Groundwater and contaminant mass fluxes monitoring in heterogeneous aquifers

Pierre JAMIN

Thesis defense

April 25th 2019

Jury

Toye Dominique (President)	University of Liège
Brouyère Serge (Promotor)	University of Liège
Dassargues Alain (Co-promotor)	University of Liège
Nguyen Frédéric	University of Liège
Goderniaux Pascal	University of Mons
Annable Michael	University of Florida
Atteia Olivier	University of Bordeaux

Groundwater

Water present in the subsurface

Provides drinking water to 50% of the global population

Represents 95% of the easy to use fresh water

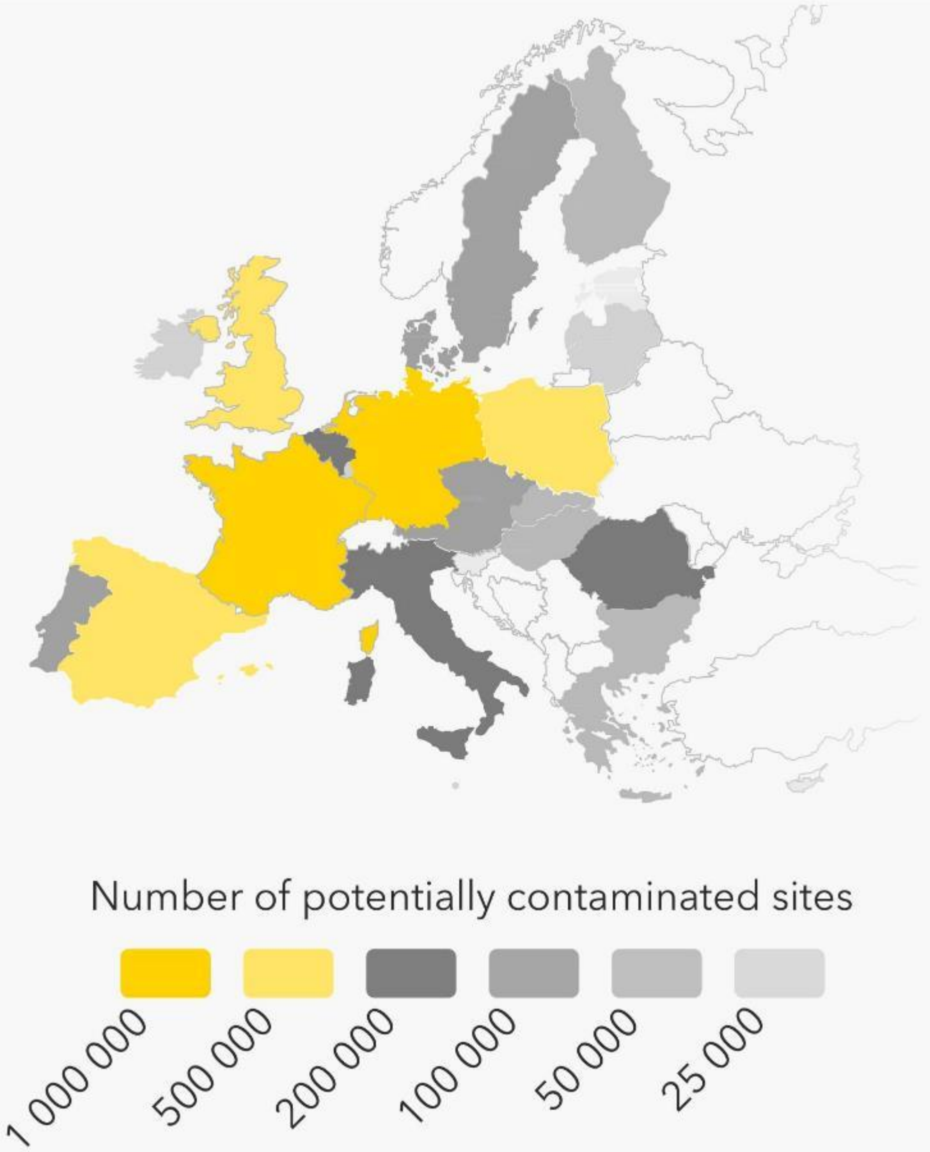
(Unesco 2018)

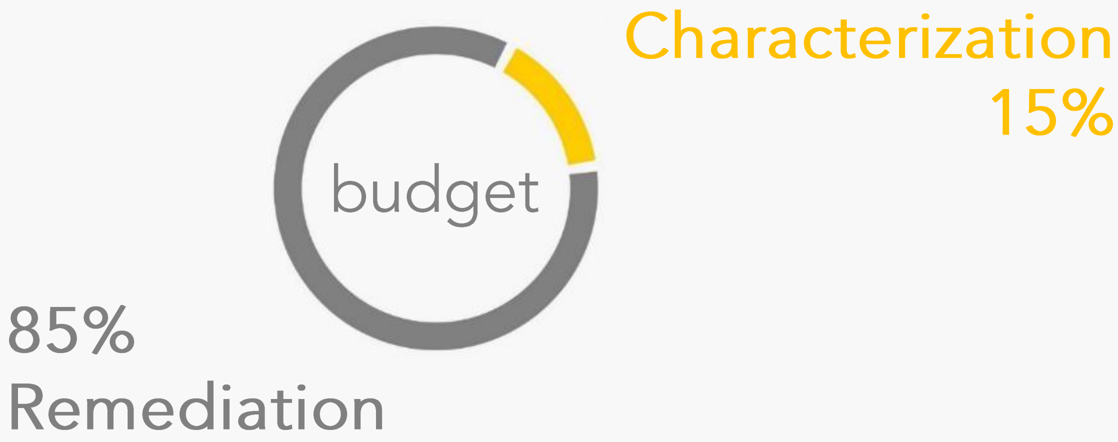
> “
>
> *At its meeting in Rome last month, UN-Water decided that*
> *“Groundwater: making the invisible visible”*
> *will be the theme for the World Water Day 2022.*
>
> *IGRAC – UNESCO, 2019*

The threat of contaminated sites

2.8 million potentially contaminated sites

3.2 billions €/year for polluted site management



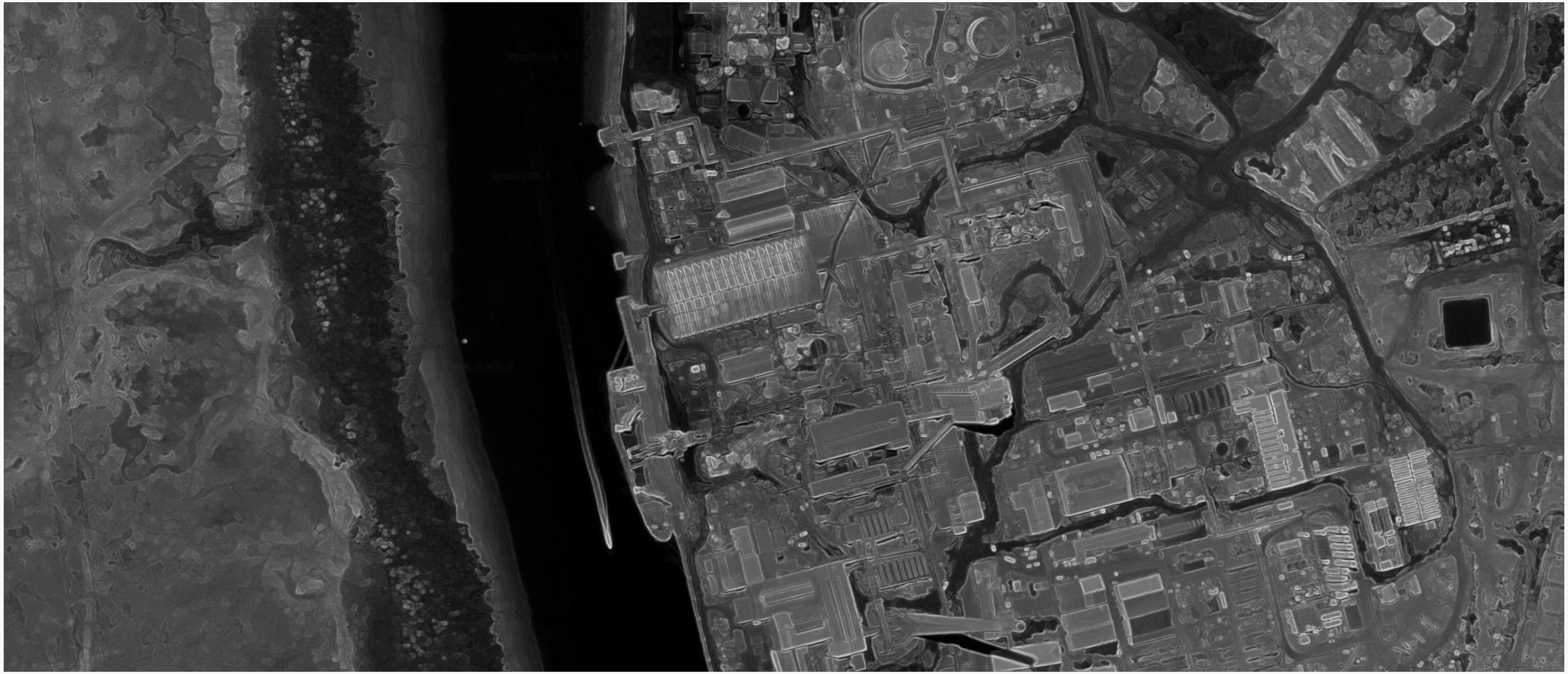


(Panagos et al. 2013, Ernst & Young 2013)

A few years ago …

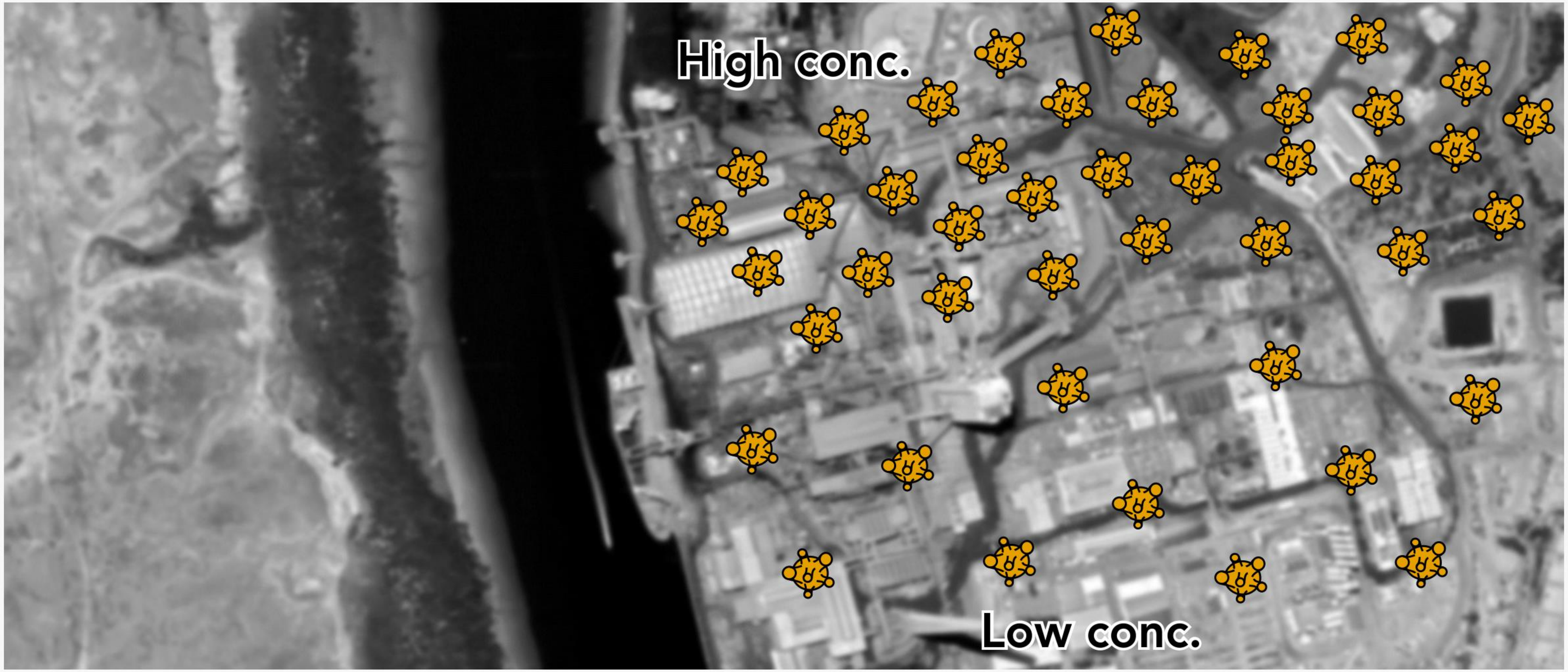
Metal processing facility located on the bank of an estuary

Underlying aquifer contaminated by heavy metals, risk for estuarine ecosystems



Characterization of a contaminated aquifer

Traditionally based on contaminant concentration in groundwater



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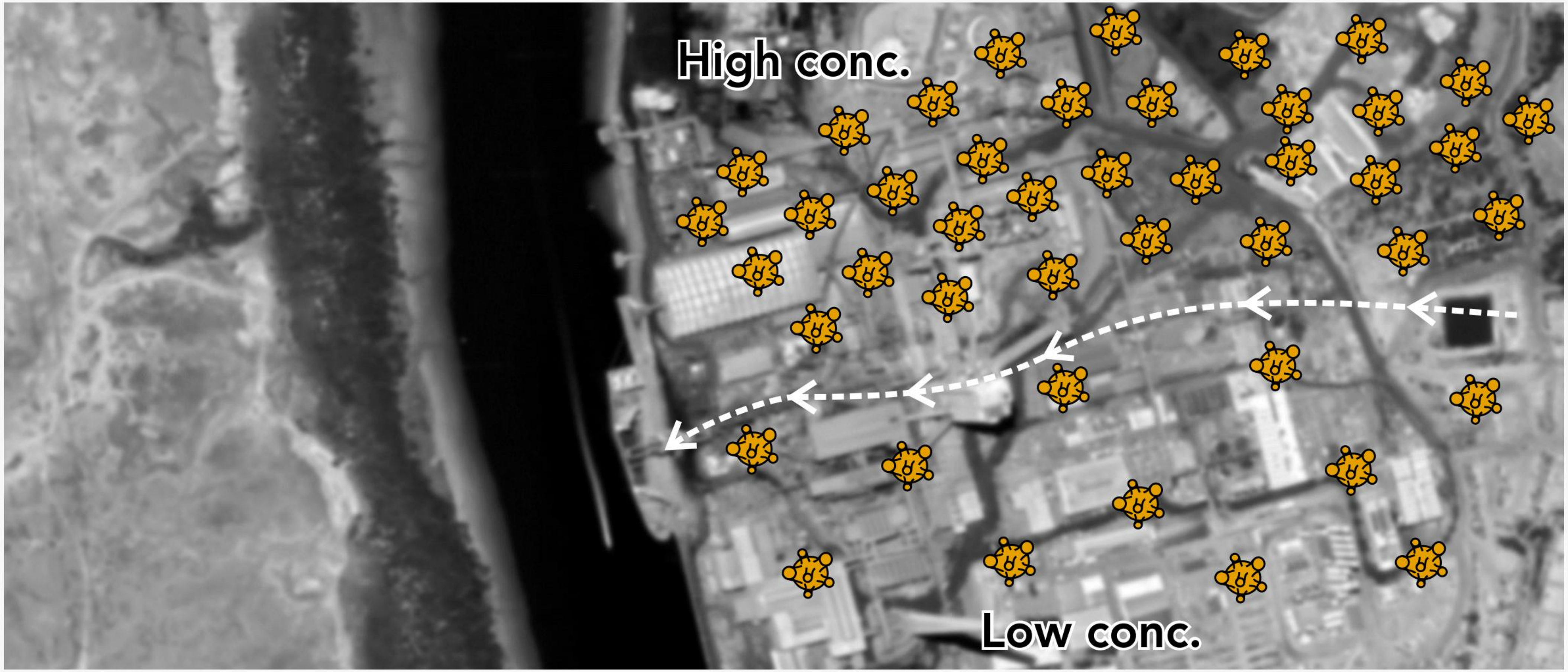

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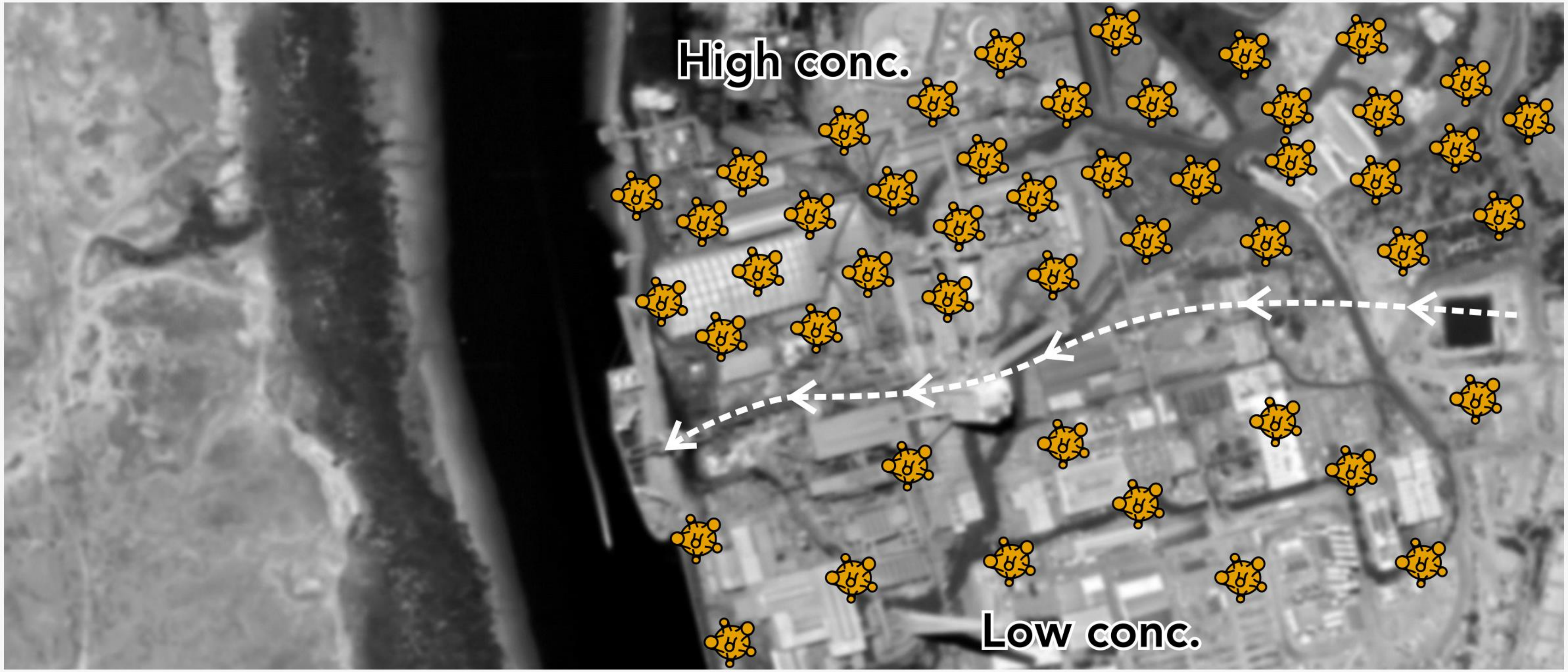

Challenge ?

Contaminant mass flux measurement are tricky due to limited access to groundwater

> “
>
> ***If Earth was transparent, Australians would know the whole truth about the Scottish kilt***
>
> *Some random geologist*

Flux measurements requires simultaneous measurements of groundwater flux and contaminant concentration

$$J = q_D \; C$$

$$[M\,L^{-2}\,T^{-1}] \qquad [L\,T^{-1}] \quad [M\,L^{-3}]$$

Contaminant mass flux

Groundwater flux

Contaminant concentration

Flux measurements requires simultaneous measurements of groundwater flux and contaminant concentration

$$J = q_D \quad C$$

$$[M\ L^{-2}\ T^{-1}] \qquad [L\ T^{-1}] \quad [M\ L^{-3}]$$

Contaminant mass flux

Contaminant concentration

Groundwater flux

My research

Develop and validate an innovative method for the
measurement of groundwater fluxes for a wide spectrum of flow conditions

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- Evaluate the accuracy, the precision and the resolution of the technique

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My research

Develop and validate an innovative method for the measurement of groundwater fluxes for a wide spectrum of flow conditions

- Evaluate the accuracy, the precision and the resolution of the technique
- Develop the mathematical framework, methodology and experimental setup required to perform continuous monitoring under transient flow conditions
- Apply the technique in different lab-scale and field-scale experiments to demonstrate the robustness and versatility of the technique

Outline

01. **The Finite Volume Point Dilution Method**
Basic concepts and experimental setup

02. **Validation**
Lab experiment in flow through tank

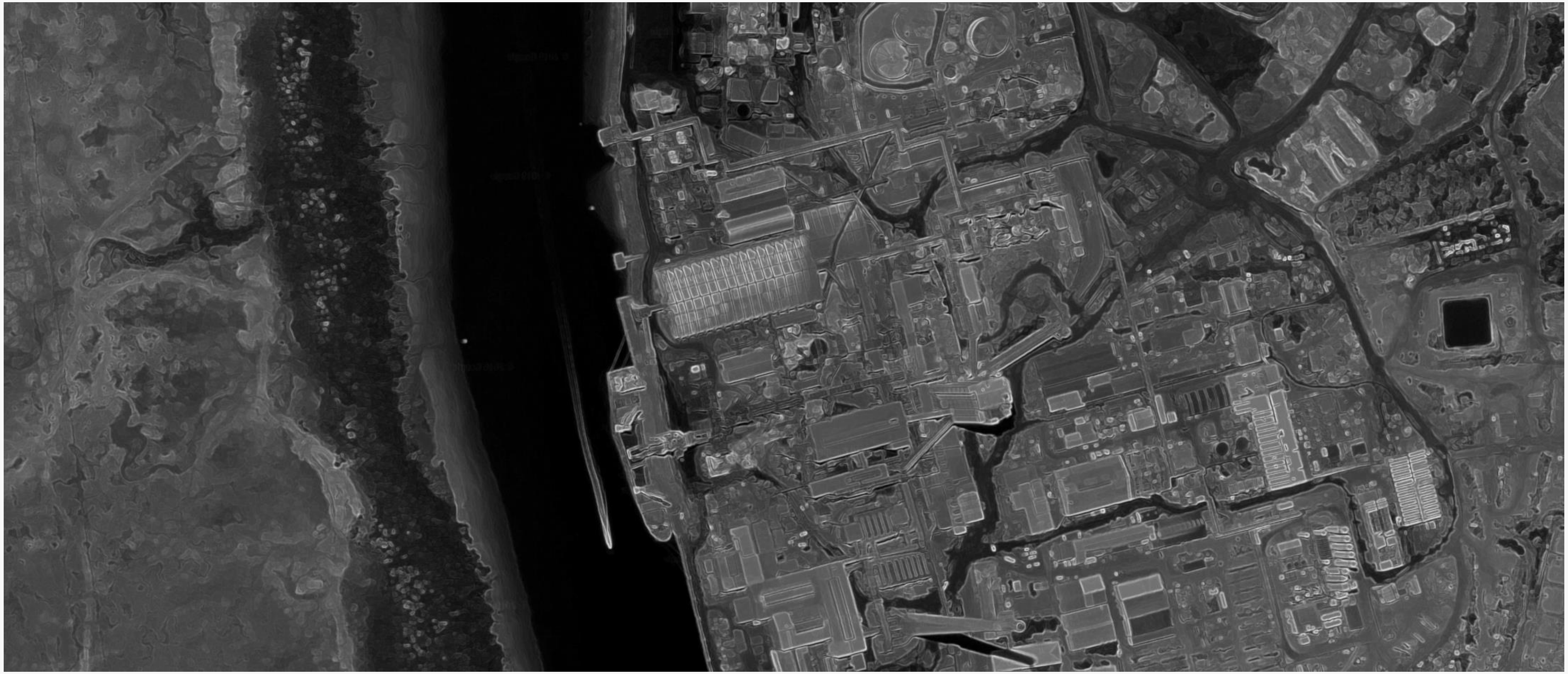
03. **Development of transient groundwater flow monitoring**
FVPDM transient solution + Experimental validation

04. **Field Applications**
Characterization of contaminated coastal aquifer + Other applications

05. **Conclusions and perspectives**

Flux-based contaminated site characterization

Need for groundwater flux measurement



The Finite Volume Point Dilution Method

(Brouyère et al. 2008 J Cont Hydrol)

Generalization of single well dilution technique by a continuous

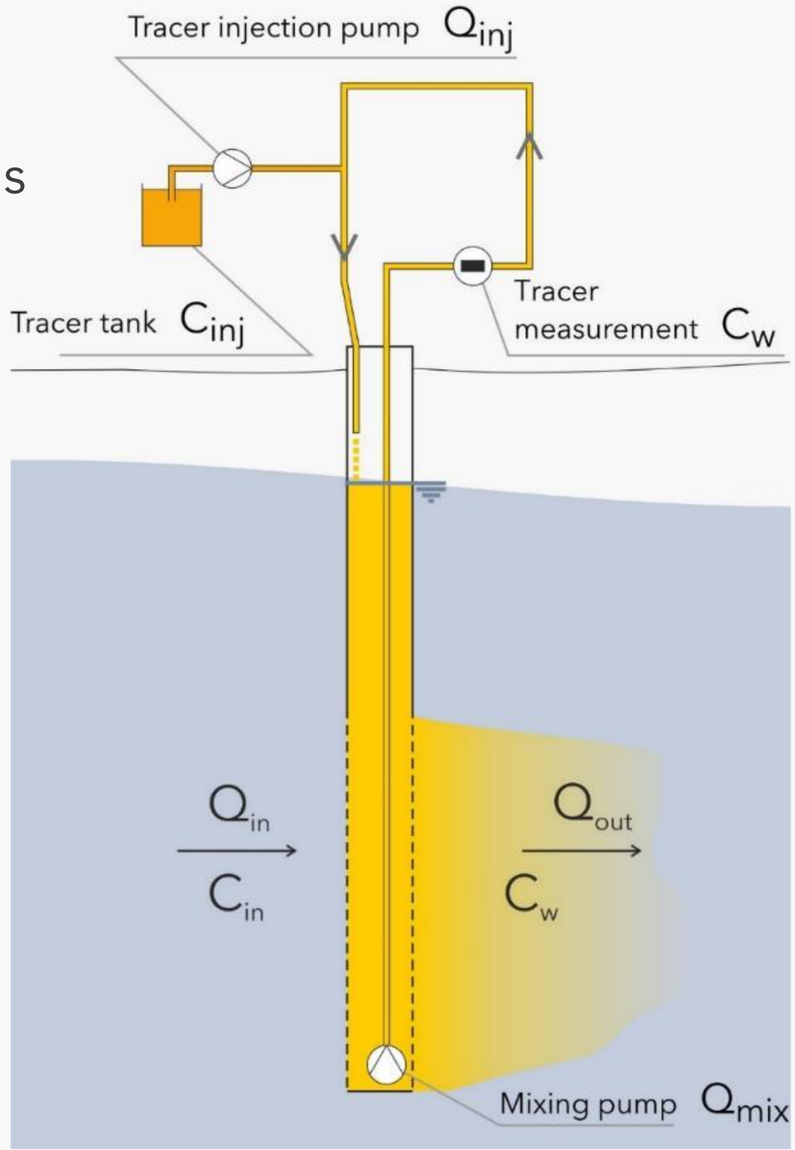
- mixing of the water column
- tracer injection in a well
- monitoring tracer concentration

$$\frac{\partial M(t)}{\partial t} = Q_{inj}\, C_{inj} + Q_{in}\, C_{in} - Q_{out}\, C_w$$

