

Continuous monitoring of transient groundwater fluxes using the Finite Volume Point Dilution Method

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9th International Association of Hydrological Sciences (IAHS) Groundwater Quality 2016
Southern University of Science and Technology (SUSTech)
July 24-28, 2016

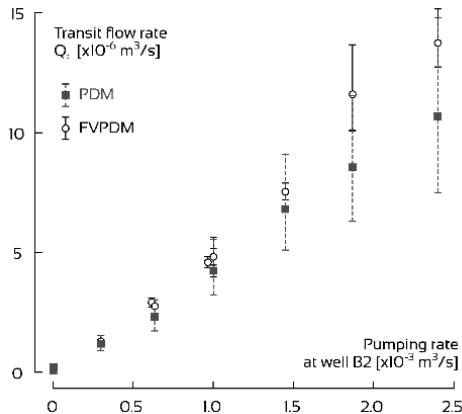
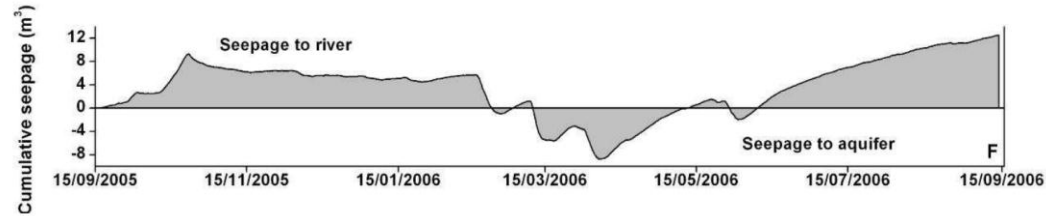


Variable groundwater flow: Nature is transient

Hydrogeological contexts intrinsically show transient groundwater fluxes...

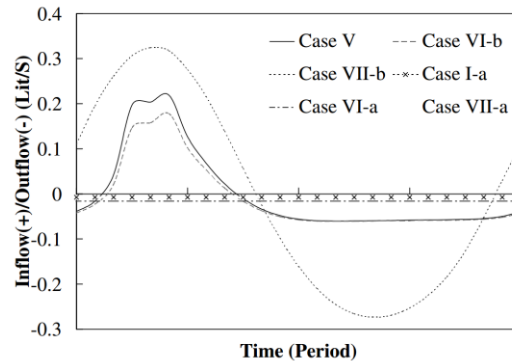
GW – Surface water interactions

“Darcy fluxes change continuously in time because of frequent changes in the difference of head between the river and its alluvial aquifer.” Batlle-Aguilar, PhD thesis. 2008



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

High recharge zones

“Intensive rainfall [...] can also provide substantial recharge to the aquifer locations considered as discharge areas. [...] certain areas may change from recharge to discharge status, depending on the temporal variability of fluxes.” Lubczynska & Gurwinb, J. of Hydrology. 2005

Variable groundwater flow: Darcy's law limitations

- **Quantifying GW fluxes on Darcy's law alone leads to cumulative errors**
(on hydraulic conductivity and on hydraulic gradient)
Devlin & McElwee, 2007, Ground Water
- **Classical methods = 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

Recent tracer technique for GW flux measurement: FVPDM

The Finite Volume Point Dilution Method: basic concepts

Generalisation of single well dilution techniques (i.e. PDM)

[Brouyère, 2003, WRR; Brouyère *et al.* 2008, J. Cont. Hydrol.]

Continuous tracer injection

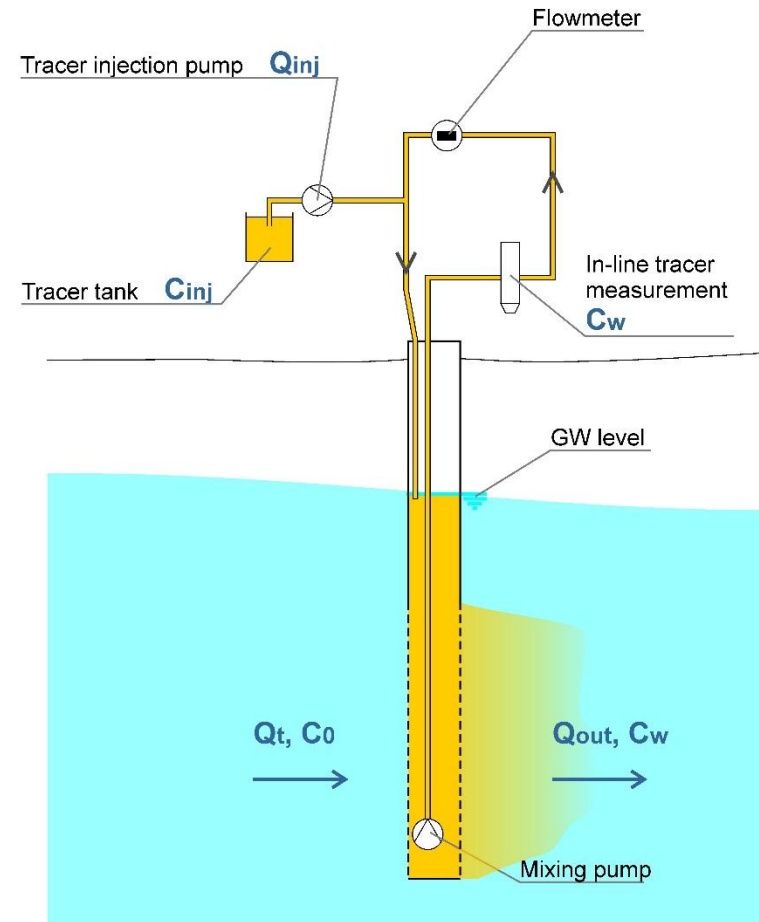
$$C_w(t) = \frac{Q_{inj} \times C_{inj} - (Q_{inj} \times C_{inj} - Q_{out} \times C_{w,0}) e^{-\frac{Q_{out}}{V_w}(t-t_0)}}{Q_{out}}$$

- Allows precise GW flux measurement
- Able to capture changes in groundwater flux between two steady states

[Jamin *et al.* 2015, J. of Cont. Hydrol.]

