GQ07: Securing Groundwater Quality in Urban and Industrial Environments (Proc. 6th International Groundwater Quality Conference held in Fremantle, Western Australia, 2–7 December 2007).

Assessing groundwater-surface water interaction and groundwater discharge in a contaminated site in an industrial, sub-urbanized area

J. BATLLE-AGUILAR[1] **& S. BROUYÈRE**[1,2]

1 *Hydrogeology Unit, Department ArGEnCo, University of Liège, Building B52/3, 4000, Sart Tilman, Belgium*
jbatlle@ulg.ac.be

2 *Also at Aquapôle ULg, Building B53, 4000, Sart Tilman, Belgium*

Abstract A contaminated site related to a former coke factory, located in the alluvial plain of the Meuse River near Liège was investigated to characterize the nature and extend of underground contamination. The major objective of the investigation was to evaluate whether an interaction exists, at the level of this particular site, between groundwater and surface water, despite the existence of river embankment, to assess the dynamics of such interactions and finally to quantify groundwater fluxes as the main potential vector of mobility of contaminants offsite. Field investigations consisted in (1) a very detailed monitoring of the dynamics of water levels in the Meuse River and in various piezometers located in the site; (2) the application of single well tracer tests using the Finite Volume Point Dilution Method (FVPDM) in different piezometers in order to obtain point estimates of Darcy fluxes. Using cross-correlation analysis, the strong relation between variations in the Meuse water levels and groundwater levels was clearly established. The FVPDM allowed obtaining point estimates of Darcy fluxes at various points along the Meuse-aquifer interface. Using an analytical solution for groundwater flow interaction with adjacent river allowed modelling accurately the dynamics of groundwater levels in function of the dynamics of the river water levels. All these results are presented, analyzed and integrated in order to quantify the groundwater discharge in the Meuse River.

Key words groundwater pollution; urbanized-industrial area; groundwater-surface water interaction; groundwater discharge; Darcy flux; analytical modelling

INTRODUCTION

In the Walloon Region of Belgium, about 9000 ha of brownfields have been estimated or identified. Many former industrial activities were located nearby navigable river to facilitate transport operations. This has resulted in the existence of numerous contaminated sites in relatively urbanized areas, posing a major risk of contaminant dispersion in the environment, particularly by migration to surface water through groundwater discharge. In such a context, it is important to be able to evaluate and to quantifying the dynamics of GW-SW interactions.

The site of concern in this study is a brownfield of 7.3 ha, corresponding to a former coke factory, on the north bank the Meuse River, located upstream of the city of Liège, in Belgium (Figure 1). The general groundwater flow direction is towards the Meuse River, topography is very flat and the mean hydraulic gradient is low with a value approximately equal to 0.1%. The gravel alluvial aquifer, located at 8 m depth from the soil surface, is heavily contaminated by inorganic (mainly sulphates and heavy metals) and organic pollutants (mainly BTEX and PAHs) due to past industrial activities. There is still no evidence of pollutants next to the transition zone between the river and the brownfield.

The major objective of the present investigation was to 1) evaluate whether an interaction exists, at the level of the mentioned brownfield, between groundwater and surface water; 2) to assess the dynamics of such interactions and to quantify groundwater fluxes as the main potential vector of mobility of contaminants offsite; and 3) to give first pieces of answers on the fact that, despite important sources of BTEX (in particular benzene) have been clearly delineated in the contaminated site, these products have never been observed in groundwater downstream from the sources, in the direction of the Meuse River.

DESCRIPTION OF FIELD EXPERIMENTS AND MONITORING

Because the surroundings of the study site are highly urbanized, direct characterization of the river bank is difficult, so the dynamics and exchanges between GW - SW had to be studied indirectly, based on the one hand on a continuous monitoring of water levels in the Meuse river and at different locations in the gravel aquifer, on the other hand using single-well tracer tests. These experiments are described here after.

Groundwater-surface water monitoring

From September 2005 to May 2007, continuous monitoring of groundwater levels (GWL) was performed in 16 piezometers located at distances ranging from 26 to 224 m from the Meuse River (Fig. 1). Four wells were monitored for a long period (i.e. P3, U5, U8 and U3), while the others were monitored for a more limited period of one month. Groundwater monitoring was performed using LevelTroll® probes at a frequency of 1 measurement/hour.

