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GROUNDWATER MANAGEMENT AND GOVERNANCE
COPING WITH WATER SCARCITY

Geothermal use of old flooded mines: from a risky trial-and-error approach towards challenging predictive simulations

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The underground… a source of energy

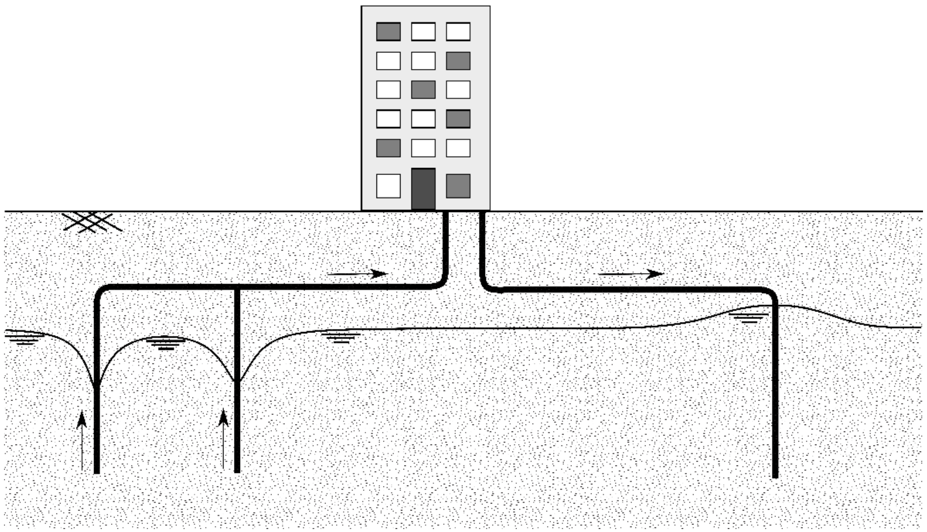
Low temperature geothermal energy is one of the source of green energy for cooling and heating systems.

Open loop geothermy

- *High heat capacity of water*
  → *nice for high power demand*
- *P proportional to the water flow*
  → *large pumping rate needed*

BUT needs an aquifer and consequently hydrogeological investigations

(Wildemeersch et al. 2014, Hermans et al. 2015, Klepikova et al. 2016)



Producing thermal energy with a heat pump, the power P (in W) :

$$P = P_{gw} / \left(1 - \frac{1}{COP}\right)$$

$$\Rightarrow P = \frac{Q \Delta T \rho_w c_w}{\left(1 - \frac{1}{COP}\right)}$$

(Stauffer et al. 2014))

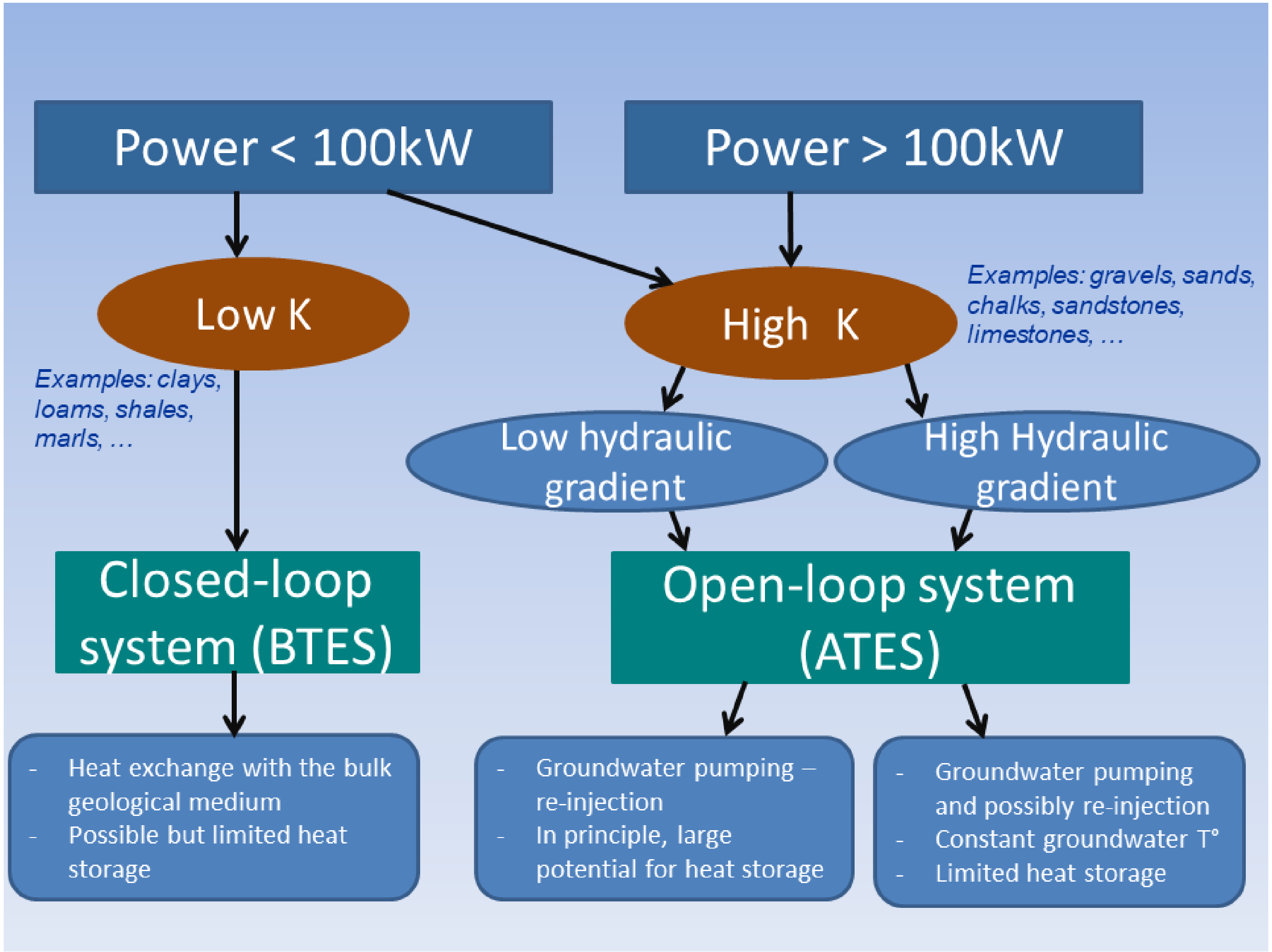
COP = coefficient of performance of the heat pump equal to the ratio between the useful produced thermal work (heating or cooling) and the required (electrical) work

Q = flow rate of the heat transfer fluid in the heat pump (m^3/s)

ΔT = temperature difference between the upstream and downstream of the heat pump (°K)

c_w the *water heat capacity* in J/(kg°K)

Open shallow geothermal systems need hydrogeological studies



(Eppelbaum et al. 2014, Dassargues 2018)

