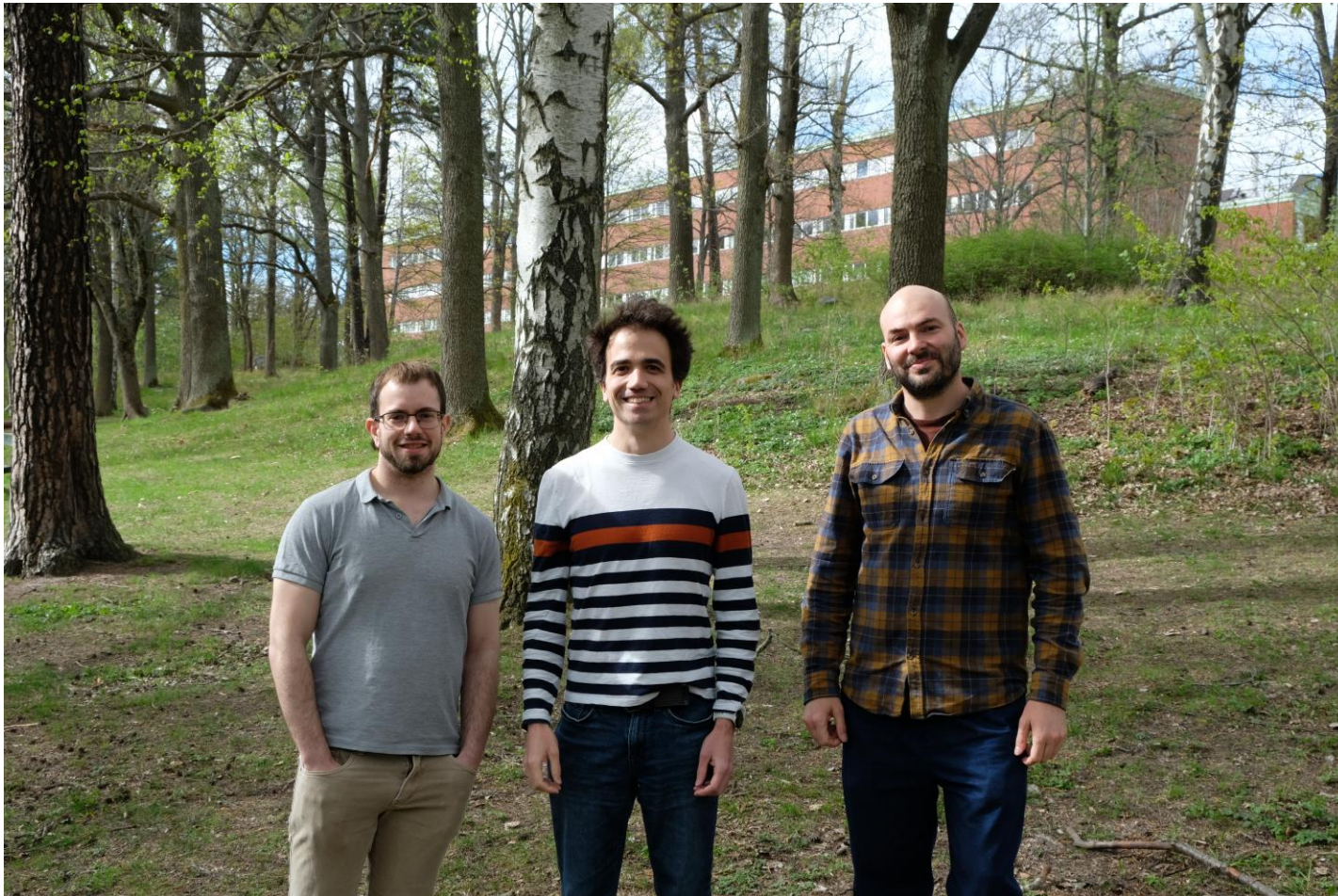




Modeling of networks of borehole heat exchangers

Alberto Lazzarotto

The team



Integrate!geo

Next generation tools for integration of large scale borehole fields in thermal networks

