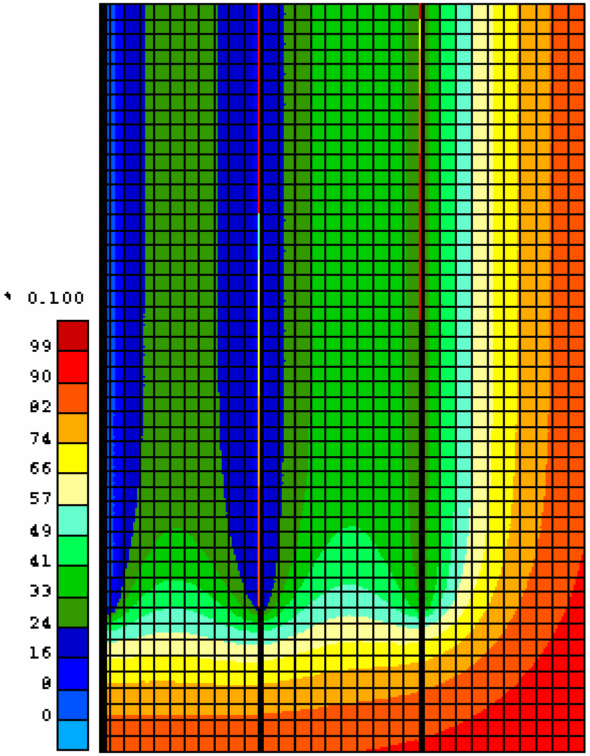

Shallow geothermy

Geothermal properties of soils and rocks

Prof. Alain Dassargues
Prof. Robert Charlier
Dr. Bertrand François

10 February 2010 – SBGIMR & UBLG study day – Shallow geothermy

Content

1. Introduction

   Why ground may be used as a geothermal ressource?

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   The link between geothermy and geotechnical and hydrogeological techniques

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   The relevant physical phenomena

4. Numerical simulations

   Tools for designing geothermal systems

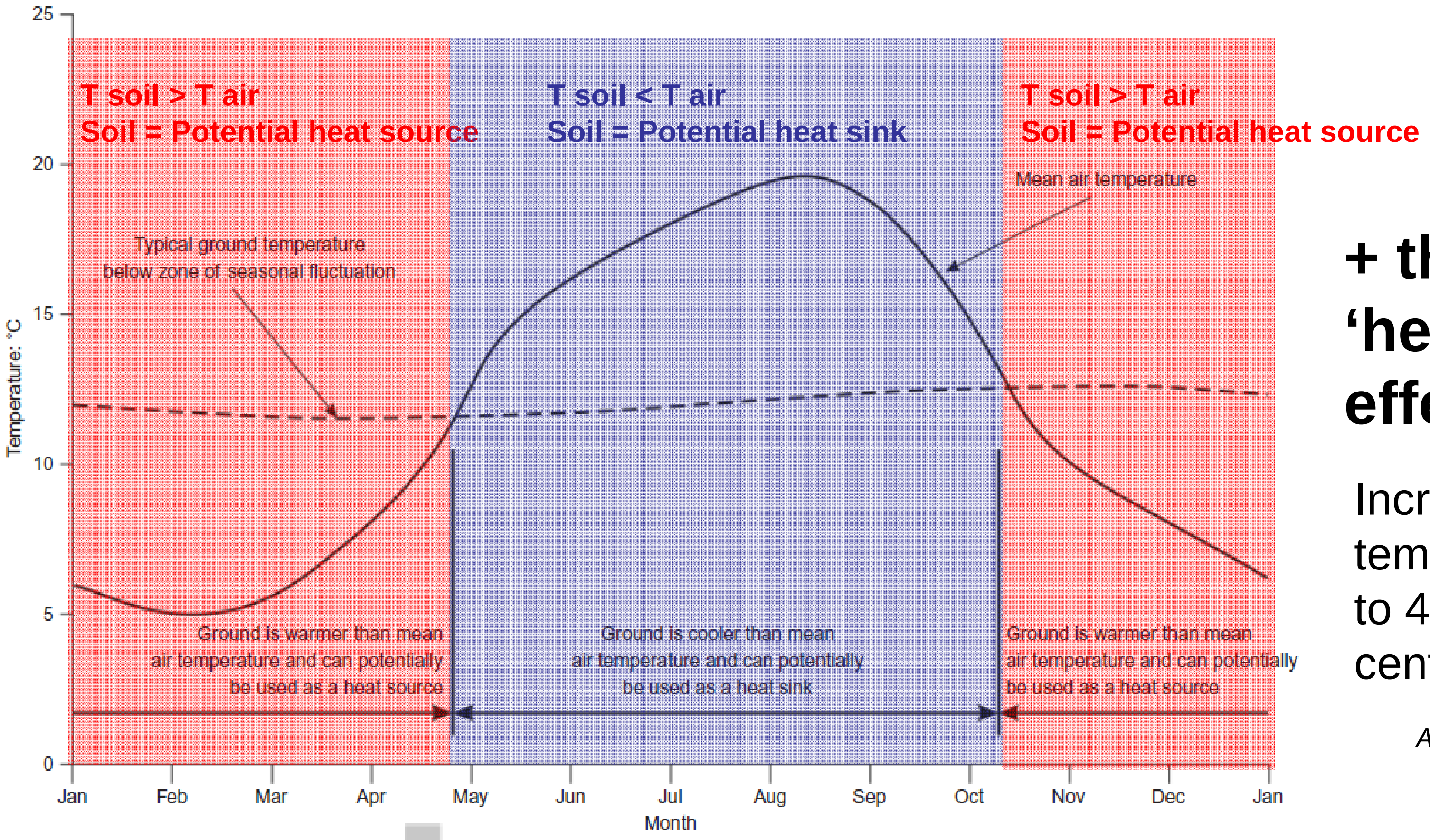
5. Conclusions

1.Introduction

Why ground may be used as a geothermal ressource?

Annual ground and air temperature evolution

(Temperature based on UK conditions)



Preene and Powrie, Geotechnique 2009

+ the urban 'heat island' effect

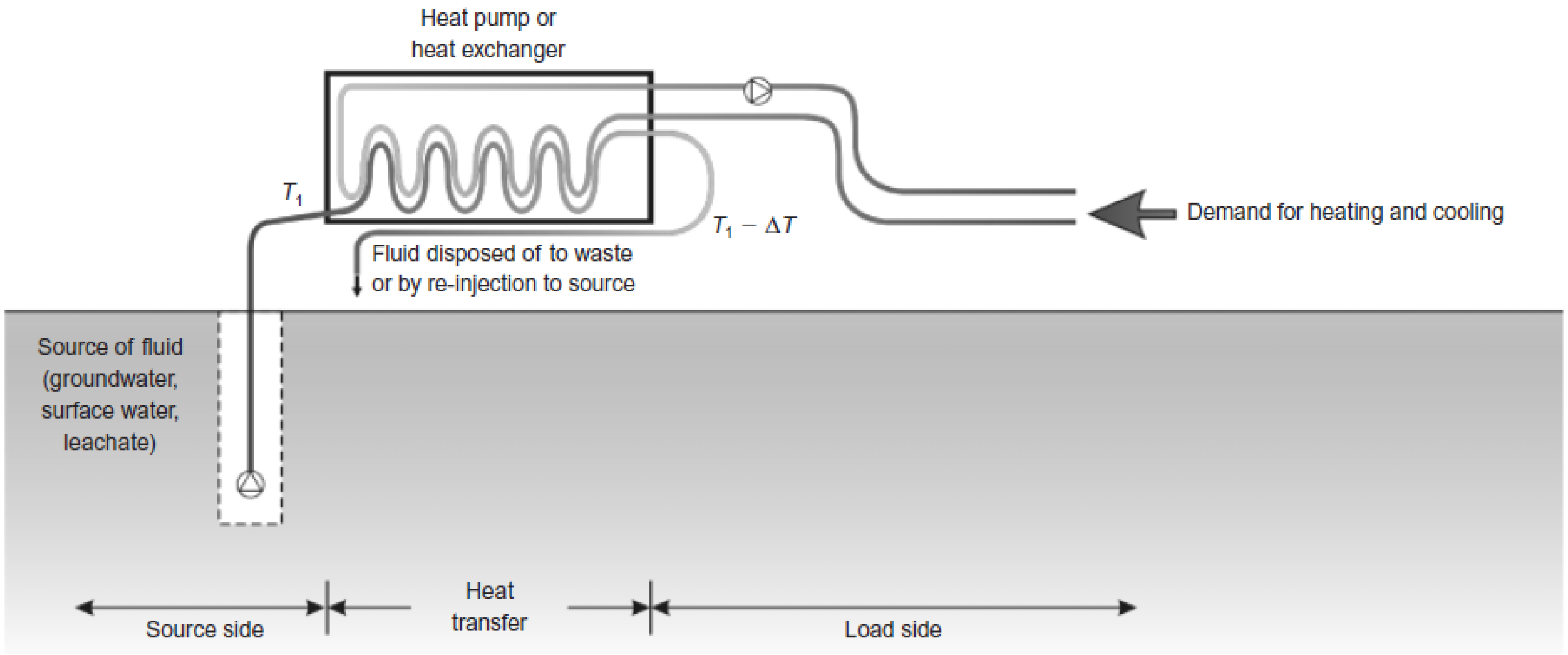
Increase of ground temperature from 2 to 4°C in city centers

Allen et al., Geothermics 2003

1. Introduction

Open-loop ground energy system

Groundwater is abstracted from the source (typically boreholes), passed through an heating pump or heat exchanger and re-injected in the ground

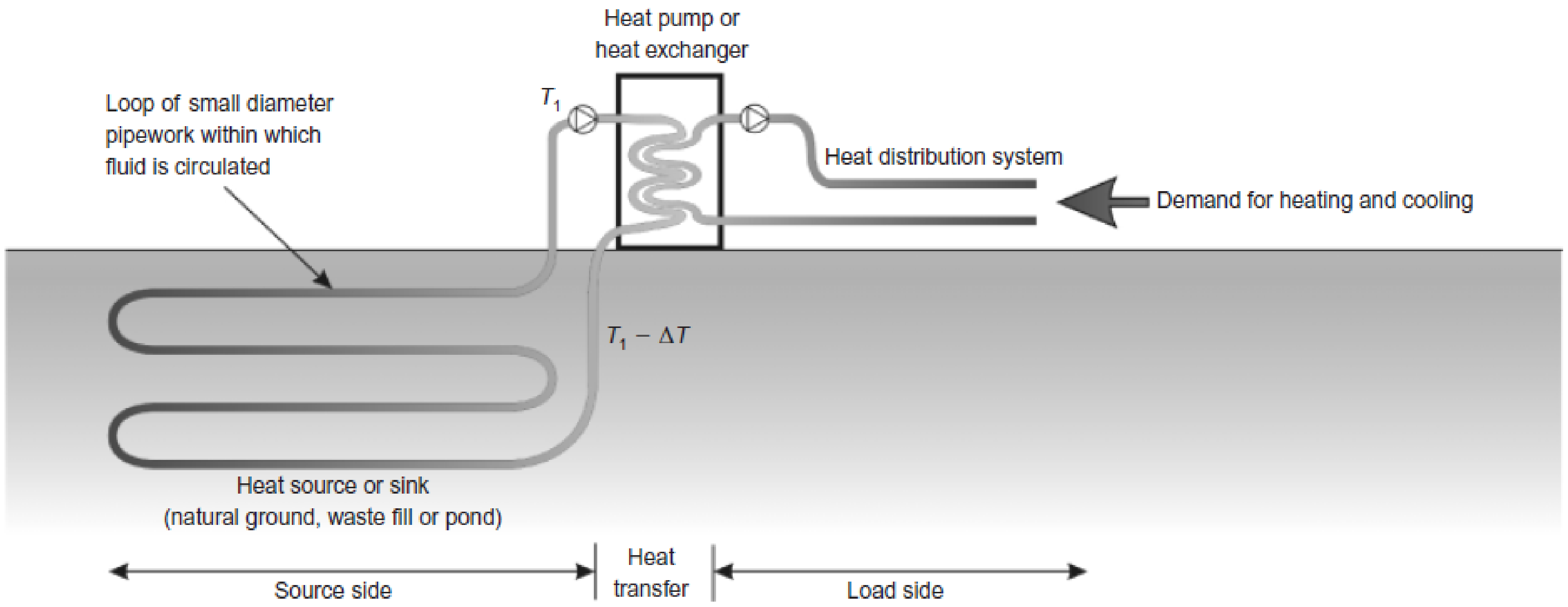


Preene and Powrie, Géotechnique 2009

1. Introduction

Closed-loop ground energy system

A thermal transfer fluid is circulating through a closed circuit of pipes embedded in the ground. This system can be incorporated in building foundations (piles, retaining wall, slabs,…)



