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Better considering tracer distribution within boreholes while FVPDM tests

Serge Brouyère[1], **Nataline Simon[1]** and Pierre Jamin[1,2]

[1]Department Urban and Environmental Engineering, Hydrogeology and Environmental Geology, Liège University, Building B52, 4000 Sart Tilman, Belgium; [2] Nagaré Tech, Liège University, Aquapôle, Building B53, 4000 Sart Tilman, Belgium

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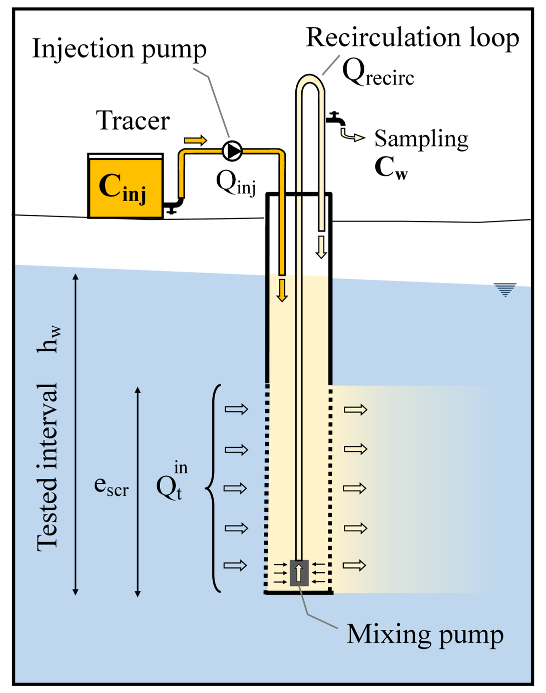
Introduction

Estimates of gorundwater fluxes → contaminant transport; groundwater-surface water interactions; geothermal applications; geotechnical engineering



Finite Volume Point Dilution Method (FVPDM) *[Brouyère et al. 2008]*

- Single-well tracer experiment
- Continuous injection of the tracer
- Recirculation loop : mixing
- A part of the injected tracer : carried out of the well by the groundwater flow
  ⇨ the higher the groundwater fluxes, the lower the tracer concentration remaining in the well

⇨ Direct estimate of the groundwater flux

Limitations

- « Classical » analytical solution *[Brouyère et al. 2008]* : assumption of the **uniform repartition** of the tracer mass in the water column (recirculation loop) ⇨ Difficult in practice
- **Non-perfect mixing conditions** → a significant portion of tracer carried out of the well before reaching the mixing pump located at the bottom of the tested interval ⇨ higher tracer concentrations at the top of the tested interval