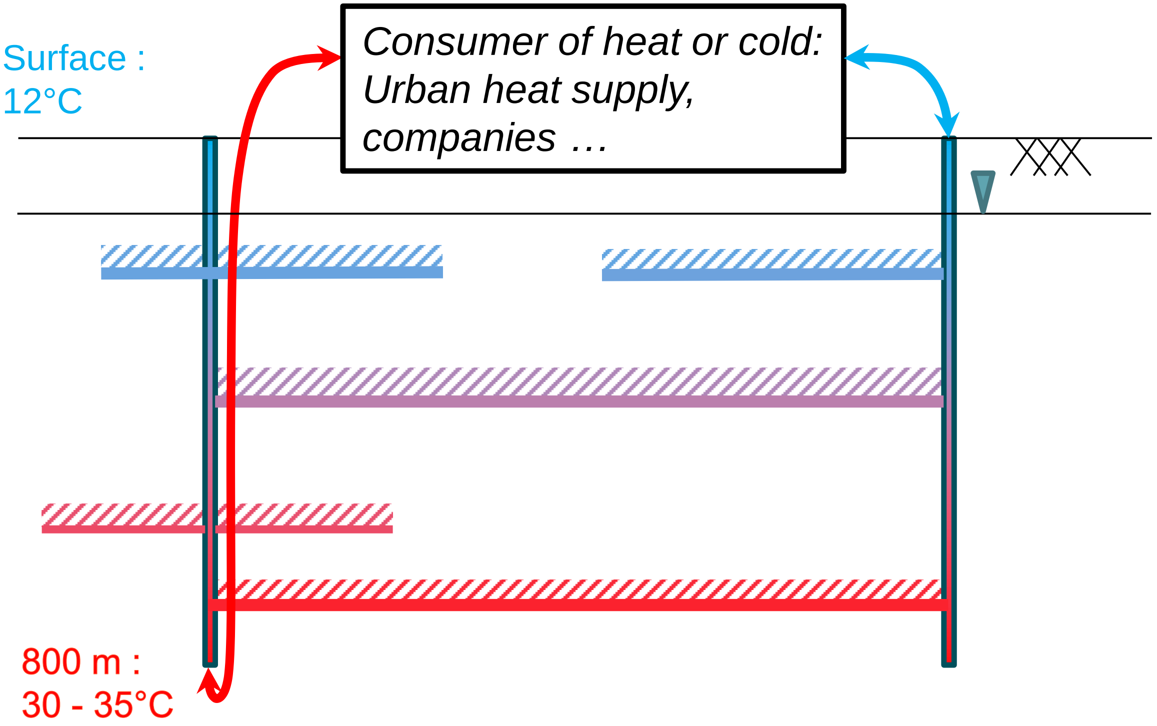
… for efficiency and impact assessment

Old flooded mines increasingly considered for low-enthalpy geothermal exploitation

But: *networks of interconnected shafts, galleries and exploited panels*
often the true geometry can be highly complex

Large voids
→ possible to pump with high flow rate

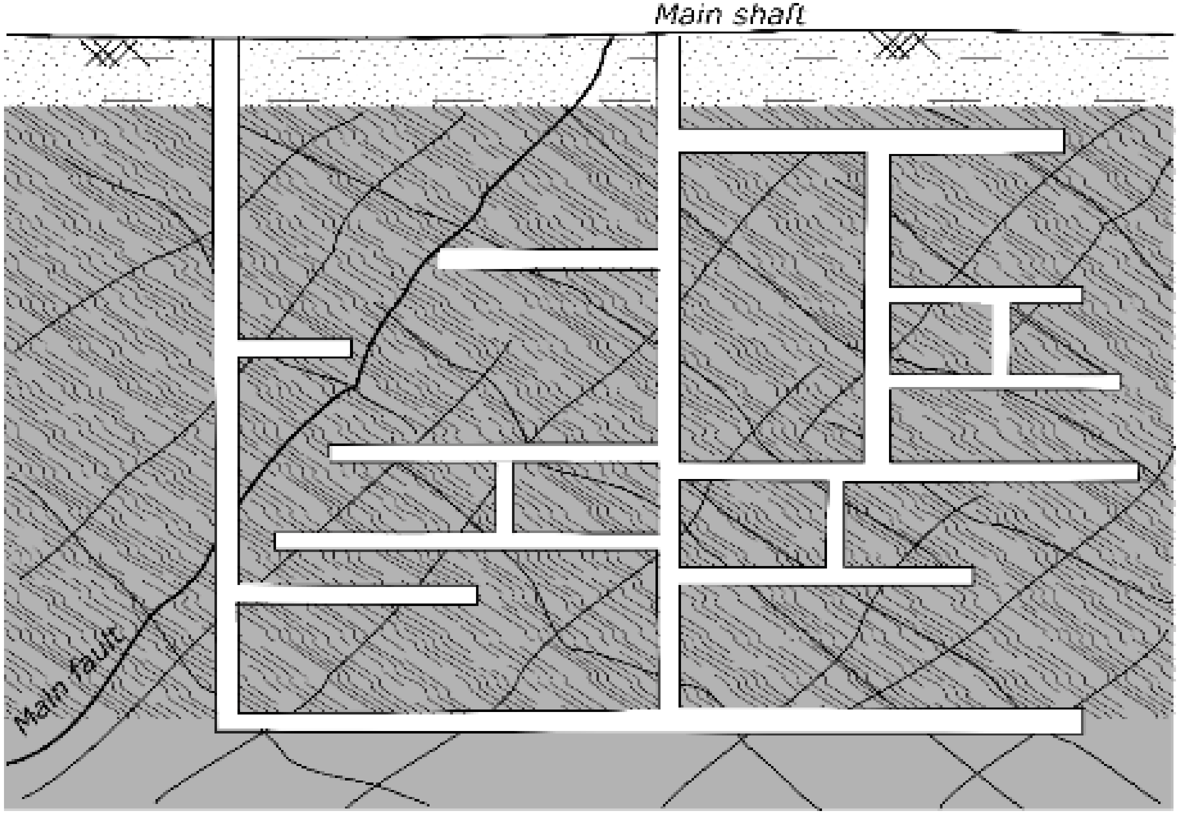
- *geothermal gradient*
  → warm and cold water
- *groundwater of poor quality, few conflicts with other uses*



Old flooded mines increasingly considered for low-enthalpy geothermal exploitation

But: *networks of interconnected shafts, galleries and exploited panels*
often the true geometry can be highly complex

- ***enhanced hydraulic conductivity values of the rock formations due to old works***
- ***high-velocity water flow expected in the shafts and galleries network, while low-velocity groundwater flow in the rock formations***

