Advanced single-well applied tracer techniques for improving reliability of groundwater and contaminant mass flux monitoring

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ELEVENTH INTERNATIONAL CONFERENCE ON REMEDIATION OF CHLORINATED AND RECALCITRANT COMPOUNDS BATTELLE 2018
Palm Springs, California
April 09-12, 2018

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There is a strong need for accurate quantification and monitoring of groundwater and pollutants mass fluxes

However, groundwater flows are complex in space and time …

Heterogeneity of aquifers

"Remediation hydrogeology has emerged and evolved from an era of "simplified bulk-averages" that was reliant on parameters and steady-state assumptions, to our current period where we collect site-specific hydrogeologic data at very high resolution and consider the importance of transient, time-dependent behavior.." Suthersan et al., GW Monit. Remed. 2016

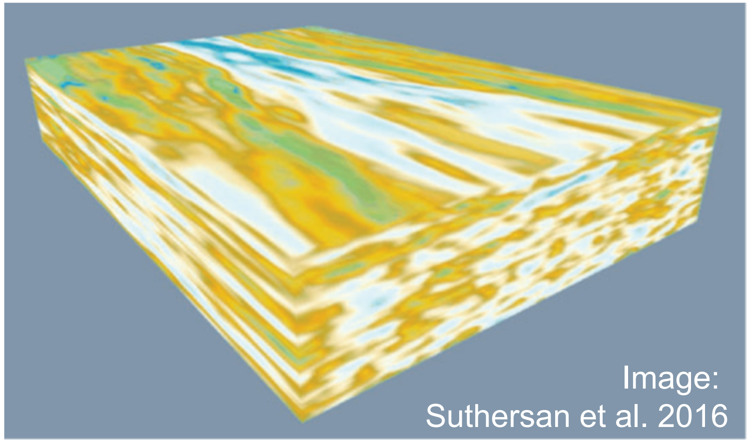
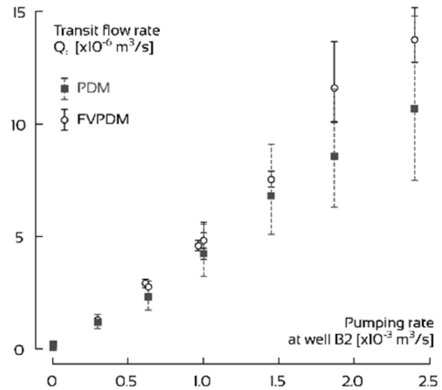


Image: Suthersan et al. 2016

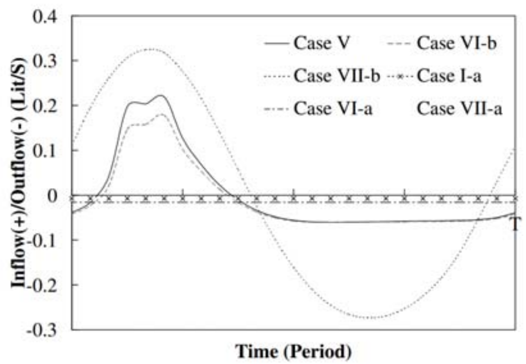


Nearby pumping wells

"The change of pumping rate at the nearby well induced changes in the groundwater flow velocity that were recorded by continuous groundwater flux measurement." Jamin *et al.,* J. of Contam. Hydrol. 2015

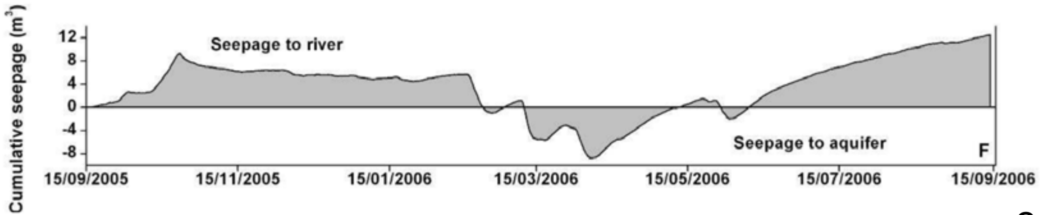
Tidal effects

"The tidal oscillations […] have an influence on regional groundwater flow." Ataie-Ashtiani *et al.*, Hydrological Processes. 2001



GW – Surface water interaction

"Darcy fluxes change continuously in time because o frequent changes in the difference of head between the rive and its alluvial aquifer." Batlle-Aguilar, PhD thesis. 200



Variable groundwater flow: Darcy's law limitations

- Application of Darcy's law leads to **bulk estimates of GW fluxes**, affected by **cumulative errors on hydraulic conductivity and gradient**

  Devlin & McElwee, 2007, Ground Water

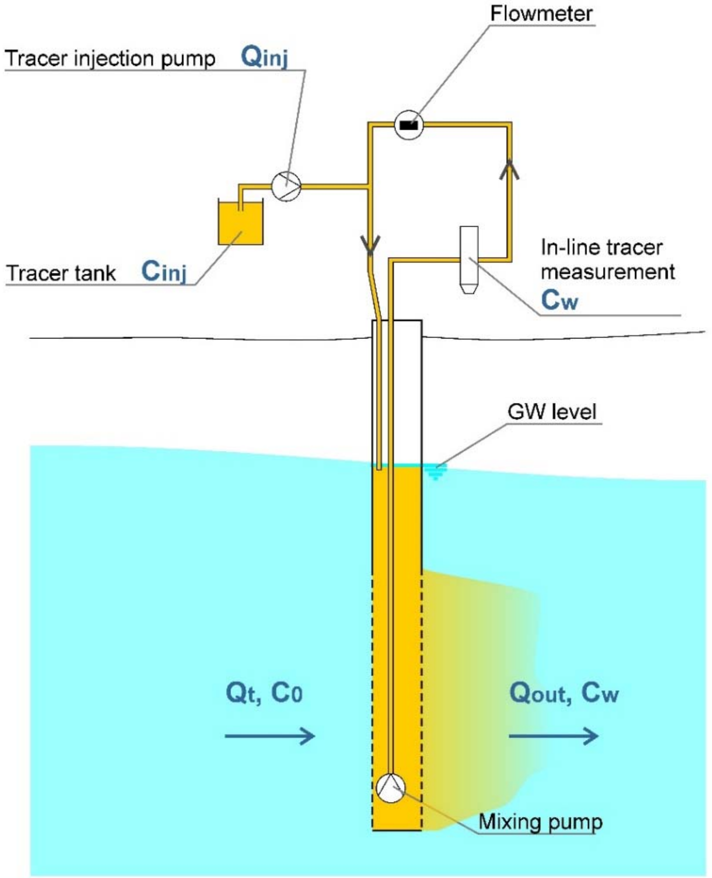
- Classical estimates = **Snapshots** unable to capture of GW flux variations on short- to mid-term time scale
  (hours to days)