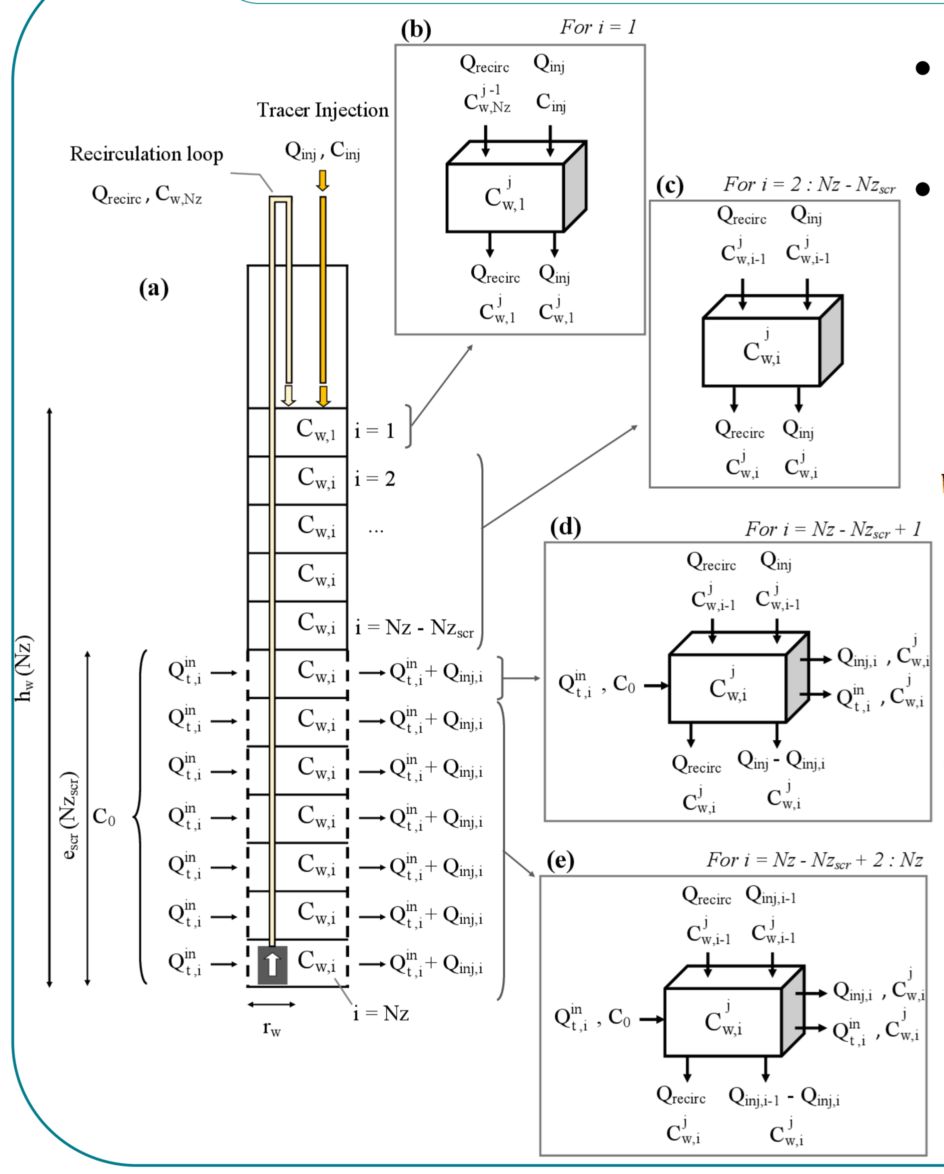
Objectives and approaches

Effect of the mixing (recirculation flow rate) on the tracer concentration distribution

⇨ A new discrete FVPDM model considering the recirculation flow rate
  ✎ simulating the distribution of the tracer concentration along the tested interval
  ✎ assessing the effect of the recirculation flow rate

⇨ **A solution for interpreting FVPDM tests performed under non-perfect mixing conditions**

The new discrete model



- Domain (the volume of water) discretized into i elementary cells with vertical size Δz_i
- Mass balance equations applied for each cell numerically evaluated through the finite difference method

→ Along the screens (d):

$$V_{wi} C_{w,i}^{j+1} = V_{wi} C_{w,i}^{j} + \left[Q_{recirc}\, C_{w,i-1}^{j} - Q_{recirc}\, C_{w,i}^{j} + Q_{t,i}^{in}\, C_0 - Q_{t,i}^{in}\, C_{w,i}^{j} + Q_{inj,i-1}\, C_{w,i-1}^{j} - Q_{inj,i}\, C_{w,i}^{j} - (Q_{inj,i-1} - Q_{inj,i}) C_{w,i}^{j}\right] \Delta t$$

→ $Q_{t,i}^{in}$: transit flow rate crossing the well screen under injection conditions :

$$Q_{t,i}^{in} = \frac{Q_{cr,i}}{\pi} \sin\left(\arccos\left(\frac{Q_{inj,i}}{Q_{cr,i}}\right)\right) - \frac{Q_{inj,i}}{2\pi}\left(2\arccos\left(\frac{Q_{inj,i}}{Q_{cr,i}}\right)\right)$$

With $Q_{cr,i}$, the injection rate above which the transit flow rate Q_t is cancelled :

