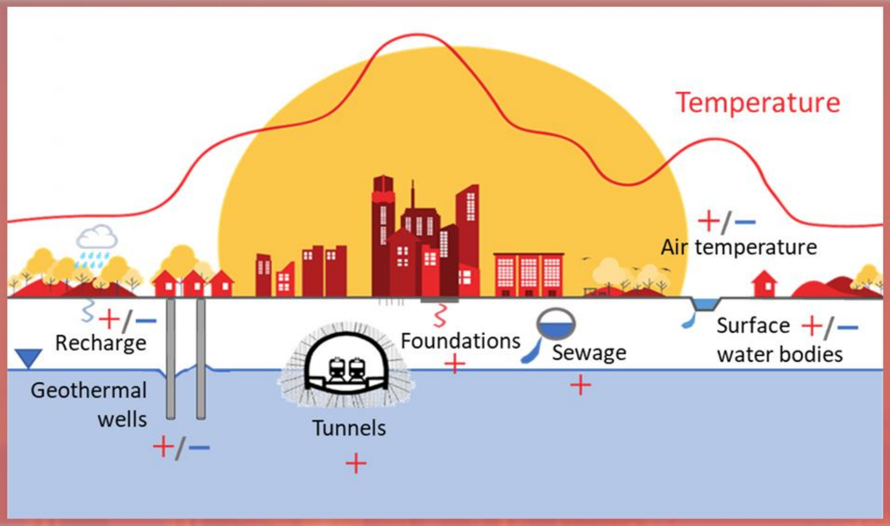
Alberto Previati (a.previati1@campus.unimib.it) , Giovanni B. Crosta and Jannis Epting

City-scale groundwater flow and heat transport modeling in the Milan Metropolitan Area

abstract

We developed a fluid-flow / thermal-transport FEM numerical model

- Considering the **heterogeneities** of hydraulic and thermal parameters at the urban scale
- Complex boundary conditions at the top of the model were applied to simulate the **interactions with the surface**
- Considering the effects of anthropogenic heat sources (e.g. **underground tunnels**, shallow **geothermal wells,** percentage of soil covered by **human-made infrastructures**)



Groundwater urban heat island

Positive **temperature anomaly** in the urban setting relative to the surrounding rural areas

ATMOSPHERE → SUBSURFACE (Soil + Groundwater)

In order to:

- Quantify the heat island effect in the subsurface and assess natural and anthropogenic contribution
- Assess the thermal regime of the shallow aquifers for geothermal planning

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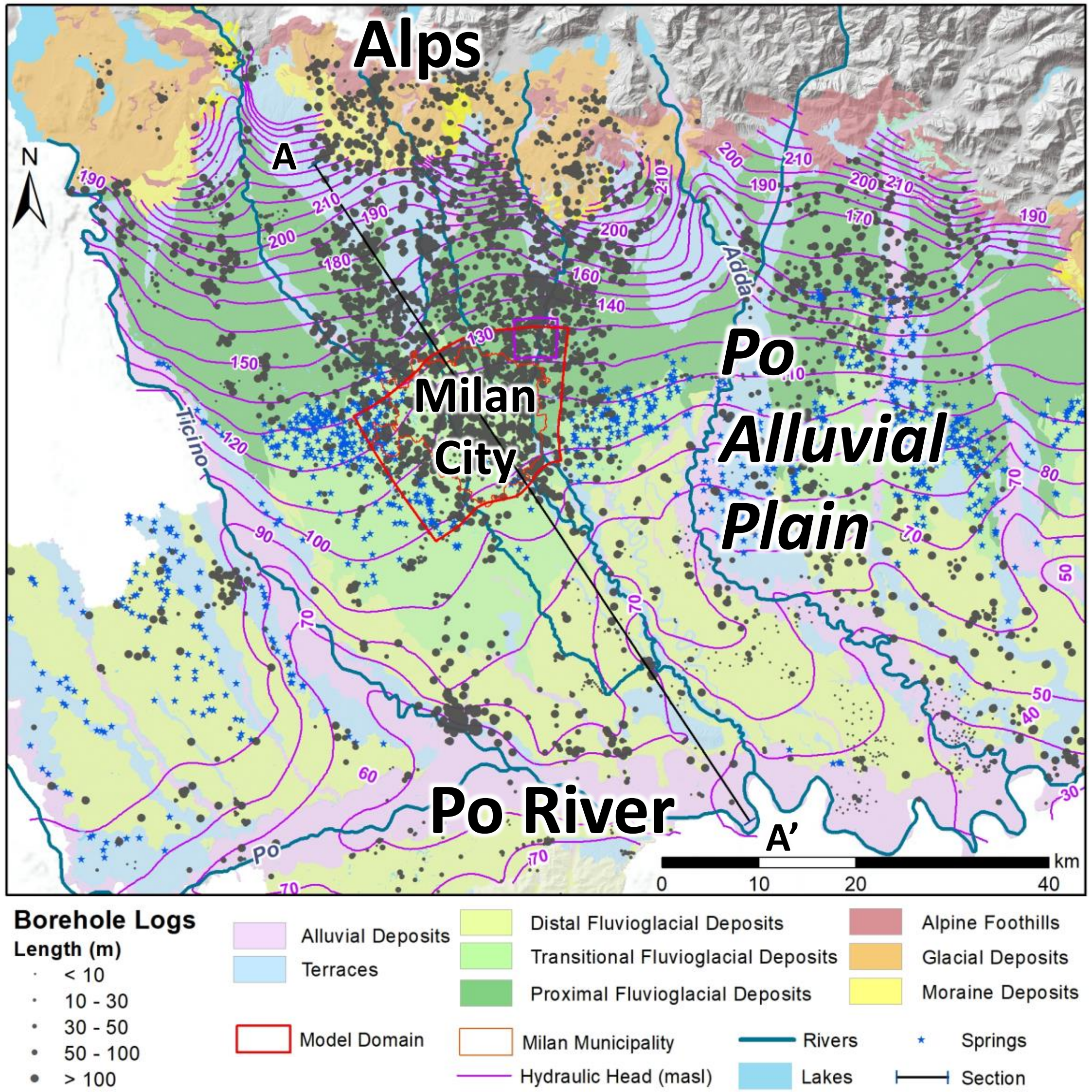
EGU General Assembly 2020

Hydrogeological settings

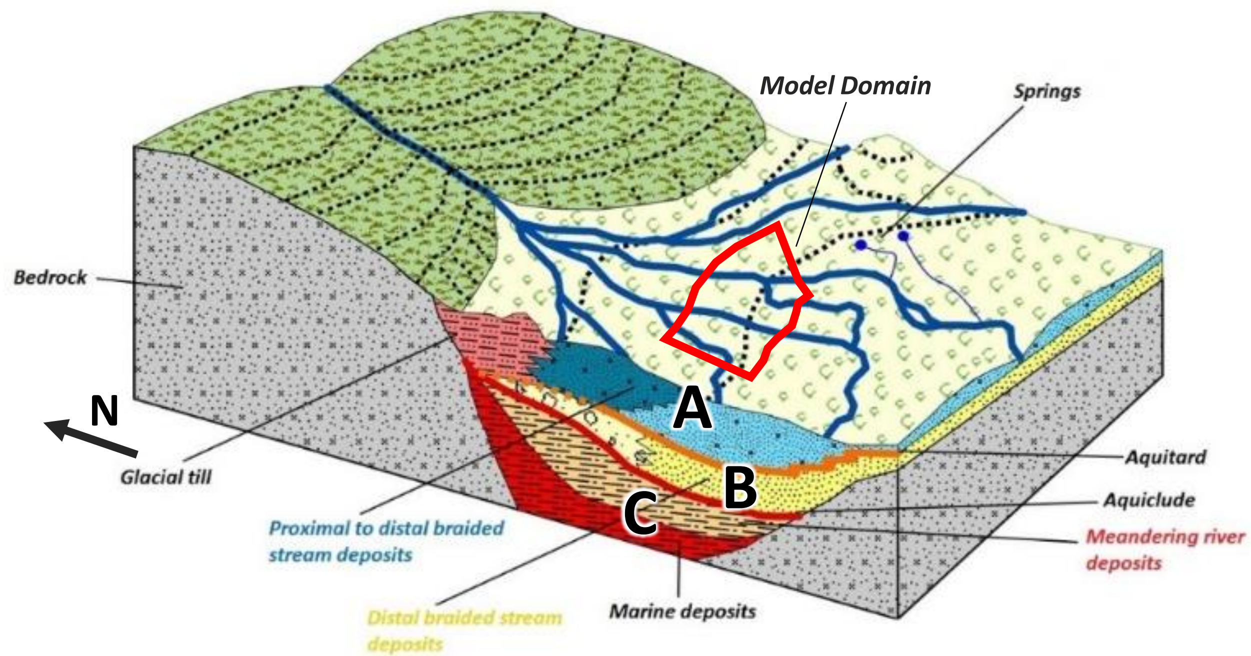


Fluvioglacial deposits separated by low permeability layers → Three main aquifer complexes

I. **Phreatic aquifer (A)** Gravel with a sandy matrix (thickness 20-50 m).
Bottom: clayey silty aquitard (continuous only southward)

II. **Semi-confined aquifer (B)** Sands and sandy gravels (thickness 50-100 m)
Bottom: clay and silt layers, and locally conglomeratic units.