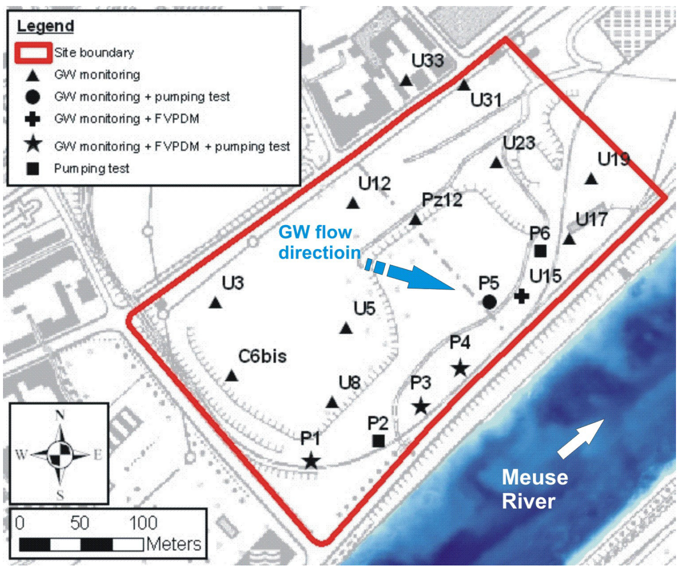

Fig. 1 Location of piezometers monitored in the site (A-A': schematic cross section, see Figure 4).

Meuse River data (discharge, temperature and water level) were obtained from a hydroelectric plant located in the opposite river bank in front of the site.

Single well tracer tests

A new and original single well tracer technique, the FVPDM (Finite Volume Point Dilution Method), designed by Brouyère (2003) and recently developed by Brouyère *et al.* (2007), was applied to evaluate groundwater fluxes as close as possible to the GW-SW interface.

The FVPDM generalizes the Point Dilution Method (Havely *et al.*, 1967). It allows estimating Darcy fluxes locally, at the injection point for any type of tracer experiment. It is based on monitoring the dilution of a tracer injected continuously, at a very low rate, in the tested observation well. The advantage over the PDM is that the FVPDM allows for an easier experimental setup and it can be used for monitoring variations with time of the Darcy fluxes. Mathematical developments and exemplifying applications of the FVPDM in the field are described in details in Brouyère *et al.* (2007).

In the present case study, FVPDM experiments were carried out between July – September 2006 in four wells (P1, P3, P4 andU15), providing estimates of Darcy fluxes between 2.05×10^{-4} and 3.0×10^{-6} m s^{-1}. Fig. 2 presents the calculated evolutions of tracer concentrations fitted to monitored ones in wells U15 and P3, located at 31 and 26 meters of the Meuse River respectively.

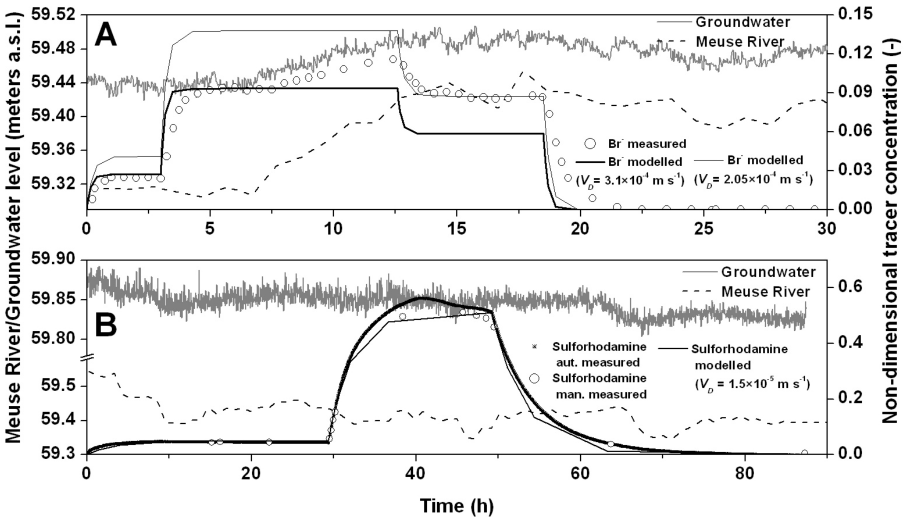

Fig. 2 Comparison between concentration evolution monitored and modelled (V_D is the Darcy's flux) and representation of the Meuse River level and GWL. (A) Well U15; (B) well P3.