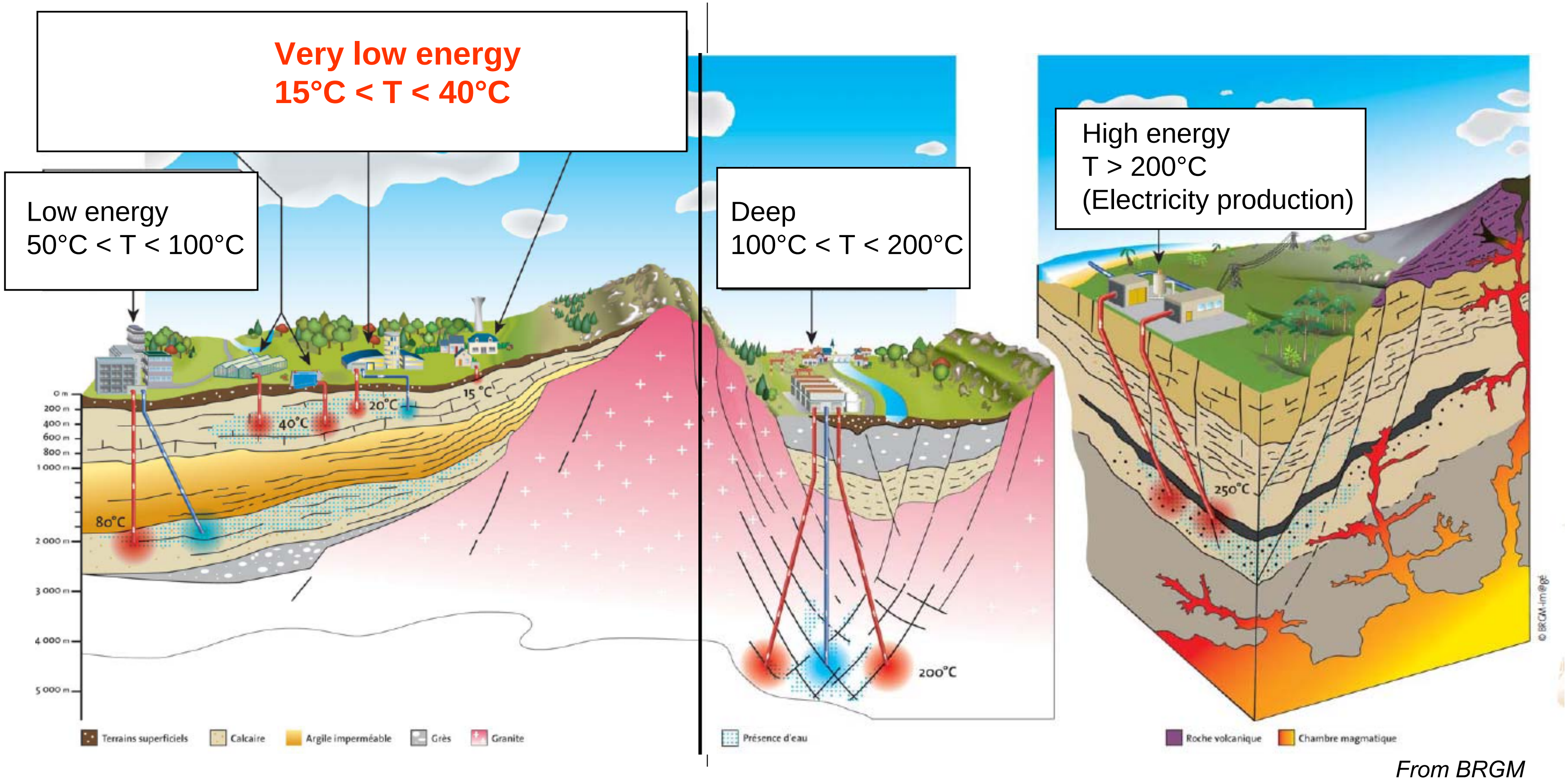
Preene and Powrie, Géotechnique 2009

2. Kinds of geothermy

The link between geothermy and geotechnical and hydrogeological techniques

2. Various kinds of geothermal exploitations

Various depths, temperatures and thermal energies



Very low energy
15°C < T < 40°C

Low energy
50°C < T < 100°C

Deep
100°C < T < 200°C

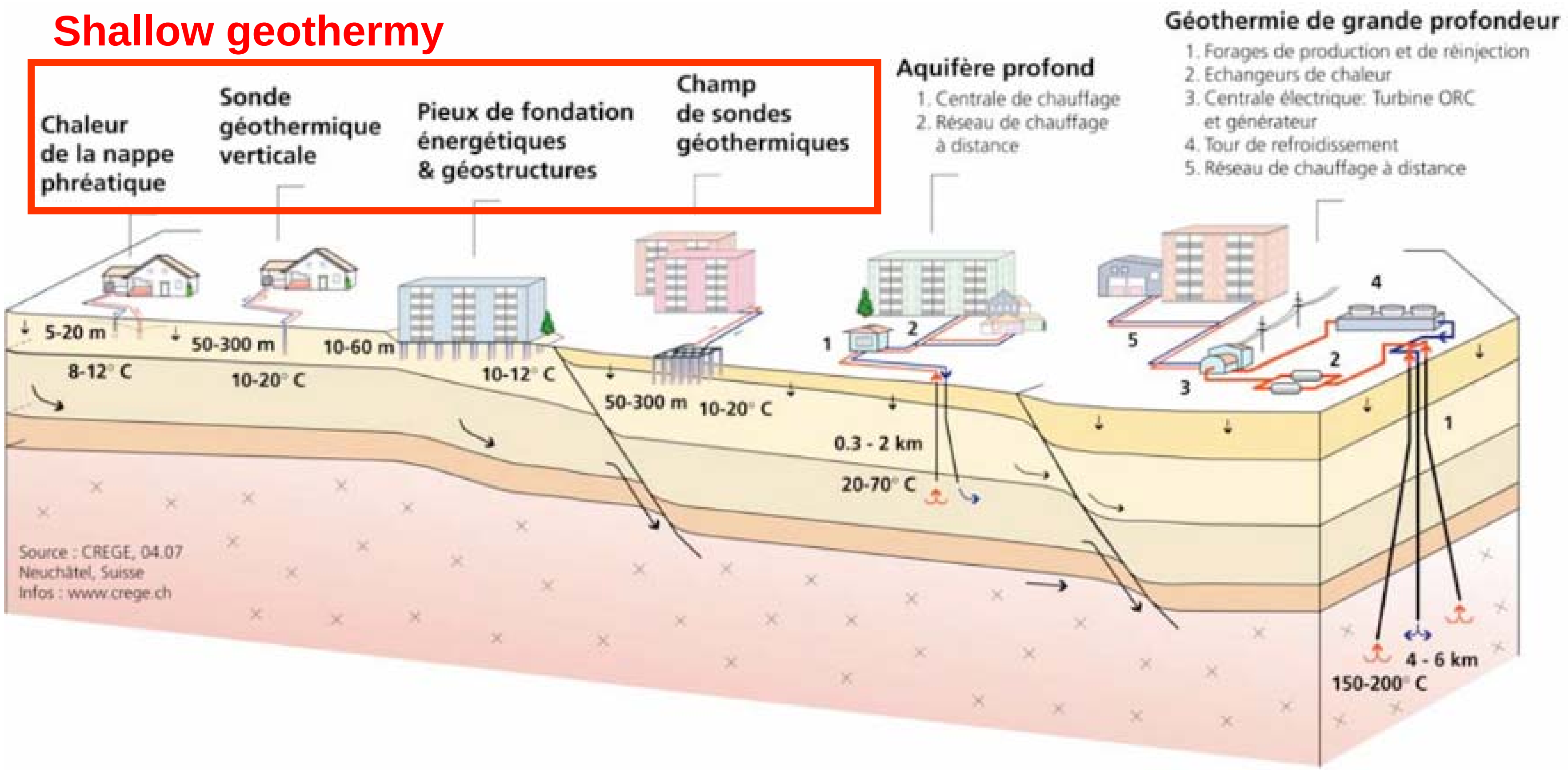
High energy
T > 200°C
(Electricity production)

From BRGM

Shallow geothermy involves **saturated or unsaturated soft soils, hard soils or porous rocks** for Building air-conditioning and Individual or collective heating

2. Various kinds of geothermal exploitations

Shallow geothermy



Source : CREGE, 04.07
Neuchâtel, Suisse
Infos : www.crege.ch

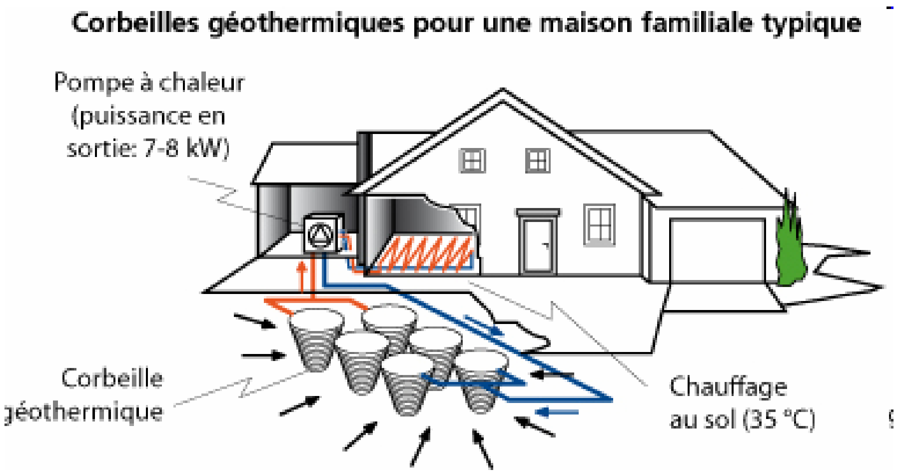
2. Various kinds of geothermal exploitations

Sub-surface tubes

- **No structural role**
- Tubes set up in a 3 to 5 m depth excavation
- Closed loop: heat exchanger fluid in tubes
- Heat pump : T from ≈10 °C to ≈25 °C
- Below 2 m depth, temperature is unaffected by daily variations, only seasonal variations

  Tmax ≈ 13°C in November

  Tmin ≈ 7°C in May
- Suitable for individual houses
- Maximal power: 7 to 8 kW for the entire system



From www.crege.ch

2. Various kinds of geothermal exploitations

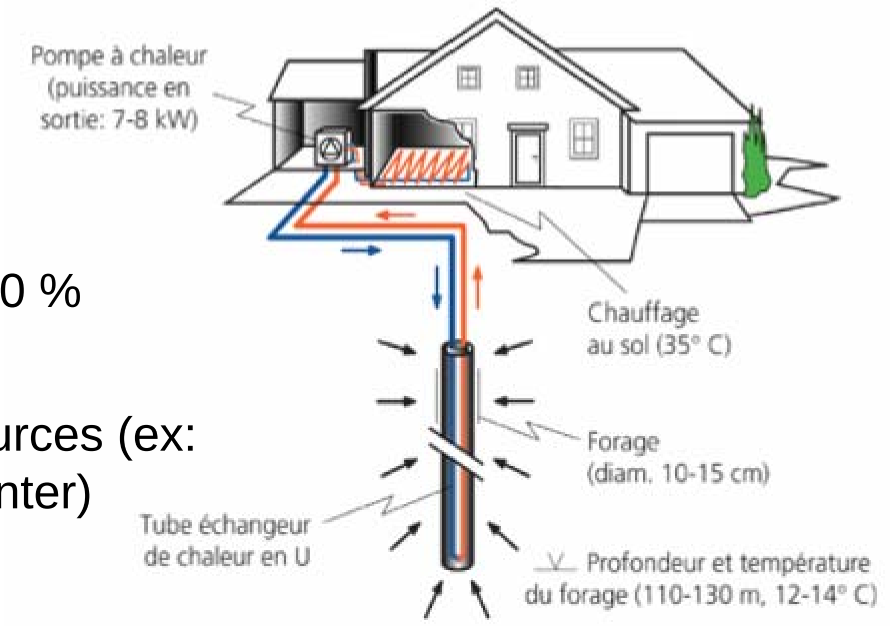
Sub-surface tubes

2. Various kinds of geothermal exploitations

Vertical geothermal probes

- **No structural role**
- Boreholes of 10-15 cm in diameter, 50 – 300 m in length
- **U tubes in borehole (closed loop)**
- Heat pump : T from $\approx$15 °C to $\approx$35 °C
- Energy balance: geothermy $\approx$ 70 %

  electricity for heat pump $\approx$ 30 %
- Maximal power: 7 to 8 kW / probe
- Possibility to combine with others energy sources (ex: solar energy stored in summer and used in winter)
- Possibility of seasonal heat storage



From www.crege.ch

2. Various kinds of geothermal exploitations

Vertical geothermal probes

Chantier de forage

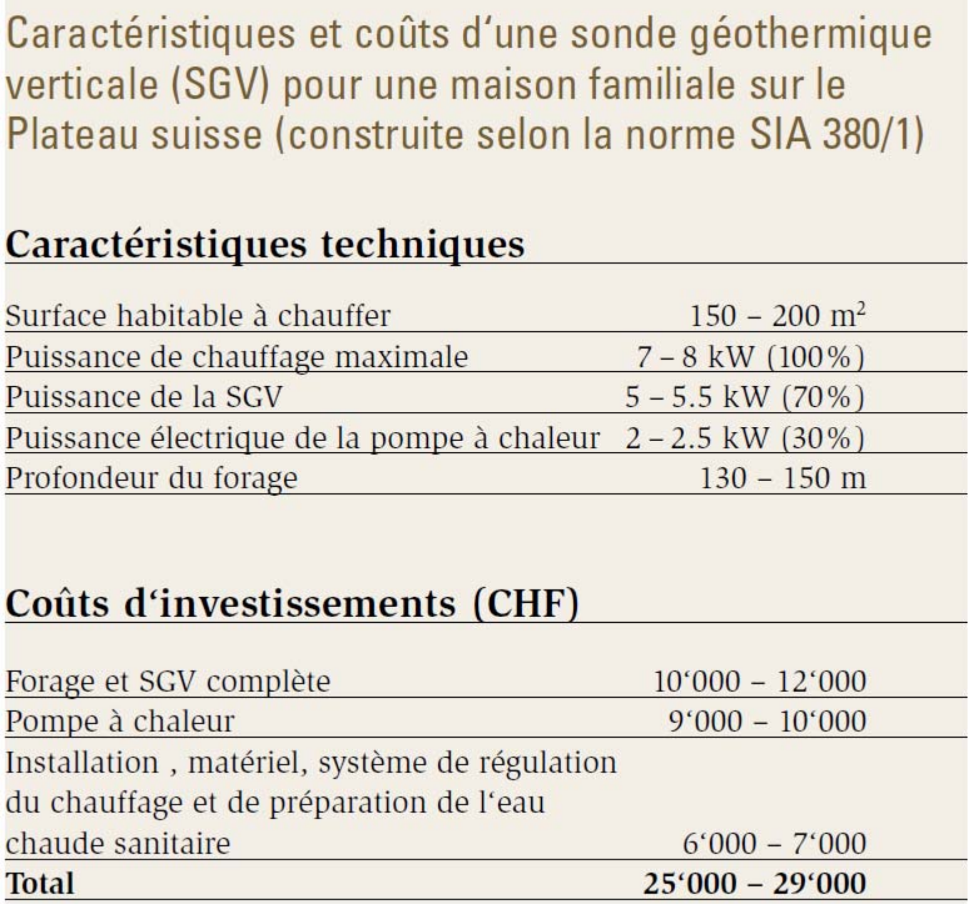
Foreuse

Outils et tiges de forage

2. Various kinds of geothermal exploitations

Vertical geothermal probes

In Switzerland *(from geothermie.ch)*



Caractéristiques et coûts d'une sonde géothermique verticale (SGV) pour une maison familiale sur le Plateau suisse (construite selon la norme SIA 380/1)

Caractéristiques techniques

Surface habitable à chauffer	150 – 200 m^2
Puissance de chauffage maximale	7 – 8 kW (100%)
Puissance de la SGV	5 – 5.5 kW (70%)
Puissance électrique de la pompe à chaleur	2 – 2.5 kW (30%)
Profondeur du forage	130 – 150 m

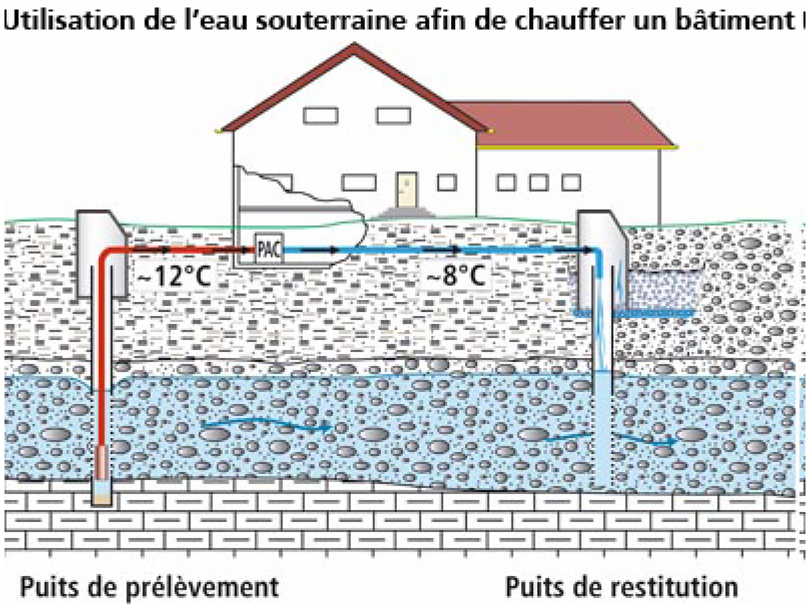
Coûts d'investissements (CHF)

Forage et SGV complète	10'000 – 12'000
Pompe à chaleur	9'000 – 10'000
Installation , matériel, système de régulation du chauffage et de préparation de l'eau chaude sanitaire	6'000 – 7'000
Total	**25'000 – 29'000**

15'000 – 20'000 €

Pumping wells

- **Heat transfer by convection**
- Boreholes with pumping in aquifers (depths < 50 m)
- **Groundwater extraction (open loop)**
- Ground water temperature ≈ 10 - 14°C (higher in town)
- Temperature in aquifers must not be increased more than +/- 3°C
- Suitable in highly water permeable ground (ex: gravel)
- Heat power extraction: up to 50 kW / wells
- Pumped water flow : > 10 m^3/ hours / wells

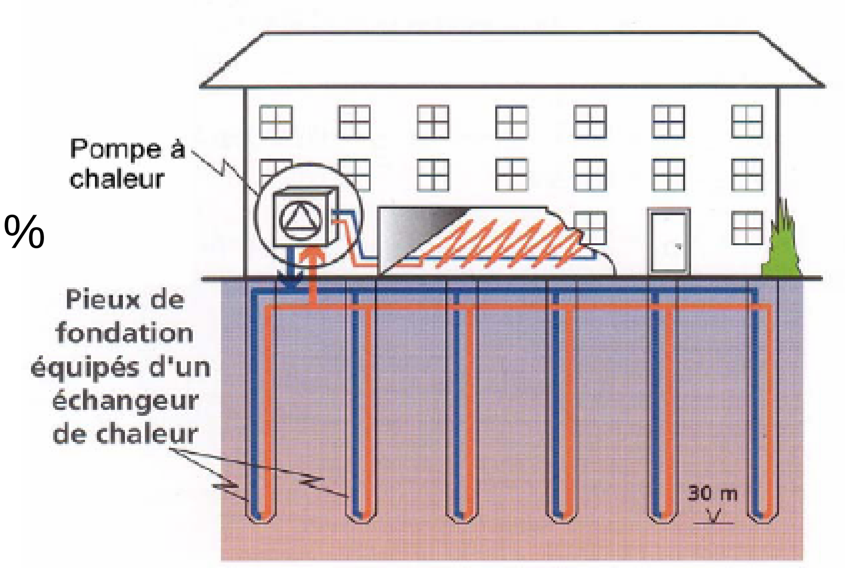


2. Various kinds of geothermal exploitations

Heat exchanger geostructures

- **Structural role** → No need of additional boreholes, the foundation is used as an heat exchanger
- **Piles, retaining walls, tunnels, pavements**
- U tubes in the geostructures
- Heat pump : T from ≈ 10°C to ≈ 30 °C
- Energy balance: geothermy ≈ 75 %

  electricity for heat pump ≈ 25 %
- Maximal power: 50 W / m of pile

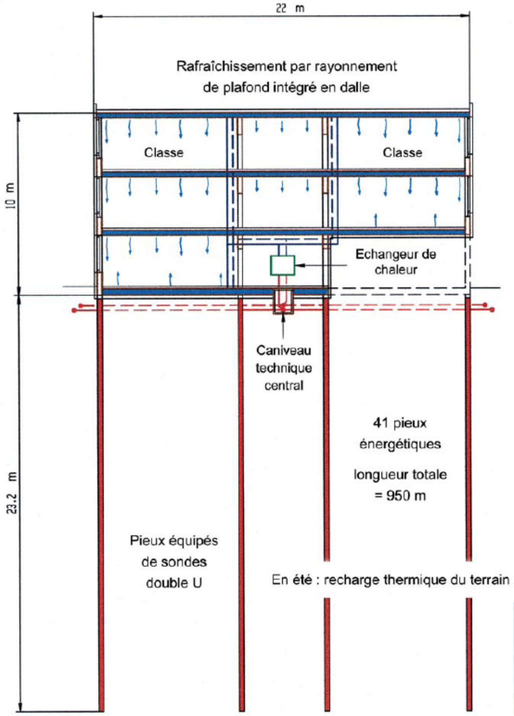


From www.crege.ch

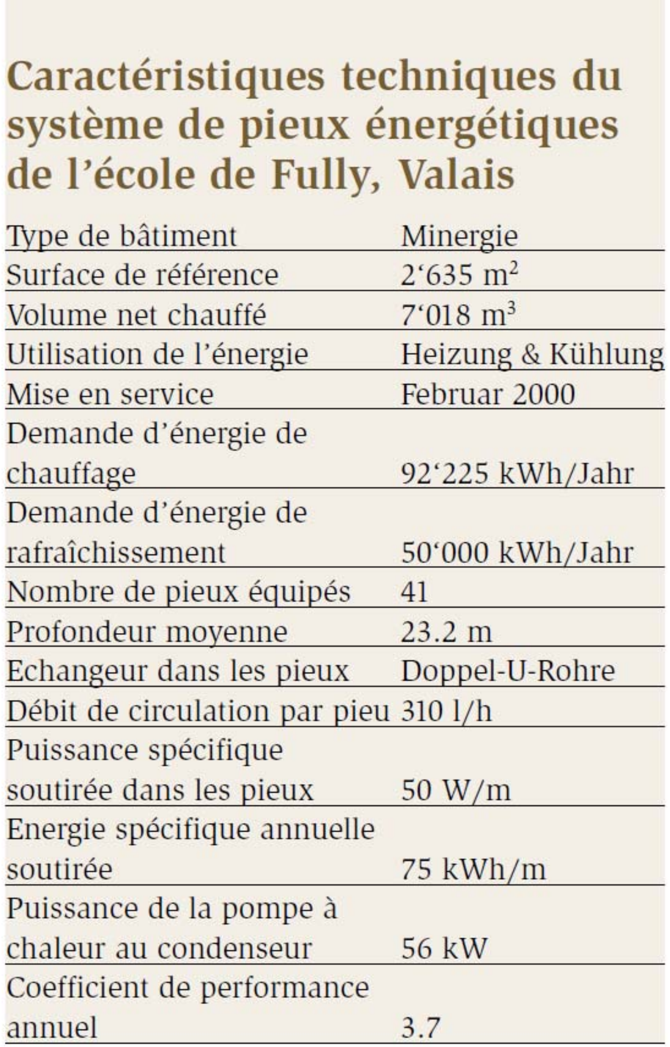
2. Various kinds of geothermal exploitations

Heat exchanger geostructures

Example in Switzerland *(from geothermie.ch)*



Principe de fonctionnement des pieux énergétiques de l'école de Fully pendant l'été.



