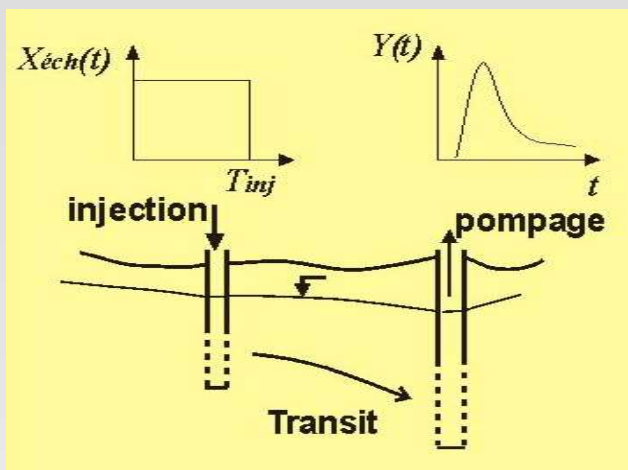


La méthode FVPDM: Origines, mise en oeuvre et perspectives

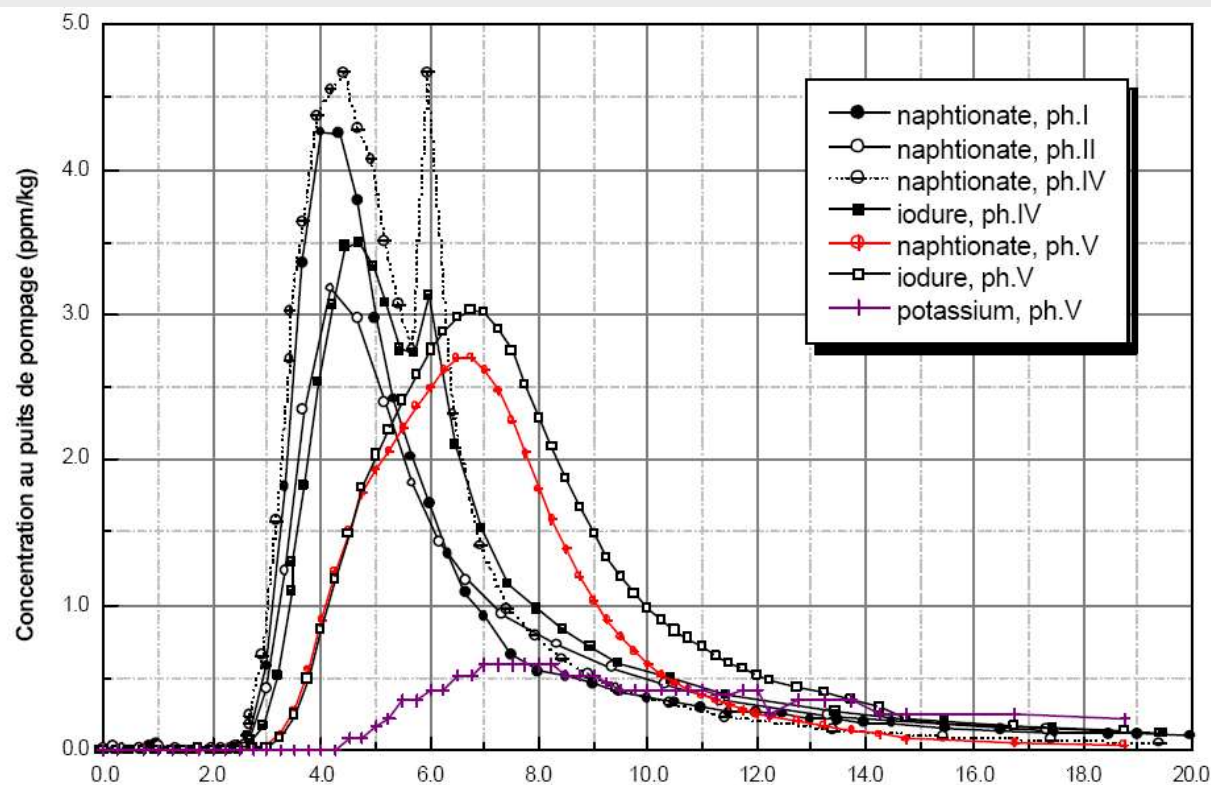
Serge BROUYERE
Université de Liège
Belgique

1. Point de départ, un constat: **il y a un intérêt à effectuer les injections de traceurs dans des piézos de manière plus intelligente** pour ...
 1. s'assurer qu'il est bien parti dans la nappe
 2. s'affranchir de toute influence potentielle de la méthode d'injection sur le résultat du traçage
 3. tirer des infos (flux eau souterraine) au voisinage du point d'injection
(si le traçage "foire", c'est toujours ça de pris!)

Motivations



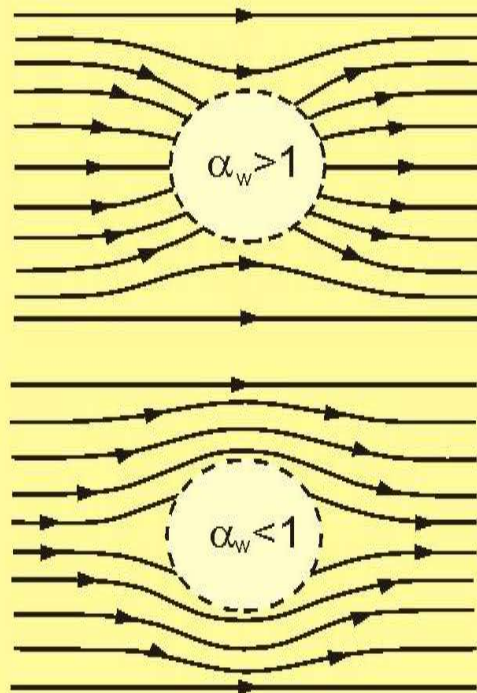
Phase	Traceur	M_{inj} (kg)	V_{inj} (m ³)	T_{inj} (s)	Q_{inj} (m ³ s ⁻¹)	V_{ch} (m ³)	T_{ch} (s)	Q_{ch} (m ³ s ⁻¹)
I	naphionate	0.2	0.007	100	7.0×10^{-5}	0.014	240	5.75×10^{-5}
II	naphionate	0.052	0.003	52	5.77×10^{-5}	0.1	268	3.73×10^{-4}
IV	naphionate	0.102	0.007	70	1.0×10^{-4}	1.4	1180	1.19×10^{-3}
	iodure	1.682	1.4	1440	9.72×10^{-4}	--	--	--
V	naphionate	0.101	0.048	2400	2.0×10^{-5}	--	--	--
	iodure	3.86	+	+	+	--	--	--
	potassium	1.19	0.152	9900	1.54×10^{-5}	--	--	--



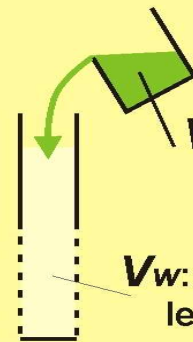
Facteurs influençant la fonction d'entrée du traceur

Durées et débits
d'injection, chasse, ...

Distorsion
du champs d'écoulement
au voisinage
du puits d'injection



Effet de mélange et de piégeage
dans le puits d'injection

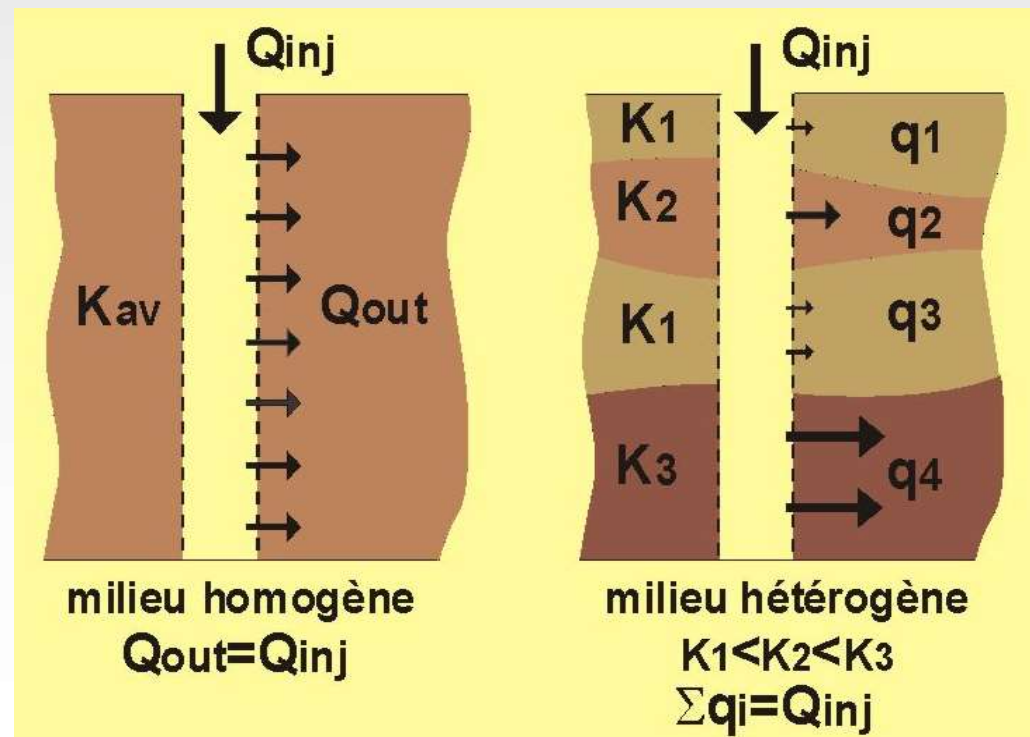


V_{inj} : volume de
fluide traceur

Coefficient de mélange
 $V_{inj}^* = V_{inj} / V_w$

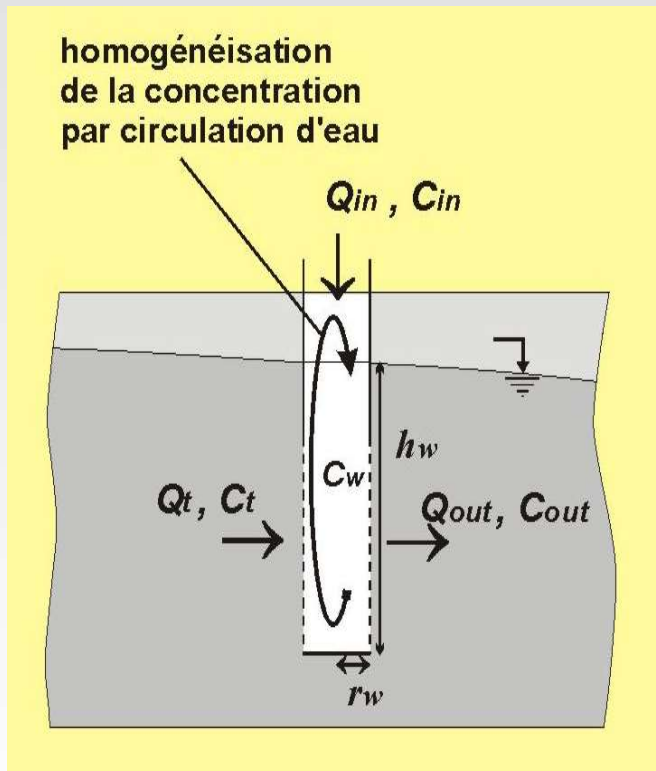
V_w : volume d'eau dans
le puits d'injection

**+ piégeage potentiel
du traceur dans le puits !**



Conceptualisation et mise en équations

Further details in Brouyère (2001) and Brouyère et al. (2008)



Water conservation

$$\frac{\partial V_w(t)}{\partial t} = \pi r_w^2 \frac{\partial h_w}{\partial t} = Q_{inj}(t) + Q_t(t) - Q_{out}(t)$$