Allows the <u>measurement of a flow rate</u>

that transits through the screen and can be

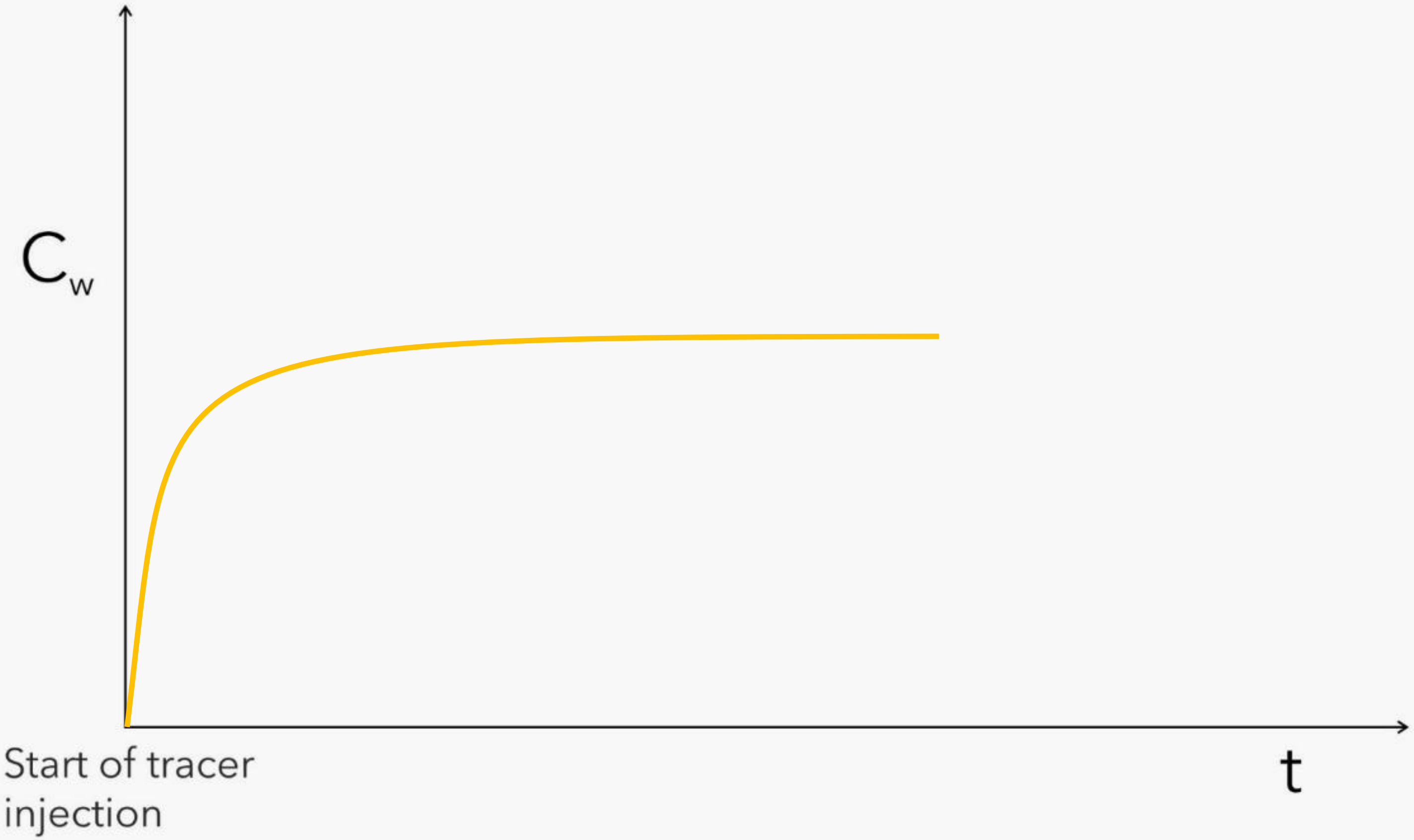
<u>converted into a groundwater flux in the aquifer.</u>



Evolution of tracer concentration in the well during FVPDM

Steady state groundwater flow

Increases and stabilizes at a value depending on the tracer injection flow rate and on the groundwater flux in the aquifer



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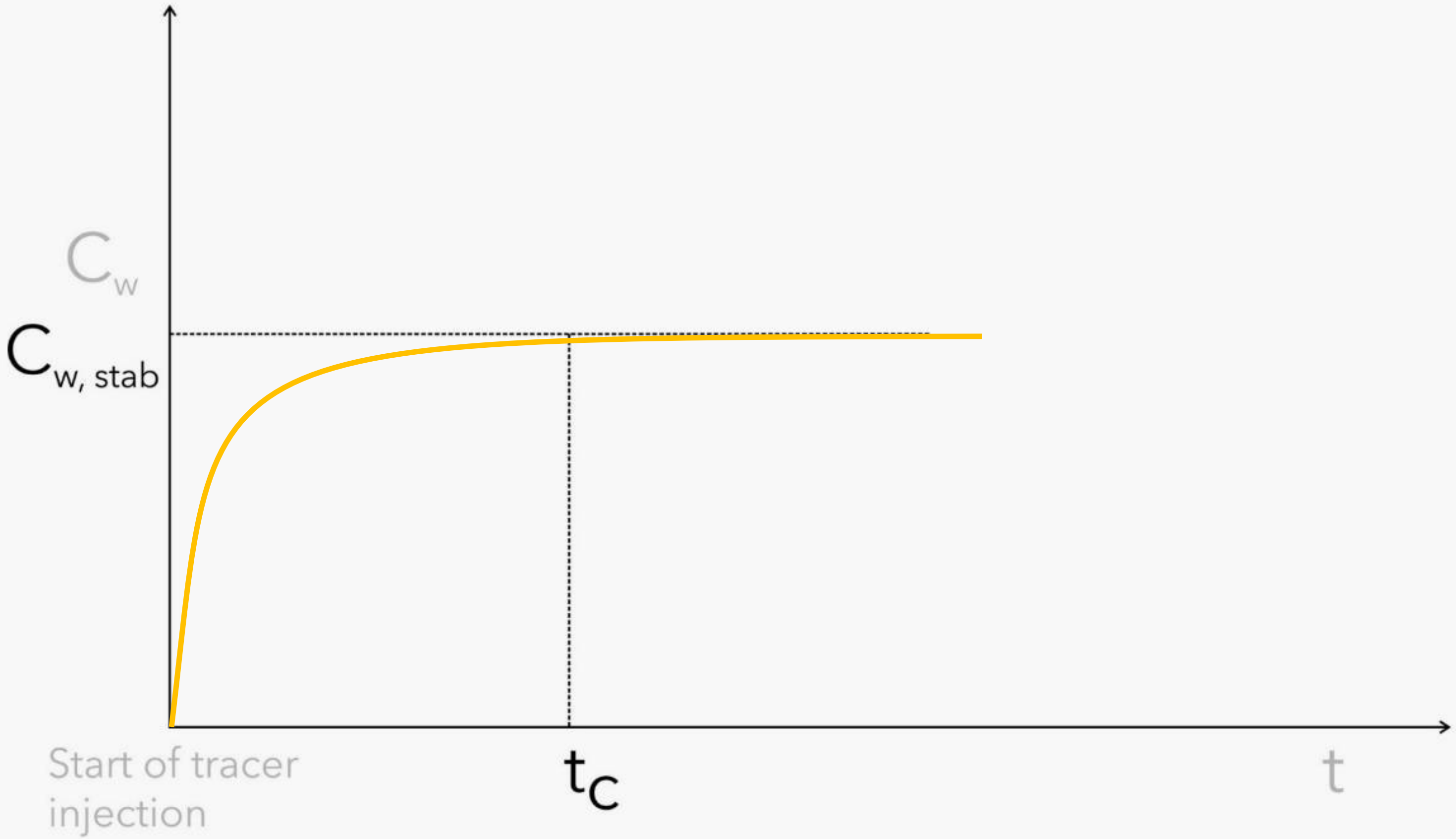

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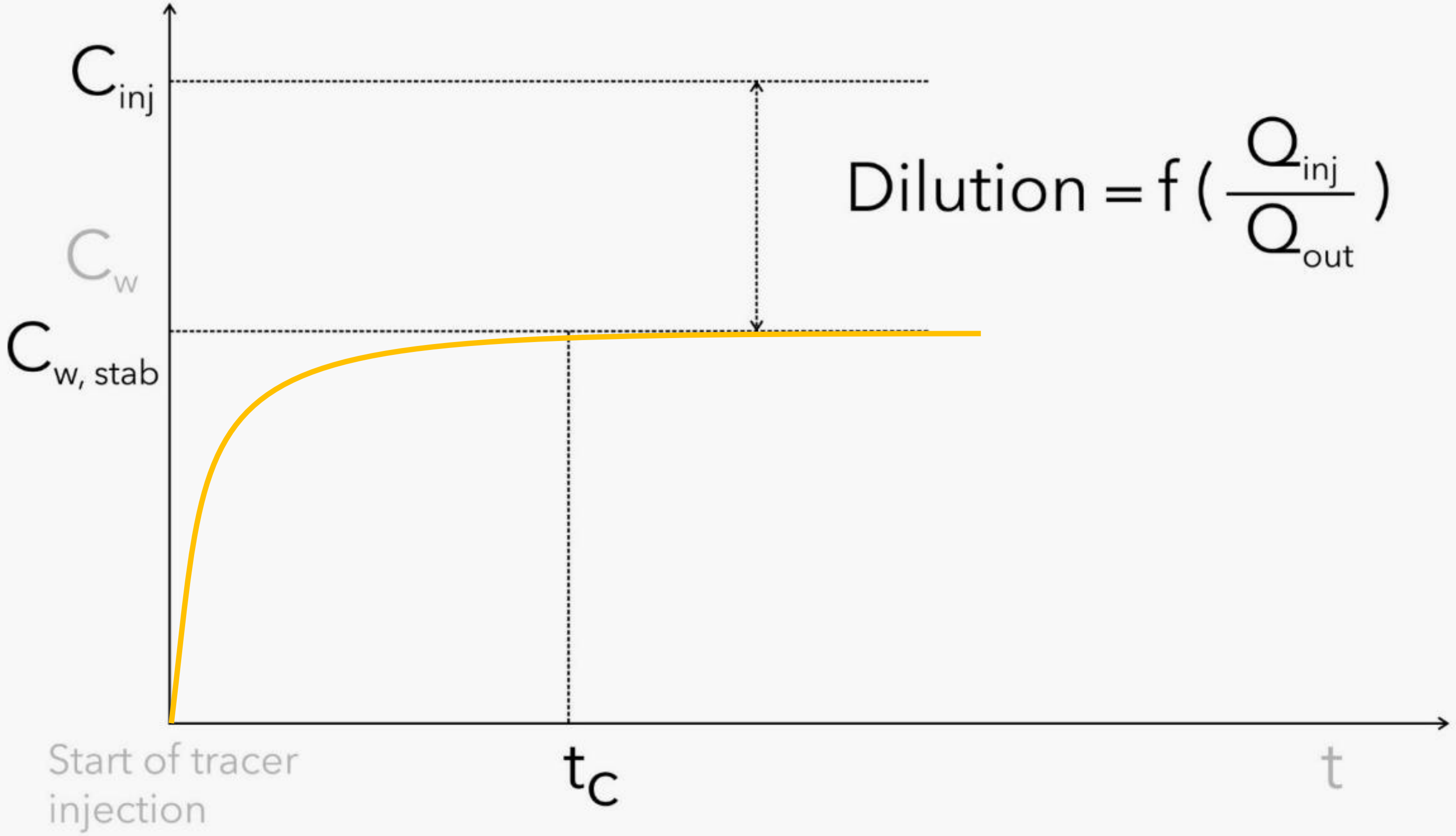

$$\text{Dilution} = f\left(\frac{Q_{inj}}{Q_{out}}\right)$$

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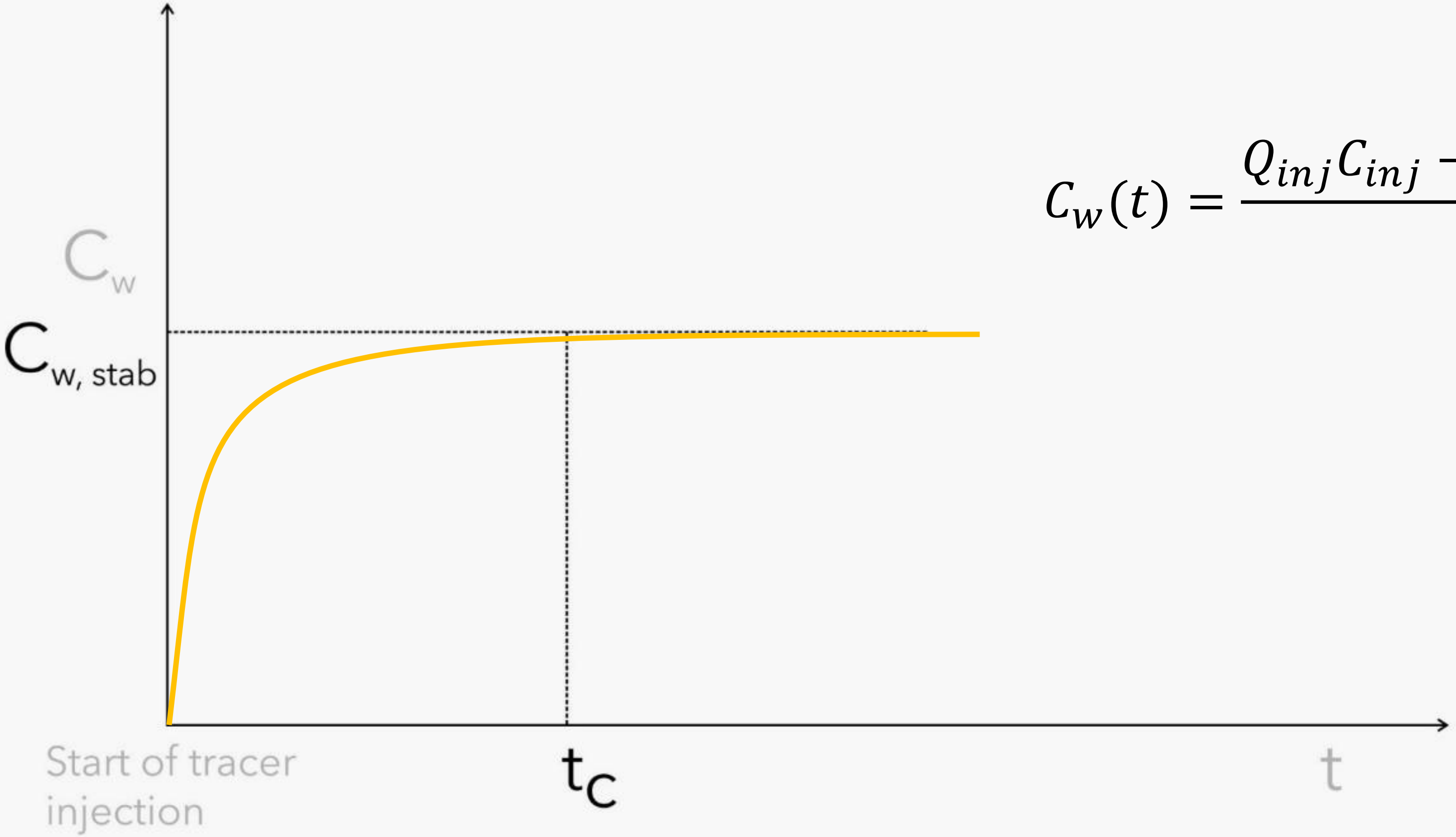


$$C_w(t) = \frac{Q_{inj}C_{inj} - \left(Q_{inj}C_{inj} - Q_{out}C_{w,0}\right)e^{-\frac{Q_{out}}{V_w}(t-t_0)}}{Q_{out}}$$

Flux-based contaminated site characterization

Simple application of the FVPDM technique

02.

Validation

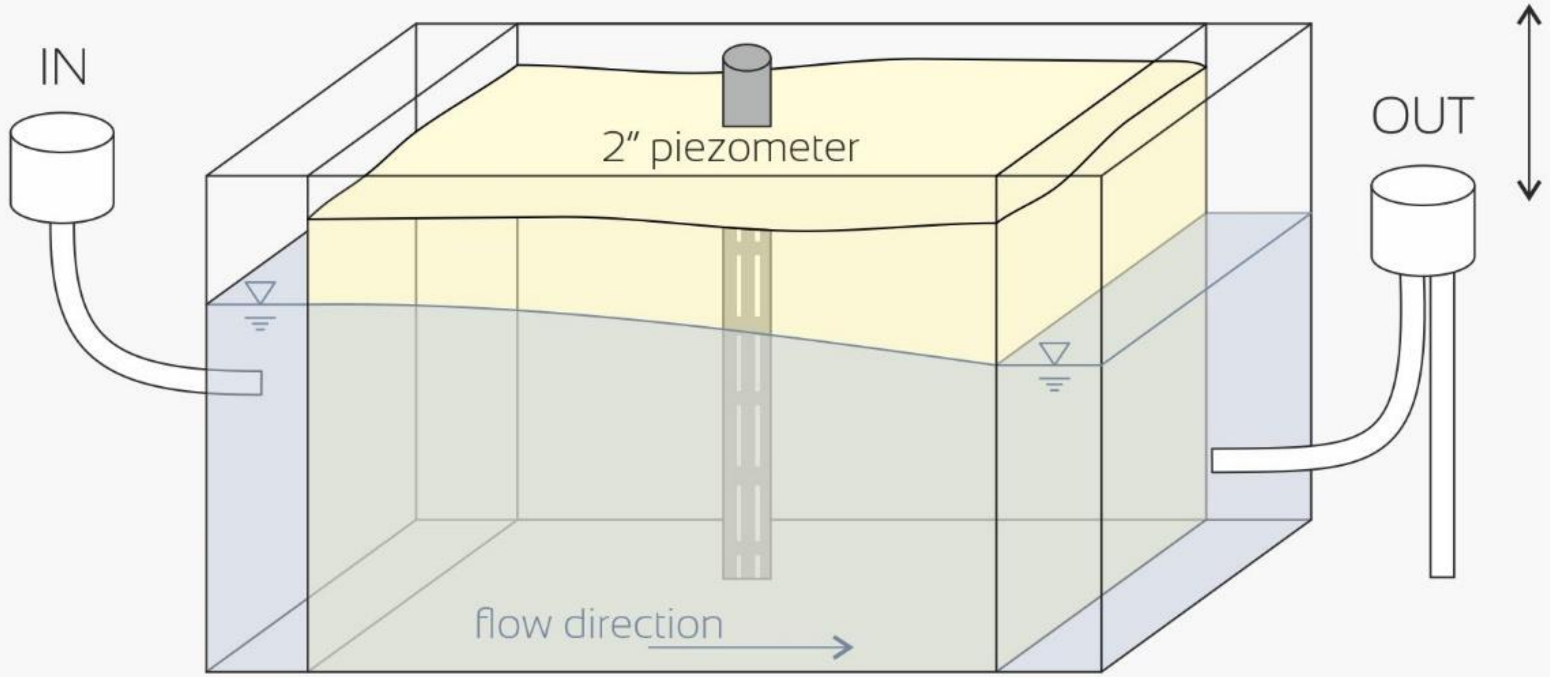
Lab experiment in flow through tank

Accuracy

Flow through tank experiment

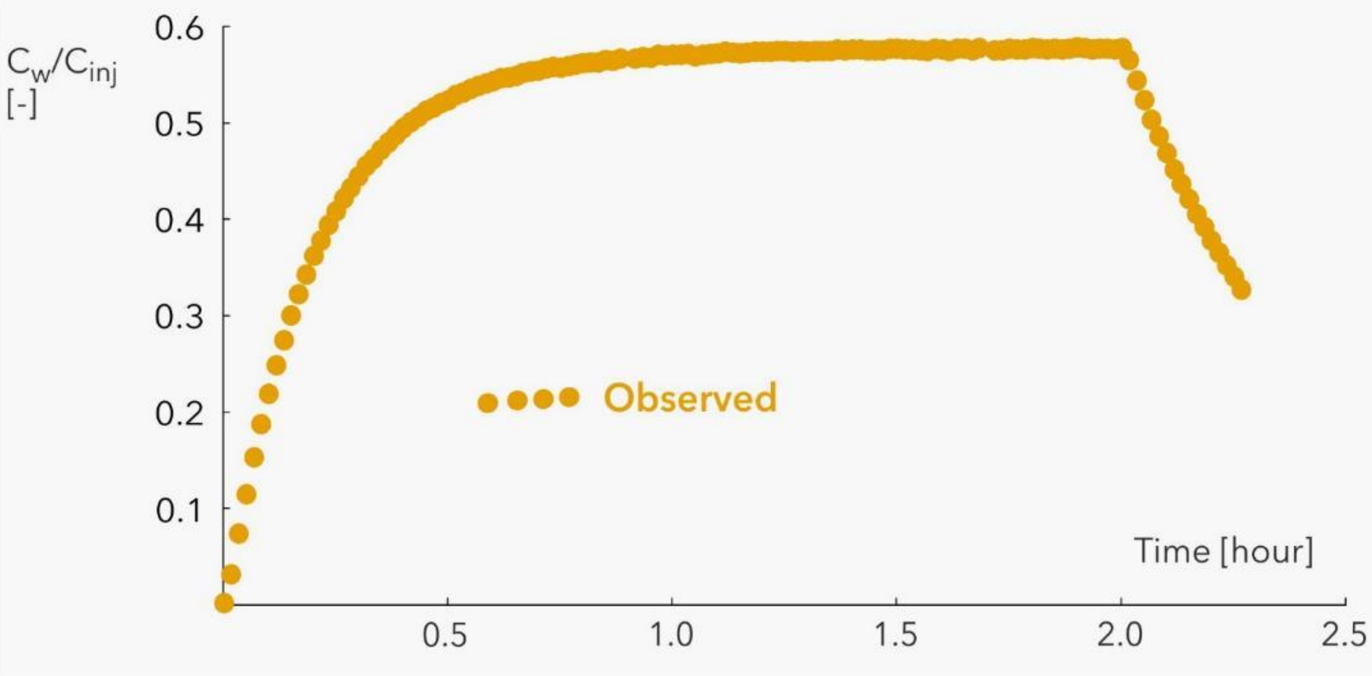
Prescribed water flux in a saturated sand box

FVPDM experiment in a piezometer in the center of the sand



Measurement of a steady state water flow

Prescribed water flux 1.021 m/d



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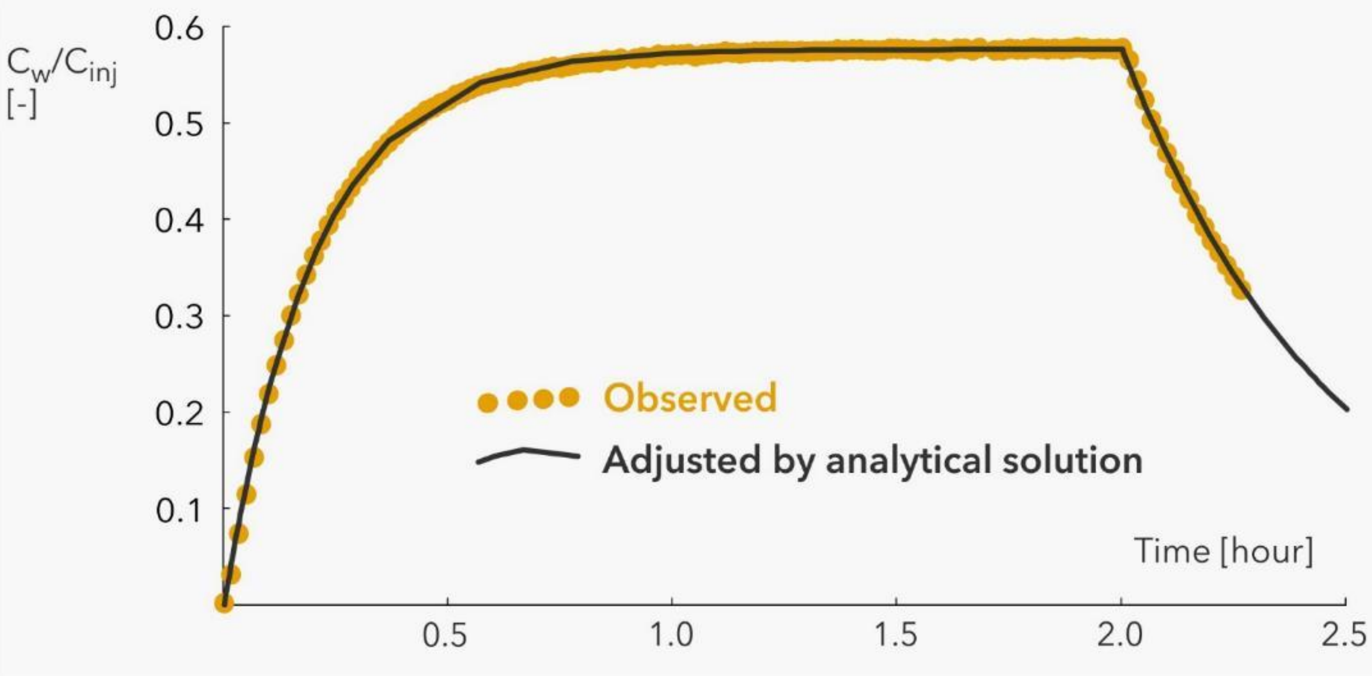
Interpretation using analytical solution

Measured water flux 1.020 ± 0.002 m/



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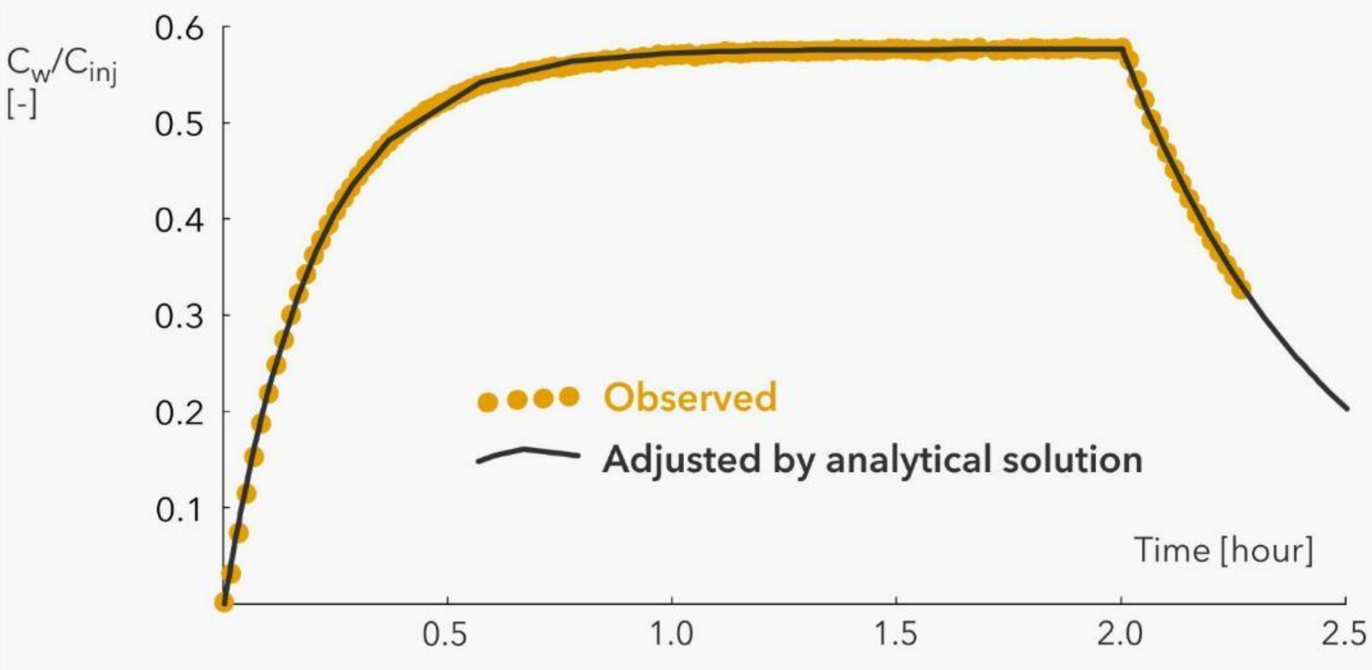


