled where fault axes or weathered chalk zones were noticed. Using MODFLOW-MT3D (McDonald & Harbaugh, 1988, Zheng, 1990), five local groundwater models (one in each studied zone) taking all detected local heterogeneities into account were achieved. They allowed by calibration on the measured breakthrough curves of 19 tracer tests, to estimate the flow and transport parameter values for various type of chalk (Table 1).

Table 1 : Chalk flow and transport parameter values.

Site	Chalk characteristic	Hydraulic conductivity (10^{-4} m/s)	Effective porosity (%)	Longitudinal dispersivity (m)
Jeneffe	matrix fissured	0.1 to 0.3 3.0 to 4.0	0.3 to 0.6 2.4	8 to 60 7
Waroux	matrix	0.03 to 1.0	3.2	50

	weathered fissured	200 1 to 10	3.2 0.2 to 0.58	50 5 to 7
Kemexhe	matrix fissured	0.02 to 4.2 5 to 20	1 0.005 to 0.32	3.5 to 10 2.6 to 6.5
Puits régulateur	matrix fissured	0.02 to 1.0 1.0 to 75	1 0.15 to 3.0	10 1 to 6.5
Juprelle	matrix fissured	0.01 to 0.8 3 to 10	2 0.02 to 0.6	10 1 to 10

The results showed that the chalk is very heterogeneous with: (a) hydraulic conductivities ranging from 0.01 10^{-4} m/s in the matrix to 200 10^{-4} m/s in the fractured zones; (b) effective porosity values from 0.3 to 3.2 % in the matrix and some very low values (as low as 0.005 %) had to be introduced in the models in fractured zones. This value is not consistent anymore with the physical definition of an effective porosity. They were often numerically needed to calibrate on the breakthrough curves; indicating that even with very small cells, the “Representative Elementary Volume” concept do not allow to represent with a full physical consistency the reality of a very rapid groundwater flow in the fractures (Hallet & Dassargues, 1998); (c) longitudinal dispersivities (in the chalk matrix) increasing with the tracer test distance *d* (Hallet, 1998) according to the following adjusted law $0.002 + 0.14*d$; (d) in the fractures, low longitudinal dispersivities ranging from 2 to 10 m, independently of the tracer test distances.

5. DELINEATION OF THE 24 H PROTECTION ZONE

After calibration, models were used to simulate multiple injections of 5000 kg of solute contaminant. The transit time is considered as the time for the pollutant to reach the gallery at a 10 ppb concentration. Results, for the protection “zone IIa”, are shown in Table 2.

Table 2 : Computed “zone IIa” extension in fractured and matrix chalk.

Site	Pumping rate (m^3/h)	Fissured chalk	Chalk matrix

		Upstream distances		Downstream distances		Upstream distances		Downstream distances	
		Max (m)	Min (m)	Max (m)	Min (m)	Max (m)	Min (m)	Max (m)	Min (m)
Southern gallery									
Jeneffe	Gravity	305	215	80	60	305	185	100	60
Waroux	Gravity	415	320	70	55	80	45	40	**30**
Northern gallery									
Kemexhe	320	**1560**	650	310	260	**315**	250	170	110
Puits régulateur	580	350	350	100	50	125	40	70	40
Juprelle	200	816	557	**796**	368	110	60	110	20
Mean		**690**	**420**	**270**	**160**	187	116	98	52

Table 2 show that the regional hydraulic gradient highly influences the “zone IIa” extension which can reach, in fractured or weathered zones, a maximum distance of 1560 m upstream the gallery and 796 m downstream (for 315 m upstream in the chalk matrix and 30 m downstream).

After interpretation of the tracer tests using those 5 groundwater models, the results were applied (extrapolated) to the whole gallery network according to geomorphologic and geophysical criteria. As the upper part of the aquifer, consisting of Maastrichtian chalk, is intensively weathered, the extension of the “zone IIa” is taken (outside zone of detected lineaments) to be the minimum distance measured in fissured zones. According to this choice, the following extensions were taken for “zone IIa” (Fig. 3):

(a) upstream the galleries :

- 1560 m front of the major lineaments that have a NS orientation and a regional extension (few kilometres length) indicating a high probability of major fissured or fractured zones;
- 690 m front of the minor lineament (less than 1 km length) indicating fractured or weathered chalk;
- 420 m outside lineaments (chalk matrix);

(b) downstream the galleries:

- 315 m front of the major lineaments;
- 270 m front of the minor lineament;
- 160 m outside lineaments.

