Karst Hydrology (Proceedings of Workshop W2 held at Rabat, Morocco, April-May 1997).
IAHS Publ. no. 247, 1997.

A modelling approach as an intermediate step for the study of protection zones in karstified limestones

ALAIN DASSARGUES & JOHAN DEROUANE

Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting, University of Liège, Bâtiment B19, B-4000 Liège, Belgium

Abstract Regulations about protection and prevention zones are based on travel time of contaminants in the saturated part of aquifers. However, in practice it is difficult to determine on a rigorous and scientific basis the effective zones which are to be delineated. It is particularly difficult to take into consideration all the data about the actual groundwater flow conditions, aquifer heterogeneities and the complex processes of contaminant transport in a fractured and karstified medium. This difficulty is illustrated by a case study of a calcareous aquifer in Belgium where collecting galleries drain the natural springs. The study included the collection of all available data dealing with local geology, morphostructural analysis, geophysical prospecting, piezometric measurements, balance studies, pumping tests and tracer tests. On basis of all these data, a highly heterogeneous deterministic model has been built to simulate, at the regional scale, the general flow and transport behaviour of the aquifer. In view of the main restrictive assumptions taken implicitly when using this kind of modelling approach based on the REV concept, great care and awareness must be observed when interpreting the results in terms of travel times. However, this model has proved to be very useful as an intermediate step for determining the next steps of the study such as additional data to be measured and tracer tests to be performed in order to reduce the uncertainty in the delineation of the protection zones.

Modélisation d'un aquifère calcaire karstifié: étape intermédiaire dans l'étude des zones de protection

Résumé Les lois concernant la protection et la prévention des eaux souterraines sont basées sur les temps de transfert des contaminants dans la zone saturée du milieu souterrain. Cependant, en pratique, il est difficile de déterminer d'une manière rigoureuse et sur base scientifique les zones effectives qui doivent être prises en considération. Il est particulièrement difficile de prendre en compte toutes les données concernant les conditions réelles d'écoulement, les hétérogénéités de l'aquifère et les processus complexes de transport de contaminant dans un milieu fracturé et karstifié. Cette difficulté est illustrée par un cas d'étude sur un aquifère calcaire en Belgique où des galeries captantes drainent les résurgences naturelles. L'étude a inclus la collecte de toutes les données disponibles traitant de la géologie locale, l'analyse morphostructurale, les prospections géophysiques, les mesures piézométriques, les études de bilan, les pompages d'essai et les essais de traçage. Sur base de toutes ces données, un modèle déterministe très hétérogène a été construit pour simuler, à l'échelle régionale, le comportement de l'aquifère du point de vue des écoulements et du transport. Au vu des hypothèses très restrictives, prises implicitement en acceptant le concept d'Elément de Volume Représentatif EVR, une grande prudence doit être observée dans l'interprétation des résultats en terme de temps de temps de transfert. Cependant, ce modèle s'est avéré très utile comme étape intermédiaire pour déterminer les prochaines recherches à réaliser concernant les données additionnelles à mesurer et les essais de traçage à réaliser pour réduire l'incertitude dans la détermination de ces zones de protection.

INTRODUCTION

Regulations about protection and prevention zones concerning exploited groundwater resources are mainly based on the transfer time of contaminants in the saturated part of the aquifer. An extensive list of allowed and prohibited activities exists for each of these protection zones. In the Walloon region of Belgium, three kinds of protection zones are defined:

(a) The *Water Supply Zone* (zone I) is defined as the zone where the effective water supply installations are located. At the circumference of these, a 10 m radius is added in all directions. This zone has to be owned by the water company exploiting the well or the spring.
(b) The *Prevention Zone* (zone II) is divided into two successive zones: zone IIa is defined as the distance in each direction corresponding to a time of pollutant transit of 24 h in the saturated zone, while zone IIb is defined similarly with a time of pollutant transit of 50 days.
(c) The *Observation Zone* (zone III) is defined as the whole alimentation basin of the catchment area.