III. **Deep confined aquifers (C)** Sandy lenses within clay and silt units
representing the lower Pliocene continental-marine facies



- The study area is located in the largest **alluvial plain** in Italy
- In this study we considered only the 2 shallower aquifers (A – Phreatic and B – Semi-Confined)

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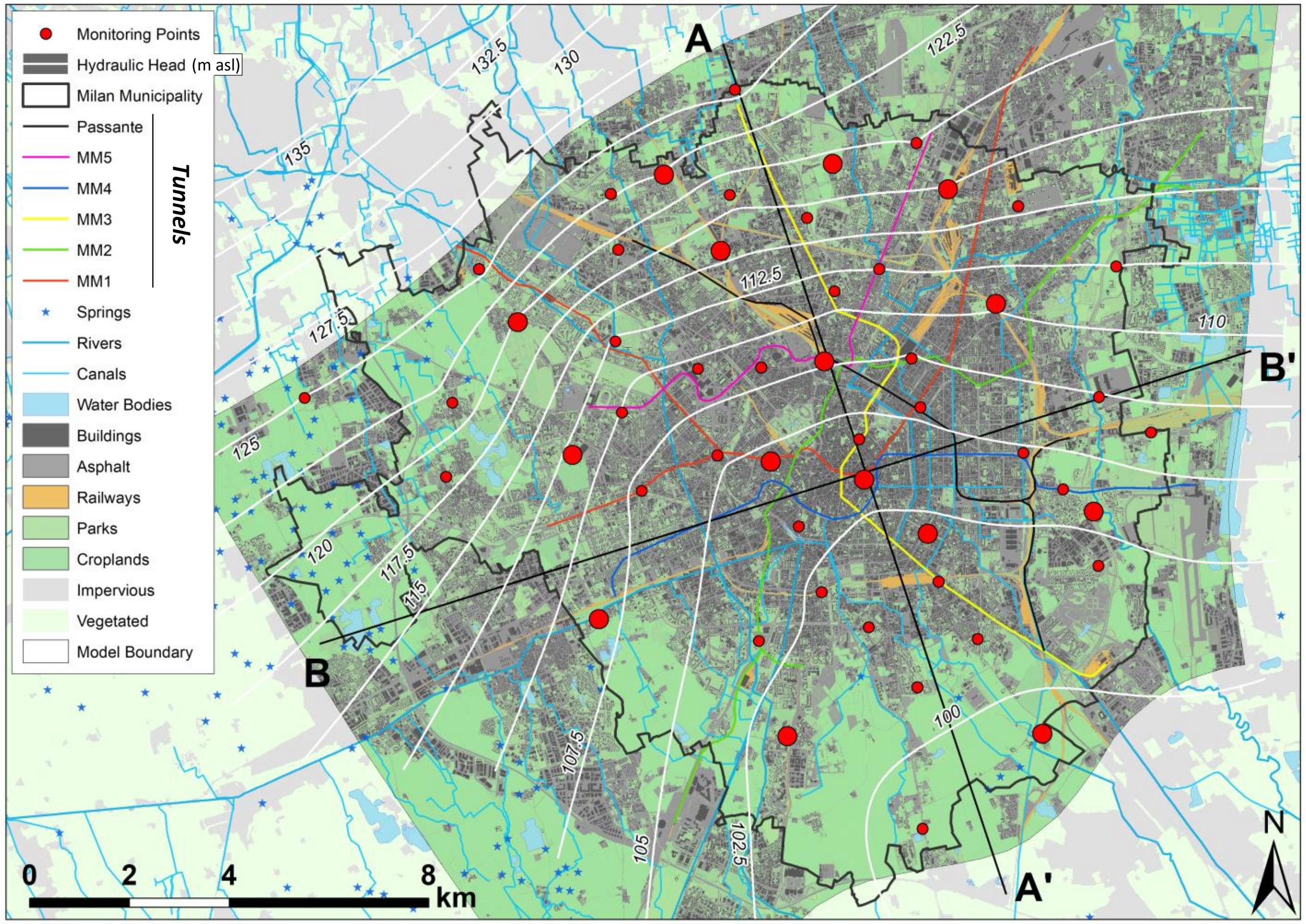
Study area

The Milan Metropolitan Area is one of the most densely populated regions in Italy and Europe

→ **6,836 inhabitants/km2** in the city of Milan

→ **5,351,148 inhabitants** in the Metropolitan Area

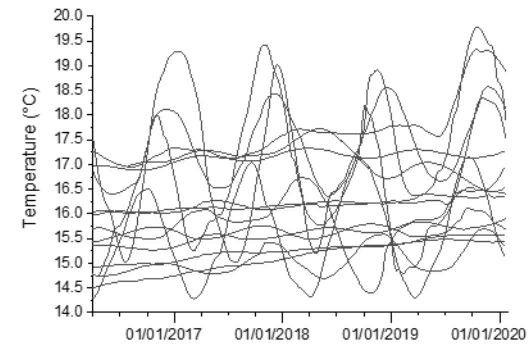


Groundwater temperature monitoring

x15

04/2016 → 04/2020

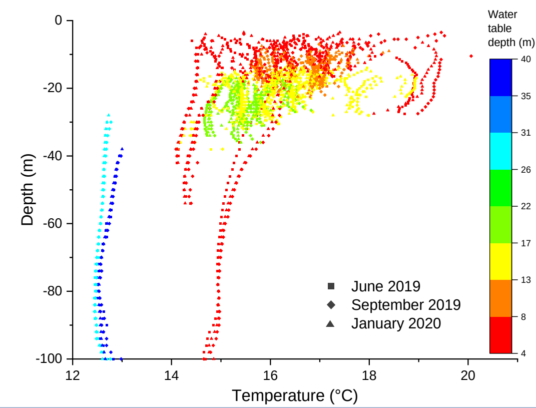
Continuous recording of GW pressure and temperature at specific depth in boreholes



x56

06/2019 – 09/2019 – 01/2020

GW temperature vertical borehole logs



- Groundwater temperature in the Milan City Area have been monitored since early 2016
- In this study i am going to present the **groundwater thermal regime** of this intensively populated area
- The extent of the urban heat island in the groundwater will be revealed

City-scale groundwater flow and heat transport modeling in the Milan Metropolitan Area

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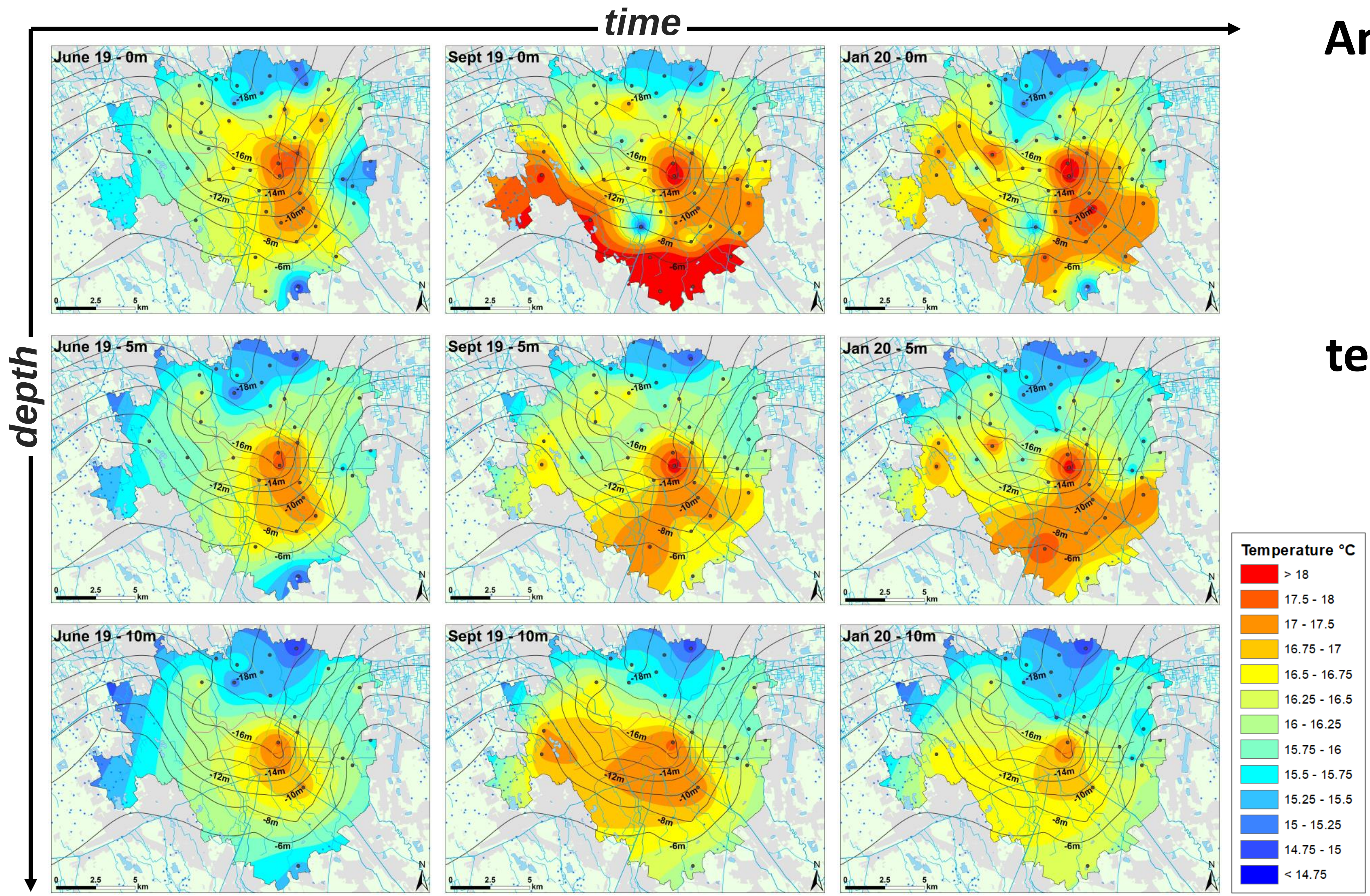

Analysis of vertical profiles

↓

Groundwater temperature maps

- By analyzing **groundwater temperature data** from the vertical logs we can observe how the groundwater temperature changes during the year and by moving deeper in the aquifer
- Depth is expressed as 0 m, 5 m, 10 m below the groundwater table