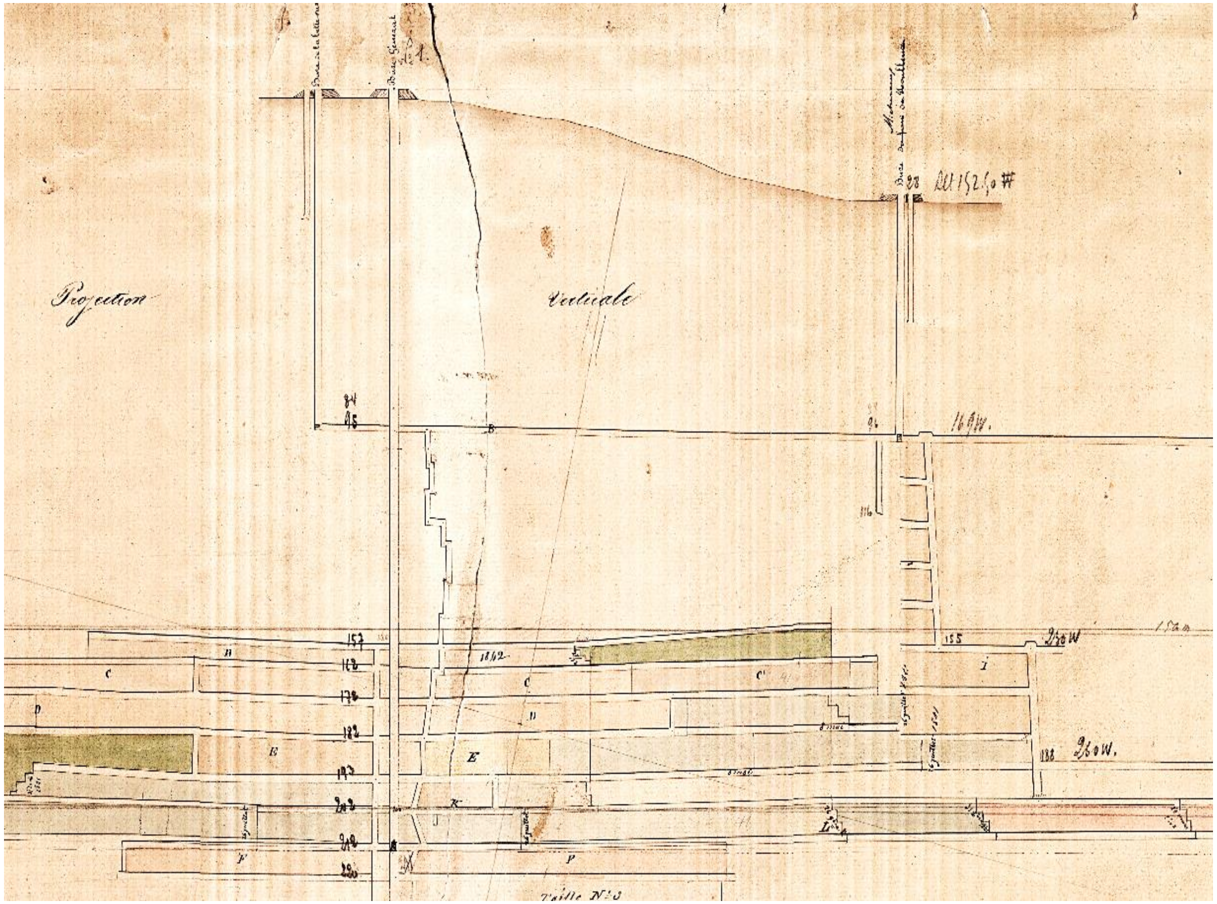


(Dassargues 2018)

Old flooded mines increasingly considered for low-enthalpy geothermal exploitation

But: *networks of interconnected shafts, galleries and exploited panels*
often the true geometry can be highly complex

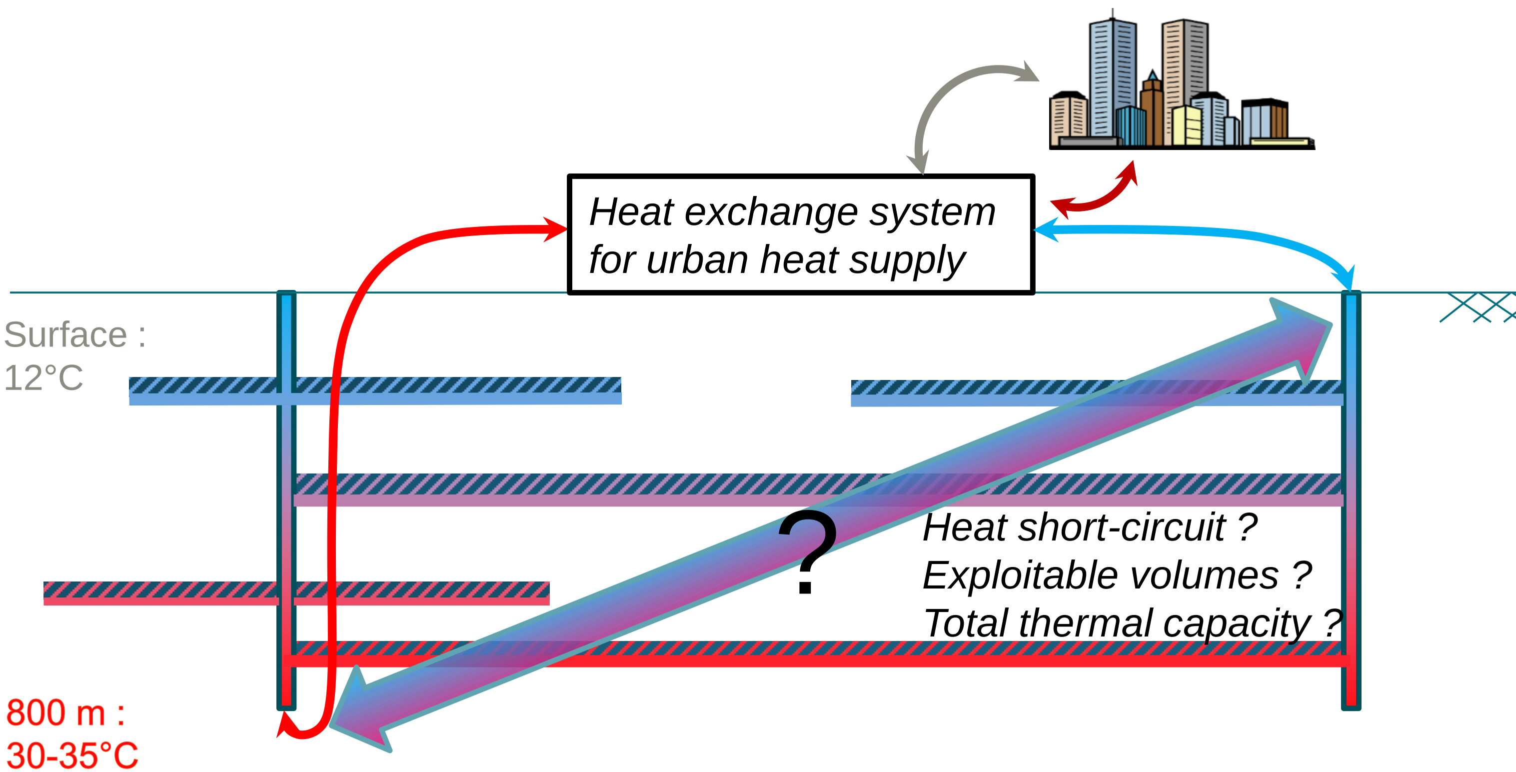
… and not so known !



Challenges

1) in a shaft, temperature evolution influences convection produced by buoyancy forces (i.e. cold water is more dense than warm water)

(Hamm and Bazargan Sabet 2010).