The calculated evolutions of tracer concentration are very close to the measured ones. For the experiment performed in well U15 (Fig. 2A), the strong deviation of concentration observed during the second injection step, at around 7.5 hours after injection is explained by a rise of about 10 cm of the Meuse water level during the experiment. The rise of the Meuse River water level has reduced the groundwater gradient and thus Darcy fluxes in the gravel aquifer near the river bank (from 3.1×10^{-4} to 2.05×10^{-4} m s^{-1}), with the consequence on the FVPDM experiment that the tracer dilution was reduced.

ANALYSIS AND MODELLING OF GW – SW DYNAMICS

Cross-correlation analysis of GW – SW levels

In order to determine the factors governing the dynamics of groundwater levels, a cross-correlation analysis was performed between Meuse River levels, groundwater levels and rainfall datasets. River stages and rainfall were considered as inputs of the system, while groundwater heads were used as outputs. To do so, the BRGM TEMPO® software (Pinault, 2001), designed to treat and to model hydrological and time series, was used. Fig. 3 shows cross-correlation functions between Meuse River stage and rainfall with GWL respectively.

This analysis allows one to conclude that the correlation degree is much higher between river stages and GWL (r = 80%) than between rainfall and GWL (r = 20%), so that the dynamics of groundwater levels in the site are mainly controlled by river stage variations rather than by rainfall variability.

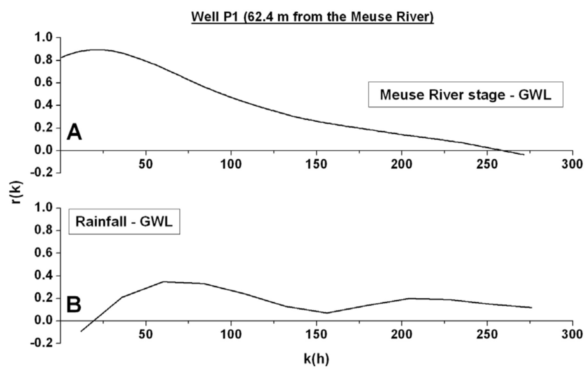

Fig. 3 Cross-correlation functions of (A) Meuse River stage and GWL and (B) rainfall and GWL (*r(k)*: correlation degree; *k(h)*: time lag in hours).

Analytical modelling of GW – SW interactions

The spread of contaminants from the river into the aquifer, or from the aquifer into the river is a problem intimately related to the hydraulics of the aquifer-river system. Groundwater levels in alluvial aquifer fluctuate with surface water levels of the neighbouring river. These fluctuations are essentially produced as a wave propagated into the aquifer (Sophocleous, 1991). The distance of influence in the aquifer of river stages is mainly dependant on the transmissivity and porosity of the aquifer and the magnitude of river stage variations (Workman *et al.*, 1997).

Using the monitored time series of water levels in the river and in the aquifer, a computer program, STWT1 (Barlow and Moench, 1998), was used to evaluate the hydrodynamic properties of the gravel aquifer and the aquifer-river interface and to estimate the water flow rates effects of river-stage fluctuations to the adjacent aquifer.
The conceptual model of the system is presented in Fig. 4. K_x is the horizontal hydraulic conductivity of the aquifer [L T^{-1}]; K_y is the ratio of vertical to horizontal

hydraulic conductivity of aquifer [-]; *h* is the saturated thickness of the aquifer [L]; x_o is the distance from the middle of the river to the river-aquifer boundary [L]; S_y is the storage coefficient [-]; *d* is the width of the semipervious riverbank material [L]; R is the recharge to the aquifer [L T^{-1}]; and β is the diffusivity of the aquifer (i.e. ratio of transmissivity to storage coefficient) [L^2 T^{-1}]. The groundwater flux that crosses the riverbank material is controlled by the riverbank leakance parameter α [L]. It accounts for the resistance due to riverbank material to flow (Barlow *et al.*, 2000) and it is defined as follows:

$$\alpha = \left(K_x d\right) / K_s \tag{1}$$

where K_s is the hydraulic conductivity of the semipervious riverbank material [L T^{-1}].