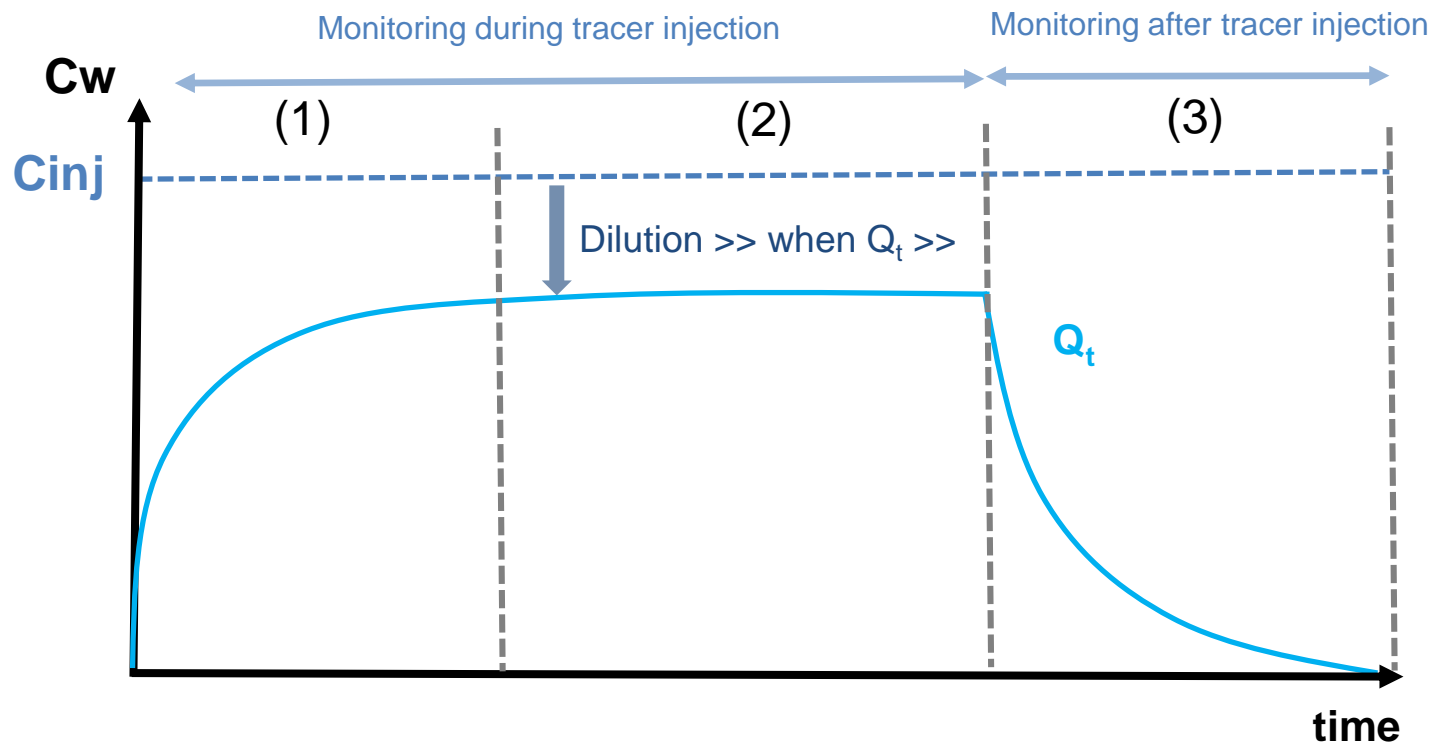
Objective :