Tracer conservation

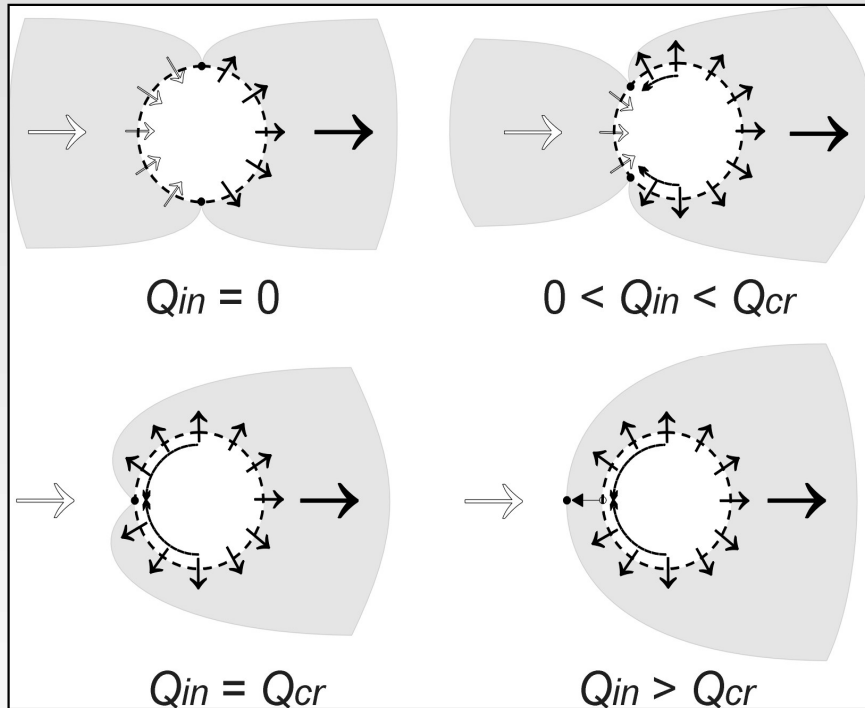
$$\frac{\partial M_t}{\partial t} = \frac{\partial}{\partial t} (V_w C_w) = Q_{inj} C_{inj} + Q_t C_t - Q_{out} C_{out}$$

Concentration evolution in the injection well

$$\pi r_w^2 h_w \frac{\partial C_w}{\partial t} = Q_{inj} (C_{inj} - C_w) + Q_t (C_t - C_w)$$

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

Conceptualisation et mise en équations



Transit flow rate calculation based on Bideaux & Tsang (1991) potential theory :

If $Q_{inj} > Q_{cr}$

$$Q_t = 0$$

If $Q_{inj} \leq Q_{cr}$

$$Q_t = 2r_w e V_w \sin(\arccos Q^*) - \frac{Q_{inj}}{2\pi} (2 \arccos Q^*)$$

$$Q^* = Q_{inj} / Q_{cr} \quad \text{and} \quad Q_{out} = Q_{inj} + Q_t$$

$$Q_{cr} = 2\pi e_{scr} r_w v_{ap} = 2\pi e_{scr} \alpha_w |v_D| \approx 3 \times Q_t^0$$

Where the condition to be satisfied is $Q_{inj} < Q_{cr}$

On the contrary, $C_w \rightarrow C_{inj}$, whatever Q_t

- Puits et piézomètres représentés par des éléments finis unidimensionnels (Sudicky *et al.*, 1995)
- Débits injectés distribués aux nœuds puits

$$Q_{in} = \sum_{K=1}^{n_w} q_{in}^K \quad Q_{out} = \sum_{K=1}^{n_w} q_{out}^K \quad Q_t = \sum_{K=1}^{n_w} q_t^K$$

- Modèle d'injection devient

$$\pi r_w^2 h_w \frac{\partial C_w}{\partial t} = Q_{in} C_{in} + \sum_K \left(q_t^K (C_t^K - C_w) - q_{in}^K C_w \right)$$

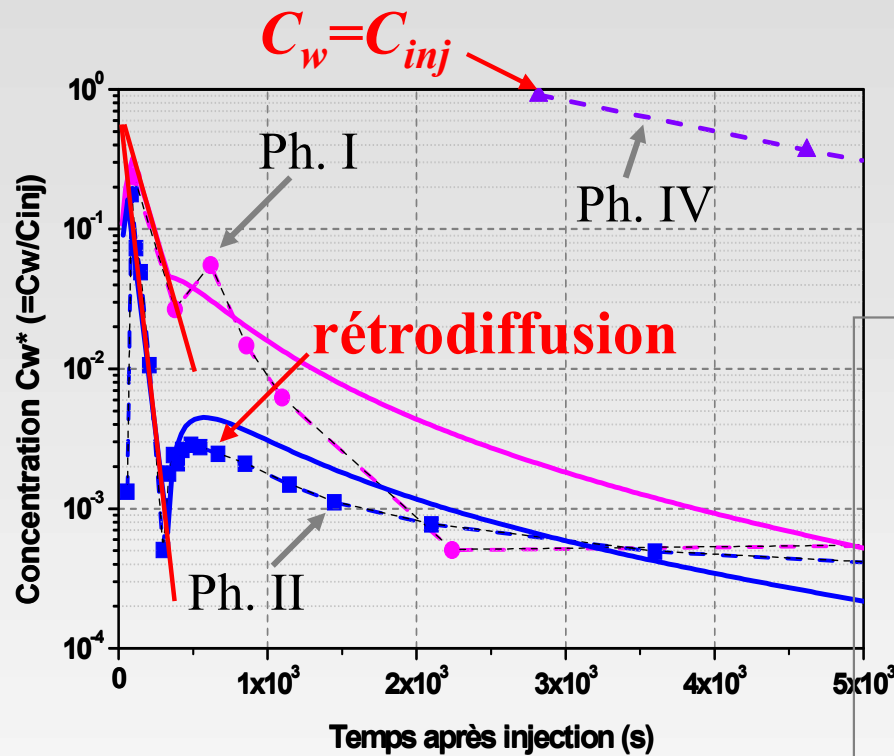
- Schéma différence finie pour la discrétisation temporelle de cette équation puis introduction dans l'équation 3D de transport

$$T_{3D}(C) - \sum_{K=1}^{n_w} \left(q_{out}^K C_w - q_t^K C_t^K \right)$$

Brouyère, WRR 2003

1. Suivi de l'évolution de la concentration à l'injection et ...
2. ... influence des conditions d'injection sur le résultats de l'essai de traçage
3. Traçage puits unique = FVPDM (finite volume point dilution method)
4. Perspectives

Evolution de la concentration à l'injection



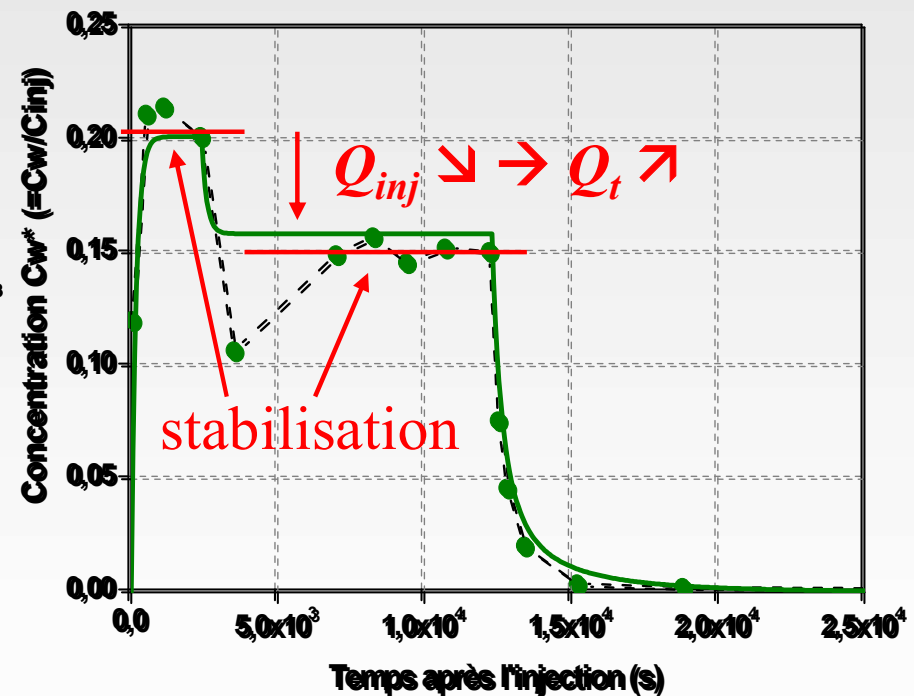
Phases I, II et IV

Phase V

Paramètres du modèle

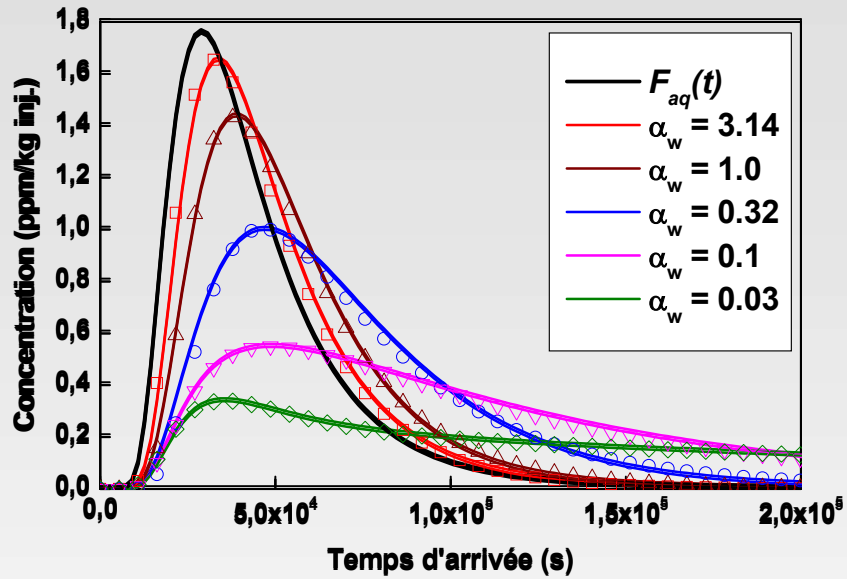
- $r_w = 2.5$ cm

- $\alpha_w = 11.5$



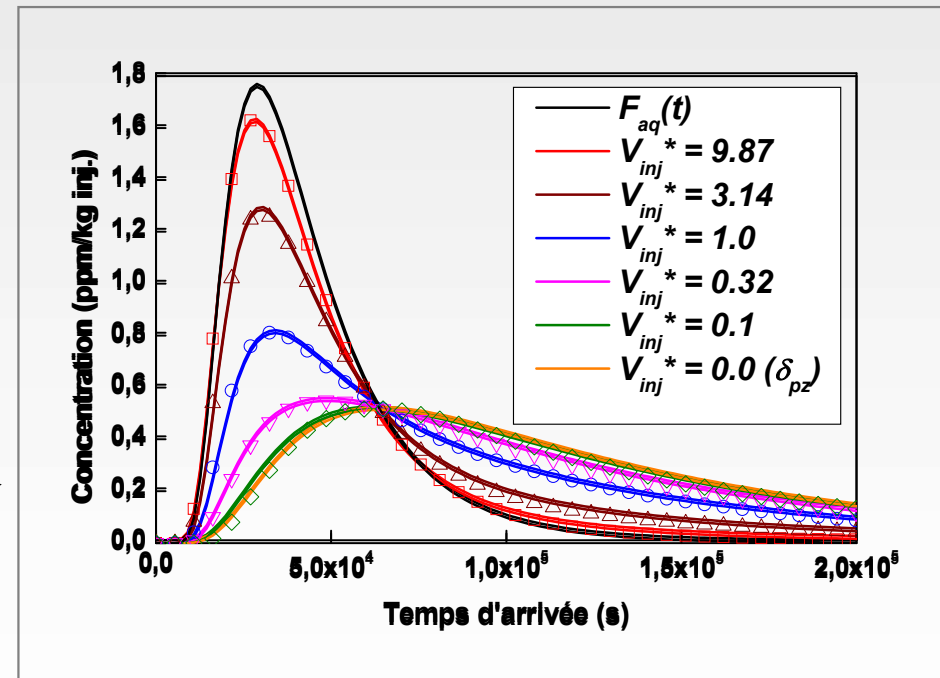
→ Fonction d'entrée plus correcte que palier de concentration