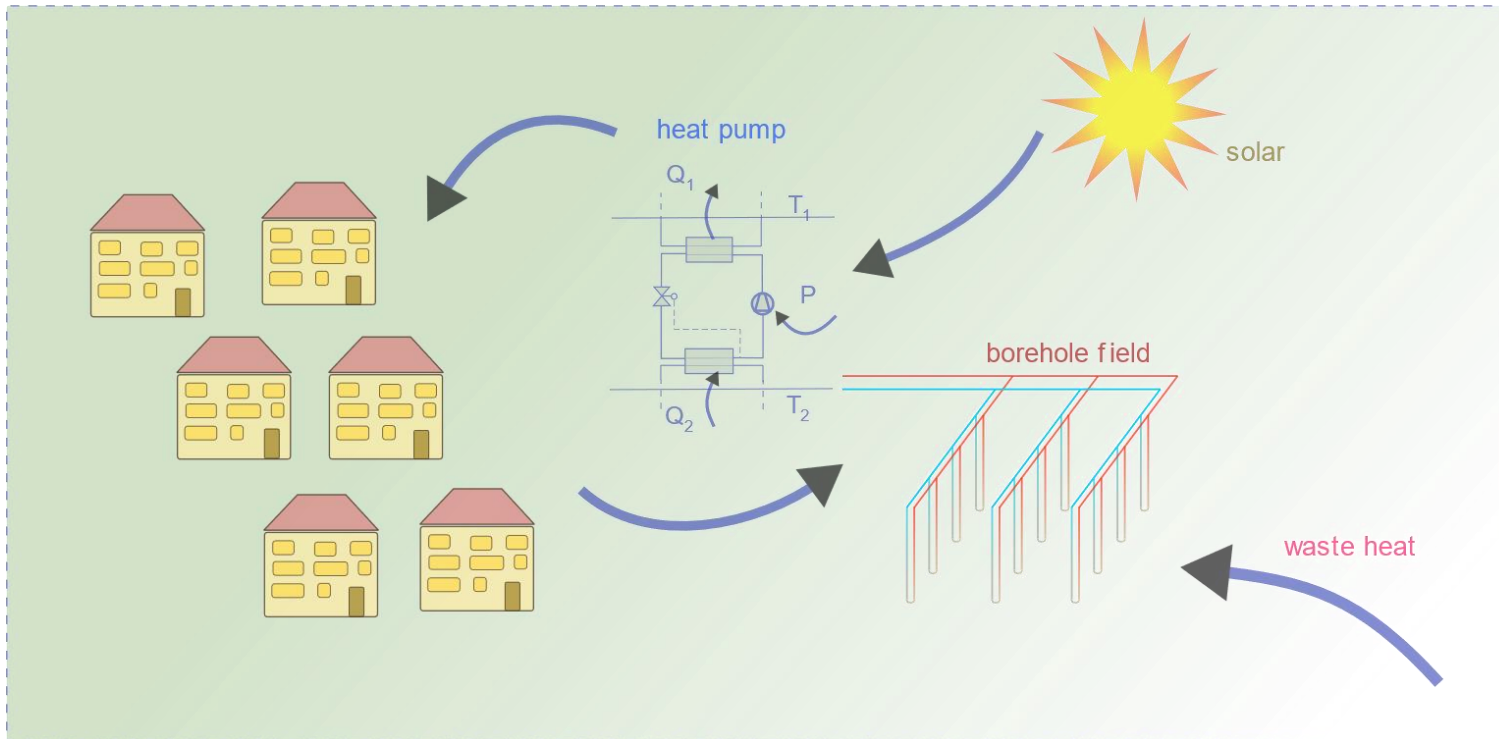


Alberto Lazzarotto, Researcher
Marc Basquens, Postdoc



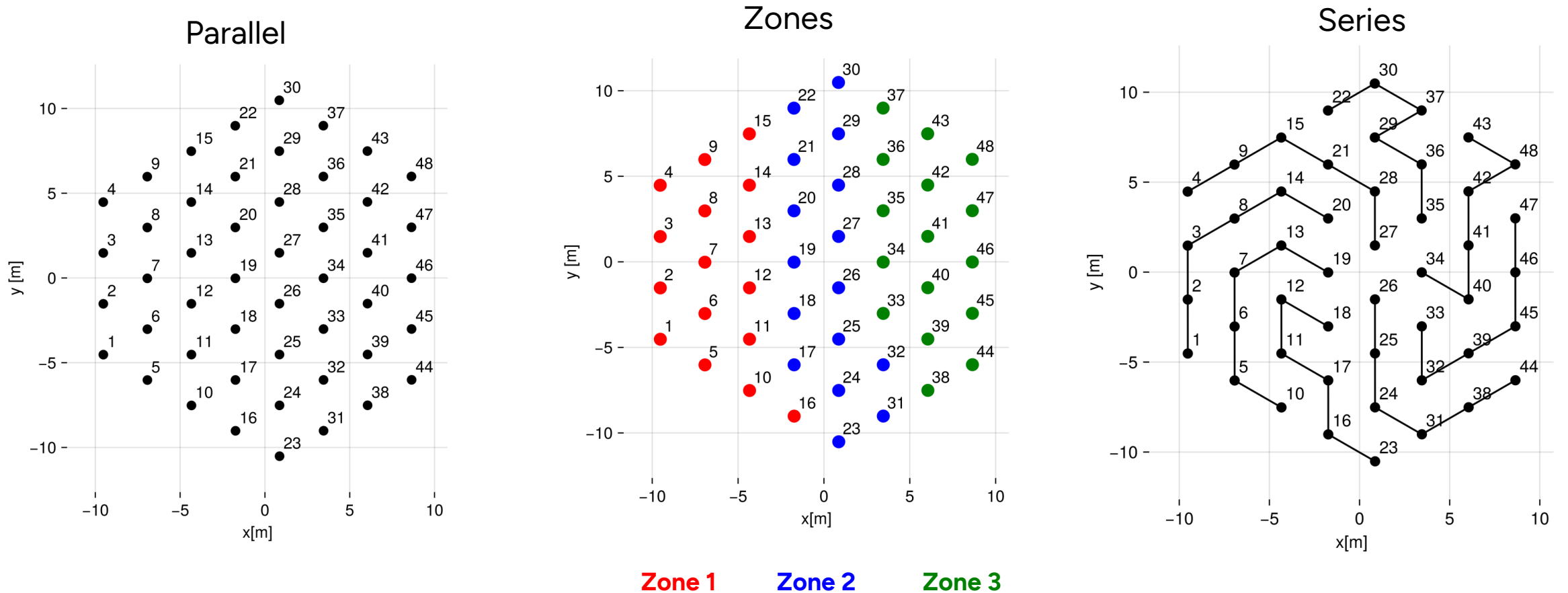
Massimo Cimmino, Associate Professor

Geothermal integration in thermal networks



- Geothermal can be used as **thermal source** or **storage**
- The ground can be coupled with several systems: **heat pumps, waste heat recovery, solar, district heating, etc.**
- **Thermal sources and needs can be intermittent**
- For flexible **integration in thermal networks** we need to be able to model the operation of geothermal with **high temporal resolution**

The borehole field can be fed and operated in different ways



Desired features for borefield simulations

- **large borehole fields**
- **long term operation**
- **short time-step** (hourly) resolution
- **Flexible layout** of borehole fields
- **Flexible topology** of the hydraulic network
- **Fast computation**

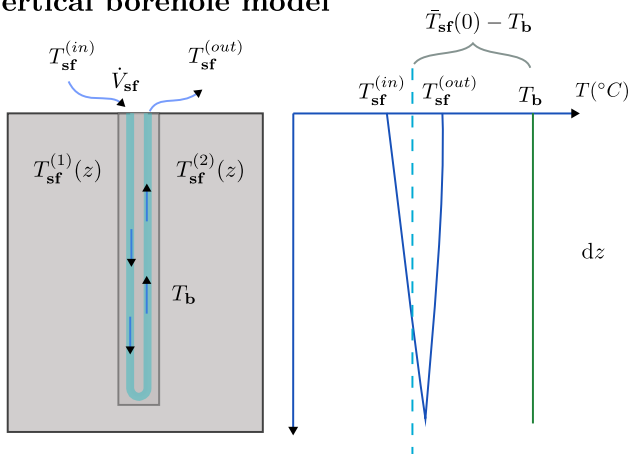
Is this even possible?

YES, if we improve the scaling properties of semi-analytical method for the simulation of boreholefields!

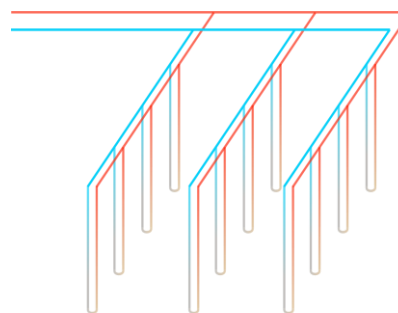
Network-based models

Borehole heat exchanger model

vertical borehole model

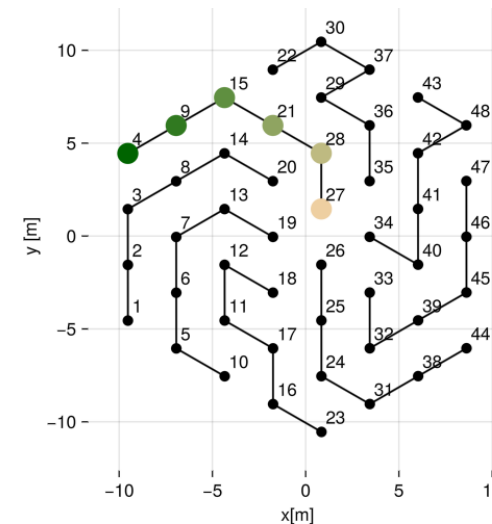


Thermal Interaction between boreholes.
Superposition of line sources in time and space