2) 'pipe-like' flow and heat transfer in the open galleries and shaft to be coupled to groundwater flow and heat transfer in the fractured rock formations

Challenge 1: thermal convection in shafts

Effect of the injection of cold water inside a vertical shaft induces mixing as cold water is denser than warm water

but on the contrary, deep groundwater can be more salted than shallow groundwater partial mitigation of the buoyancy contrast resulting from temperature changes

In a water column (i.e., without any porous or fractured medium) such as a well or a shaft, a Rayleigh dimensionless number is defined (Love et al. 2007)

$$Ra = \frac{g\beta(\Delta h)^3 \Delta T}{\nu\kappa}$$

β = *volumetric thermal expansion coefficient* (°K^{-1})
Δh = *the height of the water column in the shaft (m)*
ΔT = *the temperature difference between the bottom and top of the shaft (°K)*
ν = *the kinematic viscosity* (m^2/s)
κ = *the thermal diffusivity* (m^2/s)

a ratio between the natural convection and the thermal conduction (+ thermal dispersion, if not neglected)

Challenge 1: thermal convection in shafts

The critical value of Ra for the onset of natural convection in a vertical well or shaft mainly depends on the ratio between the well radius and the height of the water column

- $\delta = r/\Delta h$ *(Love et al. 2007, Hamm & Bazargan Sabet 2010)*

- $$Ra_c = \frac{215.6}{\delta^4}(1 + 3.84\,\delta^2)$$

- *more convenient to pump/inject groundwater through narrow wells (critical value is calculated for rigid impermeable walls: only slight changes -decreased- if a porous medium replaces the solid walls)* *(Love et al. 2007)*

Challenge 1: thermal convection in shafts

When advection is also considered, a mixed convection dimensionless number M (equal to the ratio Ra/Pe)

(Holzbecher and Yusa 1995, Graf and Simmons 2009)

$$M(T) = [\rho_{max} - \rho(T)] / \left[\rho(T)\frac{\partial h}{\partial z}\right]$$

$\frac{\partial h}{\partial z}$ = *vertical piezometric gradient.*

if M > 1 it is important to consider natural convection with regards to advection (forced convection)

$Pe = c_w \, q \, l/\lambda_b$ *= ratio between advection and thermal conduction (or thermal conduction + thermal dispersion if the latter is not neglected)*

(Huysmans & Dassargues 2005, Fox et al. 2016, Ma & Zheng 2010)

Challenge 2: 'heat short circuit'

Two approaches:

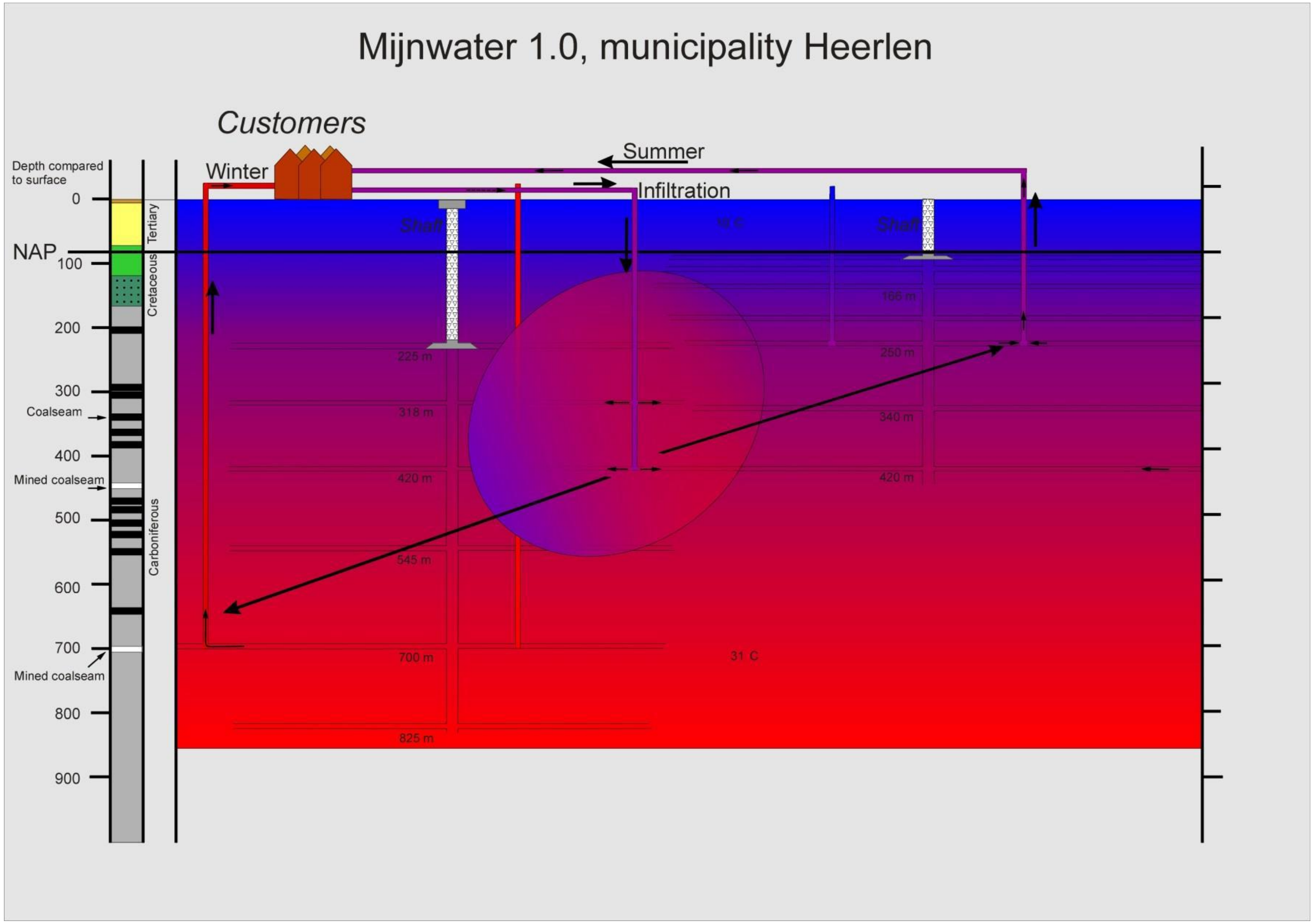
- *you don't mind: the trial and error approach*
- *coupled and complex simulations of flow and heat transport*

  *'pipe-like' flow and heat transfer in the open galleries and shaft **to be coupled** to groundwater flow and heat transfer in the fractured rock formations*

(Holzbecher and Yusa 1995, Graf and Simmons 2009)

Challenge 2: ‘heat short circuit’

If you don’t mind, you should be ready to adapt your energy system !