Caractéristiques techniques du système de pieux énergétiques de l'école de Fully, Valais

Type de bâtiment	Minergie
Surface de référence	2'635 m^2
Volume net chauffé	7'018 m^3
Utilisation de l'énergie	Heizung & Kühlung
Mise en service	Februar 2000
Demande d'énergie de chauffage	92'225 kWh/Jahr
Demande d'énergie de rafraîchissement	50'000 kWh/Jahr
Nombre de pieux équipés	41
Profondeur moyenne	23.2 m
Echangeur dans les pieux	Doppel-U-Rohre
Débit de circulation par pieu	310 l/h
Puissance spécifique soutirée dans les pieux	50 W/m
Energie spécifique annuelle soutirée	75 kWh/m
Puissance de la pompe à chaleur au condenseur	56 kW
Coefficient de performance annuel	3.7

2. Various kinds of geothermal exploitations

Heat exchanger geostructures

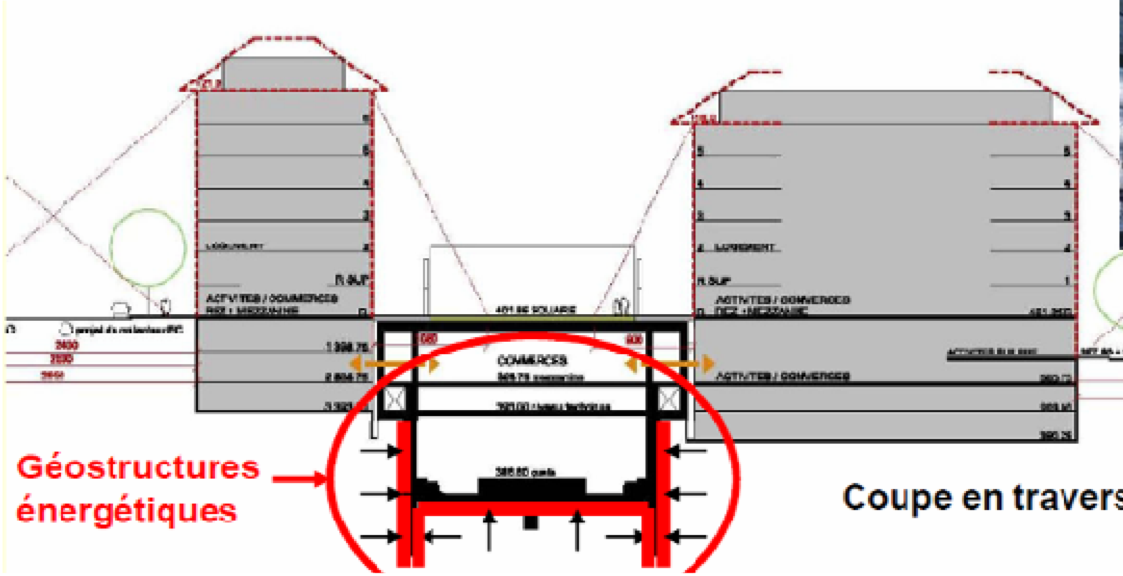
Piles

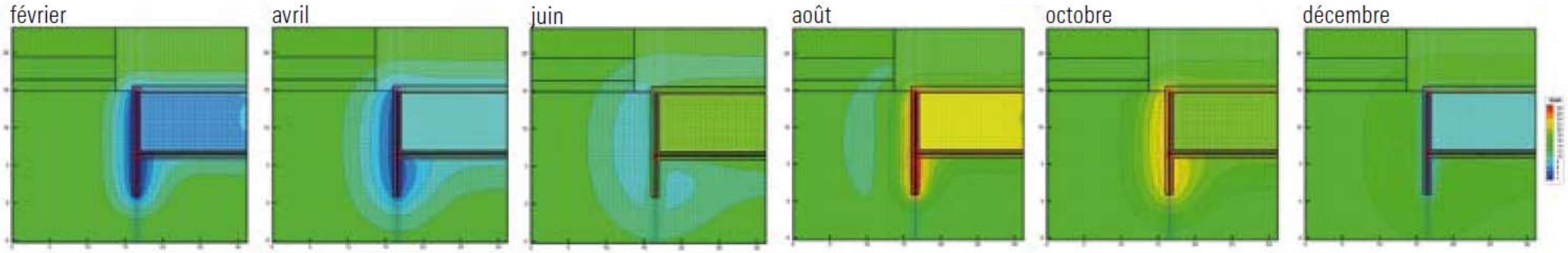
Wall

2. Various kinds of geothermal exploitations

Heat exchanger geostructures

Train station – Geneva (CH)



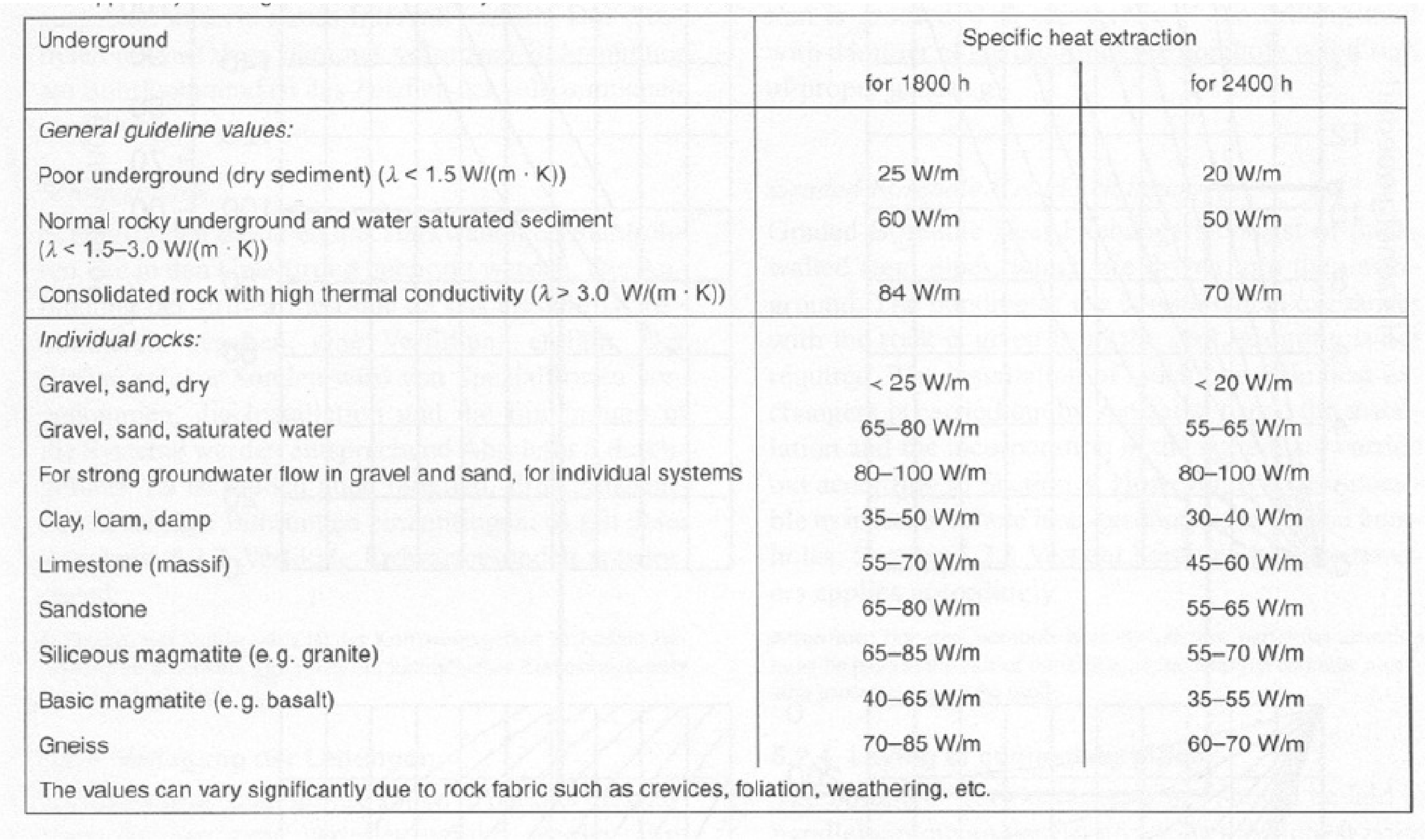


From Geowatt AG

Effect of heat exchange on the evolution of temperature in tunnel

2. Various kinds of geothermal exploitations

Possible extraction for borehole heat exchangers



Underground	Specific heat extraction	
	for 1800 h	for 2400 h
General guideline values:		
Poor underground (dry sediment) ($\lambda < 1.5$ W/(m · K))	25 W/m	20 W/m
Normal rocky underground and water saturated sediment ($\lambda < 1.5$–3.0 W/(m · K))	60 W/m	50 W/m
Consolidated rock with high thermal conductivity ($\lambda > 3.0$ W/(m · K))	84 W/m	70 W/m
Individual rocks:		
Gravel, sand, dry	< 25 W/m	< 20 W/m
Gravel, sand, saturated water	65–80 W/m	55–65 W/m
For strong groundwater flow in gravel and sand, for individual systems	80–100 W/m	80–100 W/m
Clay, loam, damp	35–50 W/m	30–40 W/m
Limestone (massif)	55–70 W/m	45–60 W/m
Sandstone	65–80 W/m	55–65 W/m
Siliceous magmatite (e.g. granite)	65–85 W/m	55–70 W/m
Basic magmatite (e.g. basalt)	40–65 W/m	35–55 W/m
Gneiss	70–85 W/m	60–70 W/m

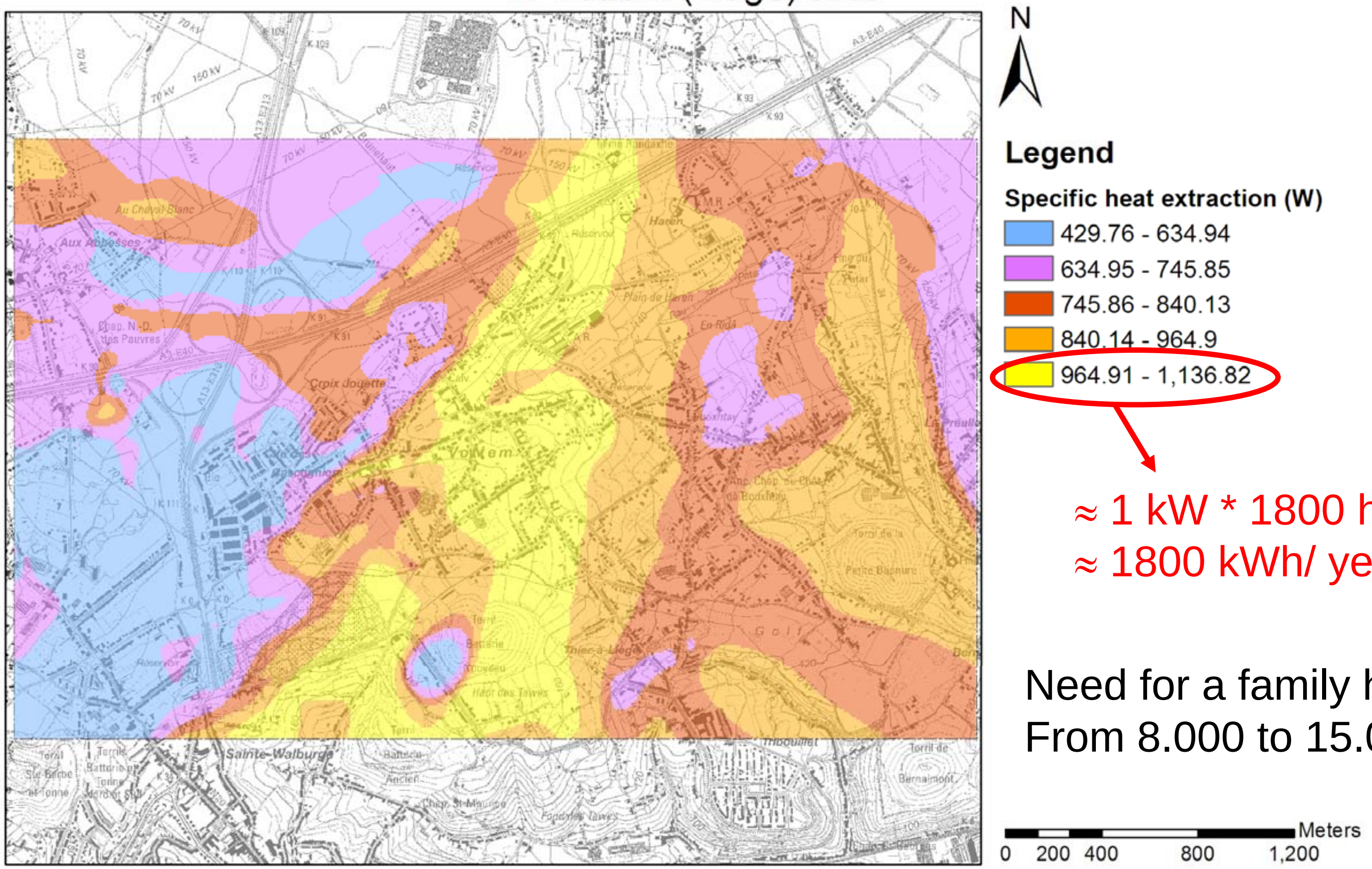
The values can vary significantly due to rock fabric such as crevices, foliation, weathering, etc.