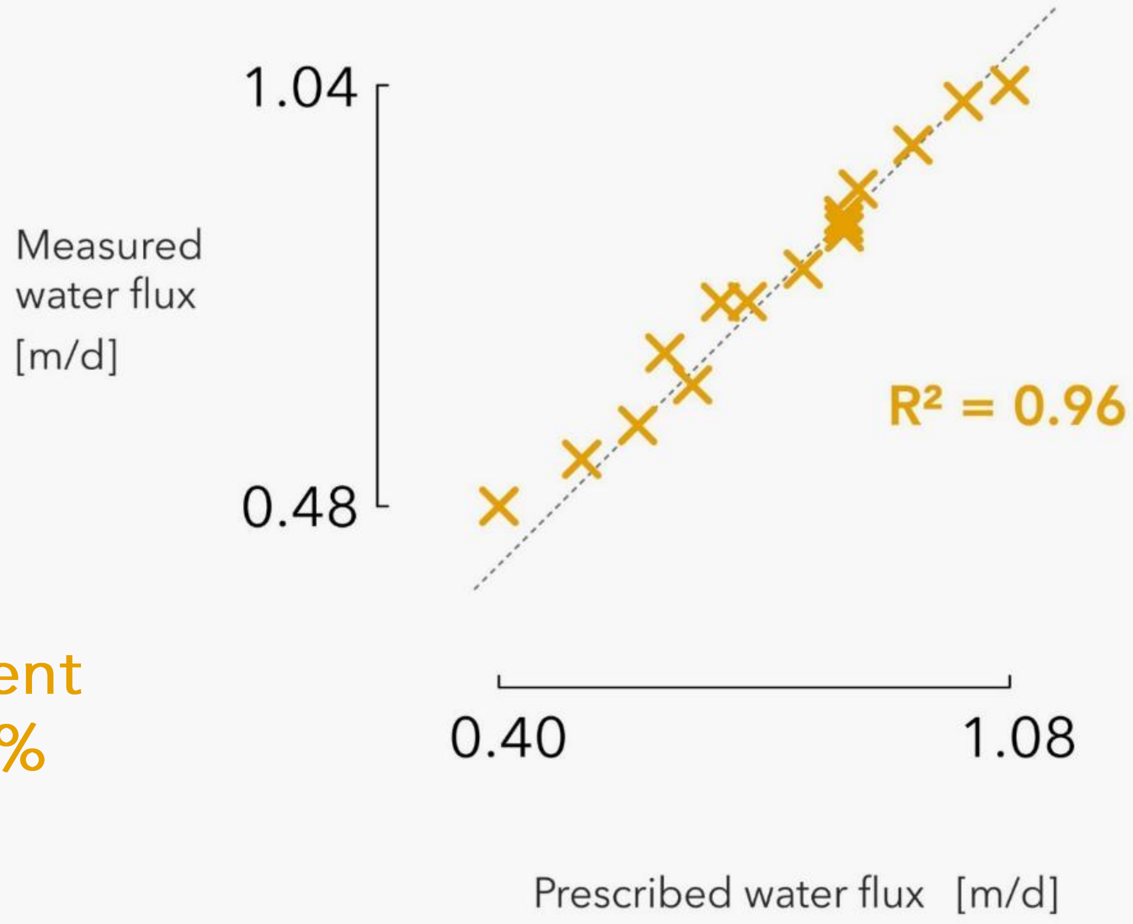
Measured water flux 1.020 ± 0.002 m/

Prescribed vs. Measured -0.15%

Measurement of different steady state water flows

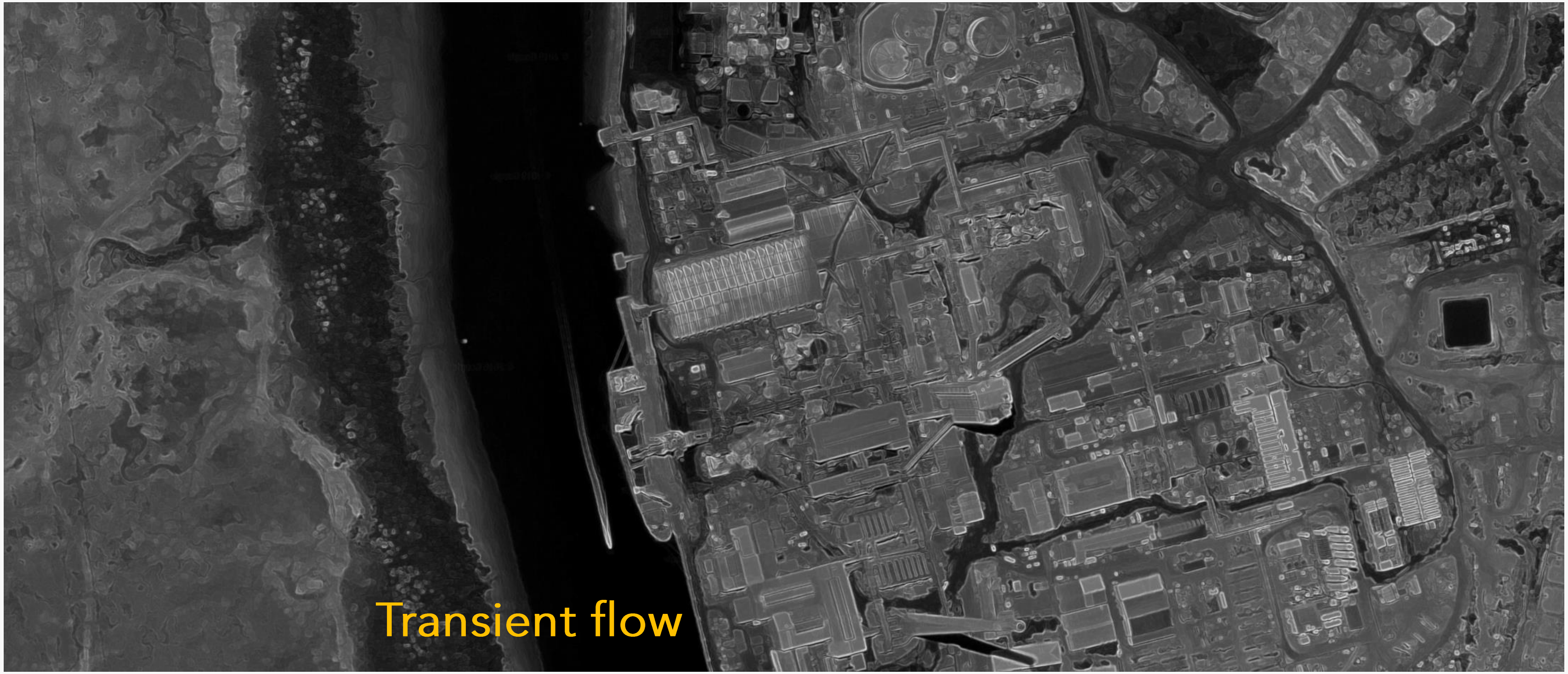
Adaptation to a wide range of water fluxes by adjusting experimental parameters

Accuracy of water flux measurement by FVPDM in lab conditions is ±5%



Flux-based contaminated site characterization

Site located on the bank of an estuary where tides occur



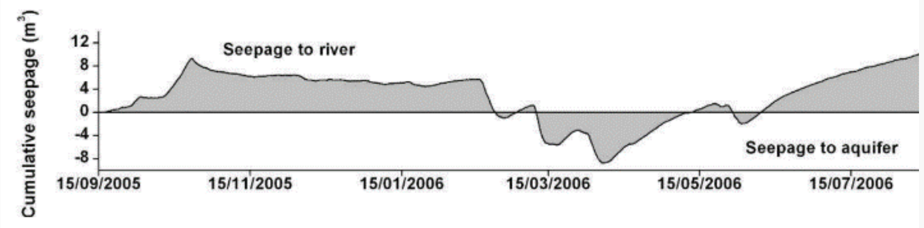
Influence of tides on groundwater fluxes in the aquifer

Tidal effect

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

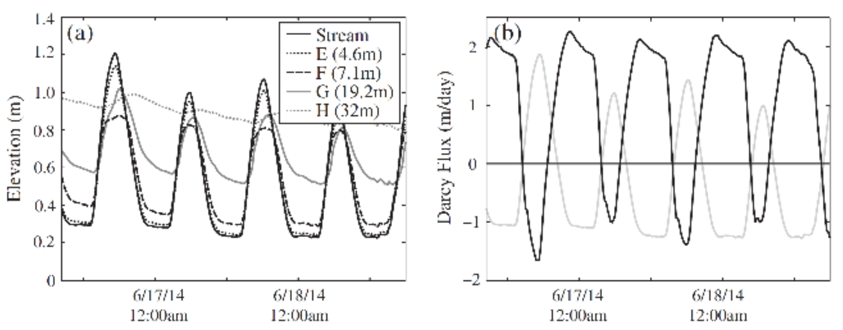
GW – SW interaction

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



River/bank water exchange

"Fluxes range from 1.66 to 2.26 m/day across the bank and 0.84 to 1.88m/day across the bed. During rising tide, river water infiltrates into the riparian aquifer." Musial *et al.*, 2016, Hydrological Processes.



Existing techniques

"… are best suited for conditions where the flow hydraulics are relatively consistent through time." Kempf et al. 2013, Remediation.

03.

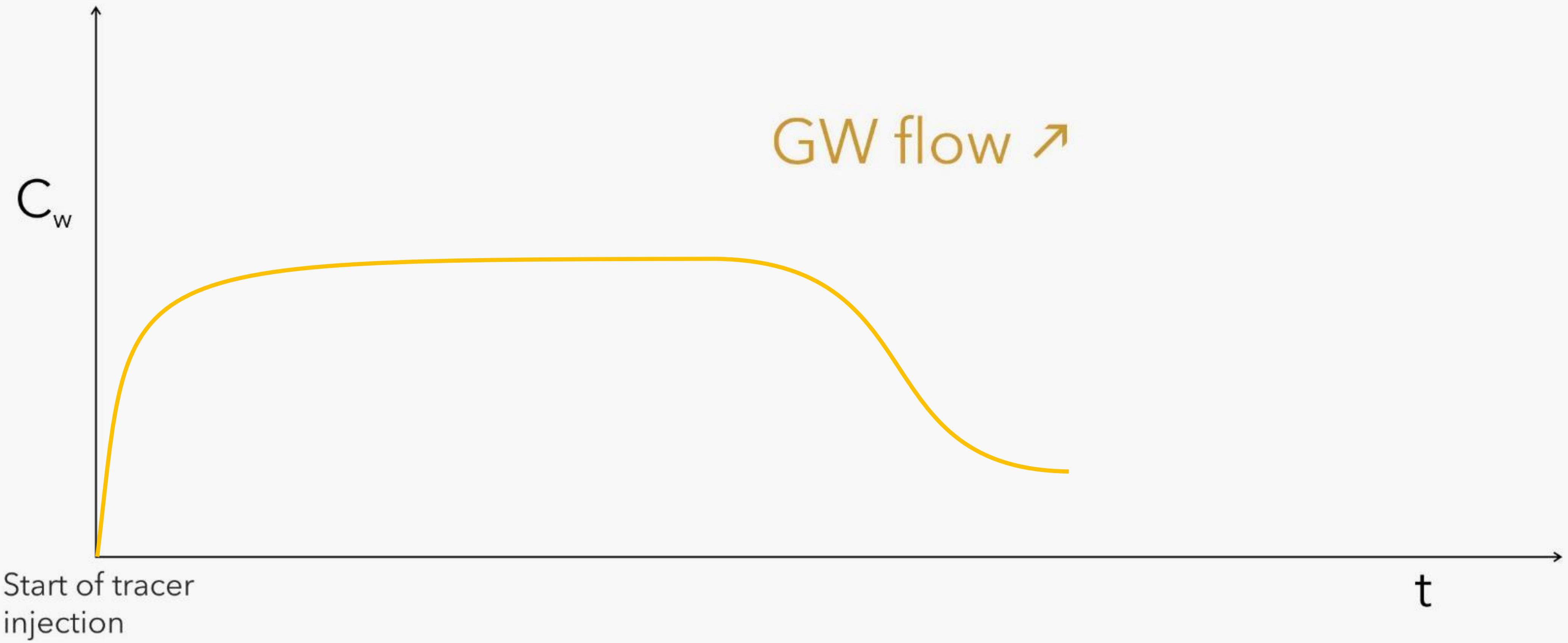
Development of transient groundwater flow monitoring

FVPDM transient solution
Experimental validation

Evolution of tracer concentration in the well during FVPDM

Transient state groundwater flow

decreases when flux increases (more dilution)



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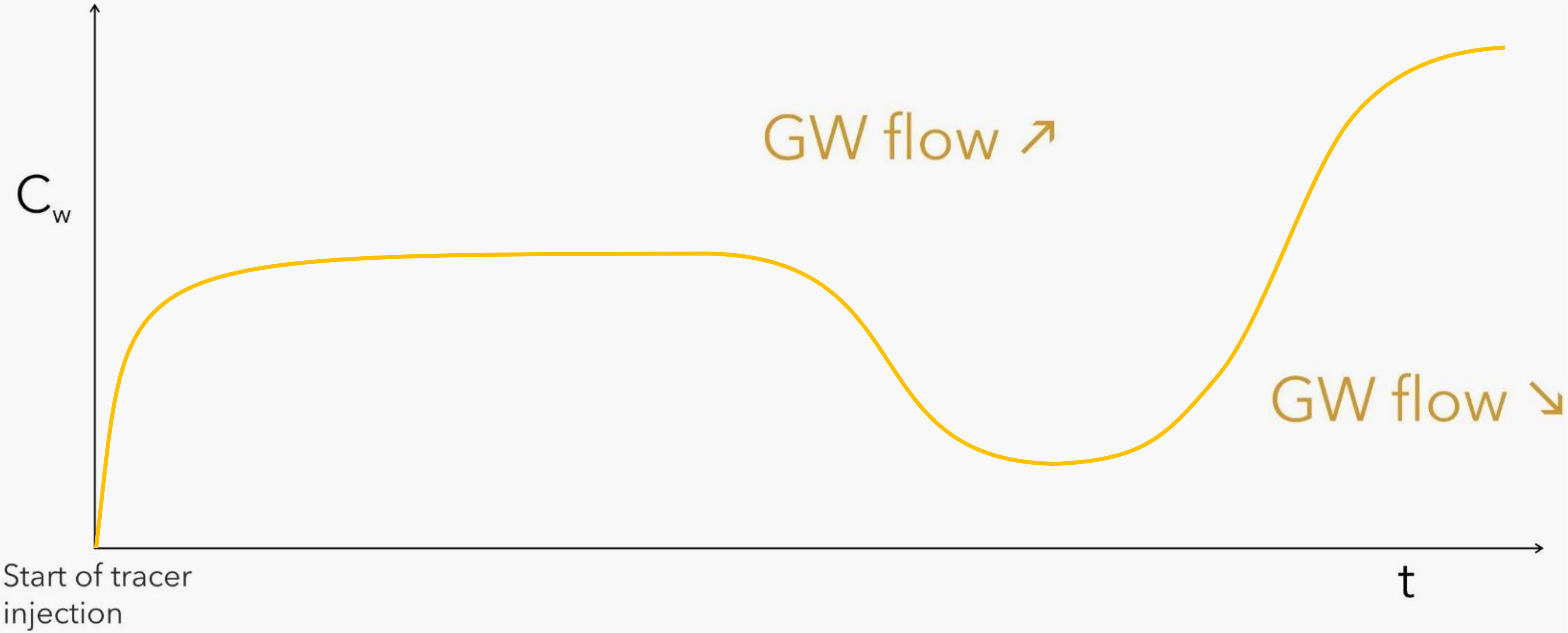
decreases when flux increases (more dilution)

increases when flux decreases (less dilution)



Interpretation under transient flow conditions

General FVPDM tracer mass balance equation can be solved using finite difference schema over the time step

$$\frac{C_w(t_{n+1}) - C_w(t_n)}{\Delta t}$$

Leads to a fully transient solution for the interpretation of FVPDM, including the variation of the water level in the well.

$$C_w(t_{n+1}) = \left(Q_{inj}\, C_{inj} + \frac{V_w(t_{n+1})}{\Delta t} C_w(t_n)\right) \Big/ \left(\frac{V_w(t_{n+1})}{\Delta t} + Q_{inj} + Q_{in}(t_{n+1})\right)$$

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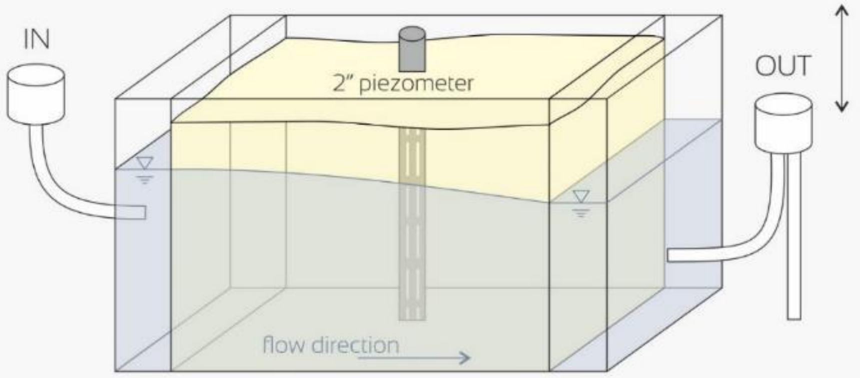
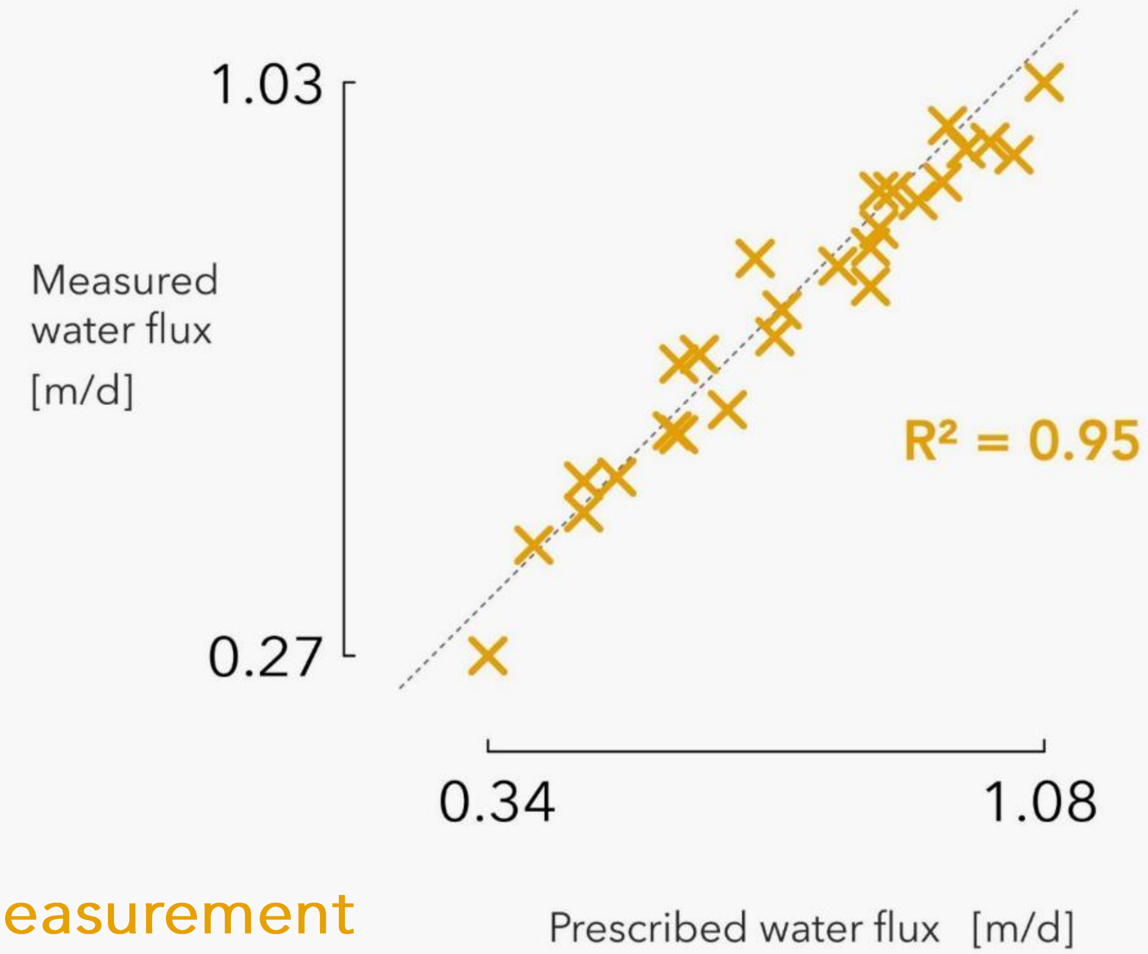
Accuracy validation of the transient solution in laboratory conditions

Test for a range of water flows

Using the same experimental setup





Accuracy of variable water flux measurement by FVPDM in lab conditions is ±5%

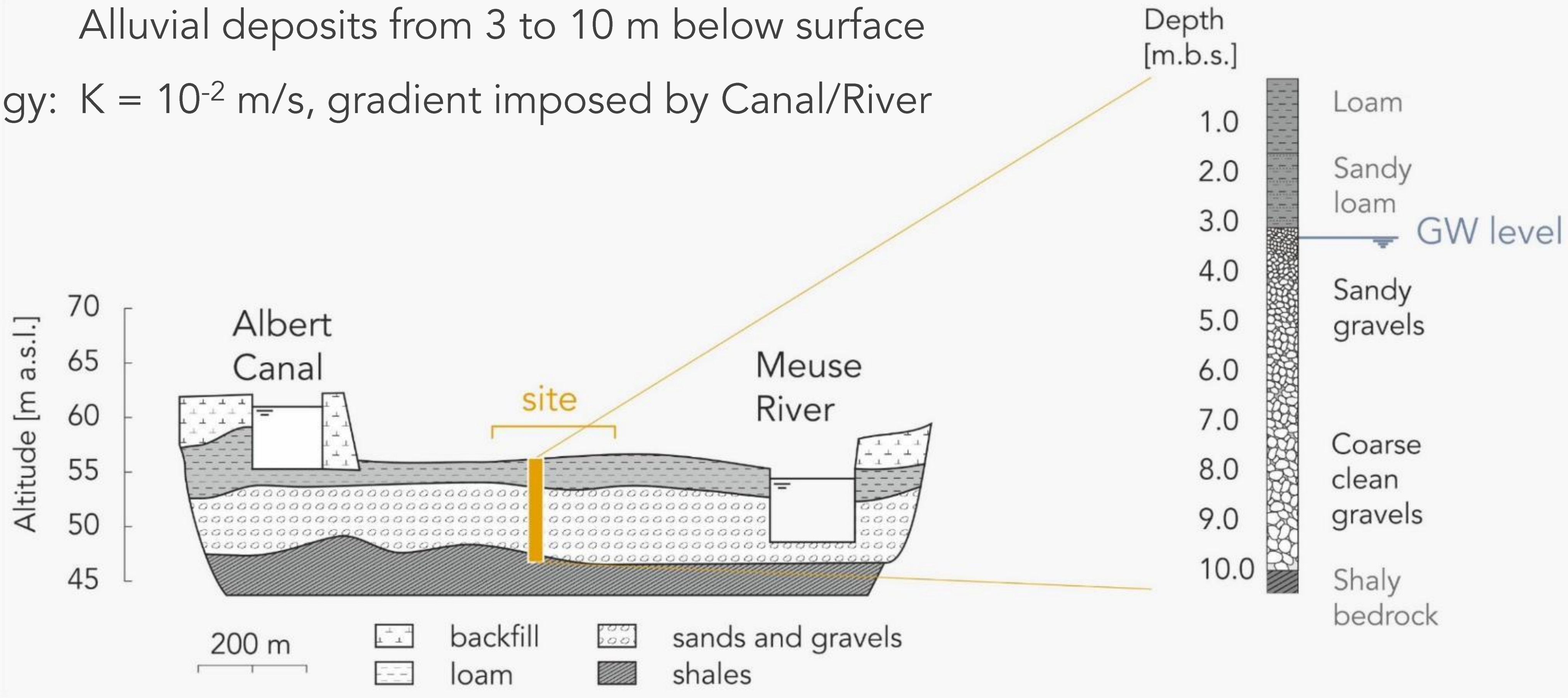
Validation of the resolution on field experiment

Monitoring of groundwater fluxes during pumping test

Test site: Hermalle /s Argenteau

Geology: Alluvial deposits from 3 to 10 m below surface

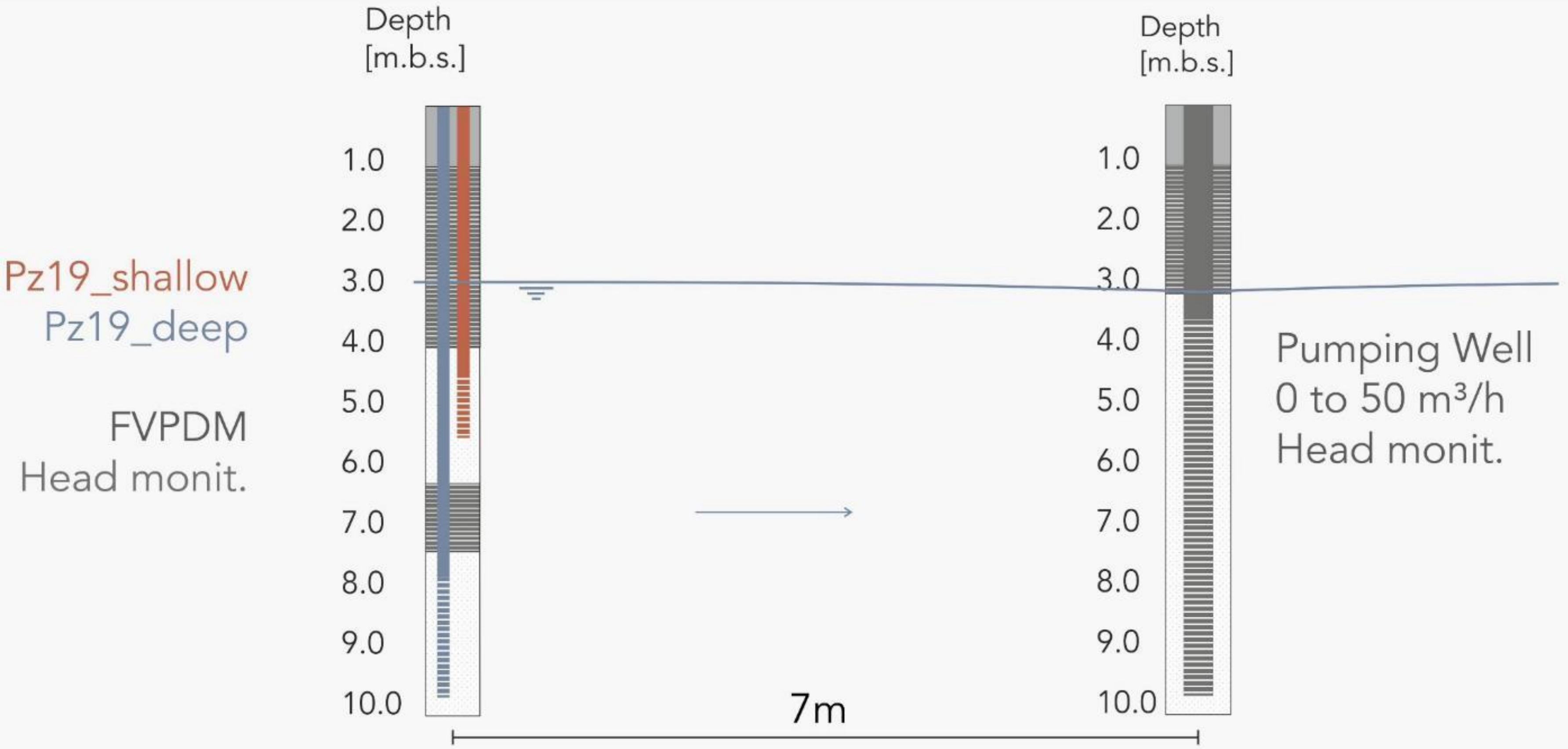
Hydrogeology: K = 10^{-2} m/s, gradient imposed by Canal/River