Application for continuous monitoring of transient groundwater flow



The Finite Volume Point Dilution Method: 3 steps

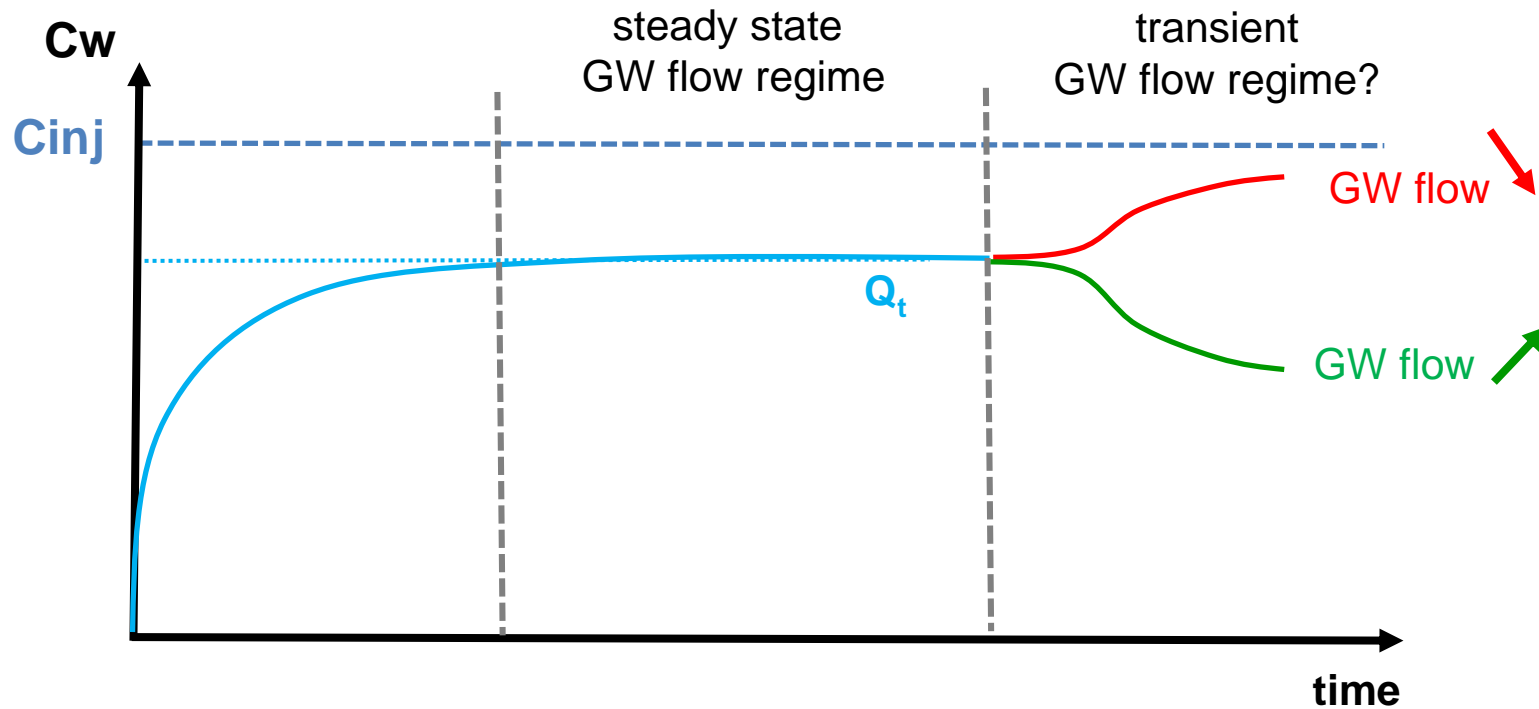
1. Transient when tracer concentration rises
2. Stabilized at equilibrium between injection and discharge in the aquifer
3. Exponential decline (= classical PDM)



The FVPDM: 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)



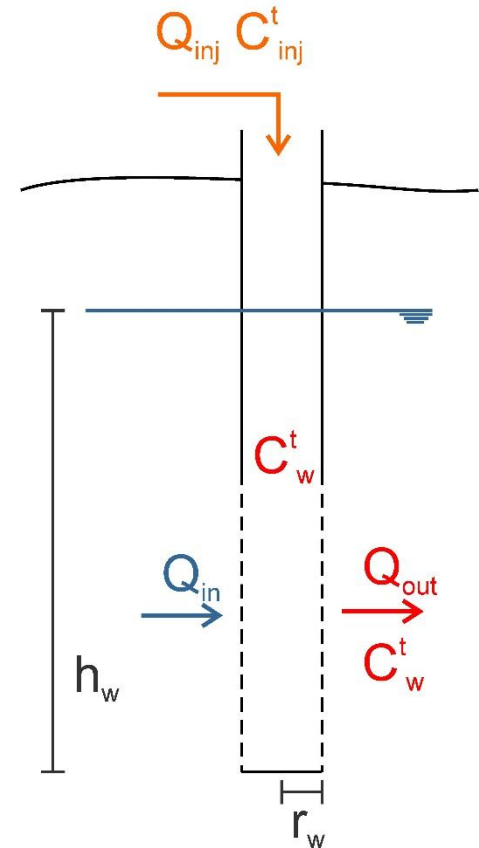
The FVPDM under transient GW fluxes: development

Development of a fully transient solution based on a finite difference schema to interpret FVPDM results in transient

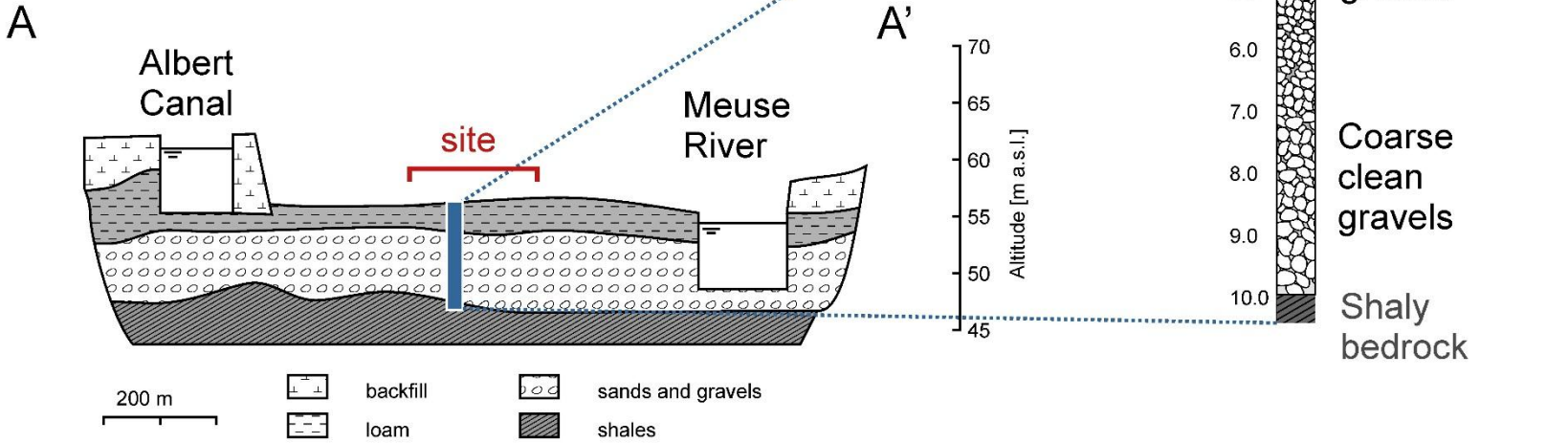
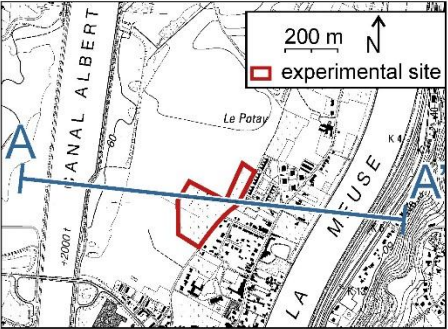
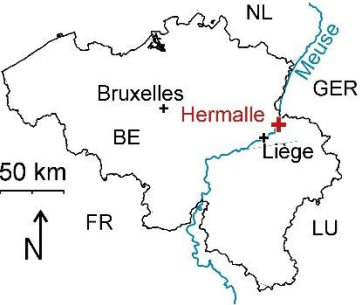
$$C_w \pi r_w^2 \frac{\partial h_w}{\partial t} + h_w \pi r_w^2 \frac{\partial C_w}{\partial t} = Q_{inj} C_{inj} - Q_{out} C_w$$

