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AquaTerra

Integrated Modelling of the river-sediment-soil-groundwater system; advanced tools for the management of catchment areas and river basins in the context of global change

Integrated Project

Thematic Priority: Sustainable development, global change and ecosystems

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Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

SUMMARY

Tracer experiments were performed in the Brévilles test site in order to highlight vertical variations in groundwater fluxes related to vertical variations hydraulic conductivity, to estimate contaminant travel time from several locations in the catchment to the springs and to identify transport processes affecting the fate of solutes in the saturated part of the aquifer. Following a first tracer experiment with uranine and sulforhodamine G in 2003, four tracer injections were performed in November 2005 in different piezometers, using uranine, sulforhodamine B, iodide and lithium. Tracer concentrations were monitored in the injection wells and at the basin outlet (spring and gauging station). Using the FVPDM method, concentration evolutions monitored in the injection wells allowed one to estimate local Darcy fluxes. At the basin outlet, only two tracers were recovered. Analyses of breakthrough curves confirm the stratification of the aquifer with more permeable levels in the lower part. They also suggest the probable occurrence of vertical interactions within the aquifer.

MILESTONES REACHED (from DOW II p. 81 to 86)

The present DL benefits from the system description presented in previous HYDRO2 DL (DL H2.1; H2.1bis) as well as COMPUTE (DL C2.1). It uses climatic and hydrometric data from the database presented in the work package BASIN (DL R1.8) and described in HYDRO2 (DL H2.2). It is an important element for the understanding of the groundwater behaviour in the Brévilles catchment (future HYDRO2 DL H2.4). It gives some useful parameters (and data) for the models to be implemented in the WP COMPUTE and TRENDS.

The present DL is not linked to a specific milestone.

Contents

Glossary

FVPDM	Finite Volume Point Dilution Method (FVPDM) generalizes the single-well point dilution method to the case of finite volumes of tracer fluid and water flush
Darcy Flux	Flux of a liquid following Darcy´s law that states that the flux through a porous medium depends on the permeability and the hydraulic gradient.
CATTI	Computer Aided Tracer Test Interpretation (Sauty et al. 1992)
flow distortion coefficient (αw)	Takes into account the fact that the well constitutes a local discontinuity in the hydraulic conductivity field
Dirac type injection	The whole quantity of tracer is injected "instantly". Practically, the injection time is as short as possible (a few seconds).
one-dimensional solution	Mathematical solution computed using parameters and variables related to only one spatial dimension (e.g.: Transport problem in X direction from an injection well to a spring. Lateral and vertical variations are not considered)
dual-porosity	Characterises a medium with two different kinds of porosity. E.g. : inter-connected red of fractures (macro-porosity) – porous matrix (micro-porosity)

1. Introduction – General context

The aquifer of the Brévilles spring, located in Montreuil-sur-Epte in the Val d'Oise (France), has been studied for 6 years by BRGM in the scope of a EU FP5 project (PEGASE) and, more recently, in the FP6-IP AquaTerra. The objective is a better understanding and prediction of the fate of pesticides in the subsurface.

The aquifer is mainly located in the Cuisian sandy formation limited at its base by impermeable clay. These sands are medium sands in the upper part of the formation to very fine sands in the lower part. The aquifer system, considered as completely closed, extends over approximately 11.6 km² and the Brévilles spring constitutes its main outlet (Figure 1).

2. Objectives

In the scope of the AquaTerra project, the Hydrogeology Group from the University of Liège has been involved in this research with the task of performing tracer experiments in the Brévilles aquifer, as a support to a better understanding and quantification of contaminant transport mechanisms in the saturated zone.

Taking advantage of newly drilled piezometers, tracer injections were performed in November 2005. These experiments followed two previous ones performed by BRGM in 2003. The objectives of the new tracer experiments were threefold:

- to highlight vertical variations in groundwater fluxes, related to vertical variations in grain size distribution and hydraulic conductivity
- to estimate contaminant travel time from several locations in the catchment to the Brévilles springs
- to identify transport processes affecting the fate of solutes in the saturated part of the aquifer and to quantify associated parameters (effective porosity, dispersivity etc).

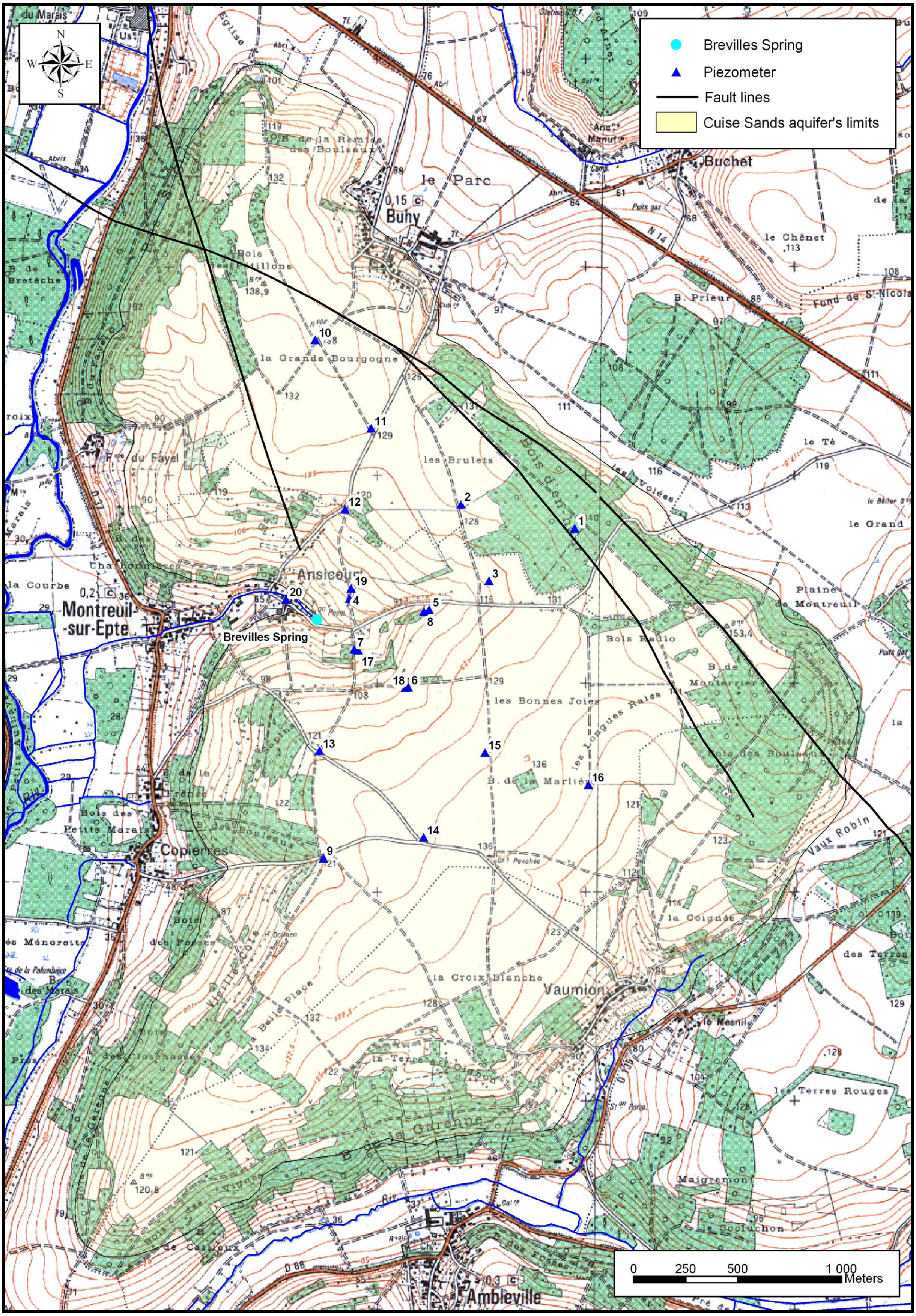

Figure 1: Brévilles spring area

3. Description of the tracer experiments

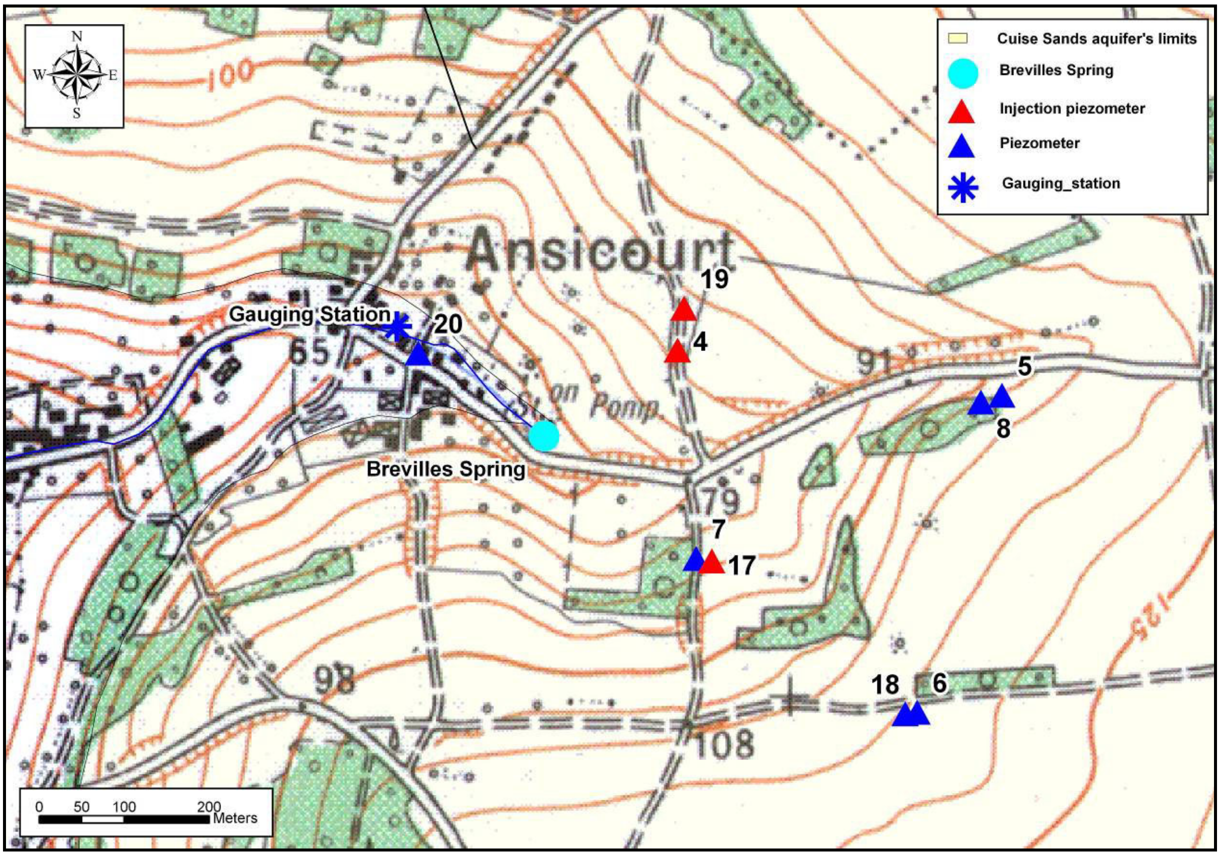

Figure 2: Experiment site map (detail from figure 1)

3.1 Previous tracer experiments (2003)

In August 2003, BRGM performed two tracer experiments in the Brévilles test site. Tracer injections were performed in Pz4 (0.4656 kg of uranine, tracing distance: 187m) and in PZ7 (0.388 kg of sulforhodamine G, tracing distance: 228m) (see Figure 1 and 2). Samples were collected at the Brévilles spring.

Sulforhodamine G was first observed at the spring 7 days after the injection. The tracer concentration rose quite rapidly and then stabilized, with an almost constant concentration observed for about 1 year. Approximately 300 days after injection, 22.6 % of the tracer mass was recovered at the spring. This atypical concentration evolution was attributed to tracer capturing in the underground, probably close to the injection point. The complete breakthrough curve and the recovered mass evolution are presented in Figure 3. The main characteristics of these curves are summed up in Table 1.

First interpretations have been realised using the software "CATTI" (Sauty et al. 1992). By varying Darcy flux V_d (L T^{-1}), effective porosity n_e (-) and longitudinal dispersivity coefficient α_L (L), it allows adjusting theoretical models on experimental data. However, these models remain quite simplistic and some phenomena, such as retardation effects, cannot be considered. In the case of this tracer test, the long-tailed breakthrough curve cannot be modelled and the subsequent interpretation has to be regarded with caution.

As a first approximation, it can be expected that, by adjusting the theoretical concentration peak on the beginning of the stabilized stage, it is possible to obtain a rough estimation of the effective porosity n_e. For Darcy fluxes V_d varying from 3×10^{-6} to 8×10^{-6} m/s (estimated on the basis of hydraulic conductivity and Darcy's law between PZ17 and the spring), n_e would be included in an interval of 15 % to 24 %.

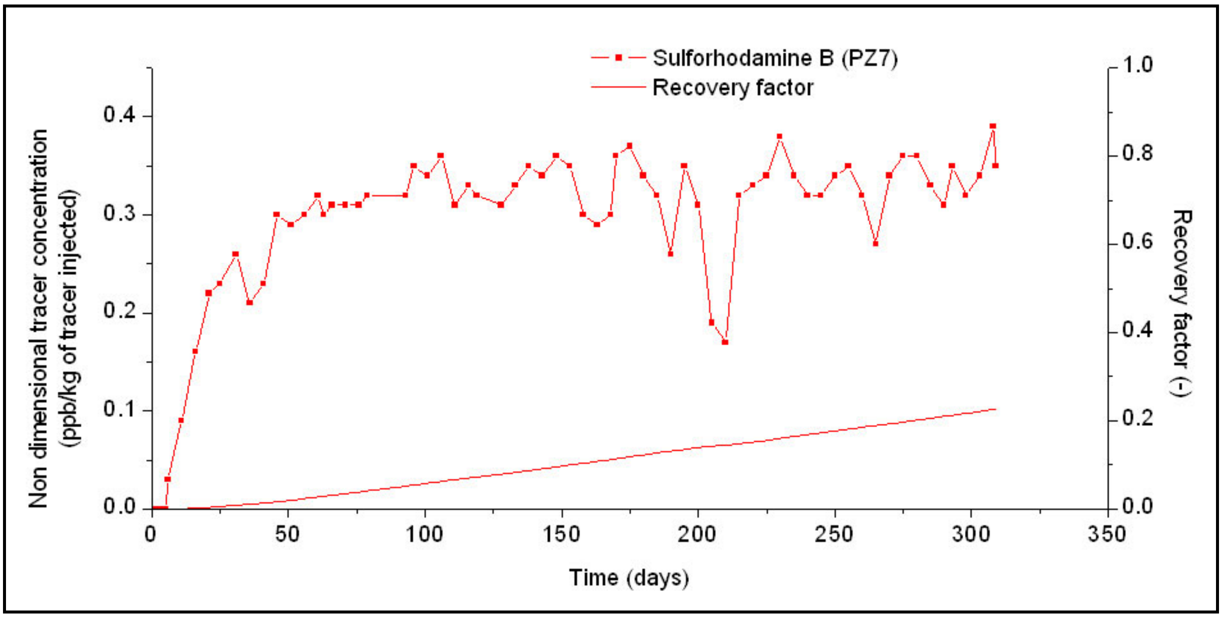

Figure 3: Breakthrough curve and recovered mass evolution for the tracer test performed between PZ7 and the Brévilles spring (Sulforhodamine G) in 2003

First detection time	7 days
Beginning of the stabilized stage	61 days
Mean concentration during the stabilized stage	0.124 ppb 0.32×10^{-4} ppb/kg of tracer injected
Calculated speed corresponding to the first detection	32.57 m/day 3.77×10^{-4} m/s
Calculated speed corresponding to the beginning of the stabilized stage	3.74 m/day 4.33×10^{-5} m/s
Recovery factor after 309 days	22.67%

Table 1: Main characteristics of the breakthrough curve (Sulforhodamine G)

The uranine tracer injected in PZ4 was never detected at the spring (sampling duration: about 1 year). Several reasons may explain the absence of recovery.

PZ4 is screened at the bottom of the sandy aquifer (see Appendix 1), where the hydraulic conductivity is supposed to be lower and chemical parameters indicate a vertical stratification of groundwater. This might explain why the tracer migrated very slowly, giving dilution and dispersion effects all the time to reduce concentrations below the detection limit (Gutierrez, 2004).

Geophysical surveys showed that PZ4, located near a fault crossing the aquifer, could be in a relatively disturbed zone. This piezometer could thus be isolated in a collapsed zone which could explain the absence of tracer recovery at the Brévilles spring (Gutierrez, 2004).

Furthermore, sampling operations were performed at the Brévilles spring only. Yet, a significant increase in water flow rate is observed between the spring itself (≈ 6 to 8 l/s) and the gauging station located 200 m downstream (≈21 to 28 l/s). This indicates that the spring does not correspond to the total outlet of the aquifer. It is thus possible that uranine was not detected at the spring because it arrived downstream of the sampling location. Simulations performed using a 2D model (Goderniaux, 2005; Darsy, 2003) developed using MARTHE (BRGM modelling code) showed that the tracer plume could have arrived between the spring and the gauging station.

Finally, even if uranine is generally considered as a conservative tracer (Käss 1994), its non-conservative behaviour has already been observed on several occasions (e.g. Brouyère 2001).

3.2 New tracer experiments (2005)

In November 2005, 4 new tracer experiments were performed by HGE-ULg. Different tracers were injected in 4 piezometers (***PZ17b***, ***PZ17c, PZ4 and PZ19***) located near the Brévilles Spring (see Figures 1 and 2). The lithological and technical logs of the 4 injection wells are presented in Appendix 1.

The four tracer experiments were dimensioned with the goal of obtaining a response at the aquifer outlet. The quantities and tracers used, as well as the distances from the injection wells to the Brévilles spring, are summarized in Table 2.

	PZ4	**PZ19**	**PZ17b**	**PZ17c**
Distance to the spring	187 m	223 m	245 m	245 m
Tracer	Lithium Li+	Sulforhodamine B	Iodide I-	Uranine
Quantity	6.6 kg Li+	10 kg	19.2 kg	5 kg

Table 2 : Main characteristics of the tracer experiments

3.2.1 Injection methodology

In order to perform the tracer injections in the Brévilles test site, a new technique was used. This technique, called the Finite Volume Point Dilution Method (FVPDM) generalizes the single-well point dilution method to the case of finite volumes of tracer fluid and water flush. It is based on an analytical solution derived from a mathematical model proposed recently that allows modelling tracer injection into a well and the tracer input function in the aquifer with greater accuracy than using a "classical" source term (Brouyère 2001, 2003, Brouyère *et al.* 2005).