Influence sur le résultat du traçage



$$V_{inj}^* = 1$$

$$\alpha_w = 0.32$$

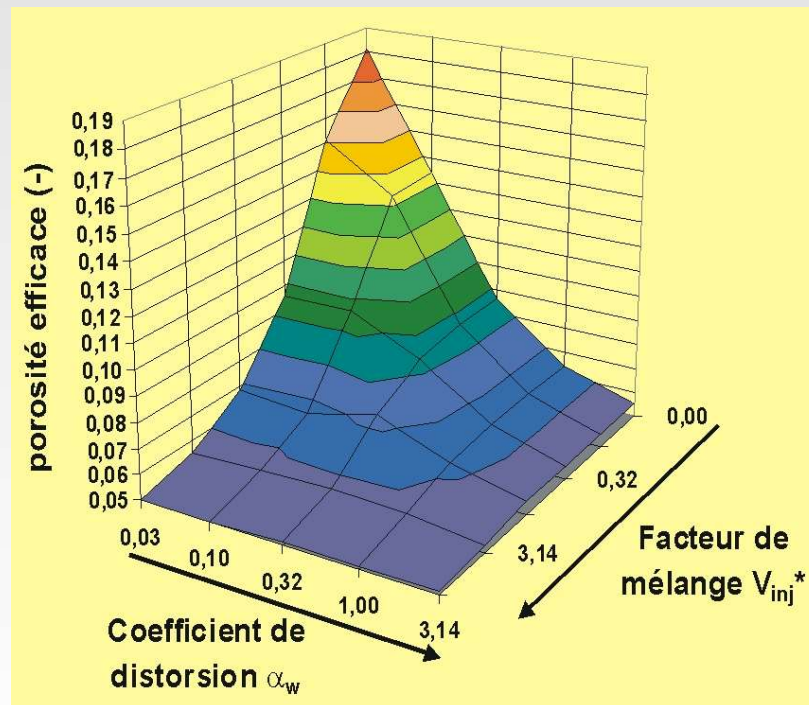


Brouyère et al., Ground Water 2005

Influence sur le résultat du traçage

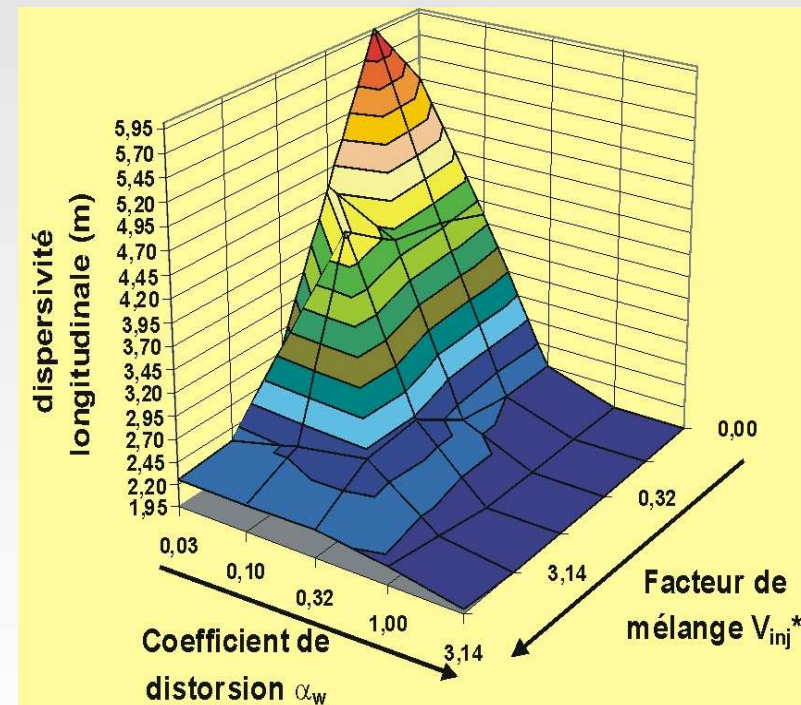
Impact sur les valeurs trouvées pour les paramètres ...

Porosité efficace



Valeur réelle: $\theta_m = 0.05$

Dispersivité longitudinale

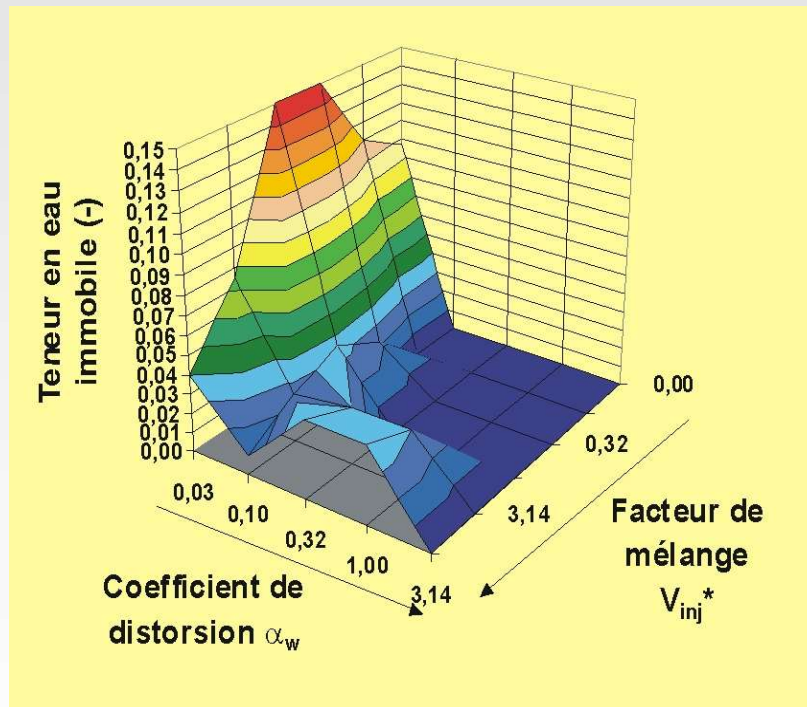


Valeur réelle: $\alpha_L = 2m$

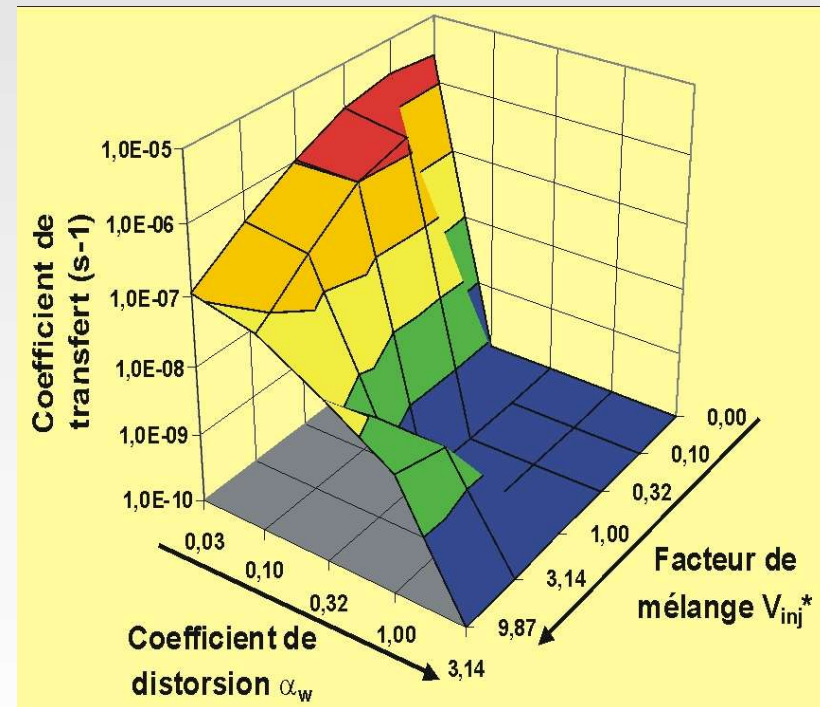
Influence sur le résultat du traçage

...et identification erronée des processus agissant !

Porosité d'eau immobile



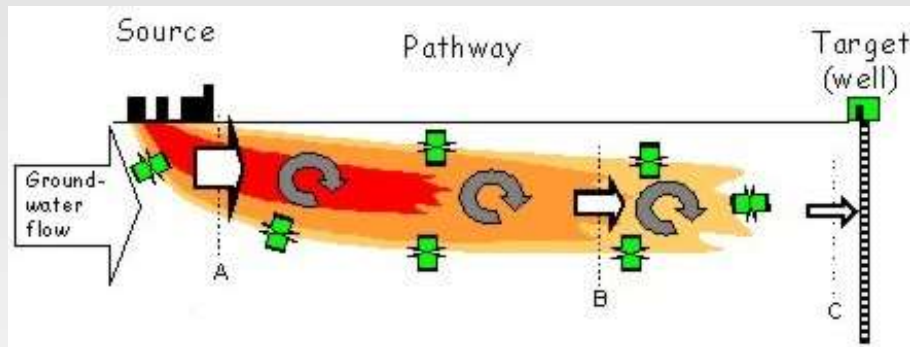
Coefficient de transfert



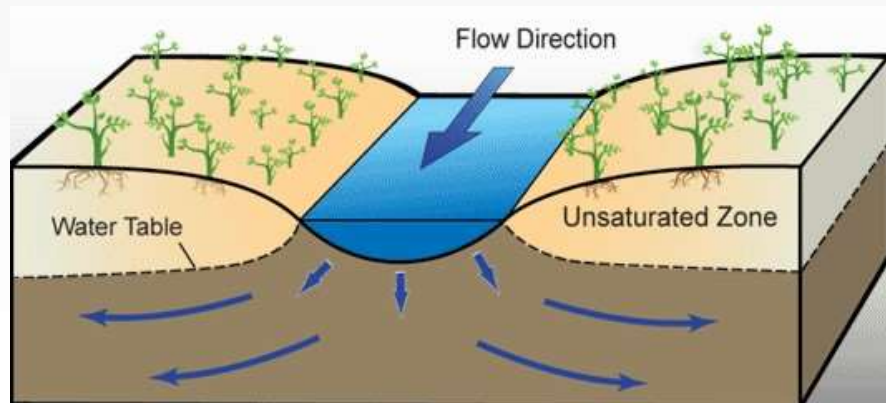
En réalité, aucun effet d'eau immobile !

FVPDM: monitoring des flux d'eau souterraine

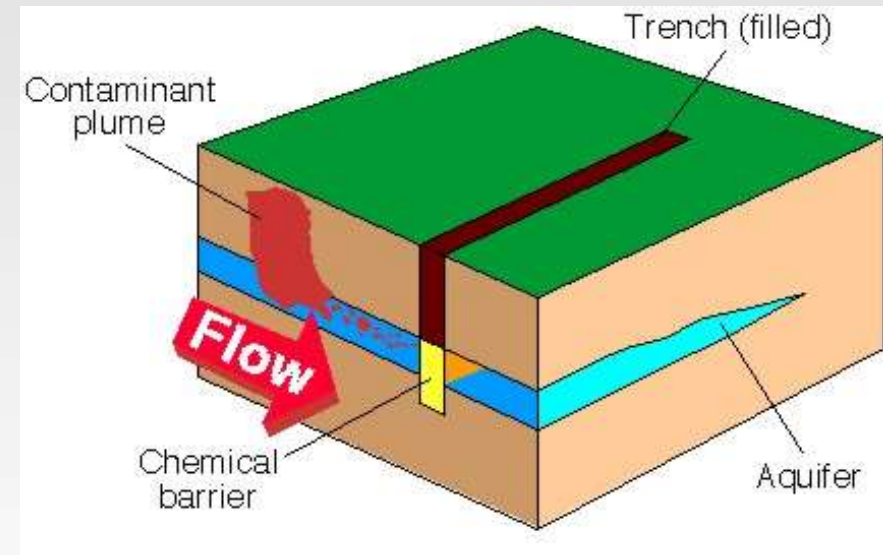
- To assess contaminant dispersion and/or natural attenuation capacity of the subsurface medium...



- understand mechanisms that govern the interactions between groundwater and surface water (hyporheic zone)...