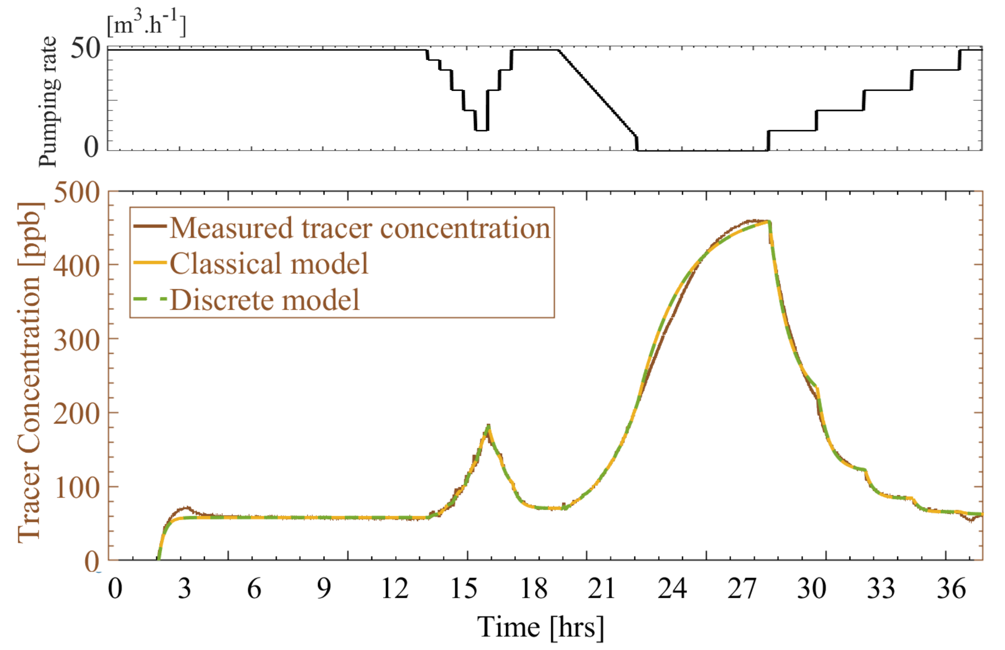
$$Q_{cr,i} = \pi\, Q_{t,i} = 2\pi\, r_w\, \Delta z\, q_{app,i}$$

Application on Field data

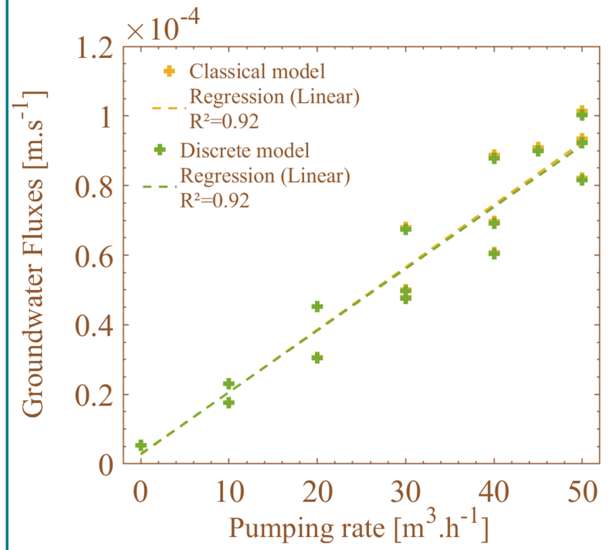
Application of the discrete model to interpret field data *[Jamin and Brouyère. 2018]*