From 20 to 80 W/m depending on ground properties

From VDI 4640 (German guideline for ground heat pumps, utes and direct thermal use of the underground)

2. Various kinds of geothermal exploitations

Estimation of potentially specific heat extraction from 20m deep borehole in Vottem (Liège) area



≈ 1 kW * 1800 h
≈ 1800 kWh/ year / pile

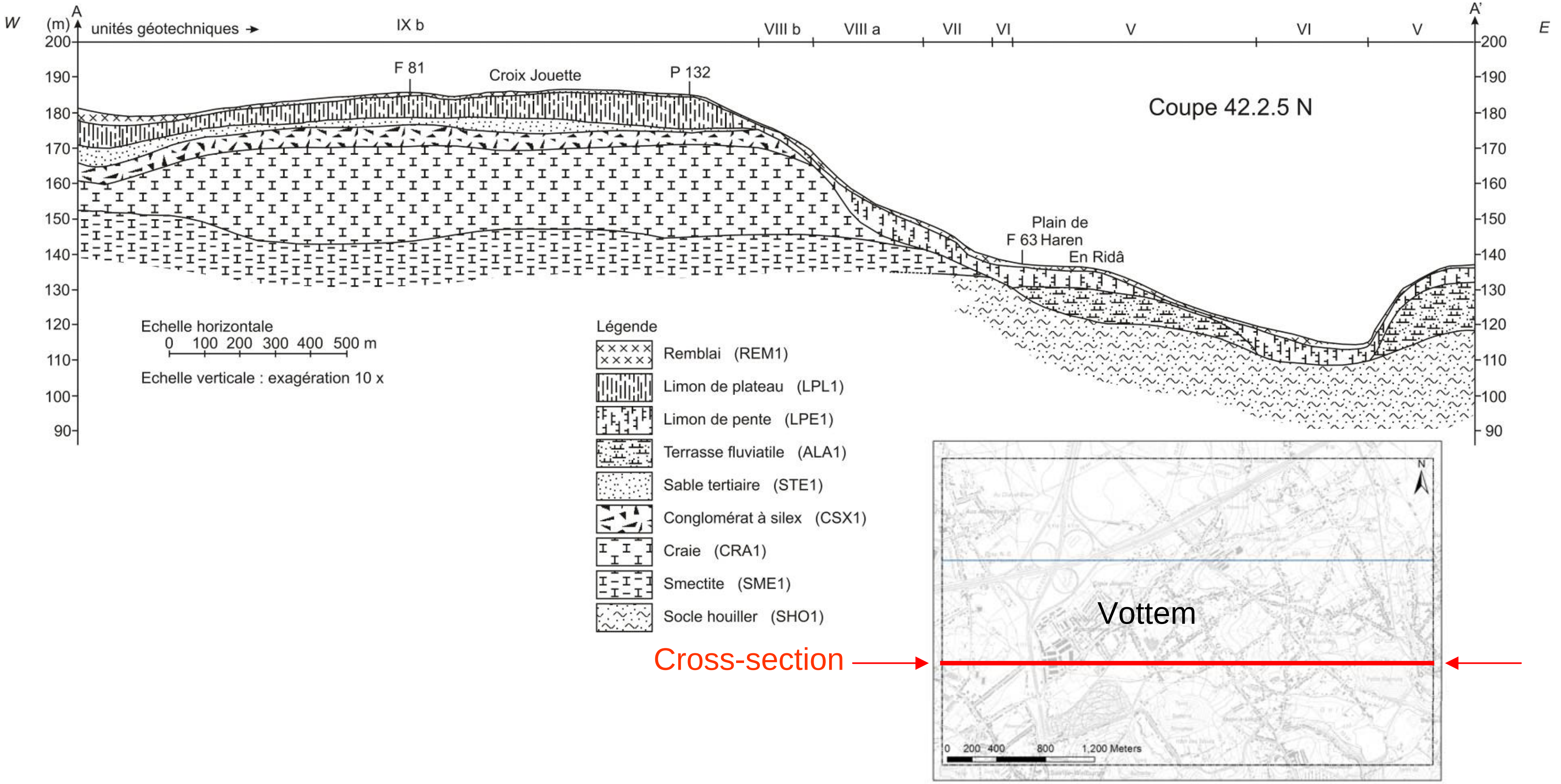
Need for a family house:
From 8.000 to 15.000 kWh/year

S. Delvoie - ULg

2. Various kinds of geothermal exploitations

Mapping of potentially extractable heat from subsoil

- Cross-section (Geotechnical Map, Vottem):



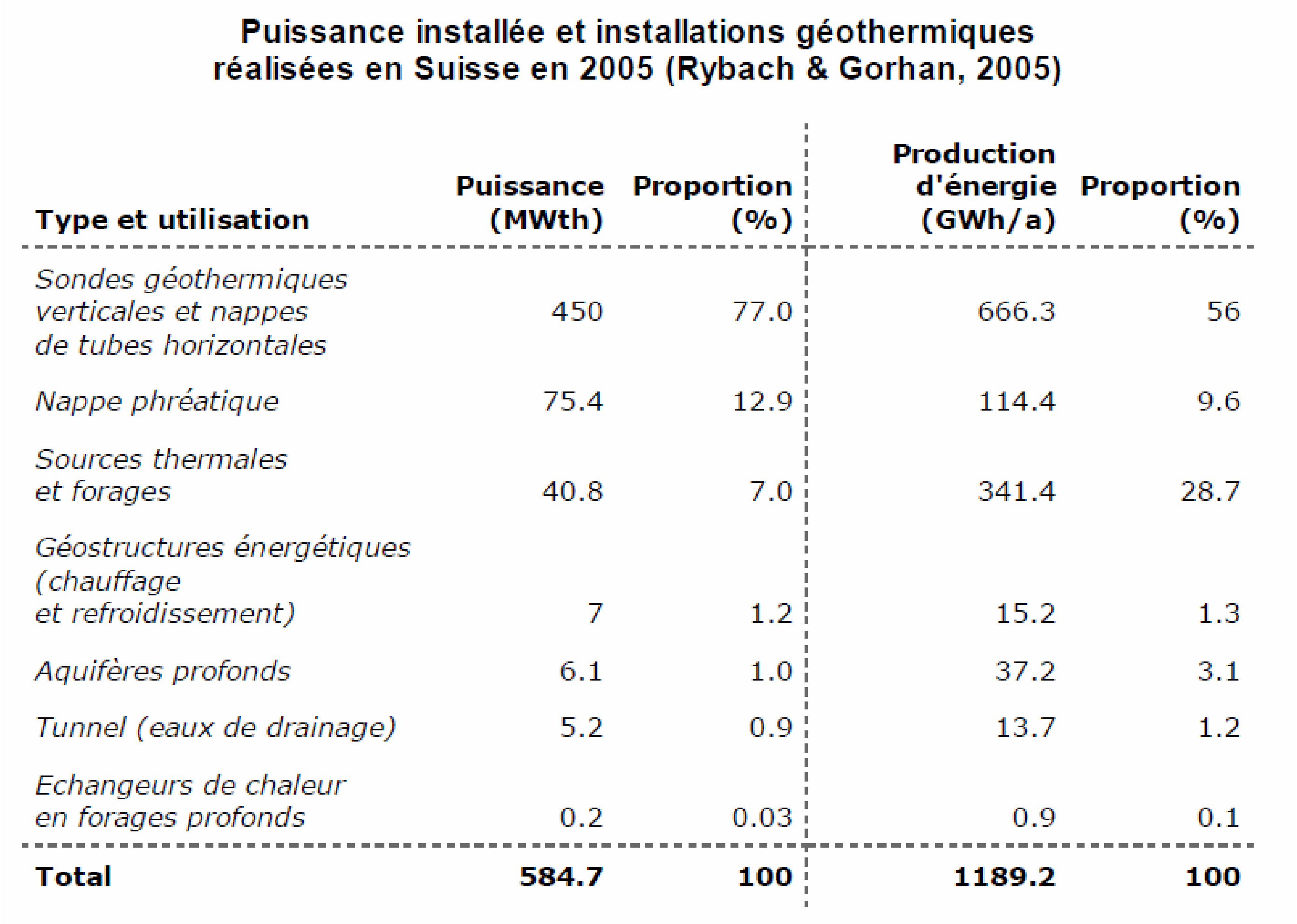
Mapping of potentially extractable heat from subsoil

- Parameters :
  - **Borehole depth** (20 m in the example)
  - Estimation of each **lithological depth**
  - Estimation of **water content** in each lithology
  - Estimation of **potentially specific heat extraction** for each lithology
  - **Specific heat extraction intensity** (1800 h/y in the example)

- Constructed from the geotechnical map

2. Various kinds of geothermal exploitations

Proportions of various geothermal installations (ex: in Switzerland)



Puissance installée et installations géothermiques
réalisées en Suisse en 2005 (Rybach & Gorhan, 2005)

Type et utilisation	**Puissance (MWth)**	**Proportion (%)**	**Production d'énergie (GWh/a)**	**Proportion (%)**
Sondes géothermiques verticales et nappes de tubes horizontales	450	77.0	666.3	56
Nappe phréatique	75.4	12.9	114.4	9.6
Sources thermales et forages	40.8	7.0	341.4	28.7
Géostructures énergétiques (chauffage et refroidissement)	7	1.2	15.2	1.3
Aquifères profonds	6.1	1.0	37.2	3.1
Tunnel (eaux de drainage)	5.2	0.9	13.7	1.2
Echangeurs de chaleur en forages profonds	0.2	0.03	0.9	0.1
Total	**584.7**	**100**	**1189.2**	**100**

Energy production from geothermy in Switzerland

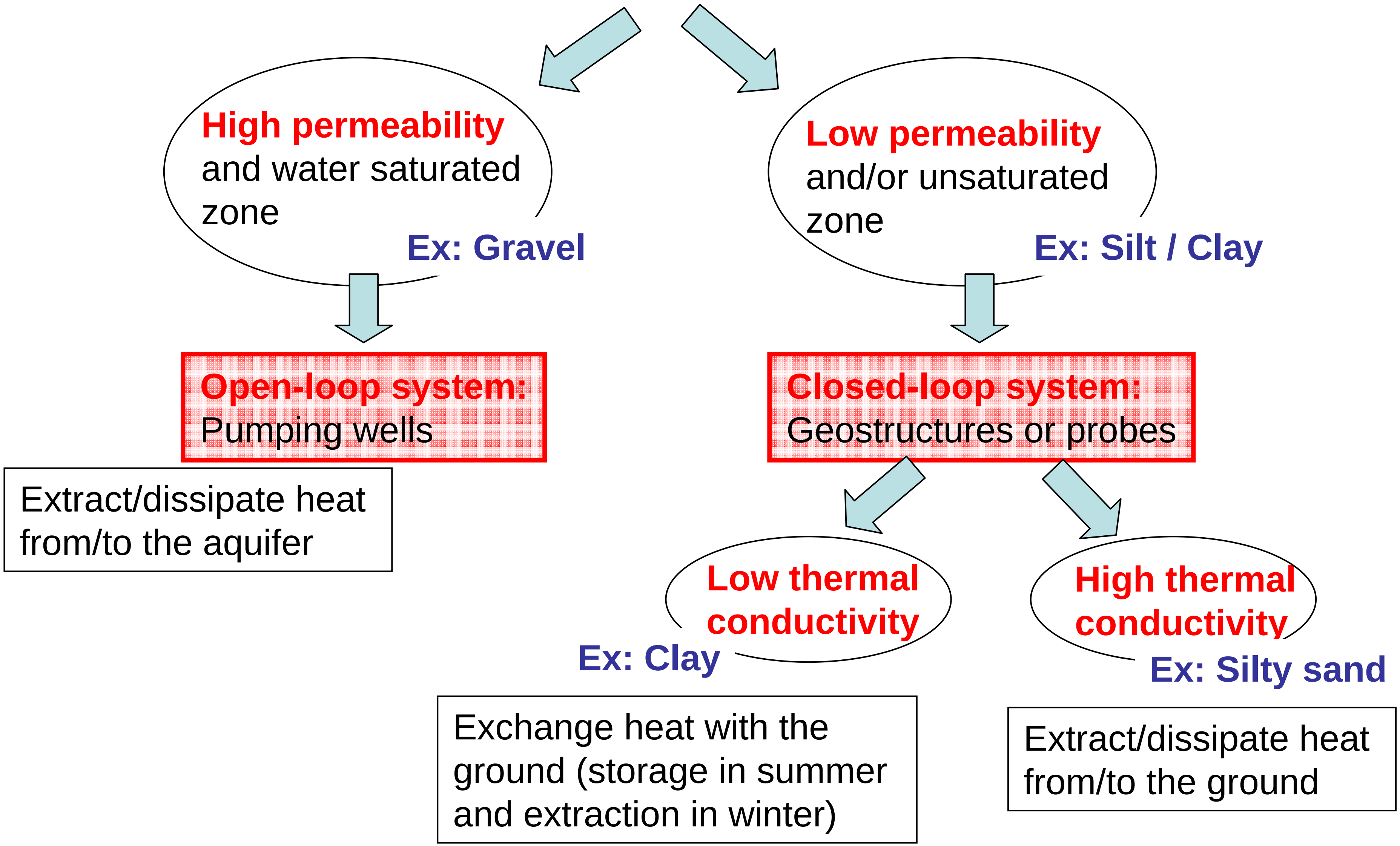
Probe : ≈ 60 %

Extraction of groundwater : ≈ 10 %

Geostructures : ≈ 1 %

Tunnels : ≈ 1 %

2. Various kinds of geothermal exploitations



High permeability and water saturated zone

Ex: Gravel

Open-loop system: Pumping wells

Extract/dissipate heat from/to the aquifer

Low permeability and/or unsaturated zone

Ex: Silt / Clay

Closed-loop system: Geostructures or probes

Low thermal conductivity

Ex: Clay

Exchange heat with the ground (storage in summer and extraction in winter)

High thermal conductivity

Ex: Silty sand

Extract/dissipate heat from/to the ground

3. Governing equations

The relevant physical phenomena

3. Governing equations

Relevant phenomena

The behaviour of soils around geothermal systems is mainly governed by :

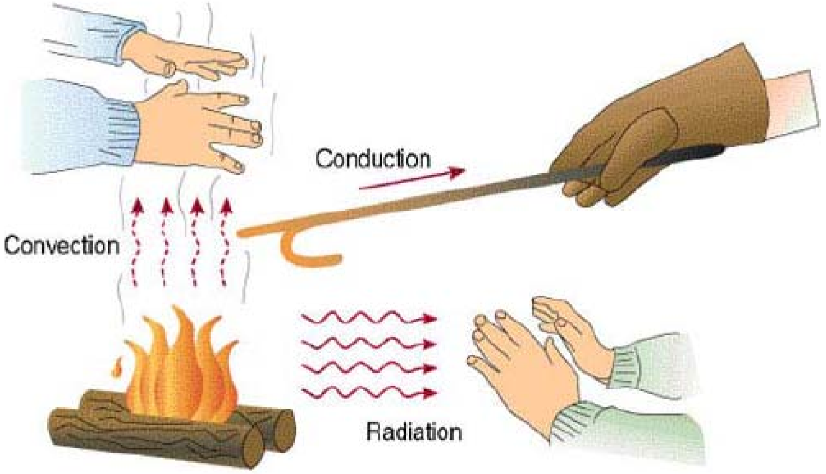
1) Heat transfer → Evolution of temperature (T)

2) Water transfer → Evolution of pore water pressure (p_w)

[3) Mechanical behaviour → Soil deformations]

3. Governing equations

Heat transfer



- **Conduction:** Heat transfer by direct contact of particles of matter
- **Convection:** Heat transfer by mass movement
- *[**Radiation:** Heat transfer by electromagnetic waves]*

3. Governing equations

Conduction (Fourier's law)

$$\mathbf{Q}_{\mathbf{T},conduction} = -\Gamma\,\mathbf{grad}(T)$$

Γ, the thermal conductivity, depends on:

- the porosity *n*
- the degree of saturation S_r
- the mineral content

$$\Gamma = \lambda_s(1-n) + \lambda_w n S_r + \lambda_g n(1-S_r)$$

solid water gas

3. Governing equations

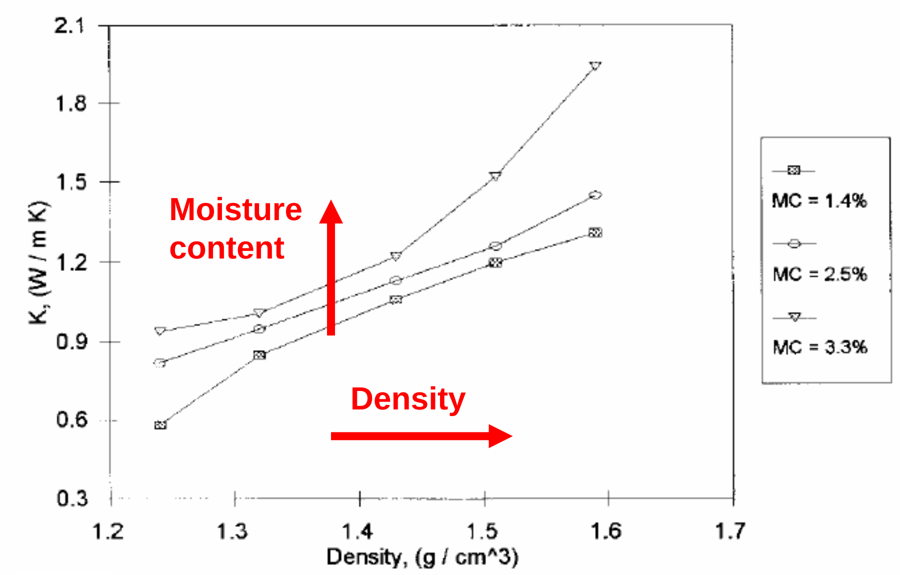
Conduction (Fourier’s law)

Thermal conductivity function of :

the degree of saturation (moisture content)

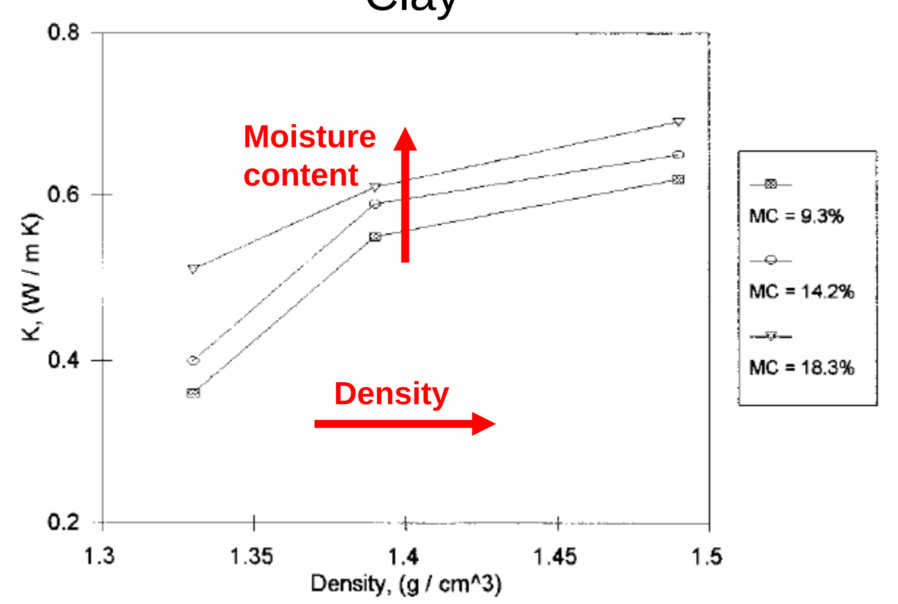
the porosity (dry density)

Sand



Thermal conductivity as a function of soil density for sand at three different moisture contents (1.4, 2.5, 3.3%).