In practice, the shape and extension of the protection zones are strongly dependent on the heterogeneity of the geological strata. These heterogeneous conditions affect the groundwater flow properties as well as the pollutant transport characteristics in the saturated part of the aquifer. For that reason, it is not easy to determine in a rigorous and scientific manner the effective zones which are to be delineated. Indeed, this difficulty is increased when considering a highly heterogeneous fractured and karstified medium (Dassargues & Brouyère, 1997). An illustration of such a case study is given below, where three collecting galleries drain the natural springs of a calcareous aquifer in the Neblon basin (Belgium).

GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT OF THE KARSTIFIED NEBLON BASIN

The study area, located in the Condroz region (south of Liège) in the eastern part of the synclinorium of Dinant, is characterized by a typical alternation of shales and sandstone anticline crest (upper Devonian or Famenian) and calcareous syncline depressions (lower Carboniferous or Dinantian). The relief is dissected by the river network flowing transversely to the general east-west geological structure (Fig. 1). The studied karstified aquifer is drained by the Neblon River, whose surface basin covers *c.* 66 km^2 (Meus, 1995). The natural outflows from the aquifer are diffuse discharges along the Neblon River, and the springs of Neblon-le-Moulin which are exploited via three collecting galleries by the local Water Company CILE.

The geological structure of the region is characterized by a succession of anticline and syncline folds whose axes are oriented approximately northeast–

