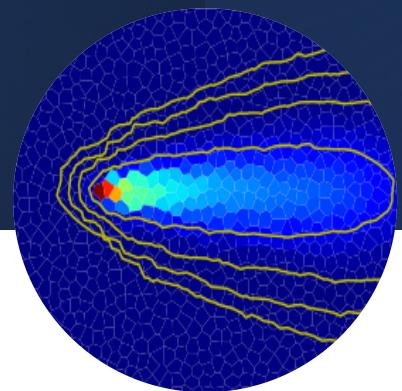
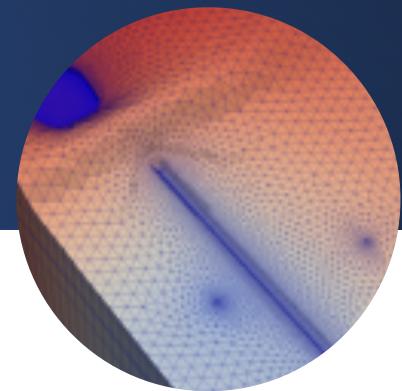
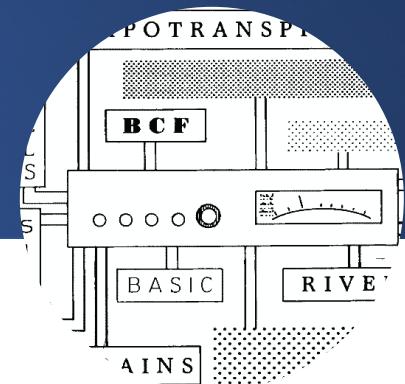


Aquifer Thermal Energy Storage (ATES)

With the Groundwater Energy package



Deltares

INTERA

$\Sigma^2\Pi$

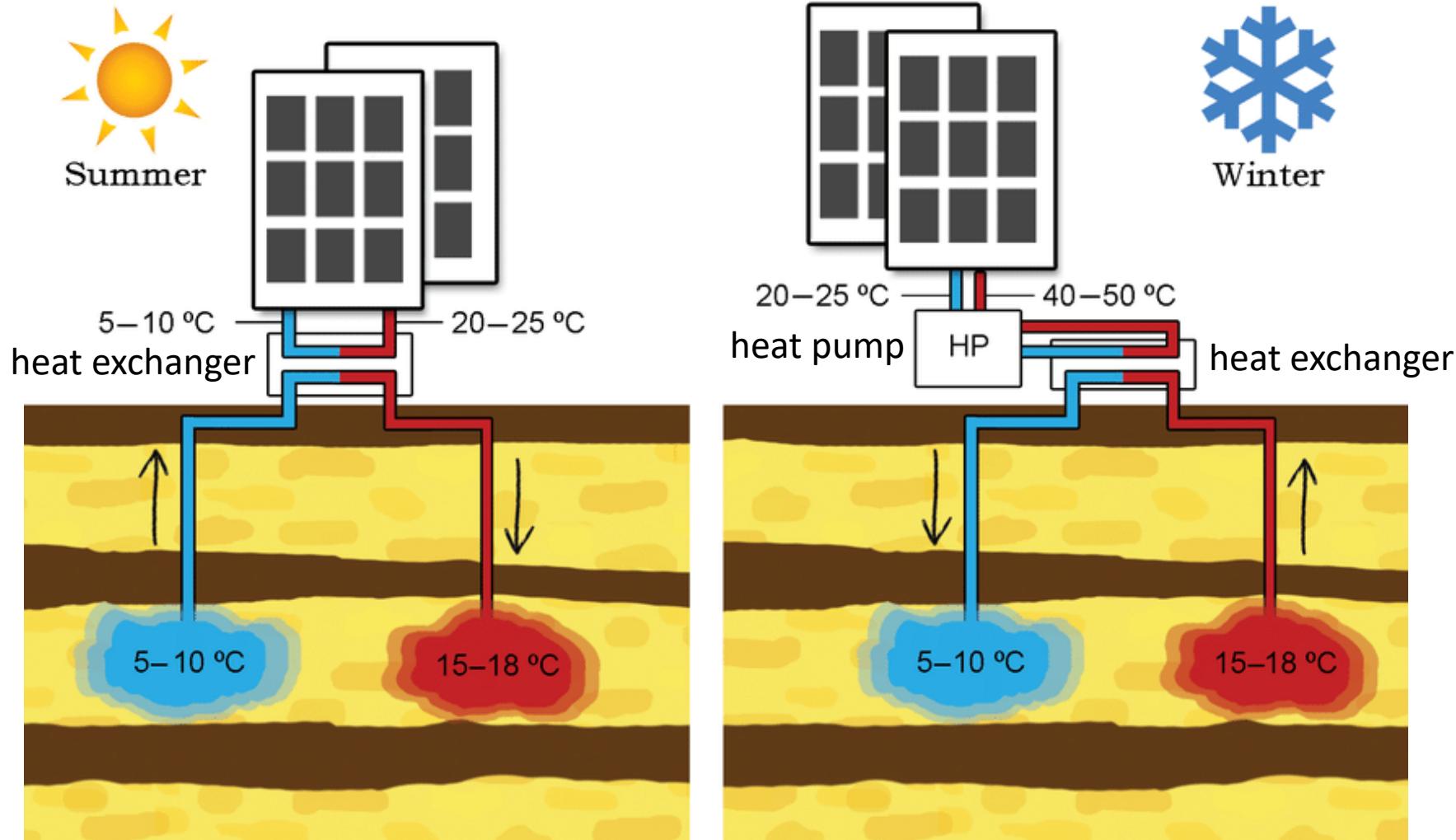
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Aquifer Thermal Energy Storage (ATES)