Experimental setup

Variable pumping at pumping well from 0 to 50 m³/h

Continuous monitoring of groundwater flux at 2 piezometers [Shallow | Deep]



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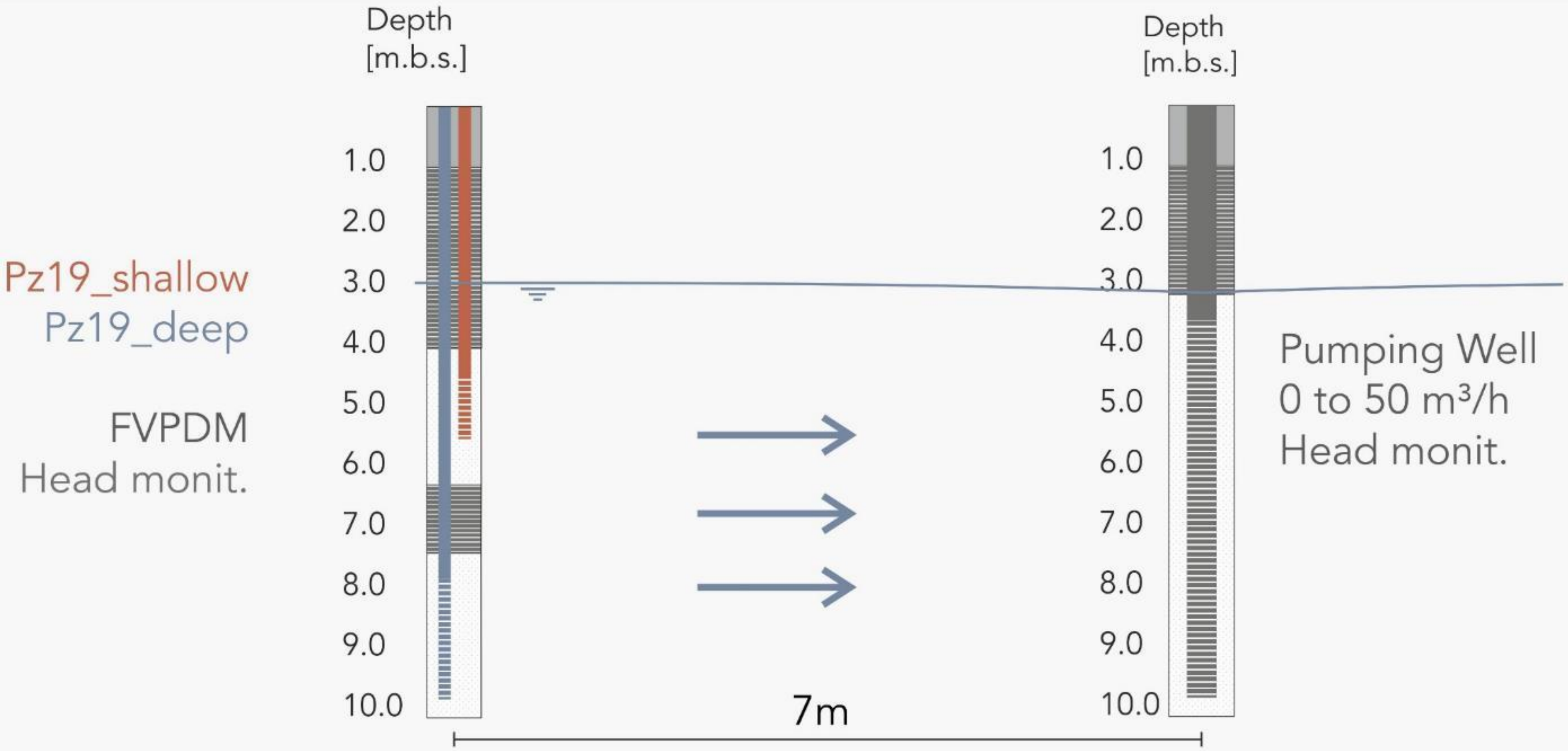

Drawdown induced by pumping

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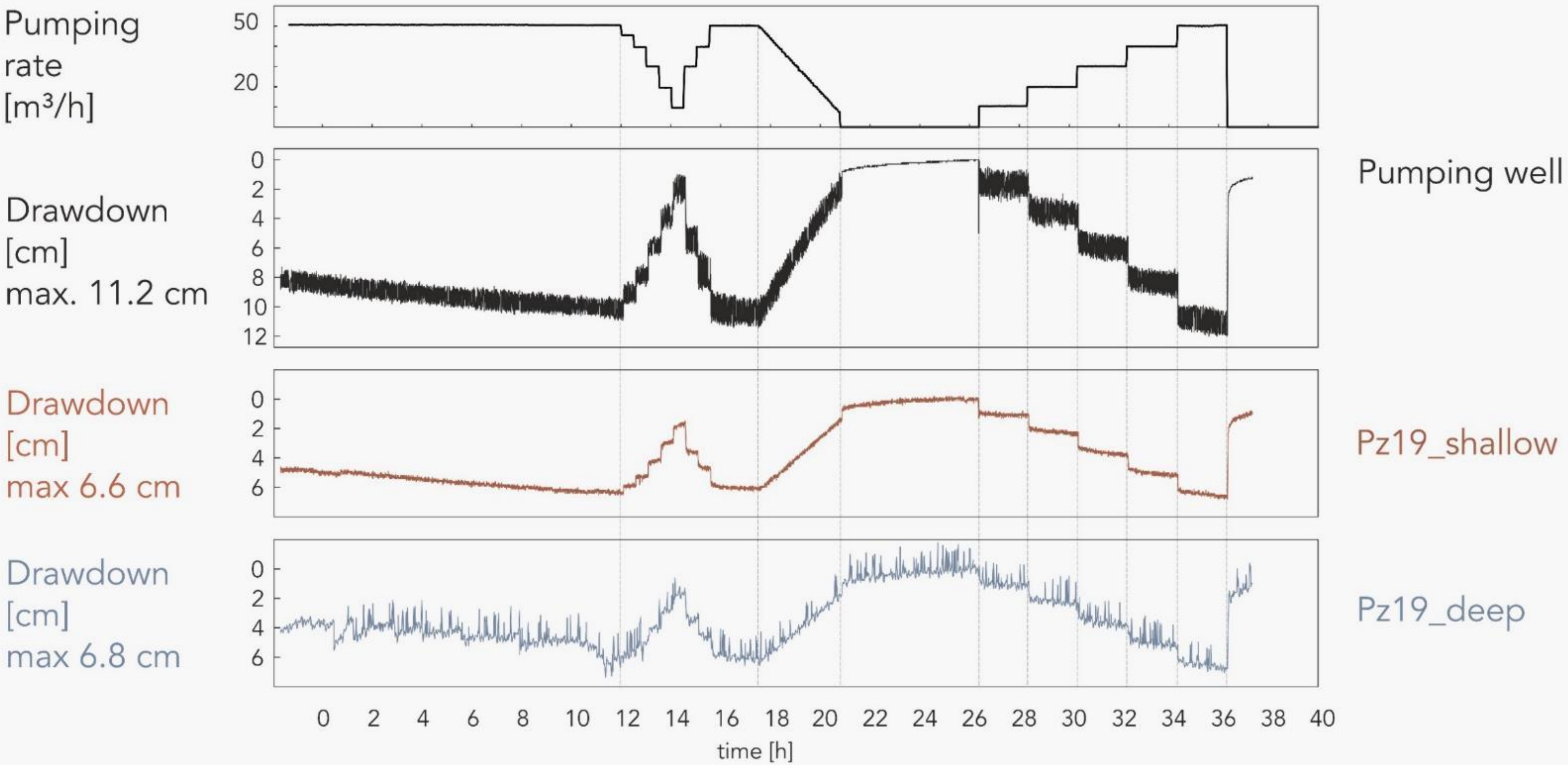
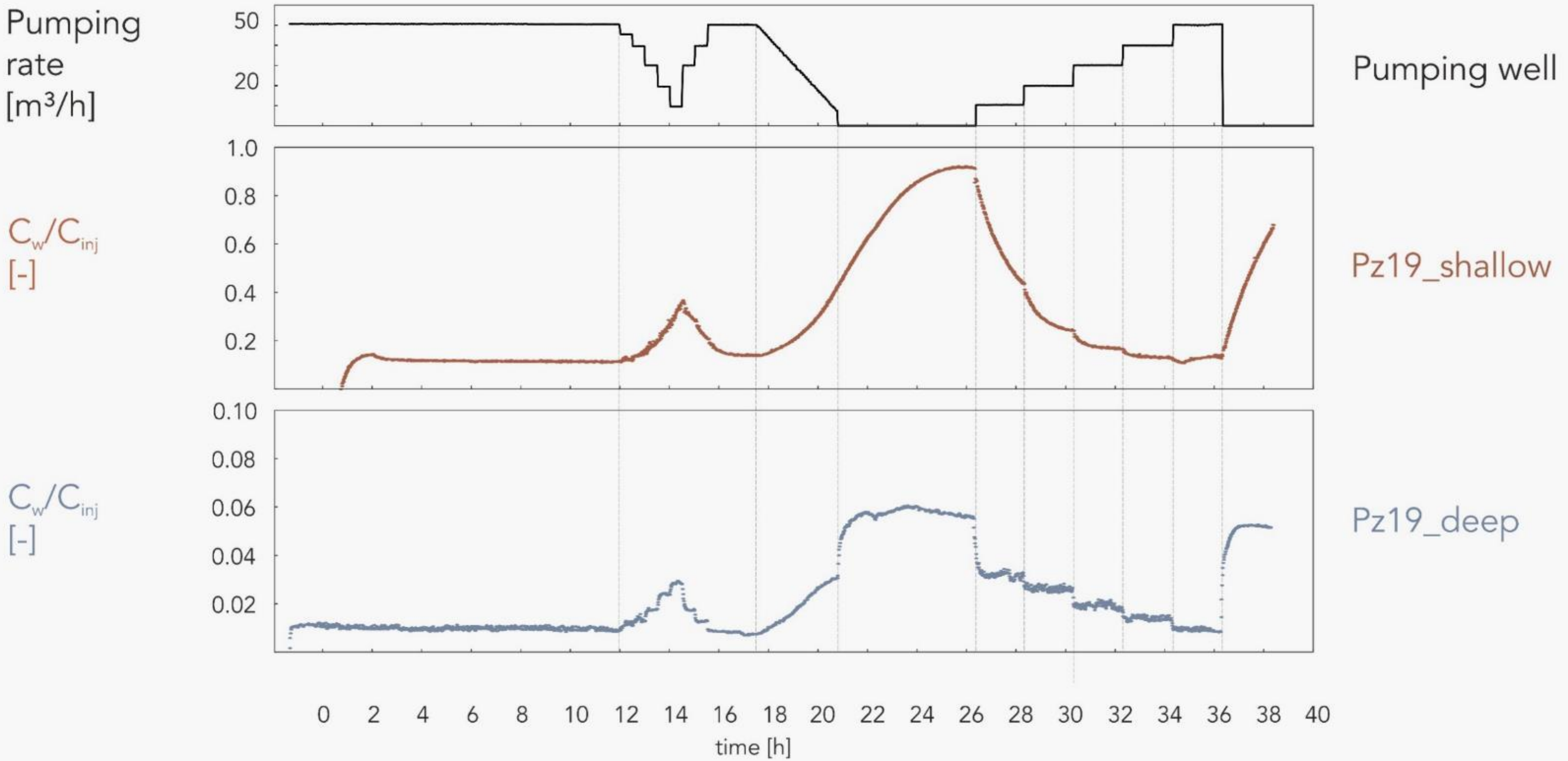


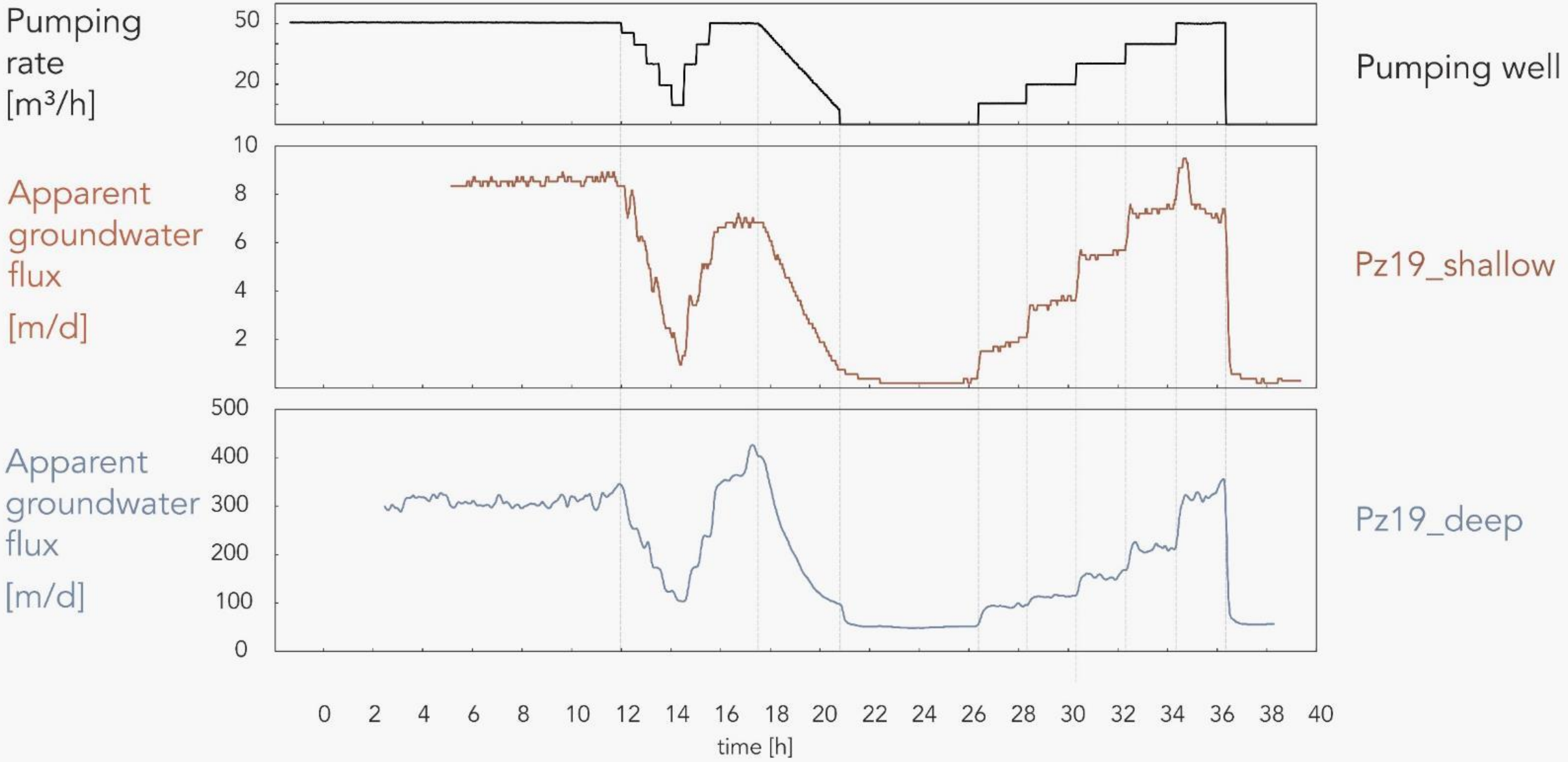
Monitoring of changing groundwater flux

The FVPDM method is sensitive to changes in groundwater flux



Monitoring of changing groundwater flux

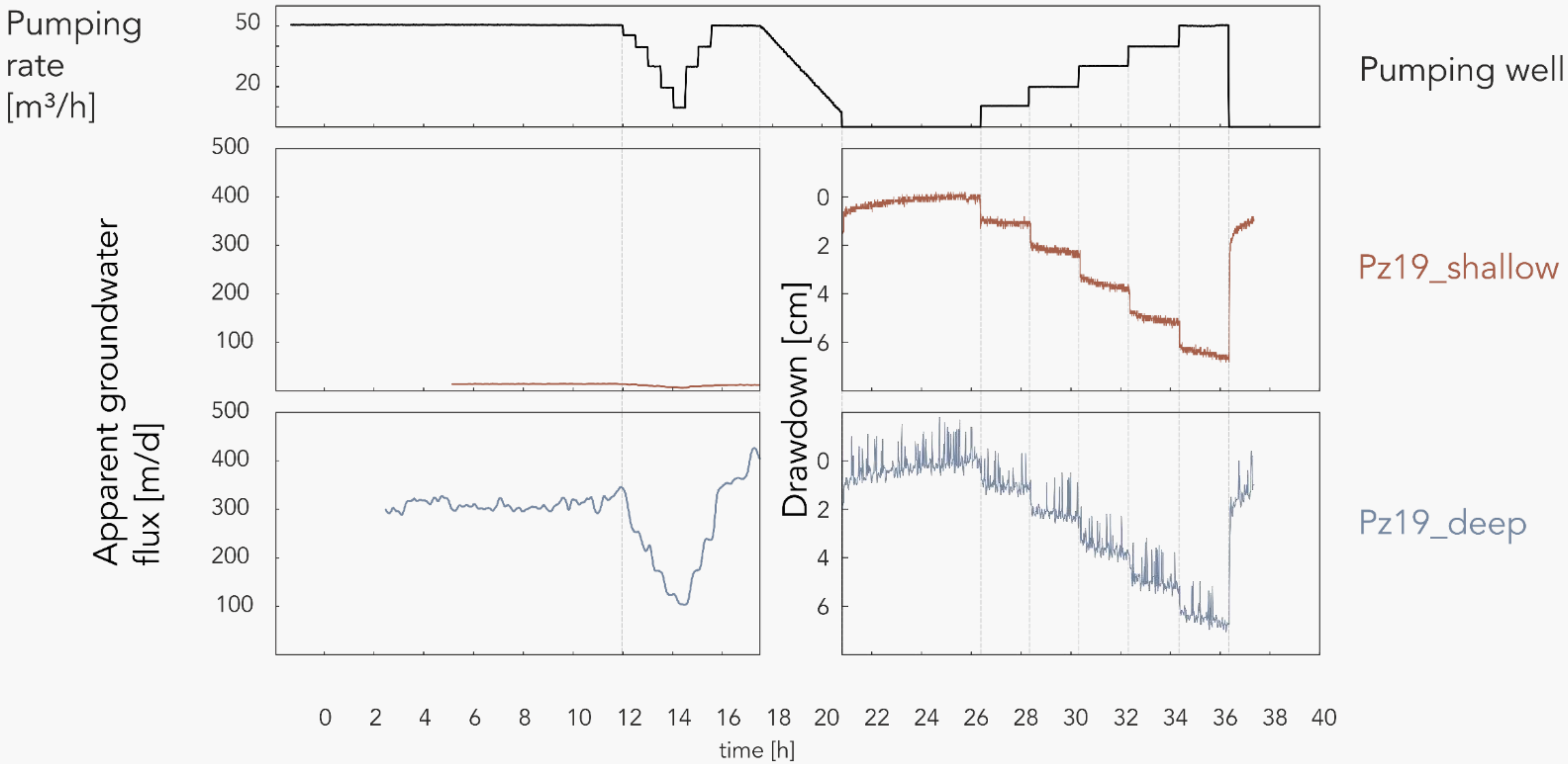
Capture apparent groundwater fluxes of 0.3 m/d to 360 m/d, resolution is ±5%



On the importance of flux vs. head measurements

Impossible to differentiate shallow/deep behavior on head measurements only

While groundwater fluxes are 30x higher in the deeper part



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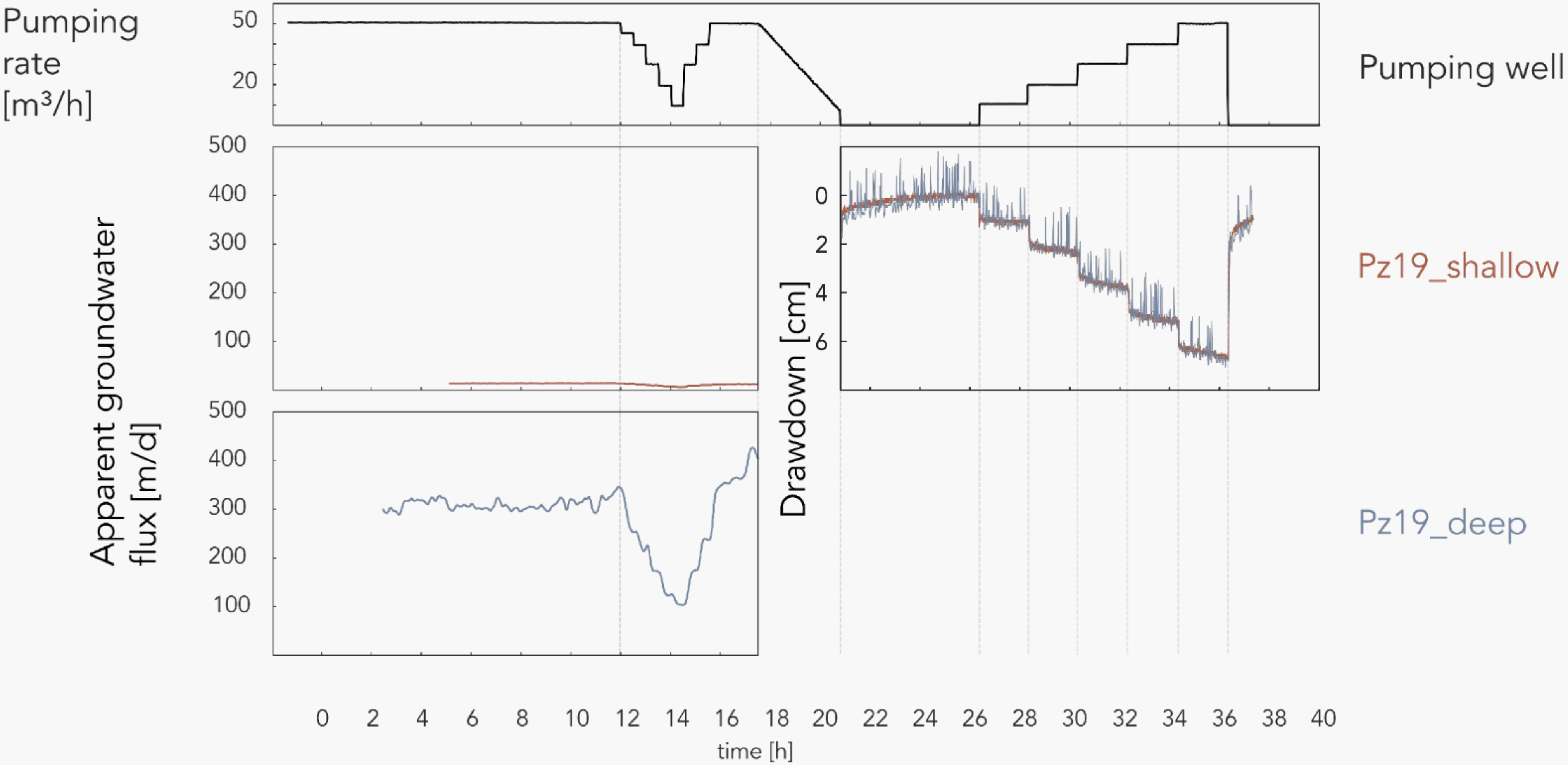
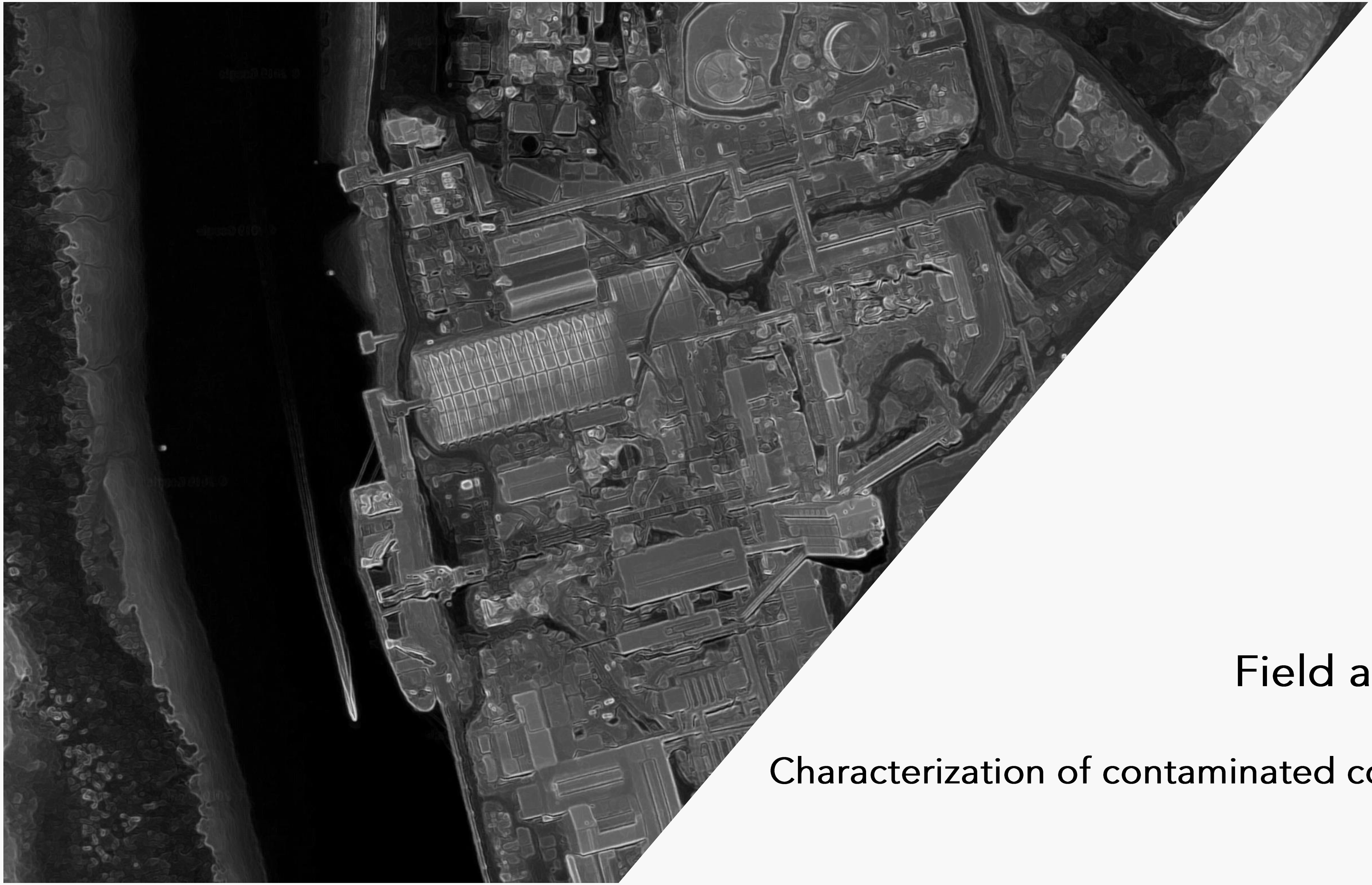




04.1

Field applications

Characterization of contaminated coastal aquifer

Coastal aquifer contaminated by heavy metals

Metal processing facility

Aquifer hydraulically connected to an estuary where tides occur

Contamination threatens the estuarine ecosystems (Mn, Zn, Cd, Pb)