In natural flow conditions, water present in the well bore is continuously renewed by water crossing the screens due to natural motion of groundwater in the aquifer. The groundwater flow rate (Q_t^0, L^3 T^{-1})[1] intercepted by the injection well at the screen level is a function of the magnitude of Darcy fluxes ($|\underline{v}_D|$, L T^{-1}) prevailing in the aquifer close to the injection well, of the flowing section at the screen level ($S_w = 2e_{scr}r_w$, with e_{scr} the screen length (L) and r_w the well radius(L)) and of a flow distortion coefficient (α_w, no units) which takes into account the fact that the well constitutes a local discontinuity in the hydraulic conductivity field:

$$Q_t^0 = \alpha_w S_w |\underline{v}_D| = 2\, e_{scr} r_w \alpha_w |\underline{v}_D| \quad (1)$$

The tracer injection is performed at a controlled, low flow rate Q_{inj} (L^3 T^{-1}) and a constant tracer injection C_{inj} (M L^{-3}). Because the objective is to quantify Q_t^0, the injection rate should be low enough so as to avoid cancelling the transit flow rate prevailing during the injection. As shown by Brouyère (2001) and Brouyère et al. (2006), a critical value of injection rate Q_{crit} can be estimated as:

$$Q_{cr} = \pi Q_t^0 \quad (2)$$

Based on Equation (2), one can estimate roughly the maximal injection rate as being approximately three times the magnitude of the flow rate prevailing in natural flow conditions, the latter being estimated a priori or based on the application of Darcy's law close to the injection well.

In the injection well, the injected tracer is homogenized by circulating the water column with a pump and water samples are collected so as to monitor the concentration evolution with time in the well-bore, $C_w(t)$. If the injection is long enough, the ratio between the concentration in the injected tracer fluid and the concentration in the well-bore should stabilize at a value which depends on the respective influence of the injection rate and of the groundwater flow intercepted by the well screens (Brouyère 2001, Brouyère et al. 2006)).

Monitoring of concentration evolution in the injection well has several advantages:

- First, it allows one to be sure that the tracer does not remain captured in the well for any reason such as very low Darcy fluxes near the injection point or because of the intrinsic characteristics of the well (e.g. well sealing or clogging).
- The knowledge of the concentration evolution in the injection well allows one to know better the "real" input function of the tracer in the aquifer. This could be of real importance especially when the transfer times to the sampling location are short in comparison to the injection duration.

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[1] The zero appearing in the term Q_t^0 stands for the fact that this value of the transit flow rate corresponds to the case when the injection rate Q_{in} = 0. During water injection (Q_{in}>0), the value of the flow rate transiting by the well screens (Q_t^{in}) decreases with increasing injection rates.

- Using the FVPDM method (see Chapter 3.3.1.1), it is possible to estimate local groundwater fluxes near the injection point.

3.2.2 Description of the injections

For each experiment, consecutive steps of constant injection rates were performed. During each injection, samples were collected in the injection well at an approximate cadence of 5 minutes. Generally, 2 to 4 injection steps were performed, after which, the remaining quantity of tracer was injected in a short time to finalize the tracer injection in a reasonable time. Because of field conditions (electrical power supplied by a generator, no protection of the equipment against vandalism…), it was actually not possible to make very long injections.

Injections performed in PZ17 b and PZ17c

The piezometers PZ17 are located close to an older piezometer, PZ7. It is composed of three piezometric boreholes distant of about 2 m one from the other. The three boreholes are screened at 3 different levels of the aquifer, respectively in the Lutetian limestone (PZ17a) and in the upper (PZ17b) and lower part (PZ17c) of the Cuise sands (see borehole logs in Appendix 1).

Tracer tests were carried out in PZ17b (iodide I^-) and PZ17c (uranine) to try to highlight and to quantify vertical variations in hydraulic conductivity and groundwater fluxes in the sandy layer aquifer. Table 3 summarizes the information relative to these injections. Figure 4 shows the injection steps together with the concentration evolution in the injection wells.

	PZ17b					PZ17c			
injected tracer	Iodide I-					Uranine			
Volume of water in the borehole (m³)	0.030					0.051			
Kmean (pumping tests) (m/s)	8.67×10^{-4}					2.75×10^{-4}			
Estimated flux through the screen (m/s) (Darcy's law between PZ and the spring)	1.97×10^{-5}					0.62×10^{-5}			
Estimated flow rate through the screen (m³/s)	0.47×10^{-5}					0.15×10^{-5}			
Estimated critical injection rate (m³/s)	1.48×10^{-5} (53.3 l/h)					4.69×10^{-6} (16.9 l/h)			
Injection concentration (ppb)	$1.06\times10^{+8}$					$1.20\times10^{+8}$			
Injection steps	*1*	*2*	*3*	*4*	***tot***	*1*	*2*	*3*	***tot***
Injection rates (l/h)	9.4	21.4	32.6	39.9		5.8	15.9	32.6	
Injection times (min)	59	35	30	25	***149***	101.5	31	16	***149***
Injection volumes (l)	9.3	12.5	16.3	16.6	***54.7***	9.8	8.2	8.7	***26.7***

Table 3: Experimental setup specific to injection operations in PZ17b and PZ17c

* The critical injection rate is the injection flow rate such that the transit flow rate becomes zero. $Q_{cr}=2\pi\ r_{well}\ e_{scr}\ V_D$ (r_{well} : well's radius; e_{scr} : screen height; V_D : Darcy flux)

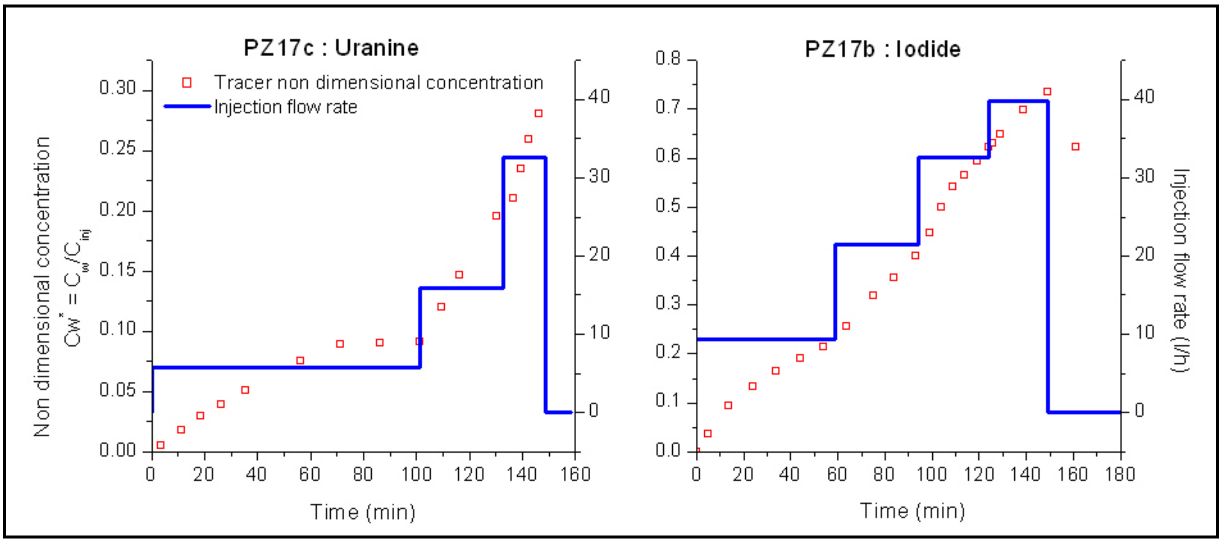

Figure 4 : Concentration evolution and injection flow rates in PZ17b (Iodide) and PZ17c (Uranine)

Injection performed in PZ4

As already explained (section 3.1), Piezometer PZ4 was drilled during a previous campaign and used for tracer experiments with uranine, never detected at the spring. The borehole is screened in the lower part of the aquifer, between 17.85 m and 26.70 m, where the flow is assumed to be slower and where anoxic conditions prevail. Tracer quantities were determined in order to have significant concentrations at the spring and a second sampling point was installed (see below) in order to increase the chances of obtaining a response at the outlet of the aquifer. Table 4 summarizes the information relative to this injection. Figure 5 shows the injection steps together with the concentration evolution in the injection well.

	PZ4		
injected tracer	Lithium Li+		
Volume of water in the borehole (m³)	0.071 m³		
Kmean (pumping tests) (m/s)	2.75×10^{-4}		
Estimated flux through the screen (m/s) (Darcy's law between PZ and the spring)	1.13×10^{-5}		
Estimated flow rate through the screen (m³/s)	0.80×10^{-5}		
Estimated critical injection rate (m³/s)	2.55×10^{-5} (91.8 l/h)		
Injection concentration (ppb)	$4.13\times10^{+7}$		
Injection steps	*1*	*2*	***tot***
Injection rates (l/h)	23.5	40.9	
Injection times (min)	79	51	***130***
Injection volumes (l)	30.9	34.8	***65.7***

Table 4 : Experimental setup specific to injection operations in PZ4

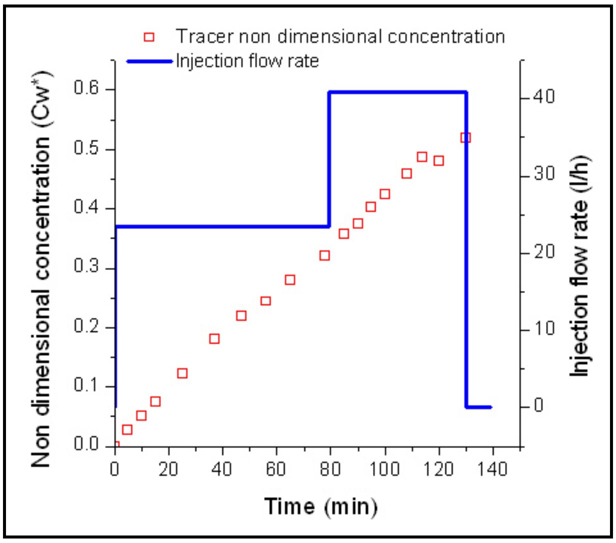

Figure 5 : Concentration evolution and injection flow rates in PZ4 (Lithium)

Injection performed in PZ19

The tracer test performed in PZ19 with sulforhodamine B was dimensioned to give new information on the area located at the North-east of the spring. The borehole is screened between the 18 and 30 m; thus it concerns almost the whole thickness of the aquifer (the static groundwater level is at 16 m below ground level). Table 5 summarizes the information relative to this injection. Figure 6 shows the injection steps together with the concentration evolution in the injection well.

	PZ19		
injected tracer	Sulforhodamine B		
Volume of water in the borehole (m³)	0.078 m³		
Kmean (pumping tests) (m/s)	4×10^{-4}		
Estimated flux through the screen (m/s) (Darcy's law between PZ and the spring)	1.53×10^{-5}		
Estimated flow rate through the screen (m³/s)	1.47×10^{-5}		
Estimated critical injection rate (m³/s)	4.61×10^{-5} (166 l/h)		
Injection concentration (ppb)	$1.12\times10^{+8}$		
Injection steps	*1*	*2*	***tot***
Injection rates (l/h)	23.5	35.3	
Injection times (min)	82	99	***181***
Injection volumes (l)	32.1	65.8	***97.8***

Table 5 : Experimental setup specific to injection operations in PZ19

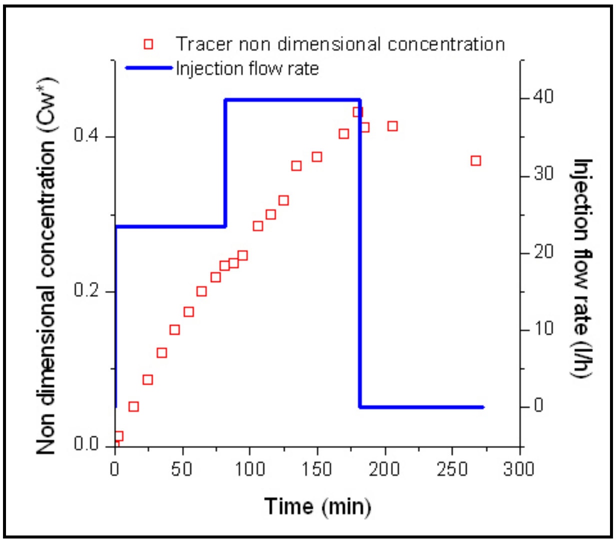

Figure 6: Concentration evolution and injection flow rates in PZ19 (Sulforhodamine B)

3.2.3 Monitoring concentration evolutions at the Brévilles spring

In order to monitor the tracer concentration evolutions at the basin outlet, samples were collected using automatic samplers at the Brévilles spring and at the level of the gauging station, 200 m downstream from the spring. As mentioned above (see 3.1), the gauging station can be considered as a more global outlet of the aquifer. Therefore, sampling at this location increases the probability of recovering the injected tracers.

Moreover, based on topographical considerations, and assuming groundwater stratification, it is probable that the spring drains groundwater coming from the upper part of the sandy layer only. Meanwhile, groundwater from the lower part of the aquifer probably flows out diffusively between the spring and the gauging station. By sampling at both locations it was expected to detect and dissociate tracer arrivals from the different aquifer layers.

Sampling operations were conducted for more than 200 days at both locations, with a time step gradually increased from 6 hours just after the injections to 2 days (after 2 months of sampling) until the end of the sampling campaign.

Lithium Li^+ (PZ4) and sulforhodamine B (PZ19) have never been detected neither at the spring nor at the gauging station. Iodide I^- and uranine appeared at the spring respectively 4 and 16 days after injection. Concentration breakthrough curves at both sampling places are presented in Figure 7.

These results will be discussed in section 3.3.2.

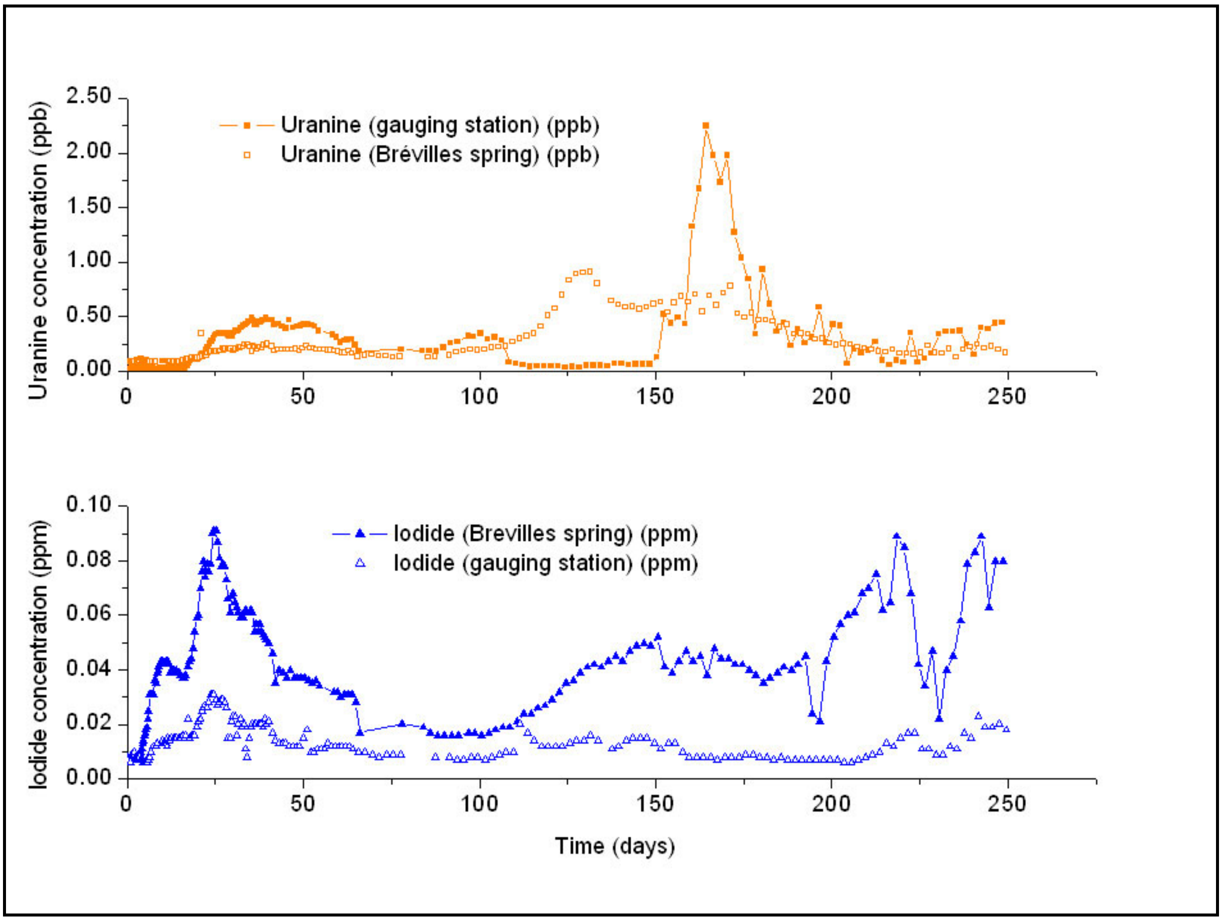

Figure 7 : Breakthrough curves of uranine and iodide (background included) at the spring and at the gauging station

3.3 Analysis and interpretation of the results

3.3.1 Modelling concentration evolutions in the injection wells

Modelling concepts

The Finite Volume Point Dilution Method (FVPDM) is based on an analytical solution derived from a new mathematical and numerical approach developed to accurately model tracer injection based on water and tracer mass balance equations integrated over the volume of water in the well (Brouyère 2003). This model is able to account for finite volumes of tracer fluid and water flush, tracer mixing and capturing in the well bore, but also for the influence of complex flow patterns around the well and for tracer back-migration into the well. It thus makes it possible to represent, in a very accurate way, tracer injection as it is performed practically in the field.

The general equation that allows computation of the concentration evolution in the well bore is (see Brouyère 2003, Equation 7):

$$\pi r_w^2 h_w \frac{dC_w}{dt} = Q_{in}\left(C_{in} - C_w\right) + Q_t^{in}\left(C - C_w\right) \qquad (3)$$

In Equation (1), the terms h_w (L) and r_w (L) represent the length of the water column in the well bore and the radius of the injection well respectively. C_w, C_{in} and C_t are variables accounting for concentrations (M L^{-3}) in, respectively, the well, the water injected at a rate Q_{in} (L^3 T^{-1}) and the flow rate Q_t^{in} (L^3 T^{-1}) intercepted by the well at the screen level (transit flow rate), due to pumping at the recovery well or, more generally, to natural motion of water in the aquifer. The superscript '*in*' in the transit flow rate variable Q_t^{in} represents the fact that this term dynamically depends on the injection rate Q_{in}. Groundwater leaves the well through the screens at flow rate Q_{out} (L^3 T^{-1}), carrying tracer at a concentration C_w.