$q_i(z)$ Power per meter and temperature at borehole i along the coordinate z
 $T_i(z)$

Hydraulic network topology



- Putting together these 3 components and relative equations **we assemble a linear system of equations** $A x = b$
- The unknowns x are relevant temperatures and powers.
- **Every time step**, the given term **b is updated** to take account for the effect of **interaction between boreholes**.
- **The update of b is the costly operation.**

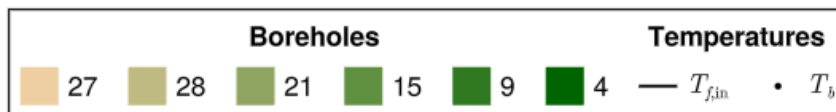
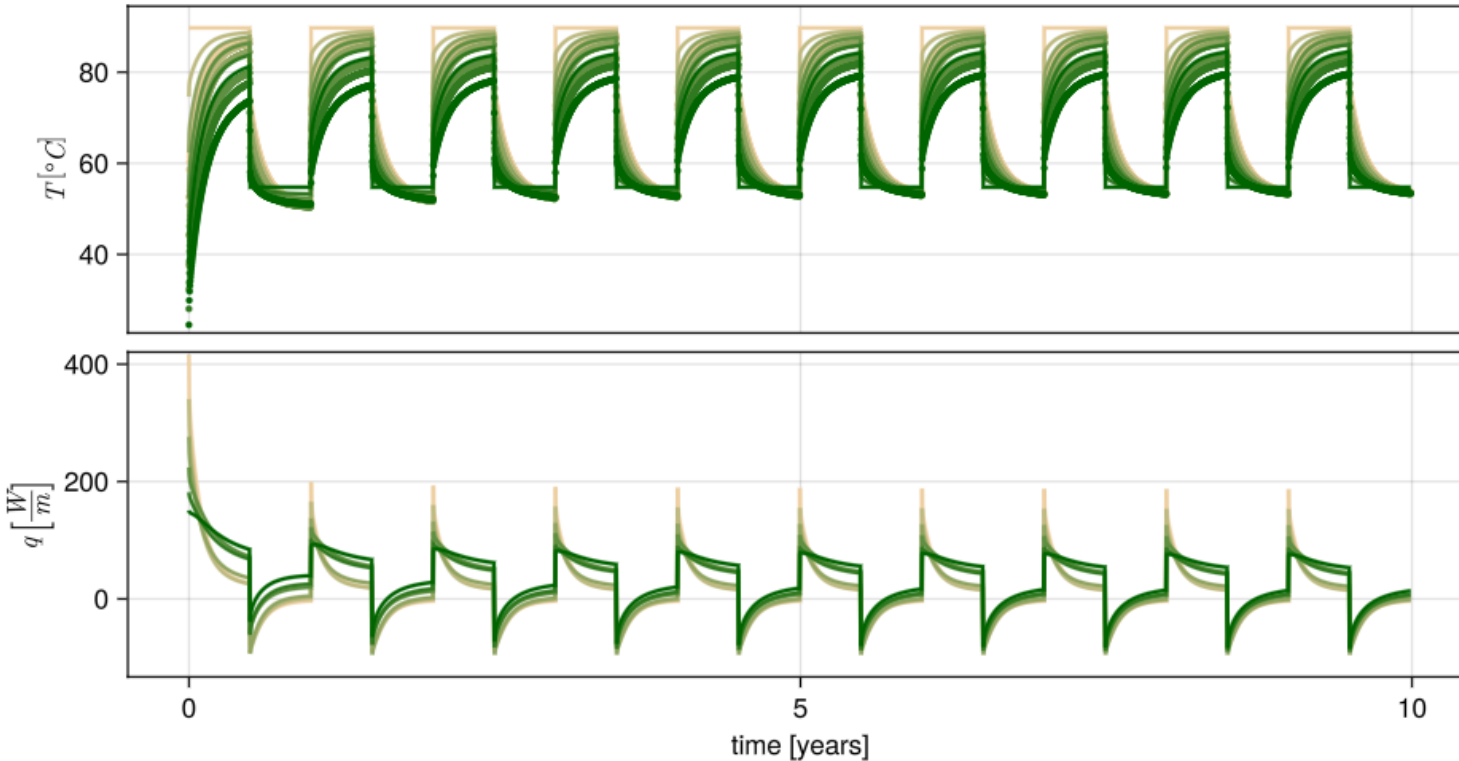
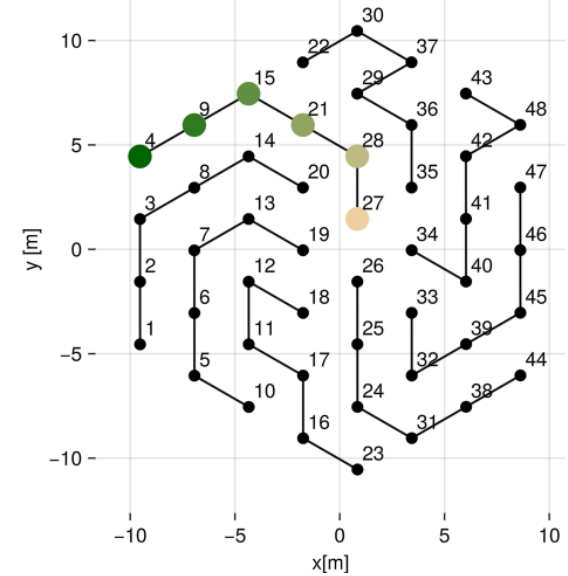
Large part of this work has been making the computation of b faster and with better scaling properties as the problem size increases

Simulation example

Why do we need detailed models?
Why do we need high time resolution?

Configuration

U-pipe in series
Borehole length 75 m
Ground conductivity 3 W/m K
Flow rate 0.5 kg/s
Adiabatic boundary condition at the surface

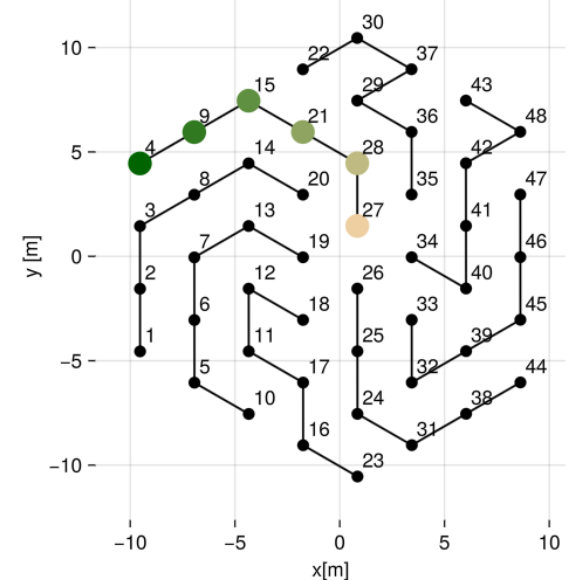


- **Charging $T_{in} = 90\text{ °C}$ circulating from inner to outer borehole.** Injection period is 6 month/year.
- **Extraction $T_{in} = 55\text{ °C}$ circulating from outer to inner boreholes.** Extraction period is 6 month/year
- We show **temperature and heat extraction per meter.**