Piezometer 1 - Perfect mixing conditions

Screen length : 0.9 m Q_{recirc} = 1.9x10^{-4} m^3.s^{-1}

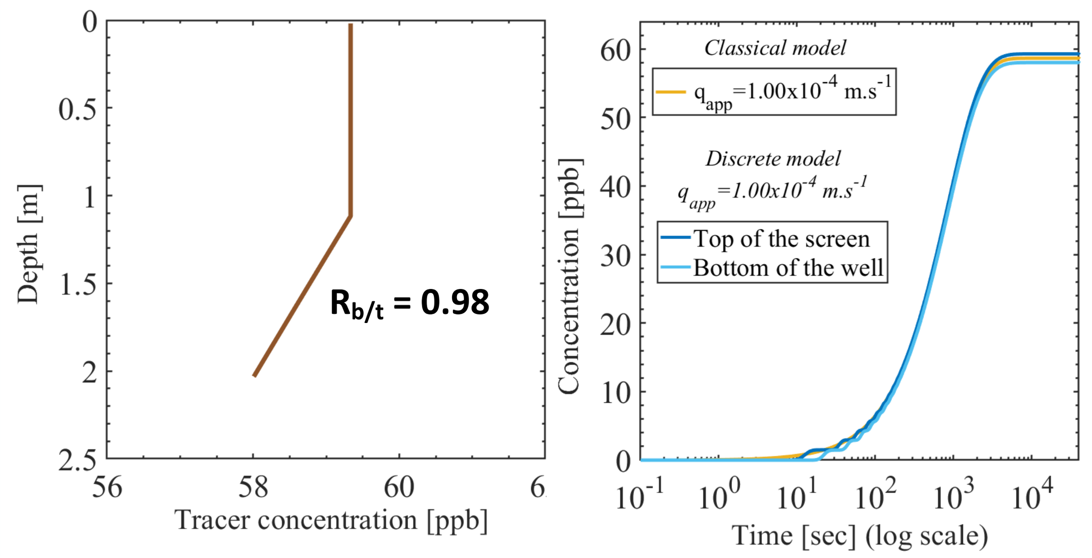


With both models : ✓ Reproducing the measured tracer C
✓ Similar GW fluxes estimates



✓ Linear evolution of the GW flux with the pumping rate

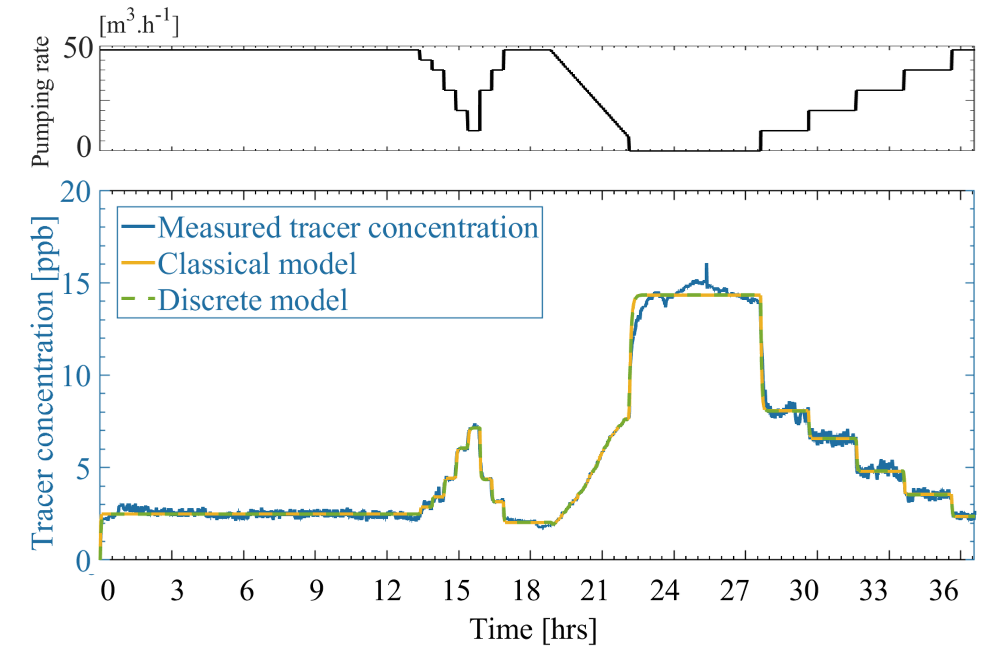
Both models can be used under perfect mixing conditions
⇨ Validating the new discrete model