Challenge 2: ‘heat short circuit’

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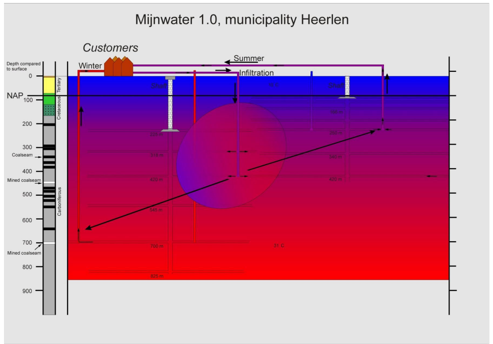
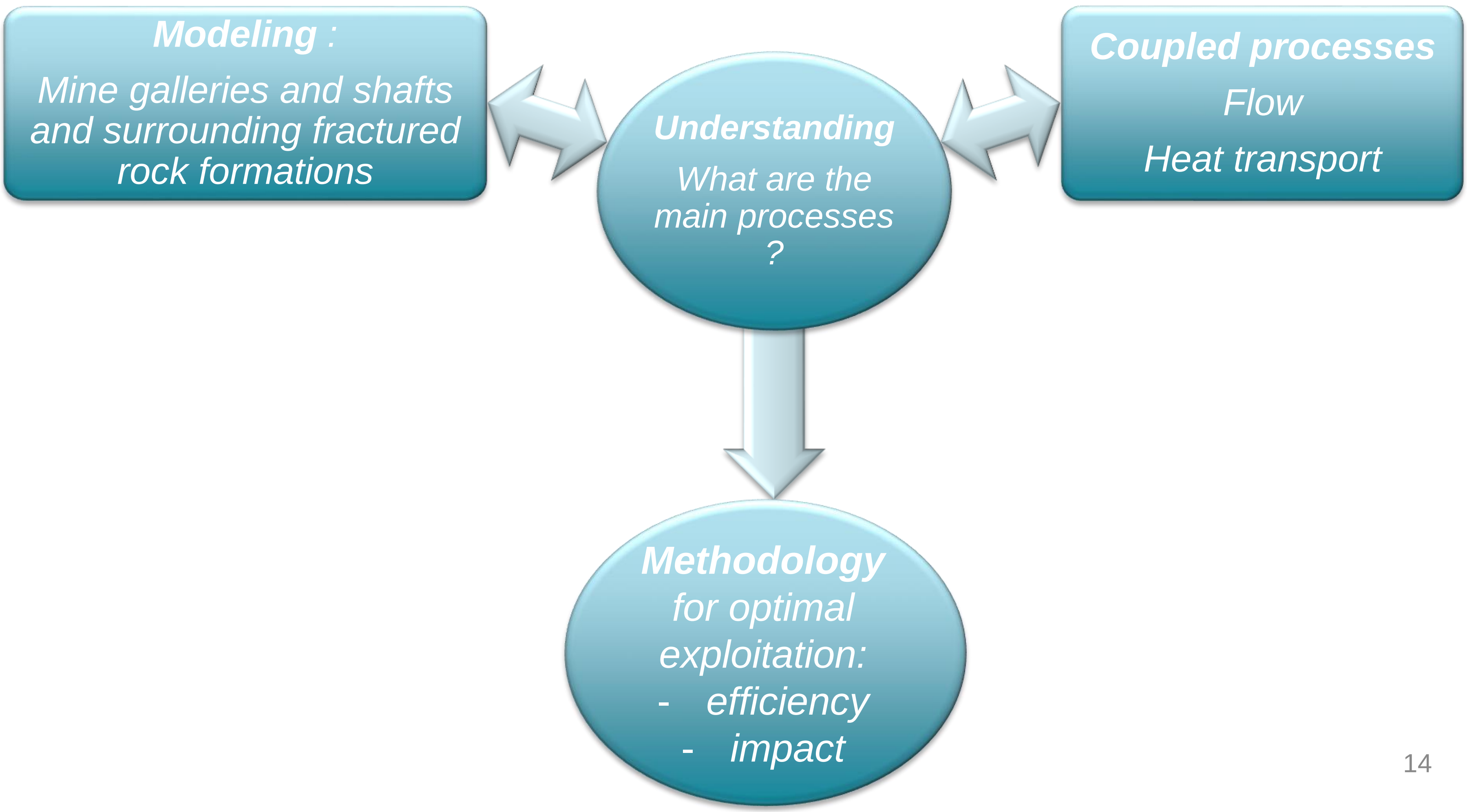


- ▶ *Minewater 1.0 (2008 – 2012)*
  - *Geothermy is a heat and cold source for urban supply*
  - *First (big) works: boreholes in 2006-2007 + heat pumps + pipe network*
- ▶ *Minewater 2.0 (2012 – 2017)*
  - *Geothermy is now used as a heat buffer*
  - *Users and energy producers (e.g. solar panels) clusters*
- ▶ *Minewater 3.0 (later)*
  - *Optimization of the grid*
  - *Use of predictive statistical methods, …*

Challenge 2: 'heat short circuit'

Second approach: coupled and complex simulations of flow and heat transport for prediction

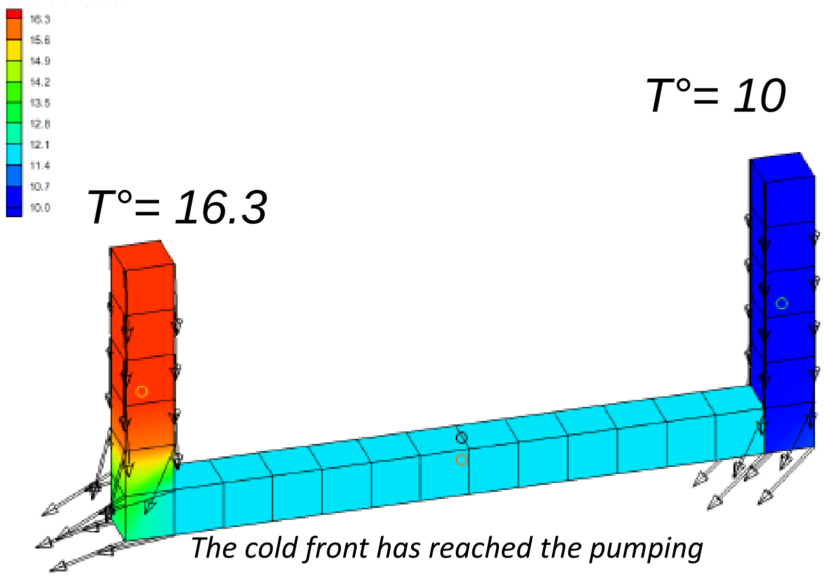


Challenge 2: ‘heat short circuit’

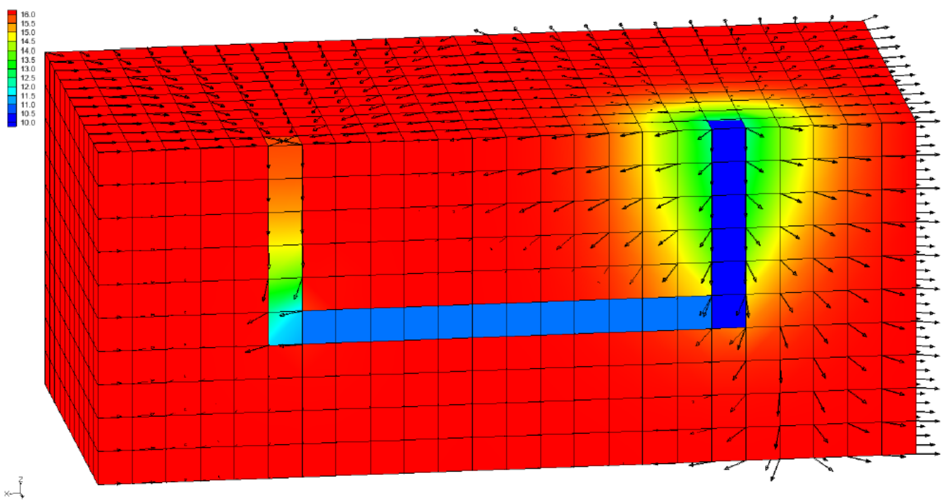
First results form MSc thesis of O. Vopat