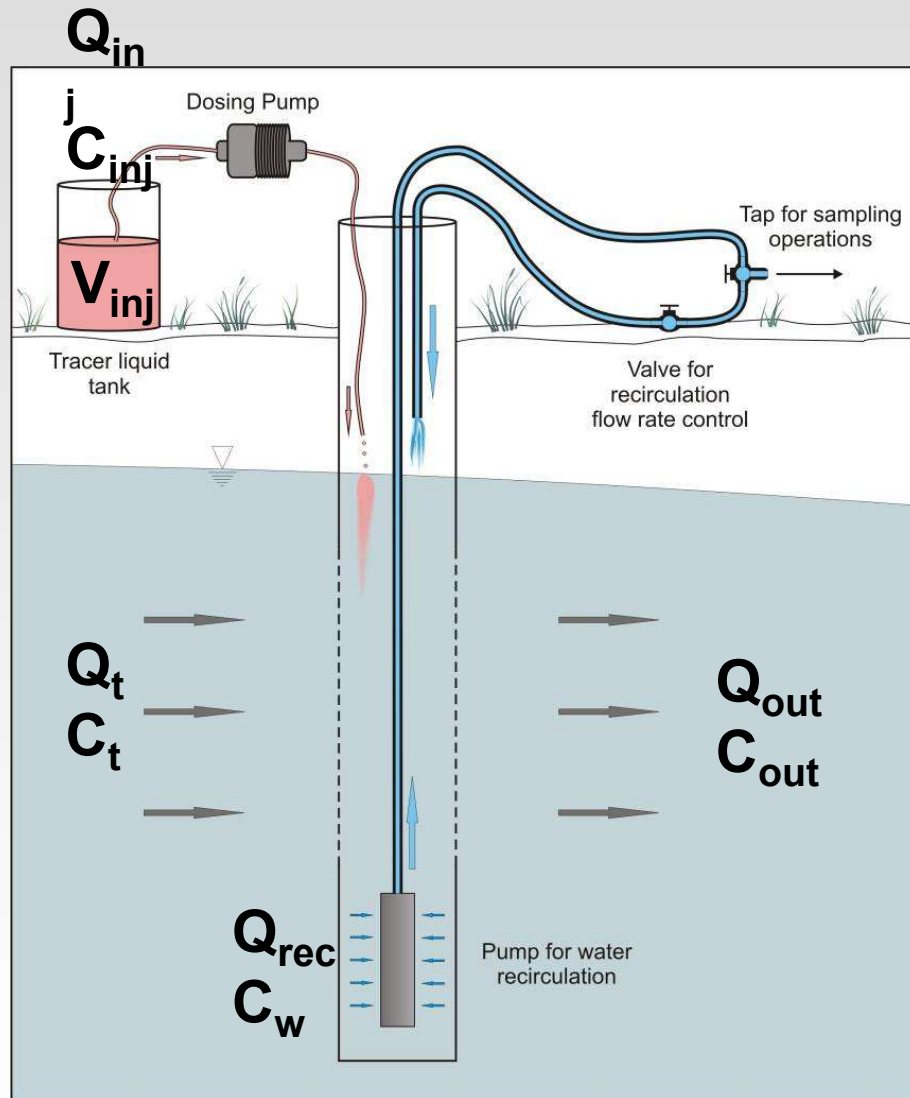


- dimensioning of remediation systems, such as reactive barrier systems...



- knowledge on local groundwater flow paths

FVPDM: monitoring des flux d'eau souterraine



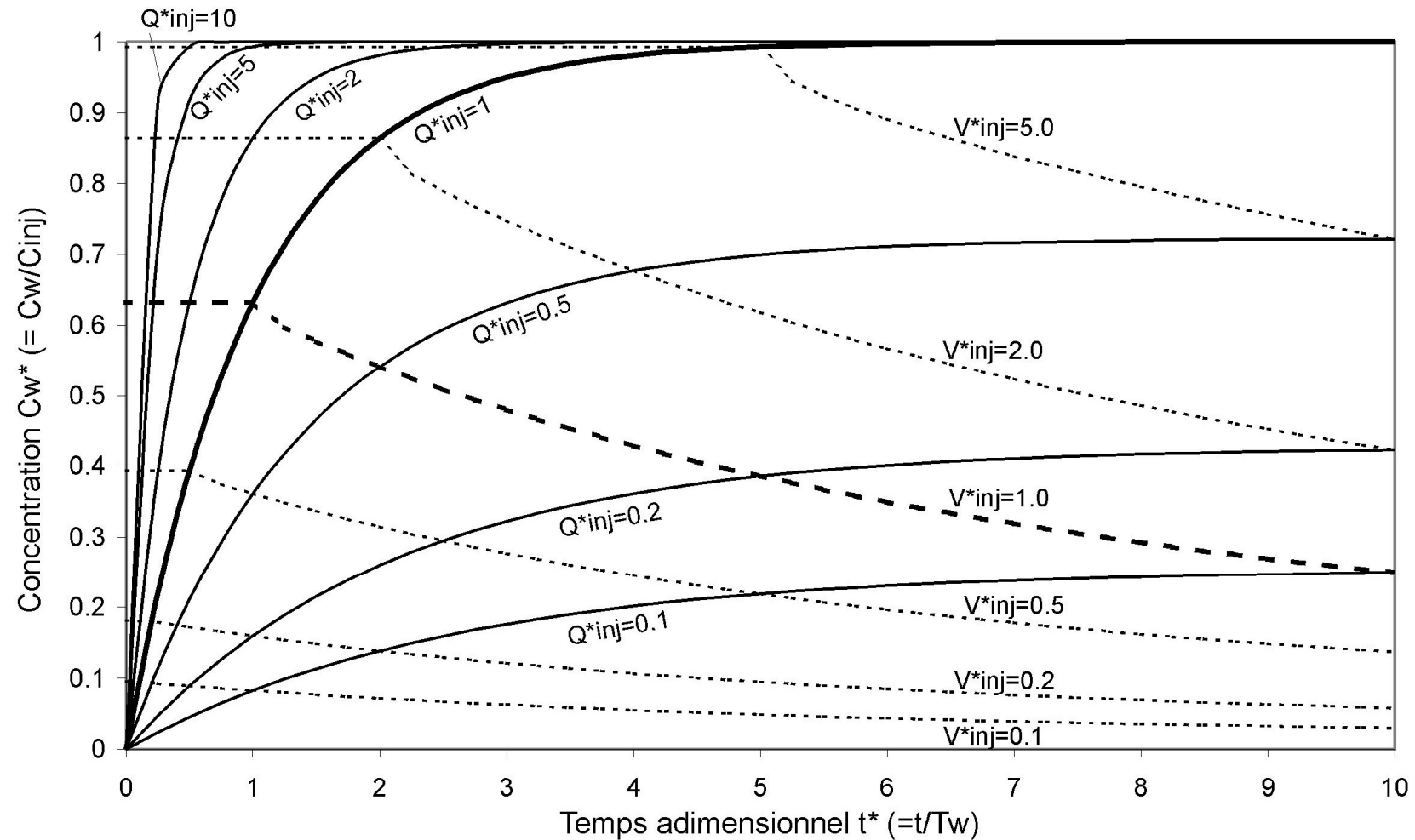
Brouyère et al., JCH 2008



Quantify $Q_t \rightarrow v_D$

FVPDM: monitoring des flux d'eau souterraine

Conditions indispensable: $Q_{inj} < Q_{cr} !!$

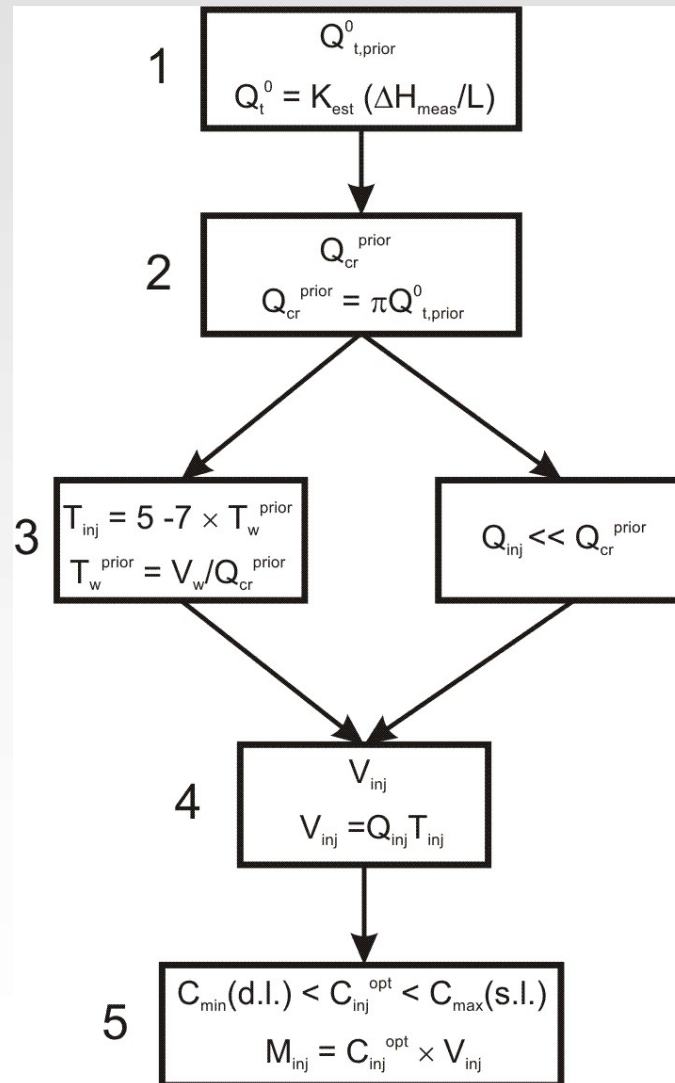


— courbes d'évolution de la concentration C_w^* pour différentes valeurs de $Q_{inj}^* = cste$
- - - courbes enveloppes du niveau de concentration $C^*_{w,max}$ atteint en fin d'injection à différents $V_{inj}^* = cste$

The FVPDM as performed in the field

→ Define injection profile:

- Q_{inj}
- V_{inj}
- T_{inj}
- M_{inj} (C_{inj})



Prior estimate of Q_t

Estimate of max Q_{inj}

Definition of Q_{inj} and T_{inj}

Definition of V_{inj}

Definition of most appropriate C_{inj} and M_{inj}

Experimental validation

Brévilles catchment (France)

Walloon Meuse basin (Belgium)

Geology of the aquifer

Layers of sand overburden by fractured marly limestones

Alluvial sands & gravels

Field conditions

- No power supply
- Limited water available
- No security (vandalism)