$$C_{w n+1} = \frac{Q_{inj} C_{inj} + \frac{h_{w n+1} \pi r_w^2 C_{w n}}{t_{n+1} - t_n}}{\frac{h_{w n+1} \pi r_w^2}{t_{n+1} - t_n} + (Q_{inj} + Q_{in n+1})}$$

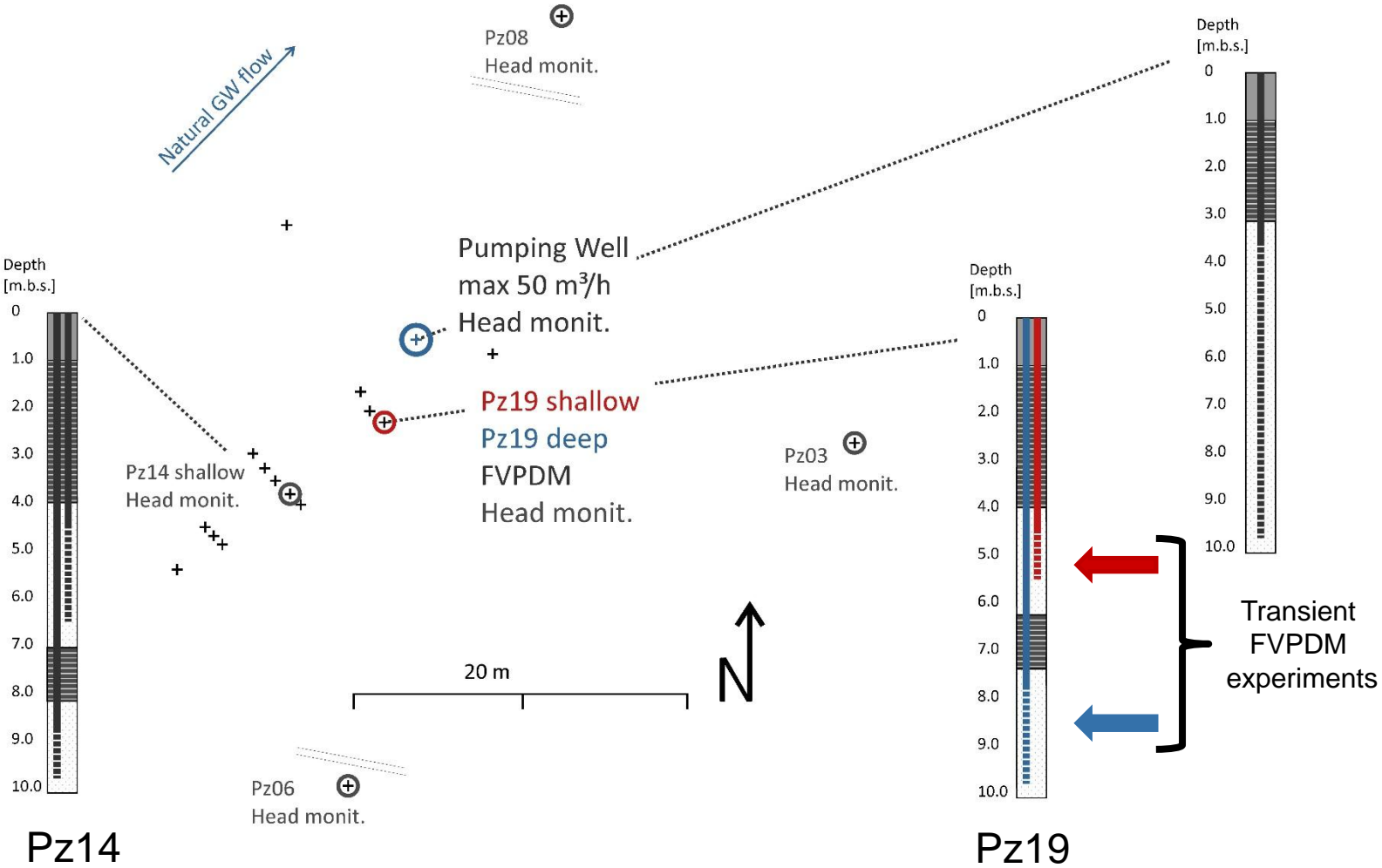
Test on a fully transient GW flux under controlled conditions for validation on field data