Brouyère et al. (2005) derived an analytical solution from Equation (3), under a few non-restrictive simplifying assumptions. First, the concentration C_t in the transit flow rate is neglected. For most of the injection process, the concentration in the well is very high and, compared to the concentration in the transit flow rate is negligible. If the injection rate is larger than the critical injection rate ($Q_{in}^* > 1$), then the transit mass flux is cancelled. Second, the volume of water $V_w = \pi r_w^2 h_w$ in the injection well is assumed to be constant. The assumption is valid if a packer system is used in the well to isolate the injection level from the rest of the well bore and if variations in water level are small compared to the height of the water column in the well. This occurs frequently since the injection rate is usually low and the hydraulic conductivity of the tested aquifer is generally relatively high.

With these assumptions, Equation (3) becomes:

$$\pi r_w^2 h_w \frac{dC_w}{dt} = V_w \frac{dC_w}{dt} = Q_{in} C_{in} - Q_{out} C_w \tag{4}$$

where $Q_{out} = Q_{in} + Q_t^{in}$.

Considering the initial condition $C_w(t = t_0) = C_{w,0}$, Equation (4) can be solved, resulting in the following expression to compute the concentration evolution in the injection well:

$$C_w(t) = \frac{Q_{in} C_{in} - (Q_{in} C_{in} - Q_{out} C_{w,0}) \exp\left(-\frac{Q_{out}}{V_w}(t - t_0) \right)}{Q_{out}} \tag{5}$$

Provided that adequate values are defined for the concentration and flow rate terms, Equation (5) can be used to compute the concentration evolution for any step of the tracer injection.

Modelling results

Monitored concentrations were adjusted by playing on the magnitude of the Darcy flux only, the other terms appearing in Equation (5) are defined based on the experimental conditions (Q_{inj}, C_{inj}, V_w…).

Figure 8 allows comparisons of monitored concentrations in the injection wells and adjusted concentrations, by trial-and-error, using the FVPDM method (Equation 5). In each diagram, the red curve corresponds to the best adjustment of Darcy flux (V_d=q_3). The other curves have been calculated for V_d equal to 10*q_3, 2*q_3, 0.5*q_3 and 0.1*q_3, to check the sensitivity of the method.

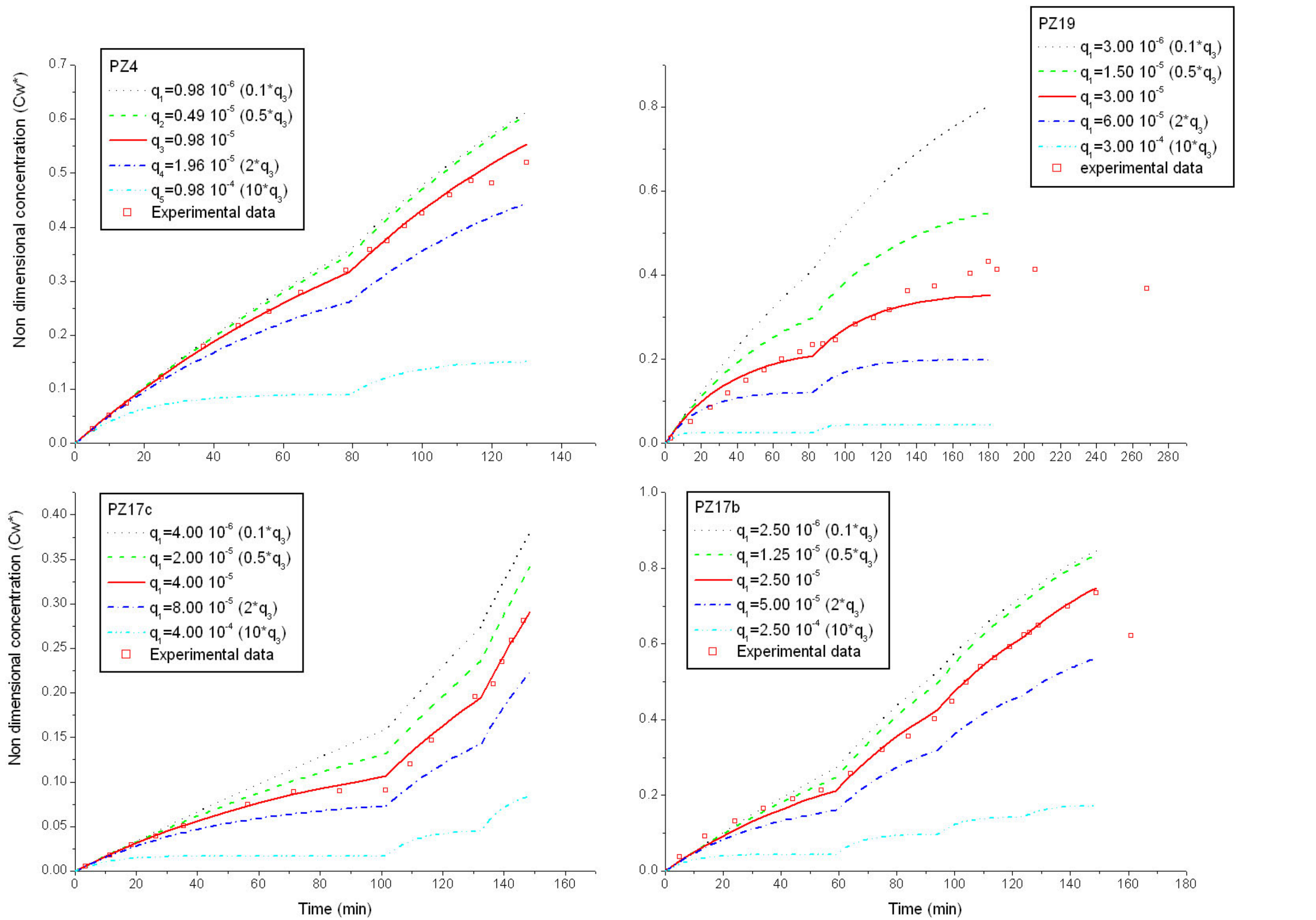

Figure 8: Comparison of monitored and calculated concentration evolutions in the injection wells

Figure 8 shows that the calculated curves almost perfectly match experimental data. Small imperfections can however be observed for PZ19. This could be due to slightly less controlled injection conditions. Indeed, during that injection, tracer sedimentation was observed at the bottom of the reservoir. It is thus possible that, during the first injection steps, the tracer concentration in the injected fluid was lower than expected, the remaining quantity of tracer being injected afterwards. A new adjustment was performed considering a lower concentration in the injected fluid and, as expected, this lead to a more satisfying result (not shown) with a resulting lower value of Darcy flux ($V_d \sim 1\times10^{-5}$ m/s).

All the results are presented in Table 6. They are in good agreement with the *a priori* estimations of Darcy fluxes obtained using the results of pumping test and the application of Darcy's law between the injection point and the spring. This confirms that the FVPDM method is a valid technique for providing point quantification of Darcy fluxes.

In PZ17c, the Darcy flux calculated based on the FVPDM interpretation is greater than the value obtained using Darcy’s law. It is even more important than the Darcy flux calculated for the upper part of the Cuise sands where the aquifer material is coarser. This might seem contradictory to the results of pumping tests performed in 2005, which indicated a diminution of hydraulic conductivity with depth. However, this could be explained by local effects (flow distortion, steeper gradient locally). It should also be pointed out that the FVPDM provides a local (point) estimation of Darcy flux, while the application of Darcy’s law provides a mean estimated Darcy flux that integrates a larger volume of aquifer (corresponding to the distance over which the piezometric gradient is calculated) and a mean hydraulic conductivity.

	Estimated Flux through the screen (Darcy's law between PZ and the spring) (m/s)	**Estimated Flux through the screen (FVPDM method) (m/s)**	**Estimated critical injection rate (FVPDM method) (m³/s)**
PZ4	$1.13\ 10^{-5}$ m/s	9.80×10^{-6}	2.18×10^{-5} (78.43 l/h)
PZ19	$1.53\ 10^{-5}$ m/s	3.00×10^{-5}	9.04×10^{-5} (325.56 l/h)
PZ17b	$1.97\ 10^{-5}$ m/s	2.50×10^{-5}	1.82×10^{-5} (65.56 l/h)
PZ17c	$0.62\ 10^{-5}$ m/s	4.00×10^{-5}	2.91×10^{-5} (104.90 l/h)

Table 6 : Results obtained using the FVPDM method

Further comments on the results obtained with the FVPDM method

When applying the FVPDM method, reaching a stabilized concentration in the injection well allows *a priori* an easier and more reliable estimation of Darcy fluxes prevailing in the aquifer close to the injection well, since the ratio C_w/C_{inj} is directly proportional to the relative importance of Q_{inj} and Q_t (Brouyère 2001). In the ascending part, the theoretical curves are closer one from the other and it could be more difficult to evaluate the quality of two different configurations.

As already mentioned, the experimental conditions prevailing during the injections did not allow us to devote sufficient time in the field for each injection to stabilize. However, the results obtained in Brévilles indicate that the FVPDM method seems to be sufficiently sensible to obtain satisfying results, even in less controlled conditions (see sensitivity in Figure 8).

One of the essential conditions for being able to calculate Darcy fluxes with the FVPDM is to inject the tracers at a rate lower than the critical injection rate. For the injections performed in Brévilles, the injections rates have never been larger than the critical injection rate. The methodology seems thus relatively reliable provided that a priori estimates of Darcy fluxes are available.

Calculating the real tracer input function in the aquifer

Most often, tracer injection is performed considering a "classical" source term. As shown by Brouyère et al. (2005), this may lead to erroneous interpretation of the tracer test results if the injection has some influence on the shape of the breakthrough curve (because of temporary tracer capturing in the well bore). The FVPDM has the further advantage to be able to reconstitute a "good estimate" of the tracer input function in the aquifer, in order to check *a posteriori* that injection conditions did not influence the results, particularly when the volume of injected tracer fluid is comparable to the volume of water in the injection well.

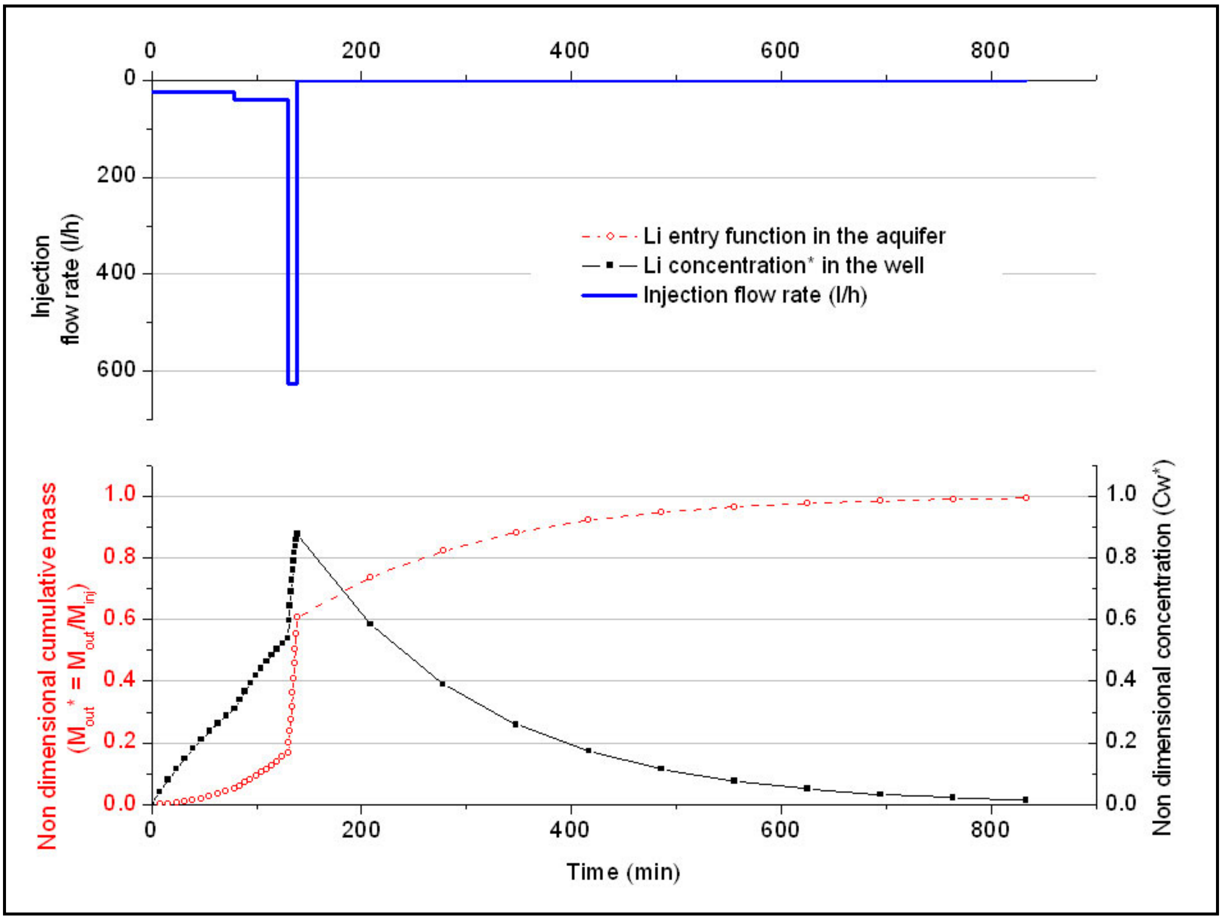

Figure 9: Tracer input function in the aquifer (PZ4)

As an illustration, Figure 9 presents the theoretical input function of cumulative tracer mass in the aquifer (PZ4 injection), calculated using the well-aquifer interaction parameter (transit flow rate) obtained using the FVPDM calibration. The cumulative input function is calculated from the beginning of injection operations until more than 600 min (10 hours) after the end of these operations. The two low flow rate injection steps performed for the FVPDM analysis were followed by a Dirac type injection (more than 600 l/h) of the remaining quantity of tracer.

The curve of cumulative mass of tracer in the aquifer shows that 4 hours after the end of injection, 90 % of the tracer mass injected is already in the aquifer. The entry functions of the three other tracer tests are very similar. Compared to the transit times (several days) of the tracer from the injection points to the Brévilles spring, this is very short and the injections can thus be globally considered as impulses. Therefore, tracer trapping in the well cannot be invoked here as a possible reason to explain the non detection of tracers at the spring or atypical shapes of breakthrough curves.

3.3.2 Interpretation of the breakthrough curves at the spring and at the gauging station

General description of the breakthrough curves

Breakthrough curves for uranine and iodide I^- are respectively presented in Figure 11 and 12. In order to facilitate comparisons, concentrations are plotted after subtraction of the background concentrations and normalization according to the injected mass of tracer. The main characteristic of the breakthrough curves are summarized in Table 7.

		First arrival		Peak 1			Peak 2		Recovery factor after 250 days (%)	Background value
		Time (day)	Calculated speed	Modal time (day)	Modal concentration*	Calculated speed	Modal time (day)	Modal concentration*		
uranine	spring	16	$1.8\ 10^{-4}$ m/s	35	$9.16\ 10^{-2}$ ppb	$8.1\ 10^{-5}$ m/s	164	$4.4\ 10^{-1}$ ppb	0.82	0.027 ppb
	station				$1.78\ 10^{-2}$ ppb		131	$1.6\ 10^{-1}$ ppb	2.11	0.092 ppb
Iodide	spring	4	$7.1\ 10^{-4}$ m/s	25	$9.1\ 10^{-2}$ ppm	$1.1\ 10^{-4}$ m/s	218	$8.9\ 10^{-2}$ ppm	23.6	0.008 ppm
	station				$2.9\ 10^{-2}$ ppm					0.008 ppm

Table 7 : Main characteristics of uranine and iodide breakthrough curves (tracer tests November 2005)

The breakthrough curves present very irregular shapes with successive peaks of concentration, far from “traditional” Gaussian curves. It is possible that precipitations had from time to time negative impacts on concentration values, through dilution during episodic peaks of discharge[2]. This could be particularly the case at the Brévilles spring where the water flow rate is less important and thus more sensible to rainy events. However, rainfall events and variations in flow rates cannot explain alone the general shape of the breakthrough curves.

Such irregularities in the tracer recoveries are probably essentially related to the complexity of groundwater flow and transport mechanisms in the aquifer. Because this complexity is still difficult to capture, the following interpretation is

[2] AquaTerra DL H2.2 has shown that the flow concentration time in the catchment is very short, i.e. peaks of discharge occur about 30 minutes after the rain event and last only a few hours.

essentially conceptual, by formulating hypotheses to explain flow mechanisms that may occur between the injection wells and Brévilles spring. This is completed by first attempts of adjustment of analytical solutions on each identified peak separately.

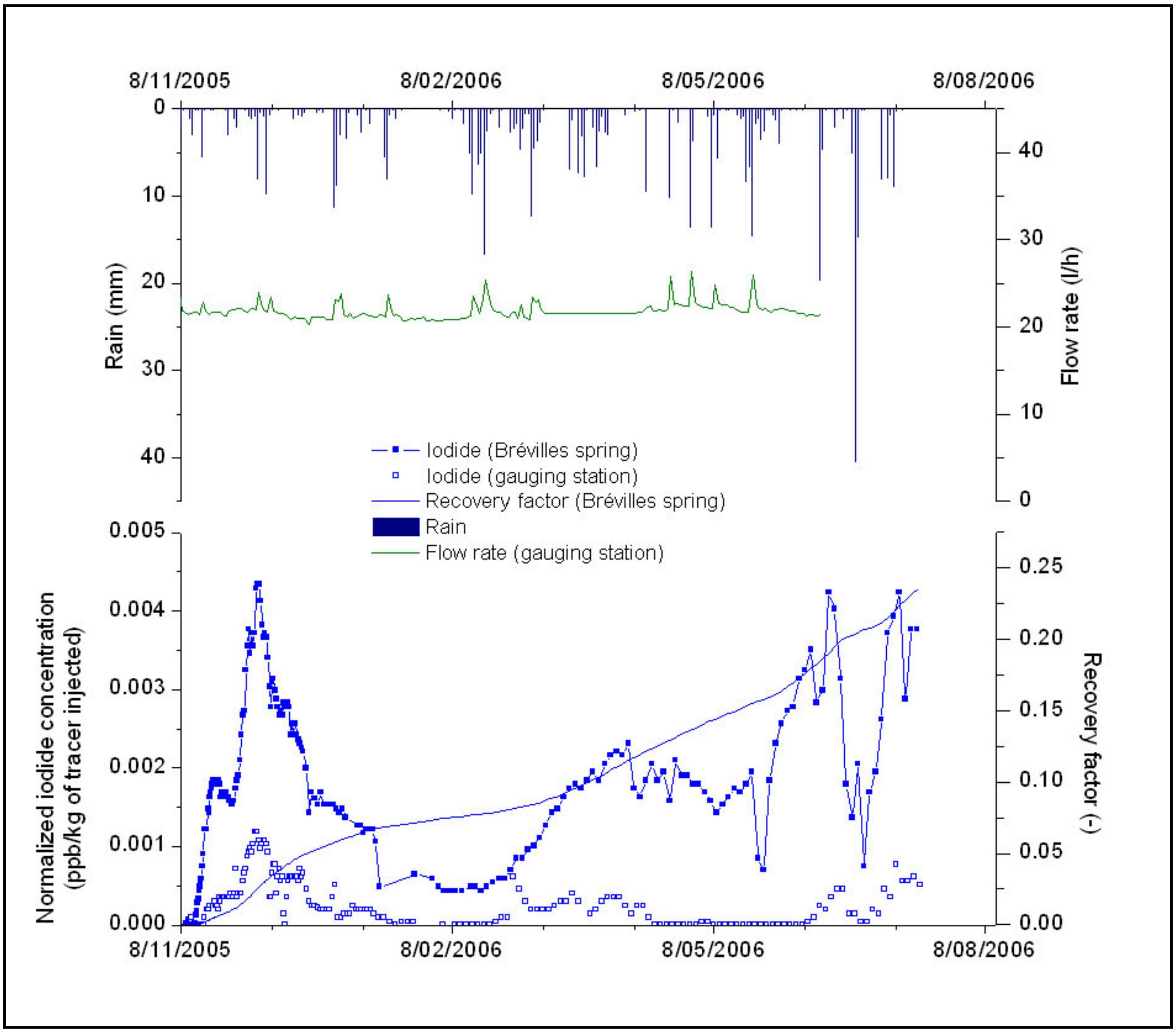

Figure 10: Normalized concentration breakthrough curves of iodide I- at the spring and at gauging station.