There is a need for direct groundwater flux monitoring technology

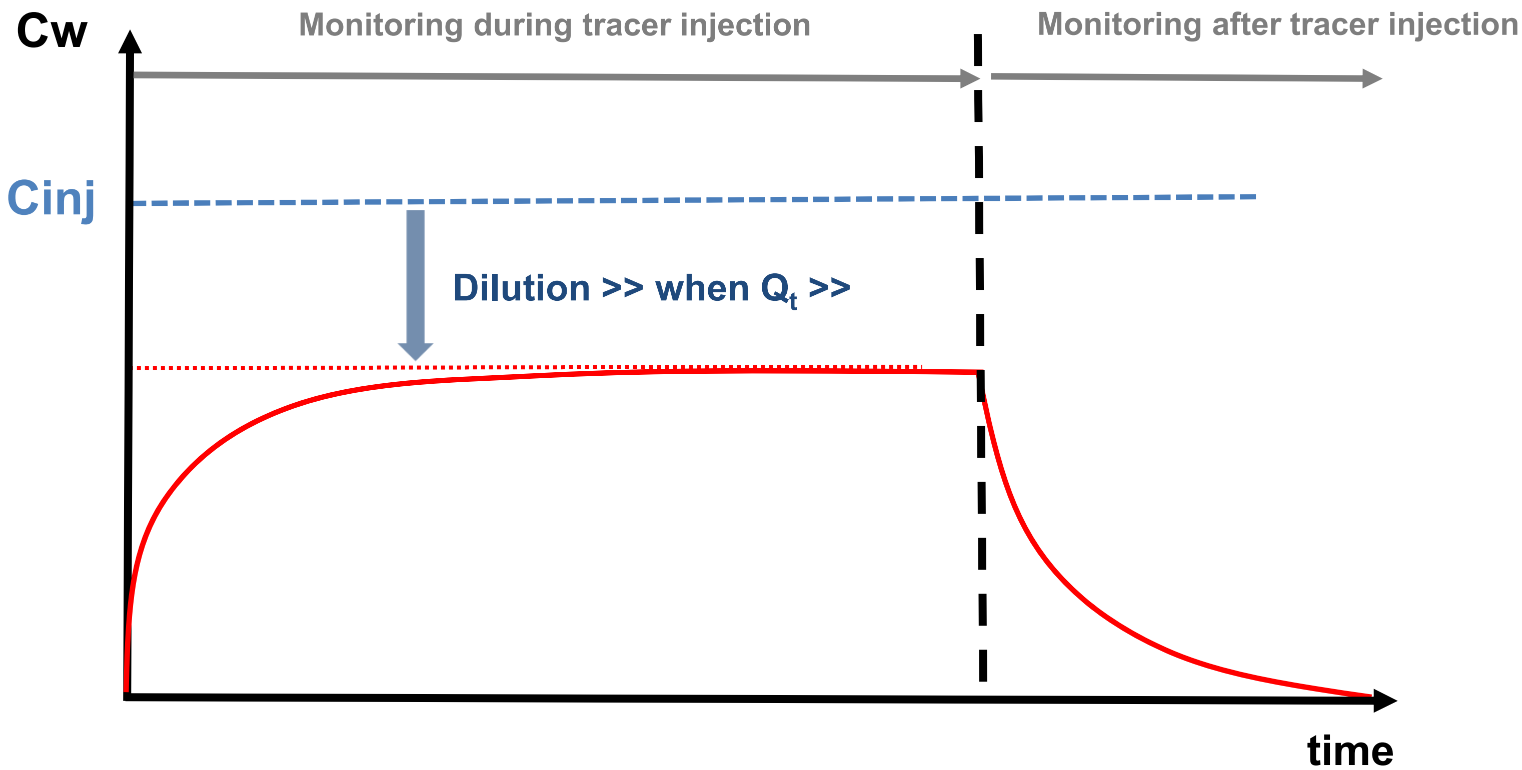
The Finite Volume Point Dilution Method (FVPDM): basic setup

Generalisation of single well dilution techniques [Brouyère *et al.* 2008, J. Cont. Hydrol.]

Key difference: the tracer is continuously injected at a low injection rate



The Finite Volume Point Dilution Method (FVPDM): 3 steps



Concentration evolution obtained using a tracer mass-balance in the injection well

Water conservation

Further details in Brouyère (2003) Water Resour. Res. and Brouyère et al. (2008) J. Contam. Hydrol.

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

Tracer mass conservation

$$\frac{\partial M_t}{\partial t} = \frac{\partial}{\partial t}(V_w C_w) = r_w^2 \left(C_w \frac{\partial h_w}{\partial t} + h_w \frac{\partial C_w}{\partial t} \right) = Q_{inj} C_{inj} + Q_t C_t - Q_{out} C_{out}$$

Concentration evolution in the injection well

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

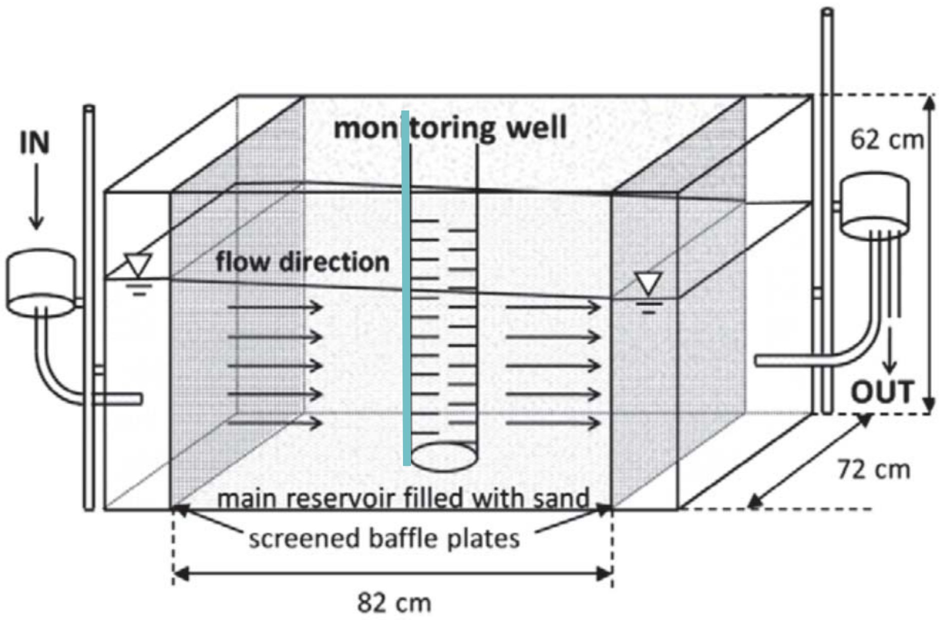
$$Q_t = Q_{out} - Q_{inj}$$

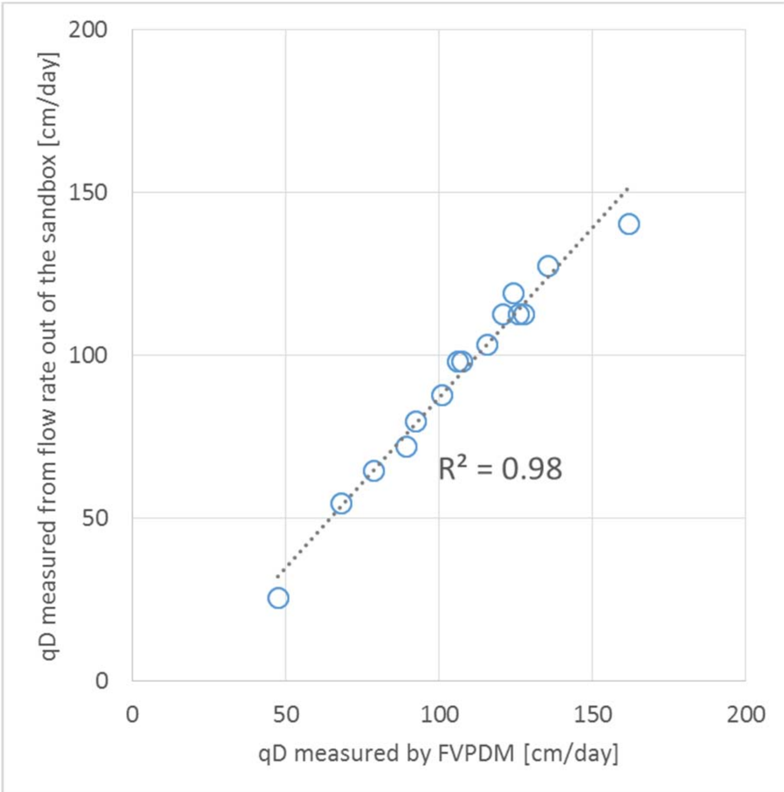
Validation : GW flux measurements with FVPDM on a sandbox

FVPDM performed under controlled flow in a sandbox

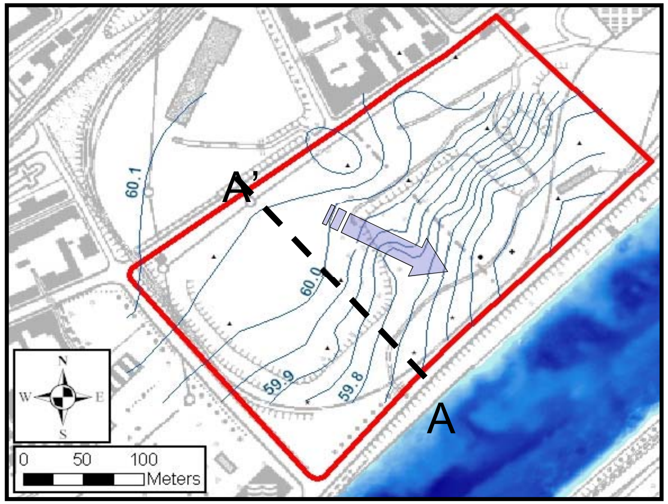
Validation for water fluxes from 0.40 to 1.6 m/day