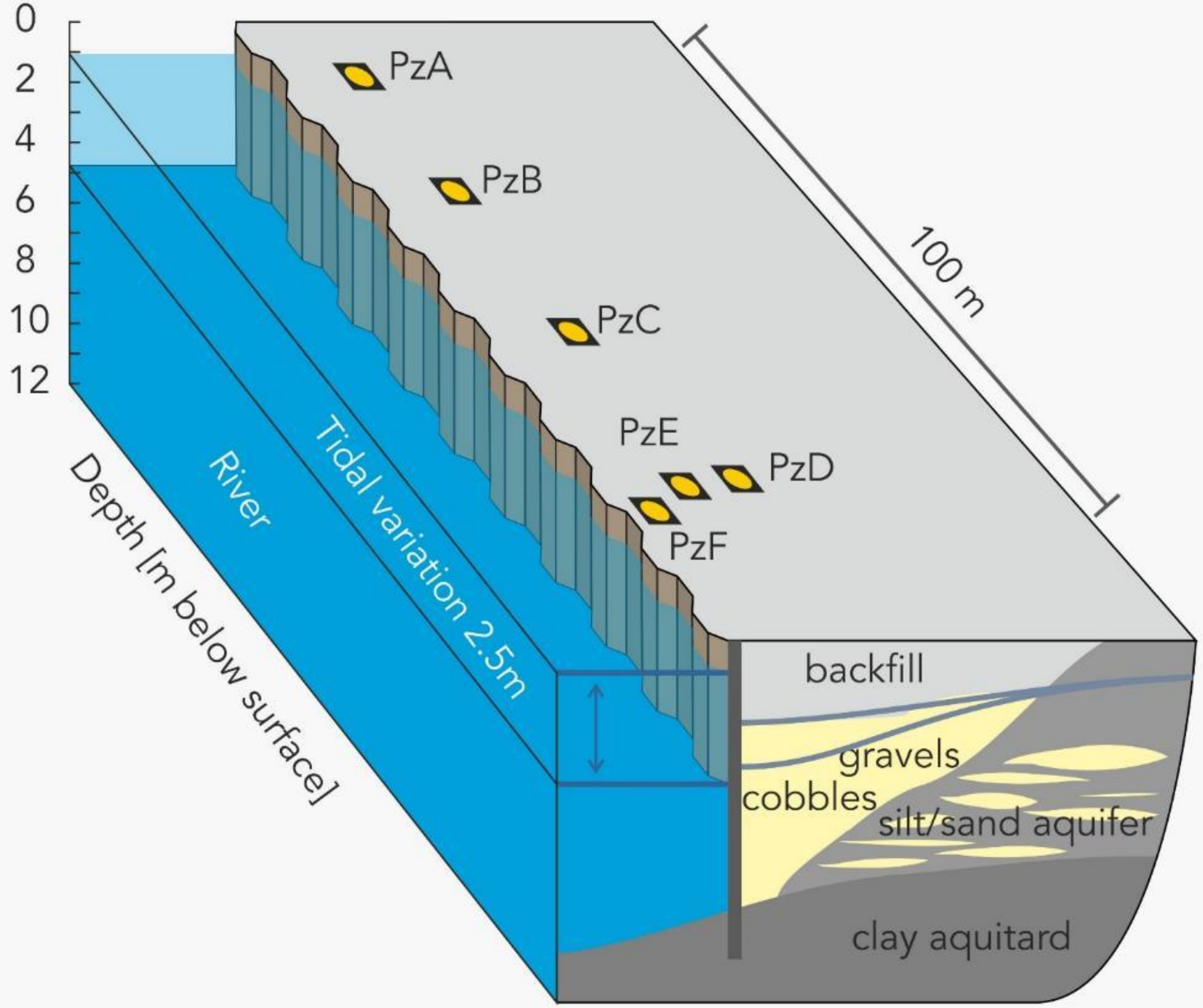
Limited access to an industrial zone

still in activity

Combined complexity of a dynamic flow within an heterogeneous aquifer

Groundwater flow influenced by tides

Different natural and backfill materials



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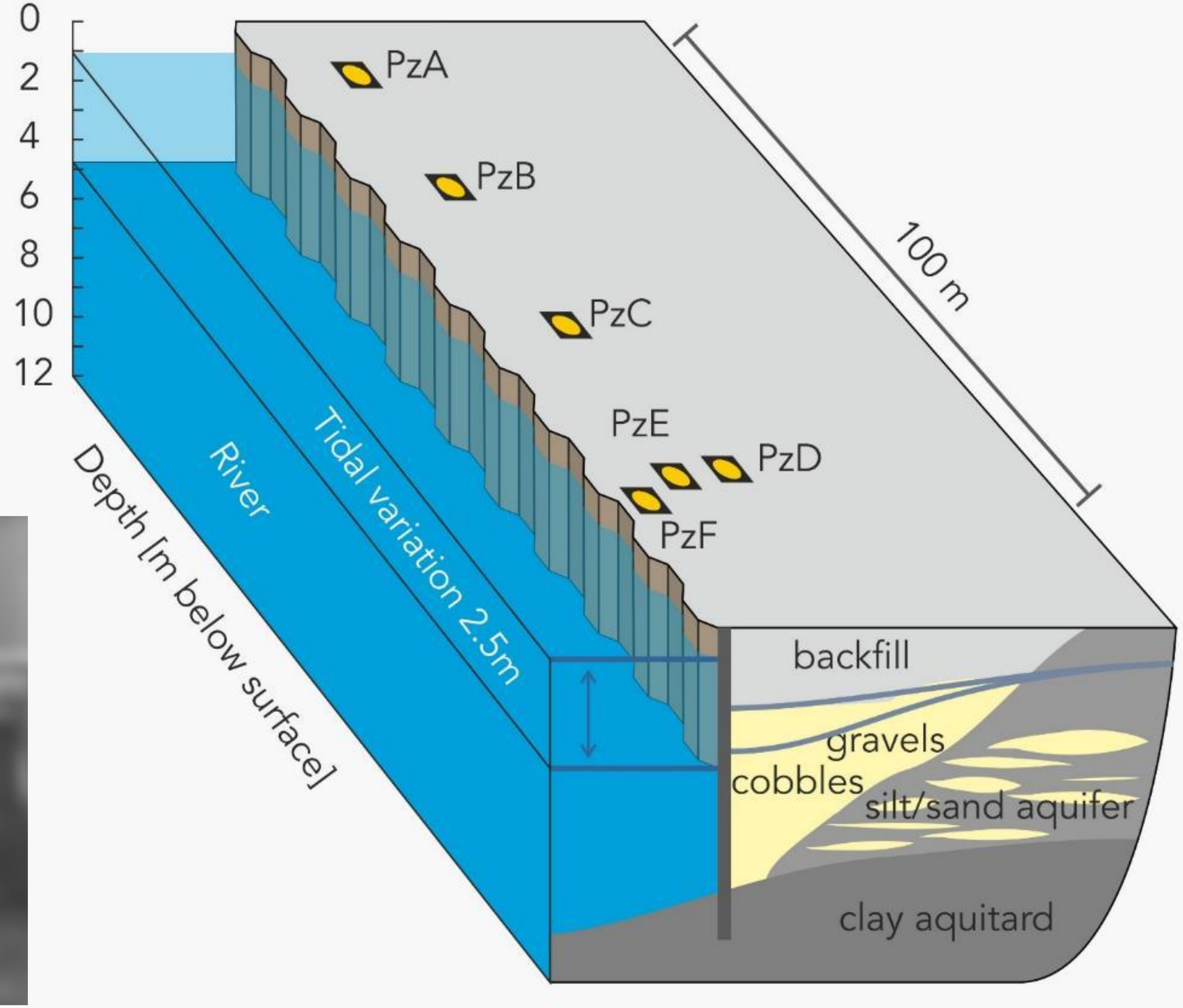
Influence of the sheet pile wall



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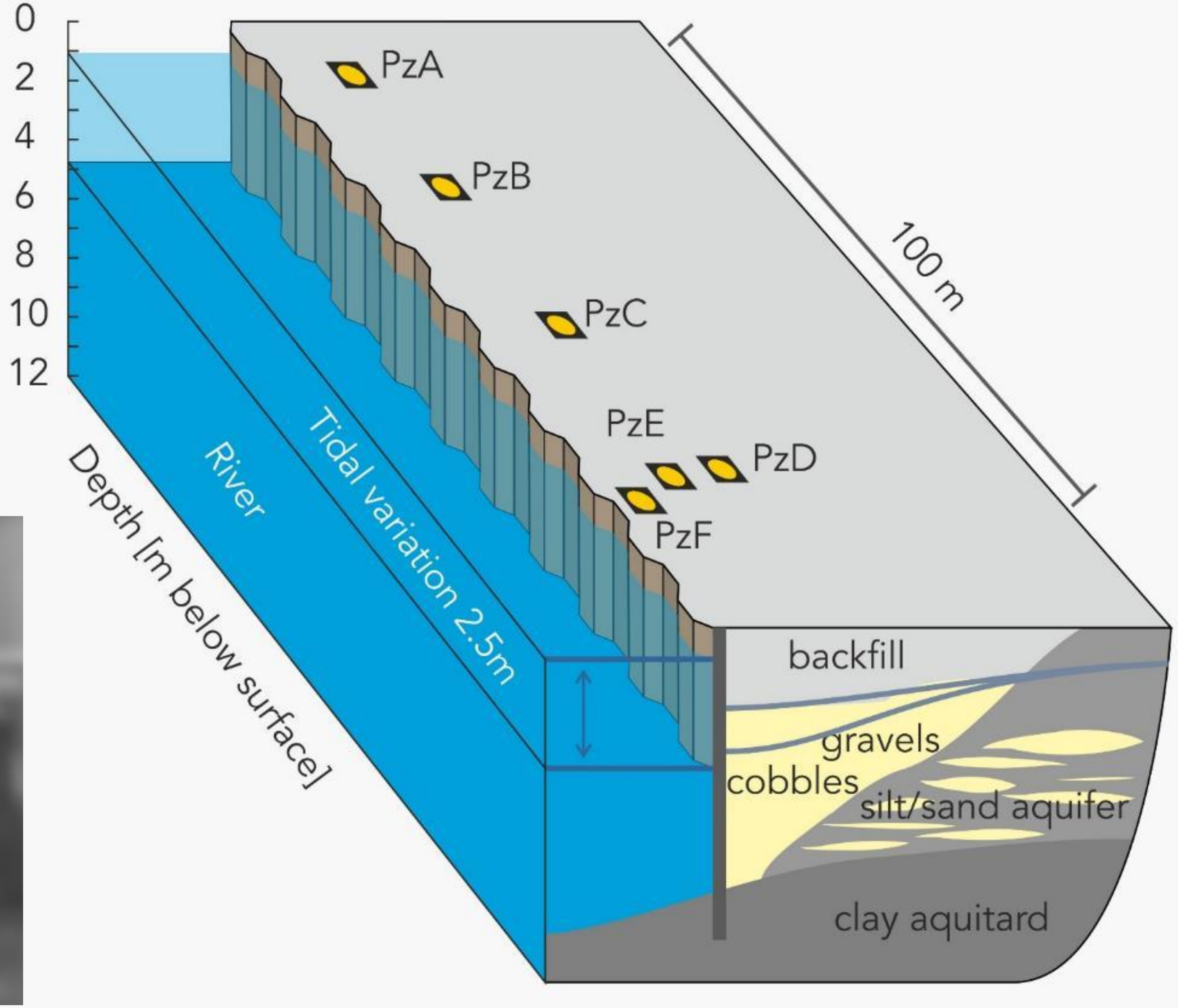


Conceptual model of the site

E-W general groundwater flow

S-N groundwater flow parallel to the wharf

Metal concentrations decrease towards North

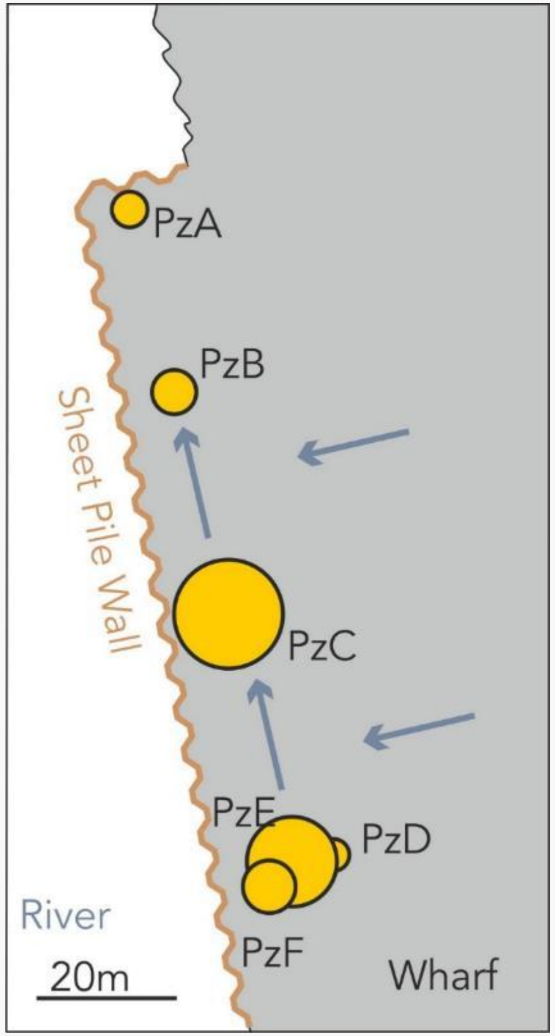
4 potential conceptual models

〰 Sheet Pile Wall

● Monitoring well
Manganese concentration

← Groundwater flux

↔ Exchange between
surface and groundwater



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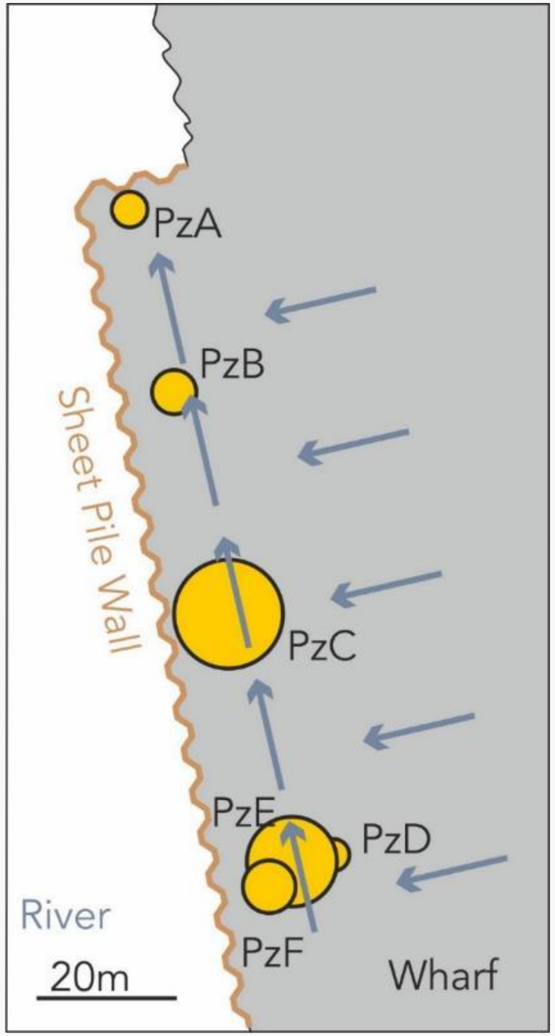
a) Plume has not reached PzB yet



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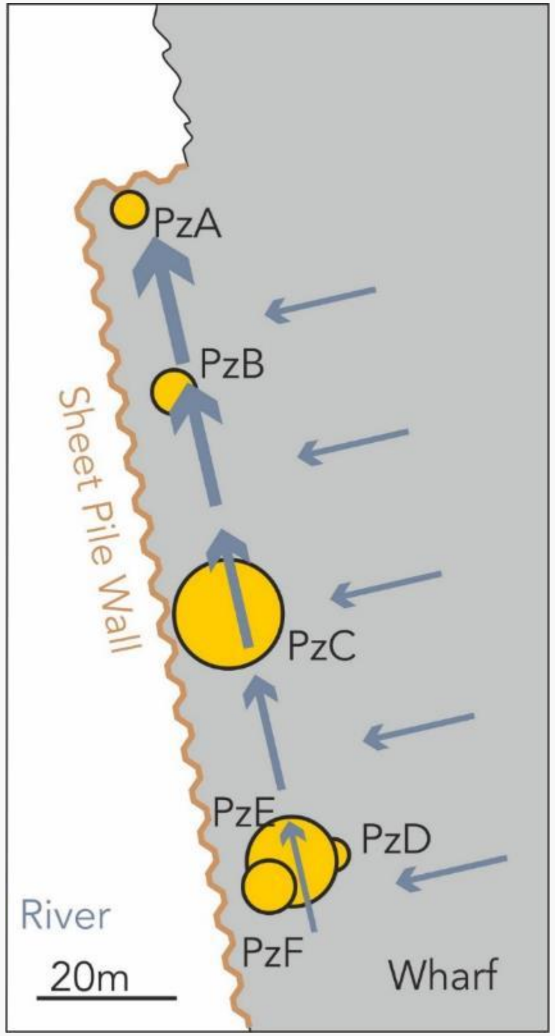
b) Dilution by GW flux from East



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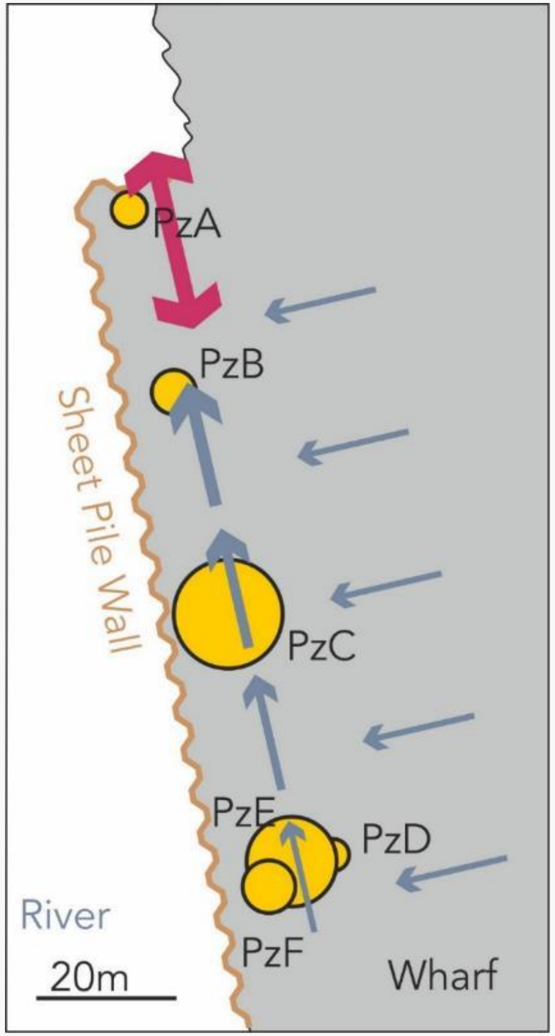
c) Tidal mixing in the northern zone



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Conceptual model of the site

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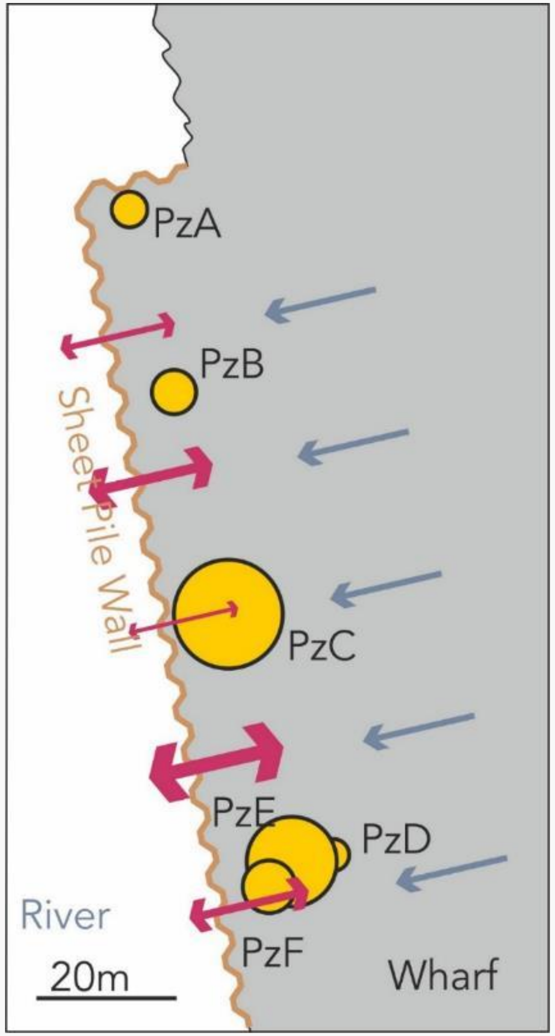
d) Water exchange through SPW



〰 Sheet Pile Wall

● Monitoring well
Manganese concentration

← Groundwater flux

↔ Exchange between
surface and groundwater

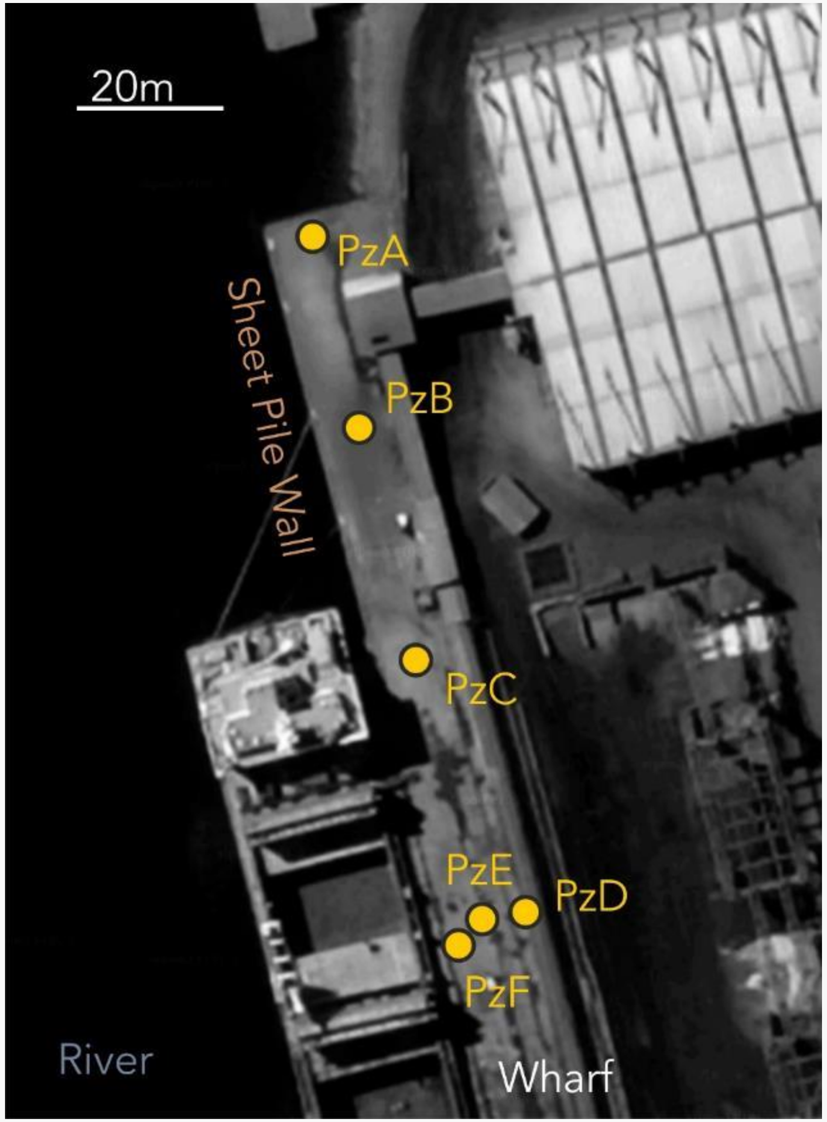
Experimental setup

Monitoring FVPDM on 6 monitoring wells

48 hours continuous running to capture 4 tide cycles

Simultaneous collection of groundwater samples

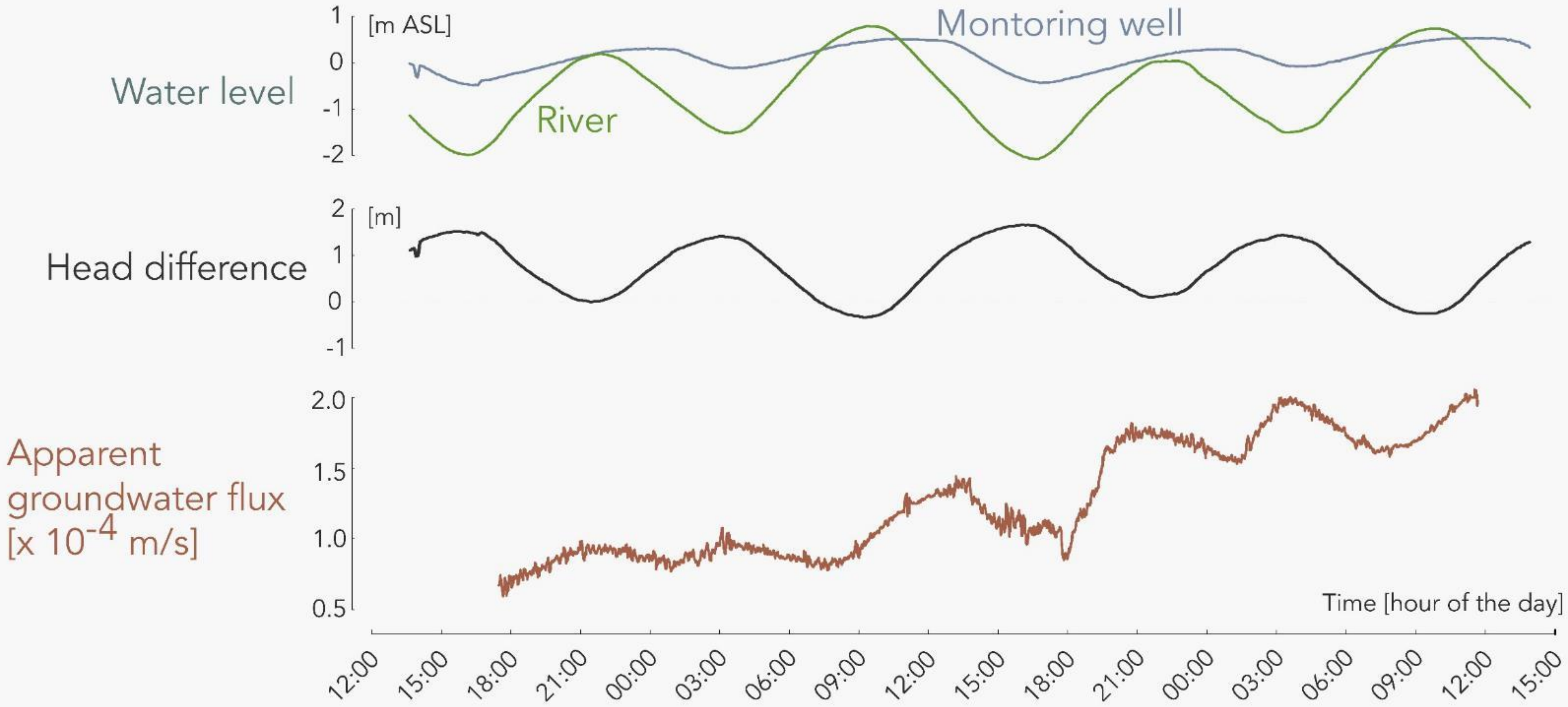
to analyze metal concentrations



Groundwater fluxes monitoring at PzE

Apparent groundwater flux varies from 0.6×10^{-4} to 2.1×10^{-4} m/s

Flux variations not strictly in phase with tide, no inversion of flow direction



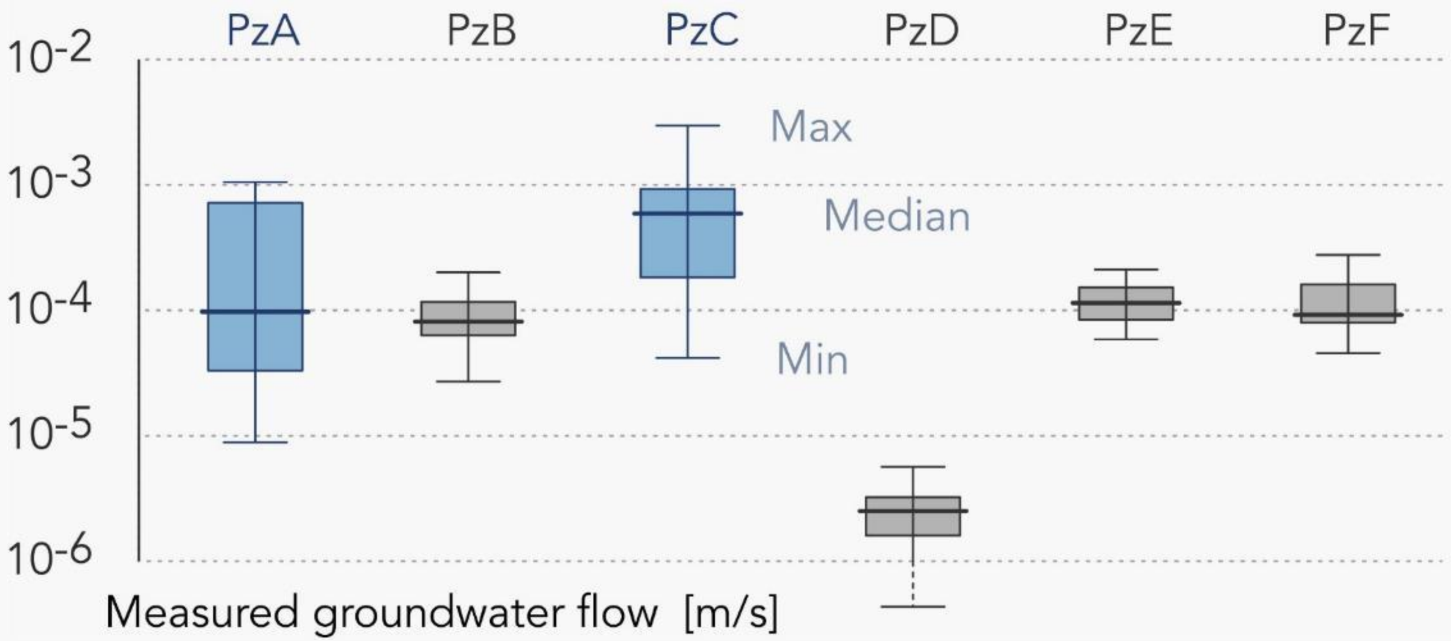
General observations of groundwater fluxes