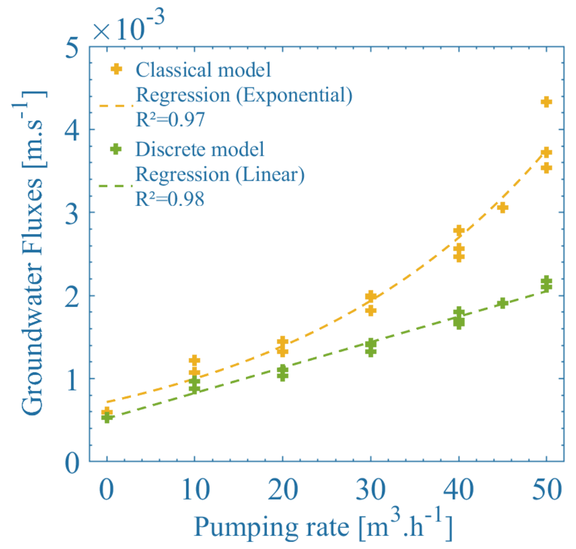
Uniform repartition of the tracer Concentration

Piezometer 2 - Non-perfect mixing conditions

Screen length : 1.8 m Q_{recirc} = 1.9x10^{-4} m^3.s^{-1}

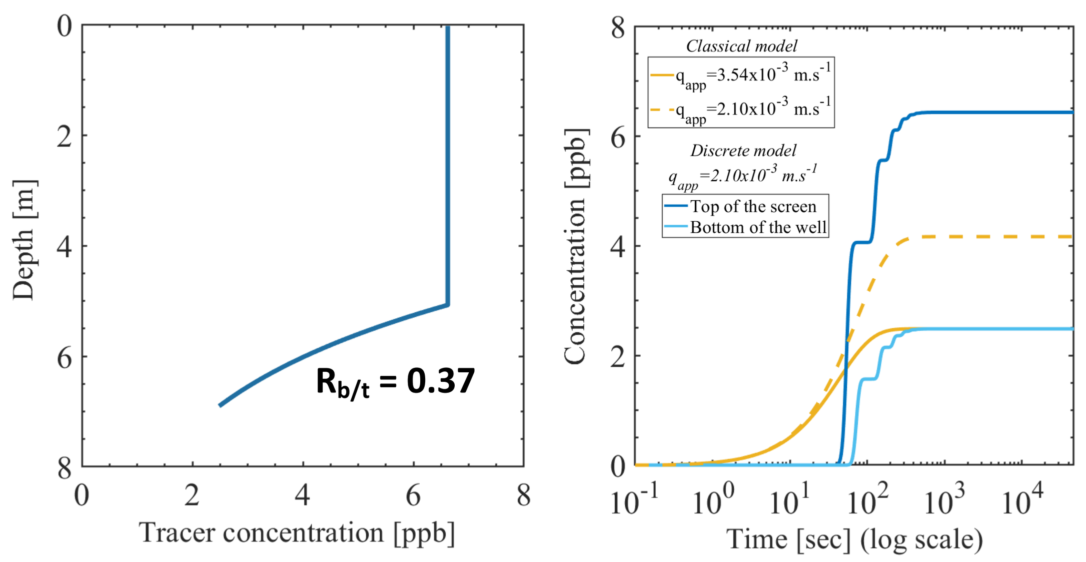


✓ Both models reproduce the measured tracer C
✗ Significant differences in GW fluxes estimates



✓ Discrete model : linear evolution of the GW flux with the pumping rate
✗ Classical model : overestimate the GW flow (24 - 82%)

⇨ Discrete model in case of non-perfect mixing conditions



Non uniform repartition of the tracer Concentration
C measured at the bottom of the well → overestimate of the flux using the classical model