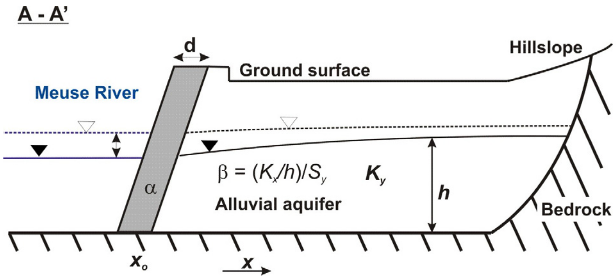

Fig. 4 Conceptual model of the analytical groundwater-surface water system modelled. Not at scale.

Modelled groundwater heads are adjusted to the measured ones by playing on the hydraulic conductivity of the semipervious riverbank material K_s (equation 1) for water height and on the diffusivity α for amplitude adjustment (distance of influence in the aquifer of river stages). The aquifer was modelled as a finite-width water-table with semipervious riverbank material and the river was considered as penetrating the full thickness of the aquifer.

The STWT1 programme solves an analytical solution that uses a convolution relation to calculate changes in groundwater levels in observation wells and the seepage rate and bank storage at the river-aquifer boundary. The convolution integral in a general form is:

$$S_o = \int_0^t S_i\left(\tau\right) Y\left(t-\tau\right) d\tau \tag{2}$$

where S_o is the system output at time *t*, S_i the system input, *Y* is the system response function, *t* the time and τ is the time variable of integration. Convolution integrals for groundwater heads $h(x,z,t)$ (equation 3) and time-varying riverbank seepage rates (equation 4), as solved by the program STWT1, are:

$$h\left(x,z,t\right) = h_i + \int_0^t F'\left(\tau\right) h_D\left(x,z,t-\tau\right) d\tau \tag{3}$$

$$Q\left(t\right) = \frac{K_x b}{x_o} \int_0^t F'\left(\tau\right) \frac{\partial h_D\left(x_o,z,t-\tau\right)}{\partial x_D} d\tau \tag{4}$$

where $h_D(x,z,t)$ is the dimensionless step-response function; $F'(\tau)$ is the time rate of change of the system stress; $Q(t)$ is seepage rate per unit length of river from (or to) one side of the river [L^3 T^{-1}]; and x_D is the dimensionless distance x/x_o.
Hydraulic properties of the aquifer and riverbank and calibration parameters are summarized in Table 1.

Table 1 Summary of hydraulic properties of the aquifer and riverbank and calibration parameters.

Hydraulic properties				Calibration parameters			
P3		U17		P3		U17	
h (m)	8	h (m)	8	K_x (m s^{-1})	9.4×10^{-4}	K_x (m s^{-1})	1.6×10^{-3}
d (m)	3	d (m)	3	K_y (-)	1.0×10^{-2}	K_y (-)	8.0×10^{-4}
x_o (m)	96.1	x_o (m)	108.7	K_s (m s^{-1})	1.91×10^{-5}	K_s (m s^{-1})	1.2×10^{-4}
				R (mm h^{-1})	0.016	R (mm h^{-1})	0.068
				S_y (-)	0.04	S_y (-)	0.06

Figure 5 allows comparison of measured and modelled groundwater levels for wells U17 and P3, located at 38.7 and 26.1 m from the river and at extreme sides of the site.