Clay



Thermal conductivity as a function of soil density for clay loam at three different moisture contents (9.3, 14.2, 18.3%).

Abu-Hamdeh and Reeder (2000)

3. Governing equations

Heat capacity

The heat capacity, C_p, characterizes the capacity of material to store or release heat

$$\frac{\partial T}{\partial t} = \frac{-div\left(\mathbf{Q}_{\mathbf{T,conduction}} + \mathbf{Q}_{\mathbf{T,convection}}\right)}{\rho C_p}$$

Thermal diffusivity

$$\alpha = \frac{\Gamma}{\rho C_p}$$

The thermal diffusivity α measures the ability of material to conduct thermal energy relative to its ability to store thermal energy

3. Governing equations

Thermal conductivity - Measurement in the lab (ULg)

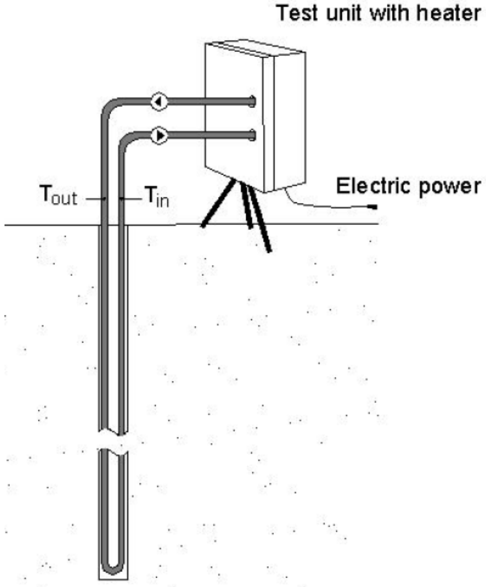
Aiguille chauffante

Echantillon d'argile sèche

Echantillons de limon et de sable secs

3. Governing equations

Thermal conductivity
Measurement in the field
(thermal response test)



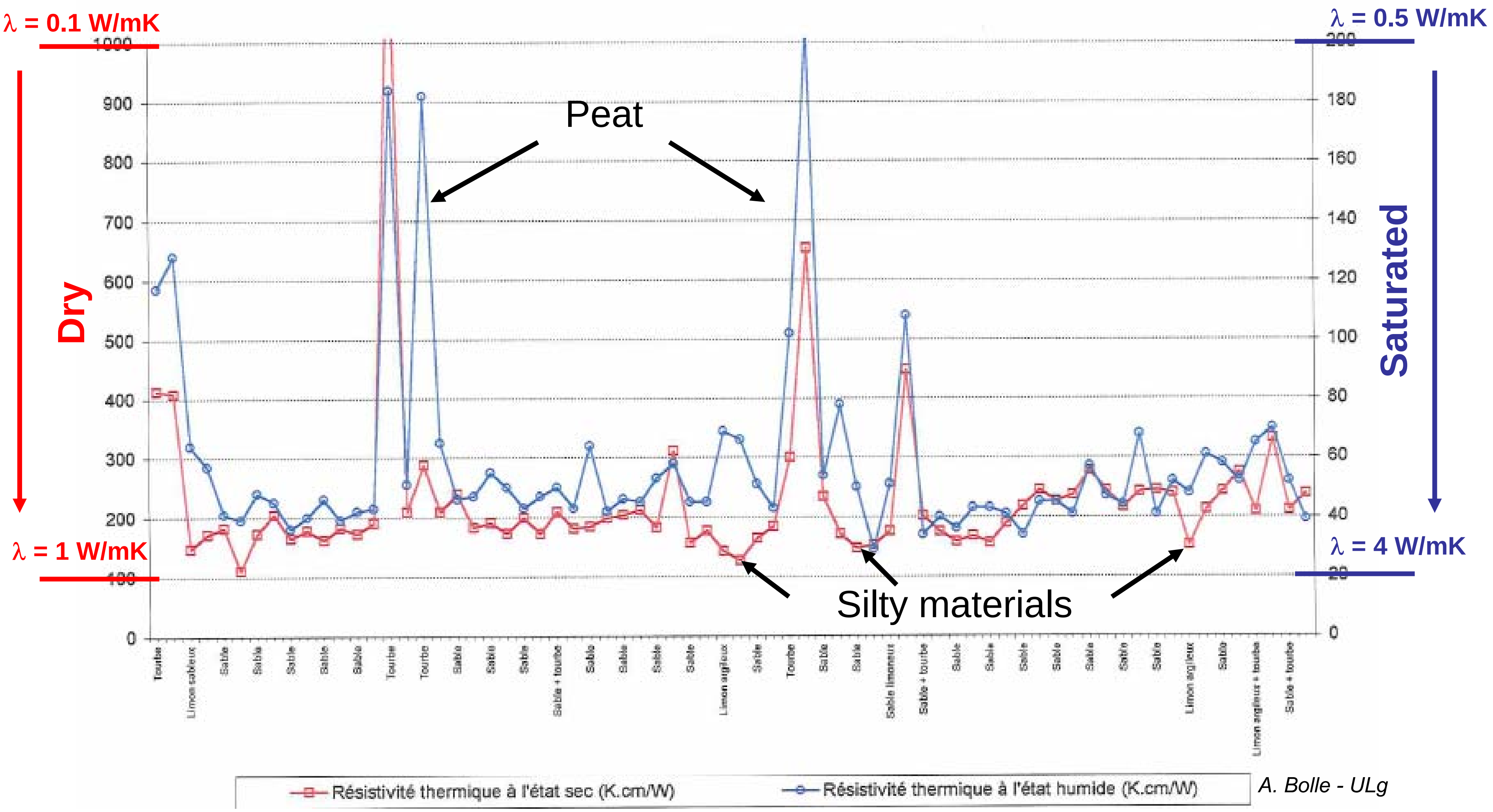
Injecting a known flow of heat and measure its response in terms of temperature change

EPFL, Lausanne (CH)

Kensa Engineering Ltd (UK)

3. Governing equations

Thermal conductivity - Measurement in the lab (ULg)



λ = 0.1 W/mK

Dry

λ = 1 W/mK

Peat

Silty materials

λ = 0.5 W/mK

Saturated

λ = 4 W/mK

A. Bolle - ULg

3. Governing equations

Convection

$$\mathbf{Q}_{\mathbf{T},convection} = c_{p,w}\rho_w\mathbf{f}_\mathbf{w}$$

with $$\mathbf{f}_\mathbf{w} = -\mathbf{K}_\mathbf{w}\mathbf{grad}\left(h_w\right)$$

Heat convection in soil is an energy transfer by **motion of fluid**.

The fluid motion is the result of **a water potential gradient** that may be due to:

- Water pressure gradient
- An hydraulic pump
- A thermal gradient that generates water flux

In addition to the water potential gradient, the water flux is a function of the **permeability of the soil**

Summary of λ, Cp and Kw for different soils

Source : SIA D0190

Soil	Permeability K_w/μ_w (m/s)	Thermal conductivity λ (W.m^{-1}K^{-1})		Thermal heat capacity C_p (MJ.m^{-3}K^{-1})	
		Dry	Saturated	Dry	Saturated
Clay	10^{-10}-10^{-8}	0.2 - 0.3	1.1 - 1.6	0.3 - 0.6	2.1 - 3.2
Silt	10^{-8} -10^{-5}	0.2 - 0.3	1.2 - 2.5	0.6 - 1.0	2.1 - 2.4
Sand	10^{-4} -10^{-3}	0.3 - 0.4	1.7 - 3.2	1.0 - 1.3	2.2 - 2.4
Gravel	10^{-3}-10^{-1}	0.3 - 0.4	1.8 - 3.3	1.2 - 1.6	2.2 - 2.4

High variability

Low variability

4. Numerical simulations

Tools for designing geothermal systems

4a. Geothermal probes

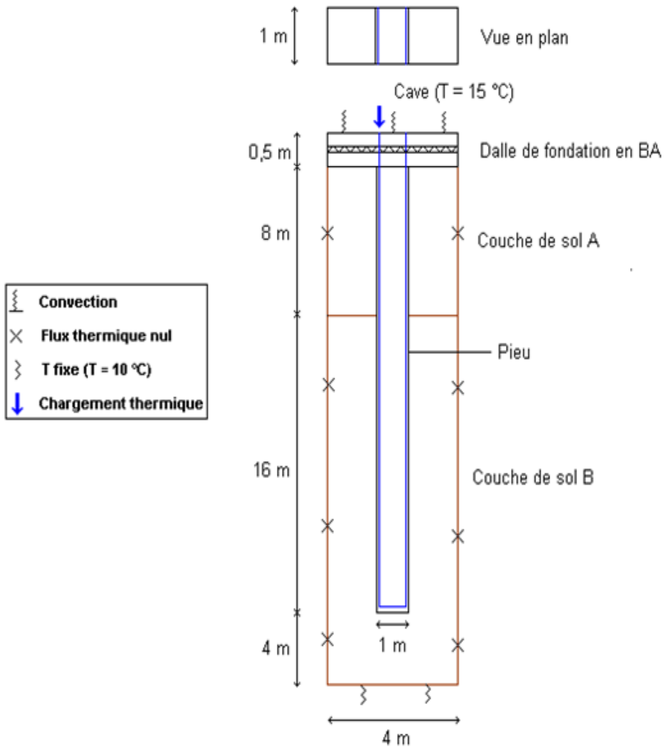
3. Governing equations

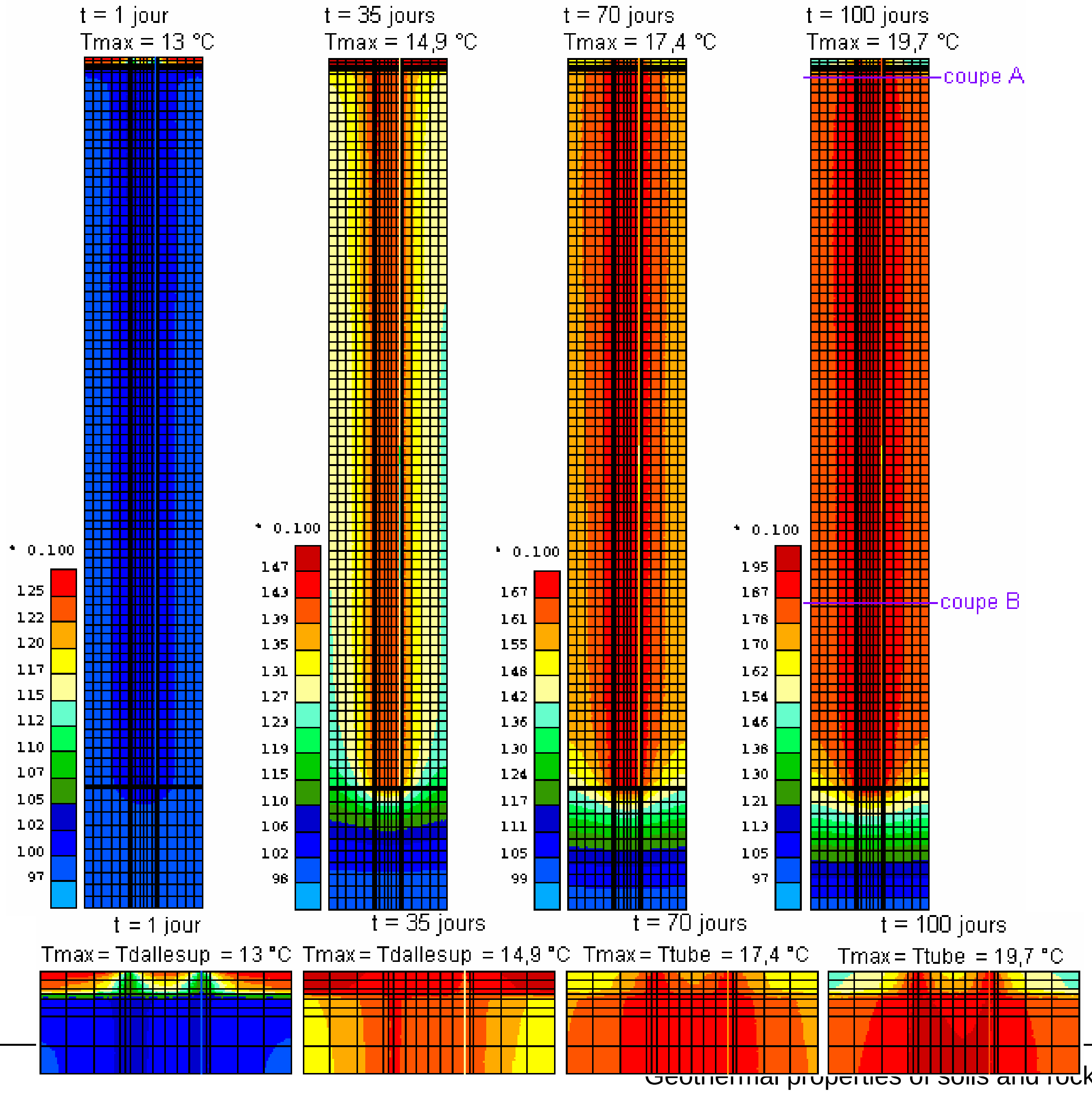
Physical aspects: Various terms of coupling

Couplings	N° of Dof 2D	N° of dof 3D
Heat diffusion T: Degree of freedom (dof) : 1 temperature	1	1
Heat diffusion + water transport coupling. dof : 1 water pressure + 1 temperature	2	2
Heat diffusion + Saturated Hydromechanical coupling. dof: coordinates + 1 water pressure + 1 temperature	4	5
Heat diffusion + two fluids flow in rigid porous media. Dof : 2 pressures (liquid + gas) + 1 temperature	3	3
Fully thermo-hydro-mechanical coupling. Dof : coordinates + 2 pressures + 1 temperature	5	6

4. Numerical simulations – TFE Tyberghein

Temperature evolution in the pile and in the soil for a constant heat flux of 25 W/m



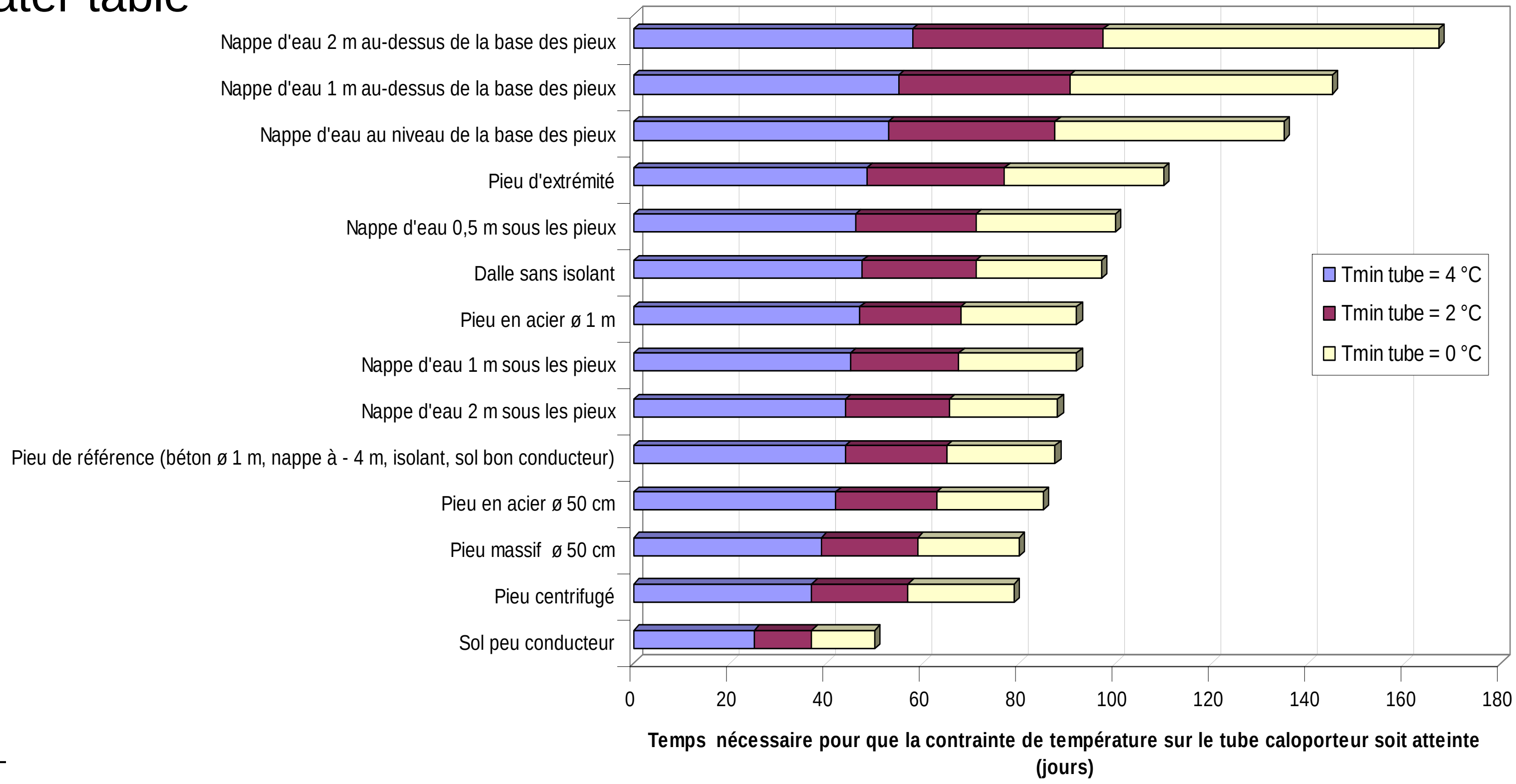


4. Numerical simulations – TFE Tyberghein

Time needed to reach $T_{fluid} = T_{min}$ (heat power: 35 W/m) – Parametric study