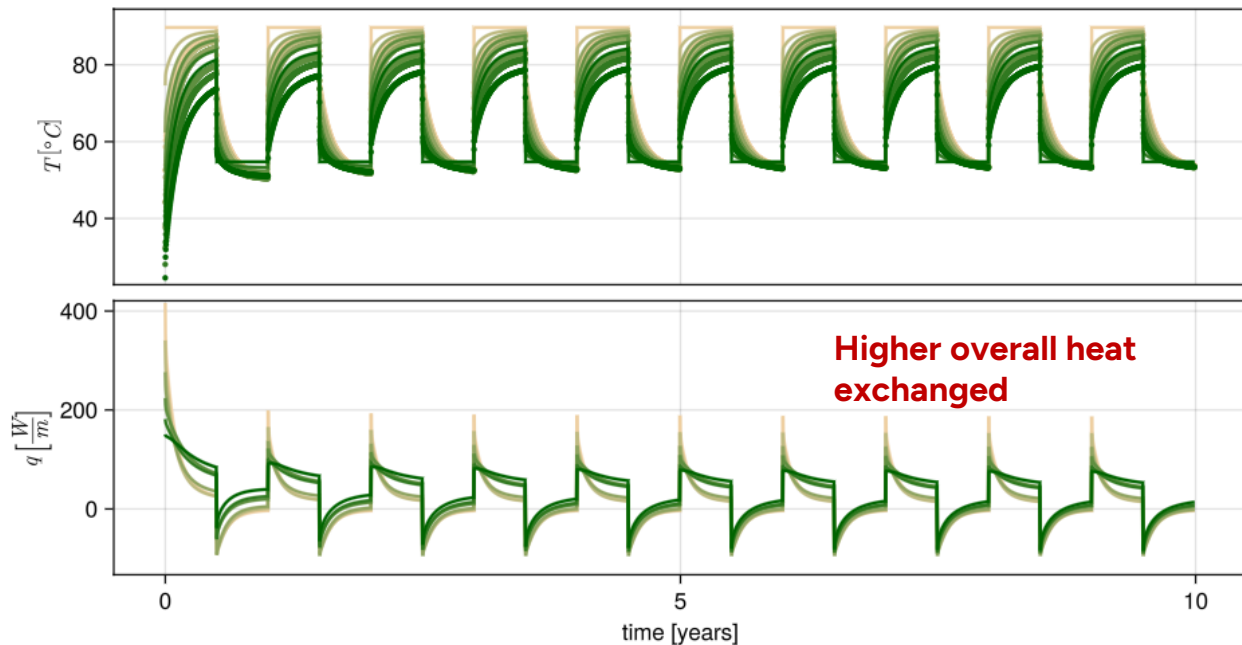
We compare **continuous** exchange, with **intermittent** exchange

Long term operation

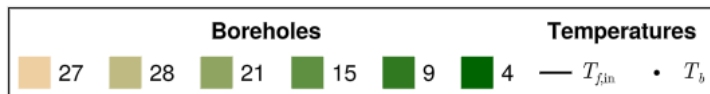
- Intermittent exchange: **only 12 hours of circulation per day.**
- The **simulations below are hourly.**
- To display 10 years, **we show daily average** temperatures and heat rates.