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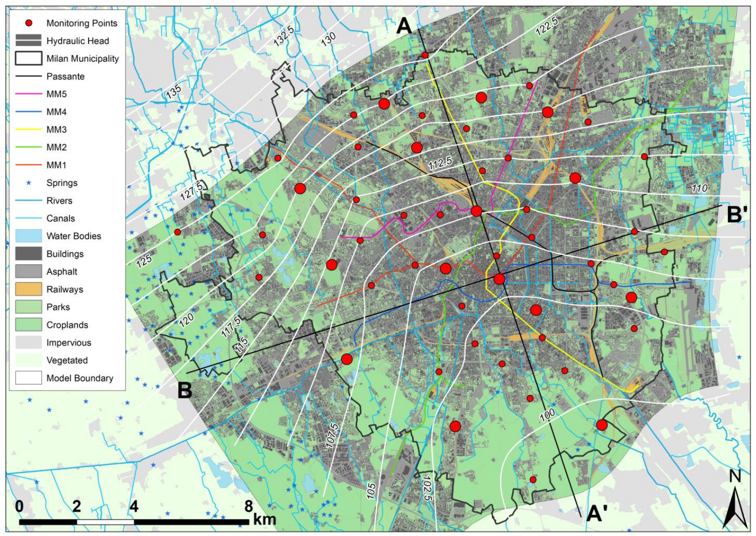
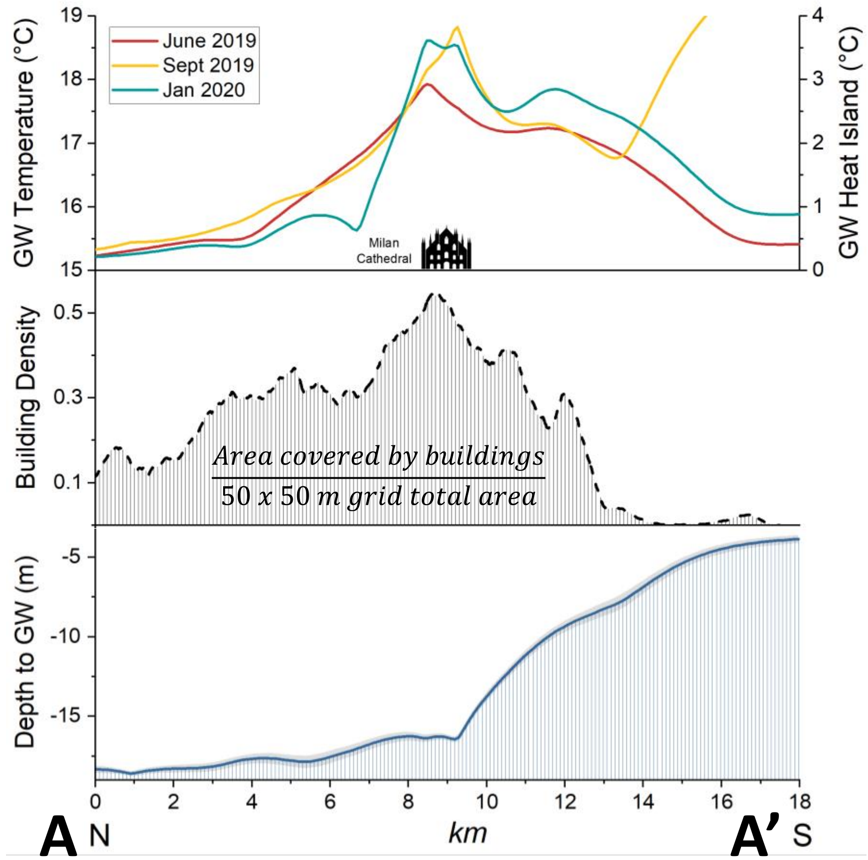
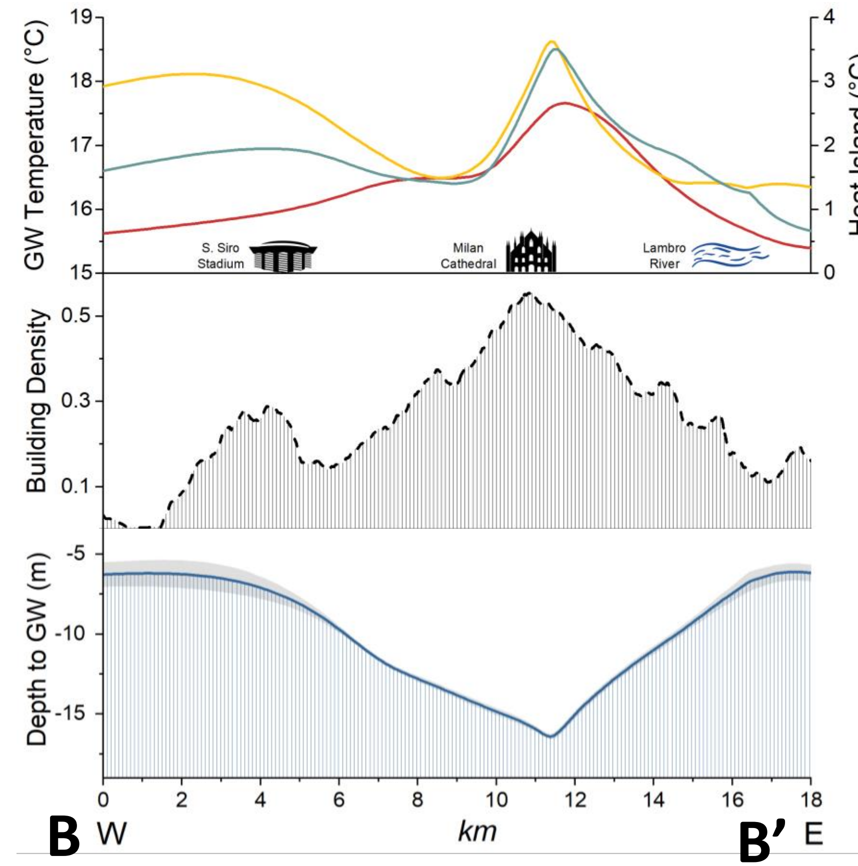
Analysis of vertical profiles → GW Temperature Heat Island







- **Temperature cross-section profiles** extracted from the temperature maps: we can observe that the **heat island intensity** in the shallow aquifer can reach up to 3.5°C during the late fall / winter period (this is the moment of the year where the heat island intensity is higher)
- The heat island is well correlated with the building density (whereas the seasonal fluctuation is correlated with the depth of GW)

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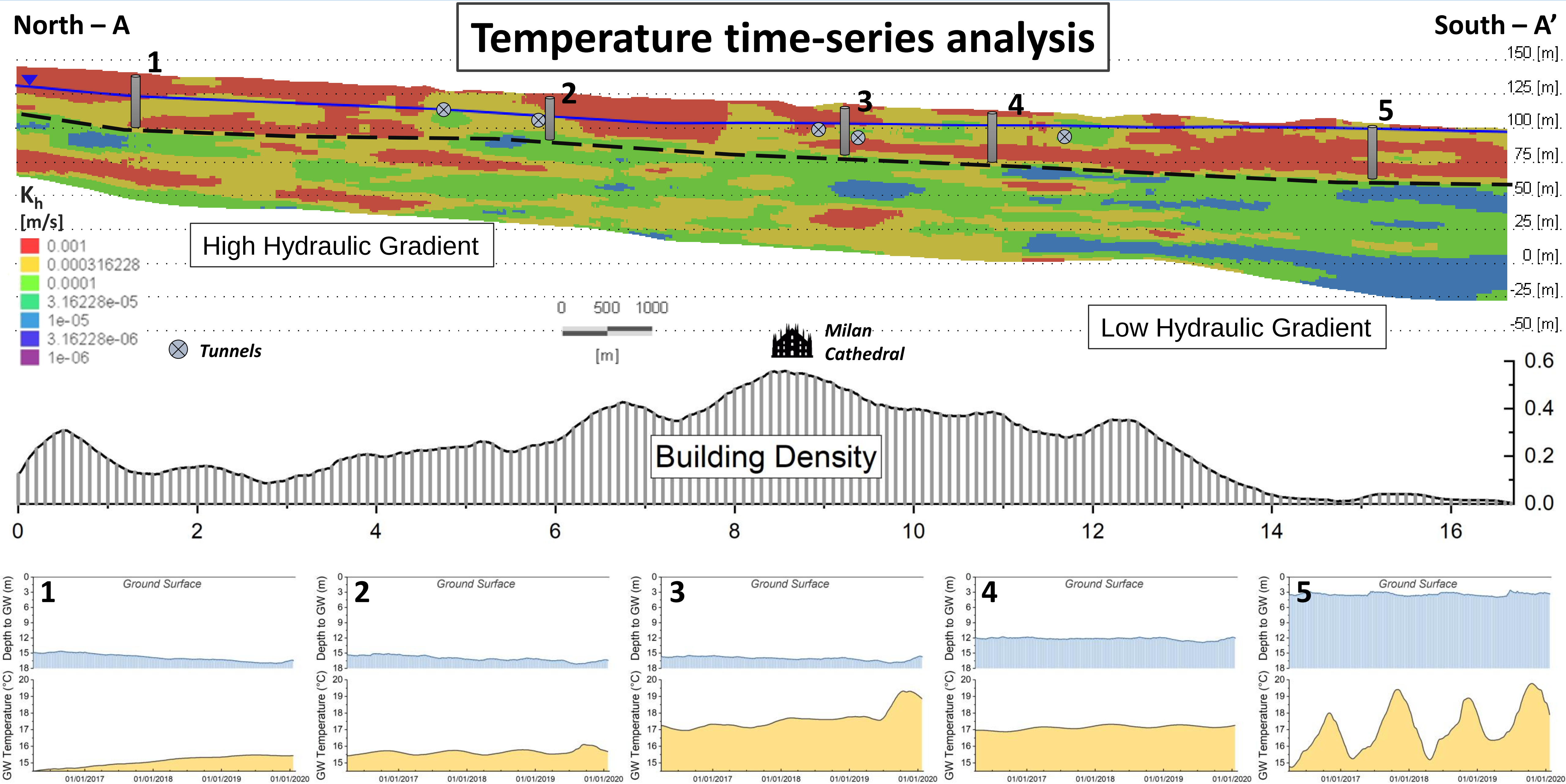
Temperature time-series analysis