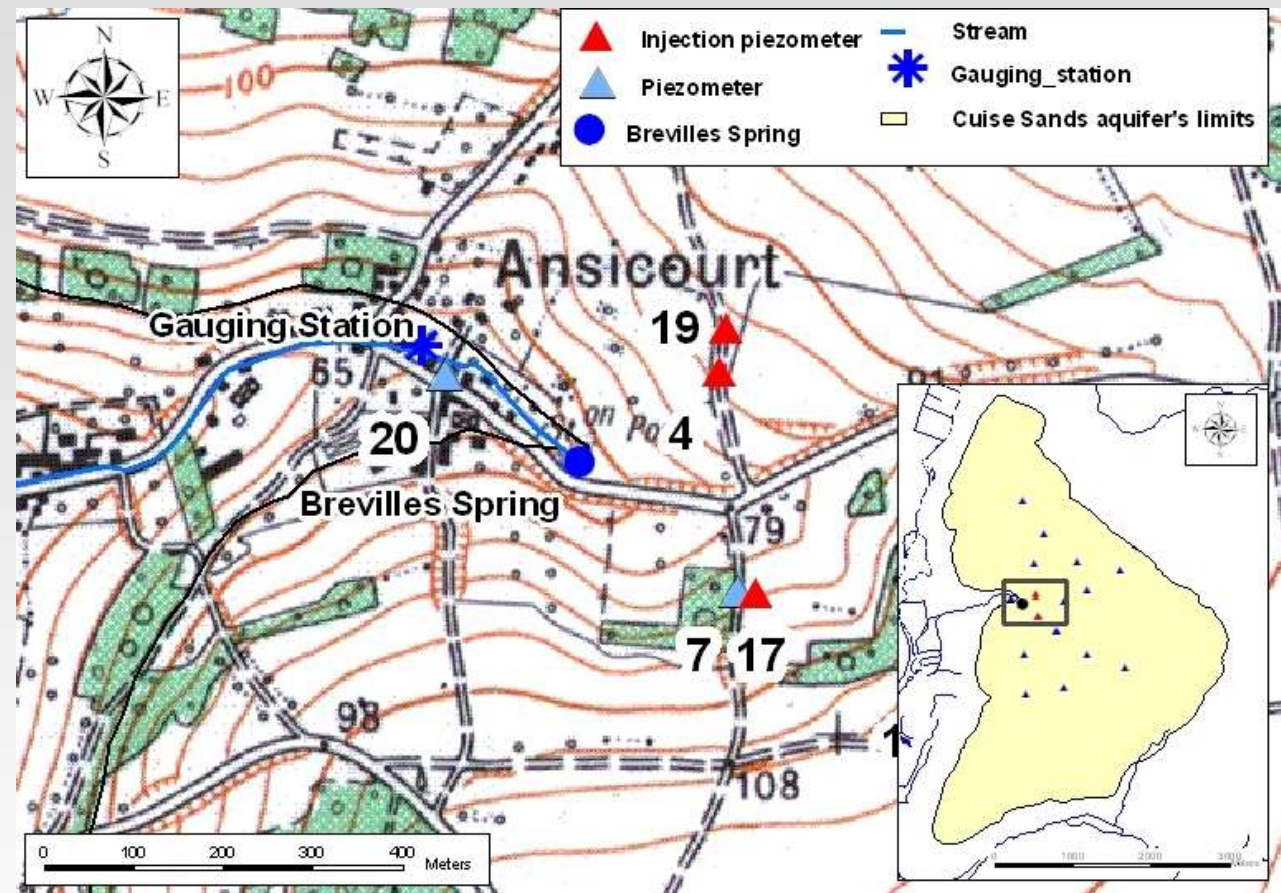
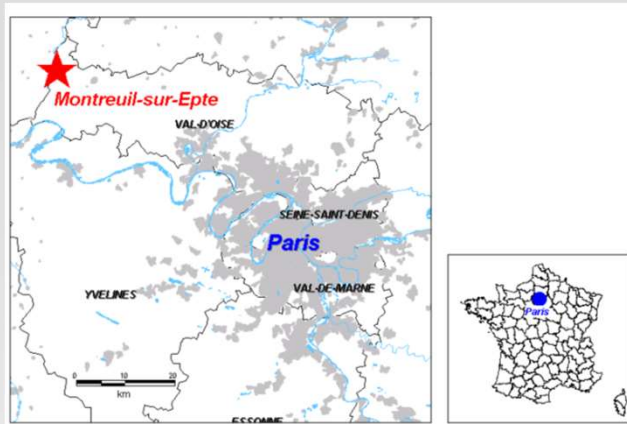
- Power supply
- Water available
- Field security

Objectives

Highlight vertical variations in groundwater fluxes

Evaluate GW fluxes discharging to the adjacent Meuse river

Brévilles catchment (France)

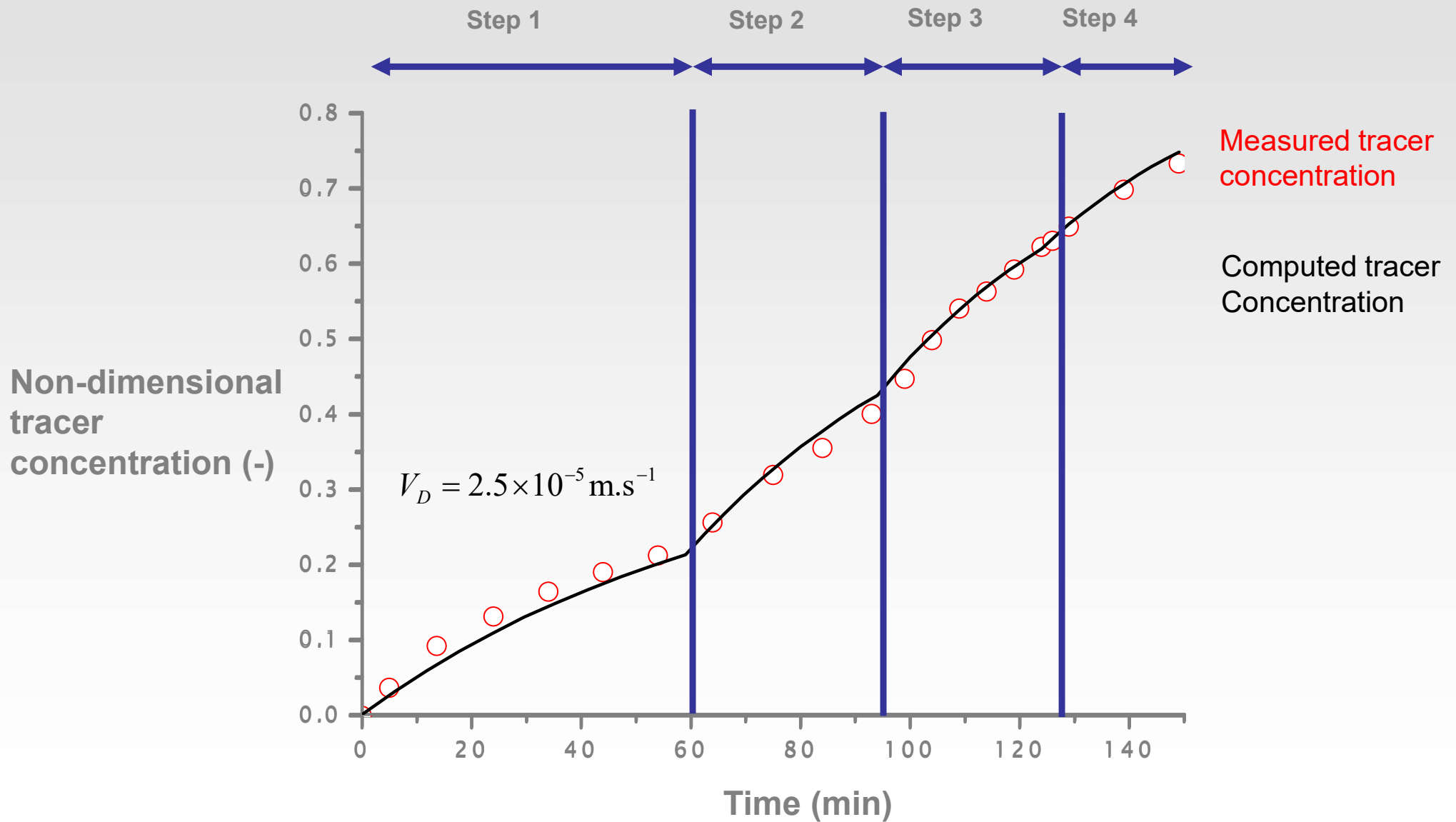


Goderniaux et al.,
Hydrogeology Journal 2010

Objectives

- Contaminant travel times from several locations in the catchment
- Transport processes in the saturated part of the aquifer
- Vertical variations in mostly horizontal groundwater fluxes in the sandy aquifer

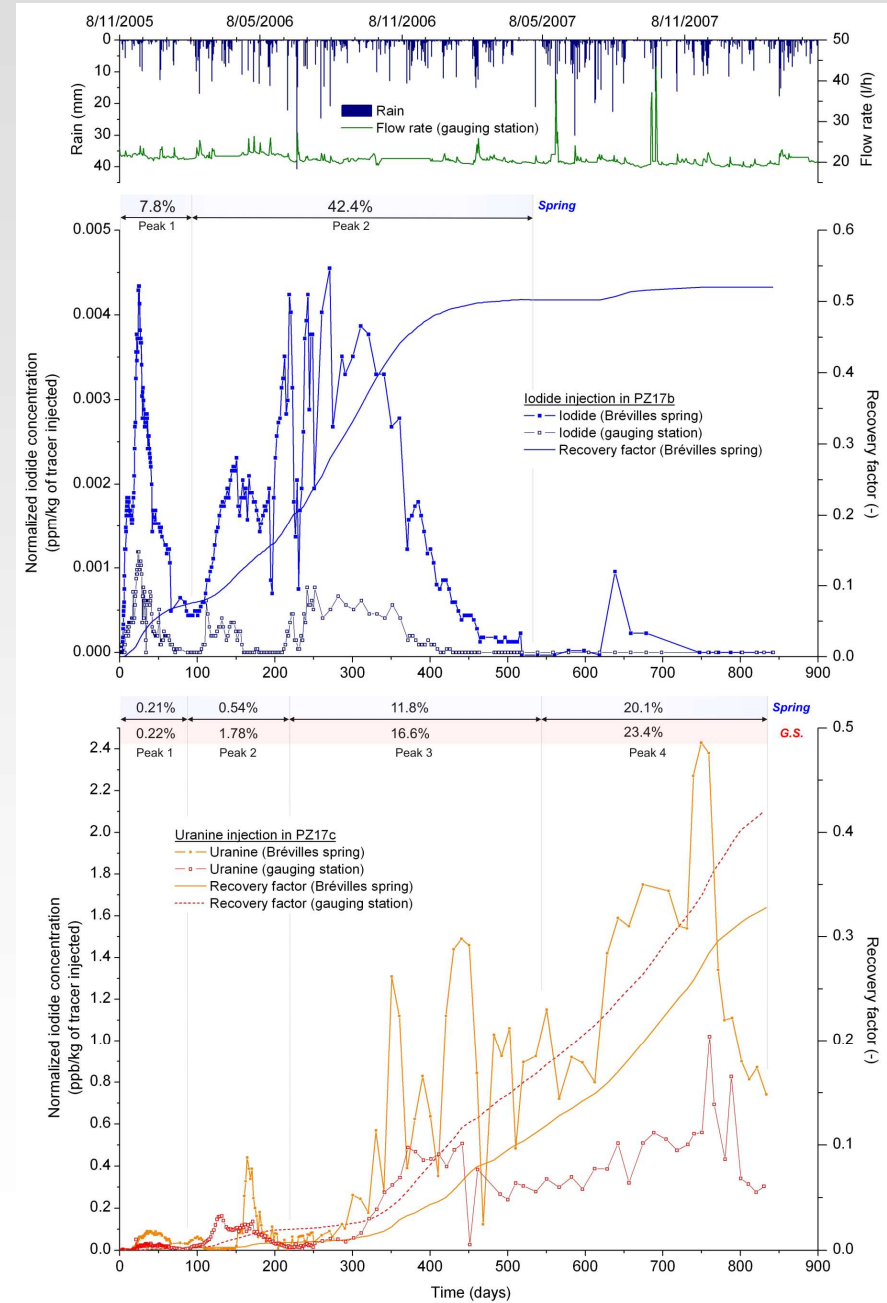
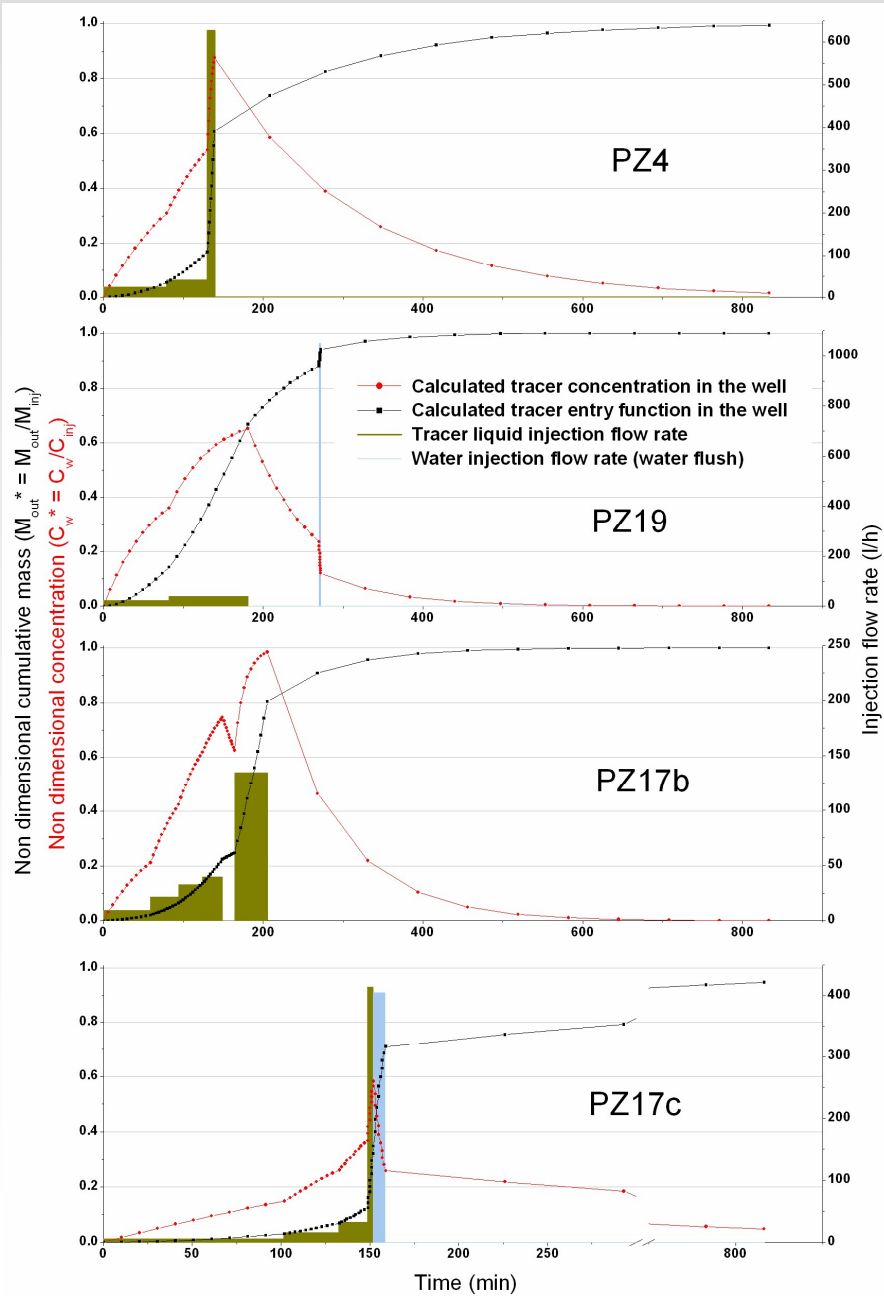
Brévilles catchment (France)