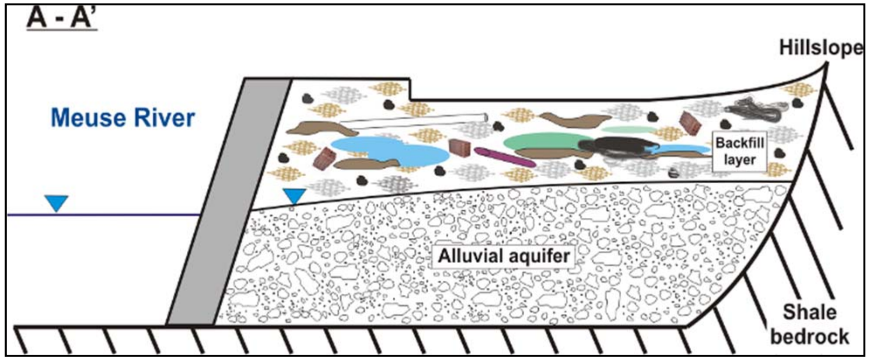
(Flow field distortion of the monitoring well 1.7 according to Verreydt et al. 2014, Groundwater)

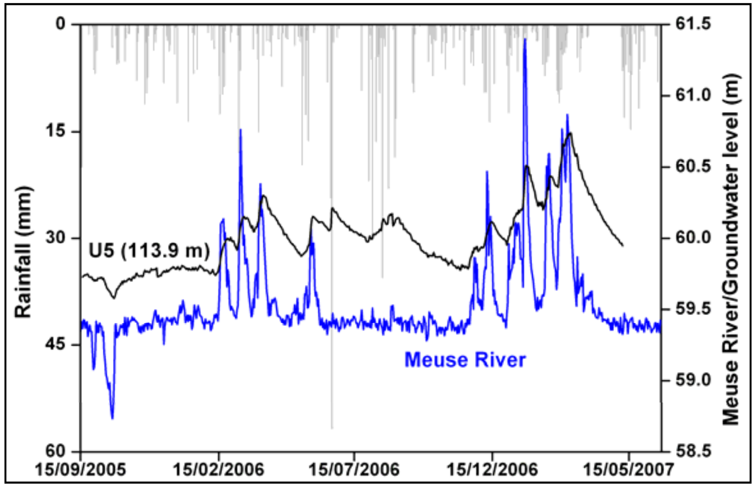


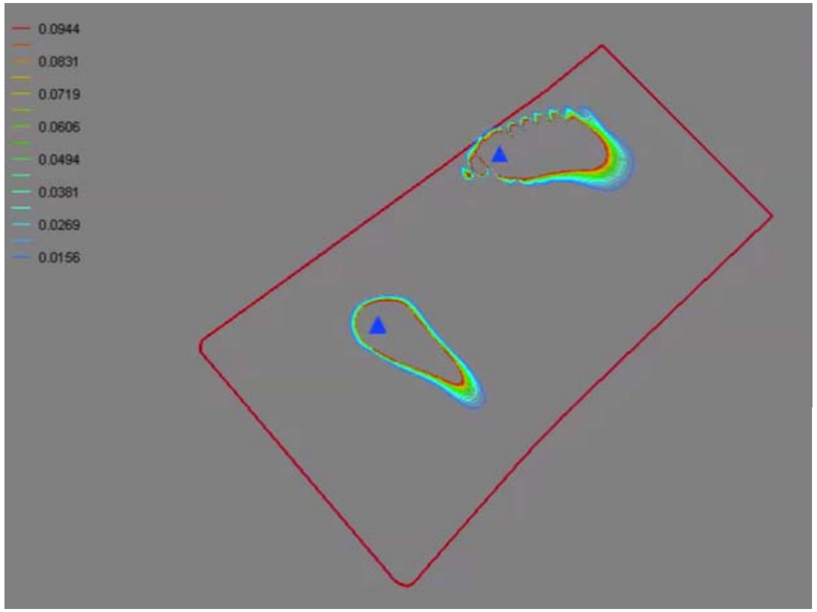


Case study 1 in Belgium: Brownfield of a former manufactured gas plant near a river (benzene plumes)