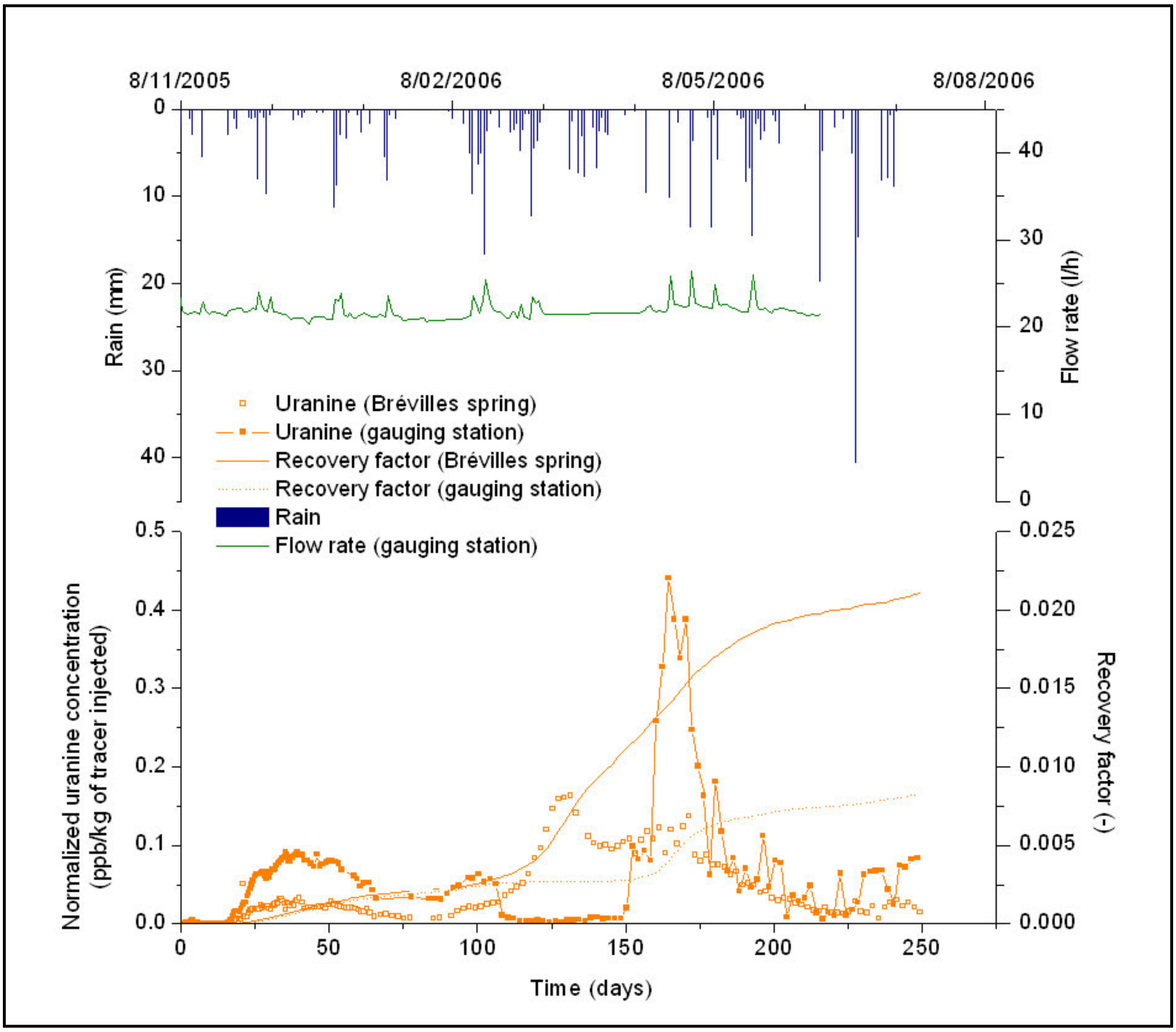

Figure 11: Normalized concentration breakthrough curves of uranine at the spring and at the gauging station.

PZ17b tracer test (Iodide)

For iodide I^-, the calculated recovery factor is equal to 24 % at the spring after 250 days[3]. This is more or less equivalent to the recovery factor calculated for the tracer test performed from PZ7 (with sulforhodamine G) in 2003. At the gauging station, measured concentrations are very close to the background. One can still detect the presence of iodide or even small concentration peaks; however, the signal to noise ratio is too low to calculate any recovery factor with these data. No significant peak, different from those observed at the spring, can be identified at the gauging station. Therefore, it can be assumed that iodide was released at the spring exclusively, the concentration being less important at the gauging station because of dilution related to the augmentation of water flow rate downstream from the spring.

[3] To do this calculation, the water flow rate at the spring (no continuous monitoring) has been artificially reconstituted. The ratio between the spring and the gauging station flow rates was assume to be 3.5, according to instant discharge measurements performed in 2001.

Using the software CATTI, two theoretical curves have been adjusted on the first concentration peak of the iodide breakthrough curve obtained at the Brévilles spring (Figure 12). To do so, a one-dimensional solution is considered with the effective porosity n_e being considered as an adjustable parameter. This model requires also an estimation of the mean Darcy flux. For calibration 1, The Darcy flux is that calculated with Darcy's law applied using pumping test results and the hydraulic gradient estimated between PZ17 and the spring. Calibration 2 is based on the Darcy flux calculated with the FVPDM. Adjusting theoretical curves on the second peak turned out impossible with physically realistic values of effective porosity (n_e). Results are presented in Table 8.

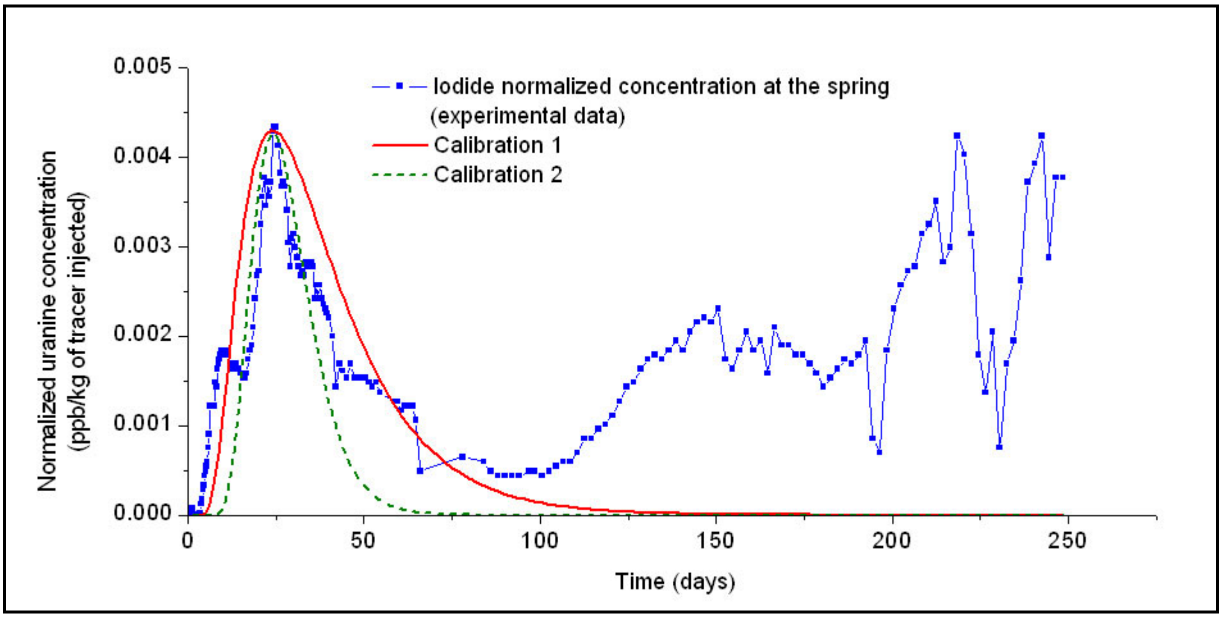

Figure 12 : Adjustment of theoretical curves using "CATTI" (Iodide breakthrough curve at the spring)

	Calibration 1	Calibration 2
Darcy flux	2.0×10^{-5} m/s (Pumping test and Darcy's law)	2.5×10^{-5} m/s (FVPDM)
Effective porosity	0.20	0.24
Dispersion	40 m	13 m

Table 8: Adjustment of theoretical curves on the iodide breakthrough curve - Adjusted parameters

Calibration attempts provide estimates of the effective porosity n_e between 20 and 24 %, in agreement with the results of the tracer test performed in 2003 from PZ7 (see section 3.1).

While the first peak corresponds most probably to advection flows in the porous media, the explanation of the late second peak is less evident. It is probably influenced by other transport mechanisms or other transport pathways. The tracer being of anionic type, “classical” sorption processes are difficult to invoke for explaining such a strong retardation. It is more likely that a non-negligible part of the iodide tracer has travelled along less pervious pathways or that it has been retarded by “large-scale” dual-porosity effects through temporary capturing in less pervious horizons. Another hypothesis would be that a part of the tracer injected would follow a different and slower way to the spring

PZ17c tracer test (Uranine)

The recovery factor for uranine is equal to 2.1 % after 250 days, using the concentration and flow rate values measured at the gauging station. The recovery factor at the level of the spring is estimated to 0.8 %. Such very small values indicate that most of the uranine tracer is still present somewhere in the aquifer.

The significant difference in recovery factor between the two sampling locations suggests that a part of the tracer flew out between the spring and the gauging station. The visual analysis of the uranine breakthrough curves (Figure 11) seems to confirm this hypothesis.

However, from 0 to 100 days after injection, the two concentration are strongly correlated, with an almost constant concentration ratio equal to 3.5 (Figure 11), identical to the discharge ratio between the two points. This indicates that, during the first 100 days, the uranine tracer which is observed at the two sampling locations reaches the spring first and follows the Brévilles brook to reach the gauging station. During that period, the uranine is observed at the downstream sampling location at a lower concentration because of dilution related to the increase of water flow rate between the spring and the gauging station.

After 100 days however, the concentration at the spring falls abruptly to almost zero while the uranine concentration starts to increase at the gauging station, the concentration ratio between the two curves (Figure 11) consequently decreases. This indicates a single arrival between the spring and the gauging station. After 150 days, the ratio is much more variable and is probably a consequence of simultaneous arrivals.

Because they are dependent on the water flow rates, the breakthrough curves presented in Figure 11 are not very representative of the tracer quantities that really arrived respectively at the spring and along the stream. In order to have a more explicit view and to make the analysis easier, the breakthrough curves were plotted using tracer mass flux units (kg of tracer/s)(4) and subtracting from the quantity of uranine “already” detected at the spring from the quantity of uranine detected at the gauging station so as to obtain a breakthrough curve that only corresponds to tracer arrivals downstream from the spring and upstream from the gauging station. The resulting breakthrough curves are presented in Figure 13. Doing so, the relative importance of each identified peak in Table 7 can be much more easily visualized and understood. More than half of the recovered uranine was released from the aquifer downstream of the spring (Table 9).

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[4] By multiplying tracer concentrations and water flow rates.

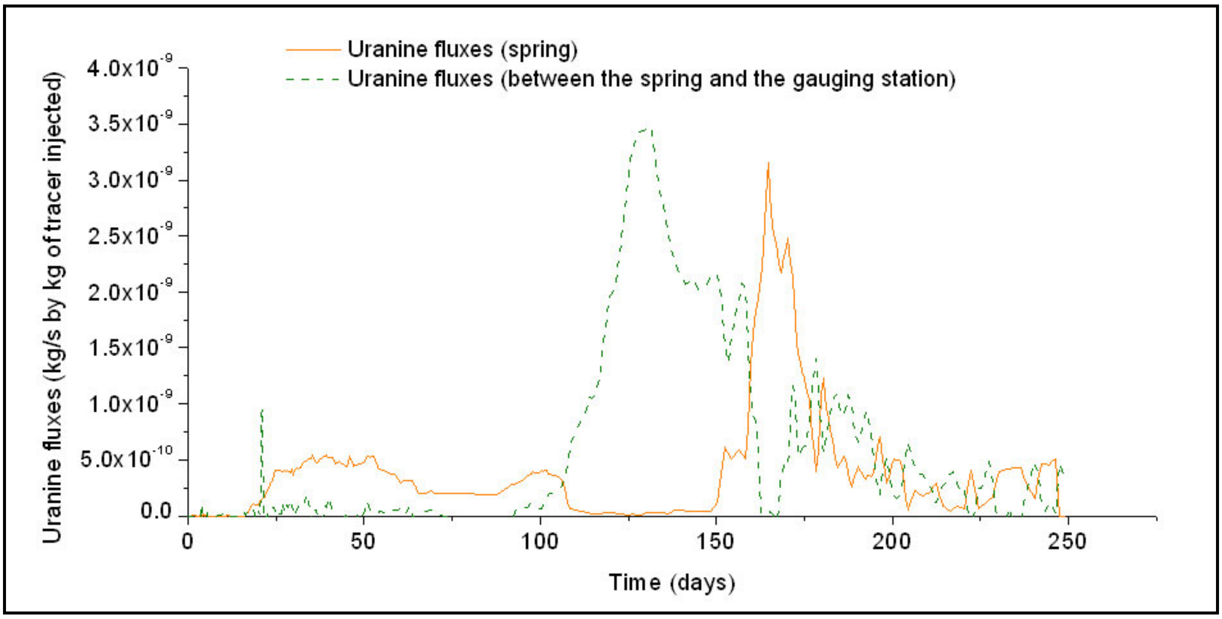

Figure 13 : Uranine flow rate (kg/s) at the spring and at the gauging station

	Location	Modal time (days)	Tracer flux (kg/s by kg of tracer injected)	Corresponding recovery factor (%)
Peak 1	spring	38.8	5.27E-10	0.26
Peak 2	between spring and gauging station	131.4	3.48E-09	1.27
Peak 3	spring	164.3	2.81E-09	0.55

Table 9 : Relative importance of each identified peak of uranine

As for the tracer test performed in PZ17b, theoretical curves were adjusted, using the one-dimensional model available in CATTI on the first concentration peaks at the spring (Peak 1, Calibration 1) and at the gauging station (Peak 2, Calibration 2). This was carried out using a Darcy flux calculated with Darcy's law (0.62×10^{-5} m/s). Results are presented on Table 10. The resulting calibrated effective porosity is equal to 10% and 14 %, respectively.

Parameters estimated for the first and only peak observed between the spring and the gauging station are probably representative of the lower part of the sand aquifer layer (see Figure 14). This hypothesis is in accordance with the idea of horizontal flows between PZ17c, screened in the lower part of the sand layer, and the gauging station, which is located at the base of the sandy layer.

The first peak observed at the spring is approximately five times less important than the peak observed at the gauging station, considering the actual quantities of tracer recovered (see Table 9). The hypothesis of a tracer transfer through a hypothetic connection between PZ17c and PZ17b is not really plausible: in this case uranine would have appeared simultaneously with iodide, but the first detection of uranine occurs more than 12 days after the first detection of iodide (injected in PZ17b). Another hypothesis is the occurrence of vertical interactions within the aquifer, from less to more permeable levels. This would explain simultaneously the time transfer between the well and the spring (more rapid than the first uranine detection time at the gauging station but slower than the first iodide detection at the spring) and the more important dispersion that characterised the first uranine peak observed at the spring.

The second concentration peak detected at the spring after more than 150 days relates back to the second iodide peak and its occurrence is probably due to the same phenomena.

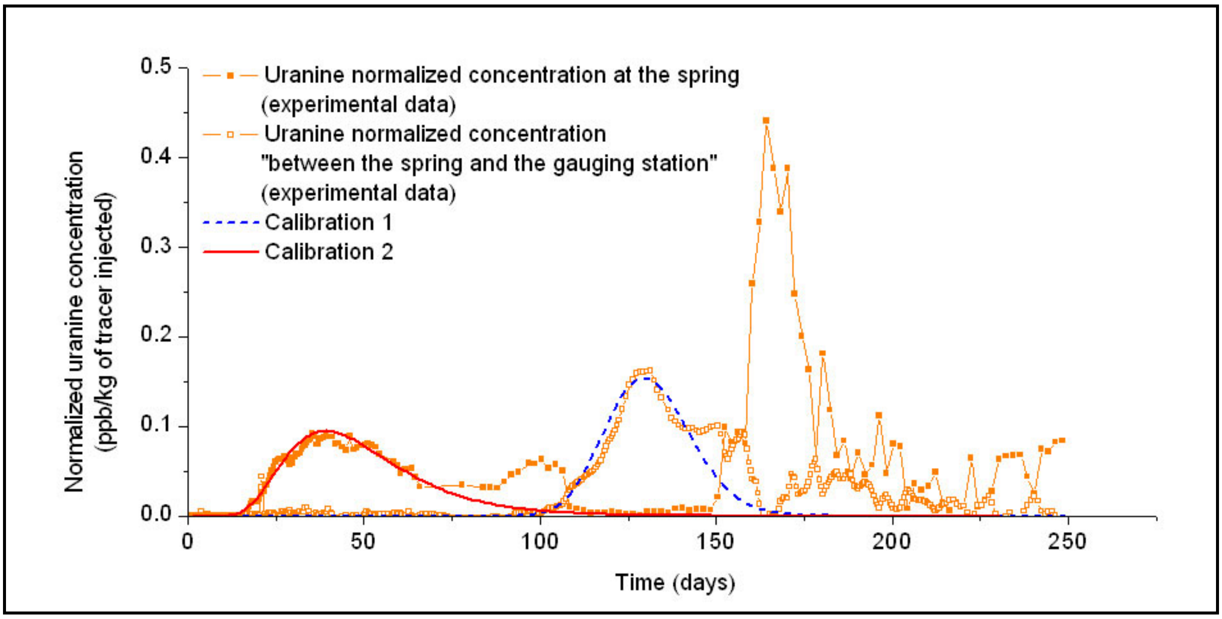

Figure 14 : Adjustment of theoretical curves on the uranine breakthrough curves at the spring and at the gauging station, using CATTI

	Calibration 1	Calibration 2
Darcy flux	0.62×10^{-5} m/s (Pumping test and Darcy's law)	0.62×10^{-5} m/s (Pumping test and Darcy's law)
Effective porosity	0.10	0.14
Dispersion	2 m	20 m

Table 10 : Parameters adjusted on the uranine breakthrough curves

Tracer tests at PZ4 and PZ19

As mentioned previously, tracers injected at PZ4 and PZ19, located at 50 m from one another and at 187 m and 223 m from the spring respectively, were never recovered from the spring or the gauging station. Several points should be considered to understand the reasons of this absence:

- ❖ Considering the mass of product used for this experiment (6.6 kg of Lithium and 10 kg of sulforhodamine B), it is not likely that these tracers did not appear because of a detection limit problem (particularly for sulforhodamine B).