- This is the N-S cross section → We can observe the **temperature time-series** recorded along this profile
- To the **north** the water table is deep, the mean annual temperature is about 15°C and seasonal fluctuations are very low
- Near the **centre** the water table is deep but the mean annual temperature is higher (17.5°C or more), seasonal fluctuations low
- To the **south** the water table is shallower, the mean annual temperature is about 16°C and seasonal fluctuations are very high

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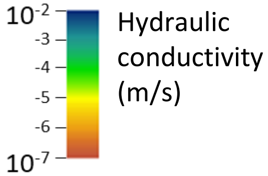
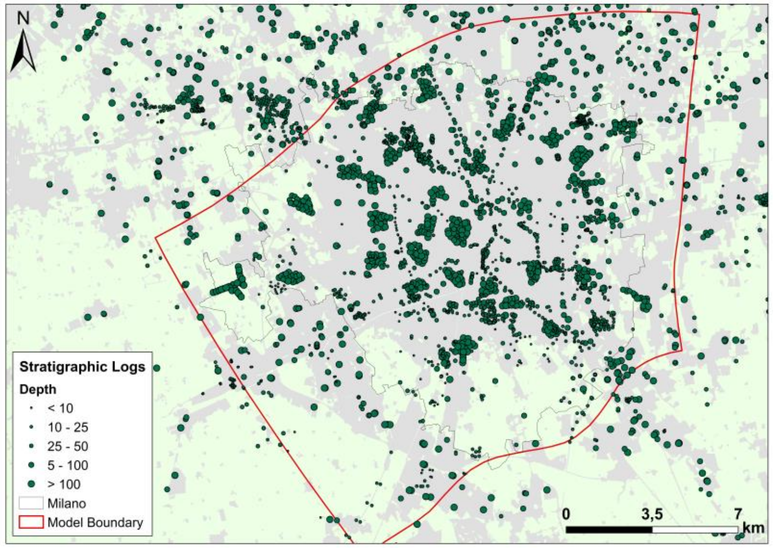
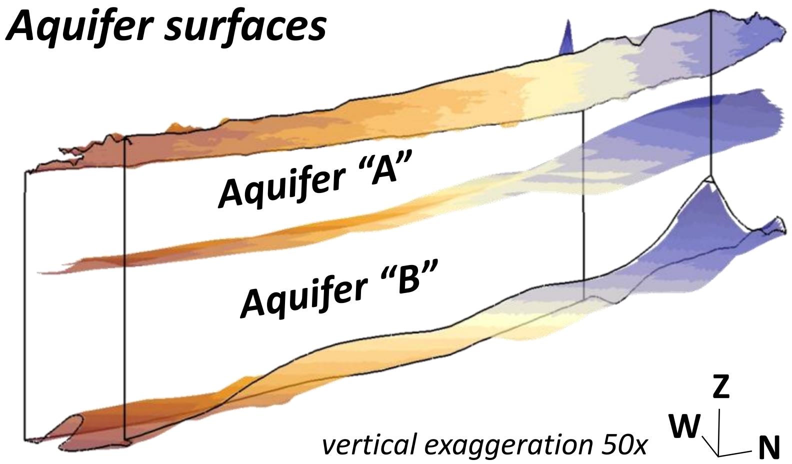
From monitoring to modeling…



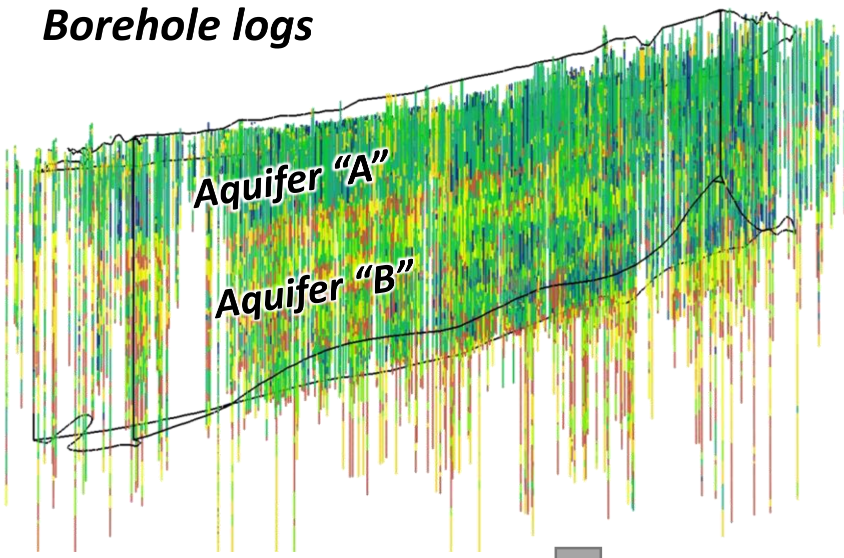
Stratigraphic database



Aquifer surfaces



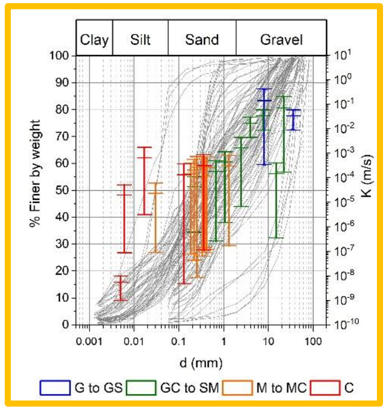
Borehole logs



Hydraulic and thermal parametrization

Grain size distribution analysis

De Caro et al., 2020



Thermal parameters from the literature

Rock	Density ρ 10^3 kg/m^3	Thermal conductivity W/(m · K)	Thermal conductivity: Typical characteristic values	Volume-related specific Heat capacity $\rho \cdot c_p$ MJ/(m^3 · K)
Unconsolidated rocks				
Gravel, dry	2.7-2.8	0.4-0.5	(0.4)	1.4-1.6
Gravel, watersaturated	approx. 2.7	approx. 1.8	(1.8)	approx. 2.4
Moraine	n.a.	1.0-2.5	(2.0)	1.5-2.5
Sand, dry	2.6-2.7	0.3-0.8	(0.4)	1.3-1.6
Sand, watersaturated	2.6-2.7	1.7-5.0	(2.4)	2.2-2.9
Clay/silt, dry	n.a.	0.4-1.0	(0.5)	1.5-1.6
Clay/silt, watersaturated	n.a.	0.9-2.3	(1.7)	1.6-3.4
Peat	n.a.	0.2-0.7	(0.4)	0.5-3.8

German VDI Guidelines

3D geostatistics

Model size:
20 km x 18 km x 250 m
Number of elements:
6,260,000
Model volume:
3.23E^{10} m^3
Element size:
5 – 200 m

- Development of a **urban-scale** fluid-flow/thermal-transport **FEM numerical model → Hydraulic and thermal parameters**
- The stratigraphic database was used to reconstruct the heterogeneities of hydraulic and thermal properties in the two aquifers analyzed by the numerical modeling

City-scale groundwater flow and heat transport modeling in the Milan Metropolitan Area

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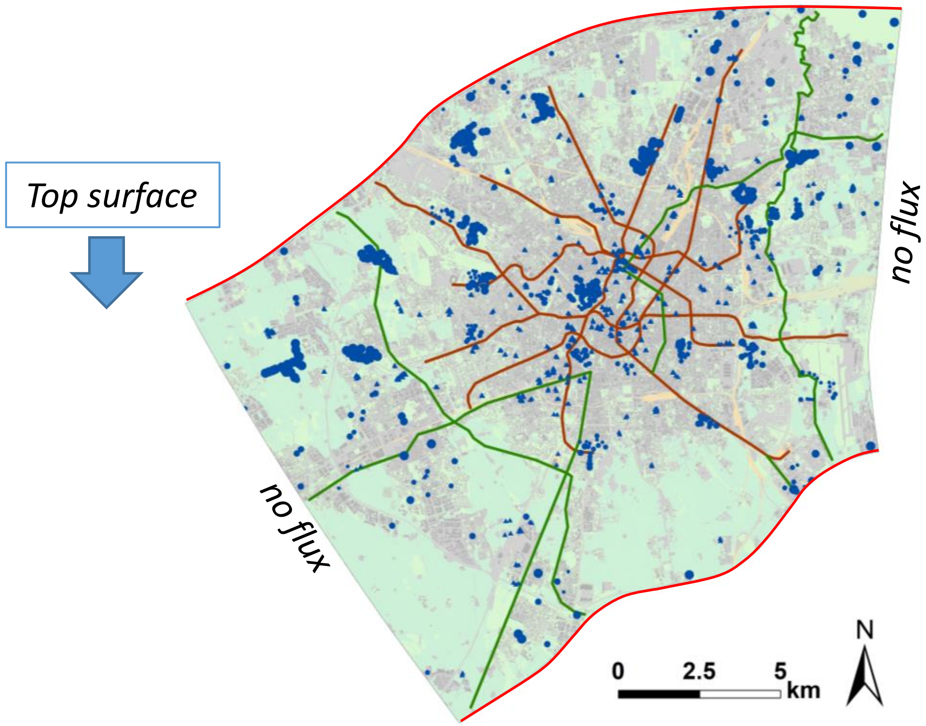
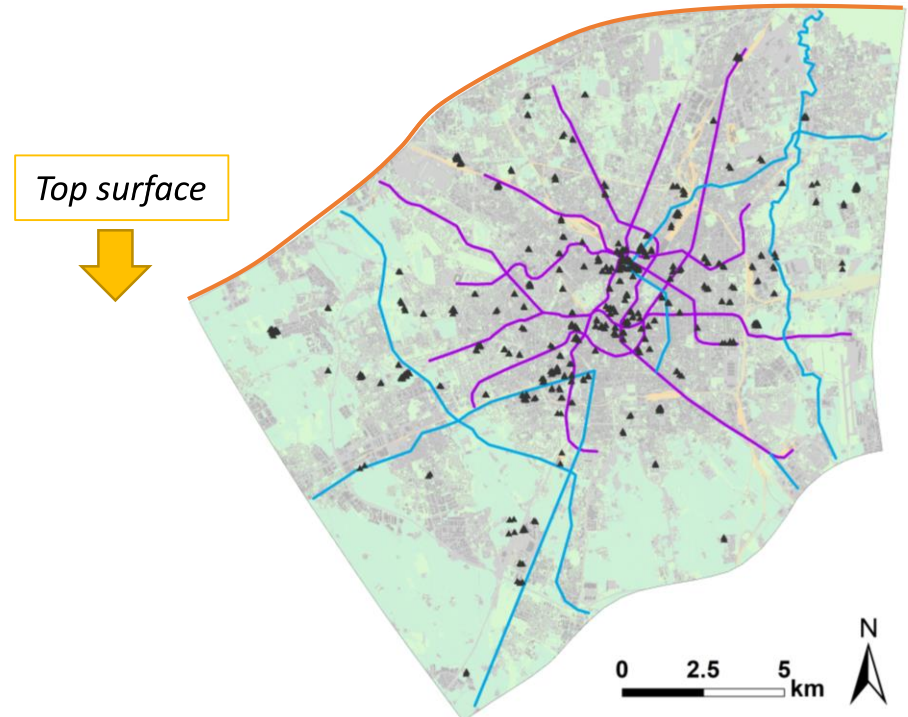
Fluid flow and heat transport settings