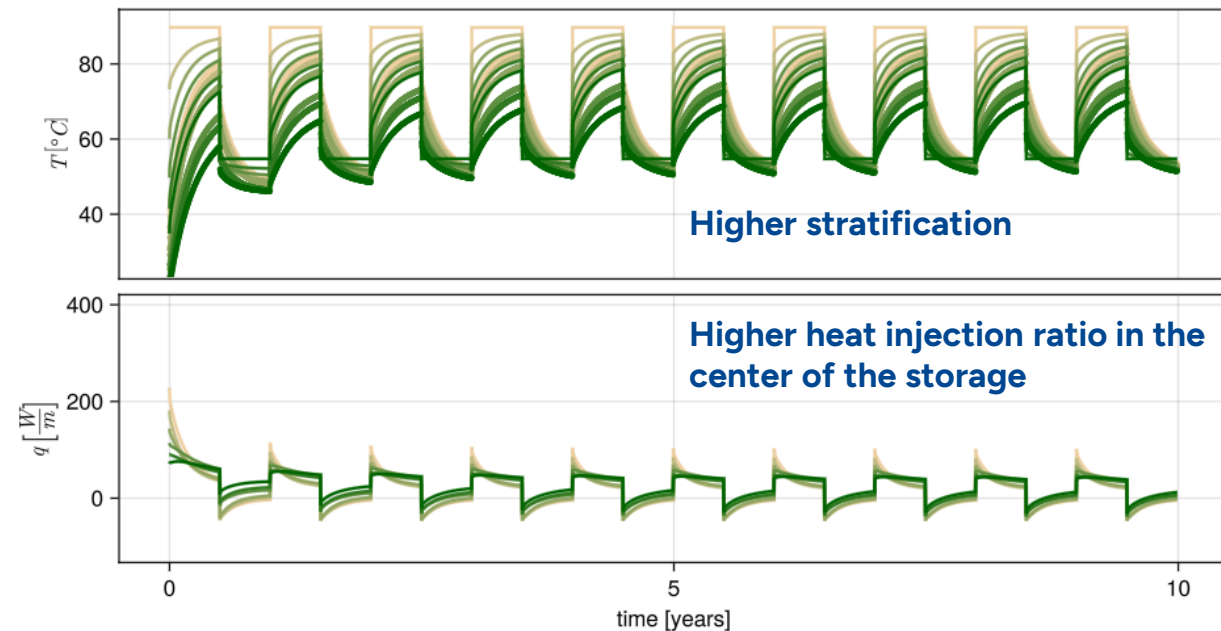
Constant exchange



Higher overall heat exchanged



Intermittent exchange



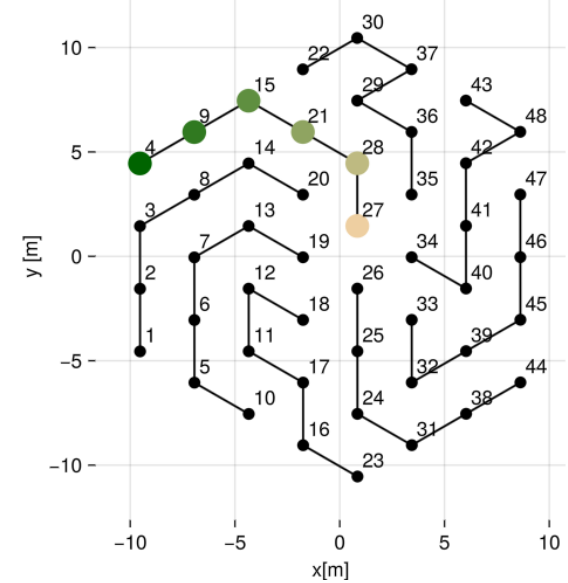
Higher stratification

Higher heat injection ratio in the center of the storage

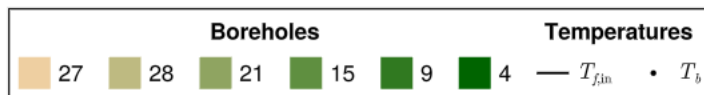
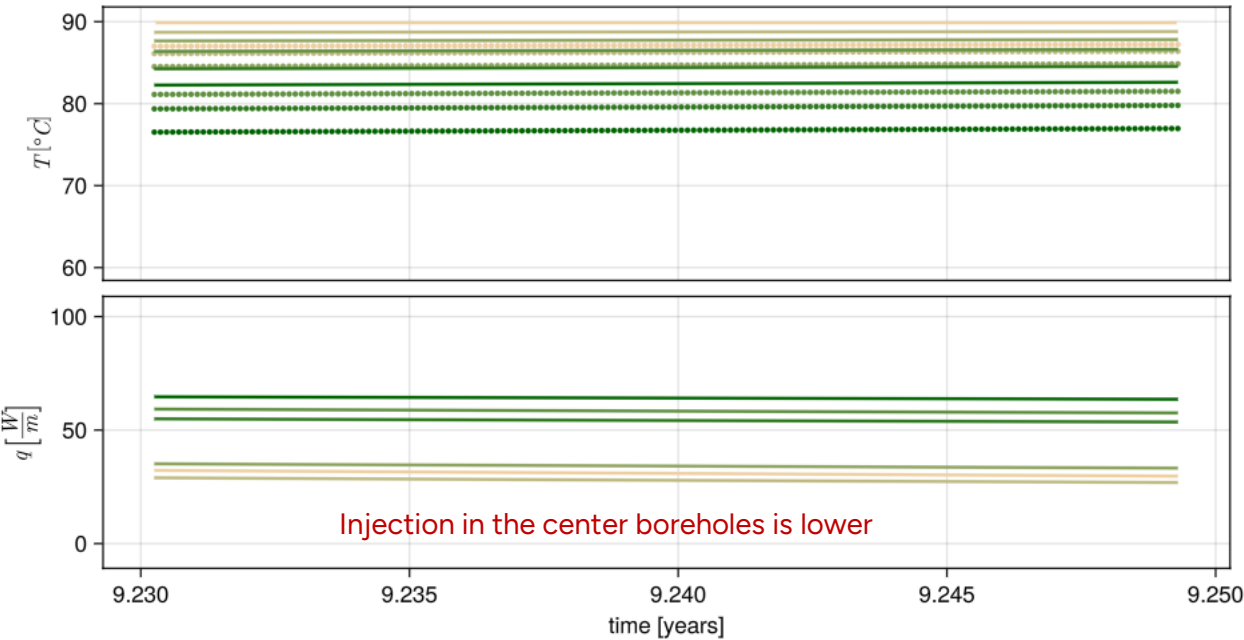


Week at mid injection season

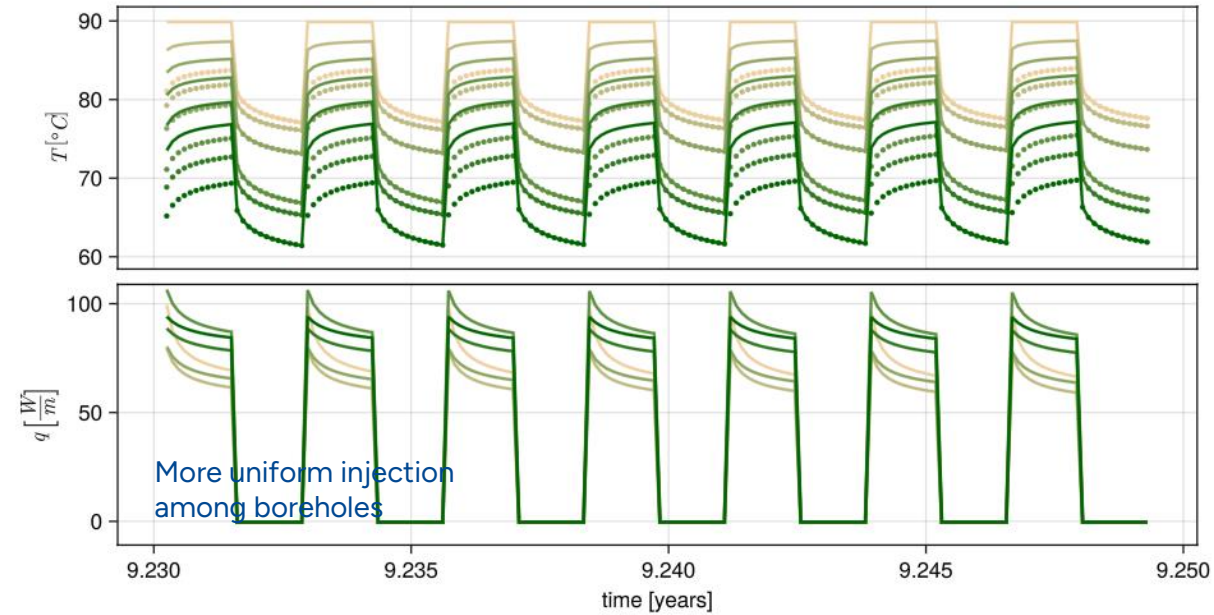
- With intermittent operation it is still **possible** to effectively **inject on the center boreholes** after 3 months of the charging.
- With intermittent operation we have **higher stratification**.