- ❖ Monitoring the concentration evolutions in the injection wells has confirmed that the tracer did not remain in the well. Other tests such as pumping tests also showed that these wells are not clogged.

- ❖ PZ4 is screened in the deeper part of the aquifer but Pz19 is not. Therefore the explanation might not be in the vertical differentiation of the aquifer.

Finally a few hypotheses remain:

- ❖ Groundwater flow in the PZ4-PZ19 area is extremely slow and the tracers are still on their way. Sampling will go on to verify this hypothesis.

- ❖ Adsorption of the tracers in the aquifer is possible. Batch or column experiments should be performed to verify this hypothesis.

- ❖ The tracers took a different pathway, leading to another outlet outside of the assumed hydrogeological catchment of the spring.

The presence of a fault has been evidenced by geophysical survey in the close vicinity of the two wells. The fault could slow down groundwater flows, acting as a barrier; trap the tracers in a compartmented “dead end” zone, or it could divert them to a remote location. Isotopic analysis carried out showed that Pz4 water had no tritium (nor nitrates or pesticides). PZ4 water is therefore older than about 40 years old, which indeed is a sign of very slow (or null) progression. On the contrary, nitrates and pesticides were detected at PZ19 (Tritium was not analysed yet).

No conclusion can thus be made yet as to explain the absence of recovery of the tracers injected at PZ4 and PZ19, but this absence clearly show that this part of the catchment is far more complex than previously estimated.

First conclusions on the interpretation of the breakthrough curves

Generally, the transfer times between the injection wells and the spring are larger for uranine, injected in the lower part of the sand layer. The quantity of uranine recovered after 250 days is also less important than the quantity of iodide recovered. This is in accordance with the idea of a higher hydraulic conductivity at the top of the formation and decreasing with depth. Finer particles of sand could also induce greater retardation effects (macroscale dual porosity effects).

The hypothesis of a strict stratification of groundwater flows within the aquifer is not verified. Even if most of the recovered uranine is detected at the gauging station only, weaker responses at the spring suggest the occurrence of vertical transfers between the lower and middle part of the sand aquifer, either by drainage, or by transverse dispersion between these two layers.

Late concentration peaks, detected at the spring for both injections, cannot be explained yet. They only suggest the influence of different flow mechanisms or pathways between the injection wells and the Brévilles spring.

Finally, the absence of recovery from the tracers injected in PZ4 and PZ19 is probably linked to the geological structure. The presence of a fault may induce a considerable delay in the tracer transfer or it could divert the pathways to other unmonitored outlets, perhaps northwards from the Brévilles spring.

4. General conclusions and perspectives

Despite the fact that the tracer experiments performed in the Brévilles test site have given results that are difficult to interpret (2 tracers have never been detected and the two others have provided atypical, multi-peaked breakthrough curves), this tracing campaign has provided interesting data and new insights for the understanding of the hydro-geological functioning of the Brévilles aquifer.

Based on the analysis and interpretation of the breakthrough curves obtained at the Brévilles spring and at the downstream gauging station, the following conceptual model can be proposed for groundwater flow and transport in the sand aquifer. The stratification of groundwater flow is confirmed by the tracer experiments. The upper aquifer is drained by the Brévilles spring only, while the lower part of the aquifer is drained downstream from the source. Solutes follow an almost horizontal path in the sand layers. The upper sand is characterized by larger transport velocities (because of a larger mean hydraulic conductivity of the coarse sand). The lower part is characterized by lower transport velocities (because of the lower hydraulic conductivity). However, from a hydraulic and hydro-dispersive point of view the lower and upper sand layers are not completely isolated. Tracer test results indicate indeed a progressive transfer of solutes from the lower, less permeable sandy layer, to the upper, more permeable, sandy layer.

At this stage, it is difficult to give precise values of hydro-dispersive parameters for the different aquifer layers. However, the first one-dimensional modelling exercise has indicated that the effective porosity is relatively large, around 20 to 24% in the upper sandy layer and around 10 to 14% in the lower sandy layer. A more detailed modelling application is required for further interpretation.

Apart from this contribution to a better understanding of the Brévilles hydrogeological context, the tracer experiments have also allowed the validation of a new tracer technique (FVPDM) that allows the estimation of local Darcy fluxes whilst providing a way of better controlling injection conditions in the field.

Because the recovery factors are generally very low (especially for uranine), sampling will continue in the future. It could also be very useful to perform batch or column experiments to provide a better understanding of the specific behaviour of the tracers and of possible interactions with the aquifer materials. However, sand samples from the aquifer have already been used for other purposes and new sand coring cannot be performed within the framework of the AquaTerra project.

5. Acknowledgement

Mr. B. Belot, from the Laboratory of water analysis of HGULg performed the analyses of Lithium and Iodide. Dr. P. Meus, from the SME "*European Water Tracing Services - EWTS*", performed the analyses of the fluorescent tracers of the 2005

tracing campaign; he is gratefully acknowledged for his suggestions and comments on the interpretation of the results.

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Appendix

1. Lithological and technical logs of injection wells

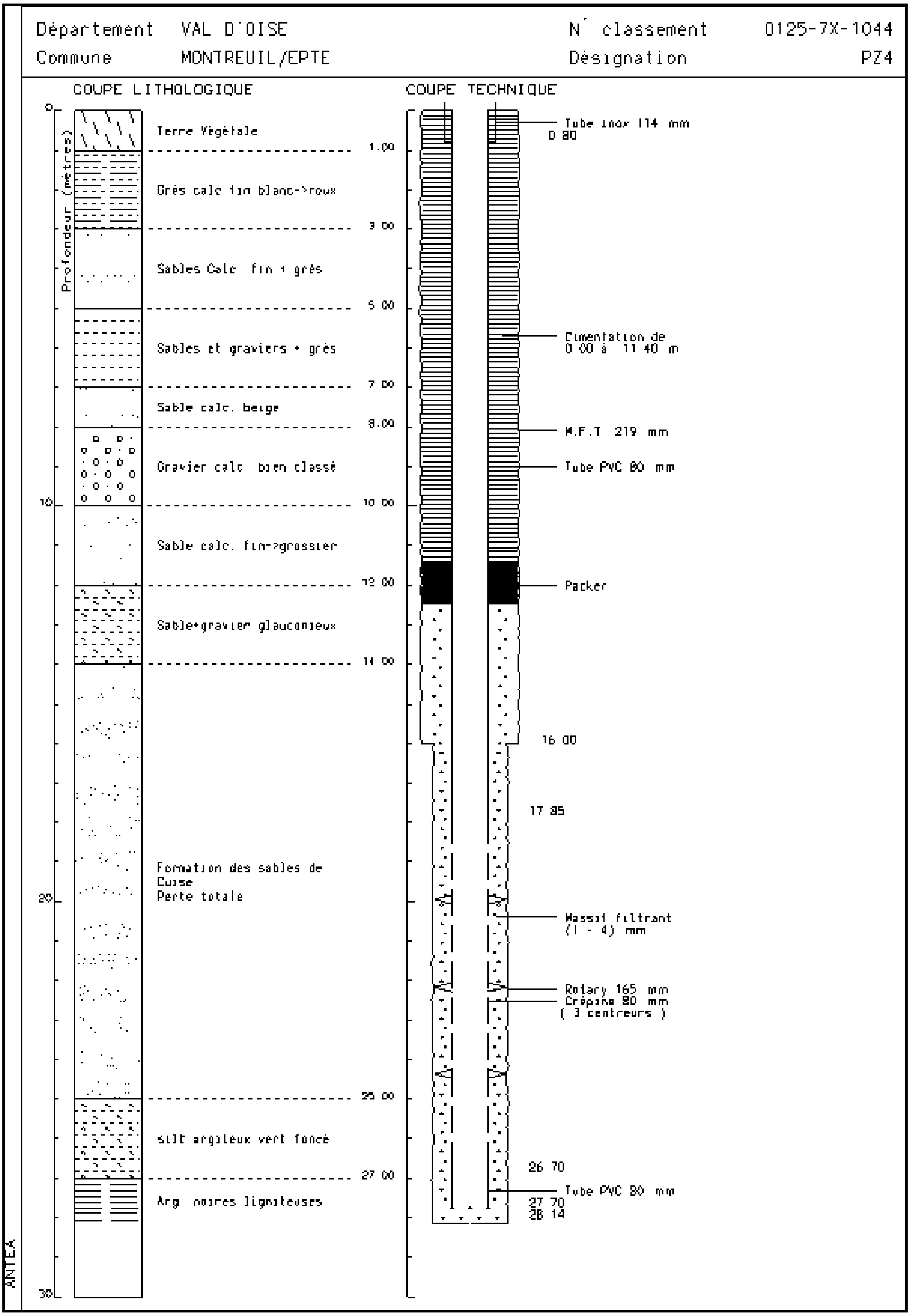


Figure 15 : Lithological and technical crosscut of PZ4

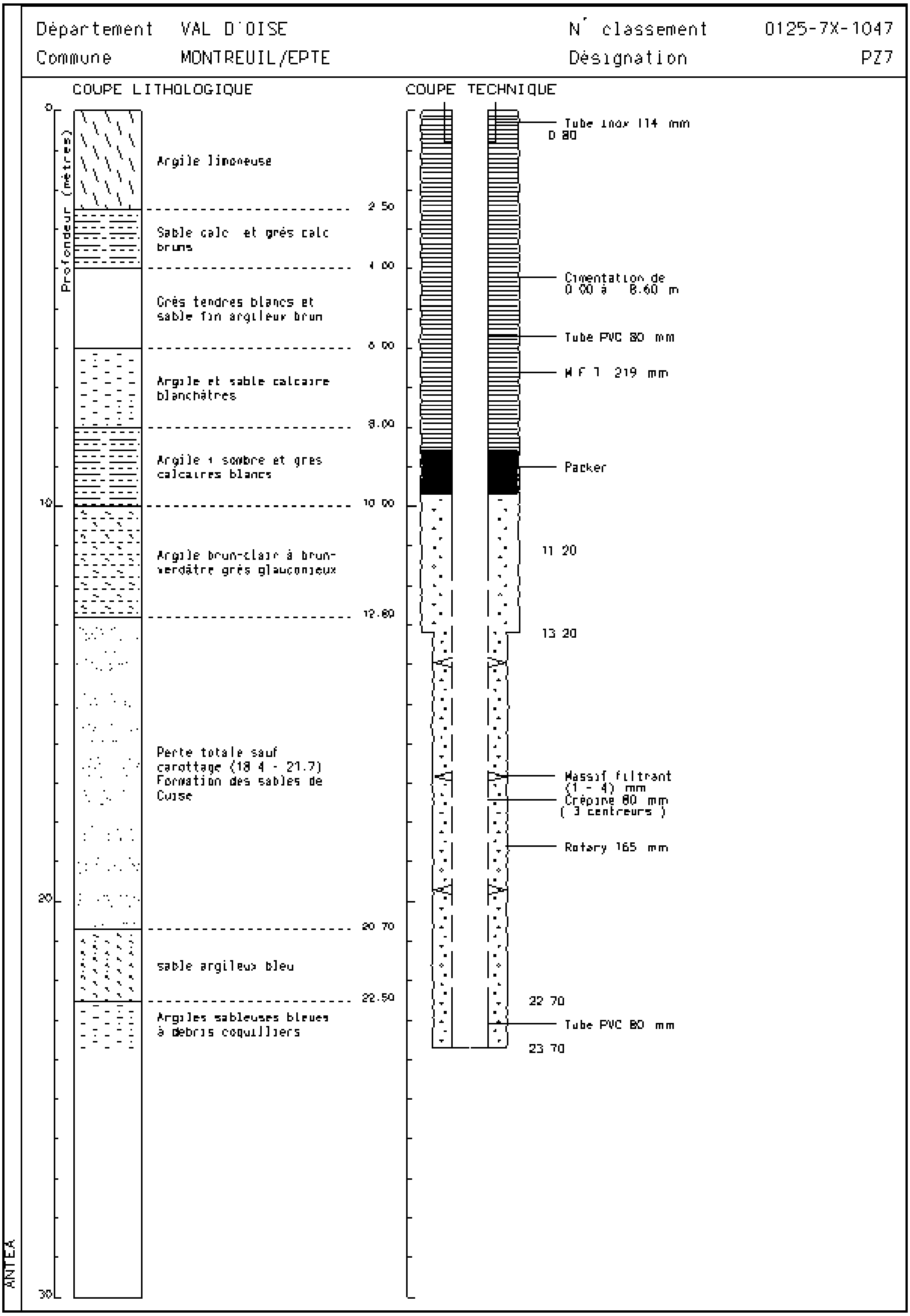


Figure 16 : Lithological and technical crosscut of PZ7

Département : Val d'Oise
Commune : Buhy

Numéro classement : 0125-7X-0017
Désignation : PZ17a-b-c

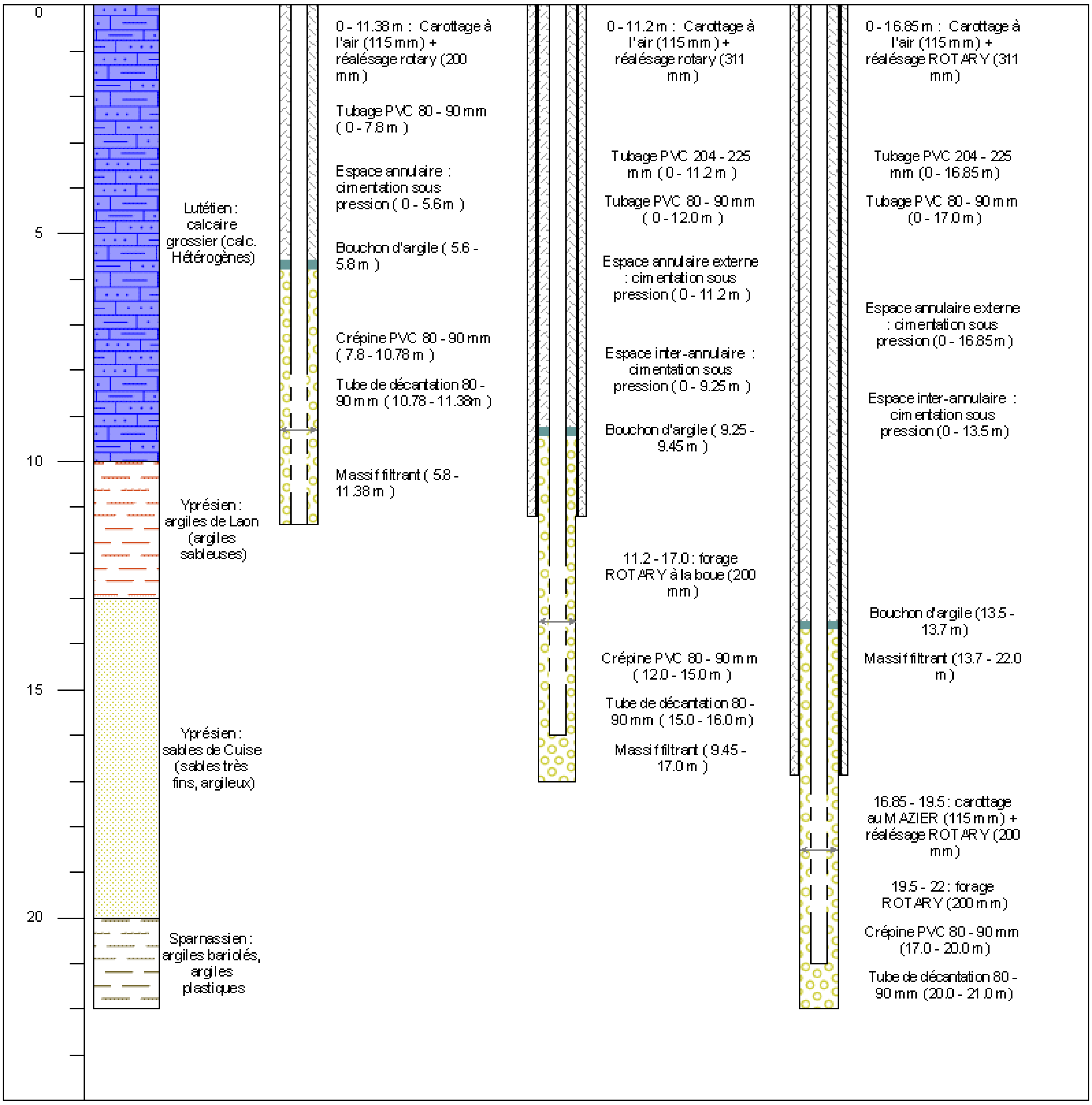
Dates d'exécution

début : 10/05/2005
fin : 26/05/2004

Localisation *(Coord. Lambert 1)*

x : 552.908 km
y : 164.163 km
z sol # 89.50 m (PZ17c)

Profondeur totale : 11.38 - 16.0 - 21 m
Niveau statique : -9.93
mesuré le 06/07/2005



Maître d'oeuvre : *BRGM*
Compagnie de forage : *Picardie forage*
Supervision : *Gutierrez A. (BRGM); Goderniaux P. (ULg)*

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Figure 17 : Lithological and technical crosscut of PZ17