Fluid flow

- Upstream and downstream hydraulic boundaries (1st kind-BC)
- Recharge from infiltration on top (2nd kind-BC)
- Interactions with surface water bodies (3rd kind-BC)
- Abstraction of GW from water supply wells (4th kind-BC)
- Abstraction/Injection of GW from geothermal wells (4th kind-BC)
- Impervious elements along the 6 tunnel axis (low k-values)

Heat transport

- Upstream thermal boundary (1st kind-BC)
- Heat in-/outflow from the top boundary (3rd kind-BC / SoilTemp[1])
- Thermal interactions with surface water bodies (3rd kind-BC)
- Abstraction/injection of heat from geothermal wells (4th kind-BC)
- Heat In-/out-flow from the tunnel elements (3rd kind-BC)

- List of the fluid-flow and thermal **boundary conditions**

[1] Rock and Kupfersberger, *3D modeling of groundwater heat transport in the shallow Westliches Leibnitzer Feld aquifer, Austria (2018)*

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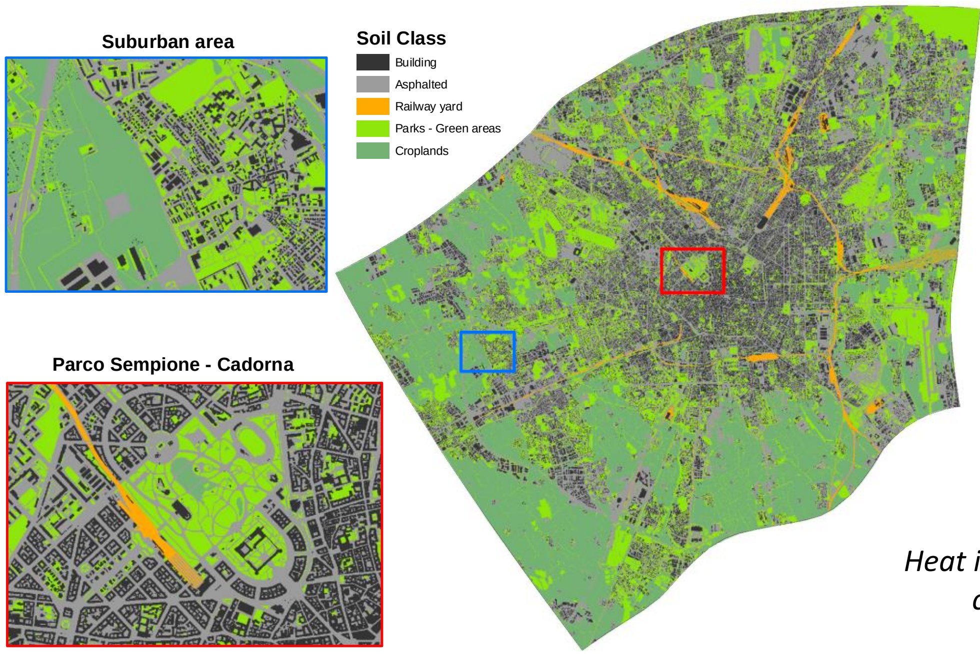
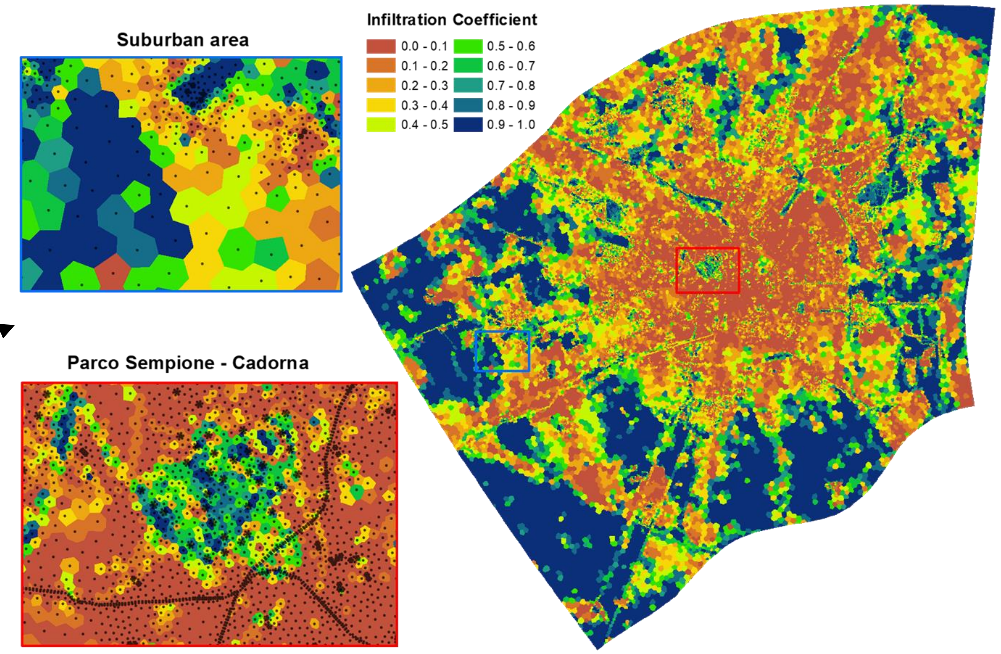
Boundary conditions at the top surface

High-resolution land use map

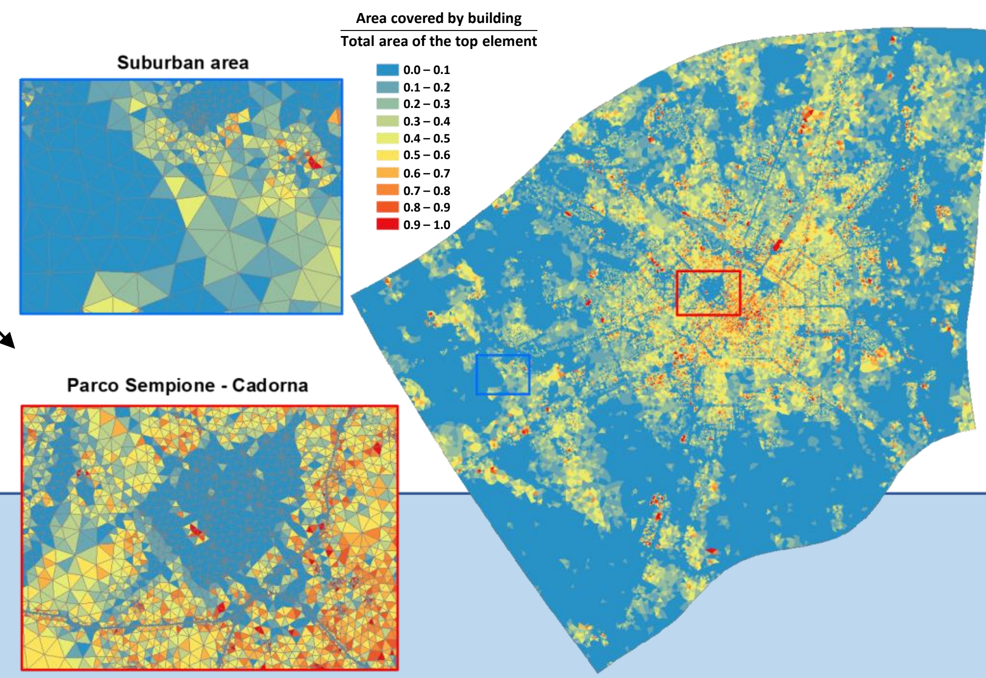


Recharge from infiltration



Heat in-/out-flow was simulated by comparing 2 approaches

- ***Cauchy** boundary condition at the top surface –*
  External temperature and transfer rate coefficients based on the land cover
- *Heat **sinks/sources** managed by the SoilTemp plug-in (Rock and Kupfersberger, 2018) –*