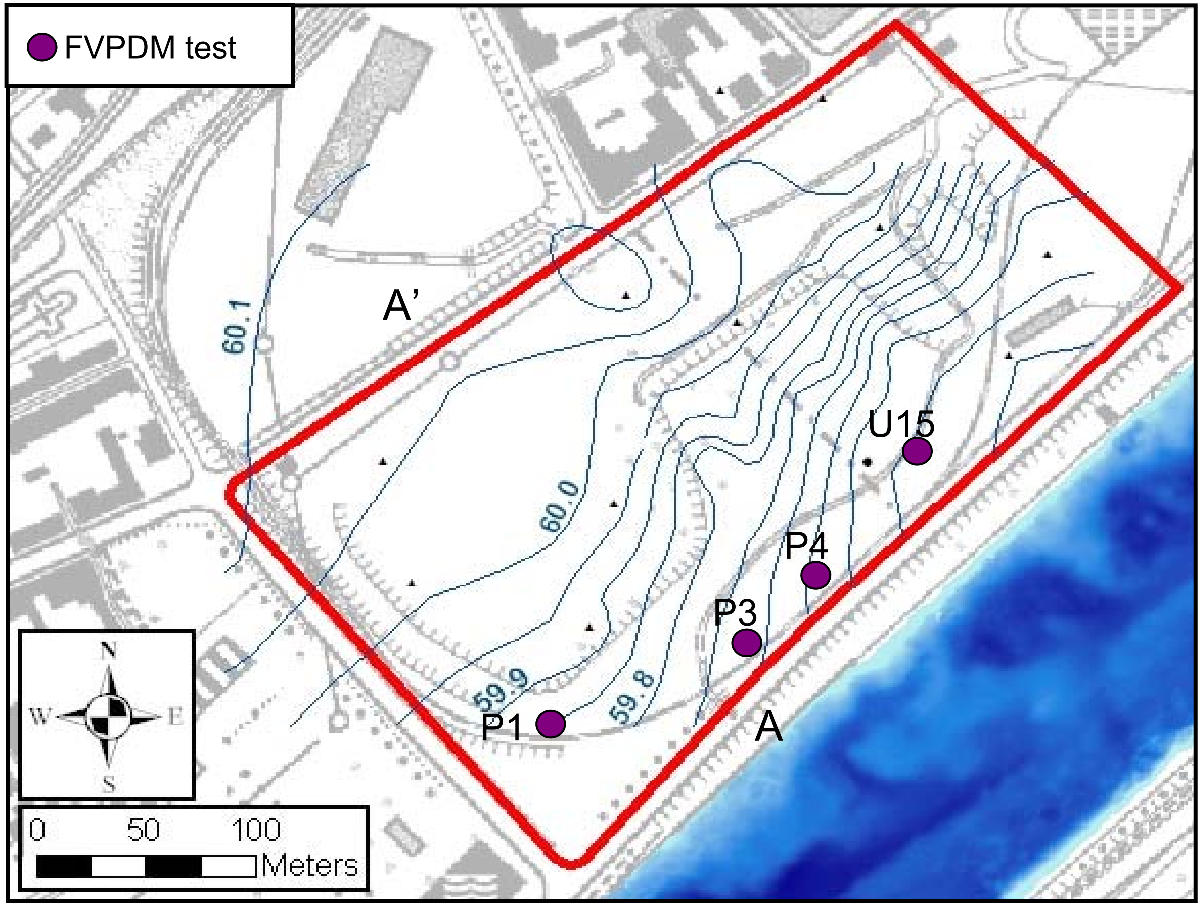




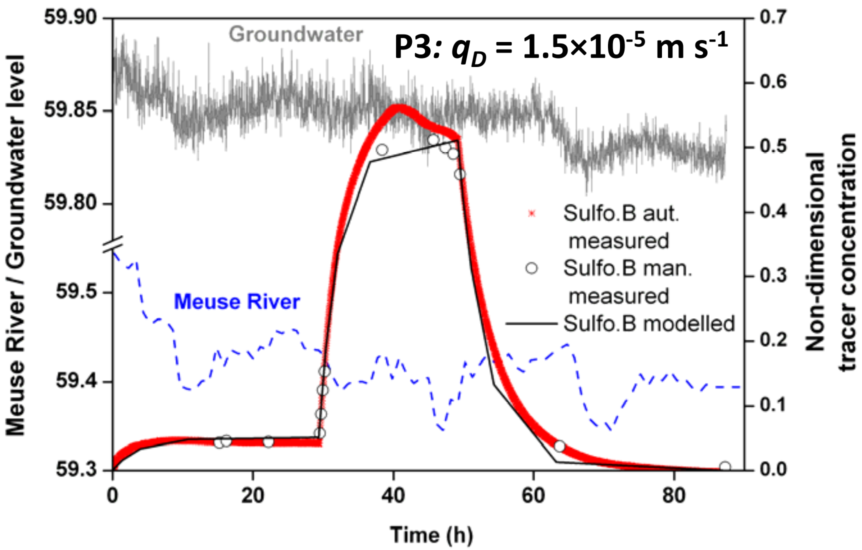


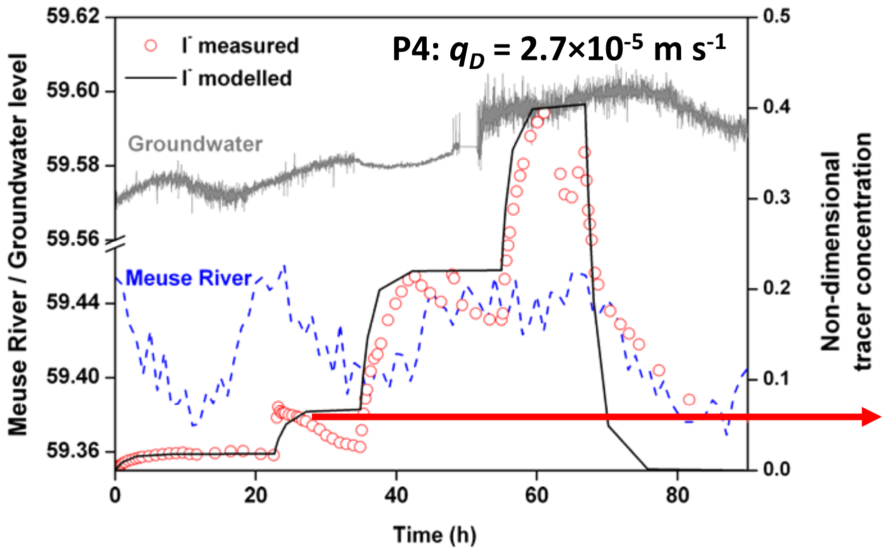
Case study 1 in Belgium : FVPDM first successful application in a contaminated brownfield

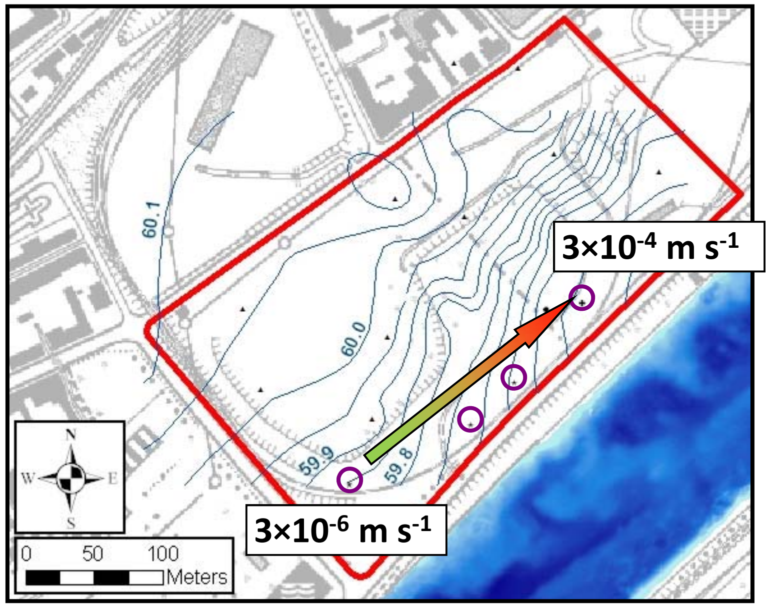
Objective: to obtain groundwater discharge rates from the contaminated alluvial aquifer to the river (Liège, Belgium)



Case study 1 in Belgium : FVPDM first successful application in a contaminated brownfield





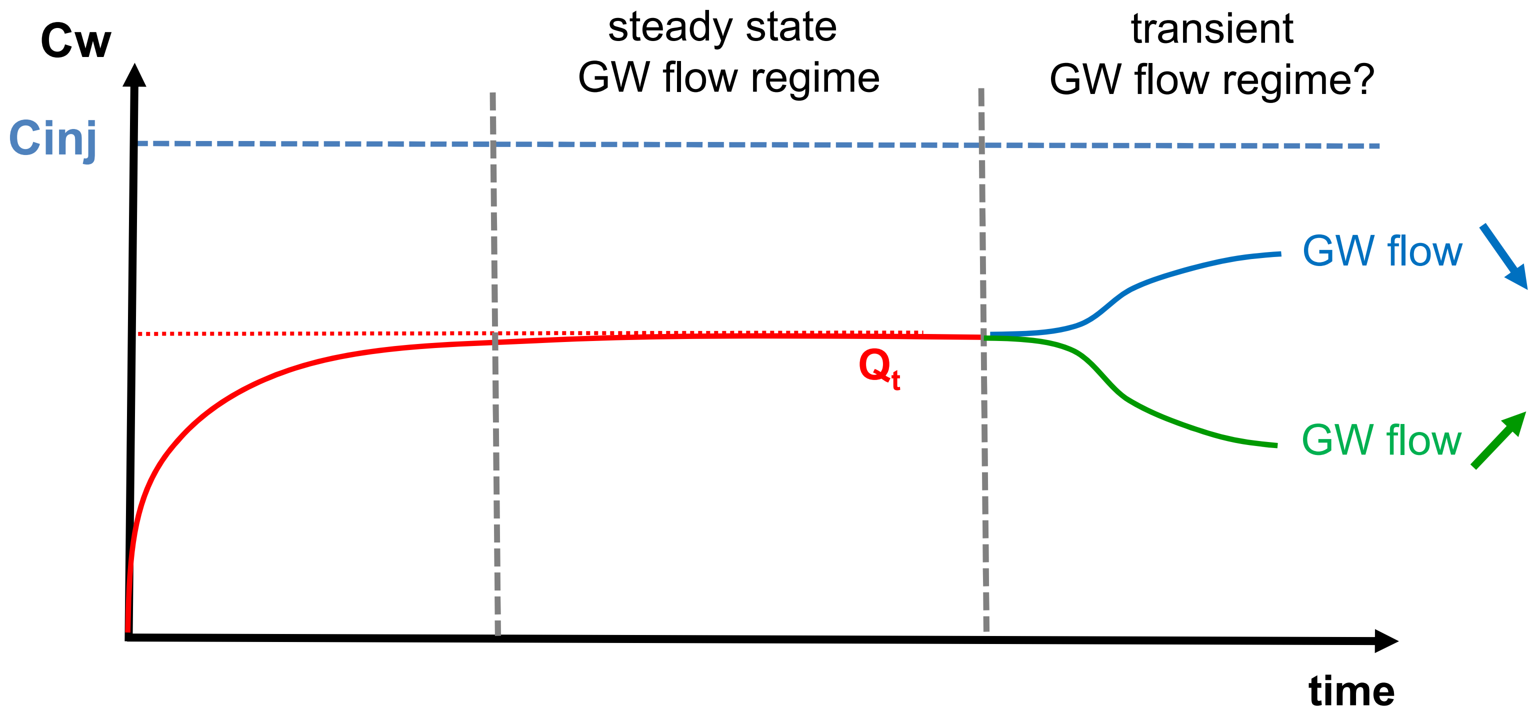


FVPDM very sensitive to changes in GW fluxes!