Département : Val d'Oise
Commune : Buhy

Numéro classement : 0125-7X-0019
Désignation : PZ19

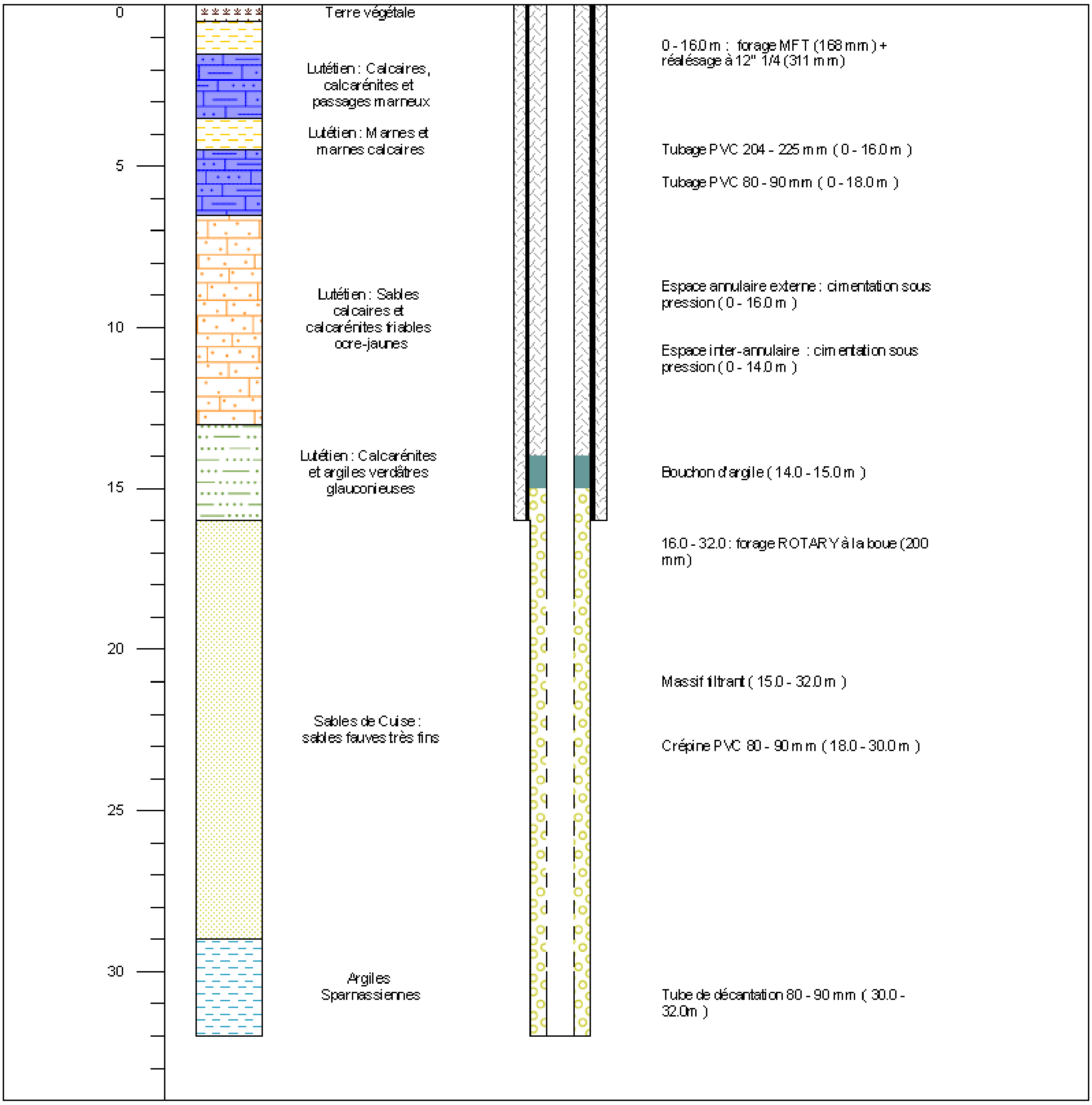
Dates d'exécution

début : 24/05/2005
fin : 03/06/2005

Localisation *(Coord. Lambert 1)*

x : 552.876 km
y : 164.460 km
z sol # 98.96 m

Profondeur totale : 32.00 m
Niveau statique : 82.56 m
mesuré le 06/07/05



Maître d'oeuvre : *BRGM*
Compagnie de forage : *Picardie forage*
Supervision : *Gutierrez A. (BRGM); Goderniaux P. (ULg)*

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Figure 18 : Lithological and technical crosscut of PZ19

2. Concentrations measured in the injection wells

2.1 Injection in PZ4

Injection piezometer	PZ4
Injection date	10/11/2005 (pm)
Depth of the well (m)	28
Water level (reference : top of external casing) (m)	13.69
Recirculation pump position (reference : top of external casing) (m)	27
Frequency of the pump during injection (recirculation) (hz)	180
Approximated recirculation flow rate (l/h)	1000
Tracer type	LiCl
Total mass of tracer injected (kg)	40.36 (LiCl) --> 6.61 (Li)
Concentration of tracer liquid (ppb)	$4.13\times10^{+7}$
Water volume in the injection piezometer (l)	71
Volume of liquid injected at a low flow rate (l)	60
Volume of liquid injected at a high flow rate (l)	100
Total volume of liquid injected (l)	160

description	Time (min)	N° sample	Concentration (ppb)	Injection flow rate (l/h)
Start of low flow rate injection	0.00			23.48
1st injection step	5.00	1	$5.60\times10^{+6}$	I
	10.00	2	$1.09\times10^{+6}$	I
	15.00	3	$1.57\times10^{+6}$	I
	25.00	4	$2.58\times10^{+6}$	I
	37.00	5	$3.82\times10^{+6}$	I
	47.00	6	$4.62\times10^{+6}$	I
	56.00	7	$5.18\times10^{+6}$	I
	65.00	8	$5.91\times10^{+6}$	I
	78.00	9	$6.78\times10^{+6}$	I
	79.00			*23.48*
2d injection step	79.00			40.91
	85.00	10	$7.60\times10^{+6}$	I
	90.00	11	$7.96\times10^{+6}$	I
	95.00	12	$8.53\times10^{+6}$	I
	100.00	13	$9.01\times10^{+6}$	I
	108.00	14	$9.74\times10^{+6}$	I
	114.00	15	$1.03\times10^{+7}$	I
	120.00	16	$1.02\times10^{+7}$	I
	130.00			*40.91*
End of low flow rate injection	130.00	17	$1.10\times10^{+7}$	0
Start of low flow rate injection	131.00			
End of low flow rate injection	139.00			

Table 11 : Concentration values measured in PZ4 during injection operations

2.2 Injection in PZ19

Injection piezometer	PZ19
Injection date	8/11/2005 (pm)
Depth of the well (m)	32 (sealed up at 28.40 m)
Water level (reference : top of external casing) (m)	18.47
Recirculation pump position (reference : top of external casing) (m)	25
Frequency of the pump during injection (recirculation) (hz)	180
Approximated recirculation flow rate (l/h)	1000
Tracer type	Sulforhodamine B
Total mass of tracer injected (kg)	10.07
Concentration of tracer liquid (ppb)	$1.06\times10^{+8}$
Water volume in the injection piezometer (l)	78
Volume of liquid injected at a low flow rate (l)	95

description	Time (min)	N° sample	Concentration (ppb)	Injection flow rate (l/h)
Start of low flow rate injection	0			23.48
1st injection step	3	1	$1.26\times10^{+6}$	I
	14	2	$5.41\times10^{+6}$	I
	25	3	$9.03\times10^{+6}$	I
	35	4	$1.27\times10^{+7}$	I
	45	5	$1.59\times10^{+7}$	I
	55	6	$1.85\times10^{+7}$	I
	65	7	$2.13\times10^{+7}$	I
	75	8	$2.31\times10^{+7}$	I
	82			*23.48*
2d injection step	82	9	$2.48\times10^{+7}$	39.85
	88	10	$2.50\times10^{+7}$	I
	95	11	$2.60\times10^{+7}$	I
	106	12	$3.01\times10^{+7}$	I
	116	13	$3.16\times10^{+7}$	I
	125	14	$3.37\times10^{+7}$	I
	135	15	$3.84\times10^{+7}$	I
	150	16	$3.96\times10^{+7}$	I
	170	17	$4.28\times10^{+7}$	I
	180	18	$4.59\times10^{+7}$	I
	181			*39.85*
End of low flow rate injection	181			0
	185	19	$4.38\times10^{+7}$	
	206	20	$4.38\times10^{+7}$	
	268	21	$3.91\times10^{+7}$	

Table 12 : Concentration values measured in PZ19 during injection operations

2.3 Injection in PZ17b

Injection piezometer	PZ17b
Injection date	09/11/2005 (am)
Depth of the well (m)	16
Water level (reference : top of external casing) (m)	10.19
Recirculation pump position (reference : top of external casing) (m)	15
Frequency of the pump during injection (recirculation) (hz)	180
Approximated recirculation flow rate (l/h)	1000
Tracer type	KI
Total mass of tracer injected (kg)	25.12 (KI) --> 19.21 (I-)
Concentration of tracer liquid (g/l)	120.03
Water volume in the injection piezometer (l)	30
Volume of liquid injected at a low flow rate (l)	68
Volume of liquid injected at a high flow rate (l)	92
Total volume of liquid injected (l)	160

description	Time (min)	N° sample	Concentration (g/l)	Injection flow rate (l/h)
Start of low flow rate injection	0.00		0.000	*9.41*
1st injection step	5.00	1	4.458	I
	13.67	2	11.154	I
	24.00	3	15.828	I
	34.00	4	19.747	I
	44.00	5	22.933	I
	54.00	6	25.590	I
	59.00			*9.41*
2d injection step	59.00			*21.43*
	64.00	7	30.821	I
	75.00	8	38.435	I
	84.00	9	42.699	I
	93.00	10	48.181	I
	94.00			*21.43*
3d injection step	94.00			*32.58*
	99.00	11	53.719	I
	104.00	12	59.917	I
	109.00	13	64.960	I
	114.00	14	67.665	I
	119.00	15	71.134	I
	124.00			*32.58*
4th injection	124.00	16	74.721	*39.85*
	126.00	17	75.774	I
	129.00	18	78.020	I
	139.00	19	83.911	I
	149.00			*39.85*
End of low flow rate injection	149.00	20	88.143	0
	161.00	21	74.631	
Start of low flow rate injection	164.00			
End of low flow rate injection	205.00			

Table 13 : Concentration values measured in PZ17b during injection operations

2.4 Injection in PZ17c

Injection piezometer	PZ17c
Injection date	09/11/2005 (pm)
Depth of the well (m)	21
Water level (reference : top of external casing) (m)	9.93
Recirculation pump position (reference : top of external casing) (m)	19.5
Frequency of the pump during injection (recirculation) (hz)	180
Approximated recirculation flow rate (l/h)	1000
Tracer type	Uranine
Total mass of tracer injected (kg)	5.03
Concentration of tracer liquid (ppb)	$1.12\times10^{+8}$
Water volume in the injection piezometer (l)	51
Volume of liquid injected at a low flow rate (l)	22
Volume of liquid injected at a high flow rate (l)	68
Total volume of liquid injected (l)	90

description	Time (min)	N° sample	Concentration (ppb)	Injection flow rate (l/h)
Start of low flow rate injection	0.00			5.79
1st injection step	3.50	1	$6.16\times10^{+5}$	I
	11.50	2	$2.00\times10^{+6}$	I
	18.50	3	$3.32\times10^{+6}$	I
	26.50	4	$4.37\times10^{+6}$	I
	35.50	5	$5.70\times10^{+6}$	I
	56.50	6	$8.37\times10^{+6}$	I
	71.50	7	$9.97\times10^{+6}$	I
	86.50	8	$1.01\times10^{+7}$	I
	101.50			*5.79*
2d injection step	101.50	9	$1.02\times10^{+7}$	15.87
	109.50	10	$1.34\times10^{+7}$	I
	116.50	11	$1.64\times10^{+7}$	I
	130.50	12	$2.18\times10^{+7}$	I
	132.50			*15.87*
3d injection step	132.50			32.58
	136.50	13	$2.35\times10^{+7}$	I
	139.50	14	$2.62\times10^{+7}$	I
	142.50	15	$2.89\times10^{+7}$	I
	146.50	16	$3.14\times10^{+7}$	I
	148.50			*32.58*
End of low flow rate injection	148.50			0
Start of low flow rate injection	149.50			
End of low flow rate injection	158.50			

Table 14 : Concentration values measured in PZ17c during injection operations

3. Concentrations measured at the spring and at the gauging station

3.1 Spring

n° sample	date - hour	time (day)			Concentrations			
					Uranine	***Sulforhodamine B***	***Li***	***I***
		Uranine	KI	Sulfo B	*ppb*	int. 564,0/584,0 nm	*ppm*	*ppm*
injection Sulfo B	08/11/2005 13:15:00			0.000				
injection KI	09/11/2005 10:35:00		0.000					
injection uranine	09/11/2005 15:09:00	0.000						
S1	09/11/2005 15:30:00	0.015	0.205	1.094	0.024	1.836	3	0.008
S2	10/11/2005 12:00:00	0.869	1.059	1.948	0.024	1.682		0.009
S3	10/11/2005 18:45:00	1.150	1.340	2.229	0.028	1.876		0.009
S4	11/11/2005 00:45:00	1.400	1.590	2.479	0.030	1.822	3	0.008
S5	11/11/2005 06:45:00	1.650	1.840	2.729	0.032	1.916		0.007
S6	11/11/2005 12:45:00	1.900	2.090	2.979	0.028	1.743		0.007
S7	11/11/2005 18:45:00	2.150	2.340	3.229	0.026	1.744	3	0.007
S8	12/11/2005 00:45:00	2.400	2.590	3.479	0.029	1.907		0.007
S9	12/11/2005 06:45:00	2.650	2.840	3.729	0.027	1.714		0.007
S10	12/11/2005 12:45:00	2.900	3.090	3.979	0.025	1.716	3	0.007
S11	12/11/2005 18:45:00	3.150	3.340	4.229	0.025	1.636		0.008
S12	13/11/2005 00:45:00	3.400	3.590	4.479	0.031	1.727		0.008
S13	13/11/2005 06:45:00	3.650	3.840	4.729	0.044	1.669	3	0.01
S14	13/11/2005 12:45:00	3.900	4.090	4.979	0.025	1.702		0.011
S15	13/11/2005 18:45:00	4.150	4.340	5.229	0.033	1.83		0.013
S16	14/11/2005 00:45:00	4.400	4.590	5.479	0.038	2.013	3	0.014
S17	14/11/2005 06:45:00	4.650	4.840	5.729	0.024	1.677		0.016
S18	14/11/2005 12:45:00	4.900	5.090	5.979	0.035	1.802		0.017
S19	14/11/2005 18:45:00	5.150	5.340	6.229	0.032	1.737	3	0.018
S20	15/11/2005 00:45:00	5.400	5.590	6.479	0.028	1.774		0.019
S21	15/11/2005 06:45:00	5.650	5.840	6.729	0.024	1.603		0.022
S22	15/11/2005 12:45:00	5.900	6.090	6.979	0.025	1.646	3	0.025
S23	15/11/2005 21:45:00	6.275	6.465	7.354	0.026	1.769		0.031
S24	16/11/2005 03:45:00	6.525	6.715	7.604	0.025	1.725		0.031
S25	16/11/2005 09:45:00	6.775	6.965	7.854	0.023	1.714		
S26	16/11/2005 15:45:00	7.025	7.215	8.104	0.023	1.652	3	0.031
S27	16/11/2005 22:00:00	7.285	7.476	8.365	0.025	1.698		0.031
S28	17/11/2005 04:00:00	7.535	7.726	8.615	0.023	1.648	3	0.036
S29	17/11/2005 10:00:00	7.785	7.976	8.865	0.022	1.629		0.036
S30	17/11/2005 16:00:00	8.035	8.226	9.115	0.022	1.563		0.035
S31	17/11/2005 22:00:00	8.285	8.476	9.365	0.023	1.684	3	0.039
S32	18/11/2005 04:00:00	8.535	8.726	9.615	0.023	1.609		0.04
S33	18/11/2005 10:00:00	8.785	8.976	9.865	0.023	1.598		0.041
S34	18/11/2005 16:00:00	9.035	9.226	10.115	0.023	1.645	3	0.042
S35	18/11/2005 22:00:00	9.285	9.476	10.365	0.031	1.783		0.043
S36	19/11/2005 04:00:00	9.535	9.726	10.615	0.024	1.717		0.043
S37	19/11/2005 10:00:00	9.785	9.976	10.865	0.023	1.647	3	0.043
S38	19/11/2005 16:00:00	10.035	10.226	11.115	0.023	1.605		0.042
S39	19/11/2005 22:00:00	10.285	10.476	11.365	0.025	1.855		0.042
S40	20/11/2005 04:00:00	10.535	10.726	11.615	0.025	1.909	3	0.042
S41	20/11/2005 10:00:00	10.785	10.976	11.865	0.027	2.003		0.043
S42	20/11/2005 16:00:00	11.035	11.226	12.115	0.028	1.972		0.043
S43	20/11/2005 22:00:00	11.285	11.476	12.365	0.030	2.217	3	0.043
S44	21/11/2005 04:00:00	11.535	11.726	12.615	0.028	1.973		0.042
S45	21/11/2005 10:00:00	11.785	11.976	12.865	0.025	1.862		0.039
S46	21/11/2005 18:10:00	12.126	12.316	13.205	0.028	2.017	3	0.039
S47	22/11/2005 00:10:00	12.376	12.566	13.455	0.025	1.815		0.04
S48	22/11/2005 06:10:00	12.626	12.816	13.705	0.026	1.891		0.04
S49	22/11/2005 12:10:00	12.876	13.066	13.955	0.025	1.916	3	0.04
S50	22/11/2005 18:30:00	13.140	13.330	14.219	0.026	1.965		0.039
S51	23/11/2005 00:30:00	13.390	13.580	14.469	0.027	1.929		0.039
S52	23/11/2005 06:30:00	13.640	13.830	14.719	0.027	1.9	3	0.04
S53	23/11/2005 12:30:00	13.890	14.080	14.969	0.026	1.835		0.039
S54	23/11/2005 20:20:00	14.216	14.406	15.295	0.027	2.04		0.039
S55	24/11/2005 02:20:00	14.466	14.656	15.545	0.024	1.726	3	0.039
S56	24/11/2005 08:20:00	14.716	14.906	15.795	0.024	1.785		0.038
S57	24/11/2005 14:20:00	14.966	15.156	16.045	0.023	1.62		0.038