- **Boundary conditions** at the top surface

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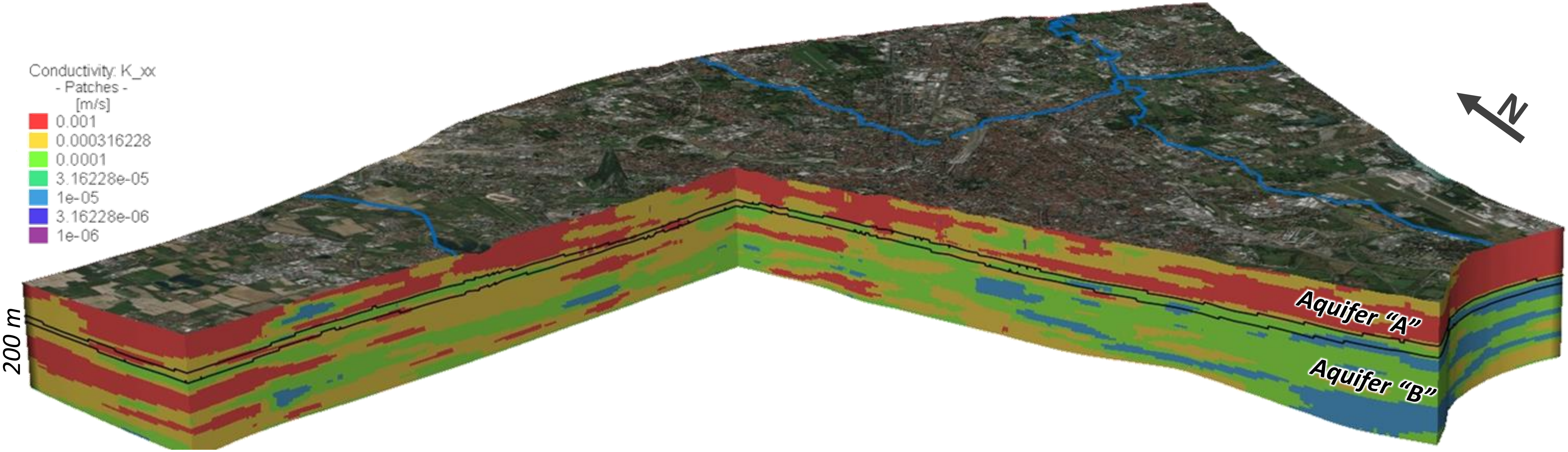
Calibration of the model



The model domain was divided in 4 subdomains by grouping the elements on specific k-values intervals

Inverse calibration with PEST

Litho-zone	Range of k_h (m/s)	Mean k_h (m/s)	Calibr k_h (m/s)
1	9*e-2 > K > 5*e-4	1.25*e-3	1.0*e-3
2	5*e-4 > K > 4*e-5	1.30*e-4	3.2*e-4
3	4*e-5 > K > 3*e-6	1.44*e-5	1.1*e-4
4	3*e-6 > K > 1*e-7	1.20*e-6	1.0*e-5

- Hydraulic conductivity, porosity, thermal conductivity and heat capacity values were **calibrated** with a "homogeneous zones" approach

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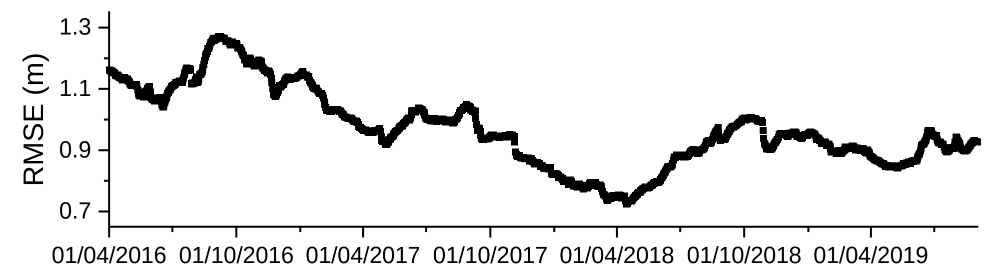
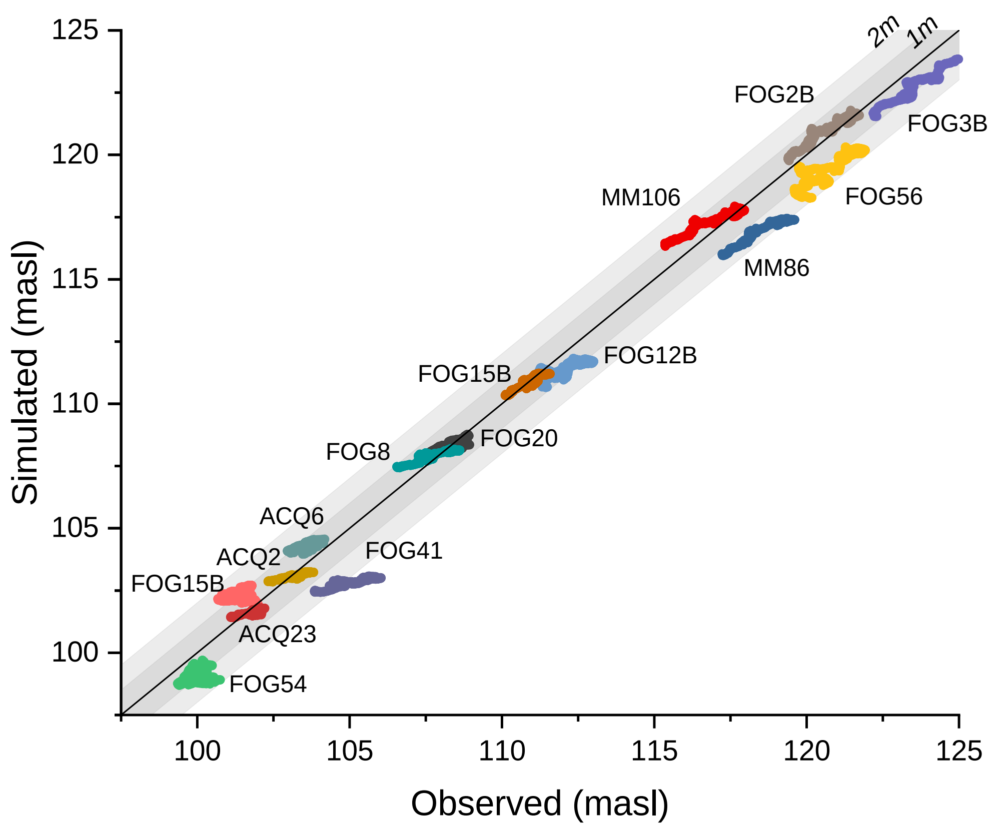
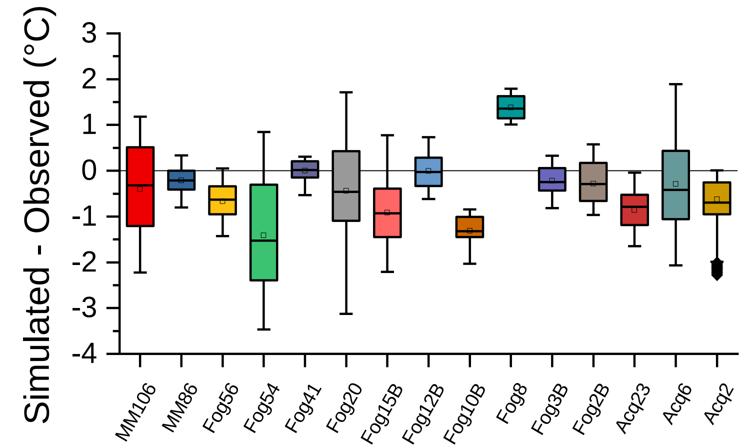
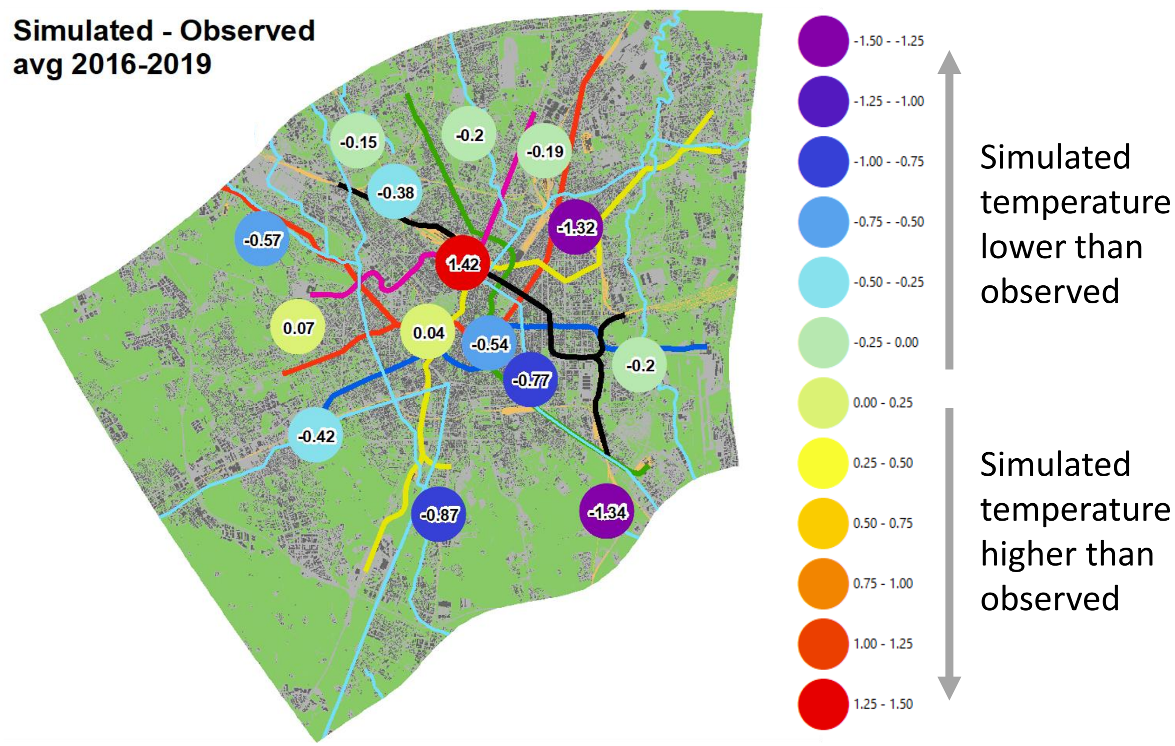
Fluid-flow results after calibration