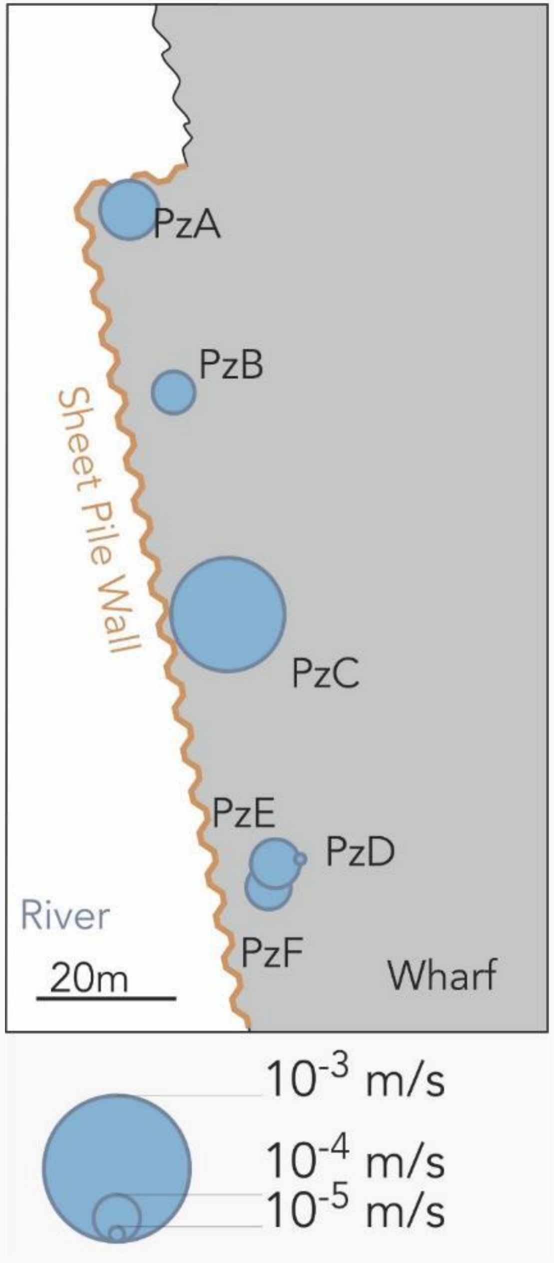
Low unsynchronized fluxes at PzB, D, E, F

High and variable fluxes at PzA, C

Highest flux at PzC 3×10^{-3} m/s

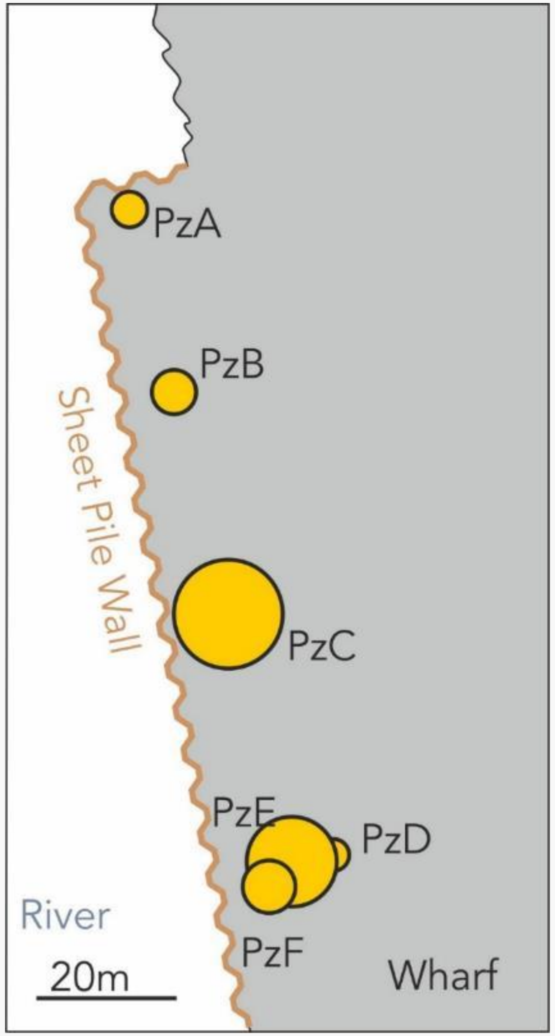
No clear evidence of groundwater flow inversion





Update of conceptual model

Constant contaminant concentration in groundwater over tide

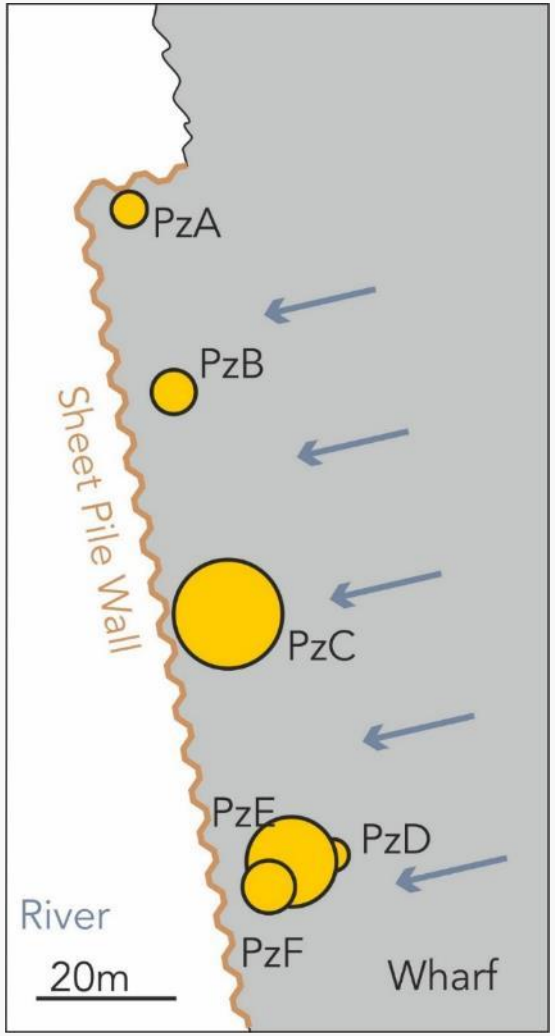


Update of conceptual model

Constant contaminant concentration in groundwater over tide

Groundwater flow system controlled

by incomes of groundwater from inland

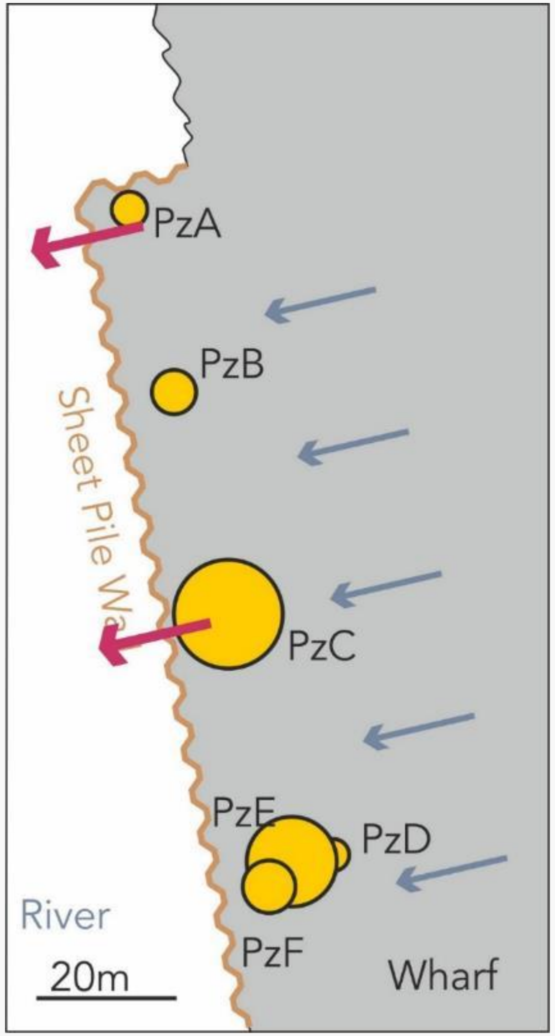


Update of conceptual model

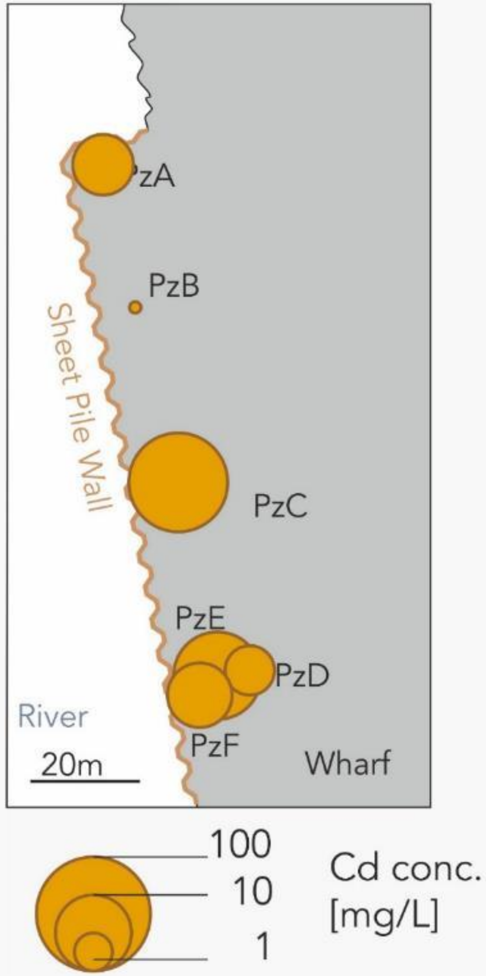
Constant contaminant concentration in groundwater over tide

Groundwater flow system controlled
by incomes of groundwater from inland

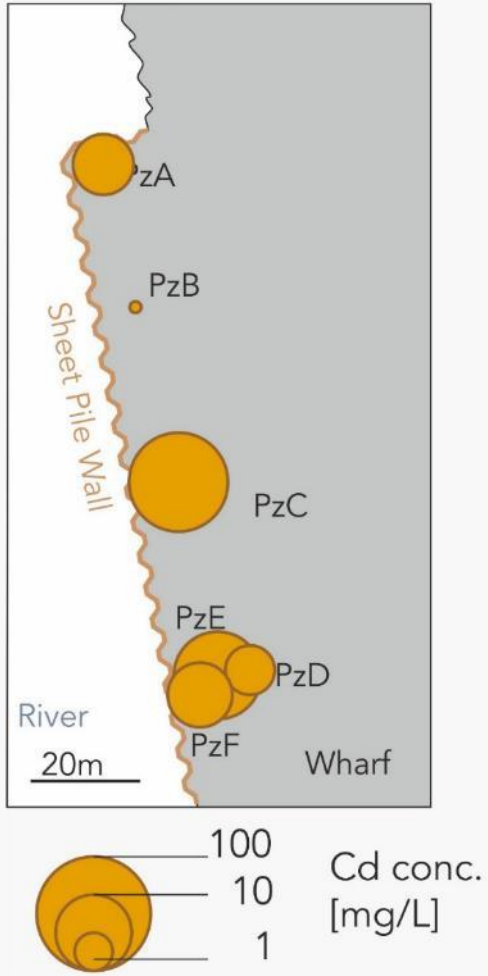
Discharge through specific points
in the sheet pile wall

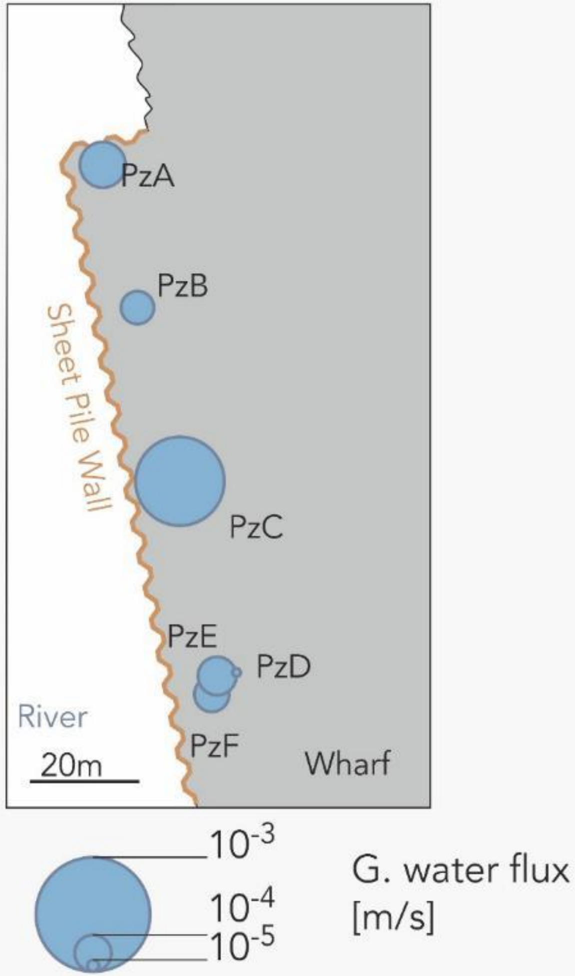


Outcome of the study



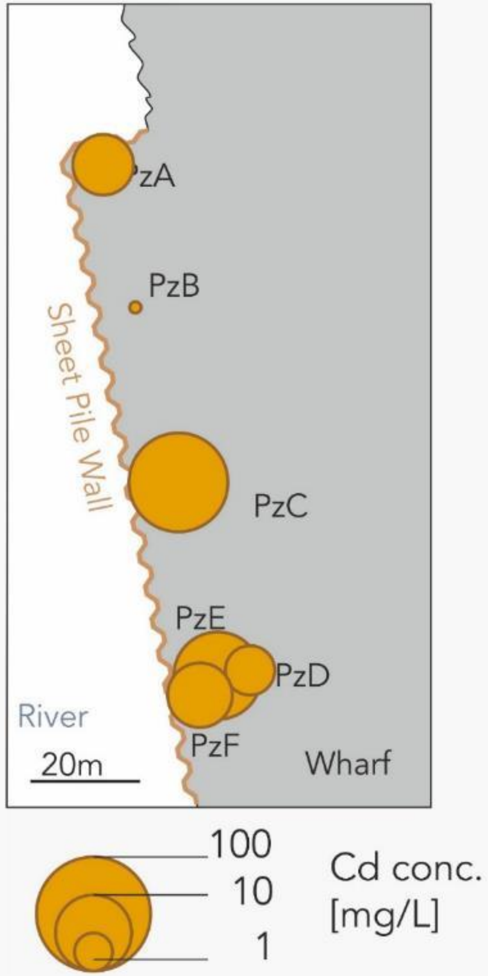
Outcome of the study

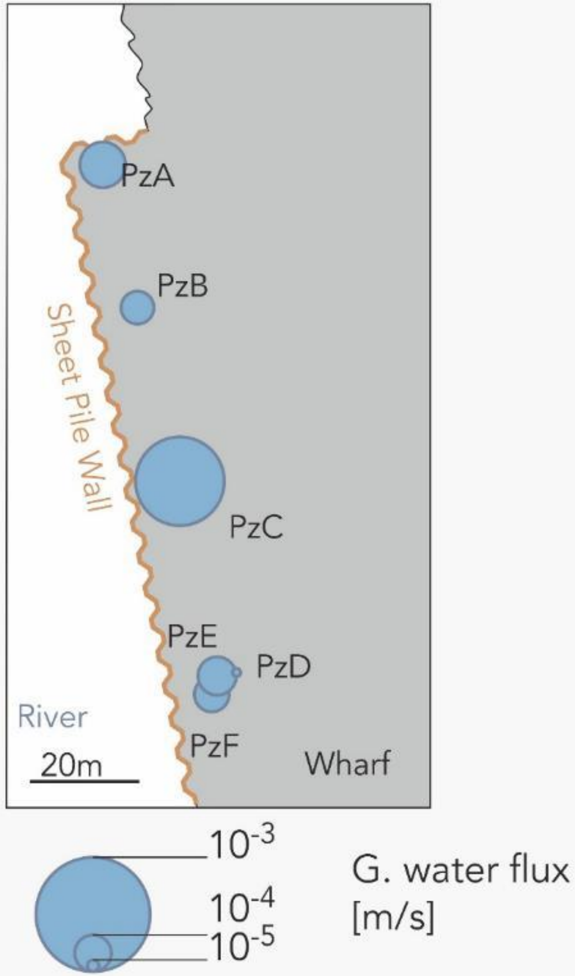


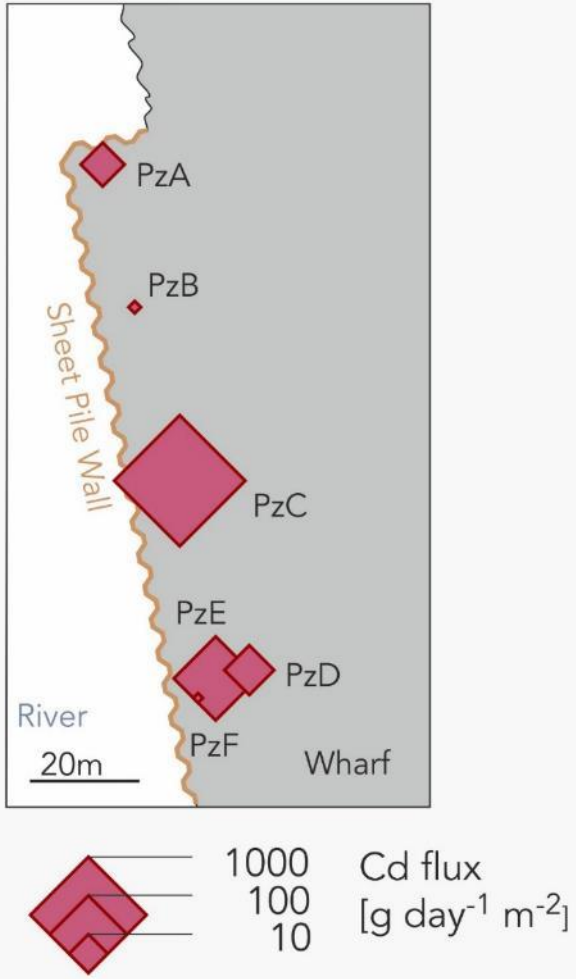


Outcome of the study

Cd mass flux at PzC is 2.4 kg m^{-2} d^{-1} -> 1000x higher than at other wells







04.2

Field applications

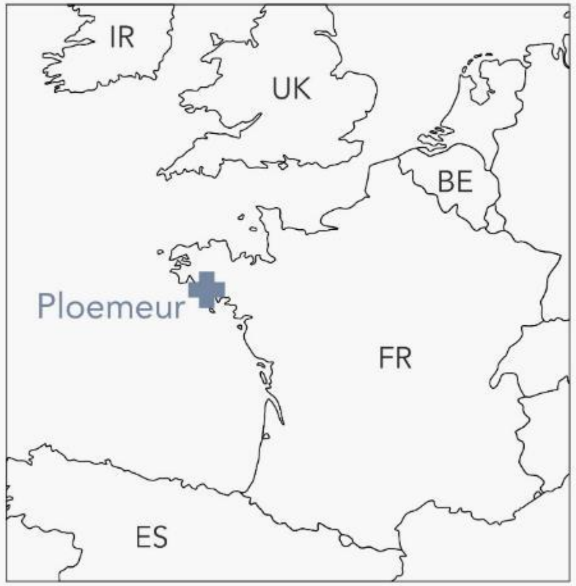
Other applications of the FVPDM

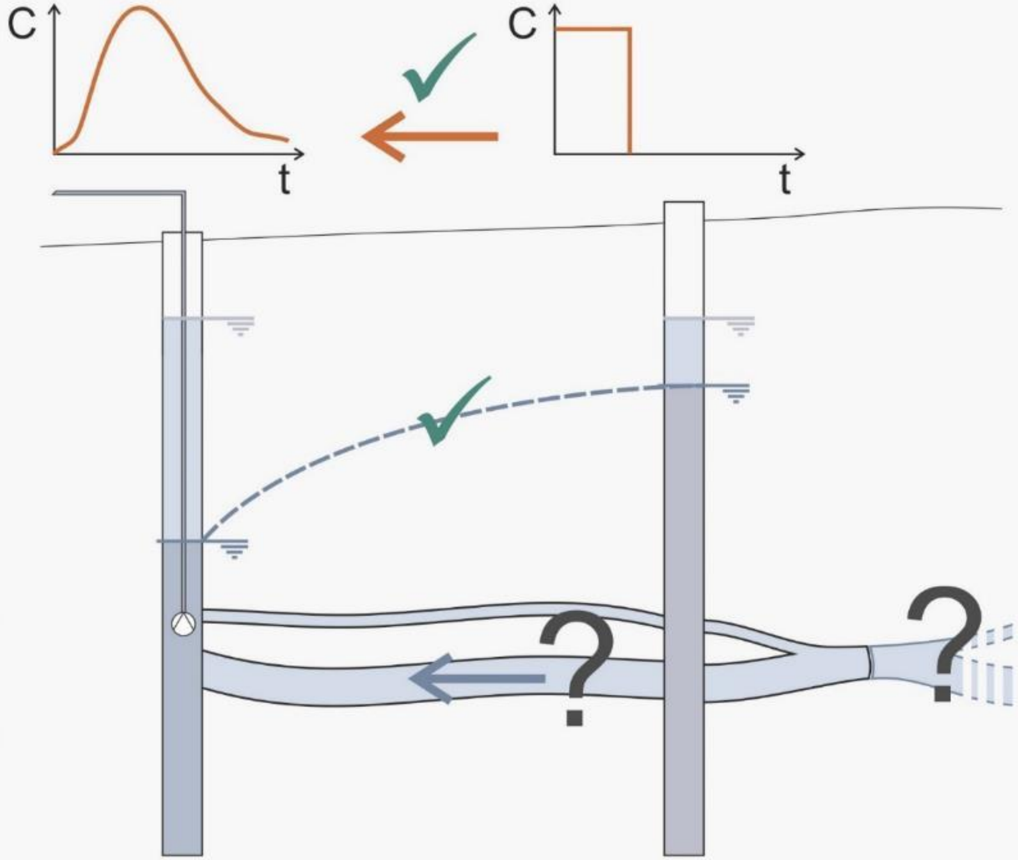
+ Application: Fracture flow ≠ hydraulic connection