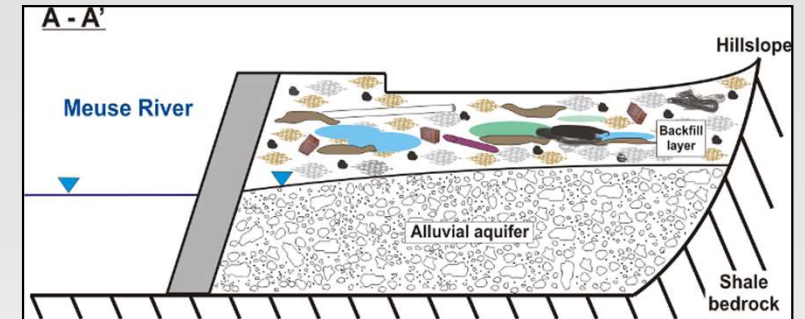
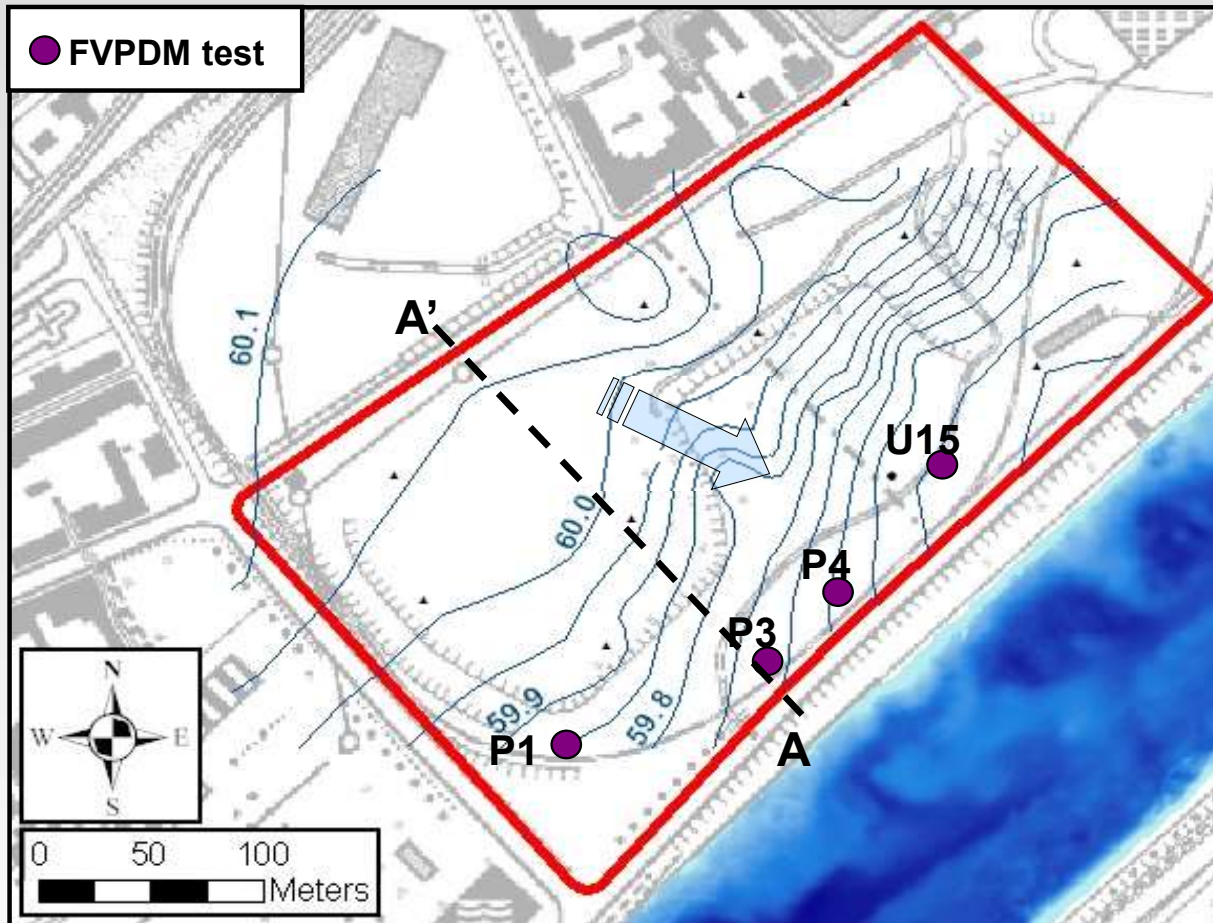
Brévilles catchment (France)

	Pz4			Pz19			Pz17b				Pz17c					
Borehole depth (m)	28			28.4			16				21					
Water column h_w (m)	14.31			9.93			5.81				11.07					
Well radius r_w (m)	0.040			0.040			0.040				0.040					
Well volume V_w (m ³)	0.071			0.078			0.030				0.051					
Screen length e_{scr} (m)	8.9			11.9			2.9				2.9					
K_{mean} (pumping test) (m·s ⁻¹)	2.75×10 ⁻⁴			4.00×10 ⁻⁴			8.67×10 ⁻⁴				2.75×10 ⁻⁴					
Estimated \underline{v}_D (m·s ⁻¹)	1.1×10 ⁻⁵			1.5×10 ⁻⁵			1.9×10 ⁻⁵				0.6×10 ⁻⁵					
Estimated Q_{cr} (m ³ ·s ⁻¹)	2.6×10 ⁻⁵			4.6×10 ⁻⁵			1.5×10 ⁻⁵				4.7×10 ⁻⁶					
	(93.61h ⁻¹)			(165.61h ⁻¹)			(54.01h ⁻¹)				(16.91h ⁻¹)					
Tracer	Li ⁺			Sulforhodamine B			I ⁻				Uranine					
Total M_{inj} (kg)	6.6			10			19.2				5					
Total V_{inj} (m ³)	0.16			0.098			0.16				0.045					
C_{inj} (kg·m ⁻³)	41.3			102.0			120.0				111.1					
Q_{rec} (m ³ ·h ⁻¹)	≈ 1.0			≈ 1.0			≈ 1.0				≈ 1.0					
	<i>Injection step</i>	<i>1</i>	<i>2</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>Total</i>
Injection parameters	Q_{inj} (l·h ⁻¹)	23.5	40.9		23.5	35.3		9.4	21.4	32.6	39.9		5.8	15.9	32.6	
	Time (min)	79	51	130	82	99	181	59	35	30	25	149	101.5	31	16	149
	Volume (m ³)	0.031	0.035	0.066	0.032	0.066	0.098	0.009	0.013	0.016	0.017	0.055	0.010	0.008	0.009	0.027
	Tracer mass (kg)	1.28	1.45	2.73	3.26	6.73	10.00	1.08	1.56	1.92	2.04	6.60	1.11	0.88	0.99	2.98
Results	Calculated \underline{v}_D (m·s ⁻¹)	9.8×10 ⁻⁶			1.0×10 ⁻⁵ - 3.0×10 ⁻⁵			2.5×10 ⁻⁵				4.0×10 ⁻⁵				
	Calculated Q_{cr} (m ³ ·s ⁻¹)	2.18×10 ⁻⁵			3.01×10 ⁻⁵ - 9.04×10 ⁻⁵			1.82×10 ⁻⁵				2.91×10 ⁻⁵				
		(78.5 1h ⁻¹)			(108.4 - 325.4 1h ⁻¹)			(65.5 1h ⁻¹)				(104.8 1h ⁻¹)				

Brévilles catchment (France)



Brownfield site in the Walloon Meuse basin (Belgium)



Objective

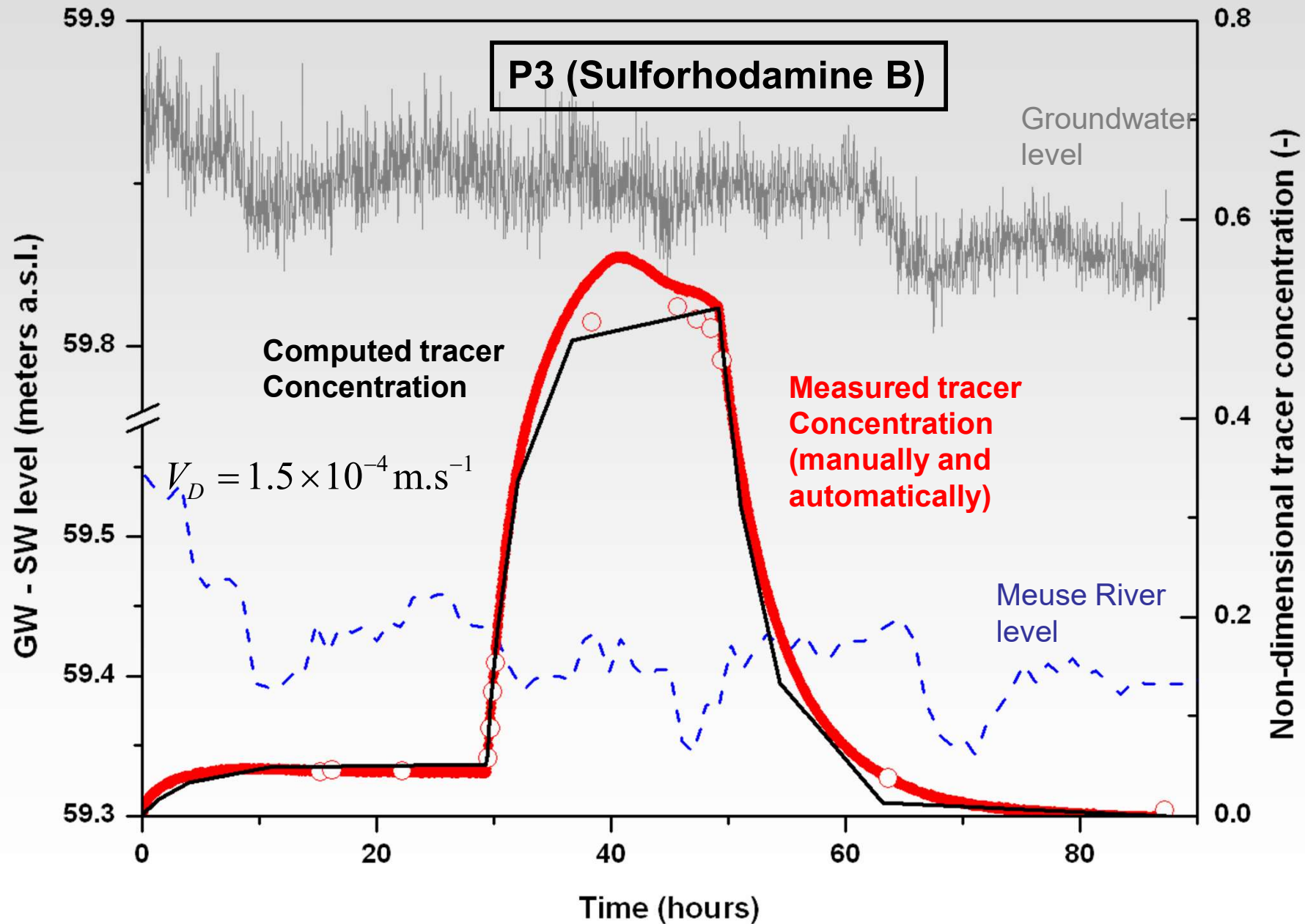
- Quantification of groundwater fluxes and groundwater discharge in the neighbouring Meuse river