Parametric study on the performance of exchanger piles:

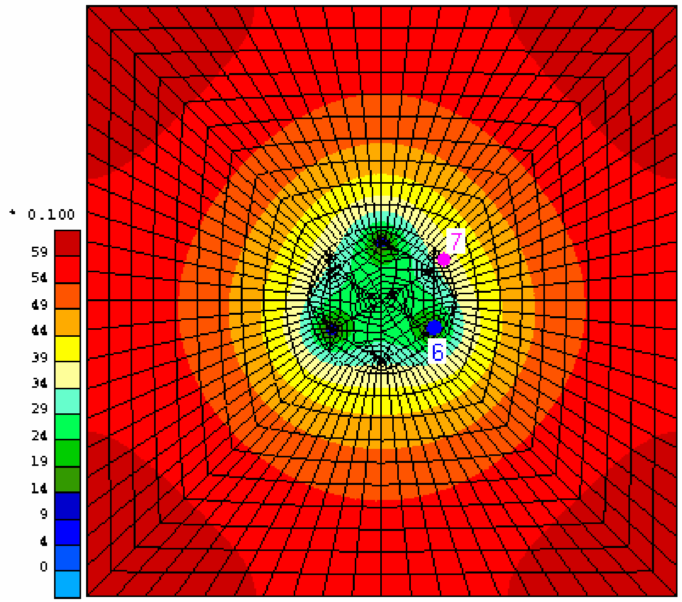
- Isolation of the building slab
- Kind and dimension of piles
- Soil characteristic
- Heigth of the water table



4. Numerical simulations – TFE Tyberghein

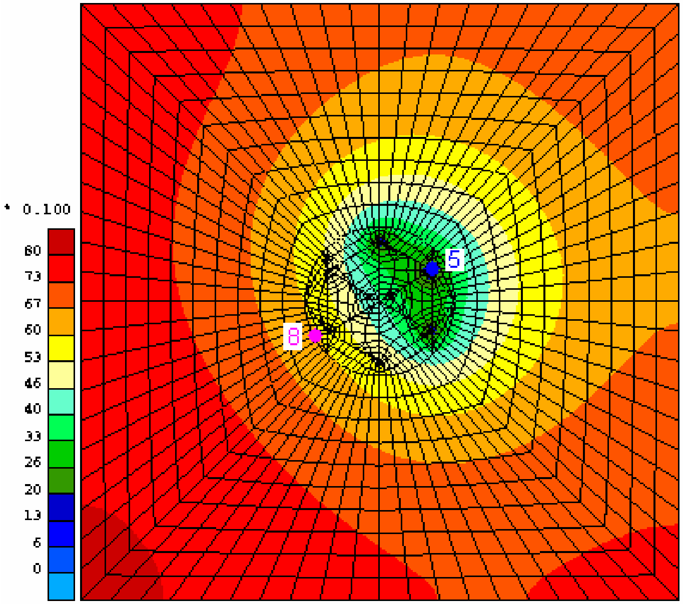
Temperature distribution in the pile

Symmetrical thermal loading



Distribution de température dans le pieu et le sol après 40 jours d'extraction de 35 W/m de chaleur de manière symétrique

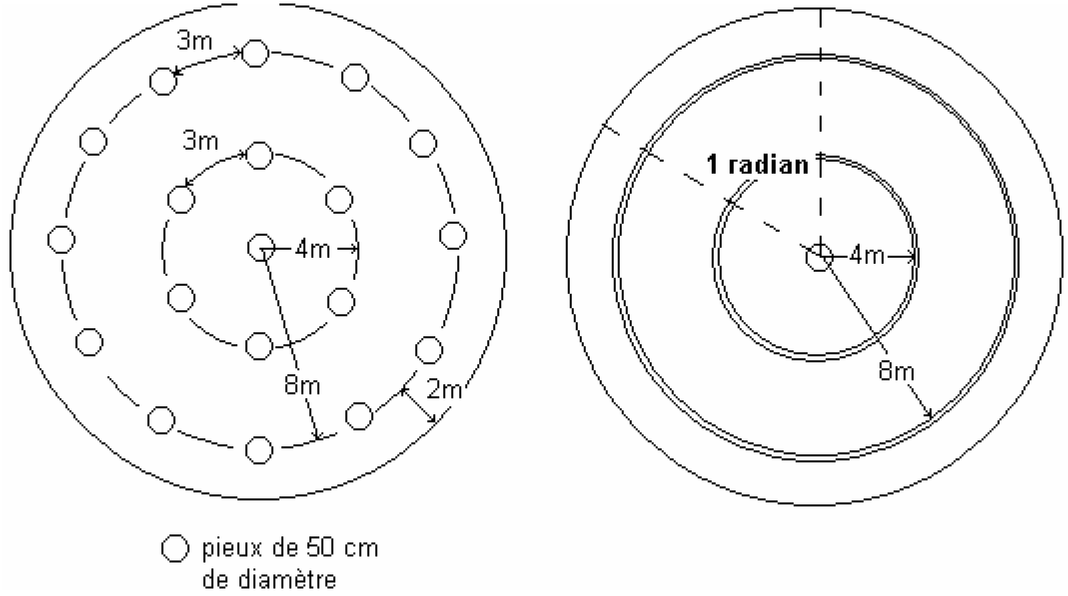
Unsymmetrical thermal loading



Distribution de température dans le pieu et le sol après 40 jours d'extraction de 35 W/m de chaleur de manière dissymétrique

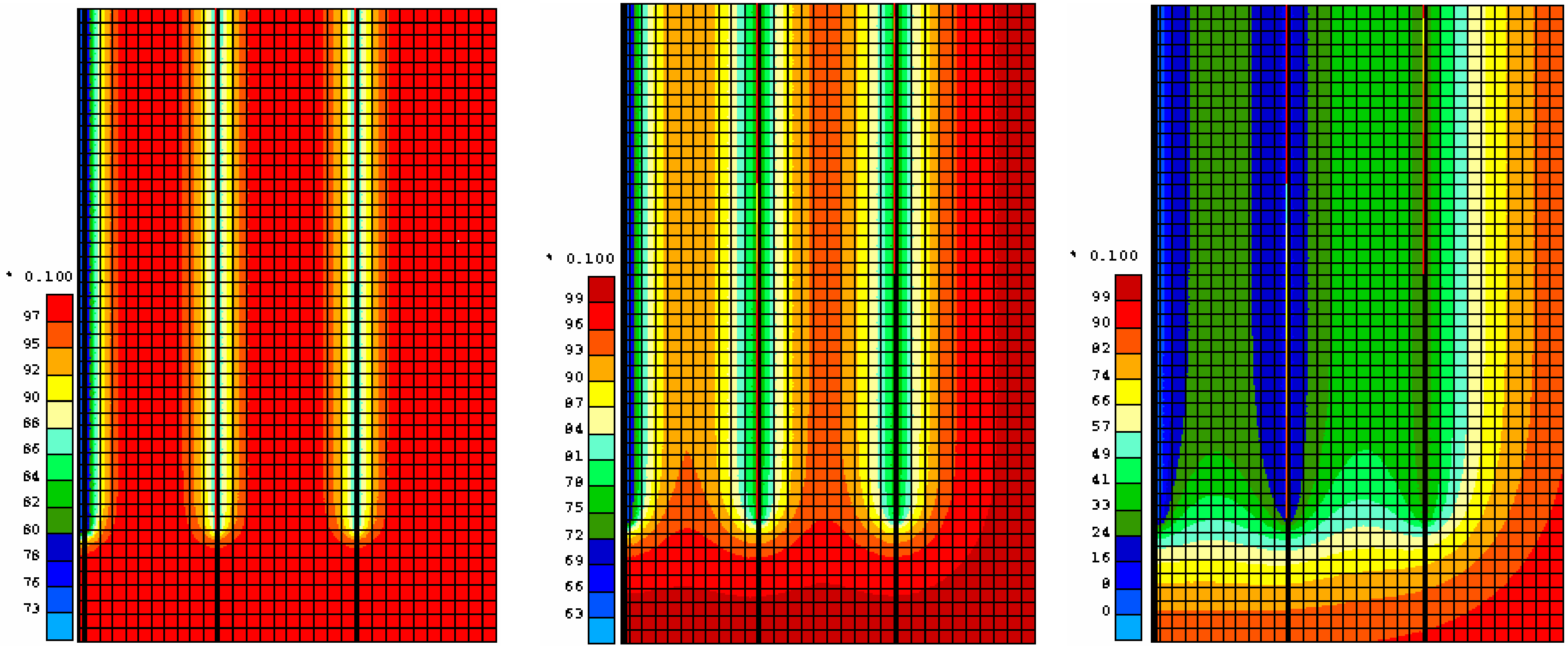
4. Numerical simulations – TFE Tyberghein

Axisymmetric modelling of a group of piles



4. Numerical simulations – TFE Tyberghein

Axisymmetric modelling of a group of piles



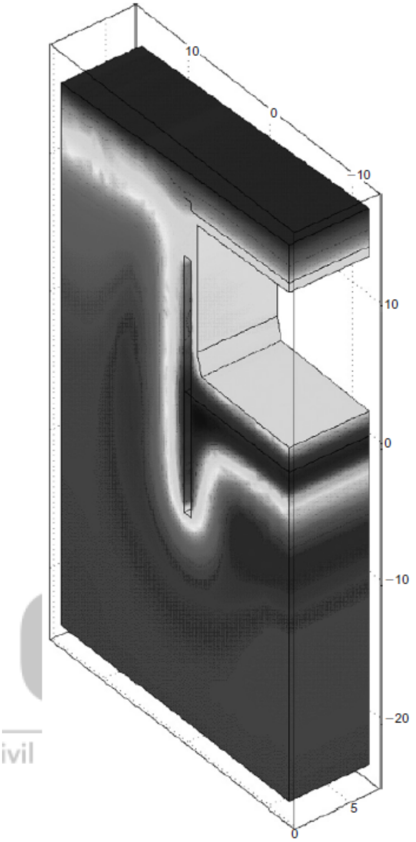
t = 5 days t = 15 days t = 100 days

Thermal power: 35 W/m

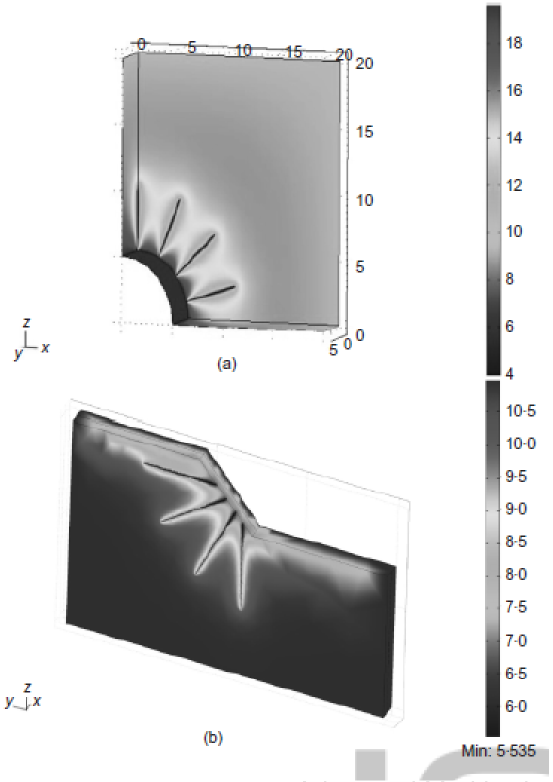
4. Numerical simulations

Modelling of the temperature distribution in various geostructures (purely thermal – no coupling)

Walls and slabs of a metro station



Energy anchors in tunnels or retaining structure



Adam and Markiewicz, Géotechnique 2009

4. Numerical simulations

4b. Pumping wells

4. Numerical simulations: heat transfer associated to groundwater saturated flow

□ Heat transport equation

$$\boxed{\left(\frac{\rho_m c_m}{n_e \rho_w c_w}\right)} . n_e . \frac{\partial T}{\partial t} = \overrightarrow{div} . \left[n_e \boxed{\left(\frac{\lambda_m}{n_e \rho_w c_w} + \mathbf{D} \right)} \overrightarrow{grad}\, T \right] - \overrightarrow{div} \boxed{(n_e . v_e . T)} + \boxed{\frac{q'}{\rho_w c_w}}$$

Thermic equilibrium

Conduction
Diffusion
Dispersion

Convection

Injection-Extraction of heat

□ Solute transport equation

$$\boxed{R.} n_e . \frac{\partial C^v}{\partial t} = \overrightarrow{div} . \left[n_e \boxed{\left(\mathbf{D_h} . \overrightarrow{grad}\, (C^v) \right.} \boxed{\left. - v_e C^v \right)} \right] + \boxed{C^{v*} q'} - n_e \lambda C^v R$$

Sorption-Desorption

Diffusion
Dispersion

Advection

Sink-Source

4. Numerical simulations: heat transfer associated to groundwater saturated flow

Non linearities:

- **Hydraulic conductivity *K***

$$K\left[\frac{m}{s}\right] = \frac{k[m^2].\rho_w.g}{\mu_w}$$

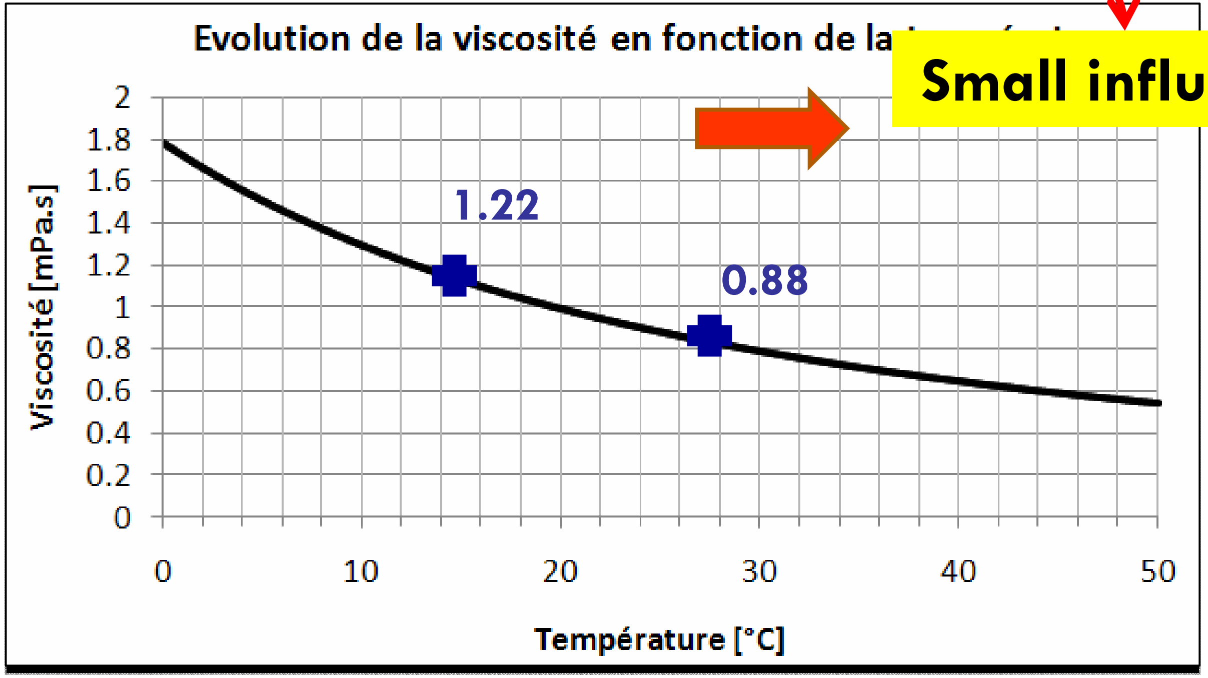
- **Thermal conductivity *λ***
- **Heat capacity *c***