Warmte Koude Opslag (WKO)



First thermal energy flux: Advection

- Heat flow with the water

$$\vec{J}_a = c_w \rho_w T \vec{q} \quad \left[\frac{\text{J}}{\text{m}^2 \text{d}} \right]$$

heat capacity (mass based) c_w [J/(kg°C)]

density ρ_w [kg/m³]

heat capacity (volume based) $c_w \rho_w$ [J/(m³ °C)]

Second thermal energy flux: Conduction

- Heat flow caused by temperature gradient (Fourier's law)

$$\vec{J}_d = -\theta \kappa_w \vec{\nabla} T - (1 - \theta) \kappa_s \vec{\nabla} T \quad \left[\frac{\text{J}}{\text{m}^2 \text{s}} \right]$$

thermal conductivity water κ_w $\left[\frac{\text{J}}{\text{ms}^\circ\text{C}} \right]$

thermal conductivity solids κ_s $\left[\frac{\text{J}}{\text{ms}^\circ\text{C}} \right]$

Darcy's law for
temperature

Conduction through both
water and solids

Important approximation: equilibrium between water and solids

Second thermal energy flux: Conduction

- Heat flow caused by temperature gradient

$$\vec{J}_d = -\theta \kappa_w \vec{\nabla}T - (1 - \theta) \kappa_s \vec{\nabla}T \quad \left[\frac{\text{J}}{\text{m}^2 \text{d}} \right]$$

$$= -\kappa_b \vec{\nabla}T$$

thermal conductivity water κ_w

thermal conductivity solids κ_s

thermal conductivity bulk κ_b

$$\left[\frac{\text{J}}{\text{ms}^\circ\text{C}} \right]$$

convert to

$$\left[\frac{\text{J}}{\text{md}^\circ\text{C}} \right]$$

Second thermal energy flux: Conduction plus Dispersion

- Heat flow caused by temperature gradient

$$\vec{J}_d = -(\kappa_b + \theta c_w \rho_w D) \vec{\nabla} T \quad \left[\frac{\text{J}}{\text{m}^2 \text{d}} \right]$$

D Dispersion coefficient computed from dispersivity and velocity

Energy balance: In - Out = Increase in Energy

- Increase in energy

$$c_b \rho_b \frac{\partial T}{\partial t}$$

bulk heat capacity $c_b \rho_b = \theta c_w \rho_w + (1 - \theta) c_s \rho_s$ [J/(m³ °C)]
(volume based)

ΔT temperature increase of 1 m³ of aquifer (water and solids)
represents $c_b \rho_b \Delta T$ Joule energy

When combining all terms, Heat Transport is governed by the Advection - Dispersion equation