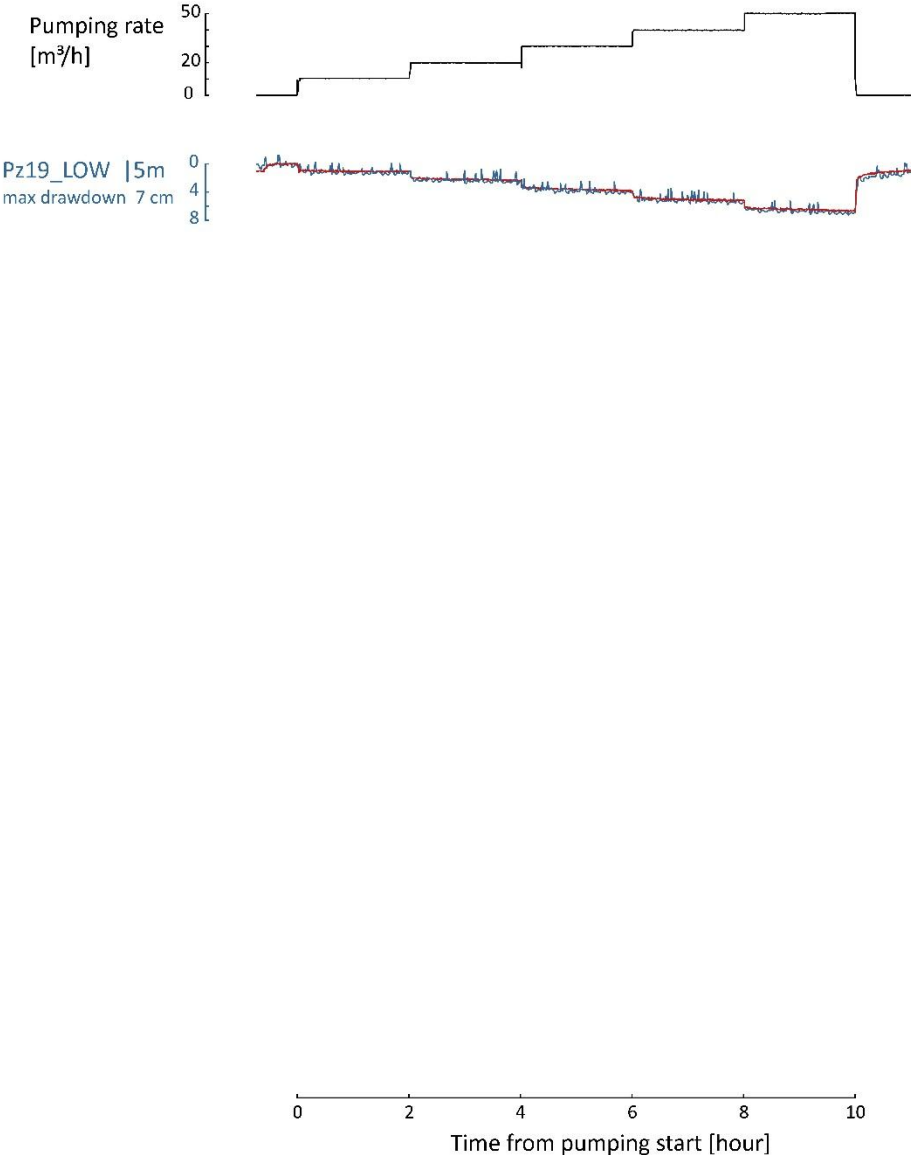
Hydrogeological context of the experience: Alluvial aquifer