	K (12°C) [m/s]	K (25°C) [m/s]	λ_s (0°C) [W/m.K]	λ_s (12°C) [W/m.K]	λ_s (25°C) [W/m.K]	c_s (12°C) [J/kg.K]	c_s (25°C) [J/kg.K]
Loam and backfill	10^{-6}	$1.4\ 10^{-6}$	1.95	1.94	1.91	790	810
Sand and gravel	0.005	0.007	1.95	1.94	1.91	790	810

4. Numerical simulations: heat transfer associated to groundwater saturated flow

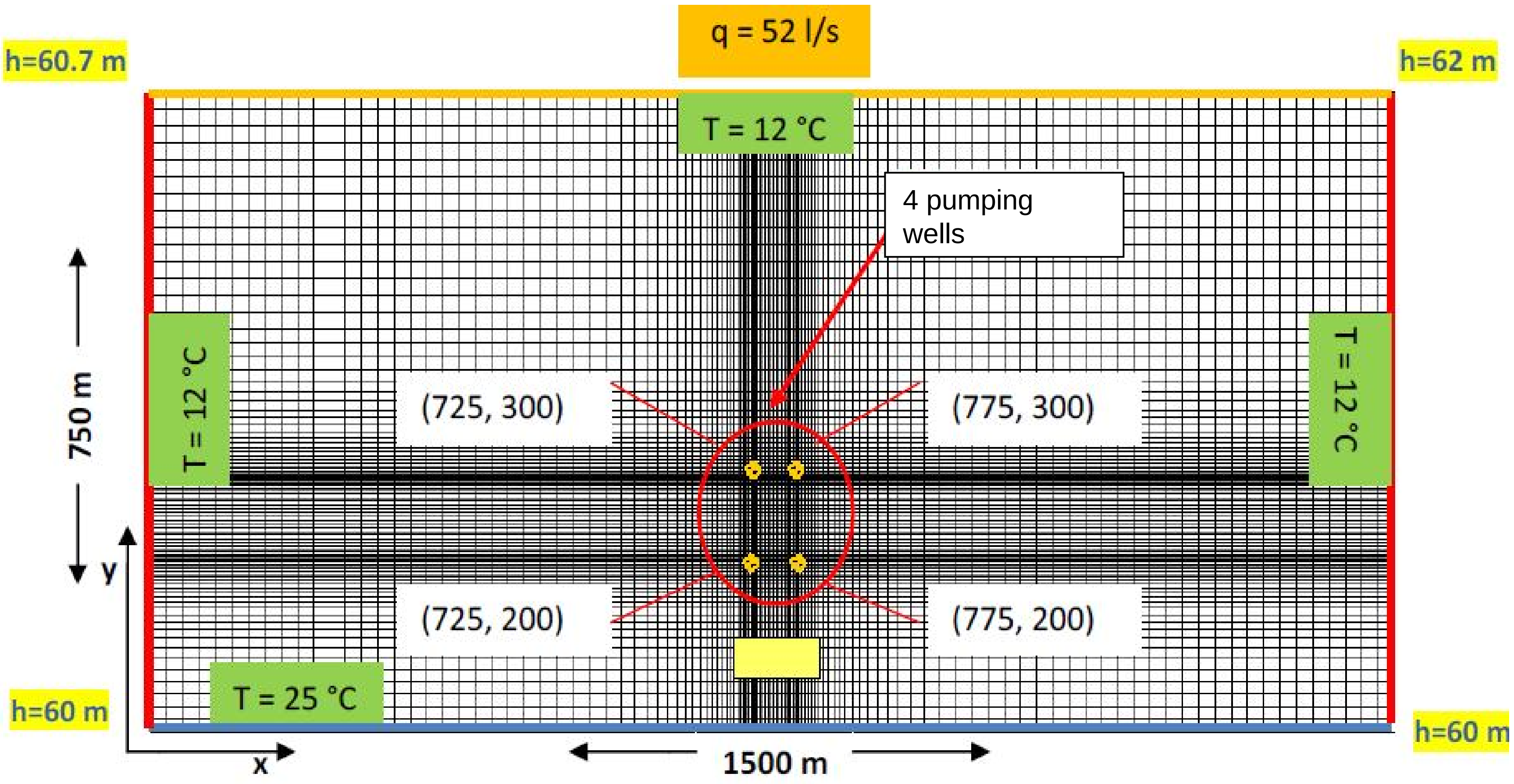
- **Hydraulic conductivity *K***

$$K\left[\frac{m}{s}\right]=\frac{k\,[m^2].\boxed{\rho_w}.g}{\boxed{\mu_w}}$$

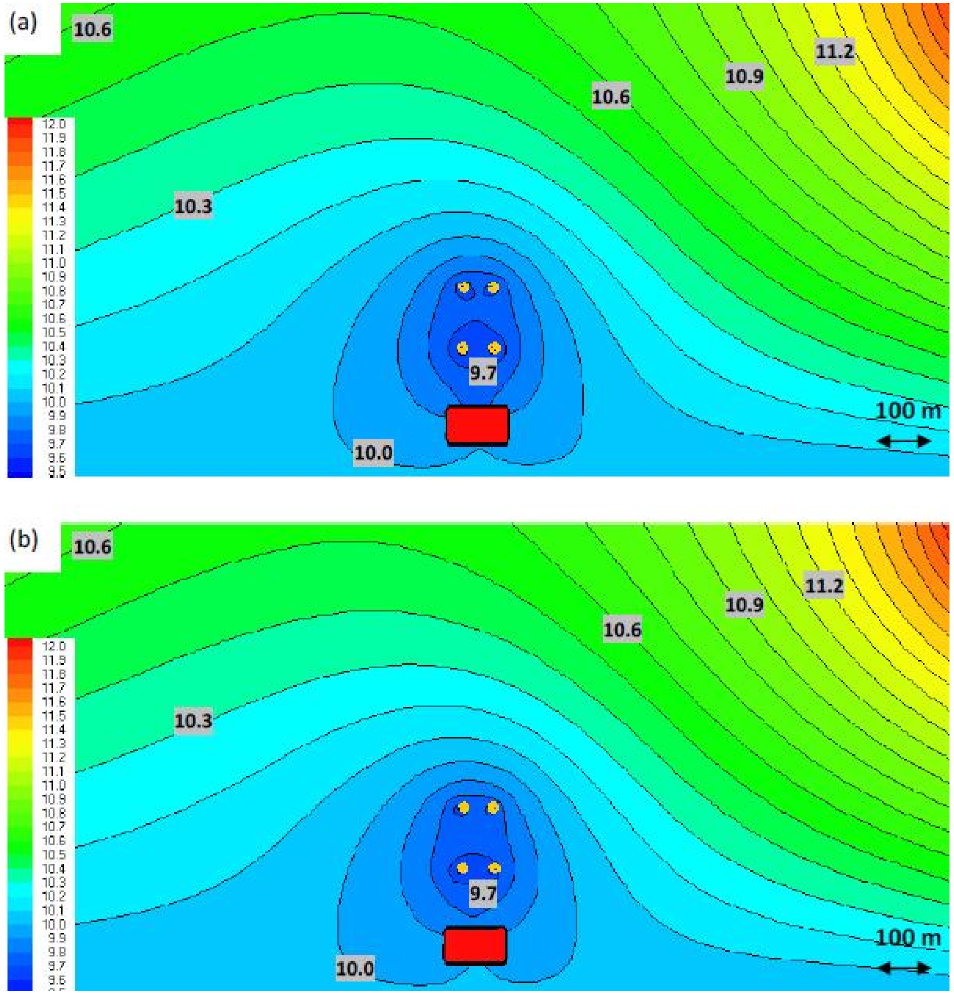


Small influence

Synthetical model



Synthetical model

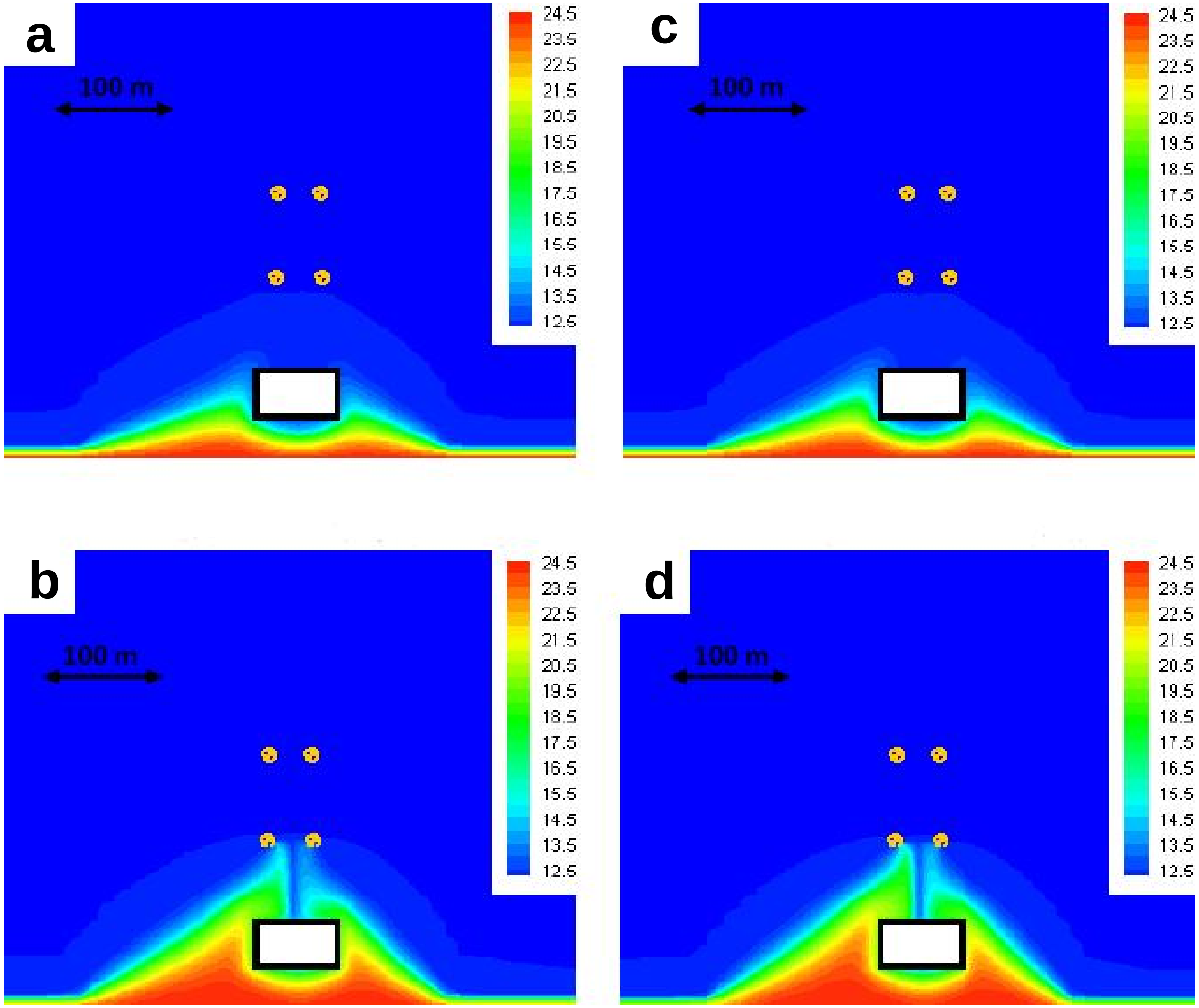


computed stabilized piezometric levels due pumping:

(a) MT3D results (constant parameters taken for a 12°C temperature);

(b) SHEMAT results (non linear parameters).

Synthetical model

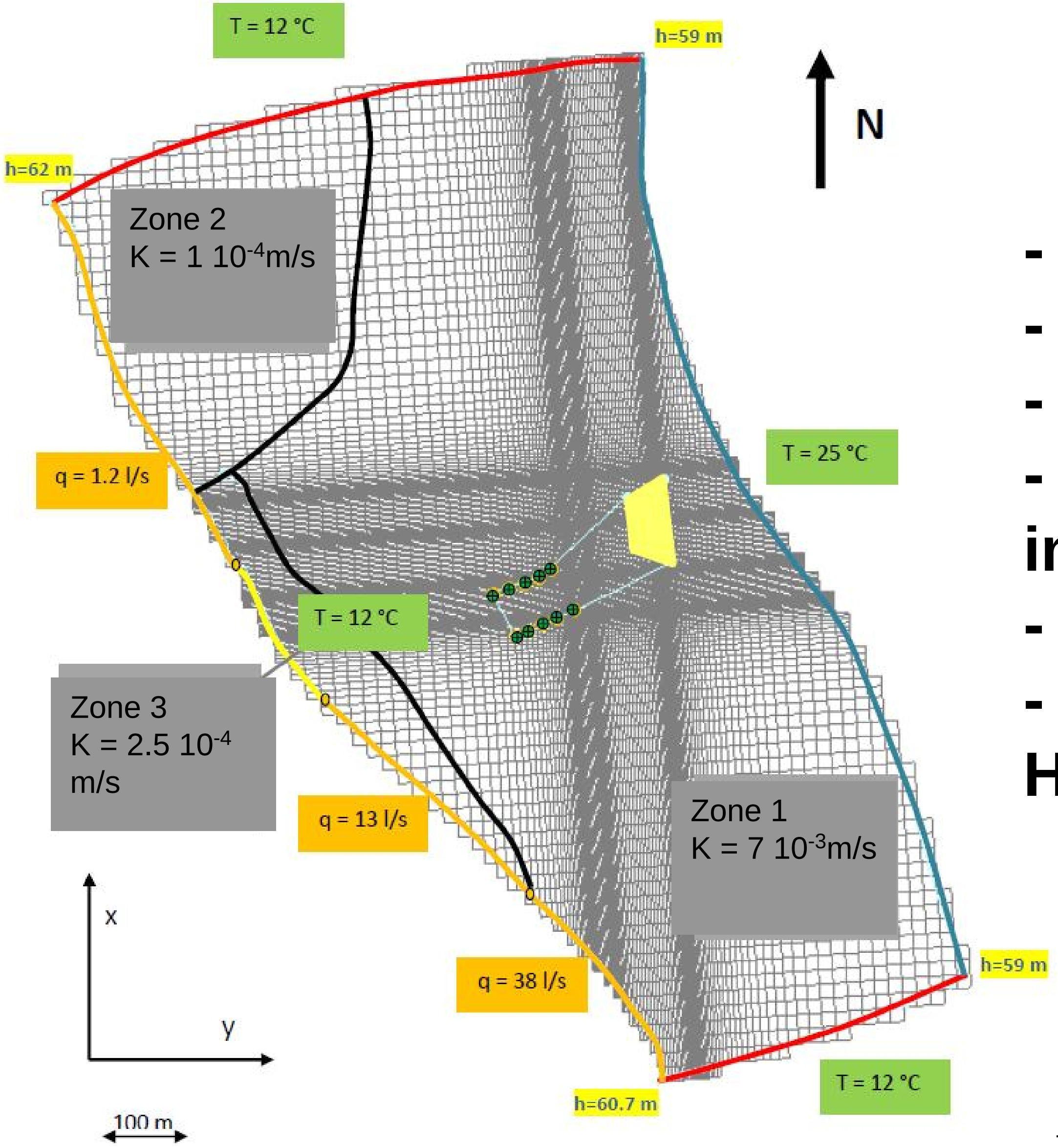


computed temperature:

(a) and (b) MT3D results respectively after 3 days and 1 week of pumping;

(c) and (d) SHEMAT results respectively after 3 days and 1 week of pumping.