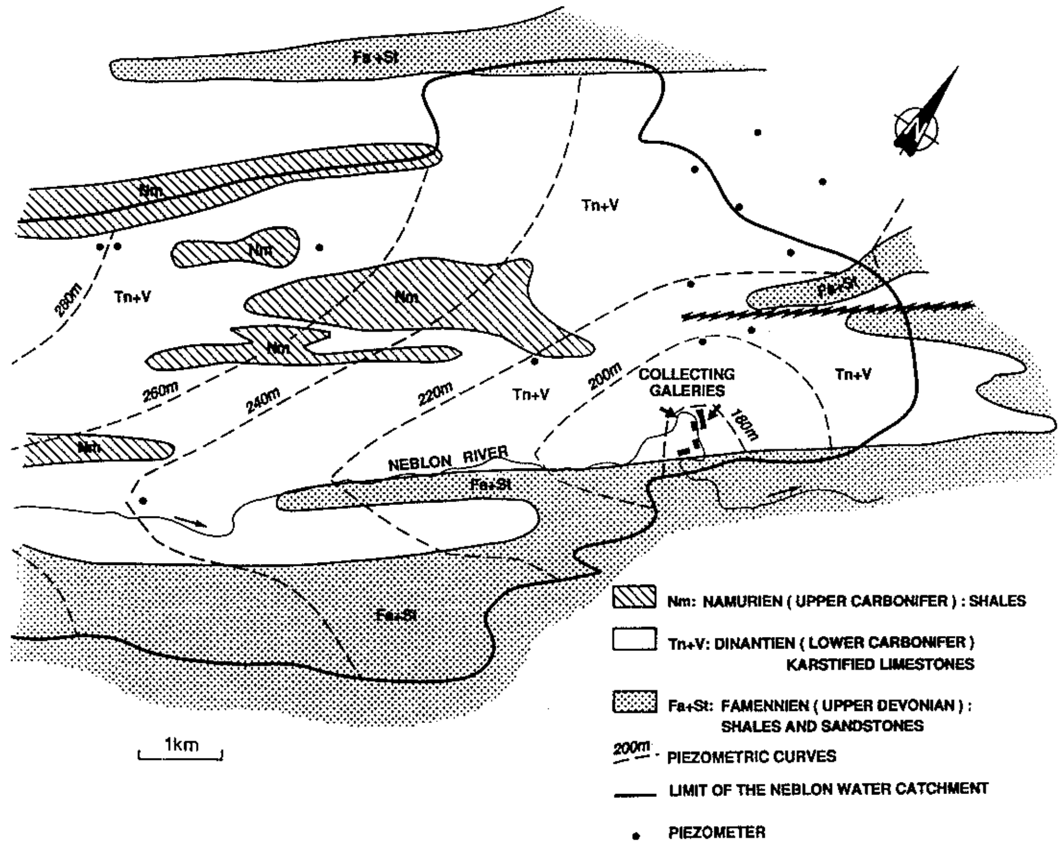

Fig. 1 Geological and piezometric map of the Neblon basin.

southwest (Fig. 2). The region is intensely fractured and the main structural features can be divided in three major groups:

- longitudinal thrust faults, east–west oriented (parallel to stratification), with great extension;
- transverse faults, NNW–SSE to north–south oriented, mainly perpendicular to fold axis—these faults and fractures, generating an anisotropy for the hydraulic conductivity, can drain the groundwater fluxes towards the collecting galleries;
- oblique faults or fractures, generally northeast–southwest oriented, having minor influences on groundwater flow.

Two different major aquifers can be identified in the basin: one in the Dinantian (Tournaisian and Visean) limestones, and the other in the fractured Famenian sandstones. The Dinantian, which constitutes the main karstified aquifer of the Neblon basin, has a high fissure permeability coefficient. The two major aquifers are separated by a low permeability layer composed of Strunian shales.

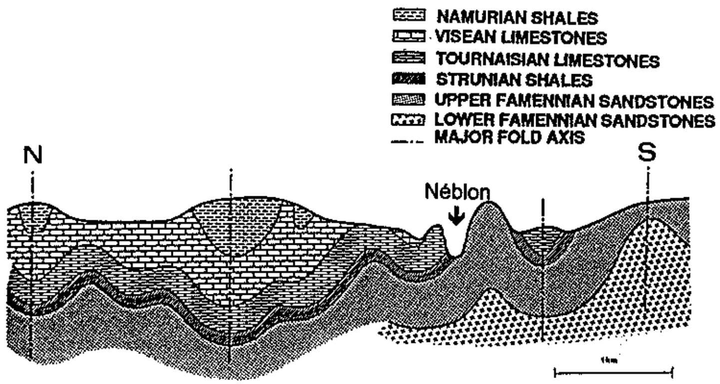

Fig. 2 North–south geological cross-section.

Karstic features

Several karstic features can be identified in the Neblon basin, the most significant being stream-sinks, resurgences, springs and dolines. Three major stream-sinks have been identified in the basin and tracers injected in one of them (the Marsee sink) have been recovered in the collecting galleries, indicating a direct karstic connection (Meus, 1993). The flow-through times of the tracers were lower than 50 h, corresponding to a maximal velocity of 73 m h^{-1}. Such velocities confirm that for some particular zones affected by a high degree of karstification, the groundwater flows overstep the limits of the Darcy's law validity domain, and probably correspond to karstic conduit flow.

Hydrogeological parameters

Average transmissivity values calculated by pumping tests performed in the calcareous aquifer range between 10^{-3} and 10^{-5} $m^2 s^{-1}$ although the transmissivity values corresponding to major fractures reach at least 10^{-2} $m^2 s^{-1}$, and are probably even higher in karstic conduits where the groundwater flow and contaminant transport laws of saturated porous medium do not apply. However, unfractured calcareous zones are characterized by lower transmissivity values.