Experimental setup: GW flux variation induced by pumping



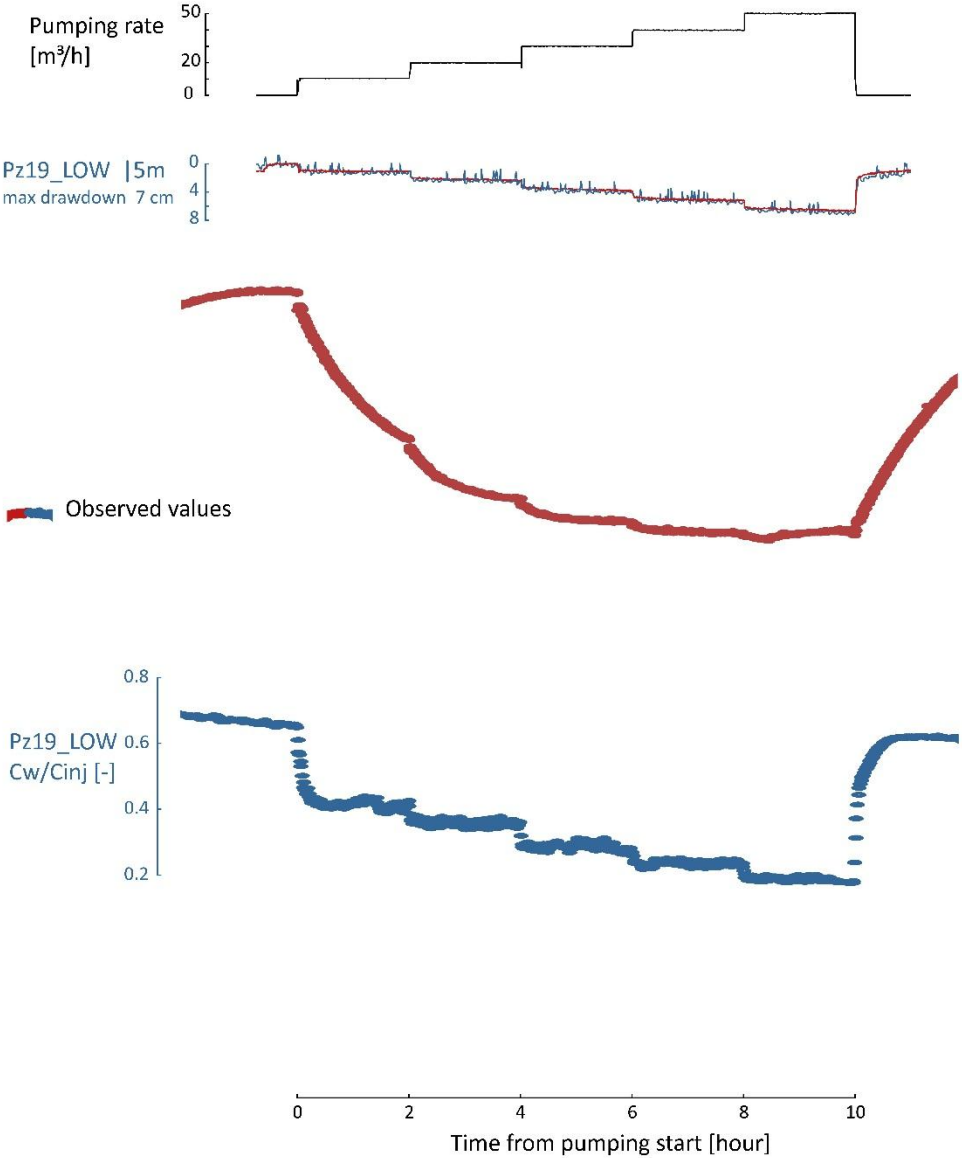
FVPDM results: Drawdown



0 Pz19_UP |5m
4 max drawdown 7 cm
8

- Drawdown identical at Pz19 up and low

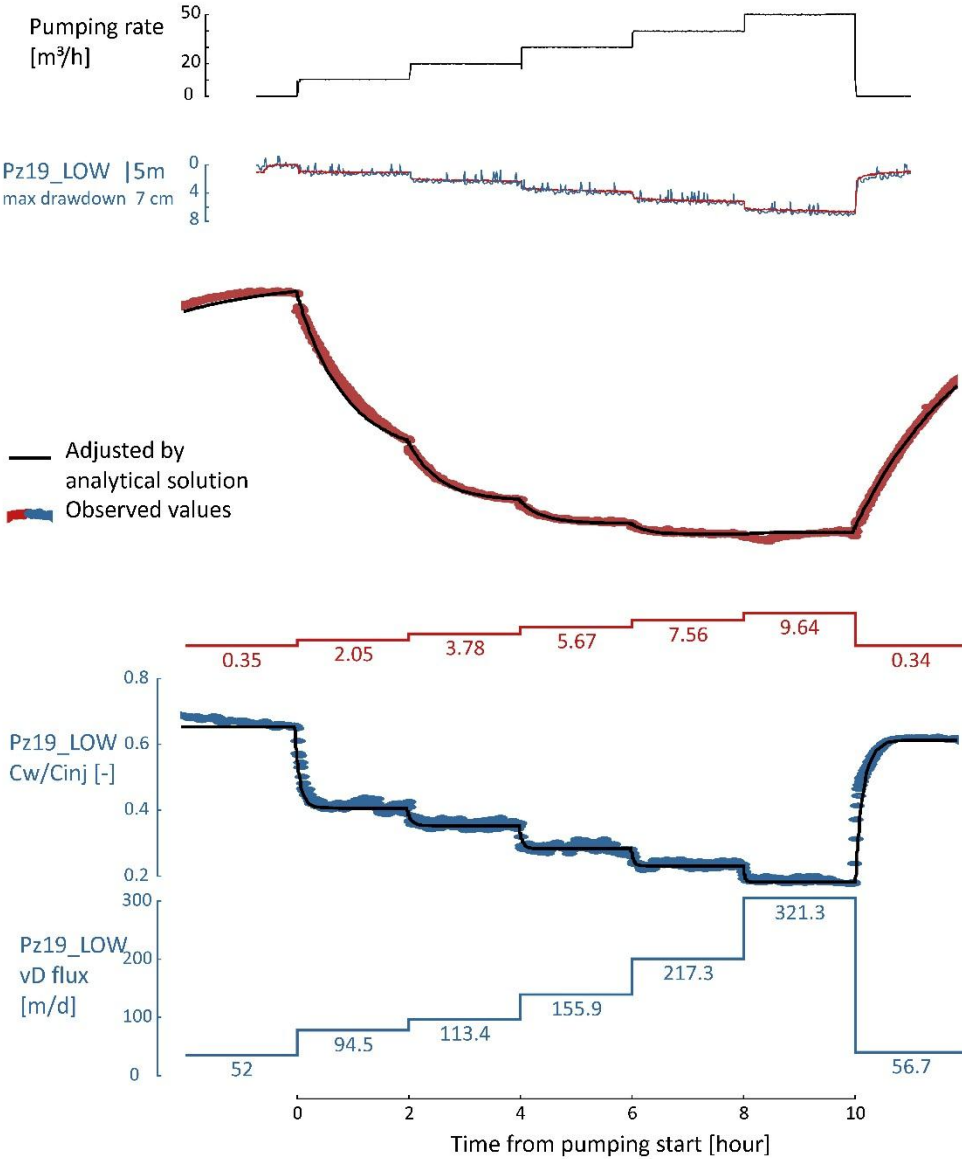
FVPDM results: GW flux higher in the lower part of aquifer



Pz19_UP |5m
max drawdown 7 cm

- Drawdown identical at Pz19 up and low
- FVPDM is sensitive to changes in GW flux
- Increased pumping rate = higher GW flux = C_w decrease in tested Pz
- Longer to stabilize in the upper screen of Pz19, suggesting slower GW flow in the upper part of the aquifer

FVPDM results: GW flux higher in the lower part of aquifer



Darcy's flux :