- Thermal dispersion coefficient

$$D = \frac{\kappa_b}{\theta c_b \rho_b} + \alpha_L |v_{\text{avg}}|$$

- Thermal retardation coefficient

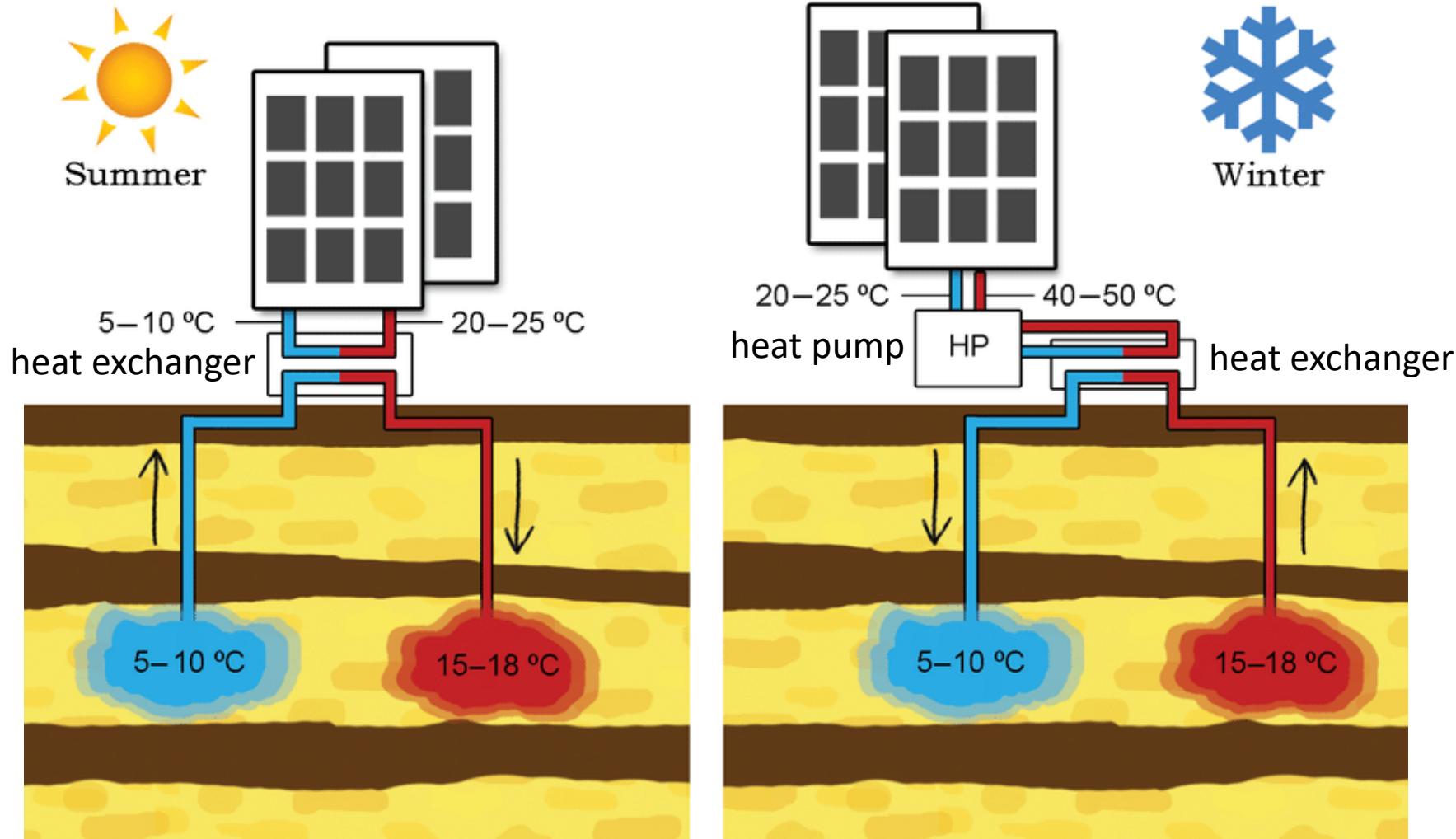
$$R = \frac{c_b \rho_b}{\theta c_w \rho_w}$$