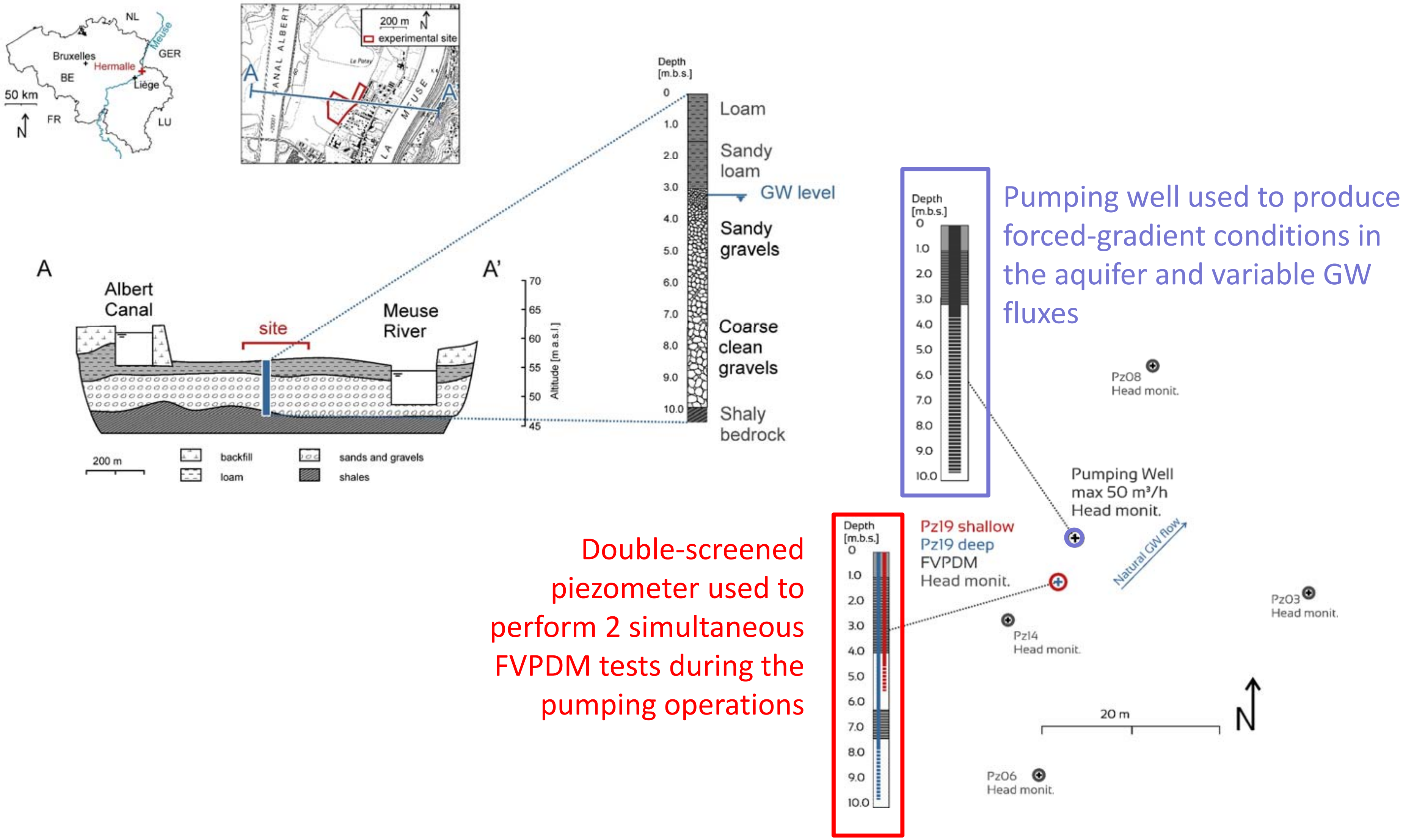
FVPDM potential: monitoring of variable GW fluxes

Constant injection of tracer and mixing during the monitoring time

Tracer concentration in the tested piezometer varies according to the GW flux (more/less dilution)

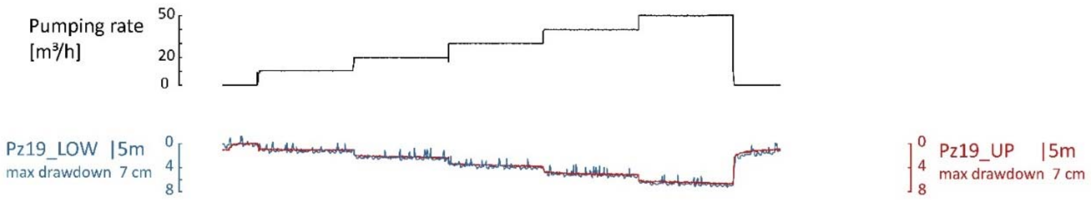


Case study 2 in Belgium: monitoring variations in GW fluxes induced by pumping operations in a neighboring abstraction well



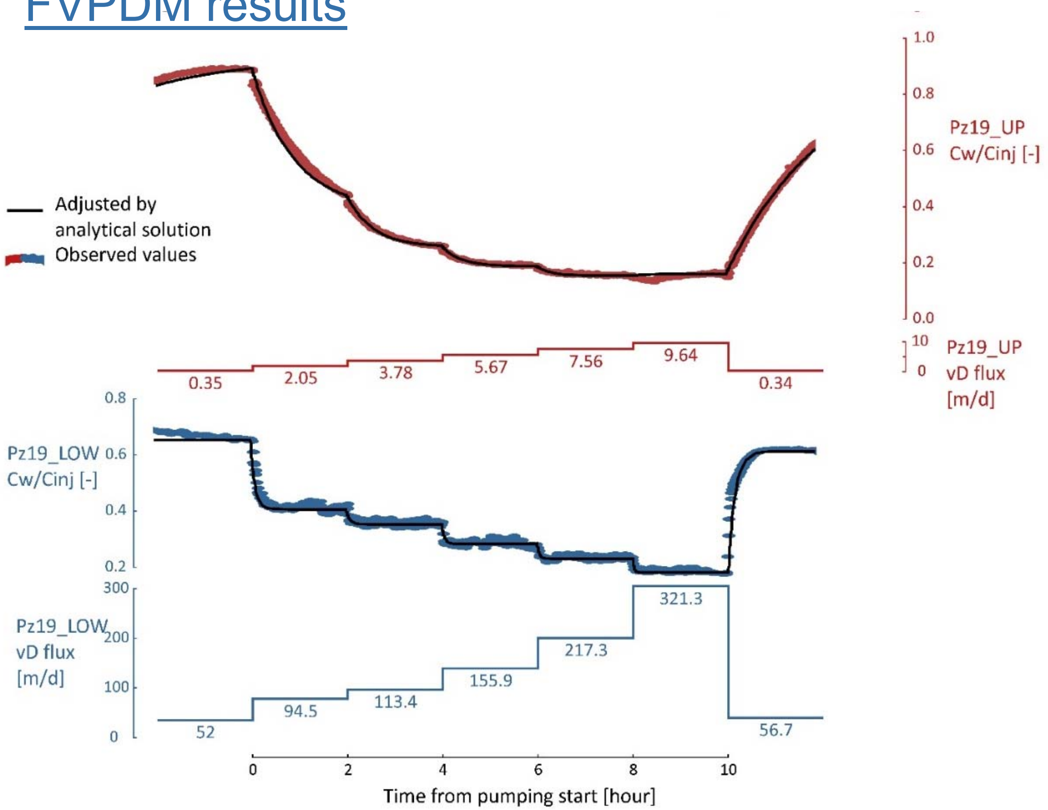
1st conclusion: Vertical heterogeneity in groundwater fluxes

Pumping test results



Pumping test results: same drawdown
→ same K value and same Darcy flux!

FVPDM results



FVPDM results: different concentration evolutions
→ different Darcy fluxes!