Laterally, along the lineaments, the “zone IIa” extension was fixed to 200 m and 100 m for, respectively, the major and the minor lineaments.

6. CONCLUSION

Determination of protection zones along collecting galleries in a heterogeneous media as the chalk formations needs in situ experimentation. Tracer tests between piezometers and galleries were performed at few selected sites and interpreted using groundwater models. Results have shown that the “zone IIa” extension (24 h) can vary between few tens of meters to more than 1500 m according to the regional gradient and the presence or not of fissured/weathered zones. Taking geomorphology and geophysical results into account, the locally computed results were extended along the whole gallery network. This provides a very irregular perimeter of the “zone IIa” with extensions that could be quite different than those obtained from fixed distance protection zones.

REFERENCES

Dassargues A., Brouyère S. and Derouane J. (1996) From calibration on tracer test data to computation of protection zones: upscaling difficulties in a deterministic modelling framework, in Calibration and Reliability in Groundwater Modelling.

In: *ModelCare'96*, (eds. K. Kovar & P. Van Der Heijde), IAHS Publ. n°237, 253-264.

Dassargues A. & Monjoie A. (1993) Chalk as an aquifer in Belgium. In*:* *Hydrogeology of the Chalk of North-west Europe*, ch. 8, 153-169, Oxford University Press.

Hallet, V. (1998) Etude de la contamination de la nappe aquifère de Hesbaye par les nitrates. PhD thesis. University of Liège.

Hallet V. & Dassargues A. (1998) Effective porosity values used in calibrated transport simulations in a fissured and slightly karstified chalk aquifer. In: *Groundwater Quality 1998* (Eds. M. Herbert & K. Kovar), Tübinger Geowissenschaftliche Arbeiten (TGA), C36, 124-126.

McDonald, J. & Harbaugh, A. (1988) MODFLOW A modular three-dimensional finite-difference groundwater flow model. Techniques of Water Resources Investigations of the U.S. Geological Survey. Book 6, 586 p.

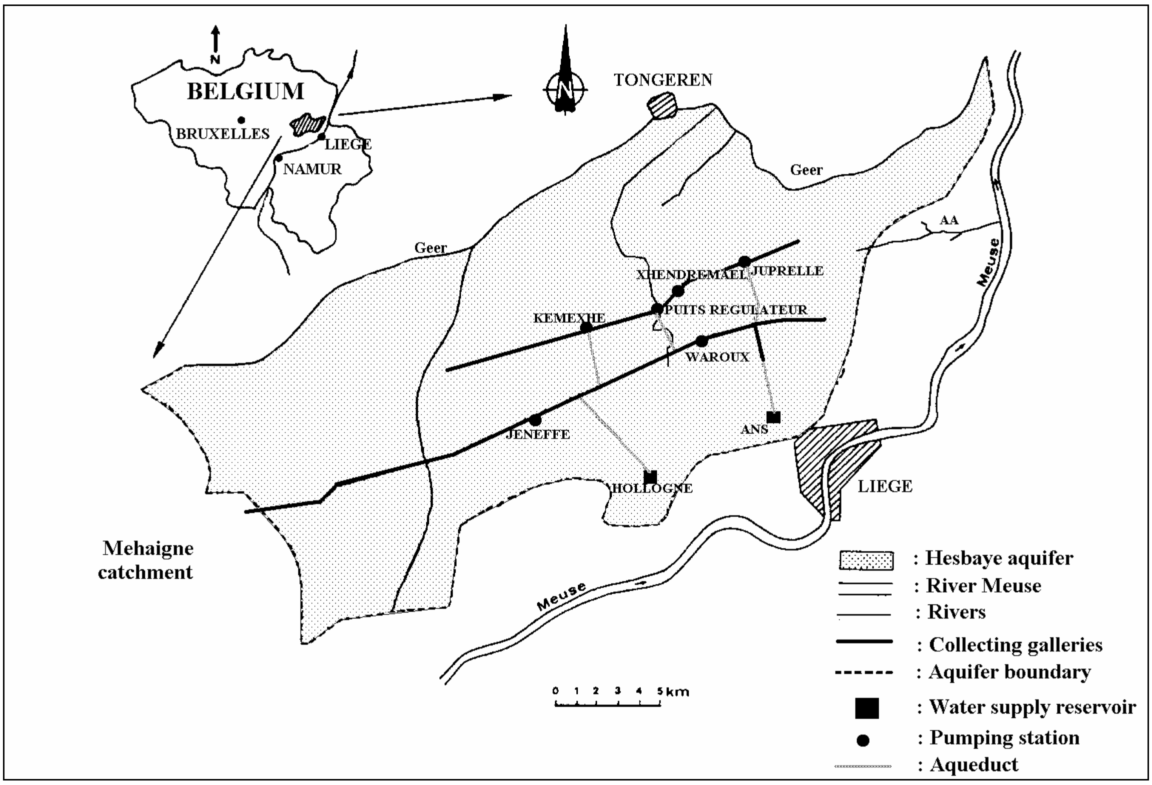
Zheng C. (1990) MT3D A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. Prepared for the U.S. Environmental Protection Agency. S.S. Papadopulos & associates, Inc.