S58	25/11/2005 02:55:00	15.490	15.681	16.569	0.025	1.782	3	0.037
S59	25/11/2005 14:55:00	15.990	16.181	17.069	0.027	1.749		0.037
S60	26/11/2005 02:55:00	16.490	16.681	17.569	0.030	1.648		0.038
S61	26/11/2005 14:55:00	16.990	17.181	18.069	0.054	1.878	3	0.041
S62	27/11/2005 02:55:00	17.490	17.681	18.569	0.075	1.853		0.043
S63	27/11/2005 14:55:00	17.990	18.181	19.069	0.095	1.781		0.044
S64	28/11/2005 02:55:00	18.490	18.681	19.569	0.110	3.751	3	0.048
S65	28/11/2005 14:55:00	18.990	19.181	20.069	0.110	1.986		0.054
S66	29/11/2005 04:20:00	19.549	19.740	20.628	0.107	1.801		0.059
S67	29/11/2005 15:30:00	20.015	20.205	21.094	0.103	1.889	3	0.06
S68	30/11/2005 03:15:00	20.504	20.694	21.583	0.122	1.806		0.07
S69	30/11/2005 15:15:00	21.004	21.194	22.083	0.148	1.855		0.076
S70	01/12/2005 03:15:00	21.504	21.694	22.583	0.165	1.877	3	0.08
S71	01/12/2005 14:10:00	21.959	22.149	23.038	0.165	1.868		0.074
S72	02/12/2005 02:10:00	22.459	22.649	23.538	0.202	1.871		0.079
S73	02/12/2005 14:10:00	22.959	23.149	24.038	0.225	1.816	3	0.076
S74	03/12/2005 02:10:00	23.459	23.649	24.538	0.252	2.713	2.8	0.079
S75	03/12/2005 14:10:00	23.959	24.149	25.038	0.279	2.536	2.6	0.090
S76	04/12/2005 02:10:00	24.459	24.649	25.538	0.302	2.574	2.7	0.091
S77	04/12/2005 14:10:00	24.959	25.149	26.038	0.329	2.698	2.6	0.091
S78	05/12/2005 02:10:00	25.459	25.649	26.538	0.341	2.517	2.5	0.087
S79	05/12/2005 14:10:00	25.959	26.149	27.038	0.345	2.544	2.6	0.081
S80	06/12/2005 03:00:00	26.494	26.684	27.573	0.344	2.083	2.5	0.078
S81	06/12/2005 15:00:00	26.994	27.184	28.073	0.349	3.221	2.5	0.079
S82	07/12/2005 03:00:00	27.494	27.684	28.573	0.356	2.522	3.3	0.078
S83	07/12/2005 15:00:00	27.994	28.184	29.073	0.349	1.924	2.4	0.073
S84	08/12/2005 03:00:00	28.494	28.684	29.573	0.334	1.993	2.5	0.066
S85	08/12/2005 15:00:00	28.994	29.184	30.073	0.316	2.297	2.6	0.061
S86	09/12/2005 00:00:00	29.369	29.559	30.448	0.356	2.807	2.6	0.067
S87	09/12/2005 12:00:00	29.869	30.059	30.948	0.322	1.174	2.2	0.068
S88	10/12/2005 00:00:00	30.369	30.559	31.448	0.355	2.278	2.3	0.065
S89	10/12/2005 12:00:00	30.869	31.059	31.948	0.376	2.248	2.4	0.063
S90	11/12/2005 00:00:00	31.369	31.559	32.448	0.367	2.37	3.6	0.061
S91	11/12/2005 12:00:00	31.869	32.059	32.948	0.377	2.075	2.5	0.059
S92	12/12/2005 00:00:00	32.369	32.559	33.448	0.402	2.428	2.3	0.060
S93	12/12/2005 12:00:00	32.869	33.059	33.948	0.417	2.03	2.5	0.059
S94	13/12/2005 00:00:00	33.369	33.559	34.448	0.422	1.124	2.5	0.062
S95	13/12/2005 12:00:00	33.869	34.059	34.948	0.433	0.937	2.2	0.061
S96	14/12/2005 00:00:00	34.369	34.559	35.448	0.450	2.781	2.2	0.061
S97	14/12/2005 12:00:00	34.869	35.059	35.948	0.456	2.186	2.3	0.062
S98	15/12/2005 00:00:00	35.369	35.559	36.448	0.487	2.657	2.2	0.061
S99	15/12/2005 12:00:00	35.869	36.059	36.948	0.469	2.687	2.4	0.054
S100	16/12/2005 00:00:00	36.369	36.559	37.448	0.427	2.336	2.6	0.057
S101	16/12/2005 12:10:00	36.876	37.066	37.955	0.425	2.331	2	0.054
S102	17/12/2005 00:10:00	37.376	37.566	38.455	0.457	2.424	2.2	0.057
S103	17/12/2005 12:10:00	37.876	38.066	38.955	0.453	2.38	2.2	0.054
S104	18/12/2005 00:10:00	38.376	38.566	39.455	0.463	2.153	2.3	0.053
S105	18/12/2005 12:10:00	38.876	39.066	39.955	0.469	1.012		0.052
S106	19/12/2005 00:10:00	39.376	39.566	40.455	0.486	2.703	2.7	0.051
S107	19/12/2005 12:10:00	39.876	40.066	40.955	0.468	3.198	2.1	0.050
S108	20/12/2005 15:35:00	41.018	41.208	42.097	0.468	2.618	2.1	0.046
S109	21/12/2005 12:00:00	41.869	42.059	42.948	0.431	2.602	3	0.035
S110	22/12/2005 13:00:00	42.910	43.101	43.990	0.433	2.491	3	0.04
S111	23/12/2005 14:00:00	43.952	44.142	45.031				
S112	24/12/2005 15:00:00	44.994	45.184	46.073	0.393	2.562	2.8	0.037
S113	25/12/2005 16:00:00	46.035	46.226	47.115	0.472	2.319	3.3	0.04
S114	26/12/2005 17:00:00	47.077	47.267	48.156	0.398	2.183	3	0.037
S115	27/12/2005 18:00:00	48.119	48.309	49.198	0.410	2.313	3	0.037
S116	28/12/2005 19:00:00	49.160	49.351	50.240				
S117	29/12/2005 20:00:00	50.202	50.392	51.281	0.428	2.424	3.3	0.037
S118	30/12/2005 21:00:00	51.244	51.434	52.323	0.432	2.404	3.3	0.036
S119	31/12/2005 22:00:00	52.285	52.476	53.365	0.424	2.315	3.2	0.035
S120	01/01/2006 23:00:00	53.327	53.517	54.406	0.412	2.468	3.3	0.036
S121	03/01/2006 00:00:00	54.369	54.559	55.448				
S122	07/01/2006 01:00:00	58.410	58.601	59.490	0.334	2.649	3.3	0.032
S123	08/01/2006 02:00:00	59.452	59.642	60.531	0.312	2.725	3.1	0.032
S124	09/01/2006 03:00:00	60.494	60.684	61.573	0.265	2.291	3.2	0.03
S125	10/01/2006 04:00:00	61.535	61.726	62.615	0.285	2.468	3.1	0.031
S126	11/01/2006 05:00:00	62.577	62.767	63.656				
S127	12/01/2006 06:00:00	63.619	63.809	64.698	0.292	2.252	3.2	0.031
S128	13/01/2006 07:00:00	64.660	64.851	65.740	0.243	2.119	2.8	0.028

S129	14/01/2006 12:00:00	65.869	66.059	66.948	0.189	3.644	2.35	0.017
S130	26/01/2006 12:00:00	77.869	78.059	78.948	0.201	3.554	2.94	0.02
S131	01/02/2006 12:00:00	83.869	84.059	84.948	0.186	3.65	2.92	0.019
S132	03/02/2006 12:00:00	85.869	86.059	86.948	0.186	3.499	2.9	0.017
S133	05/02/2006 12:00:00	87.869	88.059	88.948	0.183	3.528	2.9	0.016
S134	07/02/2006 12:00:00	89.869	90.059	90.948	0.218	3.481	3.03	0.016
S135	09/02/2006 12:00:00	91.869	92.059	92.948	0.257	3.565	3.22	
S136	11/02/2006 12:00:00	93.869	94.059	94.948	0.270	3.389	3.21	
S137	14/02/2006 12:00:00	96.869	97.059	97.948	0.321	3.352	2.99	0.017
S138	16/02/2006 00:00:00	98.369	98.559	99.448	0.317	3.743	3.12	0.017
S139	18/02/2006 00:00:00	100.369	100.559	101.448	0.345	3.464	3.21	0.016
S140	20/02/2006 00:00:00	102.369	102.559	103.448	0.294	3.037	3.18	0.017
S141	22/02/2006 00:00:00	104.369	104.559	105.448	0.315	2.881	3.12	0.018
S142	24/02/2006 00:00:00	106.369	106.559	107.448	0.280	2.511	3.07	0.019
S143	26/02/2006 00:00:00	108.369	108.559	109.448	0.080	2.716	3.08	0.019
S144	28/02/2006 00:00:00	110.369	110.559	111.448	0.066	3.255	3.05	0.021
S145	02/03/2006 00:00:00	112.369	112.559	113.448	0.060	3.057	3.24	0.024
S146	04/03/2006 00:00:00	114.369	114.559	115.448	0.041	3.141	3.03	0.024
S147	06/03/2006 00:00:00	116.369	116.559	117.448	0.044	3.166	3.06	0.026
S148	08/03/2006 00:00:00	118.369	118.559	119.448	0.046	3.215	3.09	0.027
S149	10/03/2006 00:00:00	120.369	120.559	121.448	0.048	3.321	3.09	0.029
S150	12/03/2006 00:00:00	122.369	122.559	123.448	0.043	3.319	3.14	0.032
S151	14/03/2006 00:00:00	124.369	124.559	125.448	0.033	2.884	3.17	0.035
S152	16/03/2006 00:00:00	126.369	126.559	127.448	0.040	2.955	3.07	0.036
S153	18/03/2006 00:00:00	128.369	128.559	129.448	0.032	1.581	3.07	0.039
S154	20/03/2006 00:00:00	130.369	130.559	131.448	0.049	3.359	3.27	0.041
S155	22/03/2006 00:00:00	132.369	132.559	133.448	0.050	2.963	3.2	0.042
S156	24/03/2006 00:00:00	134.369	134.559	135.448	0.054	2.66	2.99	0.041
S157	26/03/2006 00:00:00	136.369	136.559	137.448	0.046	2.763	3.07	0.043
S158	28/03/2006 00:00:00	138.369	138.559	139.448	0.067	3.047	2.98	0.045
S159	30/03/2006 00:00:00	140.369	140.559	141.448	0.070	2.736	3.05	0.043
S160	01/04/2006 00:00:00	142.369	142.559	143.448	0.058	1.927	3.1	0.047
S161	03/04/2006 00:00:00	144.369	144.559	145.448	0.063	2.252	3.02	0.049
S162	05/04/2006 00:00:00	146.369	146.559	147.448	0.062	2.146	2.96	0.05
S163	07/04/2006 00:00:00	148.369	148.559	149.448	0.061	2.179	3.05	0.049
S164	09/04/2006 00:00:00	150.369	150.559	151.448	0.130	2.093	3.04	0.052
S165	11/04/2006 00:00:00	152.369	152.559	153.448	0.524	1.832	3.35	0.041
S166	13/04/2006 00:00:00	154.369	154.559	155.448	0.442	3.943	3.46	0.039
S167	15/04/2006 00:00:00	156.369	156.559	157.448	0.494	5.041	3.59	0.043
S168	17/04/2006 00:00:00	158.369	158.559	159.448	0.434	4.436	3.57	0.047
S169	19/04/2006 00:00:00	160.369	160.559	161.448	1.327	4.195	3.76	0.043
S170	21/04/2006 00:00:00	162.369	162.559	163.448	1.673	3.535	3.74	0.045
S171	23/04/2006 00:00:00	164.369	164.559	165.448	2.244	3.583	3.97	0.038
S172	25/04/2006 00:00:00	166.369	166.559	167.448	1.979	2.114	3.98	0.048
S173	27/04/2006 00:00:00	168.369	168.559	169.448	1.730	2.95	4.02	0.044
S174	29/04/2006 00:00:00	170.369	170.559	171.448	1.975	3.245	4.11	0.044
S175	01/05/2006 00:00:00	172.369	172.559	173.448	1.275	3.129	4.2	0.042
S176	03/05/2006 00:00:00	174.369	174.559	175.448	1.038	2.574	4.22	0.042
S177	05/05/2006 00:00:00	176.369	176.559	177.448	0.845	1.654	4.24	0.04
S178	07/05/2006 00:00:00	178.369	178.559	179.448	0.343	2.105	4.32	0.038
S179	09/05/2006 00:00:00	180.369	180.559	181.448	0.935	1.638	2.97	0.035
S180	11/05/2006 00:00:00	182.369	182.559	183.448	0.617	1.674	2.96	0.037
S181	13/05/2006 00:00:00	184.369	184.559	185.448				
S182	15/05/2006 00:00:00	186.369	186.559	187.448	0.449	3.331	3.05	0.041
S183	17/05/2006 00:00:00	188.369	188.559	189.448	0.236	2.142	3	0.04
S184	19/05/2006 00:00:00	190.369	190.559	191.448	0.381	1.846	2.81	0.042
S185	21/05/2006 00:00:00	192.369	192.559	193.448	0.259	2.736	2.82	0.045
S186	23/05/2006 00:00:00	194.369	194.559	195.448	0.310	3.926	3.11	0.024
S187	25/05/2006 00:00:00	196.369	196.559	197.448	0.588	6.384	3.12	0.021
S188	27/05/2006 00:00:00	198.369	198.559	199.448	0.264	3.584	2.94	0.043
S189	29/05/2006 00:00:00	200.369	200.559	201.448	0.431	3.211	3.05	0.052
S190	31/05/2006 00:00:00	202.369	202.559	203.448	0.417	1.913	3.12	0.057
S191	02/06/2006 00:00:00	204.369	204.559	205.448	0.068	1.469	2.95	0.06
S192	04/06/2006 00:00:00	206.369	206.559	207.448	0.206	1.957	3.09	0.061
S193	06/06/2006 00:00:00	208.369	208.559	209.448	0.171	1.57	2.95	0.068
S194	08/06/2006 00:00:00	210.369	210.559	211.448	0.193	2.518	3.04	0.07
S195	10/06/2006 00:00:00	212.369	212.559	213.448	0.271	1.9	3.19	0.075
S196	12/06/2006 00:00:00	214.369	214.559	215.448	0.099	1.831	3.11	0.062
S197	14/06/2006 00:00:00	216.369	216.559	217.448	0.056	3.018	3.04	0.065

S198	16/06/2006 00:00:00	218.369	218.559	219.448	0.100	4.994	3.06	0.089
S199	18/06/2006 00:00:00	220.369	220.559	221.448	0.081	4.82	2.98	0.085
S200	20/06/2006 00:00:00	222.369	222.559	223.448	0.351	6.392	3.12	0.068
S201	22/06/2006 00:00:00	224.369	224.559	225.448	0.079	4.801	3.11	0.042
S202	24/06/2006 00:00:00	226.369	226.559	227.448	0.118	4.776	3.04	0.034
S203	26/06/2006 00:00:00	228.369	228.559	229.448	0.163	4.715	3.07	0.047
S204	28/06/2006 00:00:00	230.369	230.559	231.448	0.343	5.648	3.35	0.022
S205	30/06/2006 00:00:00	232.369	232.559	233.448	0.362	4.828	3.33	0.04
S206	02/07/2006 00:00:00	234.369	234.559	235.448	0.366	3.481	3.32	0.045
S207	04/07/2006 00:00:00	236.369	236.559	237.448	0.369	1.829	2.99	0.058
S208	06/07/2006 00:00:00	238.369	238.559	239.448	0.248	1.38	3.11	0.079
S209	08/07/2006 00:00:00	240.369	240.559	241.448	0.152	2.075	3.21	0.083
S210	10/07/2006 00:00:00	242.369	242.559	243.448	0.402	2.426	3.18	0.089
S211	12/07/2006 00:00:00	244.369	244.559	245.448	0.387	1.614	3.15	0.063
S212	14/07/2006 00:00:00	246.369	246.559	247.448	0.439	5.216	3.23	0.08
S213	16/07/2006 00:00:00	248.369	248.559	249.448	0.446	2.551	3.15	0.08