Pz19_UP

0.35 m/d without pumping

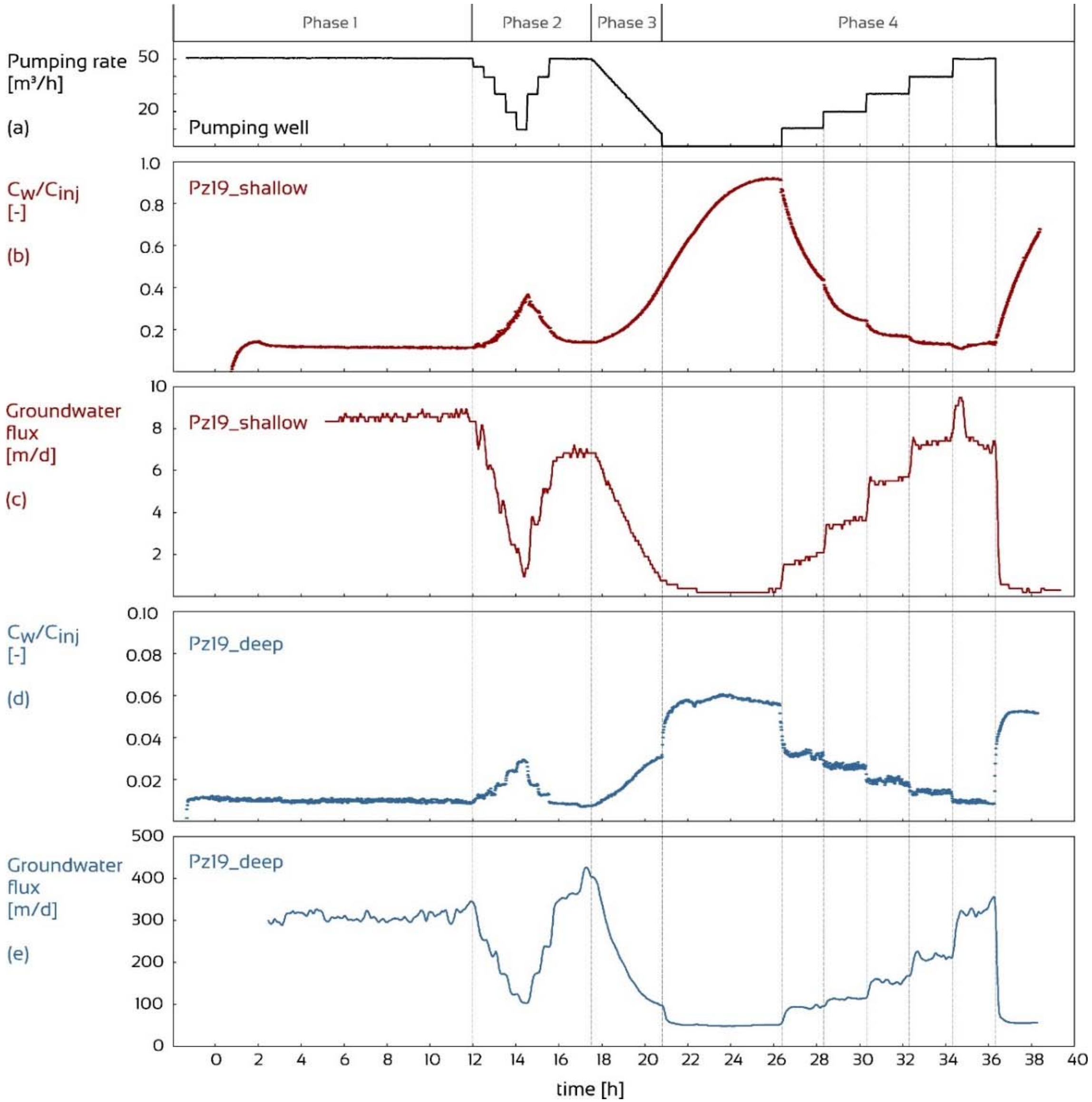
9.64 m/d at max pumping

Pz19_LOW

52 m/d without pumping

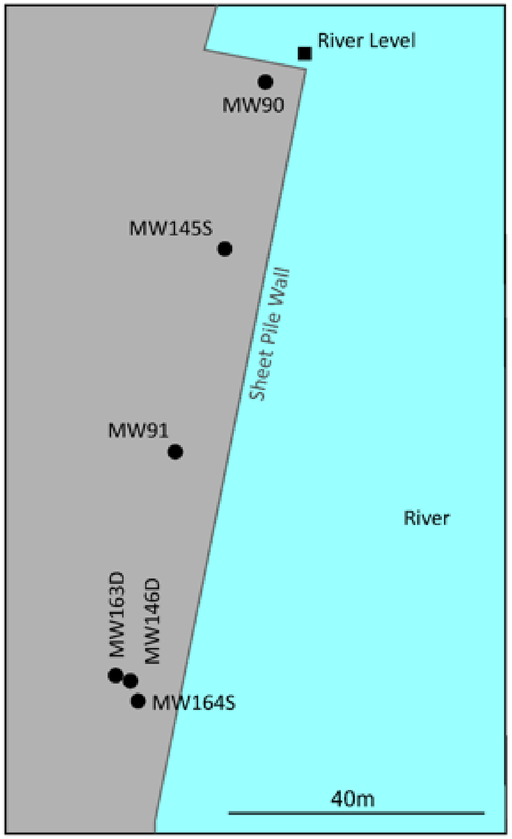
321 m/d at max pumping

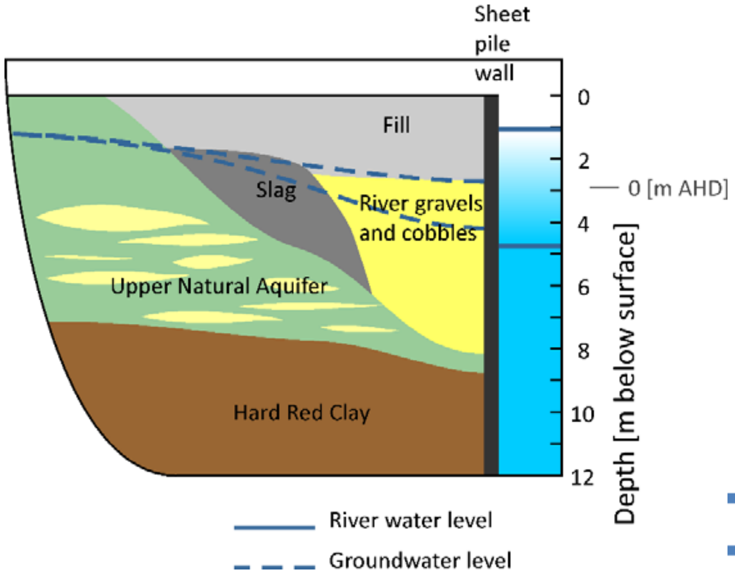
2nd conclusion: FVPDM able to monitor and quantify very transient GW fluxes, on a wide range

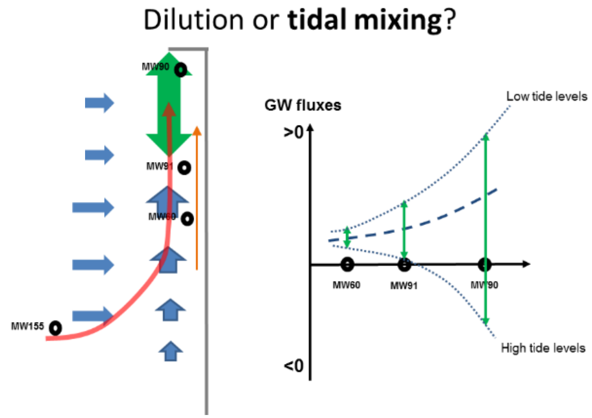


Case study 3 in Australia: Groundwater pollution under an industrial warf along an estuary (heavy metals)

- Costal aquifer hydraulically connected to tidal estuary -> complex groundwater flow
- Heavy metal contamination of GW (Mn, Zn, Cd, Pb) -> risk for estuarian ecosystems