An average effective porosity value has been estimated at 1.5–2% for the entire catchment area, based on the interpretation of the variation in annual groundwater storage. At a lower scale, only tracing tests performed locally in many different geological contexts such as weak fractured areas, major fractured axis and karstic conduits could provide more representative estimates of the effective porosity for each particular case. Tracing tests performed from piezometers in the Neblon basin gave no significant results. Only tracing tests realized in karstic conduits (from stream-sink towards the collecting galleries) were conclusive (Meus, 1993), but interpretation of the breakthrough curves, leading to estimation of the hydrodispersive parameters, has been limited to the use of a 1D (unique drain) numerical model, to the exclusion of the surrounding medium. This model was only suitable for calculation of the longitudinal dispersivity coefficient, estimated at 15 m; no effective porosity value could be determined using such a 1D interpretation.

Table 1 Values for the hydrodynamic and hydrodispersive parameters.

Karstified limestones (Tournaisian and Visean)		
Transmissivity ($m^2 s^{-1}$)	equivalent medium:	10^{-3} to 10^{-4}
	fractures:	10^{-2}
	karstic conduits:	> > > (Darcy's law not valid)
	matrix:	$<10^{-5}$
Effective porosity	equivalent medium:	1% to 2%
Longitudinal dispersivity	equivalent medium:	max. 30 m
	karstic conduits:	max. 100 m (overestimated, or not physically consistent as Darcy's law is not valid)
Transverse dispersivity	equivalent medium:	1 to 5 m
Molecular diffusivity	equivalent medium:	10^{-9} $m^2 s^{-1}$
Famenian sandstones		
Transmissivity ($m^2 s^{-1}$)	equivalent medium:	10^{-4} to 10^{-5}
Effective porosity	equivalent medium:	10%
Longitudinal dispersivity	equivalent medium:	10 m
Transverse dispersivity	equivalent medium:	1 m
Molecular diffusivity	equivalent medium:	10^{-9} $m^2 s^{-1}$

In general, dispersivity values increase with fissure porosity. Nevertheless, it should be mentioned that the calculated parameters can be affected in some places by inaccuracies due to the non validation of basic assumptions used in the models. High dispersivity values, sometimes reaching up to 100 m in large karstic conduits, may appear to be overestimated due to associated great velocity values lying out of Darcy's law validity domain. Table 1 provides the parameters values which were available at this stage of the study.

Piezometric surface of the karstified aquifer

Seasonal variations of the water level in the karstic aquifer, observed weekly in 14 piezometers in the basin over several years, show a maximal annual variation of around 30 m between higher and lower measurements in a single piezometer. Different behaviours have been observed from one piezometer to another, and this can be attributed to the high heterogeneity degree of the aquifer (Fig. 3).

Interpretation of piezometric maps leads to the direct deduction, based on Darcy's law, of local characteristics concerning the distribution of groundwater fluxes in the aquifer. Of course, these interpretations are based on the hypothesis of continuity which can be questionable in such an aquifer and without additional data (Pulido-Bosch & Padilla, 1988).

MODELLING APPROACH

The modelling stage is often considered as the final tool to be used for the calculation

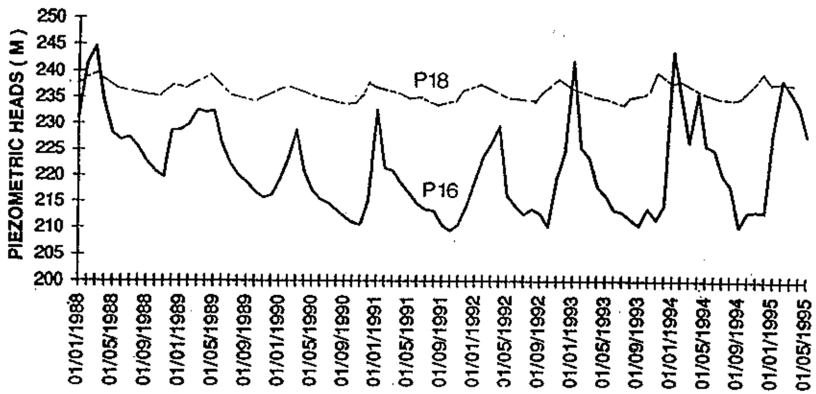

Fig. 3 Water level variations observed in two piezometers.

of protection zones, in order to best integrate a complete set of collected data. Another approach is the use of numerical simulations as an intermediate tool providing information on the necessary data to be collected and further investigations to be made, in order to achieve a better accuracy with regard to the processes occurring in the aquifer. This methodology, applied here in the Neblon basin, provides a first assessment of the protection zones and underlines the most important parameters to which the calculated transfer times are the most sensitive.