Sensitivity analysis

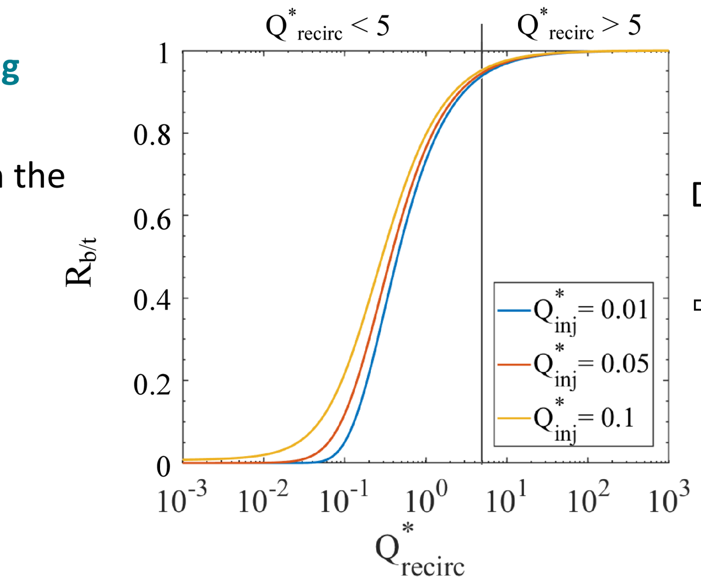
Nondimensional variables → define the domain of non-perfect mixing conditions

$Q^*_{recirc} = Q_{recirc}/Q_{cr}$

$Q^*_{inj} = Q_{inj}/Q_{cr}$

Non-Perfect mixing

Difference of C within the interval >> 5%
⇨ **Non-Uniform concentration**

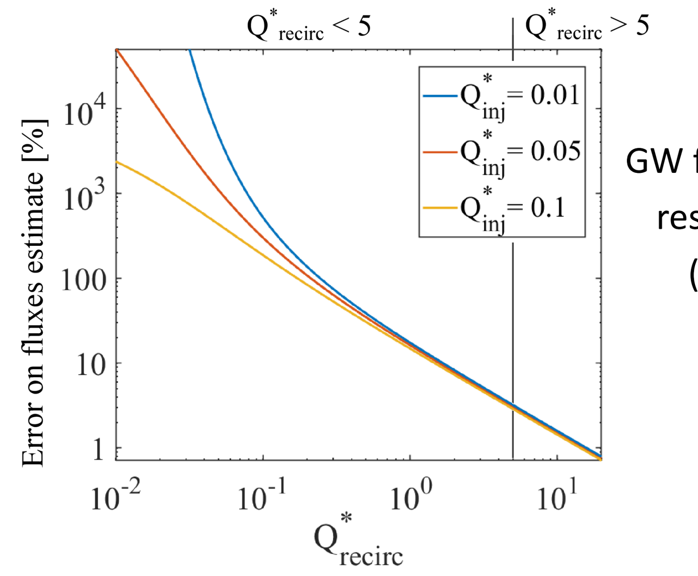


Perfect mixing

Difference of C within the interval < 5%
⇨ **Uniform concentration**

✓ Discrete model

Classical model overestimates GW fluxes
Errors > 50 % for Q^*_{recir} < 0.5 and 100% for Q^*_{recir} < 0.3



GW fluxes estimates : similar results with both models (discrete or classical)
Difference < 3.5 %

Conclusions

- Mixing within the tested interval depends on the recirculation flow rate compared to the groundwater flow rate crossing the well screens
  → Q^*_{recir} > 5 : Perfect mixing conditions (Piezometer 1)
    ✎ recirculation high enough to ensure the homogenization of the tracer within the tested interval
    ✎ both models (classical and discrete) to interpret field data
  → Q^*_{recir} < 5 : Non-Perfect mixing conditions (Piezometer 2)
    ✎ Non-uniform repartition of the tracer
    ✎ **Discrete model** only (classical model overestimates of the flux)
- Discrete model
  → assessing the vertical transport of the tracer along the well axis
  → estimating fluxes even if experimental conditions are not ideal
  → very permeable aquifer materials, long-screened boreholes, vertical variabilities

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