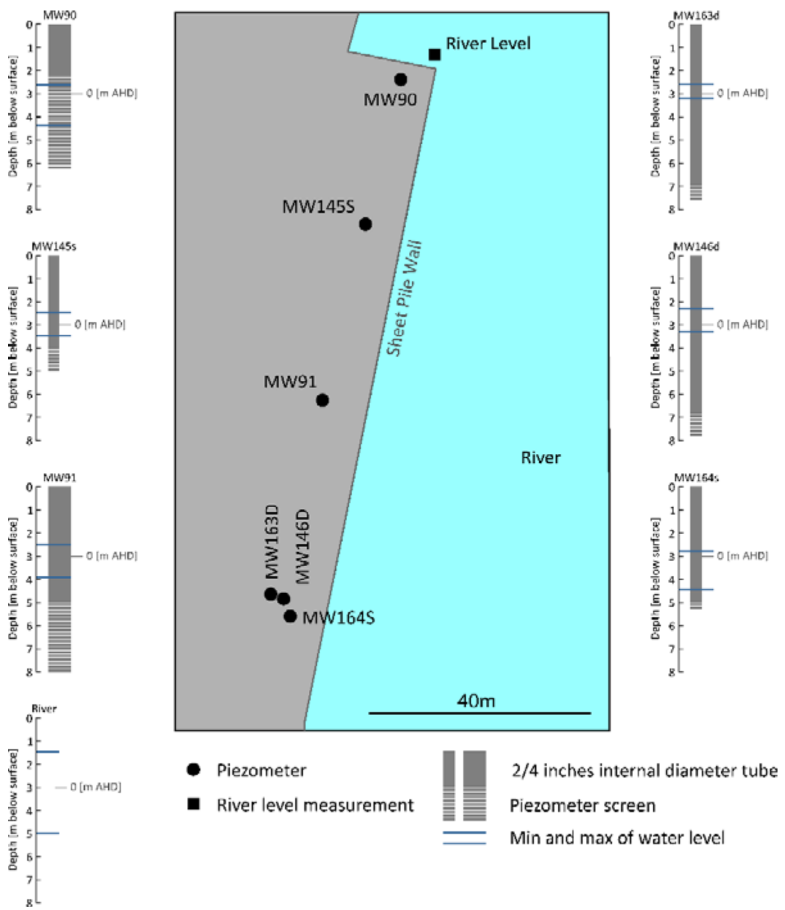






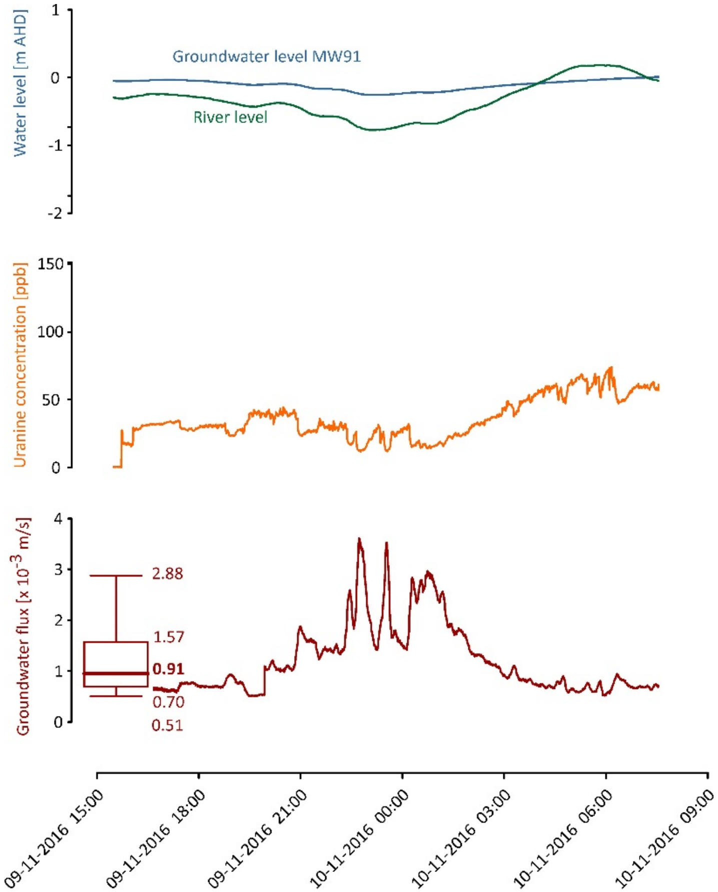
Case study 3 in Australia: Groundwater pollution under an industrial warf along an estuary (heavy metals)

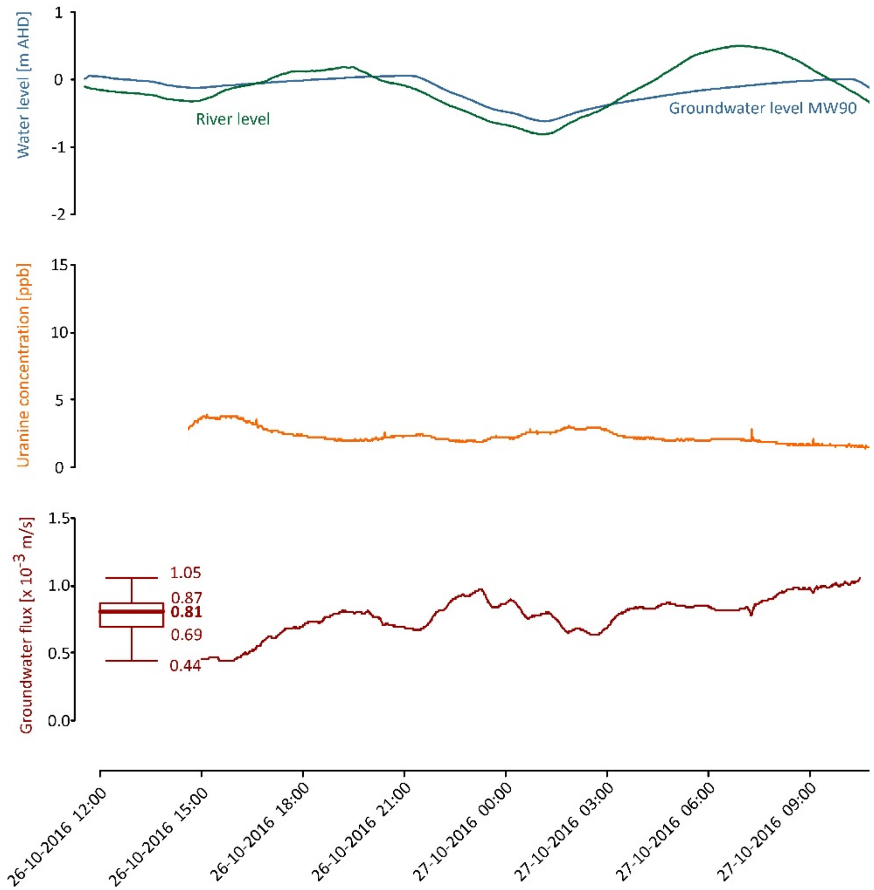
- Continuous FVPDM monitoring for 48 hours (4 tide cycles) in 7 piezometers
- GW sampling for HM concentrations