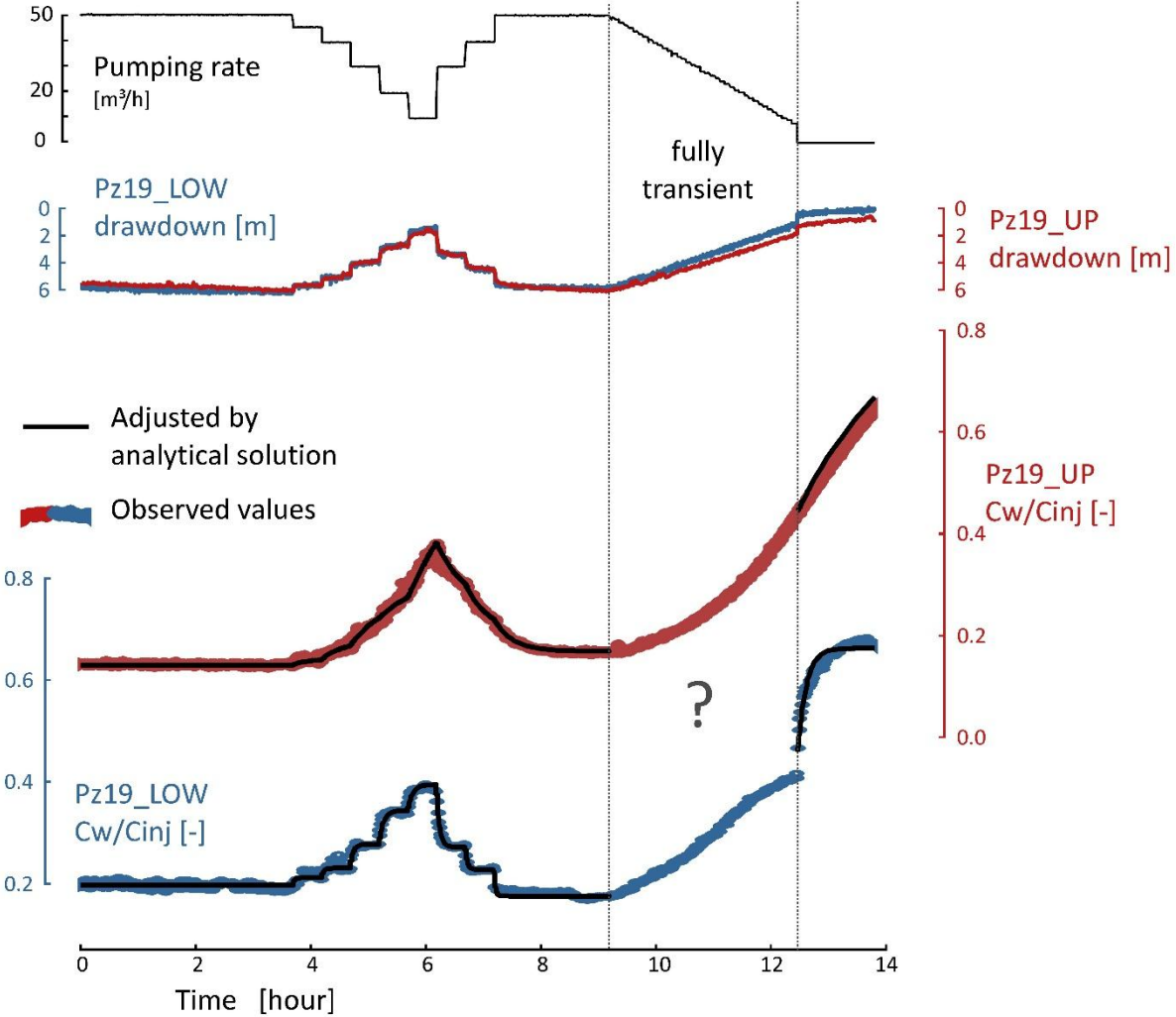
Pz19 UP

- 0.35 m/d without pumping
- 9.64 m/d at max pumping
- Δ pumping step : + 1.9 m/d

Pz19 LOW

- 52 m/d without pumping
- 321 m/d at max pumping
- Δ pumping step : variable

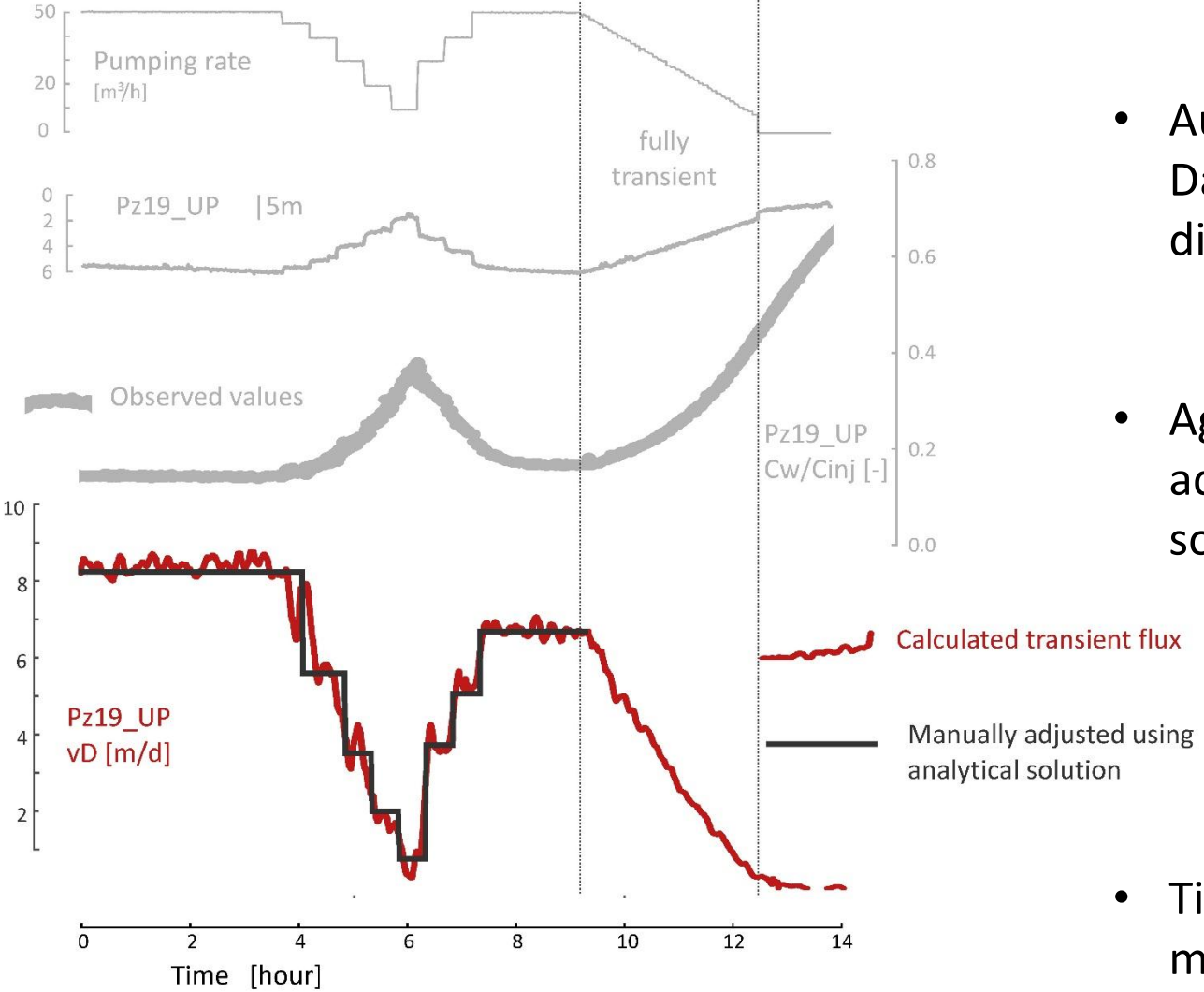
FVPDM abilities: Simulated transient GW fluxes