Constant exchange

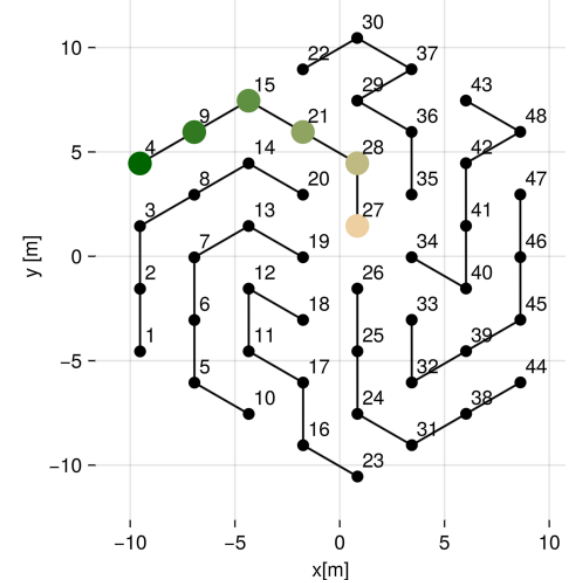


Intermittent exchange

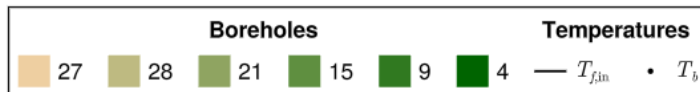
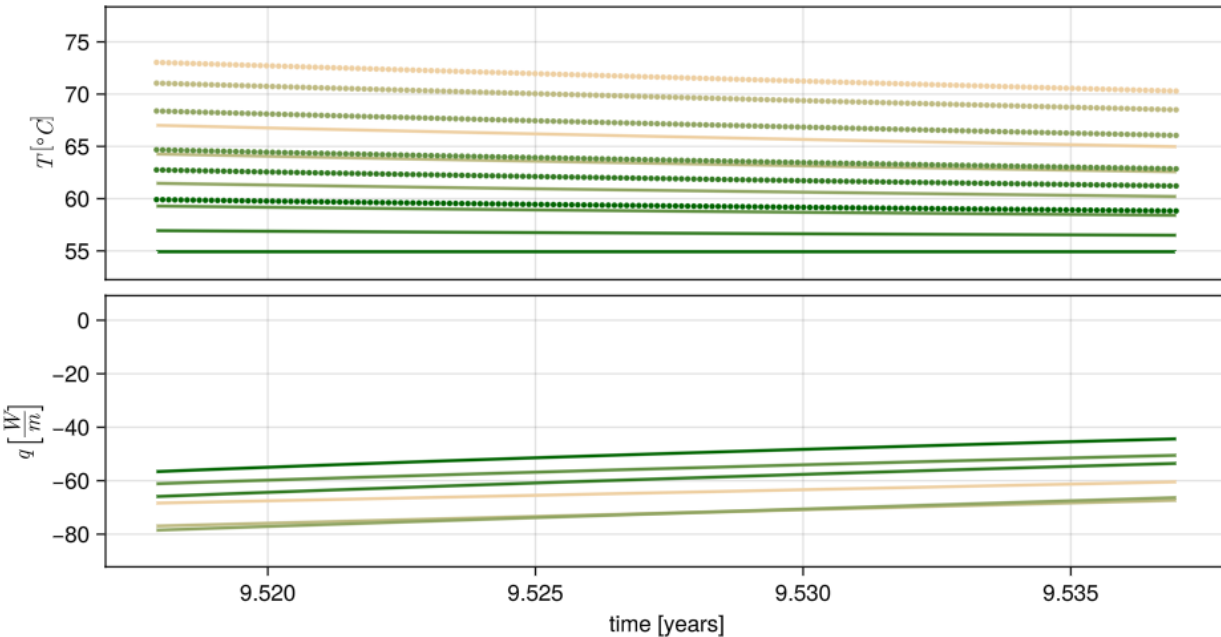


Week at the beginning of the extraction season

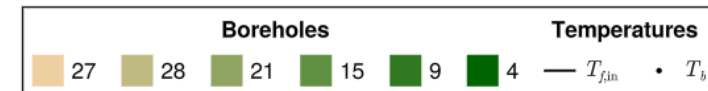
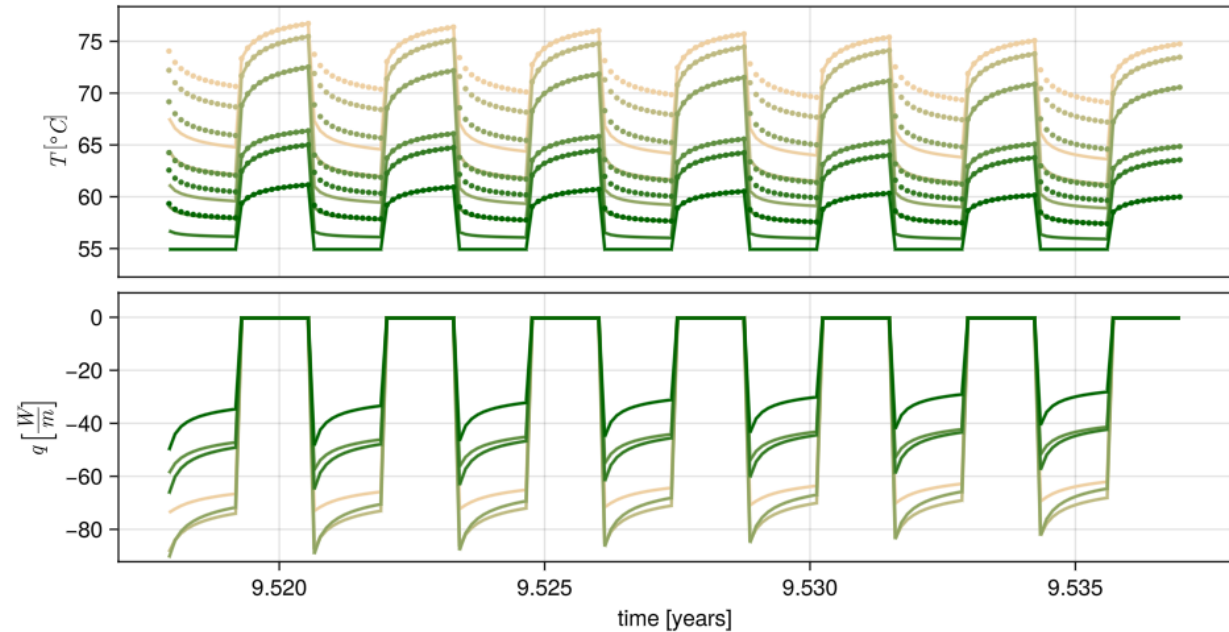
- For **intermittent** operation we mostly extract from the inner boreholes