Location: Ploemeur, Brittany, France

Geology: Fractured granite

Objective: Characterization of fracture flow



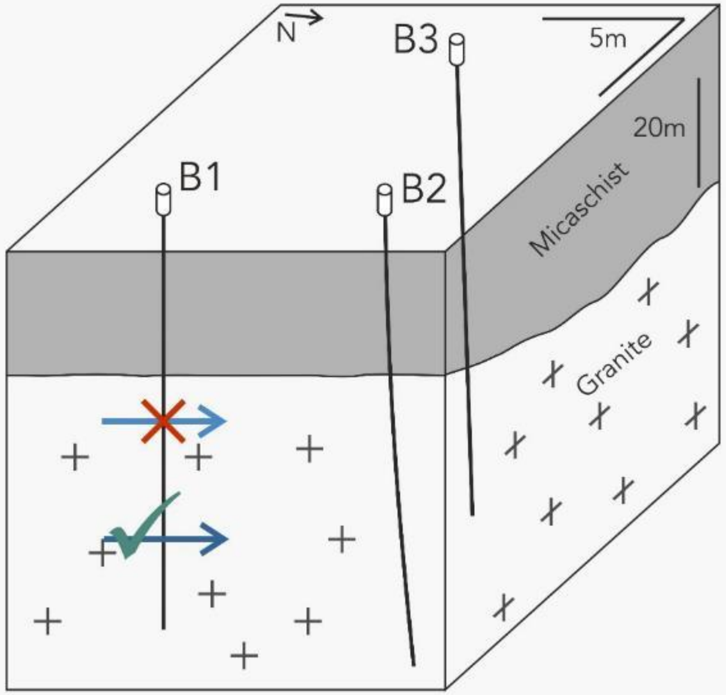


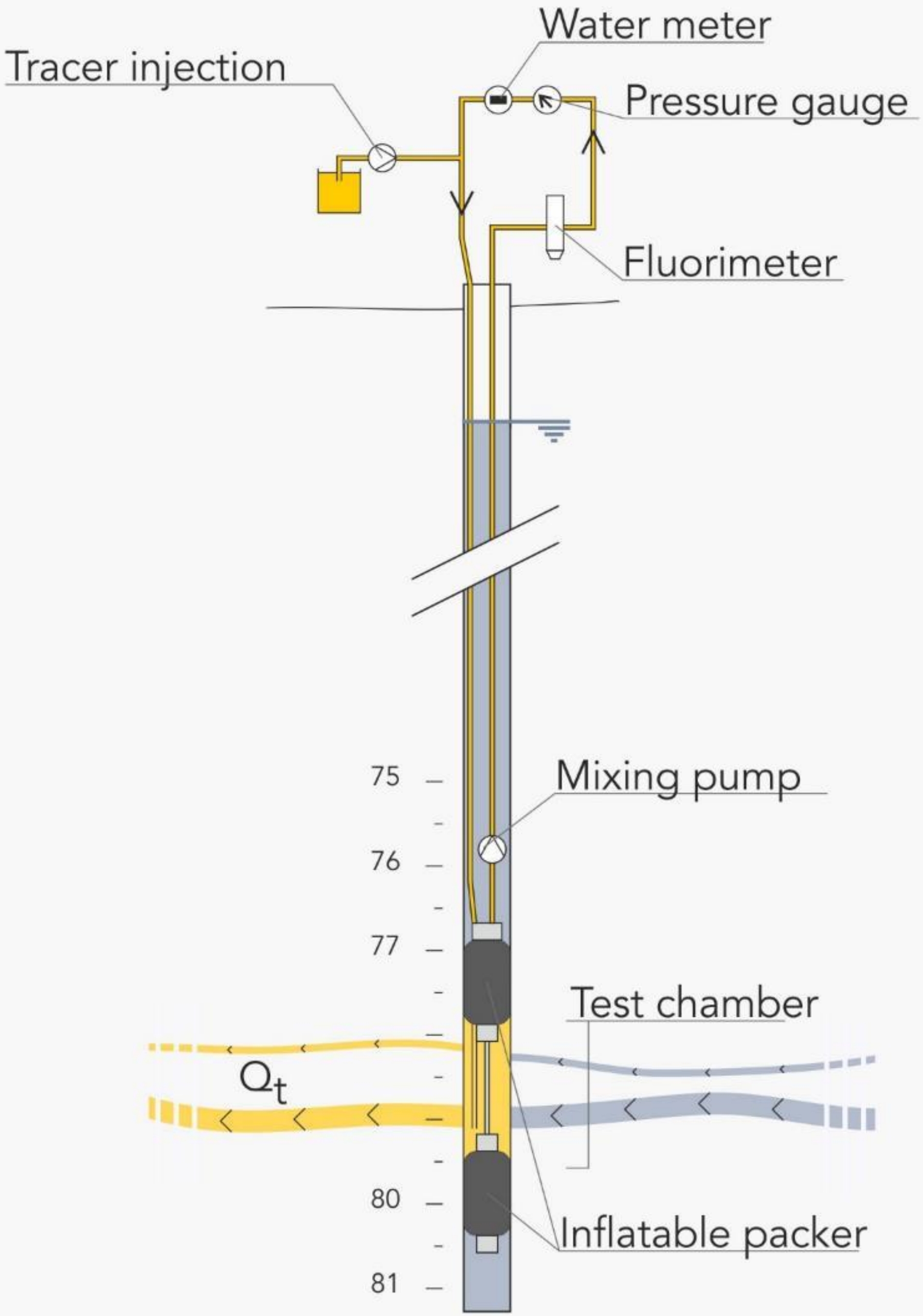
+ Application: Fracture flow

Setup: Straddle packer system

1m test chamber

Measure flow in a fracture 80m and 50m deep



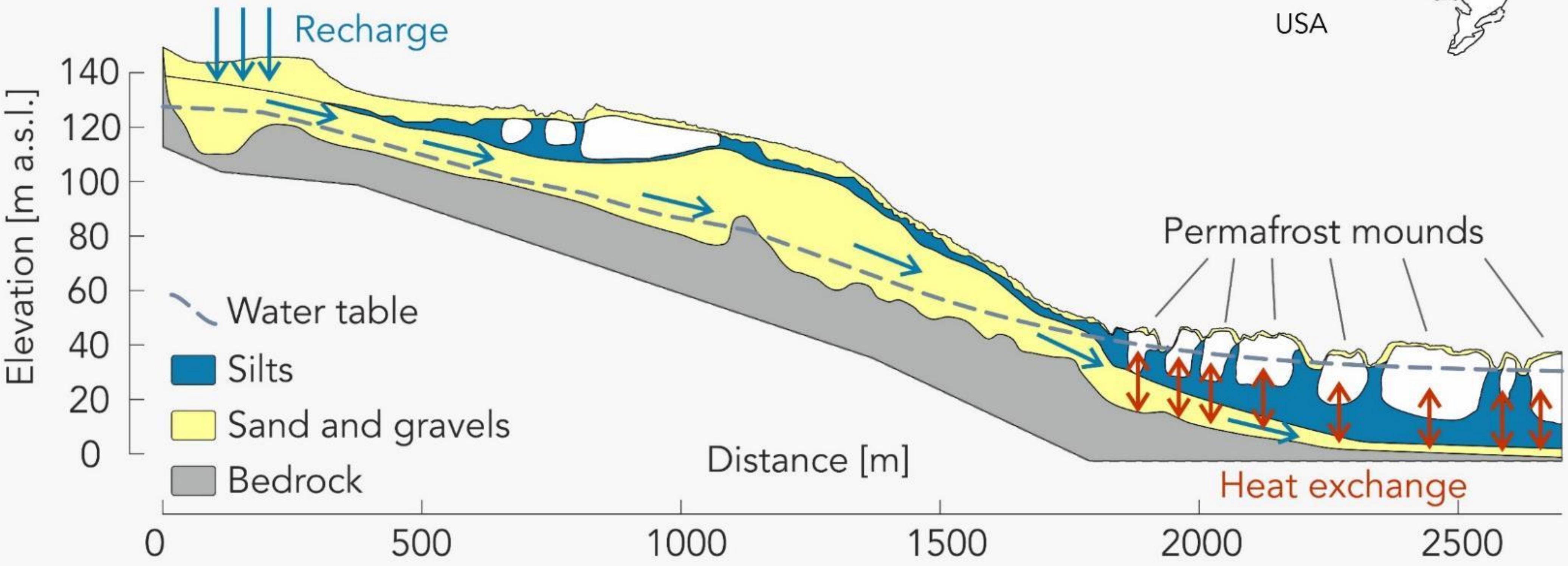


+ Application: Groundwater flow under permafrost

Location: Umiujaq, Nunavik, Canada

Geology: Sandy fluvio-glacial sediments

Objective: Groundwater flow measurement

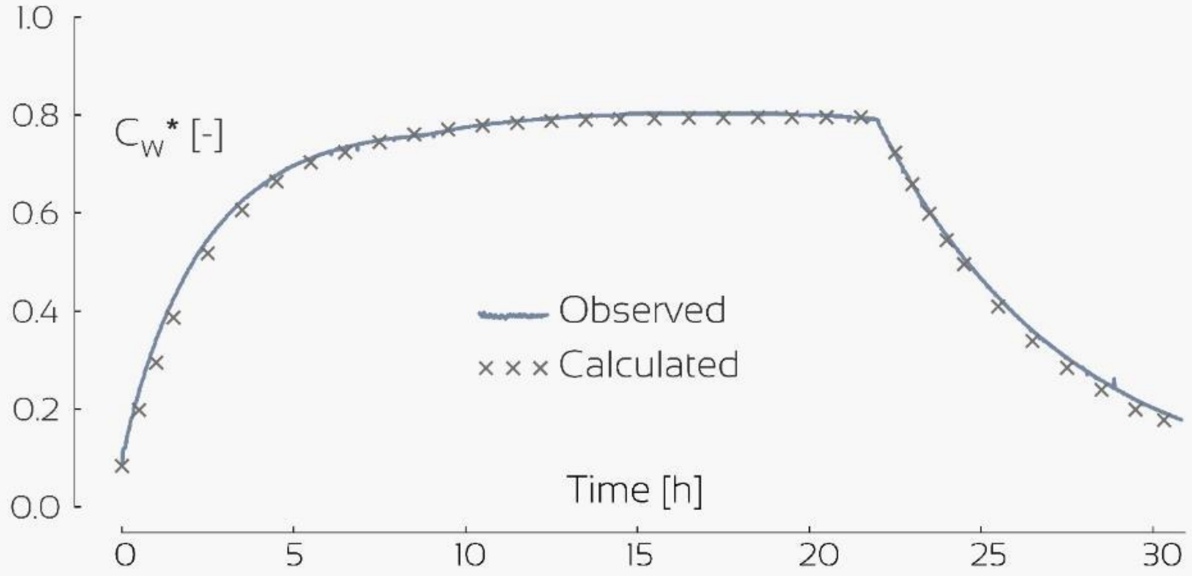


+ Application: Groundwater flow under permafrost

Specificity: Remote natural environment

1.5 inch. piezometers, 40 m deep

Run for 30+ hours with limited resources



06.

Conclusions and perspectives

Research outcomes

Range of application

FVPDM

Research outcomes

Range of application

Lab | Field

FVPDM

Research outcomes

Range of application

Lab | Field

4 countries | 3 continents

FVPDM

Research outcomes

Range of application

Lab | Field

4 countries | 3 continents

FVPDM

Research | Consulting

Research outcomes

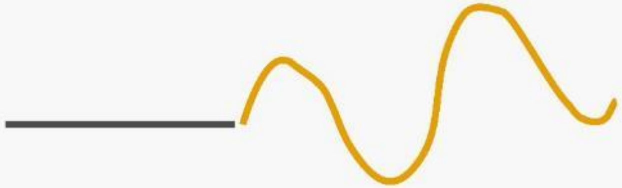
Range of application

Lab | Field

4 countries | 3 continents

FVPDM

Research | Consulting



Steady | Transient

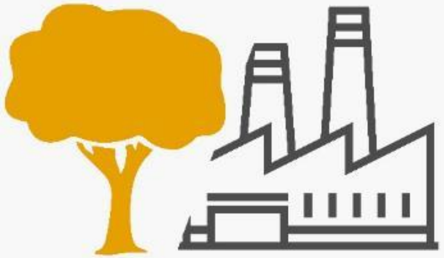
Research outcomes

Range of application

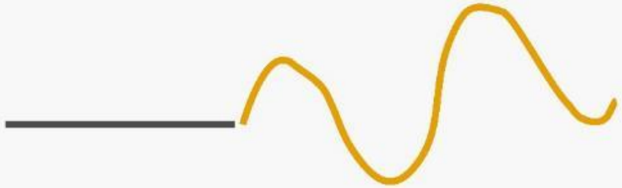
Lab | Field

4 countries | 3 continents

FVPDM



Natural | Industrial



Steady | Transient

Research | Consulting

Research outcomes

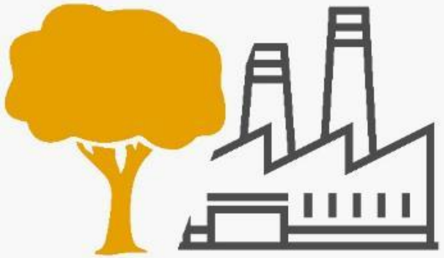
Range of application

Porous | Fratured

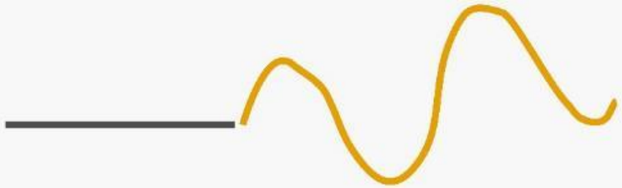
Lab | Field

4 countries | 3 continents

FVPDM



Natural | Industrial

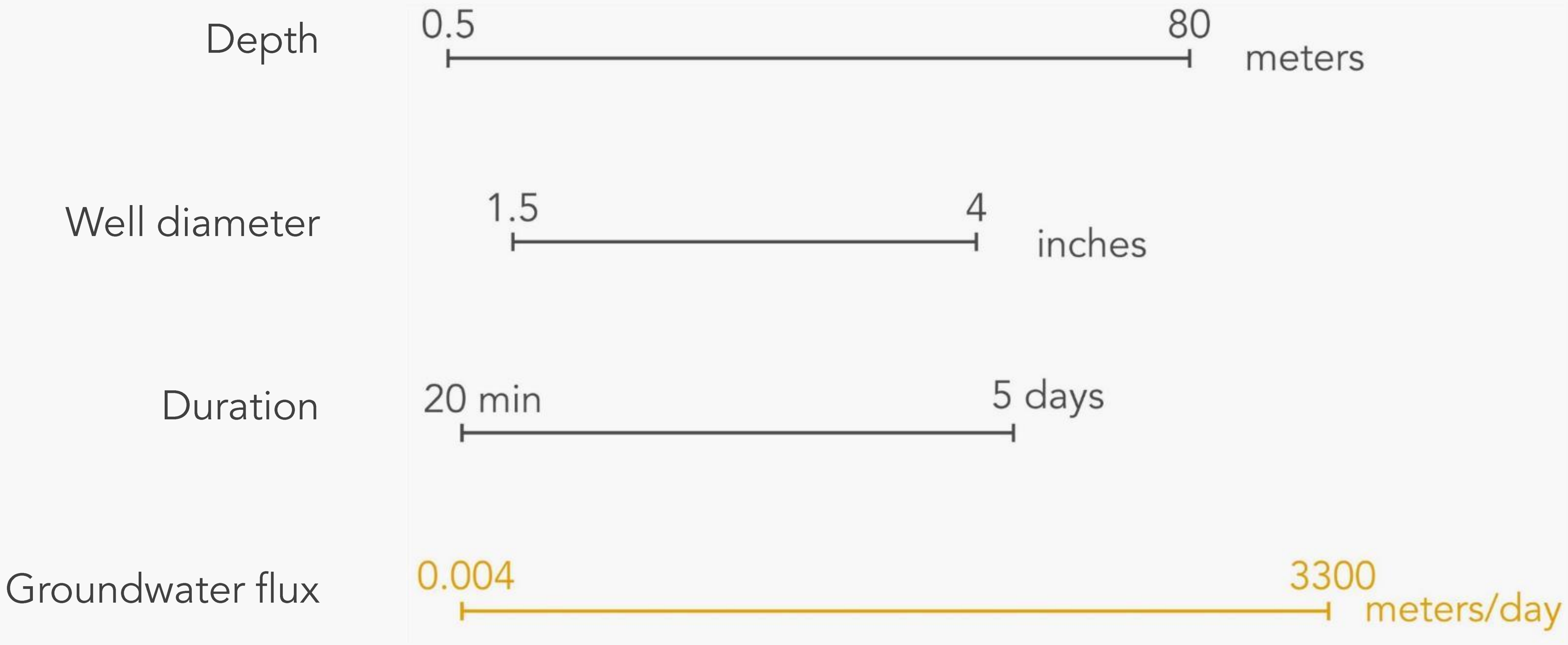


Steady | Transient

Research | Consulting

Research outcomes

Range of application



Depth	0.5	80	meters
Well diameter	1.5	4	inches
Duration	20 min	5 days	
Groundwater flux	0.004	3300	meters/day

Research outcomes

Specifications

Uncertainties	±0.2 to ± 5%	
	Depends on the experiment duration -> Stabilized tracer conc. Code available to evaluate the uncertainties	
Accuracy	± 5%	on in–well groundwater flux
	± 10%	on aquifer Darcy flux (flow field distortion around the well)
Resolution	± 5%	

Conclusion

The FVPDM is a reliable, robust and versatile method for groundwater flux measurement, in both steady state and transient state groundwater flow.

Perspectives

Development

Improving the setup

More integrated

More portable

4G live connection

Applications

Efficiency of remediation systems

Geotechnical

Move forward

Think FLUX

Mass flux for risk assessment

Risk for humain health is defined by exposure doses
= Amount of pollutant in contact with biological barriers

Ingestion/contact $\mathrm{mg/kg_{b.m.}/day}$ (adult 70kg, child 15kg)

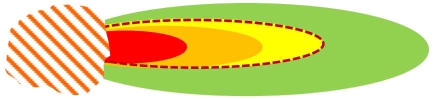
$$\underset{\text{exp. totale}}{DJE} = \underset{\text{cutanée sol}}{DA} + \underset{\text{cutanée eau douche}}{DA_w} + \underset{\text{ingestion sol}}{DI} + \underset{\text{ingestion ea}}{DI_w} + \underset{\text{ing. plantes}}{VI} + \underset{\text{ing. lait}}{MI_m} + \underset{\text{ing. viande}}{Mime}$$

Exposure = mg/day
Mass discharge = md/day

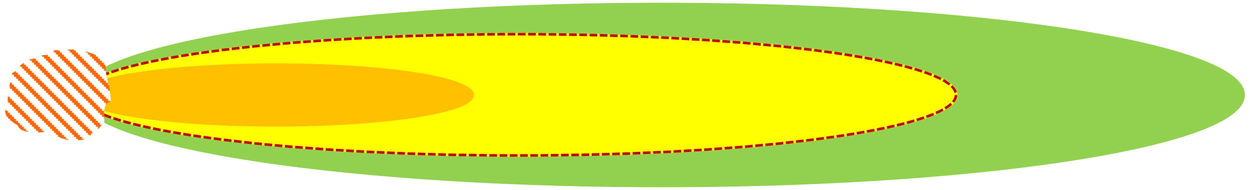
Mass flux for risk assessment

Concentration are only representative at the receptor
Not in the aquifer before the receptor

High concentration in clay aquitard



Low concentration in sand aquifer...



Mass flux for risk assessment

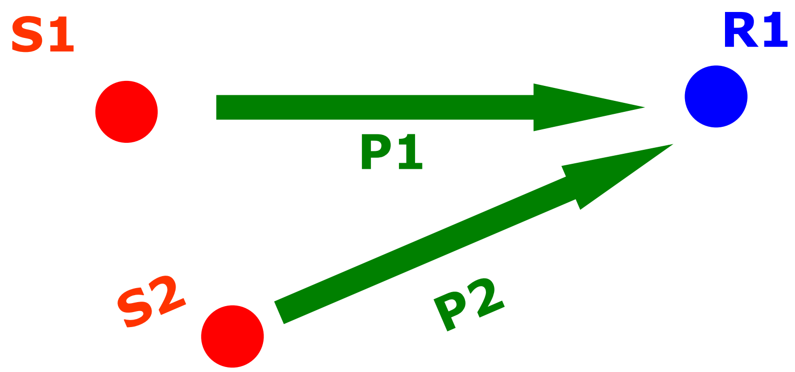
Need and evolution of the legislations

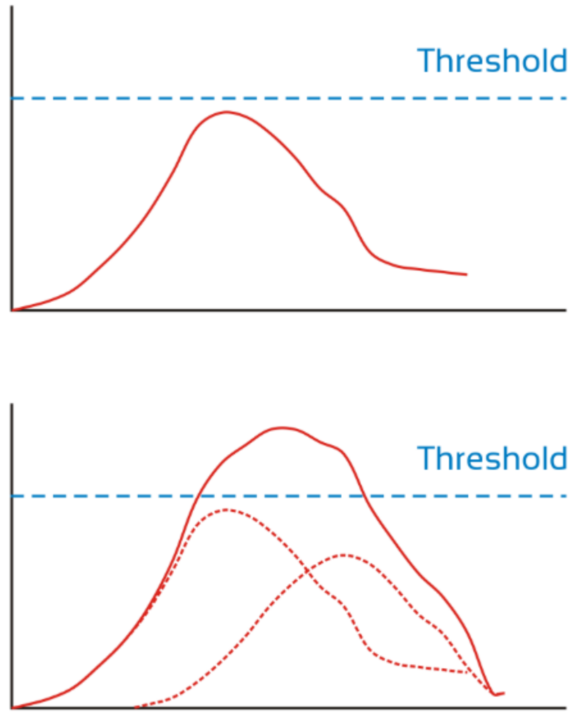
Austria defines threshold values and clean up targets in terms of mass discharge

Walloon Region is currently updating the guidelines to integrate mass fluxes approaches

Mass flux for risk assessment

Additivity of sources



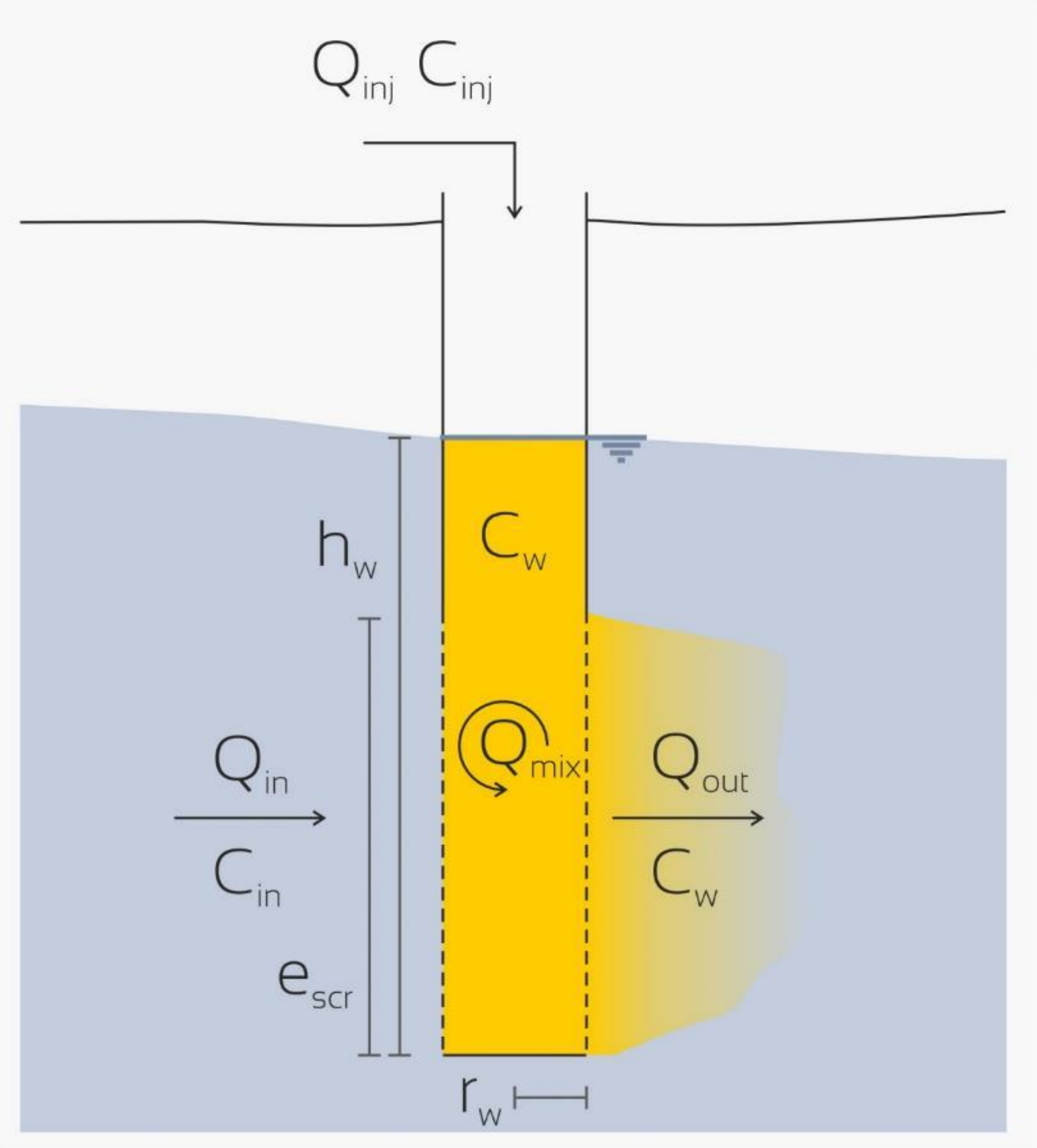


FVPDM tracer mass balance in well

Natural flow
$Q_{in} = Q_{out} = Q_t$

During FVPDM, tracer injection
$Q_{out} = Q_{in} + Q_{inj}$

$$Q_{in} = Q_t \sin\left(arcos\left(\frac{Q_{inj}}{\pi Q_t}\right)\right) - \frac{Q_{inj}}{\pi} arcos\left(\frac{Q_{inj}}{\pi Q_t}\right)$$

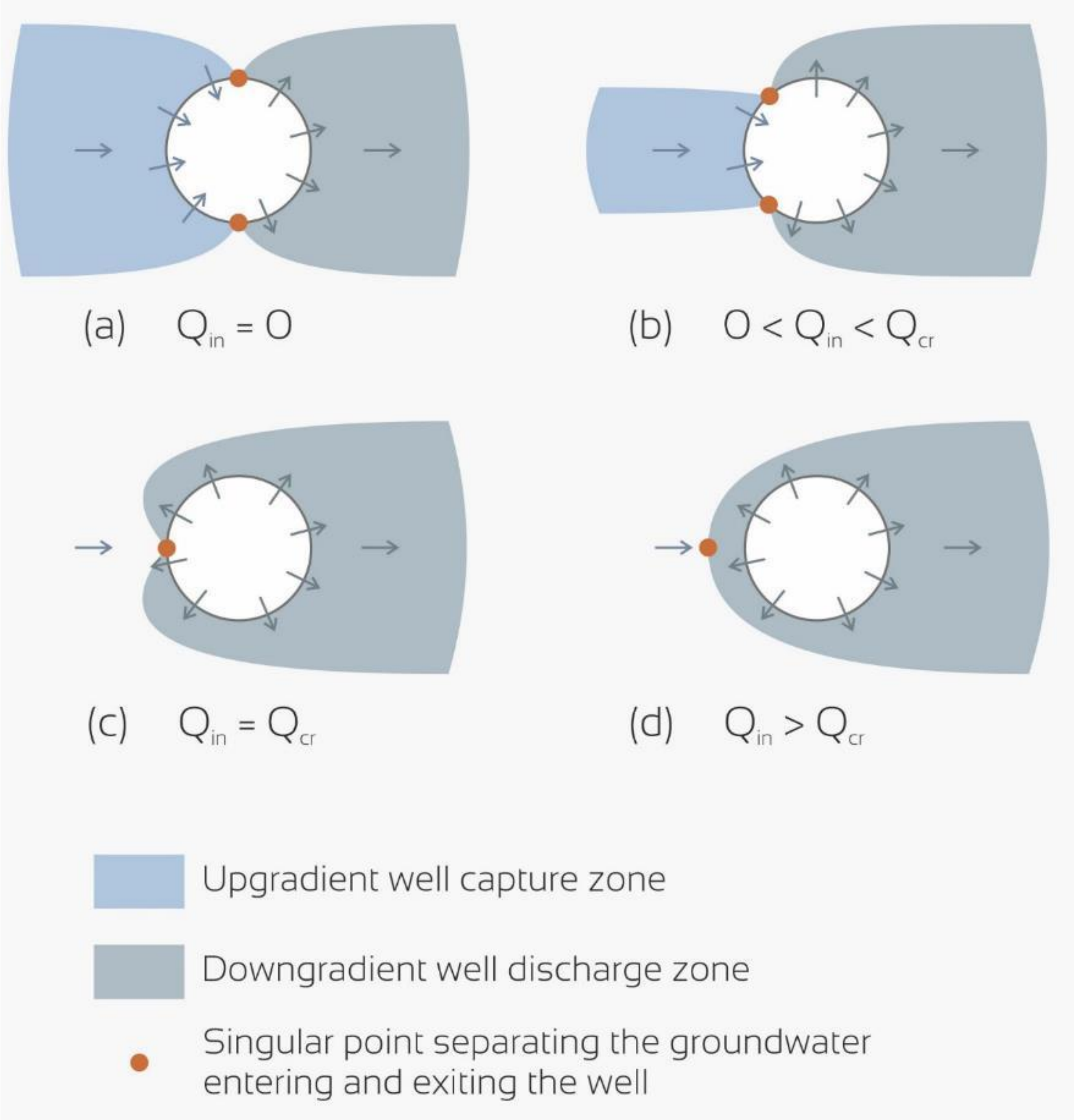


FVPDM critical injection flow rate

Q_{inj} always $< Q_{cr}$

Otherwise radial divergent flow that cancels the transit flow rate

$Q_{cr} = \pi Q_t$



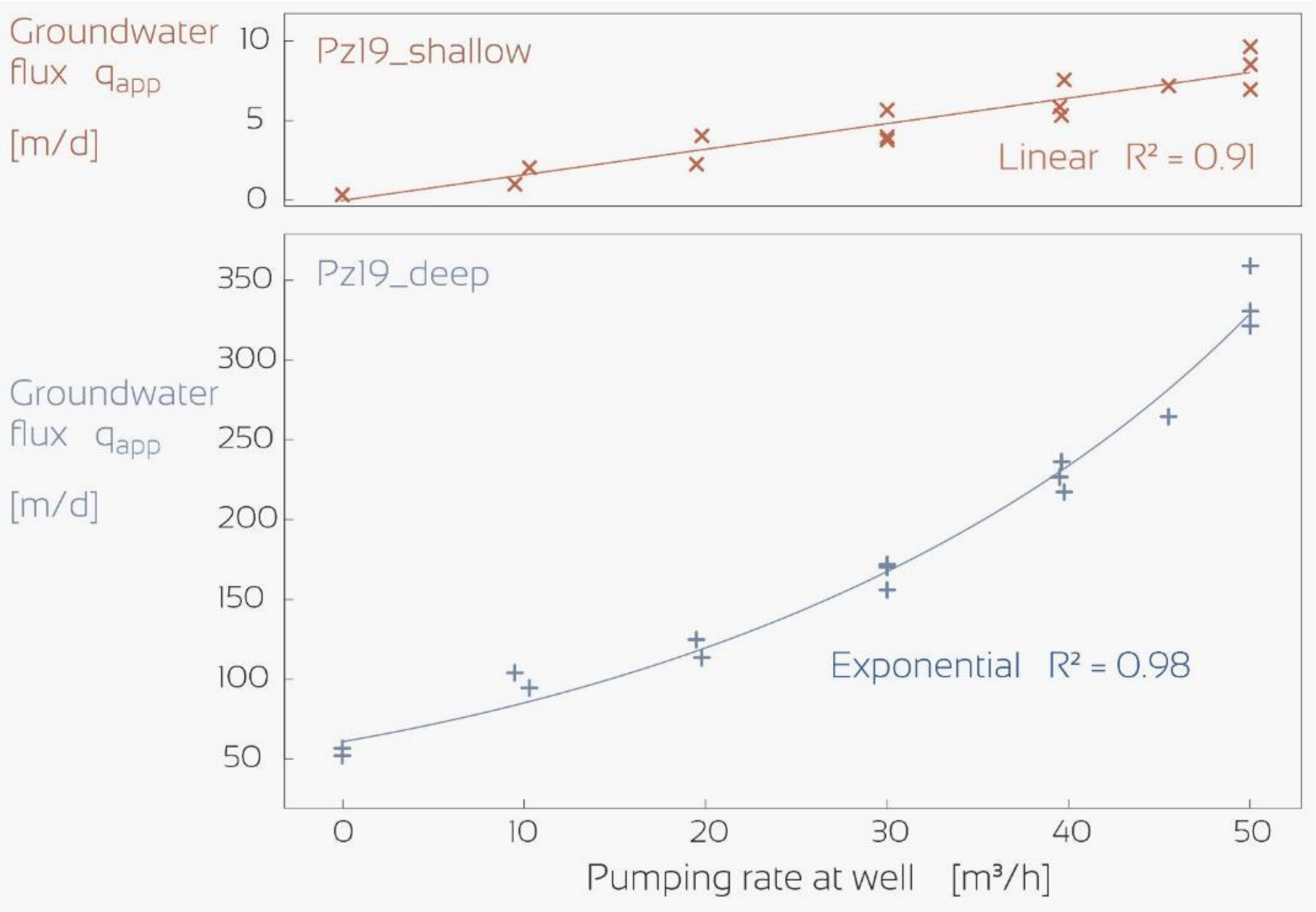
Imperfect mixing

$Q_{mix} >>> Q_t$

Example of Burkina Faso

Example of HssA

Q_{mix} is a parameter of the experimental setup that needs a proper dimensioning