Table 15 : Concentration values measured at the Brévilles spring

3.2 Gauging station

n° échantillon	heure - date	temps (j)			Concentrations			
					Uranine	***Sulforhodamine G***	***Li***	***I (ppm)***
		Uranine	KI	Sulfo B	***brutes (ppb)***	564,0/584,0	***brutes (ppb)***	***brutes (ppm)***
injection Sulfo B	08/11/2005 13:15:00			0.000				
injection KI	09/11/2005 10:35:00		0.000					
injection uranine	09/11/2005 15:09:00	0.000						
D1	09/11/2005 15:30:00	0.015	0.205	1.094	0.089	1.615	3	0.007
D2	10/11/2005 10:00:00	0.785	0.976	1.865	0.089	1.655		0.006
D3	10/11/2005 19:15:00	1.171	1.361	2.250	0.091	1.624		0.009
D4	11/11/2005 01:15:00	1.421	1.611	2.500	0.083	1.595	3	0.009
D5	11/11/2005 07:15:00	1.671	1.861	2.750	0.093	1.646		0.009
D6	11/11/2005 13:15:00	1.921	2.111	3.000	0.093	1.740		0.01
D7	11/11/2005 19:15:00	2.171	2.361	3.250	0.085	1.521	3	0.008
D8	12/11/2005 01:15:00	2.421	2.611	3.500				
D9	12/11/2005 07:15:00	2.671	2.861	3.750	0.092	1.662		0.008
D10	12/11/2005 13:15:00	2.921	3.111	4.000	0.096	1.704	3	0.008
D11	12/11/2005 19:15:00	3.171	3.361	4.250	0.092	1.634		0.008
D12	13/11/2005 01:15:00	3.421	3.611	4.500	0.093	1.654		0.007
D13	13/11/2005 07:15:00	3.671	3.861	4.750	0.096	1.687	3	0.007
D14	13/11/2005 13:15:00	3.921	4.111	5.000	0.116	2.124		0.007
D15	13/11/2005 19:15:00	4.171	4.361	5.250	0.098	1.751		0.007
D16	14/11/2005 01:15:00	4.421	4.611	5.500	0.093	1.672	3	0.006
D17	14/11/2005 07:15:00	4.671	4.861	5.750	0.095	1.692		0.006
D18	14/11/2005 13:15:00	4.921	5.111	6.000	0.093	1.574		0.006
D19	14/11/2005 19:15:00	5.171	5.361	6.250	0.092	1.626	3	0.006
D20	15/11/2005 01:15:00	5.421	5.611	6.500	0.089	1.629		0.006
D21	15/11/2005 07:15:00	5.671	5.861	6.750	0.099	1.730		0.008
D22	15/11/2005 13:15:00	5.921	6.111	7.000	0.091	1.770	3	0.007
D23	15/11/2005 21:15:00	6.254	6.444	7.333	0.091	1.756		0.008
D24	16/11/2005 01:15:00	6.421	6.611	7.500	0.088	1.791		0.01
D25	16/11/2005 21:30:00	7.265	7.455	8.344	0.089	1.662	3	0.012
D26	17/11/2005 12:15:00	7.879	8.069	8.958	0.092	1.739		0.012
D27	17/11/2005 18:45:00	8.150	8.340	9.229	0.089	1.703		0.013
D28	19/11/2005 12:00:00	9.869	10.059	10.948	0.095	1.766	3	0.014
D29	19/11/2005 18:10:00	10.126	10.316	11.205	0.091	1.737		0.013
D30	20/11/2005 00:10:00	10.376	10.566	11.455	0.092	1.759		0.013
D31	20/11/2005 06:10:00	10.626	10.816	11.705	0.094	1.641	3	0.013
D32	20/11/2005 12:10:00	10.876	11.066	11.955	0.090	1.710		0.013
D33	20/11/2005 18:10:00	11.126	11.316	12.205	0.093	1.813		0.012
D34	21/11/2005 00:10:00	11.376	11.566	12.455	0.092	1.704	3	0.015
D35	21/11/2005 06:10:00	11.626	11.816	12.705	0.090	1.729		0.014
D36	21/11/2005 11:45:00	11.858	12.049	12.938	0.089	1.671		0.014
D37	22/11/2005 00:00:00	12.369	12.559	13.448	0.091	1.704	3	0.015
D38	22/11/2005 12:00:00	12.869	13.059	13.948	0.089	1.695		0.015
D39	23/11/2005 00:00:00	13.369	13.559	14.448	0.088	1.826		0.015
D40	23/11/2005 12:00:00	13.869	14.059	14.948	0.086	1.619	3	0.015
D41	24/11/2005 00:00:00	14.369	14.559	15.448	0.086	1.662		0.015
D42	24/11/2005 10:00:00	14.785	14.976	15.865	0.087	1.804		0.015
D43	25/11/2005 02:40:00	15.480	15.670	16.559	0.089	1.731	3	0.016
D44	25/11/2005 14:40:00	15.980	16.170	17.059	0.098	2.037		0.015
D45	26/11/2005 02:40:00	16.480	16.670	17.559	0.093	1.899		0.016
D46	26/11/2005 14:40:00	16.980	17.170	18.059	0.108	2.203	3	0.022
D47	27/11/2005 02:40:00	17.480	17.670	18.559	0.111	1.808		0.015
D48	27/11/2005 14:40:00	17.980	18.170	19.059	0.115	1.882		0.016
D49	28/11/2005 02:40:00	18.480	18.670	19.559	0.127	2.23	3	0.016
D50	28/11/2005 14:40:00	18.980	19.170	20.059	0.116	1.904		0.016
D51	29/11/2005 04:00:00	19.535	19.726	20.615	0.108	1.26		0.019
D52	29/11/2005 15:10:00	20.001	20.191	21.080	0.123	1.913	3	0.021
D53	30/11/2005 03:15:00	20.504	20.694	21.583	0.119	1.366		0.022
D54	30/11/2005 15:15:00	21.004	21.194	22.083	0.347	1.752		0.025
D55	01/12/2005 03:15:00	21.504	21.694	22.583	0.134	1.657	3	0.026
D56	01/12/2005 14:00:00	21.952	22.142	23.031	0.139	1.508		0.027
D57	02/12/2005 02:00:00	22.452	22.642	23.531	0.137	1.376		0.026
D58	02/12/2005 14:00:00	22.952	23.142	24.031	0.163	1.538	3	0.028
D59	03/12/2005 02:00:00	23.452	23.642	24.531	0.176	2.569	2.4	0.031
D60	03/12/2005 14:00:00	23.952	24.142	25.031	0.181	2.469	2.4	0.031
D61	04/12/2005 02:00:00	24.452	24.642	25.531	0.187	2.383	2.6	0.031
D62	04/12/2005 14:00:00	24.952	25.142	26.031	0.184	2.052	2.4	0.029
D63	05/12/2005 02:00:00	25.452	25.642	26.531	0.180	2.155	2.6	0.027
D64	05/12/2005 14:00:00	25.952	26.142	27.031	0.187	2.116	2.5	0.028
D65	06/12/2005 02:40:00	26.480	26.670	27.559	0.186	1.759	2.4	0.029
D66	06/12/2005 14:40:00	26.980	27.170	28.059	0.210	2.537	2.6	0.029
D67	07/12/2005 02:40:00	27.480	27.670	28.559	0.193	1.758	3	0.028
D68	07/12/2005 14:40:00	27.980	28.170	29.059	0.206	2.359	2.4	0.026
D69	08/12/2005 02:40:00	28.480	28.670	29.559	0.196	3.577	2.1	0.015
D70	08/12/2005 14:40:00	28.980	29.170	30.059	0.205	2.483	2.6	0.015
D71	09/12/2005 00:15:00	29.379	29.569	30.458	0.206	2.709	2.3	0.021
D72	09/12/2005 12:15:00	29.879	30.069	30.958	0.189	1.501	2.3	0.023
D73	10/12/2005 00:15:00	30.379	30.569	31.458	0.186	0.758	2.4	0.023
D74	10/12/2005 12:15:00	30.879	31.069	31.958	0.205	2.246	2.4	0.016
D75	11/12/2005 00:15:00	31.379	31.569	32.458	0.209	2.397	2.7	0.020

D76	11/12/2005 12:15:00	31.879	32.069	32.958	0.218	2.699	2.3	0.022
D77	12/12/2005 00:15:00	32.379	32.569	33.458	0.224	2.697	2.3	0.019
D78	12/12/2005 12:15:00	32.879	33.069	33.958	0.227	2.578	2.2	0.020
D79	13/12/2005 00:15:00	33.379	33.569	34.458	0.249	3.254	2.4	0.011
D80	13/12/2005 12:15:00	33.879	34.069	34.958	0.250	3.182	2.3	0.008
D81	14/12/2005 00:15:00	34.379	34.569	35.458	0.239	2.514	2.2	0.015
D82	14/12/2005 12:15:00	34.879	35.069	35.958	0.220	1.077	2.2	0.019
D83	15/12/2005 00:15:00	35.379	35.569	36.458	0.181	0.933	2.7	0.020
D84	15/12/2005 12:00:00	35.869	36.059	36.948	0.229	1.25	2.2	0.020
D85	16/12/2005 00:00:00	36.369	36.559	37.448	0.220	1.409	2.3	0.020
D86	16/12/2005 12:00:00	36.869	37.059	37.948	0.206	0.854	2	0.020
D87	17/12/2005 00:00:00	37.369	37.559	38.448	0.221	1.264	2.3	0.020
D88	17/12/2005 12:00:00	37.869	38.059	38.948	0.221	2.457	2.2	0.020
D89	18/12/2005 00:00:00	38.369	38.559	39.448	0.211	1.015	2.1	0.019
D90	18/12/2005 12:00:00	38.869	39.059	39.948	0.239	3.427	2.9	0.022
D91	19/12/2005 00:00:00	39.369	39.559	40.448	0.241	2.49	2.8	0.020
D92	19/12/2005 12:00:00	39.869	40.059	40.948	0.255	3.146	2.6	0.021
D93	20/12/2005 16:00:00	41.035	41.226	42.115	0.228	2.426	2.2	0.017
D94	21/12/2005 12:00:00	41.869	42.059	42.948	0.187	2.322	2.8	0.014
D95	22/12/2005 12:00:00	42.869	43.059	43.948	0.196	2.336	2.7	0.013
D96	23/12/2005 12:00:00	43.869	44.059	44.948	0.196	2.243	2.7	0.013
D97	24/12/2005 12:00:00	44.869	45.059	45.948				
D98	25/12/2005 12:00:00	45.869	46.059	46.948	0.198	2.283	2.7	0.012
D99	26/12/2005 12:00:00	46.869	47.059	47.948	0.200	2.403	2.9	0.012
D100	27/12/2005 12:00:00	47.869	48.059	48.948	0.206	2.497	3	0.012
D101	28/12/2005 12:00:00	48.869	49.059	49.948	0.188	2.393	2.8	0.012
D102	29/12/2005 12:00:00	49.869	50.059	50.948				
D103	30/12/2005 12:00:00	50.869	51.059	51.948	0.234	3.49	3.4	0.018
D104	31/12/2005 12:00:00	51.869	52.059	52.948	0.215	2.53	3.2	0.01
D105	01/01/2006 12:00:00	52.869	53.059	53.948	0.210	2.5	3.2	0.01
D106	02/01/2006 12:00:00	53.869	54.059	54.948	0.202	2.291	3.1	0.011
D107	03/01/2006 12:00:00	54.869	55.059	55.948				
D108	04/01/2006 12:00:00	55.869	56.059	56.948	0.195	2.373	3.1	0.011
D109	05/01/2006 12:00:00	56.869	57.059	57.948	0.194	2.232	3.1	0.013
D110	06/01/2006 12:00:00	57.869	58.059	58.948	0.193	2.334	3	0.012
D111	07/01/2006 12:00:00	58.869	59.059	59.948	0.191	2.392	3.1	0.012
D112	08/01/2006 12:00:00	59.869	60.059	60.948				
D113	09/01/2006 12:00:00	60.869	61.059	61.948	0.170	2.335	3.2	0.012
D114	10/01/2006 12:00:00	61.869	62.059	62.948	0.170	2.349	3.1	0.012
D115	11/01/2006 12:00:00	62.869	63.059	63.948	0.188	2.786	3.2	0.012
D116	12/01/2006 12:00:00	63.869	64.059	64.948	0.162	2.521	3	0.011
D117	14/01/2006 00:00:00	65.369	65.559	66.448	0.136	3.19	2.39	0.01
D118	16/01/2006 00:00:00	67.369	67.559	68.448	0.148	3.131	2.56	0.01
D119	18/01/2006 00:00:00	69.369	69.559	70.448	0.152	3.558	2.72	0.009
D120	20/01/2006 00:00:00	71.369	71.559	72.448	0.141	3.114	2.64	0.008
D121	22/01/2006 00:00:00	73.369	73.559	74.448	0.139	3.124	2.65	0.009
D122	24/01/2006 00:00:00	75.369	75.559	76.448	0.127	3.074	2.55	0.009
D123	26/01/2006 00:00:00	77.369	77.559	78.448	0.131	2.821	2.64	0.009
D124	28/01/2006 00:00:00	79.369	79.559	80.448				
D125	30/01/2006 00:00:00	81.369	81.559	82.448				
D126	01/02/2006 00:00:00	83.369	83.559	84.448				
D127	03/02/2006 00:00:00	85.369	85.559	86.448	0.127	2.410	2.95	
D128	05/02/2006 00:00:00	87.369	87.559	88.448	0.131	2.484	2.77	0.008
D129	07/02/2006 00:00:00	89.369	89.559	90.448				
D130	09/02/2006 00:00:00	91.369	91.559	92.448	0.143	3.053	2.63	0.008
D131	11/02/2006 00:00:00	93.369	93.559	94.448	0.175	3.339	2.76	0.007
D132	13/02/2006 00:00:00	95.369	95.559	96.448	0.188	3.051	2.83	0.007
D133	15/02/2006 00:00:00	97.369	97.559	98.448	0.200	2.816	2.9	0.008
D134	17/02/2006 00:00:00	99.369	99.559	100.448	0.194	3.005	2.84	0.008
D135	19/02/2006 00:00:00	101.369	101.559	102.448	0.201	2.94	2.92	0.007
D136	21/02/2006 00:00:00	103.369	103.559	104.448	0.216	2.964	2.92	0.008
D137	23/02/2006 00:00:00	105.369	105.559	106.448	0.225	2.898	2.94	0.009
D138	25/02/2006 00:00:00	107.369	107.559	108.448	0.229	2.358	2.95	0.01
D139	27/02/2006 00:00:00	109.369	109.559	110.448	0.272	2.712	2.71	0.01
D140	01/03/2006 00:00:00	111.369	111.559	112.448	0.298	3.191	3.65	0.02
D141	03/03/2006 00:00:00	113.369	113.559	114.448	0.326	2.744	3.43	0.017
D142	05/03/2006 00:00:00	115.369	115.559	116.448	0.350	2.691	2.97	0.014
D143	07/03/2006 00:00:00	117.369	117.559	118.448	0.409	2.436	2.79	0.012
D144	09/03/2006 00:00:00	119.369	119.559	120.448	0.512	3.115	2.88	0.012
D145	11/03/2006 00:00:00	121.369	121.559	122.448	0.575	2.005	2.83	0.012
D146	13/03/2006 00:00:00	123.369	123.559	124.448	0.697	2.765	2.84	0.012
D147	15/03/2006 00:00:00	125.369	125.559	126.448	0.832	2.099	2.81	0.013
D148	17/03/2006 00:00:00	127.369	127.559	128.448	0.891	2.51	2.9	0.014
D149	19/03/2006 00:00:00	129.369	129.559	130.448	0.903	2.773	2.93	0.014
D150	21/03/2006 00:00:00	131.369	131.559	132.448	0.909	2.838	3.07	0.016
D151	23/03/2006 00:00:00	133.369	133.559	134.448	0.802	3.033	2.93	0.014
D152	27/03/2006 00:00:00	137.369	137.559	138.448	0.648	2.954	2.9	0.011

D153	29/03/2006 00:00:00	139.369	139.559	140.448	0.609	2.762	2.95	0.012
D154	31/03/2006 00:00:00	141.369	141.559	142.448	0.587	3.072	2.9	0.014
D155	02/04/2006 00:00:00	143.369	143.559	144.448	0.596	3.131	2.93	0.015
D156	04/04/2006 00:00:00	145.369	145.559	146.448	0.569	2.985	2.91	0.015
D157	06/04/2006 00:00:00	147.369	147.559	148.448	0.587	2.509	2.94	0.015
D158	08/04/2006 00:00:00	149.369	149.559	150.448	0.616	3.133	2.96	0.013
D159	10/04/2006 00:00:00	151.369	151.559	152.448	0.632	3.046	3.03	0.011
D160	12/04/2006 00:00:00	153.369	153.559	154.448	0.541	4.943	2.05	0.013
D161	14/04/2006 00:00:00	155.369	155.559	156.448	0.628	5.005	1.98	0.013
D162	16/04/2006 00:00:00	157.369	157.559	158.448	0.686	4.835	1.83	0.01
D163	18/04/2006 00:00:00	159.369	159.559	160.448	0.635	4.991	1.76	0.008
D164	20/04/2006 00:00:00	161.369	161.559	162.448	0.703	4.181	1.74	0.008
D165	22/04/2006 00:00:00	163.369	163.559	164.448	0.546	4.286	1.56	0.008
D166	24/04/2006 00:00:00	165.369	165.559	166.448	0.695	3.453	1.65	0.008
D167	26/04/2006 00:00:00	167.369	167.559	168.448	0.606	3.075	2.1	0.007
D168	28/04/2006 00:00:00	169.369	169.559	170.448	0.716	4.294	1.83	0.008
D169	30/04/2006 00:00:00	171.369	171.559	172.448	0.780	5.358	1.73	0.008
D170	02/05/2006 00:00:00	173.369	173.559	174.448	0.531	4.608	1.88	0.008
D171	04/05/2006 00:00:00	175.369	175.559	176.448	0.494	3.588	1.79	0.009
D172	06/05/2006 00:00:00	177.369	177.559	178.448	0.532	4.662	1.68	0.009
D173	08/05/2006 00:00:00	179.369	179.559	180.448	0.469	4.73	1.49	0.008
D174	10/05/2006 00:00:00	181.369	181.559	182.448	0.472	3.508	1.54	0.008
D175	12/05/2006 00:00:00	183.369	183.559	184.448	0.456	4.39	1.46	0.007
D176	14/05/2006 00:00:00	185.369	185.559	186.448	0.407	3.503	1.38	0.008
D177	16/05/2006 00:00:00	187.369	187.559	188.448	0.428	4.179	1.47	0.007
D178	18/05/2006 00:00:00	189.369	189.559	190.448	0.339	2.441	1.23	0.007
D179	20/05/2006 00:00:00	191.369	191.559	192.448	0.349	3.898	1.2	0.007
D180	22/05/2006 00:00:00	193.369	193.559	194.448	0.339	4.164	2.72	0.007
D181	24/05/2006 00:00:00	195.369	195.559	196.448	0.292	2.861	2.56	0.007
D182	26/05/2006 00:00:00	197.369	197.559	198.448	0.300	2.869	2.51	0.007
D183	28/05/2006 00:00:00	199.369	199.559	200.448	0.257	2.84	2.54	0.007
D184	30/05/2006 00:00:00	201.369	201.559	202.448	0.241	2.175	2.49	0.007
D185	01/06/2006 00:00:00	203.369	203.559	204.448	0.256	2.167	2.55	0.006
D186	03/06/2006 00:00:00	205.369	205.559	206.448	0.250	2.942	2.48	0.006
D187	05/06/2006 00:00:00	207.369	207.559	208.448	0.224	2.406	2.39	0.007
D188	07/06/2006 00:00:00	209.369	209.559	210.448	0.214	2.324	2.49	0.008
D189	09/06/2006 00:00:00	211.369	211.559	212.448	0.199	1.894	2.28	0.009
D190	11/06/2006 00:00:00	213.369	213.559	214.448	0.179	2.193	2.33	0.01
D191	13/06/2006 00:00:00	215.369	215.559	216.448	0.175	1.405	2.29	0.013
D192	15/06/2006 00:00:00	217.369	217.559	218.448	0.197	3.392	2.2	0.012
D193	17/06/2006 00:00:00	219.369	219.559	220.448	0.160	2.805	2.11	0.015
D194	19/06/2006 00:00:00	221.369	221.559	222.448	0.163	2.594	2.12	0.017
D195	21/06/2006 00:00:00	223.369	223.559	224.448	0.159	1.529	1.99	0.017
D196	23/06/2006 00:00:00	225.369	225.559	226.448	0.169	3.233	2.05	0.011
D197	25/06/2006 00:00:00	227.369	227.559	228.448	0.236	4.313	1.47	0.011
D198	27/06/2006 00:00:00	229.369	229.559	230.448	0.169	3.839	1.93	0.009
D199	29/06/2006 00:00:00	231.369	231.559	232.448	0.163	4.627	1.88	0.009
D200	01/07/2006 00:00:00	233.369	233.559	234.448	0.205	8.421	1.82	0.012
D201	03/07/2006 00:00:00	235.369	235.559	236.448	0.127	2.69	2.1	0.011
D202	05/07/2006 00:00:00	237.369	237.559	238.448	0.197	5.066	1.81	0.017
D203	07/07/2006 00:00:00	239.369	239.559	240.448	0.227	4.405	1.75	0.015
D204	09/07/2006 00:00:00	241.369	241.559	242.448	0.246	5.076	1.65	0.023
D205	11/07/2006 00:00:00	243.369	243.559	244.448	0.207	3.345	1.3	0.019
D206	13/07/2006 00:00:00	245.369	245.559	246.448	0.228	4.754	2.83	0.019
D207	15/07/2006 00:00:00	247.369	247.559	248.448	0.198	2.402	2.66	0.02
D208	17/07/2006 00:00:00	249.369	249.559	250.448	0.166	2.498	2.51	0.018

Figure 19 : Concentration values measured at the gauging station