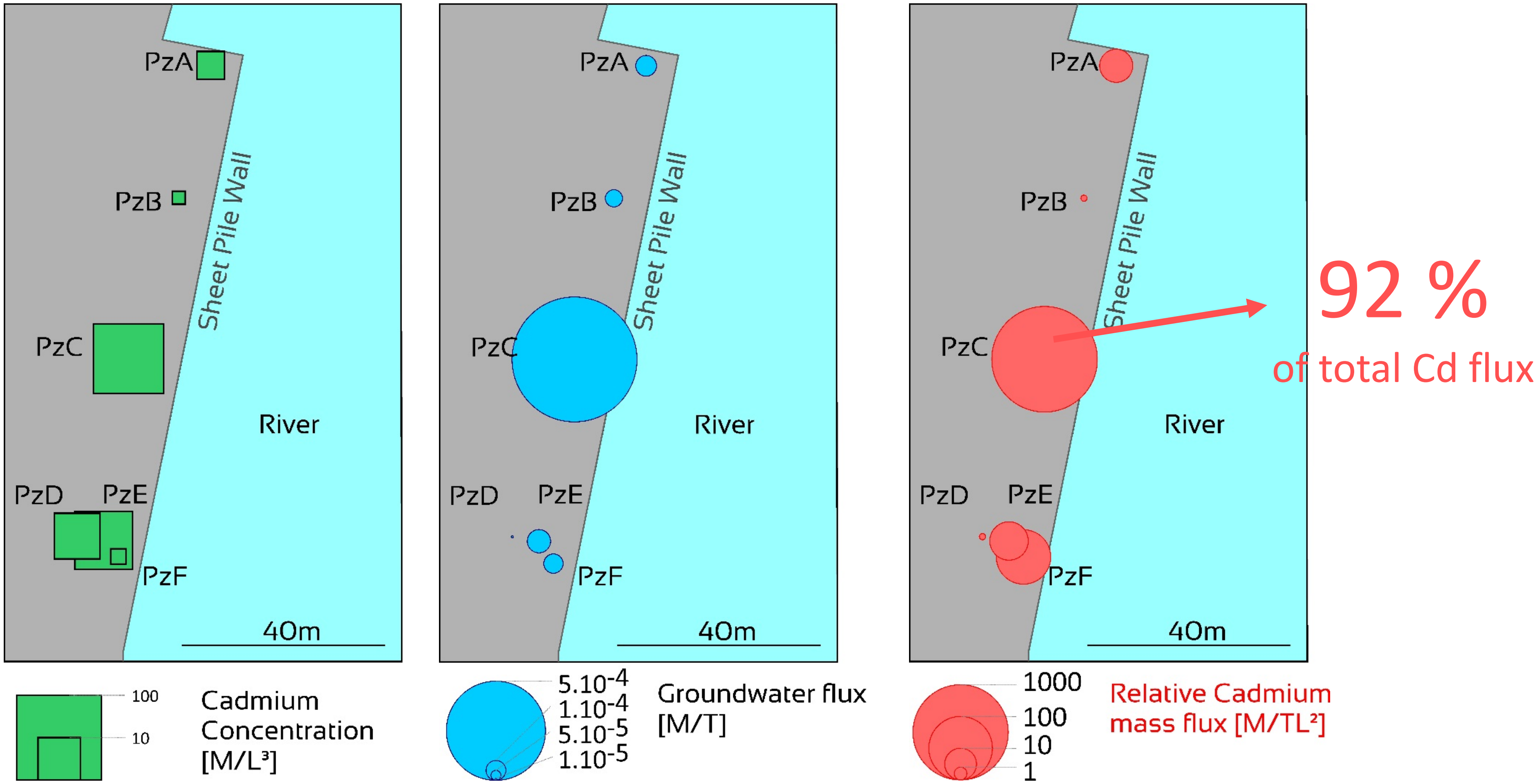
Result 1: No inversion of GW flow direction

- The GW fluxes coming from upgradient are so important that we observed no inversion of GW flow during high river level



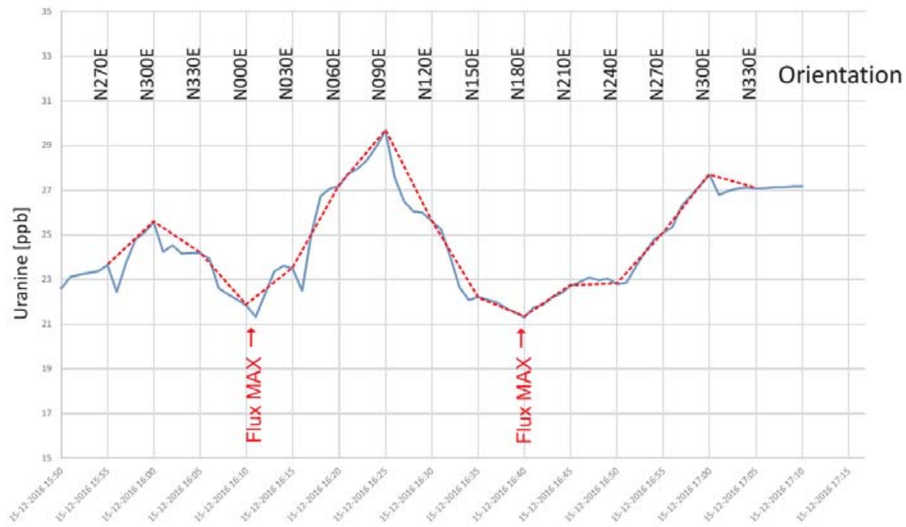


Result 2: Benefits for mass fluxes measurements

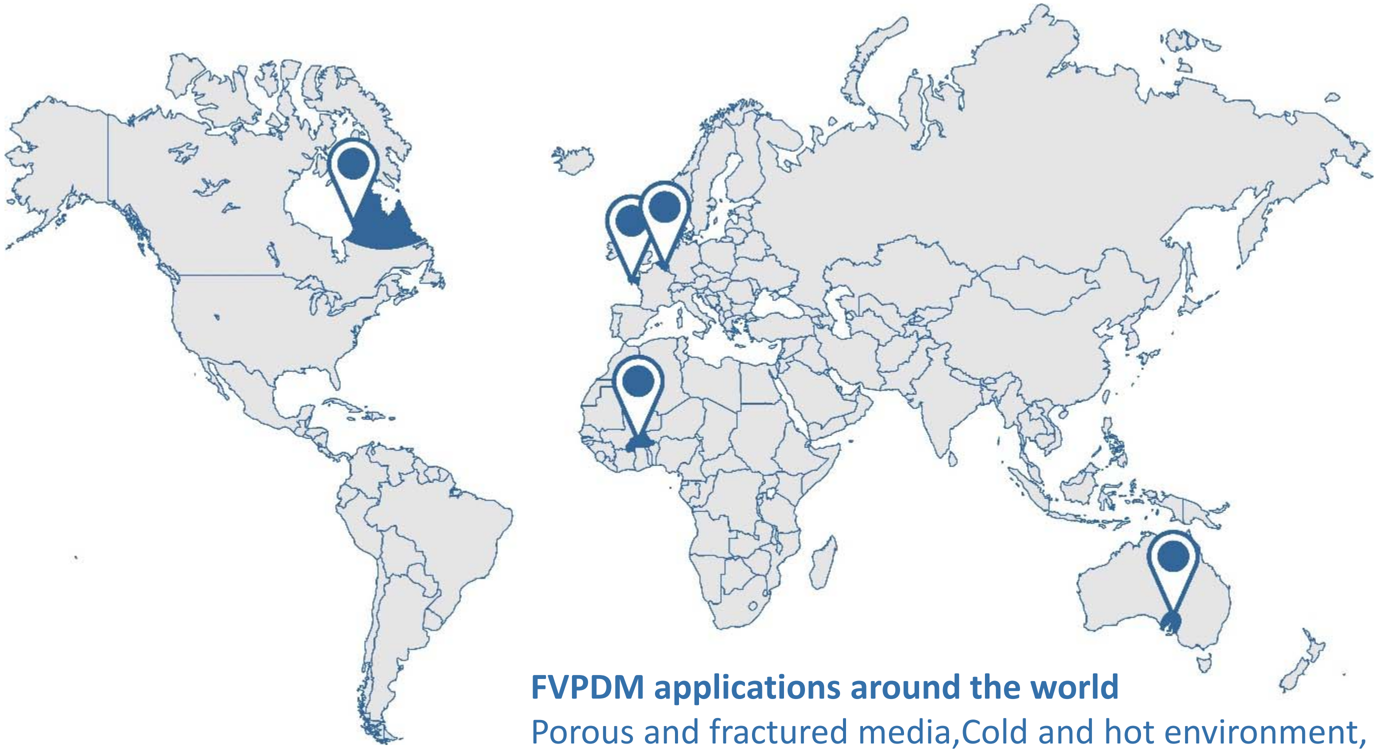


FVPDM : Conclusions and perspectives

- FVPDM able to quantify precisely GW fluxes
- FVPDM captures small and fast changes in GW fluxes
- Coupled to measurements of concentrations in contaminants, FVPDM able to deliver precise and useful estimates of mass fluxes
- **Perspectives**
  - Full coupling of FVPDM and contaminant monitoring
  - Directional FVPDM



Any questions?



FVPDM applications around the world
Porous and fractured media,Cold and hot environment,
1.5’’ to 4’’ diameter wells, 0.5m to 80m deep

Groundwater Quality 2019

Groundwater Quality 2019
The next IAHS conference on Groundwater Quality (**GQ 2019**) will be held in Liège (Belgium) on 9-12 September 2019 !
With the support of IAH, UK CL:AIRE and EU H2020 ITN iNSPIRATION

More information : **aimontefiore.org/GQ2019**
Contact: c.dizier@aim-association.org – serge.brouyere@uliege.be

Further reading on FVPDM

- Brouyère, S. (2003). Modeling tracer injection and well-aquifer interactions: A new mathematical and numerical approach. Water Resources Research, 39(3). http://hdl.handle.net/2268/2321
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