Heat transport results after calibration





- **Calibration results**

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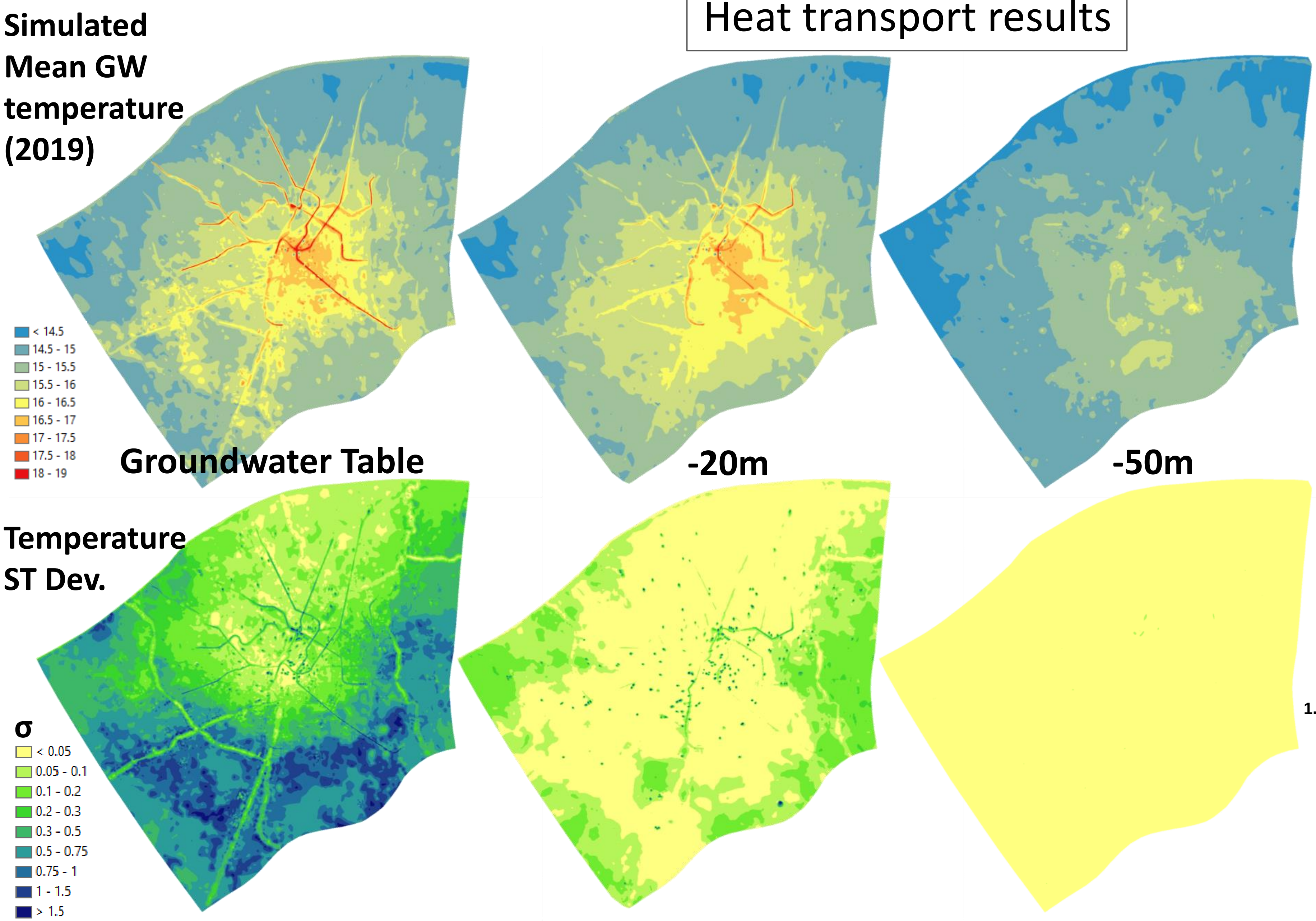
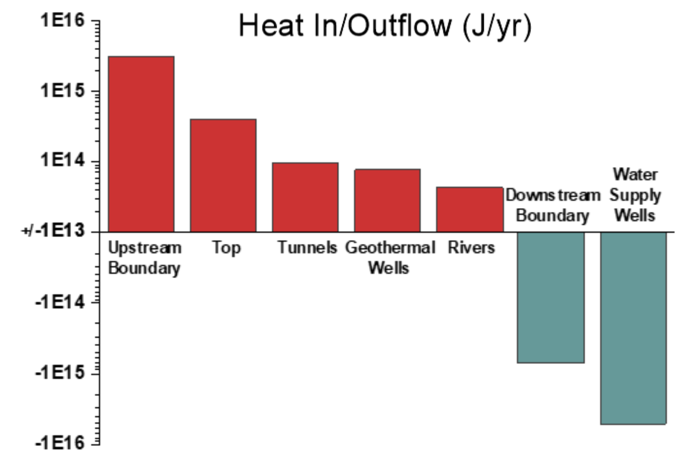
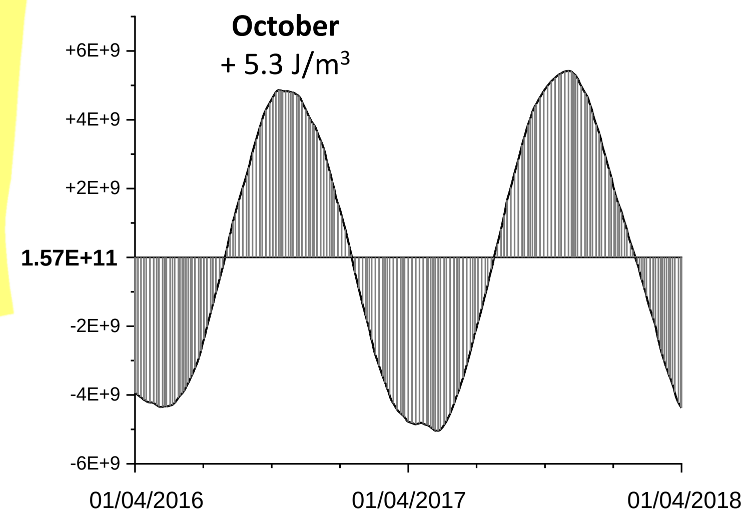
Heat transport results



Yearly Heat Budget



Energy stored in the Shallow phreatic aquifer (MJ)



- Maps showing the spatial distribution at different depths of the **simulated** mean annual GW **temperature** and the standard deviation calculated for one year of simulation
- Graphs on the right show the **natural** and **anthropogenic** heat **in-/out-flows** and the **energy stored** in the phreatic aquifer

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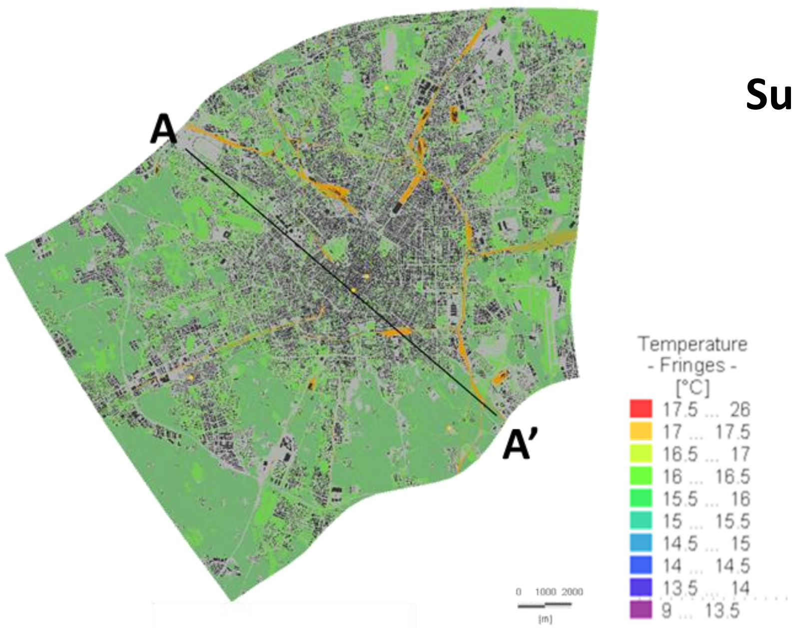
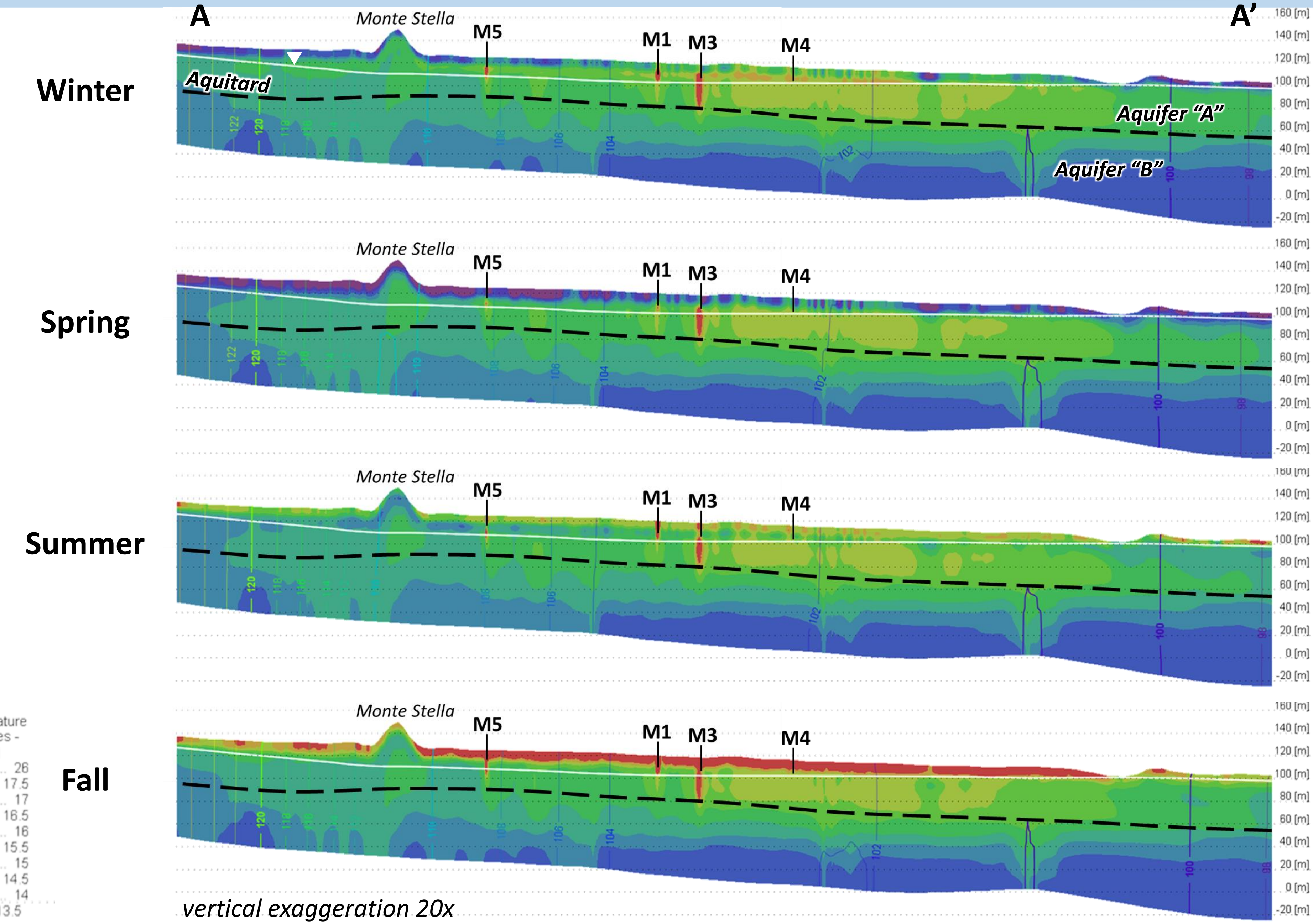
Simulated temperature cross-section