… development of a coupled modeling approach

- *tests with linear reservoirs for the flow and heat transport in galleries and shafts*
- *+ the groundwater flow and heat transport in rock formations*



The cold front has reached the pumping

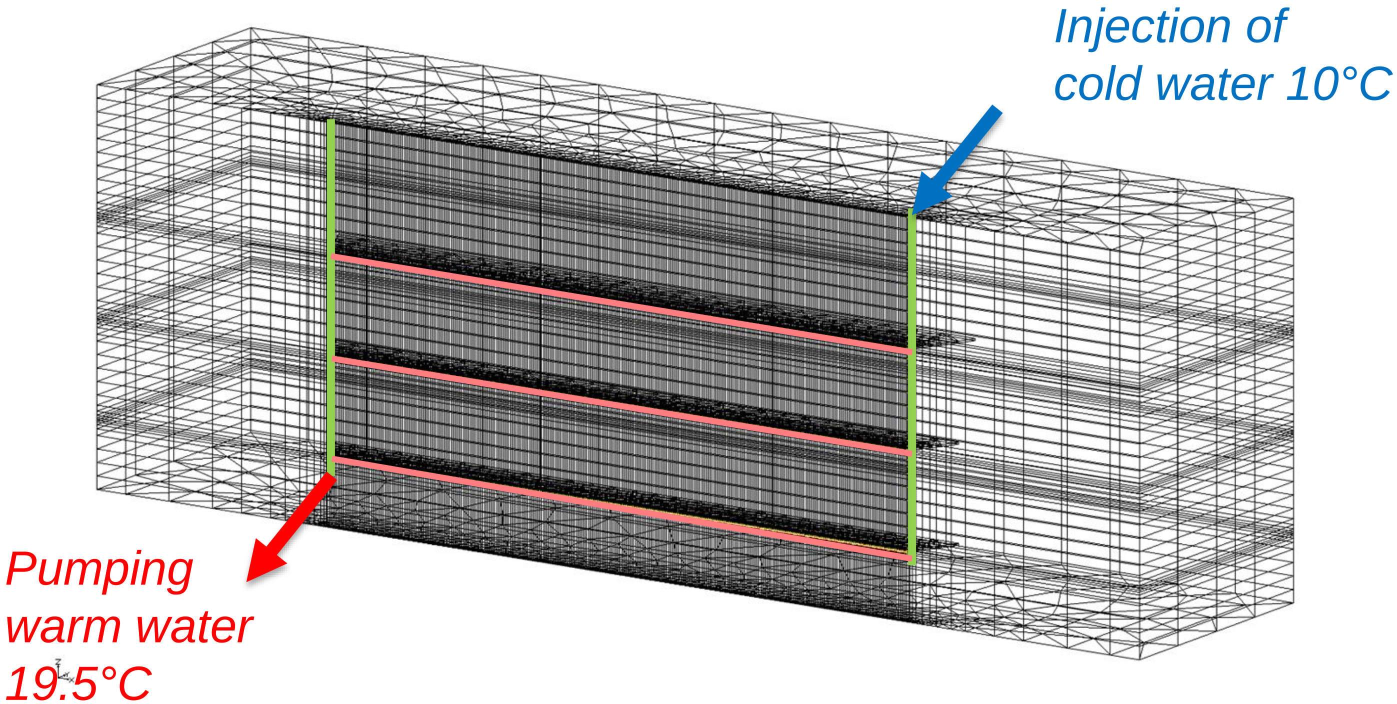


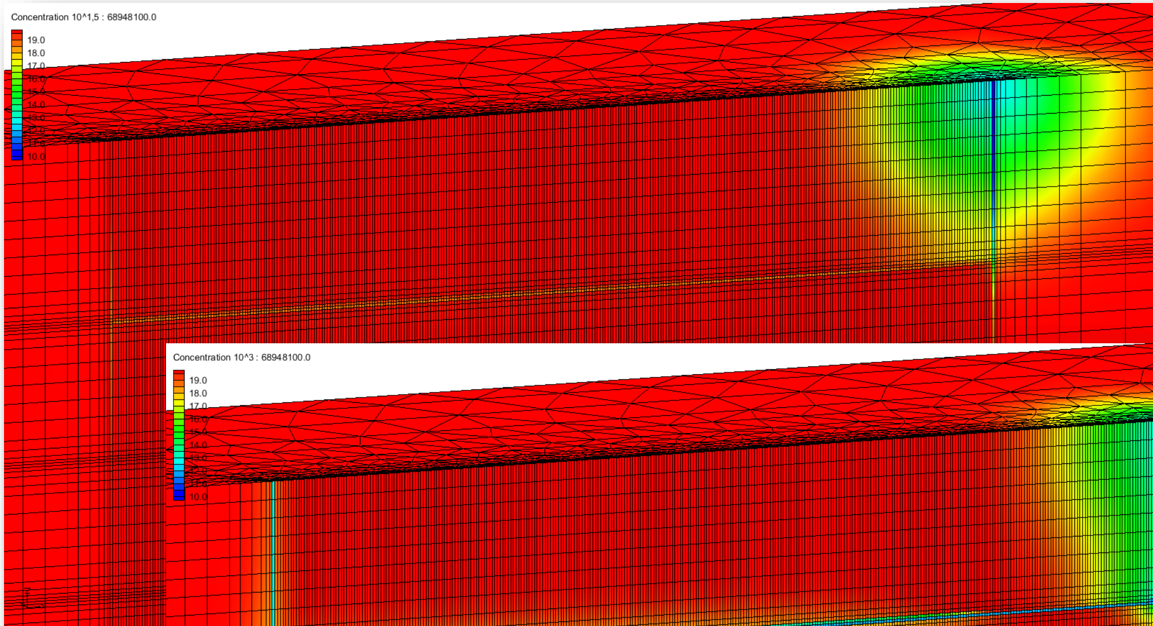
Challenge 2: ‘heat short circuit’