Batlle-Aguilar, PhD 2009

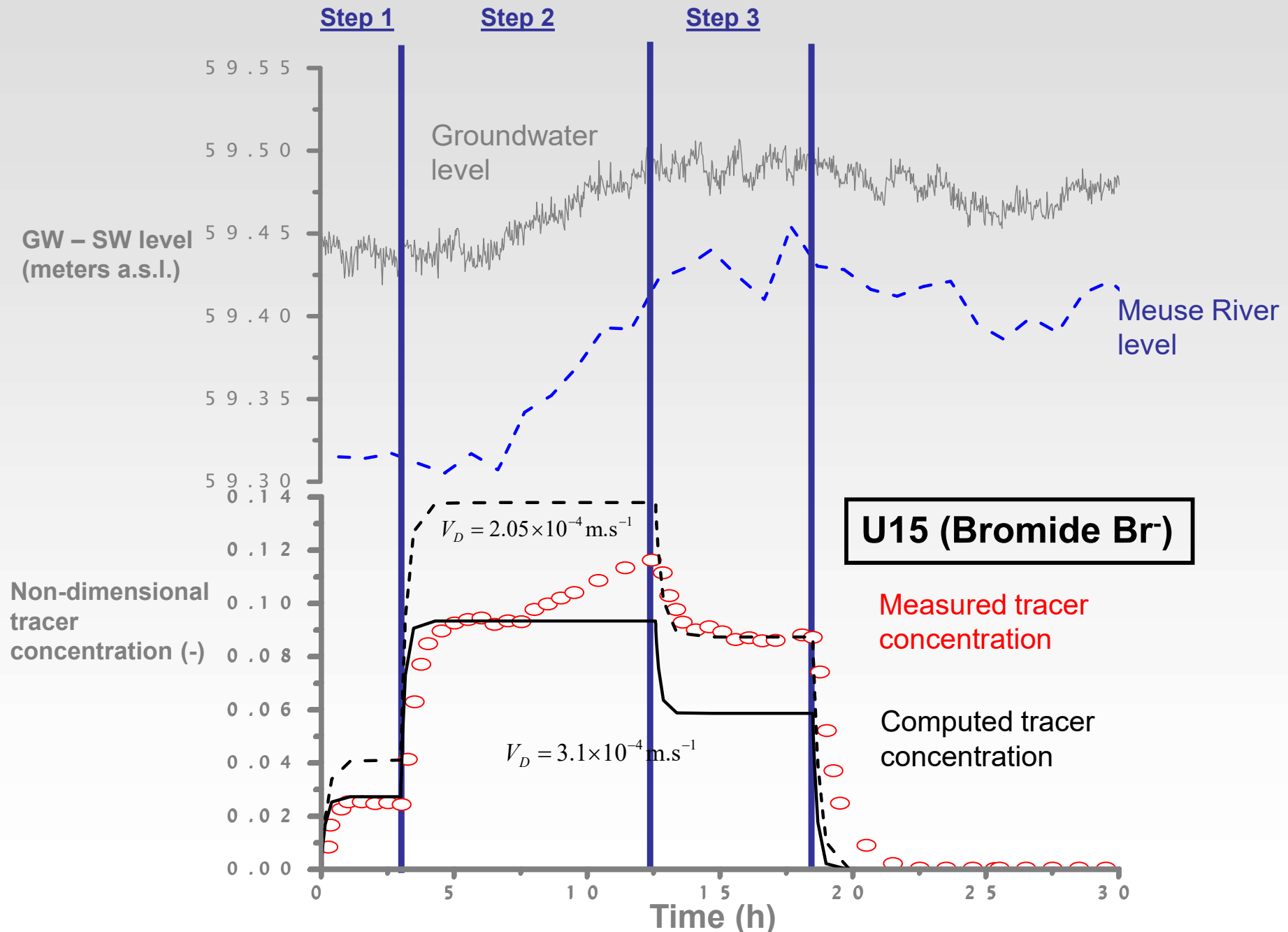
Batlle-Aguilar et al., J.Hydrol., 2009

Batlle-Aguilar & Brouyère, submitted to J.Hydrol

Brownfield site in the Walloon Meuse basin (Belgium)



Brownfield site in the Walloon Meuse basin (Belgium)



Brownfield site in the Walloon Meuse basin (Belgium)

	U15				P4					P3			P1			
Borehole depth (m)	14.2				15.5					15.0			18.2			
Water column h_w (m)	6.66				7.32					7.03			10.11			
Well radius r_w (m)	0.05				0.075					0.075			0.075			
Well volume V_w (m ³)	0.05				0.13					0.12			0.18			
Screen length e_{scr} (m)	3.0				5.5					4.0			4.25			
K_{mean} (pumping test) (m.s ⁻¹)	3.3×10 ⁻³				1.1×10 ⁻³					4.0×10 ⁻⁴			2.7×10 ⁻⁴			
Estimated V_D (m.s ⁻¹)	1.1×10 ⁻⁵				4.8×10 ⁻⁶					9.8×10 ⁻⁷			5.6×10 ⁻⁷			
Estimated Q_{cr} (m ³ .s ⁻¹)	1.1×10 ⁻⁵				1.3×10 ⁻⁵					1.9×10 ⁻⁶			1.1×10 ⁻⁶			
	(39.6 l.h ⁻¹)				(46.8 l.h ⁻¹)					(6.84 l.h ⁻¹)			(3.96 l.h ⁻¹)			
Tracer	Br ⁻				I ⁻					Slufohodamine B			Uranine			
Total M_{inj} (kg)	2.69				2.77					4.45×10 ⁻⁵			4.25×10 ⁻⁵			
Total V_{inj} (m ³)	0.46				0.98					0.50			0.50			
C_{inj} (ppm)	5818				2775					0.088			0.085			
Q_{rec} (m ³ .h ⁻¹)	0.3				3.0					1.0			0.3			
	<i>Injection step</i>															
		<i>1</i>	<i>2</i>	<i>3</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>Total</i>	<i>1</i>	<i>2</i>	<i>Total</i>
Injection parameters	Q_{inj} (l.h ⁻¹)	9.3	32.9	20.3		1.5	5.4	19.2	39.4		1.7	22.8		10.5	20.1	
	Time (h)	3.00	9.58	5.92	18.50	23.4	12.62	20.73	12.30	69.05	29.37	19.83	49.20	19.08	14.92	34.00
	Volume (m ³)	0.028	0.315	0.120	0.463	0.035	0.068	0.398	0.485	0.986	0.050	0.450	0.500	0.200	0.300	0.500
	Tracer mass (kg)	0.16	1.83	0.70	2.69	0.10	0.19	1.12	1.36	2.77	4.4×10 ⁻⁶	4.0×10 ⁻⁵	4.4×10⁻⁵	1.7×10 ⁻⁵	2.5×10 ⁻⁵	4.2×10⁻⁵
Results	Darcy's flow V_D (m.s ⁻¹)	2.05 – 3.1×10 ⁻⁴				2.7×10 ⁻⁵					1.5×10 ⁻⁵			3.0×10 ⁻⁶		
	Calculated Q_{cr} (m ³ .s ⁻¹)	9.66×10 ⁻⁵ – 1.46×10 ⁻⁴				3.50×10 ⁻⁵					1.51×10 ⁻⁵			3.01×10 ⁻⁶		
	(347.8 – 525.6 l.h ⁻¹)				(126.0 l.h ⁻¹)					(54.4 l.h ⁻¹)			(10.8 l.h ⁻¹)			

- FVPDM : stand-alone technique or in combination with any other (multiple-well) tracer technique
- Very robust, reliable and sensitive to groundwater flow conditions
- Wide range of applications in contrasted experimental conditions, such as:
 - Monitoring groundwater – surface water interactions in the hyporheic zone
 - Quantification of groundwater (and contaminant) fluxes from contaminated sites
- Fortran90 application and user's manual for FVPDM interpretation available upon request

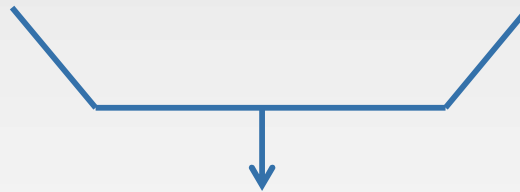
- Thèse de doctorat de Pierre Jamin (ULg, 2010-2013) : Quantification et monitoring des flux de contaminants en milieu souterrain hétérogène

