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HEAT TRANSFER CHARACTERIZATION USING HEAT AND SOLUTE TRACER TESTS IN A SHALLOW ALLUVIAL AQUIFER

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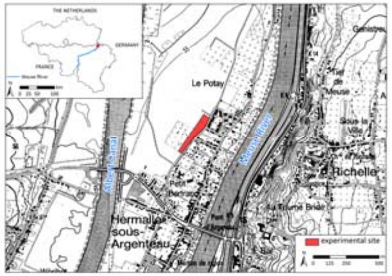
Context, objectives, methodology

Innovative and efficient strategies for renewable energy
Shallow groundwater widely available for local cooling/heating systems.

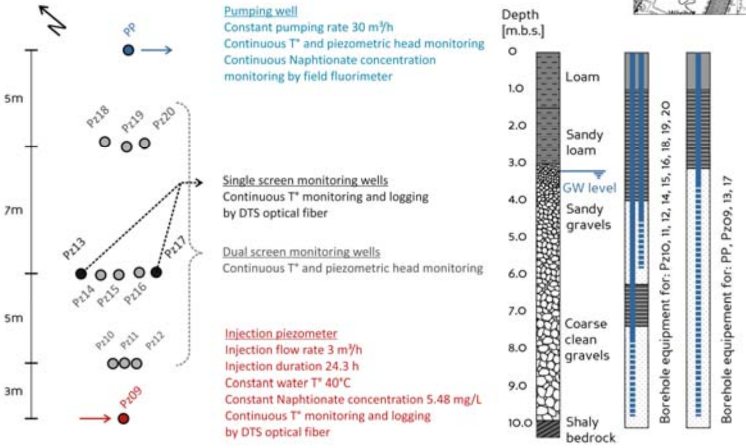
TO BE IMPROVED: Relevant dimensioning for efficiency of the HP system and impact study for preserving groundwater resource quantity and quality

- few techniques are available to quantify the **subsurface heat transfer parameters** and most of them rely on simplistic empirical laws (like the well-known “TRT” thermal response test that can gives Thermal Conductivity of the subsurface media)
- objective was to find alternative field experiments that can improve the estimation of these heat transfer parameters
- methodology we propose is to perform a tracer test with heat. The idea is to inject hot water into an aquifer, and to monitor temperature at a series of piezometers located down gradient. The particularity is here that a dye tracer is injected simultaneously with the heat. This double tracer test allows a direct comparison of heat and solute transport in the subsurface.

Test site and experimental setup



- alluvial deposits with loam near the surface until 1.5 meter and then gravels that becomes increasingly coarse and depleted in sand with depth. The shaly bedrock is found around 10 m below surface and constitutes the basement of the alluvial aquifer.
- groundwater level is 3 meter below surface and the groundwater flow is directed to the North East.
- double-screened piezometers installed with and upper screen located in the fine sandy gravels and a lower screen in the coarse gravels.



Pumping well
Constant pumping rate 30 m³/h
Continuous T° and piezometric head monitoring
Continuous Naphtionate concentration monitoring by field fluorimeter

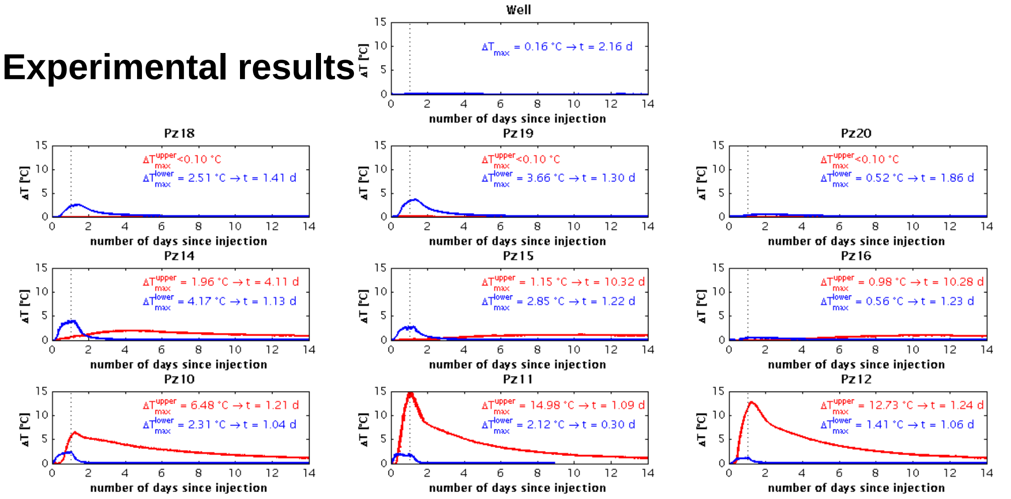
Single screen monitoring wells
Continuous T° monitoring and logging by DTS optical fiber

Dual screen monitoring wells
Continuous T° and piezometric head monitoring

Injection piezometer
Injection flow rate 3 m³/h
Injection duration 24.3 h
Constant water T° 40°C
Constant Naphtionate concentration 5.48 mg/L
Continuous T° monitoring and logging by DTS optical fiber