Constant exchange

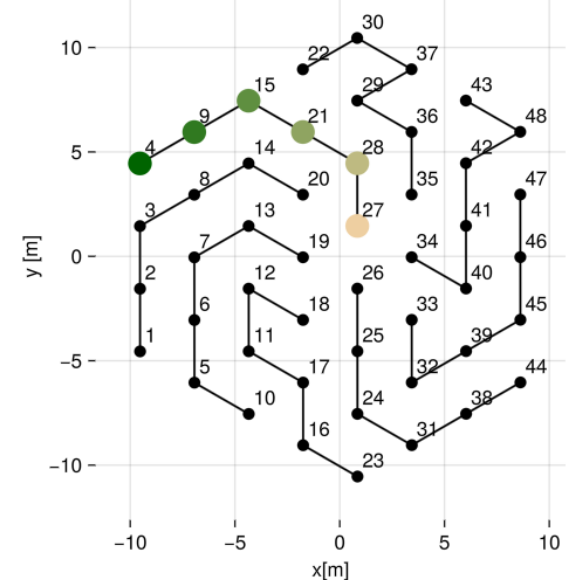


Intermittent exchange

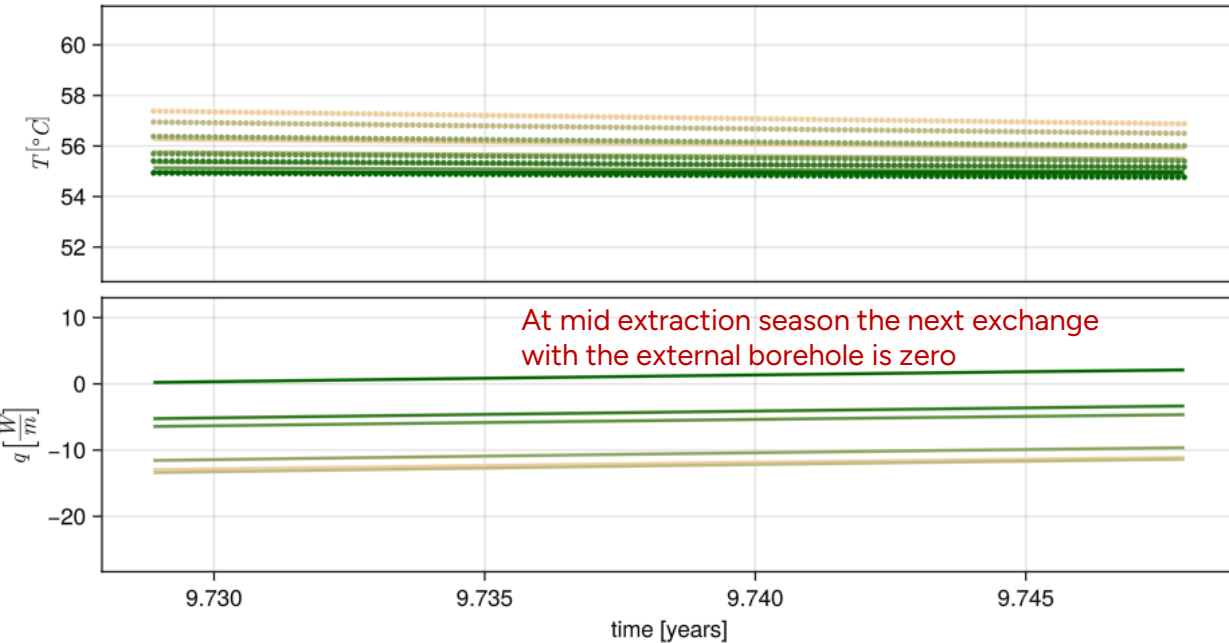


Week at mid extraction season

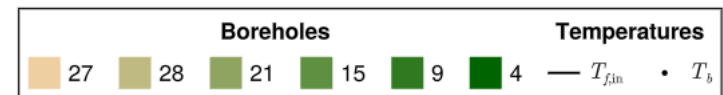
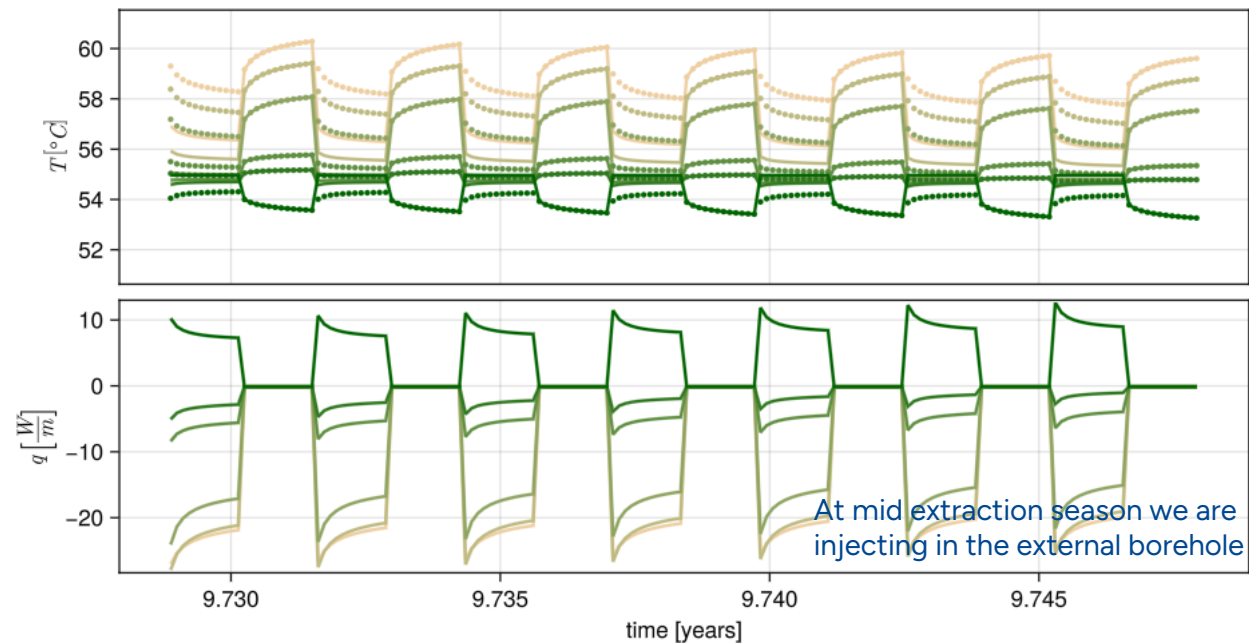
- At mid extraction season intermittent exchange with inlet temperature 55°C results in injection in external boreholes as they are at a lower temperature



Constant exchange



Intermittent exchange



Detailed model allows to investigate how the heat is distributed in the subsurface.

- **Hourly resolution** combined with **detailed borehole network** modeling allows to represent complex operations.
- The overall **heat exchange is not imposed** but is the result of the simulation.
- **Operation affects the distribution of heat**, and in turn the temperature in the storage.
- **Intermittent operation** results in **higher stratification**, and **extraction temperatures**.



Computational Complexity

*Large part of this work has been making the computation of superposition of the effect in time and space faster and with **better scaling** properties as the problem size increases*

$$O(N_{\text{sources}}^2 N_{\text{timestep}}^2)$$

In the naïve implementation of superposition, the number of **operations** is **proportional to the square** of the **number of sources** and to the square of the **number of time steps**

EXAMPLE: effect of increase in time resolution

10 years **DAILY** simulation

$$N_{\text{timestep}} = 365 \text{ day/year} \times 10 \text{ years} = 3650 \text{ days}$$

$$N_{\text{timestep}}^2 = 3650^2 \cong 1.3 \times 10^7$$

10 years **HOURLY** simulation

$$N_{\text{timestep}} = 8760 \text{ hour/year} \times 10 \text{ years} = 87600 \text{ hours}$$

$$N_{\text{timestep}}^2 = 87600^2 \cong 7.6 \times 10^9$$



THE **NUMBER OF STEPS INCREASE BY A FACTOR 24**

BUT THE **NUMBER OF OPERATIONS IN THE SIMULATION INCREASE BY A FACTOR $24^2 = 576$**



Contribution to the reduction of complexity associated to the time superposition

- **Load aggregation method**

We proposed a variation of the load aggregation method for borehole fields where **far field interactions** are **treated differently** compared to close field thermal interaction.