Shortening time steps to

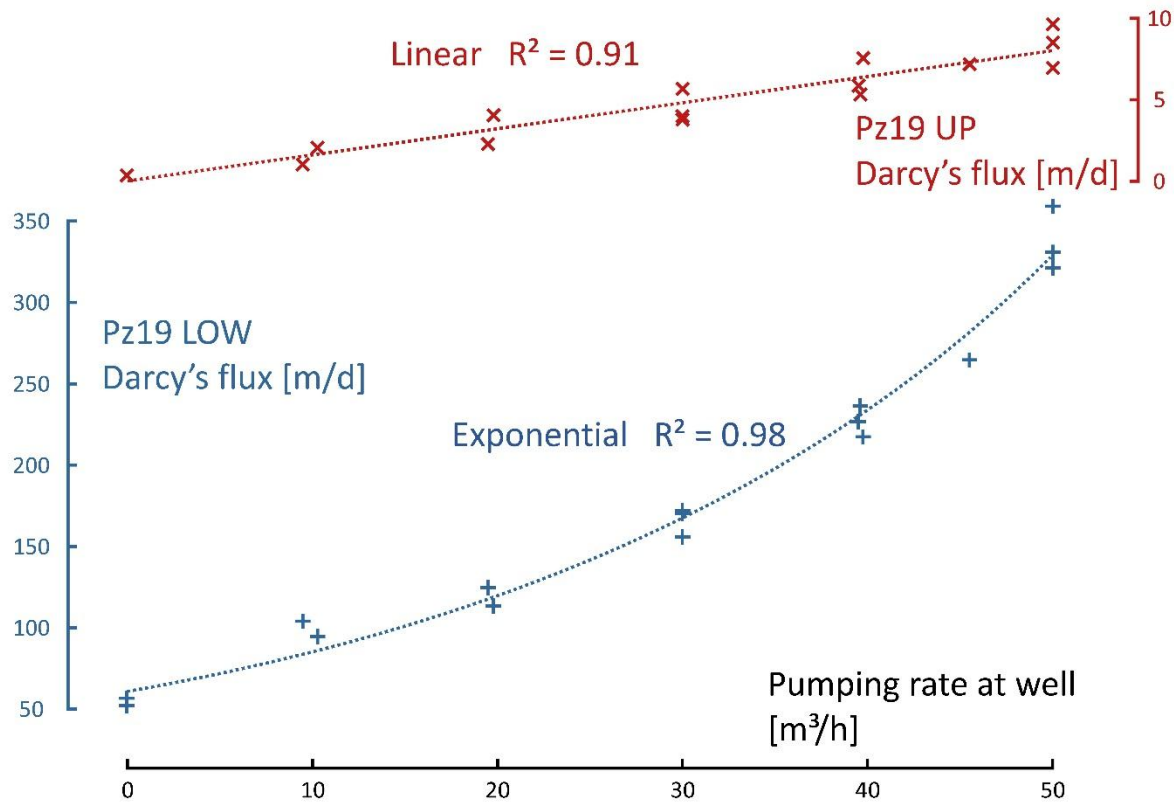
- 30 min : Pz19_LOW still stabilizing, not Pz19_UP
- 5 min : no stabilization, fully transient GW flow field. Captured by FVPDM, changes in C_w

FVPDM transient: Calculation of transient GW fluxes



- Automated calculation of Darcy's flux based finite difference schema
- Agreement with manual adjustment on analytical solution
- Time period of 5 to 15 minutes to reach low noise for interpretation

Contribution of FVPDM: Flow regimes in the aquifer



- FVPDM shows the difference in GW fluxes in the different part of the aquifer
- FVPDM emphasizes different GW fluxes response to pumping on different parts of the aquifer

FVPDM monitoring: Conclusions and perspectives

- The Finite Volume Point Dilution Method is able to monitor variable GW fluxes
- Captures even small changes in GW fluxes
- An automated solution fitting has been developed to calculate in real time changes in transient GW fluxes

- The perspective is now to implement a long term FVPDM monitoring in a context of highly variable GW fluxes such as GW-surface water interactions / tidal effects