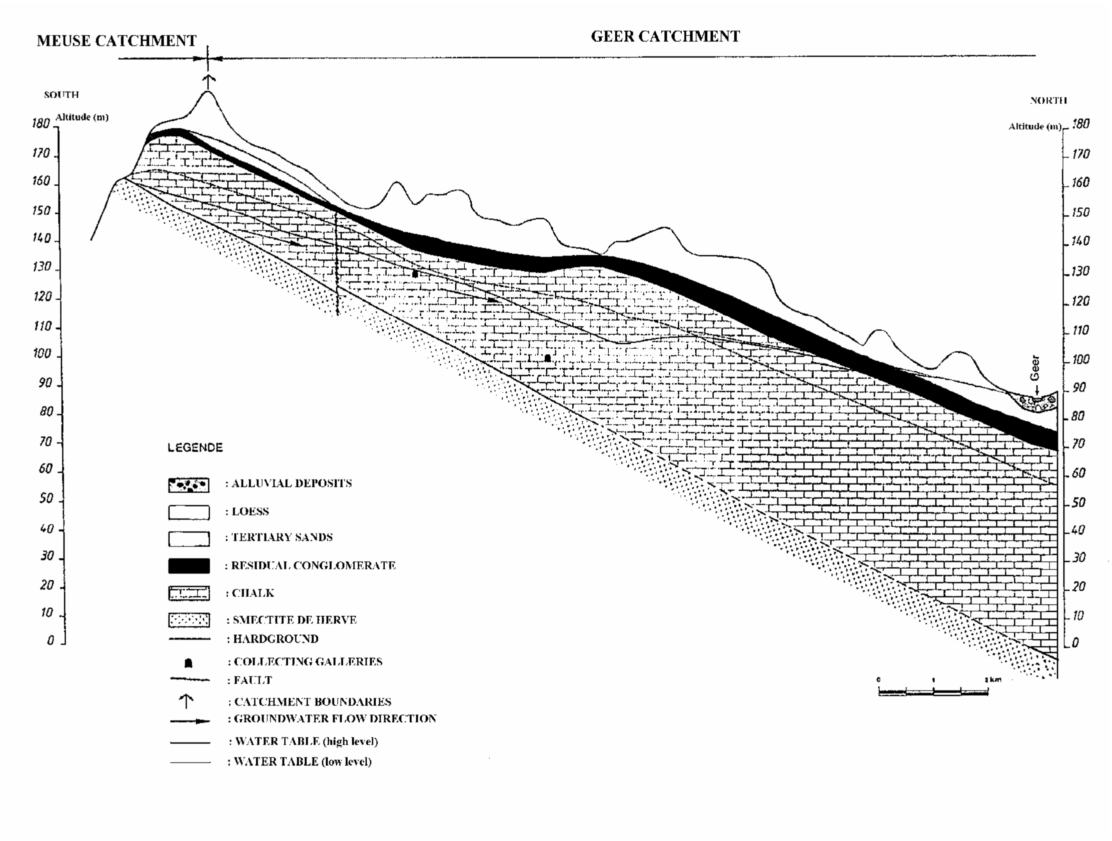
FIGURE CAPTIONS

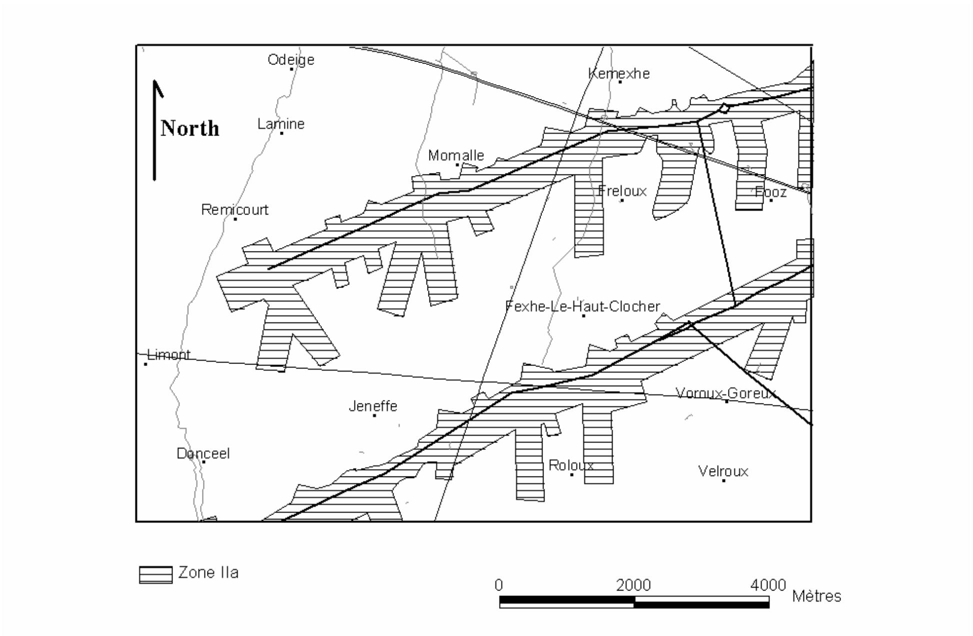
Fig. 1 Location map.

Fig. 2 Vertical cross-section through the Hesbaye aquifer

Fig. 3 Example of “Zone IIa” along the collecting galleries


N
BELGIUM
BRUXELLES
LIEGE
NAMUR
N
TONGEREN
Geer
Geer
AA
Meuse
XHENDREMAEL
JUPRELLE
PUITS REGULATEUR
KEMEXHE
WAROUX
ANS
JENEFFE
HOLLOGNE
LIEGE
Mehaigne catchment
Meuse
0 1 2 3 4 5km
: Hesbaye aquifer
: River Meuse
: Rivers
: Collecting galleries
: Aquifer boundary
: Water supply reservoir
: Pumping station
: Aqueduct


MEUSE CATCHMENT
GEER CATCHMENT
SOUTH
NORTH
Altitude (m)
Altitude (m)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Geer
LEGENDE
: ALLUVIAL DEPOSITS
: LOESS
: TERTIARY SANDS
: RESIDUAL CONGLOMERATE
: CHALK
: SMECTITE DE HERVE
: HARDGROUND
: COLLECTING GALLERIES
: FAULT
: CATCHMENT BOUNDARIES
: GROUNDWATER FLOW DIRECTION
: WATER TABLE (high level)
: WATER TABLE (low level)
0
1
2 km


North
Odeige
Lamine
Remicourt
Momalle
Kemexhe
Freloux
Fooz
Fexhe-Le-Haut-Clocher
Limont
Jeneffe
Donceel
Roloux
Voroux-Goreux
Velroux
Zone IIa
0
2000
4000
Mètres