… schematic application on a given abandoned coal mine in Belgium

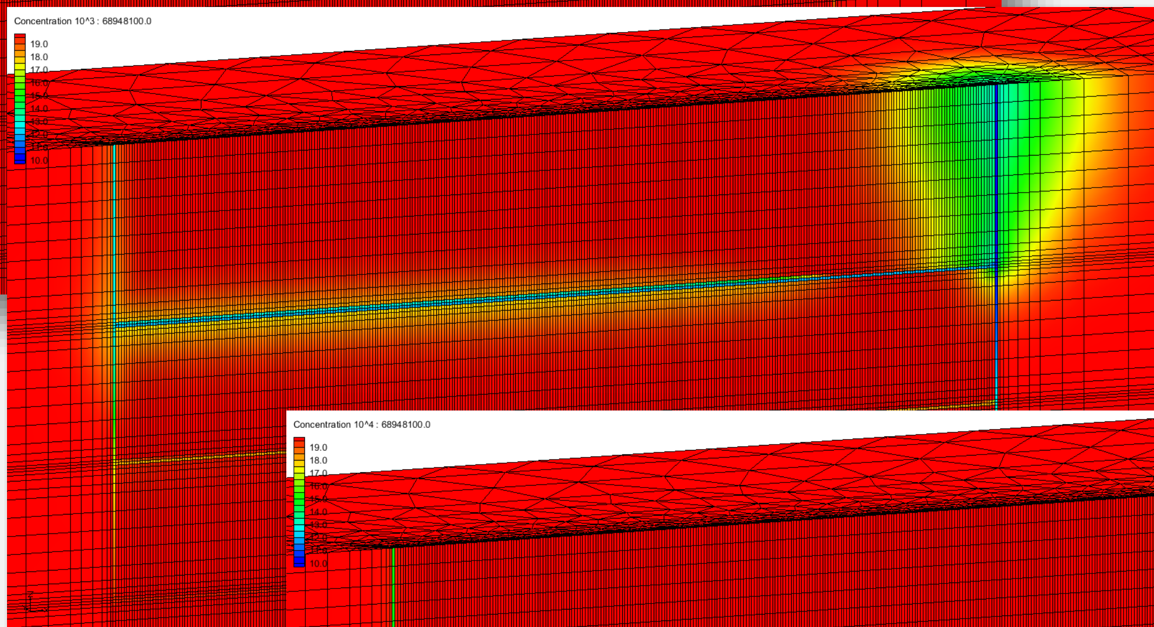
Rmk: the shafts have been backfilled 40 years ago with undetermined materials