4. Numerical simulations: heat transfer associated to groundwater saturated flow



Case study

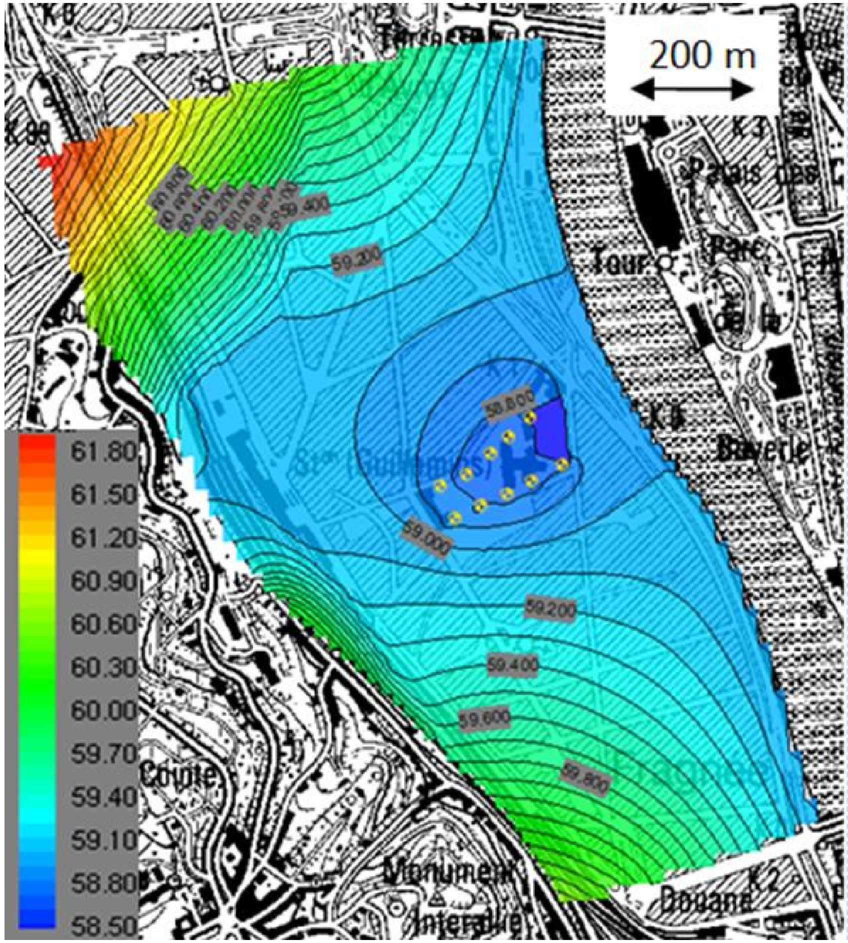
- two layers model
- worst case scenario
- max pumping 7d/week
- no recharge (neglected infiltration)
- river at 25 °C
- constant parameters with HGS and MT3D

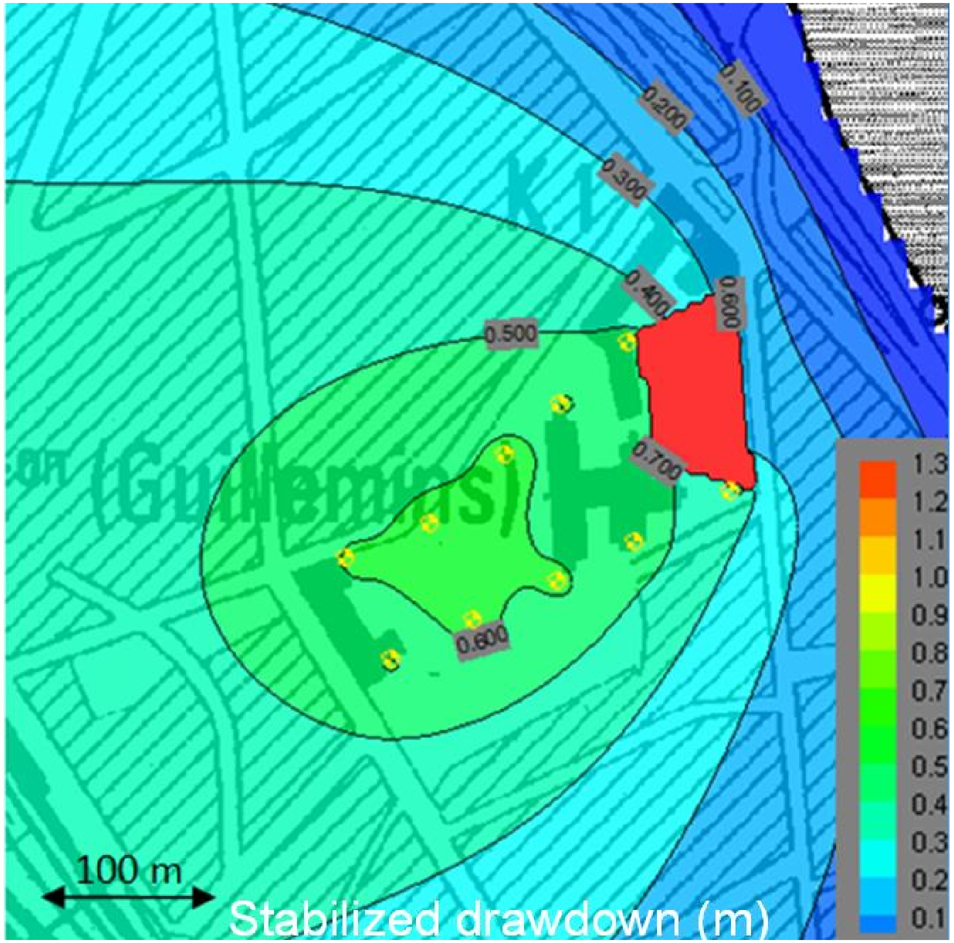
Alain Dassargues, Robert Charlier, Bertrand François

4. Numerical simulations: heat transfer associated to groundwater saturated flow

Stabilised piezometric heads and drawdown as modelled for a continuous pumping of 20 m³/h in each of the 10 wells

Case study

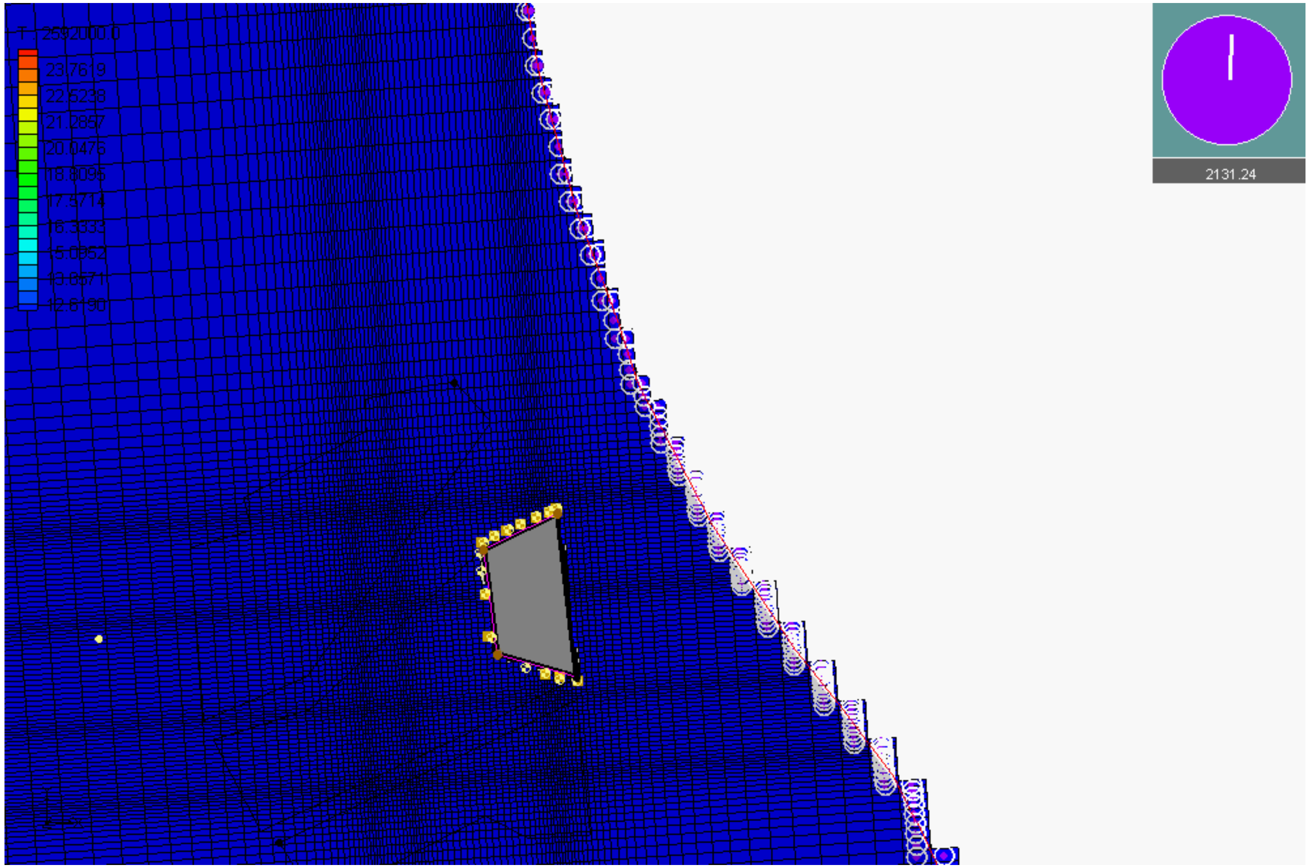




4. Numerical simulations: heat transfer associated to groundwater saturated flow

Computed temperature in the aquifer with a continuous pumping of 20 m³/h in each of the 10 wells

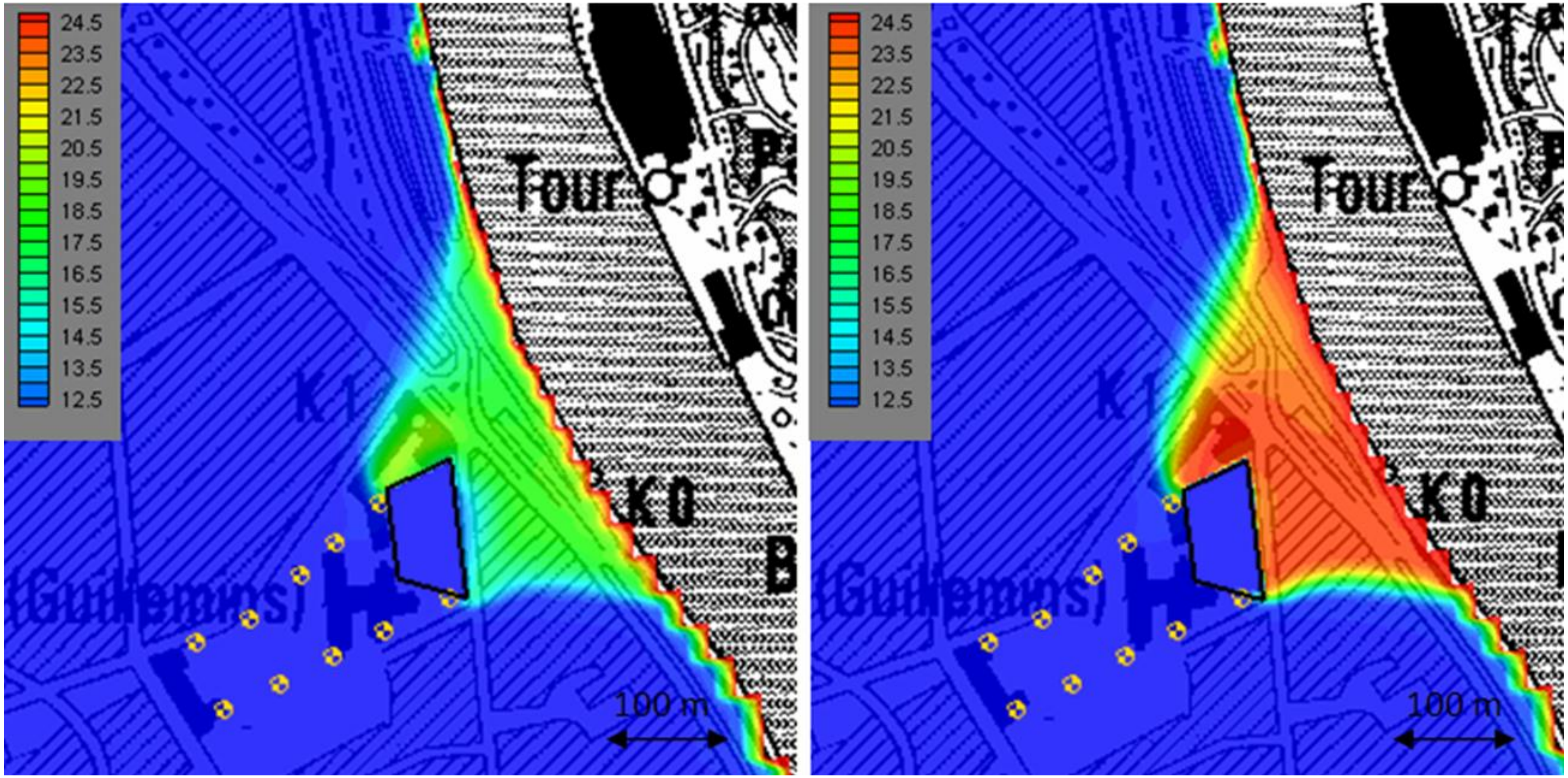
Case study



4. Numerical simulations: heat transfer associated to groundwater saturated flow

Computed temperature in the aquifer after 1 month and 3 months with a continuous pumping of 20 m³/h in each of the 10 wells

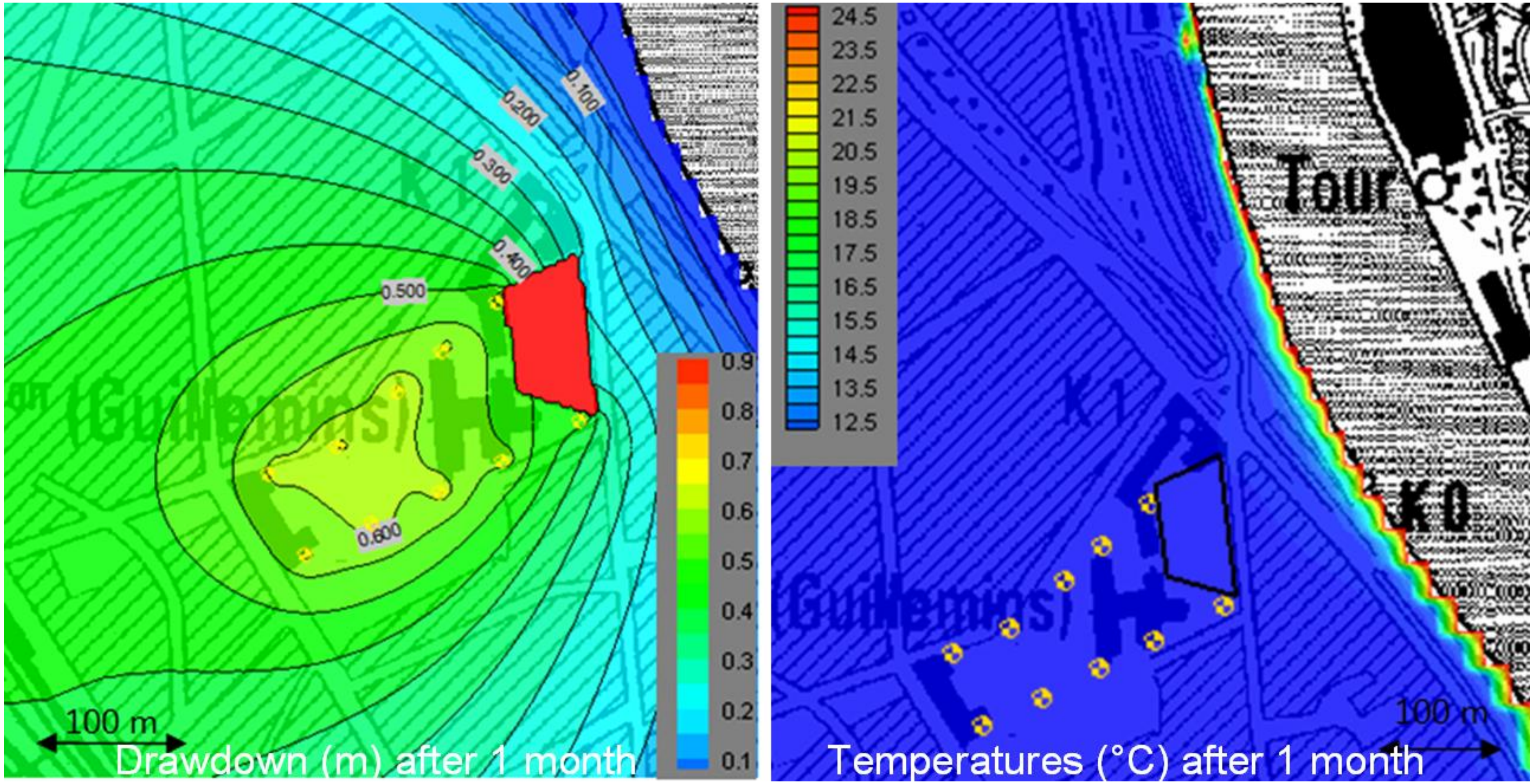
Case study



4. Numerical simulations: heat transfer associated to groundwater saturated flow

Computed maximum drawdown (left) and computed spatial distribution of the temperature (right) in the aquifer after 1 month of intermittent pumping.

Case study



Lessons from the case study

Hydraulic convection = dominant process

- **Best scenario ?**
  - Intermittent pumping **200 m³/h**
- **Sensitivity analysis ?**
  - *K* : very sensitive !

    → **Needed pumping test for a better calibration**
- **On the security side ?**
  - No heat adsorption by porous medium matrix taken into account
  - « Worst case scenario »
- **Weakness of the analysis ?**
  - Constant parameters with temperature

    →**coupled and non linear model could be needed for higher t°**

6. Conclusions

5. Conclusions

- **link between geothermal systems and geotechnical and hydrogeological technologies** well established in many European countries (CH, A, UK, DE). What about Belgium ?
- possibility to **combine geothermy and geostructures**
- need of a **characterisation of the ground** (thermal and hydraulic behaviours)
- **design of geostructures** (ex: heat exchanger piles) combine the geothermal probe design and the classical pile design
- **optimisation of groundwater pumping** with respect to heat transport in the aquifer
- no clear European or National standards, only **recommendations**
- **numerical tools are ready but experimental data are scarce and legislation not adapted**