Effect of thermal interaction between boreholes can be solved **less frequently** than every hour (e.g. every week) .

- **Non-history dependent acceleration method**

We made **significant developments** to the non-history acceleration method of Lamarche.

We showed that for **point sources** the method can be expressed with an **analytical expression**.

The **extension to line sources**, relevant for borehole simulation, has been also investigated.

Load aggregation and **Non-history** acceleration method have **LINEAR SCALING** as opposed to square scaling of the naïve implementation of convolution.

In the **non-history** method the **error can be controlled**.

The **load aggregation** is more **intuitive** and **simple** to implement



Publications



IGSHPA Research Conference
Montréal, May 28-30, 2024

Load aggregation for thermal interactions between boreholes

Massimo Cimmino

Alberto Lazzarotto

ABSTRACT

A load aggregation method is proposed for efficient simulations with multiple boreholes using network-based simulation methods. The method splits fast and slow dynamics. Fast dynamics, i.e. the impact of boreholes on themselves, are solved every timestep using available load aggregation methods. Slow dynamics, i.e. heat interactions between heat sources, are solved at a lower frequency by introducing a time delay in the update of their calculation. A first order correction term is proposed to estimate the variation of temperatures in-between updates. The error caused by the delayed update depends on the distance between the boreholes and the frequency of updates: more distanced boreholes can use a lower frequency of updates to achieve acceptable accuracy. A 20 yr hourly simulation of two interacting bore fields showed that a maximum error of 0.003 °C on the inlet fluid temperatures can be obtained while decreasing the calculation time from 275 s to 26.2 s.



IGSHPA Research Conference
Montréal, May 28-30, 2024

A non-history dependent temporal superposition algorithm for the point source solution

Alberto Lazzarotto

Marc Basquens

Massimo Cimmino

ABSTRACT

Optimal design and operation of borehole fields require accurate prediction of the dynamic heat transfer in the ground. For large borehole systems, current simulation algorithms do not have the scaling properties to enable complex borehole network simulations with both fine source discretizations as well as fine time resolution. This paper is focused on the so called “non-history dependent” method, a procedure for the acceleration of the time superposition process with promising properties that could be instrumental to improve on current scaling limitations. In this development, we considered the case of the point source and we derived an analytical expression for the scheme. The computation of the temperature involves the integration of an oscillatory function. A scheme for the numerical integration step of the algorithm based on integration techniques for oscillatory integrals is proposed. We study the computational complexity of the algorithm, which is linear in the number of time steps and in the number of integration points. Additionally, refining the discretizations used to perform the numerical integral leads to accuracy close to double precision. As a result, we conclude that the algorithm presents both favorable accuracy and performance features.

- **A non-history dependent temporal superposition algorithm for the finite line source solution**
Alberto Lazzarotto, Marc Basquens, Massimo Cimmino (submitted to journal) <https://arxiv.org/abs/2501.16027>
- **Higher-order semi-analytical model for the simulation of geothermal boreholes**
Massimo Cimmino, Marc Basquens, Alberto Lazzarotto (submitted to journal)

Models developed

- **BoreholeNetworksSimulator.jl** : an open source software to simulate borehole networks which offers the possibility to simulate complex operations of the system. The model offer an implementation of the non-history acceleration algorithm for the time superposition.
<https://github.com/marcbasquensmunoz/BoreholeNetworksSimulator.jl>
- **Geothermsim**: an open-source semi-analytical transient heat transfer modeling tool for geothermal borehole fields. The method uses high-order piecewise polynomial approximations of heat extraction rates along line trajectories representing the boreholes and evaluates ground temperature changes from the spatial and temporal superposition of heat source solutions. Quasi-steady-state variations of heat carrier fluid temperatures inside boreholes are evaluated by leveraging the multipole method to build and solve a system of ordinary differential equations.
<https://github.com/MassimoCimmino/geothermsim>



Conclusion

- We studied and implemented acceleration algorithms to improve the scaling of borehole field simulations.
- We developed **algorithm and tools** to enable the **simulation of detailed borehole networks operations**
- We demonstrated the application and relevance of such simulations through examples.

Future work

- Improve **scaling in the number of sources** to speed up simulations of large borehole field and to enable more flexibility in the boundary conditions.



Thank you for your attention!



The methodology

- We use **semi-analytical** model of the ground
- Borehole are modeled as line heat sources
- The temperature is obtained as superposition in time and space of the effect of these sources

Advantages:

The **domain is not discretized** we only **discretize the sources**.

The problem can be described with a relative **low amount of variables** (i.e. power heat power and temperatures along the borehole)

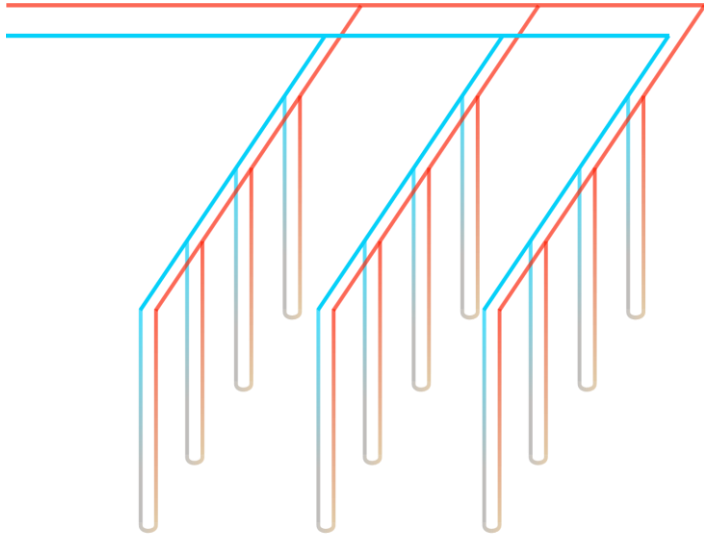
Modeling through line source is an effective and elegant way to deal with the extreme aspect ratio of boreholes which is inconvenient for methods using domain discretizations

These methods are **fast, accurate and suitable** for the simulation of long operation of borehole systems

Limitations:

There are currently limitations in the boundary conditions that can be used.

The computation scale with the square of the number of sources and on the number of time-steps



$q_i(z)$ Power per meter and temperature at borehole i along the coordinate z

$T_i(z)$