➡ *simulations for different ratio $K_{shaft+galleries}/K_{bedrock}$*

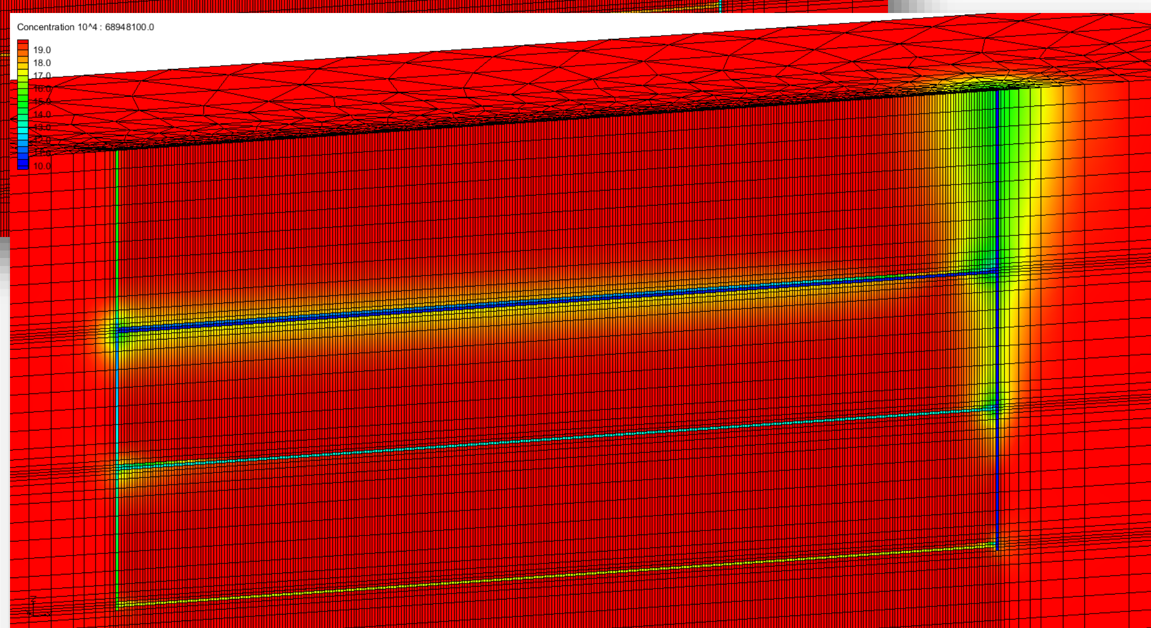




$$\frac{K_{shaft+galleries}}{K_{bedrock}} = 10^{1,5}$$

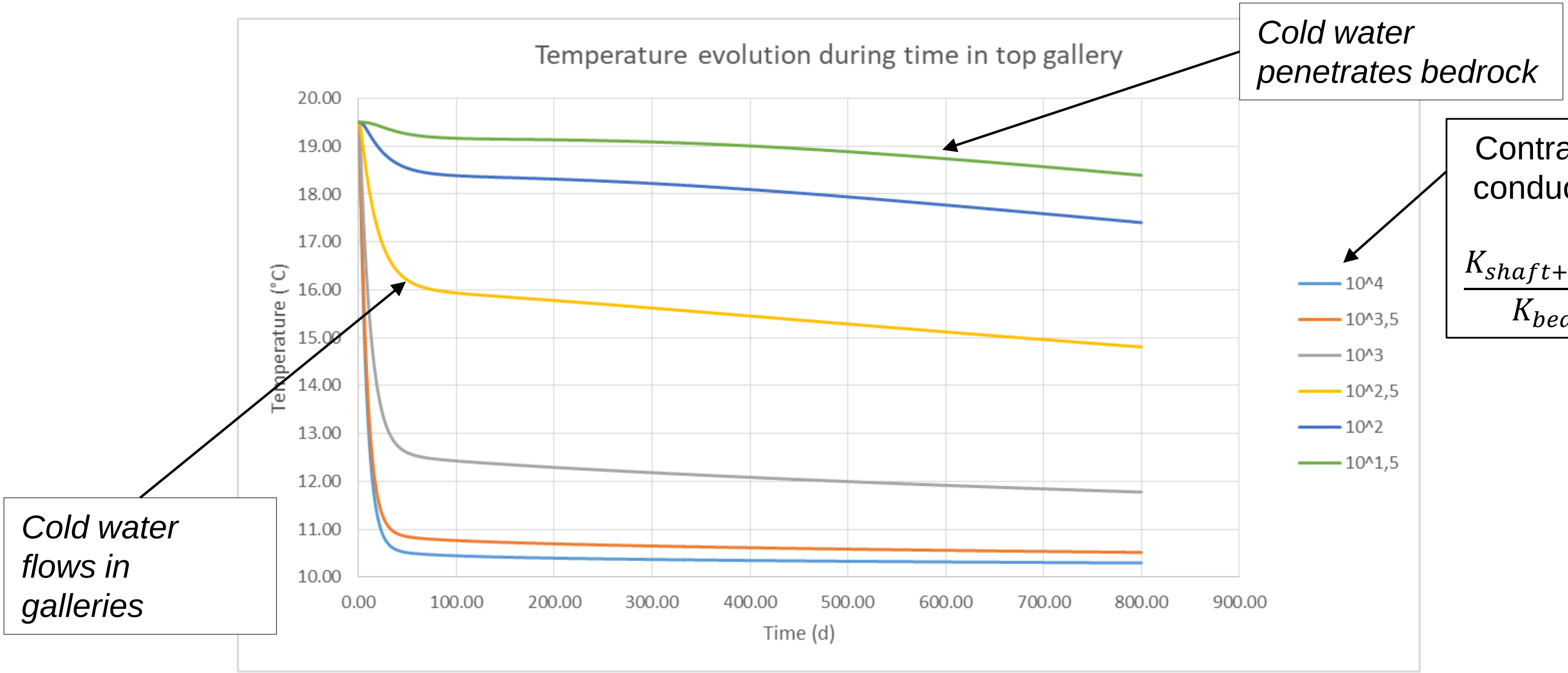


$$\frac{K_{shafts+galleries}}{K_{bedrock}} = 10^{3}$$



$$\frac{K_{shafts+galleries}}{K_{bedrock}} = 10^{4}$$

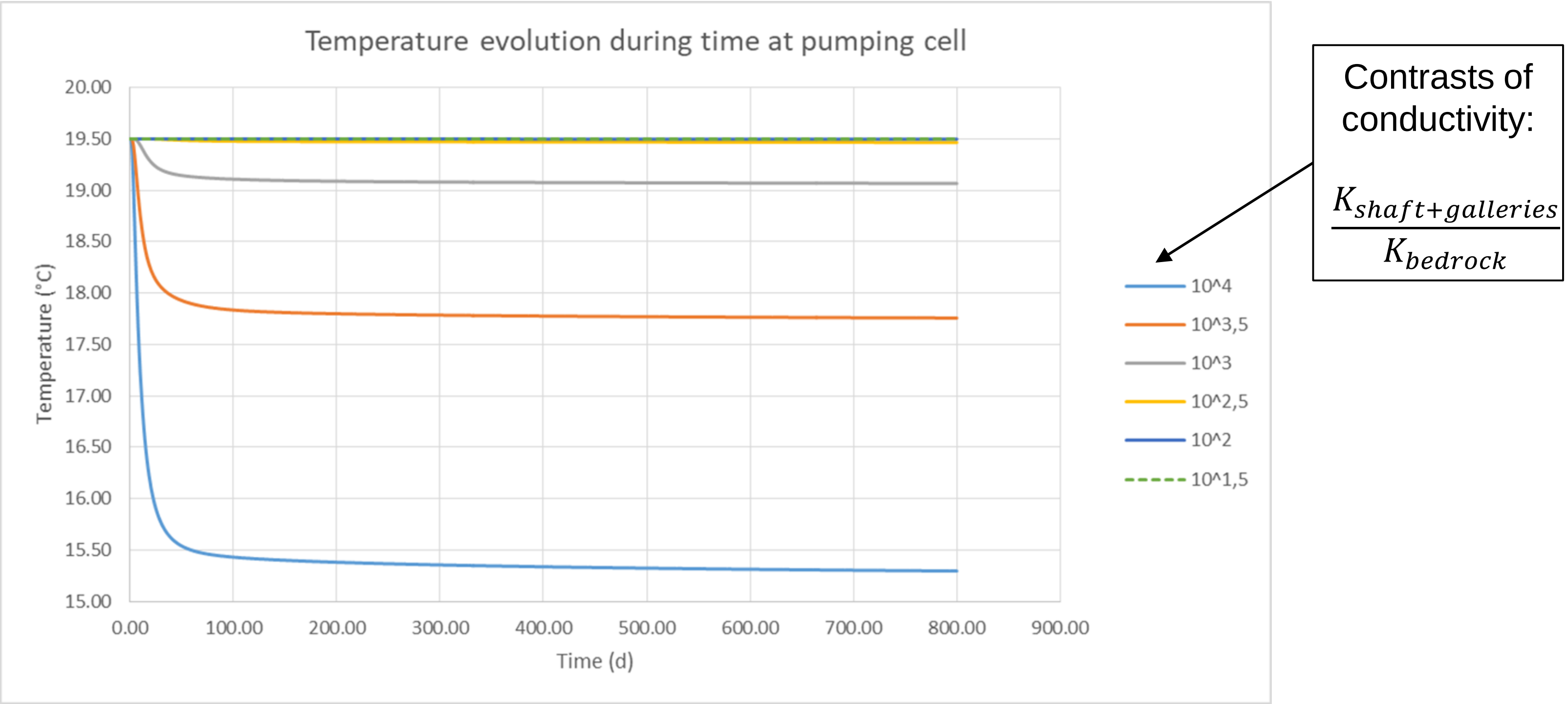
Influence of the bedrock on the temperature evolution … in the top gallery



Contrasts of conductivity:

$$\frac{K_{shaft+galleries}}{K_{bedrock}}$$

Temperature evolution at the pumping location



Facing the challenges

Our limitations:

- *few data*
- *a large and complex domain to be simulated*
- *high differences of porosity, of flow speed and maybe also of flow laws*
- *domains with very different shapes and orientations (galleries, shafts, unconsolidated zones, hard rock…)*

Classical modeling technique are not appropriate

Our ambitions:

- ► *optimization: to find the highest exploitable flow with coolest/warmest temperatures*
- ► *maximizing the exploitable bedrock and mine energy (impacted volume)*
- ► *predicting long term efficiency of the system*
- ► *predicting short-, mid- and long-term possible impacts in the surrounding aquifers*

(Florea et al. 2017, Kabuth et al. 2017)

Conclusions, what we have learnt …

- *open old mine loop systems have to be correctly designed and managed to ensure their geothermal efficiency*
- *galleries - bedrock interactions can play a key-role*
- *appropriate modelling tools adapted to mine have to be used for design purposes*

Needed

- *What are the needed info and data ?*
- *What could be the direct 'a priori' criteria for rejecting a site ?*
- *Potential gained energy versus energy needs*

Modeling

- *Modeling what ? How to model ?*
- *What are the main indicators in the results ?*

Optimal exploitation scenario

- *For a given real old mine network*
- *Introducing uncertainties in computations*

References *(among others)*

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Flow and heat transfer equations

Groundwater flow in porous media

$$S_S \frac{\partial h}{\partial t} = div\left[\underline{\underline{K}} \cdot \overrightarrow{\nabla h}\right] + Q$$

Water flow in a linear reservoir

$$S\, A_{res} \frac{\partial h}{\partial t} = -\alpha_{res}\, (h - h_b) + Q$$

Heat transfer in porous media

$$C_m \frac{\partial T}{\partial t} = div\left[\left(\lambda_m + n\, C_w\, D_{diff} + n_e C_w \underline{\underline{D_{disp}}}\right) \cdot \overrightarrow{\nabla T}\right]$$

In galleries

- *Flow : Darcy-Weisbach*

$$\Delta h = f\,\frac{L}{D}\frac{v^2}{2g}$$

Friction coefficient f dependent on Re

- *Heat transfer : Rodriguez et Diaz (2008)*

$$Q = 2\pi l h (T_p - T_w)$$

$h = \lambda \frac{Nu}{2r}$ *with* $Nu = 0.021\,Re^{0.8} Pr^{0.43}$ *if turbulent ;*

$Nu = 3.66$ *if laminar*