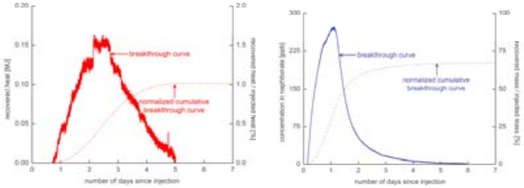
WILDEMEERSCH S., JAMIN P., ORBAN Ph., HERMANS T., NGUYEN F., BROUYERE S. & DASSARGUES A., 2013, Coupling heat and chemical tracer experiments for estimating heat transfer parameters in shallow alluvial aquifers, Submitted to *Journal of Contaminant Hydrology*

Experimental results



- Blue curves: heat transfer is mainly convective in the lower zone (gravels)
- Red curves: heat transfer is mainly conductive/dispersive in the upper zone (sands).
- Temperatures evolution varies from one piezometer to another demonstrating subsurface heterogeneity and the highest changes in temperatures aren’t necessary observed in the central piezometers.

Naphtionate vs T°



Heat more dissipated in the saturated porous medium than solute …
due to thermal diffusivity (thermal conduction + heat capacity)

Processes equations

$$\frac{\kappa_e}{\rho_m \times c_m} \times \nabla^2 T - \frac{\rho_w \times c_w}{\rho_m \times c_m} \times \nabla . (T \times ve) = \frac{\partial T}{\partial t}$$

ρ_w = density of the water [kg/m³],
c_w = specific heat capacity of the water [J/kg/K]
ρ_m = density of the saturated porous medium [kg/m³]
c_m = specific heat capacity of the saturated porous medium [J/kg/K]
ve = effective velocity [m/s]

$$\frac{\kappa_e}{\rho_m \times c_m} = \frac{n \times \kappa_w + (1-n) \times \kappa_s}{n \times \rho_w \times c_w + (1-n) \times \rho_s \times c_s} + \alpha^* \times |ve| = \frac{\kappa_0}{\rho_m \times c_m} + \alpha^* \times |ve|$$

$\rho_m \times c_m$ = volumetric heat capacity of the saturated porous medium [J/m³/K]
κ_w and κ_s = thermal conductivity for water and solids [W/m/K]
$\rho_w \times c_w$ and $\rho_s \times c_s$ volumetric heat capacity of the water and solids [J/m³/K]
α^* = thermal dispersivity [m]
κ_0 = effective thermal conductivity of the saturated porous medium [W/m/K]
$\frac{\kappa_0}{\rho_m \times c_m}$ thermal diffusivity …far more important than molecular diffusion in solute transport

First interpretations

Energy balance

$$\dot{M}_{inj} \times c_w \times T_{inj} + (\dot{M}_{ext} - \dot{M}_{inj}) \times c_w \times T_0 - \dot{M}_{ext} \times c_w \times T_{ext} - \underbrace{\dot{Q}_{lost}} = \underbrace{M_m} \times \underbrace{c_m} \times \frac{dT_m}{dt}$$

unknowns

$\dot{M}_{inj}$ = mass rate of water injected into the aquifer [kg/s],
c_w = specific heat capacity of water [J/kg/K],
T_{inj} = temperature of injected water [K],
$\dot{M}_{ext}$ = mass rate of water abstracted from the aquifer [kg/s],
T_0 = initial temperature of groundwater [K],
T_{ext} = temperature of abstracted groundwater [K],
$\dot{Q}_{lost}$ = lost energy flux [J/s], M_m = mass of saturated porous medium [kg],
c_m = specific heat capacity of the saturated porous medium [J/kg/K],
$T_m \approx T_{ext}$ = temperature of saturated porous medium [K]

→ $\dot{Q}_{lost}$ estimated when measured steady state T° plateau reached after 51 h

volumetric heat capacity of the saturated porous medium: $C_m = \frac{M_m \times c_m}{V_m}$

C_m is estimated to 2.47 MJ/m³/K

TRAC (Analytical solution, BRGM))

→ Analogies between solute transport and heat transfer processes allows defining the retardation factor for heat as (Hecht-Méndez et al., 2010): $R = \frac{C_m}{n \times C_w}$

$C_m = \rho_m \times c_m$ = volumetric heat capacity of the porous medium (total phase)
$C_w = \rho_w \times c_w$ = volumetric heat capacity of the water (porous phase)

→ C_m = 2.30 MJ/m³/K

→ indeed, for heterogeneity analysis we need a spatially distributed model

	Naphtionate	Temperature
Longitudinal dispersion (α_L) [m]	3	
Effective porosity (ne) [-]	0.04	
1st order degradation coefficient λ [s^{-1}]	1.5×10^{-5}	0
Retardation factor R [-]	1	5

Conclusions/perspectives

- **improving understanding of heat transfer in a highly heterogeneous and relatively stratified shallow alluvial aquifer**
- **heat transfer is conduction-dominated in the upper part of the aquifer and convection-dominated in the lower part**
- **highly dependent on the specific heat capacity of the saturated porous medium**
- **values of specific heat capacity estimated between 2.3 and 2.5 MJ/m3/K**
- **data gathered potentially contain enough information for deducing the entire set of heat transfer parameters as well as their spatial distribution (requiring developing a full numerical model)**

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