The procedure which has been followed within the framework of this preliminary study consists of the collection, synthesis and integration of existing and available in the model. These data concern essentially the nature and geometry of the geological layers; definition of the limits of the surface water catchment and hydrogeological basin; morphostructural analysis based on photo-interpretation and applied geophysics; the regional and local piezometric levels; the hydrologic budget of the basin, and finally the set of physical properties of the medium (permeability or transmissivity, storage coefficient, effective porosity, dispersivity, molecular diffusion, ...).

A first numerical model has been realized at the scale of the whole basin, in order to simulate the groundwater flow and the pollutant transport for the whole catchment area supplying the collecting galleries and the River Neblon. This global 2D model has been discretized using 3615 triangular finite elements, whose side lengths range from 250 m (regular primitive mesh) to a few metres (Fig. 4). The size of the elements and the shape of the mesh are suited to the geometry of the geological limits, faults and fractures, collecting galleries and piezometers in order to depict them explicitly in the model. The global model, calibrated on measured water levels and water balance, has been used to provide a first estimate of the isochrone corresponding to a 50 days transfer time for a contaminant to reach the collecting galleries as well as the whole course of the River Neblon in the studied basin. In such a karstified limestone aquifer, it can indeed be considered that any pollution affecting the River Neblon could nearly instantaneously contaminate the collecting galleries downstream.

Afterwards, two other models have been realized at more local scales, in order to estimate the isochrone (of transfer time for dissolved contaminant) lines corresponding to protection zones IIa (24 h) and IIb (50 days) considering pollutant transits only towards the collecting galleries themselves and a limited portion of the River Neblon close to the galleries. These two models (containing respectively 2041 and 1048 elements) can be considered as isolated parts of the global model, inside which the mesh has been refined in order to obtain a sufficient level of precision in the description of the heterogeneities.

The groundwater flow models are fitted in steady-state conditions, on the basis of a piezometric map corresponding to a high-water situation (Fig. 1). Calibration of the models has included the fitting of groundwater fluxes balance. The cumulative flow rate of the three collecting galleries is around 26 000 m^3 day^{-1}, while the "baseflow" corresponding to the contribution of groundwater fluxes in the River Neblon is estimated at 12 000 m^3 day^{-1}. A general anisotropy factor for transmissivity values $Ty = 1.5\ Tx$ has been introduced, corresponding to the main direction of transverse faults and fractures and globally orthogonal to fold axis and stratification.
It should be kept in mind that the parameter values introduced in both flow and transport models refer to a Representative Elementary Volume (REV) (Dassargues & Brouyère, 1997). Therefore, the calculated fluxes may be widely underestimated compared with the real groundwater flow observed in highly fractured zones and even more in karstic conduits. Contrasts in specific fluxes are strongly smoothed by the choice of equivalent values of permeability in each element. Dealing with contaminant advective velocities, there is an additional strong smoothing procedure induced by the choice of an equivalent value of the effective porosity in each finite element of the model (Dassargues *et al.*, 1996).