What we need for a heat transport simulation

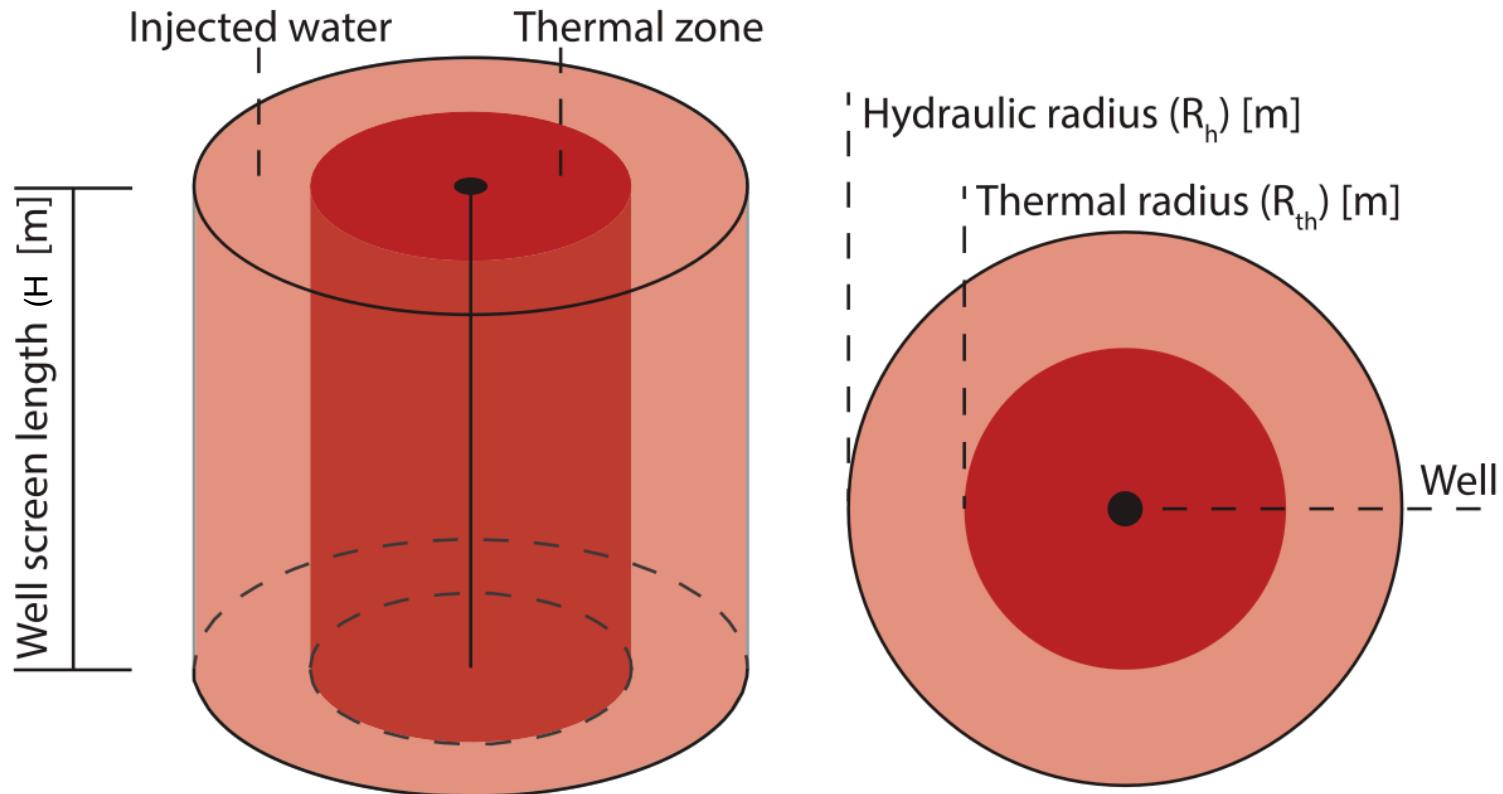
- Heat capacity of water and solids (mass based) C [J/(kg°C)]
- Density of water and solids ρ [kg/m³]
- Thermal conductivity of heat and solids κ [J/(md°C)]

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Designing ATES systems: Approximate injected volume V as a cylinder



Cylinder in absence of conduction and dispersion

$$R_h = \sqrt{\frac{V}{\theta \pi H}}$$

$$R_{th} = \sqrt{\frac{c_w \rho_w V}{c_b \rho_b \pi H}}$$