- The heat island effect is observed mainly in the shallow phreatic aquifer
- The moment of the year when the heat island effect is higher is during late fall/early winter





- **Cross-sections** showing the **simulated temperature**
- The **heat island** effect is observed mainly in the shallow phreatic aquifer
- The moment of the year when the heat island effect is higher is during late fall/early winter

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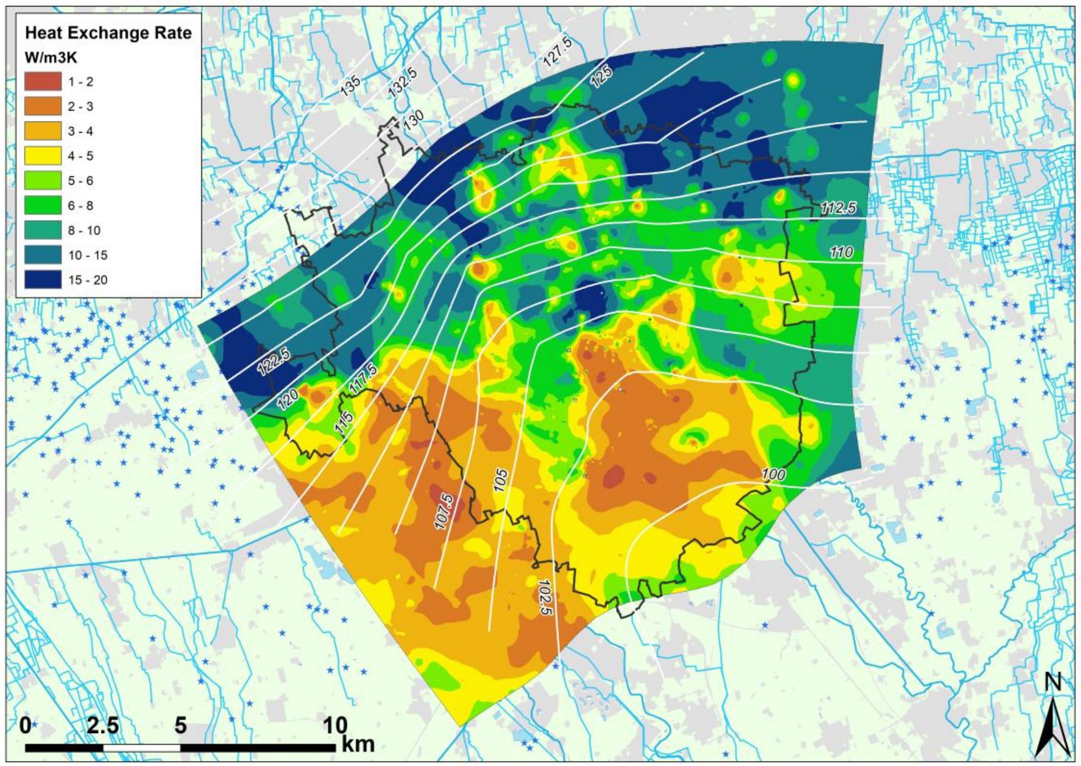
Deriving the thermal potential

Specific heat exchange rate (HER)

$$\boxed{v_d \rho c_{fluid} * \frac{\partial T}{\partial dir_v} + \lambda_{bulk} * \nabla^2 T}$$

$\frac{W}{m^3 °C}$ *amount of extractable heat for a unit temperature variation (ΔT=1)*



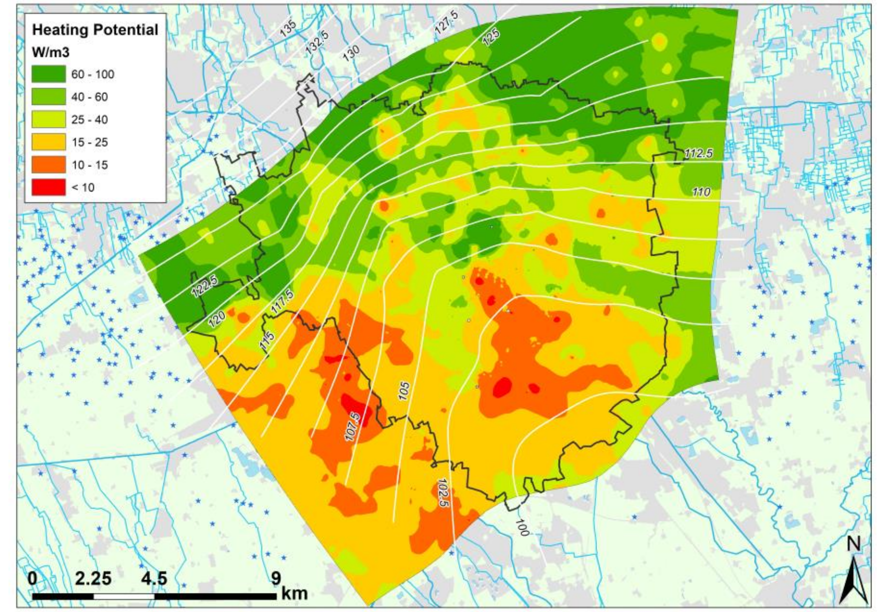
Considering only the shallow phreatic aquifer (“A”)

X Allowable temperature drop

Heating

$$\Delta T = \begin{cases} 5 & , T_0 - T_{lim} \geq 5 \\ T_0 - T_{lim} & , T_0 - T_{lim} < 5 \end{cases}$$

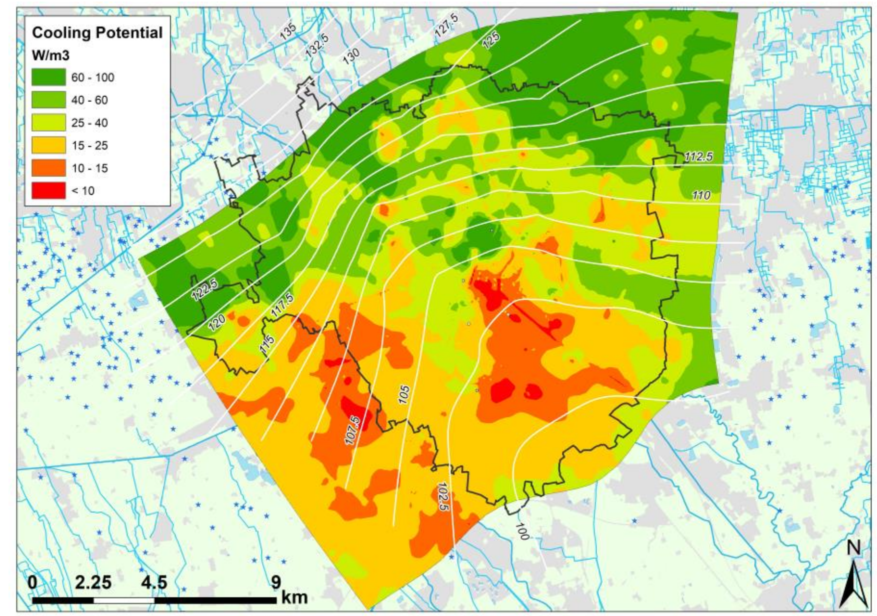
$$T_{lim} = 10°C$$



Cooling

$$\Delta T = \begin{cases} 5 & , T_{lim} - T_0 \geq 5 \\ T_{lim} - T_0 & , T_{lim} - T_0 < 5 \end{cases}$$

$$T_{lim} = 21°C$$



- The **thermal potential** for the shallow phreatic aquifer (“A”) was derived from model results by means of the heat transport equation
- First, we obtained the **heat exchange rate** by combining the advective and conductive heat-transport phenomenon
- Then, by multiplying the HER by the **allowable temperature drop** we obtained the amount of energy that could be exchanged by a m^3 of aquifer

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Conclusions

In this study we developed a fluid-flow/thermal-transport FEM numerical model for the Milan Metropolitan Area

Considering

- The **heterogeneity** of hydraulic and thermal parameters **at the urban scale**
- Complex boundary conditions at the top of the model were applied to simulate the **interaction with the surface**
- The effects of anthropogenic heat sources (e.g. **underground tunnels**, shallow **geothermal wells,** percentage of soil covered by **human-made infrastructures**)

By analyzing monitoring data and modeling results representing the present-day thermal status of the sallow aquifers we were able to:

✓ Quantify the heat island effect in the subsurface and assess natural and anthropogenic contribution

✓ Assess the thermal regime of the shallow aquifers for geothermal planning

○ Development of future scenarios under climate change, demographic growth and land use assumptions

We think that this approach can be adapted at different scales and for many cities worldwide

Thank you for your attention!!!