First estimation of the protection zones IIa and IIb

Despite all these important remarks, a first estimation of the 24-h and 50-days isochrone lines determined with equivalent parameters can be useful to direct the

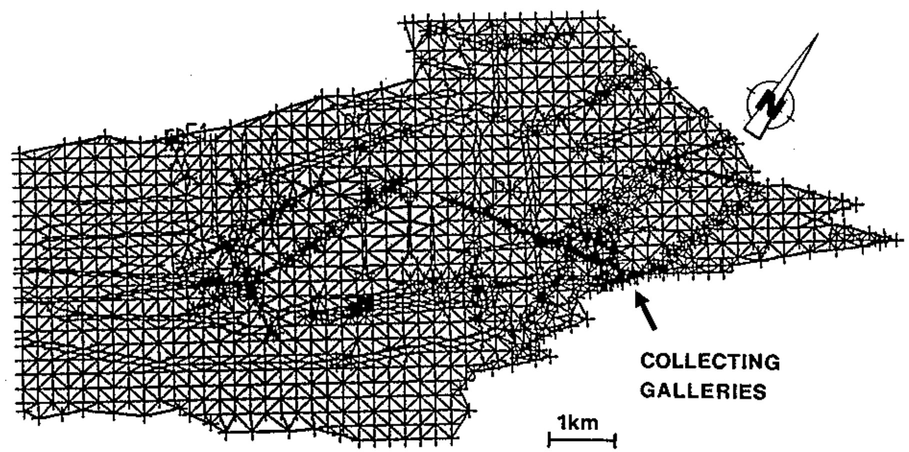

Fig. 4 Discretization of the global 2D model.

further investigations. Simulations of pollutant injections, from many points (more than 250) distributed in the aquifer, have been performed using each of the three developed transport models in order to compute the transfer time of contaminant to the galleries. As seen above, two options are possible, corresponding respectively to (a) isochrones of the transfer time to the collecting galleries as well as to the whole upstream course of the river in the basin (option 1), and (b) isochrones of the transfer time to the collecting galleries and only to a part of the river describing a meander in the area close to the galleries (option 2). The calculations have been performed taking the longitudinal and transverse dispersivities into account. It has been conventionally chosen that calculated isochrones correspond to the first arrivals of pollutant, defined at 10 ppb for an injected mass of 5 kg at the defined observation points.

The results of the simulations suggest an estimated distance upstream from the galleries or the river which can reach up to 3500 m for the 50-days isochrone (Fig. 5), and more than 350 m for the 24-h isochrone. It appears logical that the fractured axis explicitly represented in the model generates locally larger extension