1. Mesure du flux d'eau

Développement technique de traçage en puits unique FVPDM

2. Mesure de la concentration en polluant

Echantillonnage passif

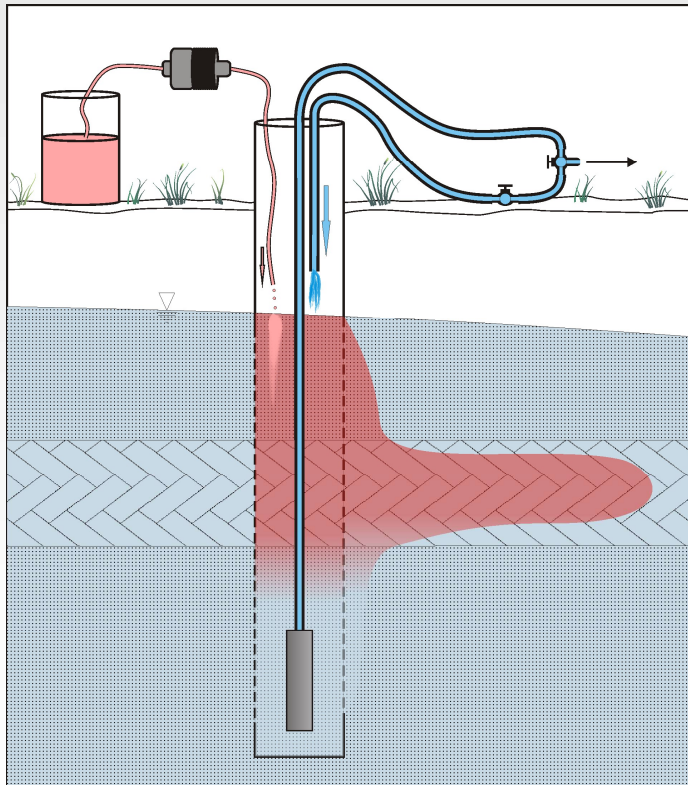


3. Mesure du flux de polluant

Variabilité spatiale et temporelle des flux de contaminants

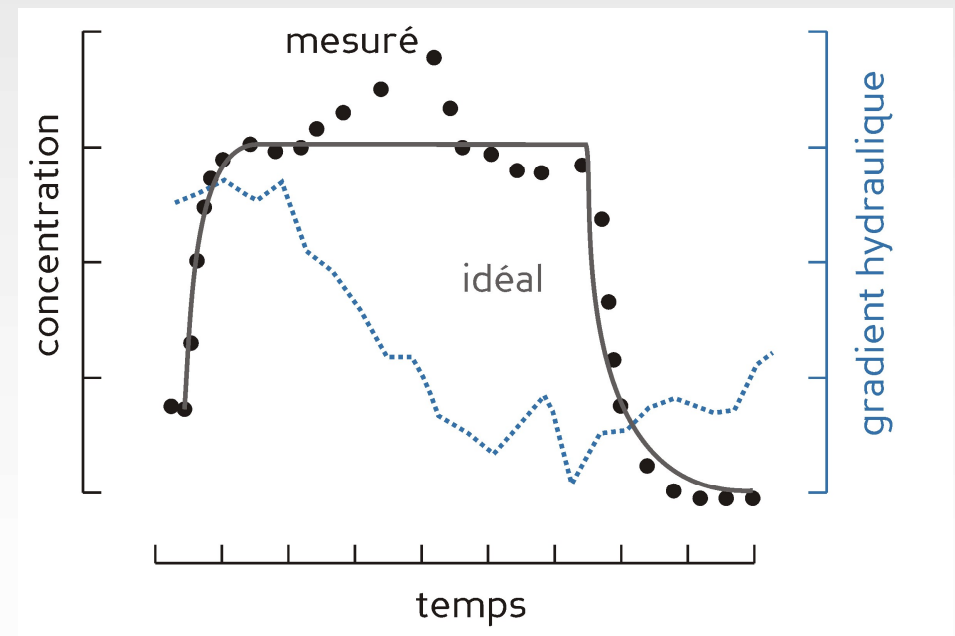
- Développement de la FVPDM (logging / transitoire)

1) Logging vertical des flux d'eau souterraine à la manière de diagraphies



Ex: traçage dans des grès fracturés au Burkina Faso

2) Etude de la dynamique temporelle du flux d'eau souterraine



- Echantillonnage passif des polluants

Représentatif et simple à mettre en œuvre pour des résultats fiables

(représentatif du flux moyen de polluant, du gradient vertical de concentration, intégrateur sur le temps ...).

- ✱ Sorption sur résine

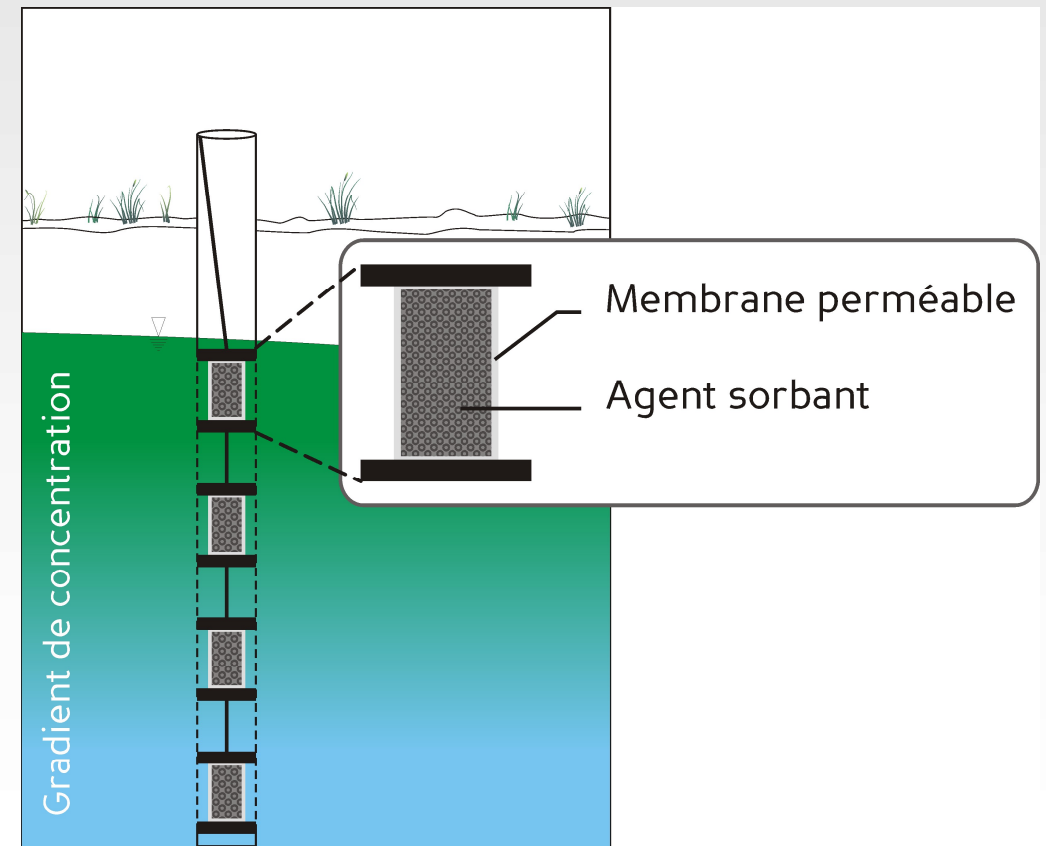
Passive Flux Meter, Ceramic Dosimeter
(Hatfield *et al.* 2002, 2004,
Martin *et al.* 2003, Bopp *et al.* 2005)

- ✱ Diffusion au travers de membranes semi-perméables

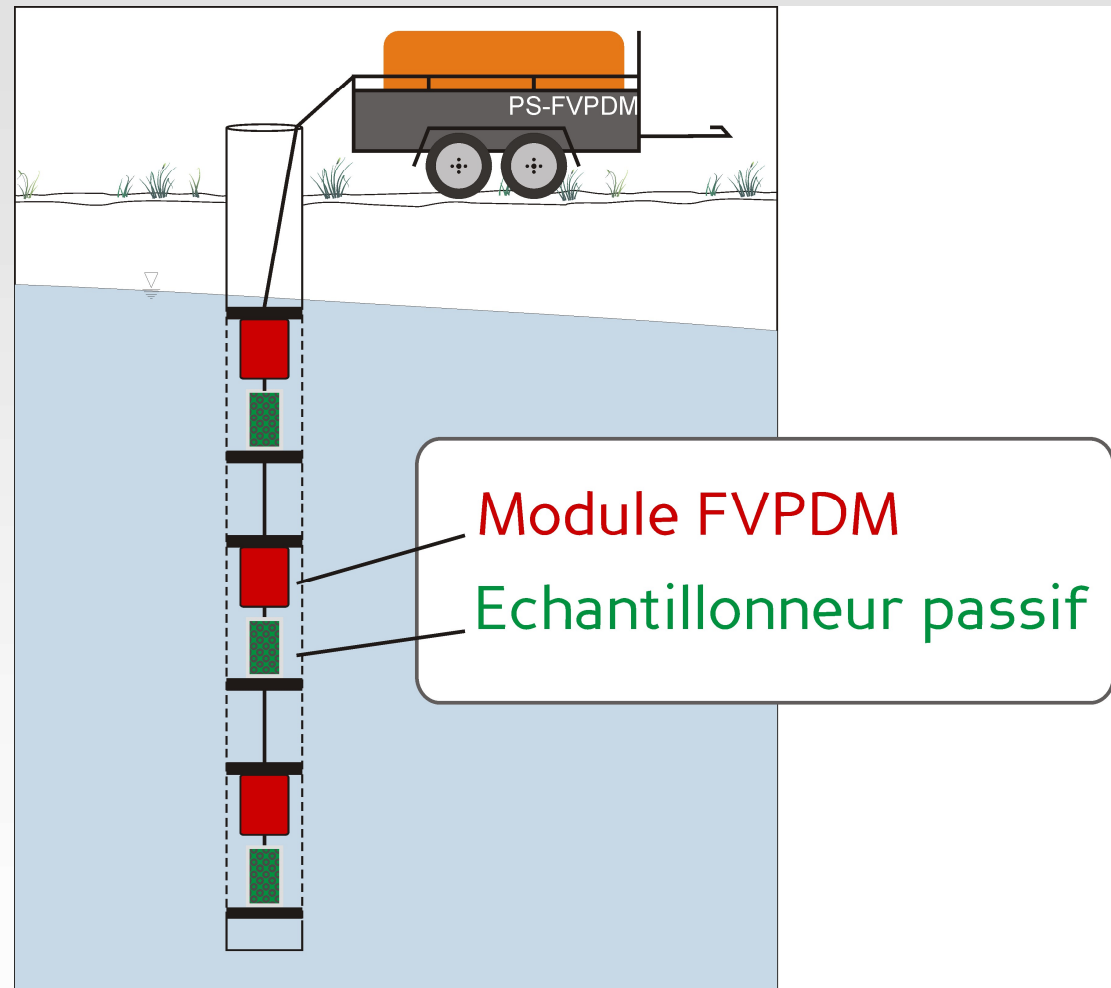
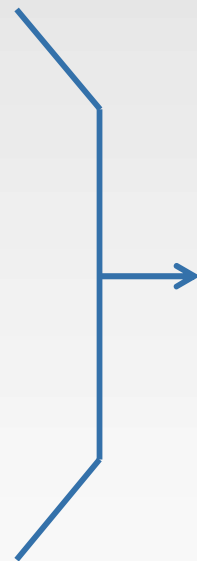
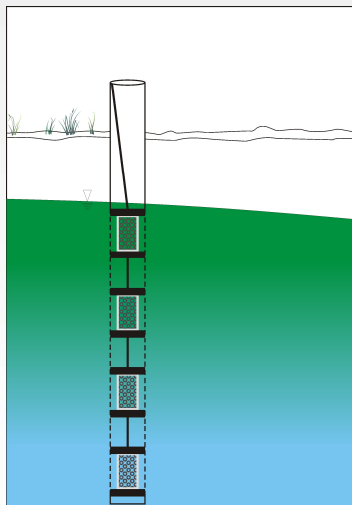
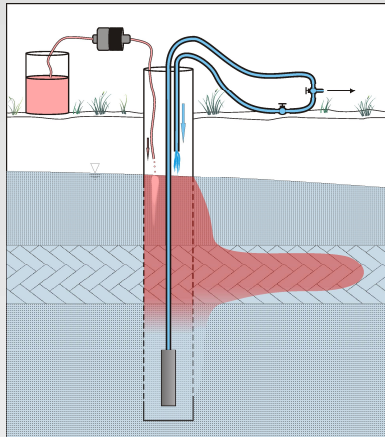
Polyethylene Diffusion Bags, Dialysis Cells
(Barrez & Mania 2009)

- ✱ Prélèvement physique

Snap Sampler
(Parker *et al.* 2009)



- FVPDM + échantillonnage passif → mesure des flux de polluants



✳ Intégration des deux techniques en un système unique PS-FVPDM

Contacts scientifiques / industriels

Industriels

Geolys [be]



SORESMA [be]



URS [be]



Scientifiques

Hatfield K., Annable M. [usa]



Binning P., Bjerg P. [dk]



Diels L. [be]



Administrations wallonnes

Office Wallon des
Déchets (DPS)



SPAQuE



References

- Brouyère, S., J. Batlle-Aguilar, P. Goderniaux, A. Dassargues (2008). A new tracer technique for monitoring groundwater fluxes: The Finite Volume Point Dilution Method (FVPDM). *J. Contaminant Hydrology*, Vol.95, pp 121-140. doi: 10.1016/j.jconhyd.2007.09.001

Acknowledgement

- FP6 Integrated Project AquaTerra (Project nb 505428)
- BELSPO SSD Project FRAC-WECO (Contract nb SD/TE/02A)
- AquaPôle Research Funds

- BRGM Service Eau (A. Gutierrez, C. Mouvet)
- SPAQuE (H. Halen, A. Lox)
- SPE (P. Theunissen)

- EWTS (Ph. Meus)

**Et bien sûr, on est disponibles pour de futures collaborations,
notamment via Pascal !**