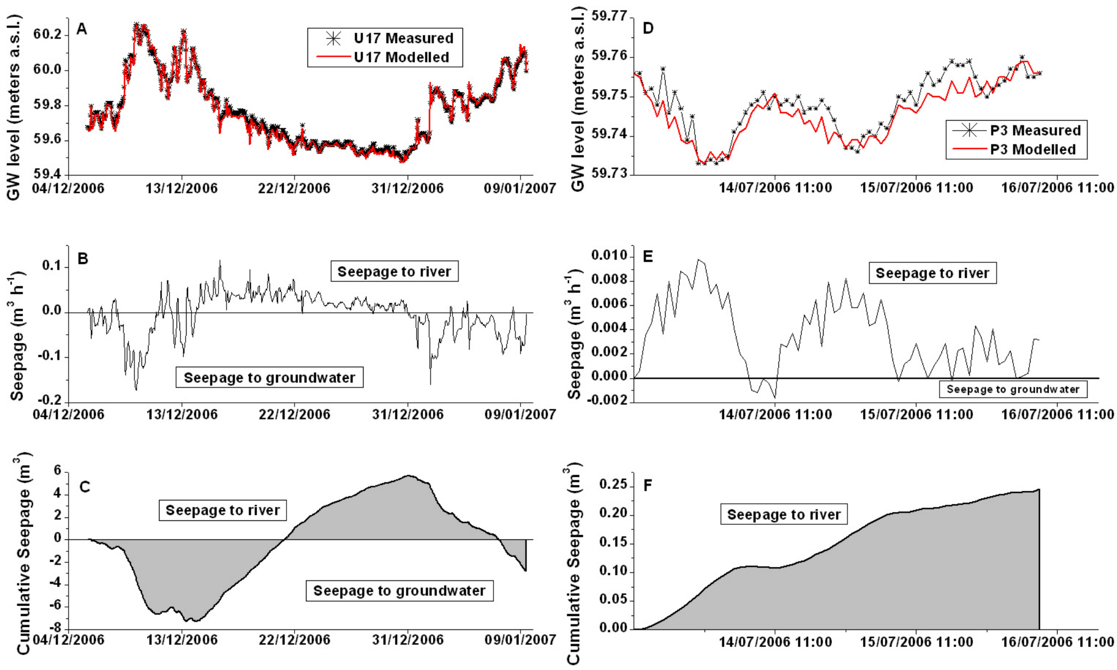

Fig. 5 Groundwater head measured and modelled in the observation well U17 (A); corresponding seepage rate (m^3 h^{-1} m river reach) between the Meuse River and the aquifer (B); corresponding cumulative seepage (m^3 m river reach) during the modelled period (C); groundwater head measured and modelled in the observation well P3 (D); corresponding seepage rate (m^3 h^{-1} m river reach) between the Meuse River and the aquifer (E); corresponding cumulative seepage (m^3 m river reach) during the modelled period (F).

Seepage flow rates, as calculated by the analytical solution highlights the gaining character of the river in normal conditions (water level of the Meuse River at 59.5

meters a.s.l.), while it becomes a losing river when its level rises of some centimetres (Fig. 5B).

DISCUSSION OF RESULTS

During the period of monitoring in well P3 presented in Fig. 5D, a FVPDM experiment was carried out in well P4. The Darcy fluxes as estimated from this experiment were equal to 2.7×10^{-5} m s^{-1}, which is two orders of magnitude higher than the estimation obtained using the analytical solution, which is around 1.2×10^{-7} m s^{-1}. Using Darcy's law and an average value of K_x equal to 1×10^{-4} m s^{-1}, estimated using pumping test results, the estimated Darcy flux is 2.3×10^{-7} m s^{-1}, closer to that obtained using the analytical model.

Different reasons can probably explain such differences. First, the FVPDM provides a point estimate of Darcy fluxes, with limited integration of aquifer heterogeneity around the tested well and with a possible influence of flow field distortion in the vicinity of the injection well bore (Brouyère, 2003). Secondly, wells P3 and P4 are distant of about 40 m and lateral aquifer heterogeneity can probably explain the differences in Darcy fluxes over that distance. But above all, the analytical solution is affected by an undetermination. Multiplying the applied recharge and the hydraulic conductivity terms of the model by a same factor leads to the calculated groundwater levels, but a transiting groundwater flux that is multiplied by that factor.

The combined monitoring of water levels and the analytical solution provides a very efficient, easy to deploy in the field, way of quantifying groundwater fluxes and GW – SW dynamics. However, even if the orders of magnitude of the different coefficients introduced in the analytical model are consistent with measurements and observations in the field (Table 1), it is possible that Darcy fluxes are higher, on the order of those obtained using the FVPDM. Further investigations are on the way, using a numerical model, in order to diminish the uncertainty in groundwater flux quantification resulting from this combined analysis.