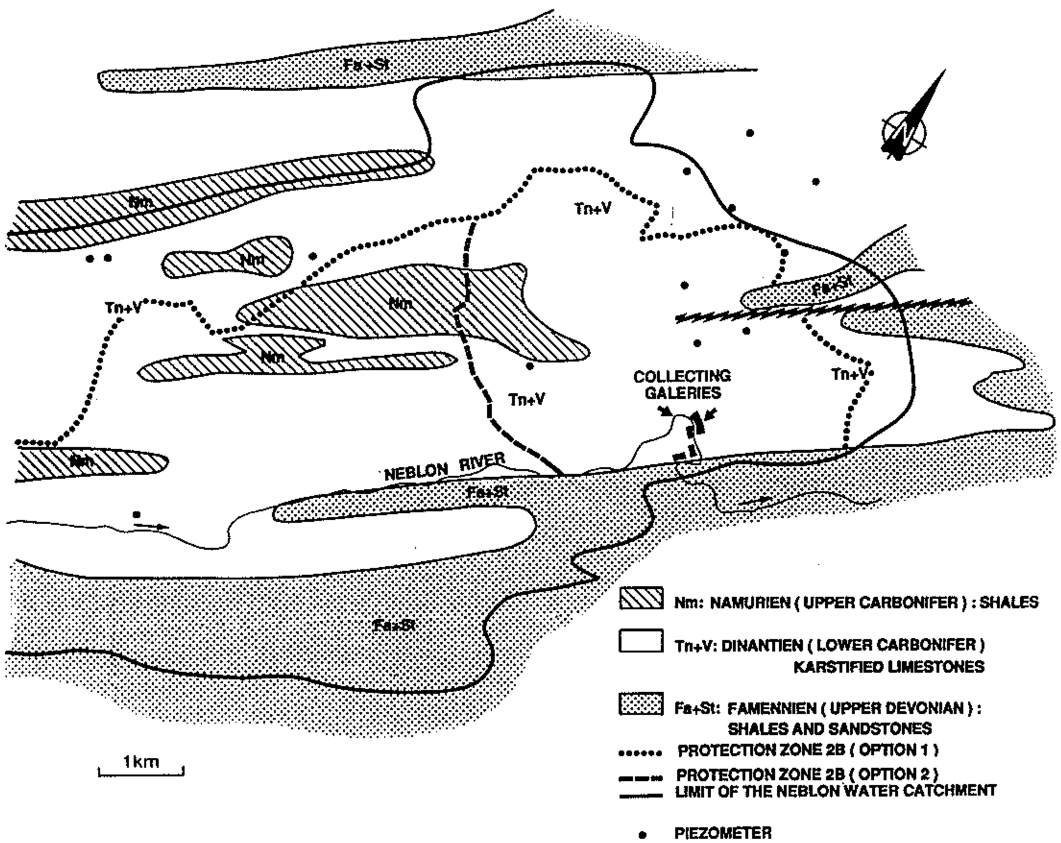

Fig. 5 Delineation of the 50-day isochrones (two options).

of the zones, since the transfer velocities are greater. The transfer velocities observed in the field by tracing tests in a major karstic conduit between a stream-sink and the galleries (Meus, 1993) are much greater than those calculated by the model. The calculated isochrones are certainly underestimated, due to the averaging of the physical properties introduced in the model at the scale of the considered Representative Elementary Volume (REV). This generates a smoothing of the contrasts between fractured axis and the matrix, compared to what can be observed in reality. For that reason, it has been recommended to include all the observed stream-sink areas in protection zone IIa.

CONCLUSIONS

At the conclusion of this preliminary study, it appears that a more systematic methodology should be performed next, using all the parameters affecting the intrinsic vulnerability of the aquifer (Doerflinger & Zwahlen, 1995). On the basis of the exhaustive collection of the necessary information, the realization of complementary tracing tests should lead to a better knowledge of the karstic system. It is only through the analysis of these essential but still insufficient data that we can expect a more adequate delineation of the protection zones around the collecting galleries of the Neblon basin.

REFERENCES

Dassargues, A. & Brouyère, S. (1997) Are deterministic models helpful to delineate groundwater protection zones in karstic aquifers? In: *Karst Waters and Environmental Impacts*, 109–116. Balkema, Rotterdam.

Dassargues, A., Brouyère, S. & 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* (ed. by K. Kovar & P. van der Heijde) (Proc. ModelCare'96 Conf., Golden, Colorado, September 1996), 253–264. IAHS Publ. no. 237.

Doerflinger, N. & Zwahlen, F. (1995) EPIK, a new method for the delineation of protection areas in karstic environment. In: *Karst Waters and Environmental Impacts* (ed. by G. Günay & A. I. Johnson), 117–123. Balkema, Rotterdam.

Meus, P. (1993) Hydrogéologie d'un aquifère karstique dans les calcaires carbonifères (Neblon-Anthisnes, Belgique). Apport des traçages à la connaissance des milieux fissurés et karstiques. PhD Thesis, Sciences Faculty of the University of Liège, Belgium.

Meus, P. (1995) Distribution and main characteristics of the Palaeozoic limestones in Belgium. In: National Report of Belgium, COST65: *Hydrogeological Aspects of Groundwater Protection in Karstic Areas*. European Commission, Report EUR 16547 EN, 37–63.

Pulido-Bosch, A. & Padilla, A. (1988) Some considerations about the simulation of karstic aquifers. In: *Karst Hydrogeology and Karst Environment Protection* (Proc. the IAH XXI Congress, Guilin, October 1998), vol. 2, 583–588. IAHS Publ. no. 176.