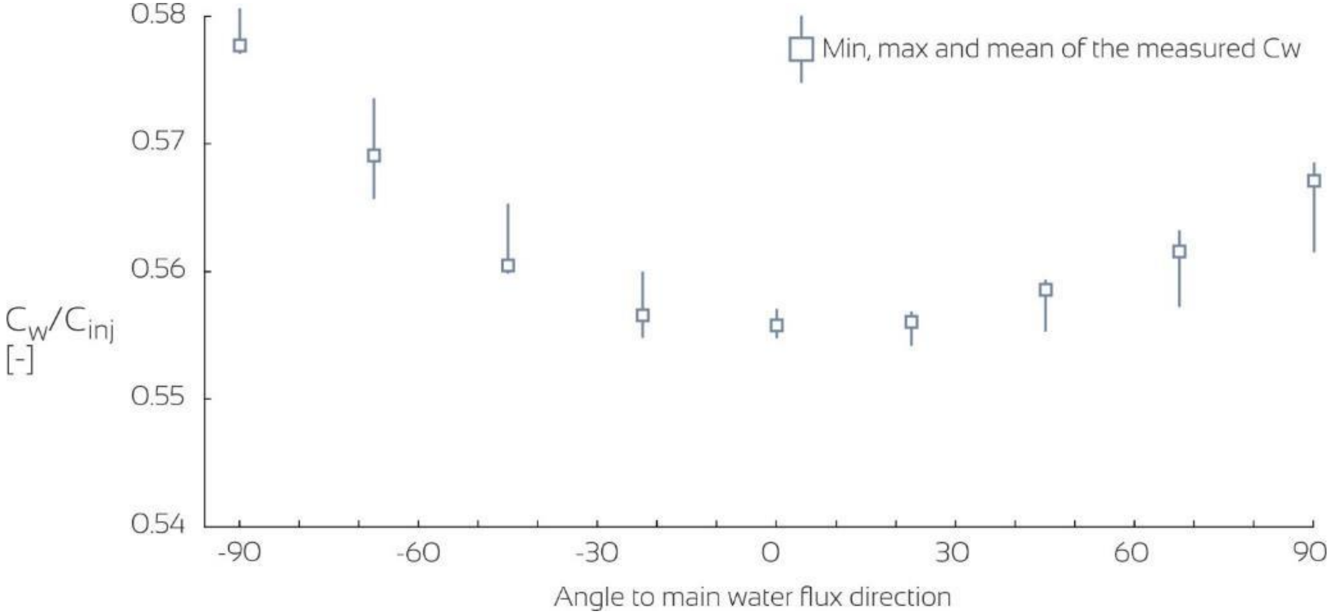


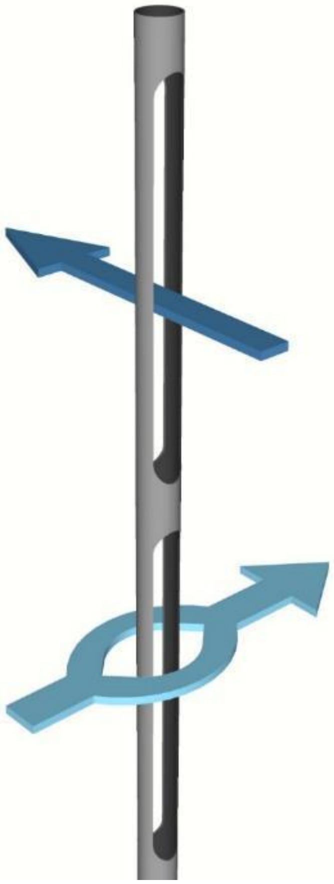
Direction of groundwater flow

Cw/Cinj seems a small variation

But in terms of what I measured it was a difference of 40 mV with a detector resolution of 0.1 mV

Limited to shallow wells
Limited to radially screened wells



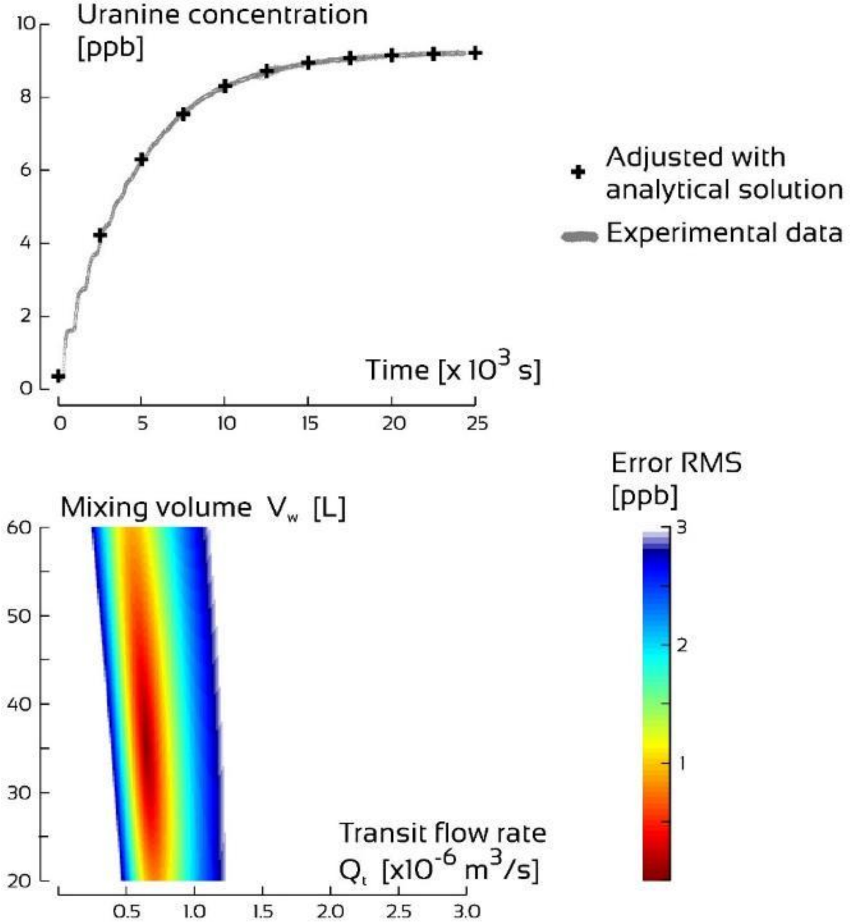


FVPDM vs PDM

FVPDM : Unique solution

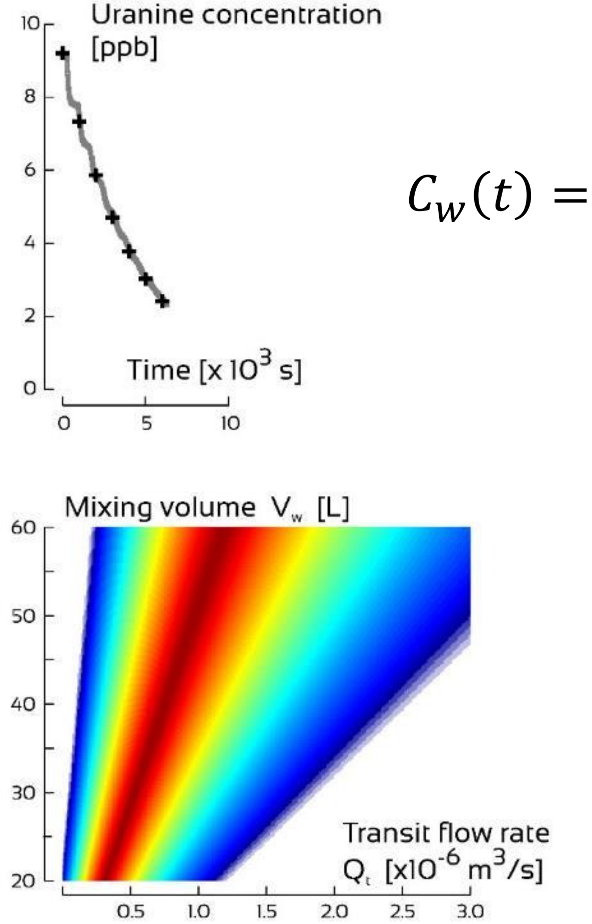
Q_t = 0.45 L/min

V_w = 35 L



PDM : Unfinite couples [Q_t, V_w]

as long as Q_t/V_w satisfies the PDM equation



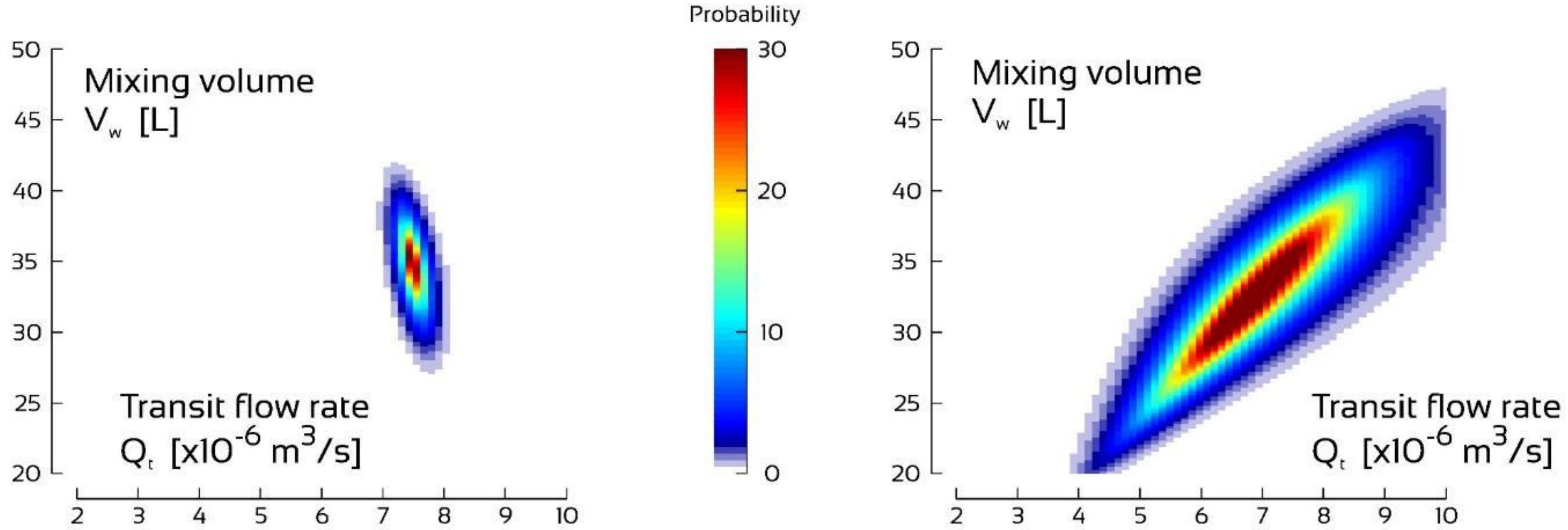
$$C_w(t) = C_{w,0} \cdot e^{-\frac{Q_t}{V_w}\cdot(t-t_0)}$$

FVPDM vs PDM

Integration of the external estimation of Vw = 32 ± 5L

PDM precision depends on the precision on Vw

	FVPDM	PDM
Q_t [L/min]	0.45 ±0.02	0.41 ±0.12
V_w [L]	34.0 ±4.4	32.2 ±7.9

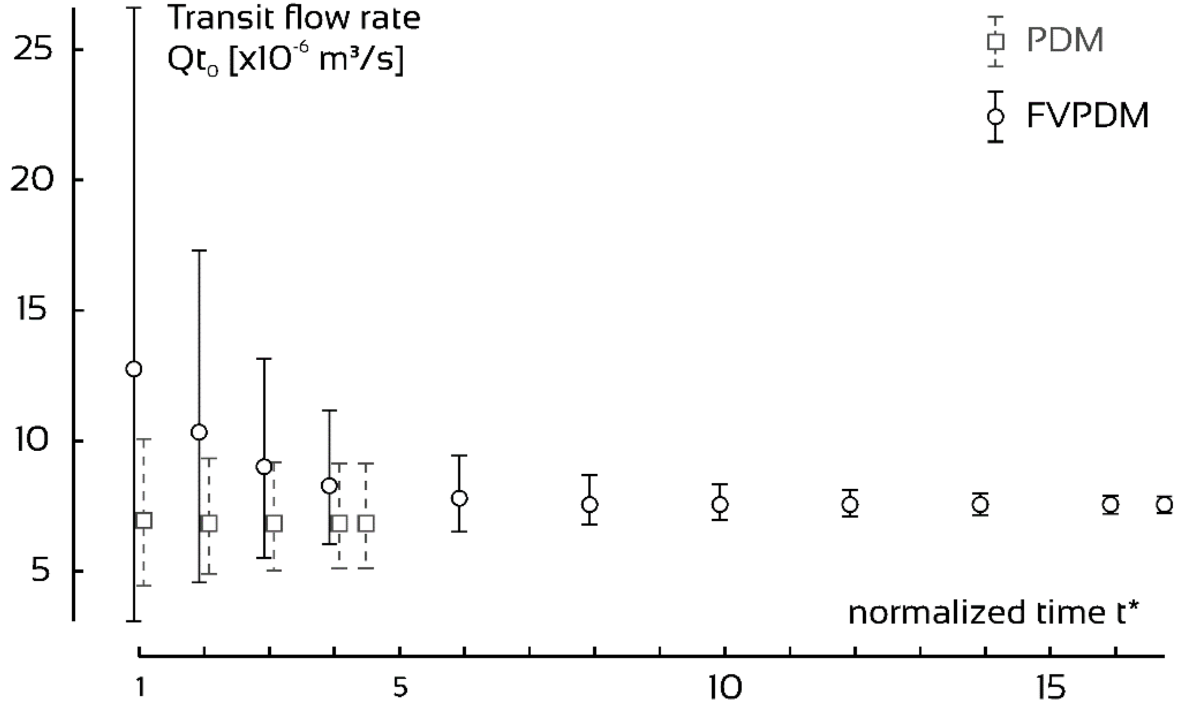


FVPDM vs PDM

Uncertainty evaluation repeated using restricted number of data

Necessary to normalize time to take into account the difference of groundwater flow

FVPDM is more precise from 5t* (in this case 2 hours)



$$t^* = \frac{V_w}{\pi\, Q_t}$$

High groundwater flux at HssA test site

K = 10^{-2} m/s to locally 10^{-1} m/s

Hydraulic gradient controlled by the Canal and the River Meuse

360 m/d is apparent in well groundwater flux with flow distortion coefficient = 3.4

Aquifer Darcy flux is around 100 m/d still high (overestimated due to $Q_{mix}<Q_t$)

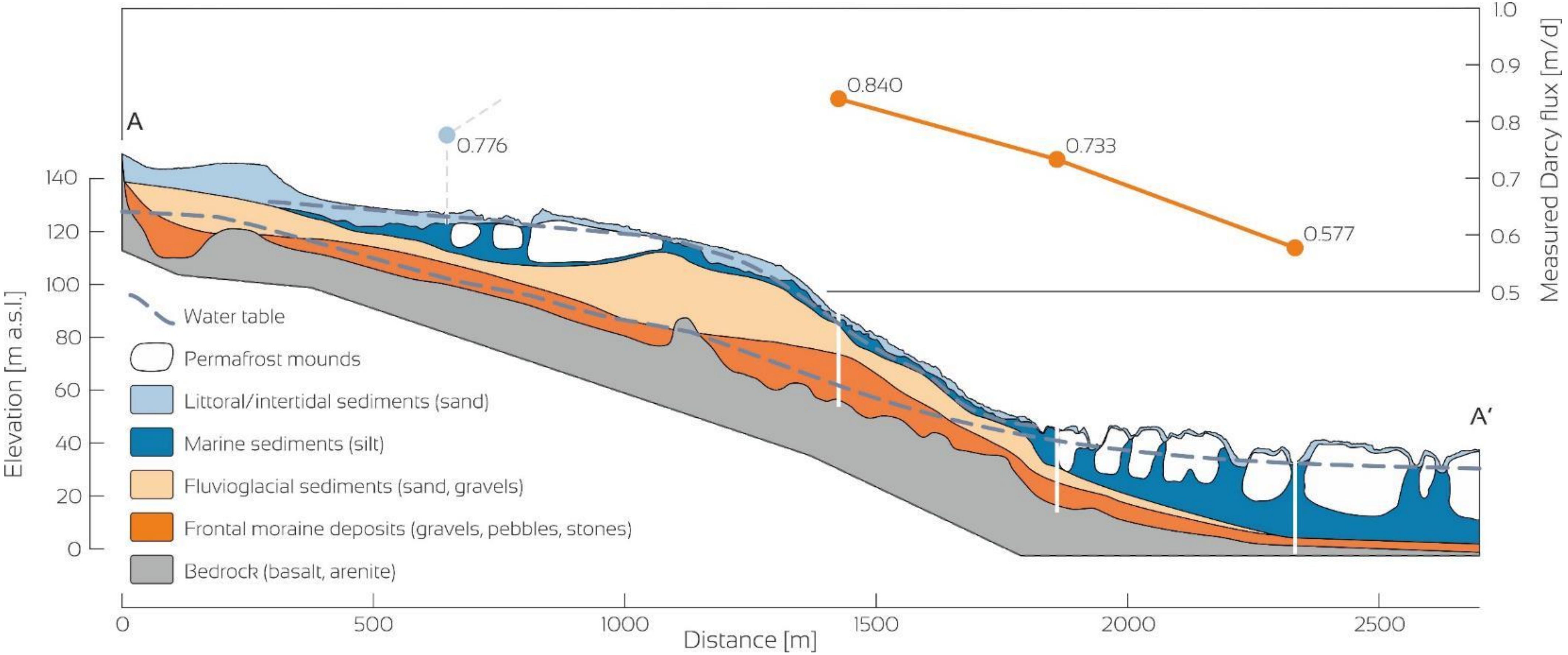
Using Darcy law and hydraulic gradient during pumping 6 to 60 m/d

Effective porosity is 4%,	Velocity is 2500 m/d (distance to well 7m, 50m^3/h)
Tracer test in 2012,	Velocity was 120 m/d (distance to well 20m, 30m^3/h)

Umiujaq groundwater flux results

Only 5 piezometers on the whole watershed

Not aligned along flow path



Time to reach Cw stab

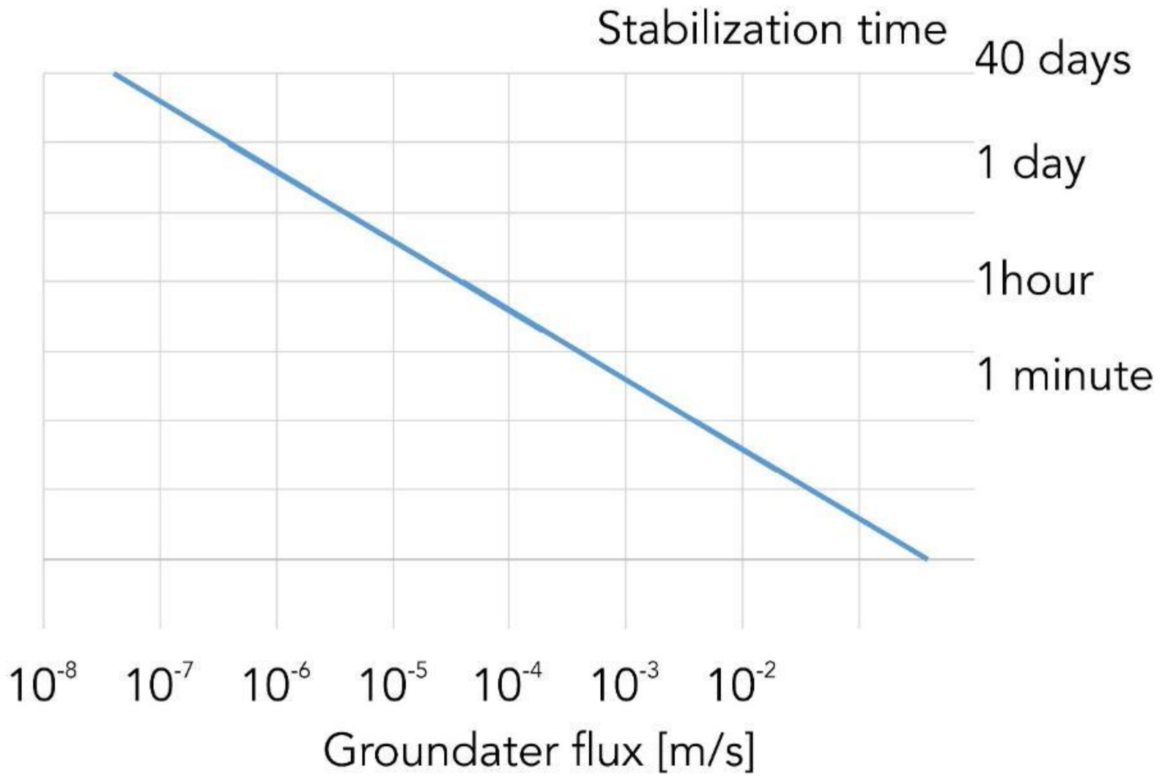
Guarantee the full precision of the method

Typical alluvial plain monitoring well

10m deep

5m screen

2 inches

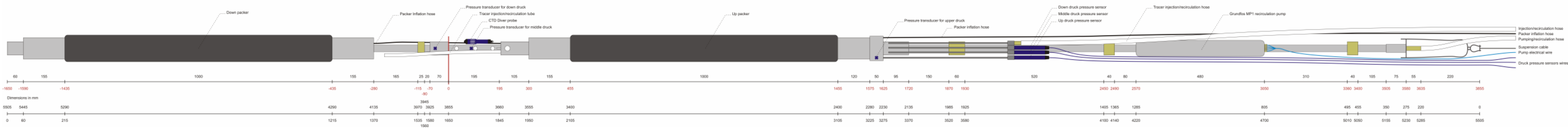


FVPDM setups

Choice of pumps (stable flow rate)

Gaining experience with dimensioning

Plumbing…

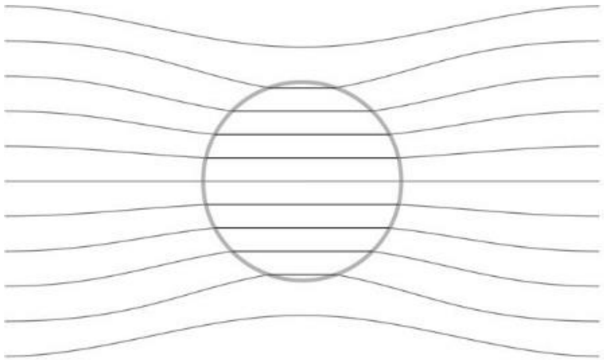


Double packer configuration for FVPDM, PDM, push-pull and convergent test for june 2012 experiments on Stang er Brune

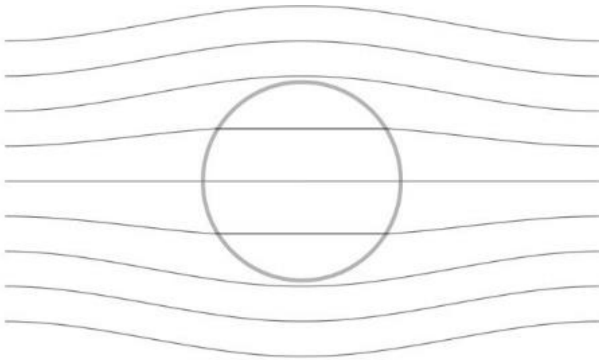
Flow field distortion

Estimation with formula or modelling

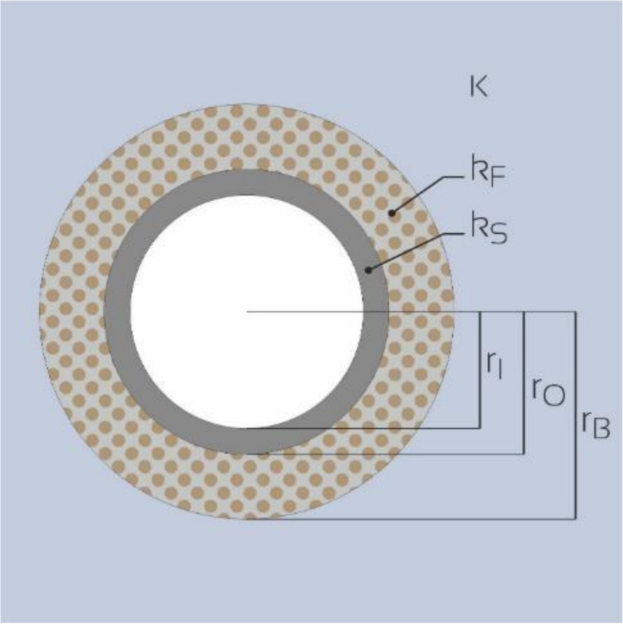
In this work 2.45 to 3.5



$\alpha_W > 1$



$\alpha_W < 1$



$$\alpha_w = \frac{q_{app}}{q_D} = \frac{8}{\left(1+\frac{K}{k_F}\right)\left(\left(1+\left(\frac{r_I}{r_O}\right)^2\right)+\frac{k_F}{k_S}\left(1-\left(\frac{r_S}{r_B}\right)^2\right)\right)+\left(1-\frac{K}{k_F}\right)\left(\left(\frac{r_I}{r_B}\right)^2+\left(\frac{r_O}{r_B}\right)^2\right)+\left(\frac{k_F}{k_S}\right)\left(\left(\frac{r_I}{r_B}\right)^2-\left(\frac{r_O}{r_B}\right)^2\right)}$$