CONCLUSIONS AND PERSPECTIVES

Based on field experiments and monitoring, the analysis performed in the studied brownfield confirms that there is a relationship between groundwater and the neighbouring river, with groundwater levels being strongly correlated with variations in surface water levels. The various estimates of Darcy fluxes (analytical modelling and application of Darcy's law, FVPDM) range between 2.3×10^{-7} and 2.7×10^{-5} m s^{-1}. This can be related to the scale at which the different estimates apply, from very local for the FVPDM to site scale for the two others. The analytical model potentially provides very useful information on GW – SW interaction dynamics and quantification of groundwater fluxes exchanged between the aquifer and the adjacent river, but it is an undetermined on groundwater fluxes. From this point of view, the FVPDM technique is a reliable candidate to restrain groundwater flux evolution calculated with the analytical solution and it is likely that a combined FVPDM – water level monitoring approach is a more reliable solution for the quantification of GW – SW exchanges.

The results of the analytical model indicate that under normal conditions seepage is from the aquifer to the river. However, because the Meuse River water levels vary continuously, there are frequent changes from gaining to losing conditions. In particular, there are periods during which surface water penetrates in the alluvial aquifer. This surface water flux is likely to be a source of oxygen contributing to the degradation of BTEX (Atteia and Guillot, 2007). This might be an explanation for the fact that BTEX compounds have never been monitored downstream from the sources of contamination. Complementary investigations and numerical modelling are on the way in order to evaluate the evolution of dissolved oxygen with the dynamics of GW – SW interactions at the border of the site and to confirm or not the proposed hypothesis for the degradation of BTEX.

Acknowledgements This work was supported by the European FP6 Integrated Project AquaTerra (Project no. 505428) under the thematic priority, sustainable development, global change and ecosystems. Authors had benefit of research funds from Aquapôle ULg. Thanks to the SPAQuE, especially H. Halen and A. Lox, for access to data and to the brownfield site. Grateful acknowledgement is made for P. Theunissen (SPE-TGV) for his gracious contribution on Meuse River data time series. Thanks are due to Dr. Paul Barlow (USGS) for his comments.

REFERENCES

Atteia, O. & Guillot, C. (2007) Factors controlling BTEX and chlorinated solvents plume length under natural attenuation conditions. *J. Contam. Hydrol.* **90**, 81-104.

Barlow, P. M., DeSimone, L. A. & Moench, A. F. (2000) Aquifer response to stream-stage and recharge variations. II. Convolution method and applications. *J. Hydrol.* **230**, 211-229.

Barlow, P. M. & Moench, A. F. (1998) Analytical solutions and computer programs for hydraulic interactions of stream-aquifer systems. *US Geol. Survey Open File Report 98-415A*. 99 pp.

Brouyère, S. (2003) Modeling tracer injection and well-aquifer interactions: a new mathematical and numerical approach. *Water Resour. Res.* **39**(3), doi:10.1029/2002WR001813.

Brouyère, S., Batlle-Aguilar, J., Goderniaux, P. & Dassargues, A. (2007) A new tracer technique for monitoring groundwater fluxes: the Finite Volume Point Dilution Method. *J. Contam. Hydrol.*: doi 10.1016/j.jconhyd.2007.09.001.

Havely, E., Moser, H., Zellhofer, O. & Zuber, E. (1967) Borehole dilution techniques: a critical review. In *Isotopes in Hydrology*, I.A.E.A., Vienna, Austria, 531-564 pp.

Pinault, J.-L. (2001) Manuel utilisateur de TEMPO. Logiciel de traitement et de modélisation des séries temporelles en hydrogéologie et en hydrogéochimie (In French). *RP-51459-FR*. 233 pp.

Sophocleous, M. A. (1991) Stream-floodwave propagation through the Great Bend alluvial aquifer, Kansas: field measurements and numerical simulations. *J. Hydrol.* **124**, 207-228.

Workman, S. R., Serrano, S. E. & Liberty, K. (1997) Development and application of an analytical model of stream/aquifer interaction. *J. Hydrol.* **200**, 149-163.