A surrogate model to investigate the geothermal potential with variable groundwater flow velocity

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Introduction

Alluvial aquifers have a great potential for shallow geothermal installations due to the thermal characteristics of water-saturated porous media.

Many techniques have been adopted to estimate the **low temperature geothermal potential** defining the thermal energy that can be exchanged over time per unit length between the BHE and the surrounding ground. Most of them are based on the **heat conduction** law. However, due to groundwater flow and **advective heat transport** this potential may be far greater but it is often neglected.

Analytical methods are typically fast and easy to implement in a GIS environment but commonly neglect the effects of groundwater advection on heat transfer mechanisms. On the other hand, **numerical methods** couple conductive and advective heat transport but have the limitation of domain size/resolution that makes modeling unfeasible at large scale where the variability of hydrodynamic settings can be appreciable.

Hence, a **new large-scale solution** to estimate the geothermal potential covering a great variability of **groundwater flow** regimes is presented:

- a synthetic transient-state **3D FEM model** reproducing the infinite line/cylinder source (ILS/ICS) configuration was generated
- for a large set of parameters, the thermal perturbation at radial distances and at different time stages was used to obtain specific ***g-functions*** considering also the groundwater flow velocity
- the simulated thermal perturbation was then used to calculate the **thermal resistance of the aquifer** and the corresponding thermal potential (extraction rate / energy replenishment)
- then, a **machine learning regression-based surrogate model** was generated fitting the calculated response for all possible combinations of input variables.
- finally, the model response was implemented in a GIS to obtain large scale **geothermal potential maps** with highly variable groundwater flow velocity (from 0.01 up to 1000 m/y)

Methodology

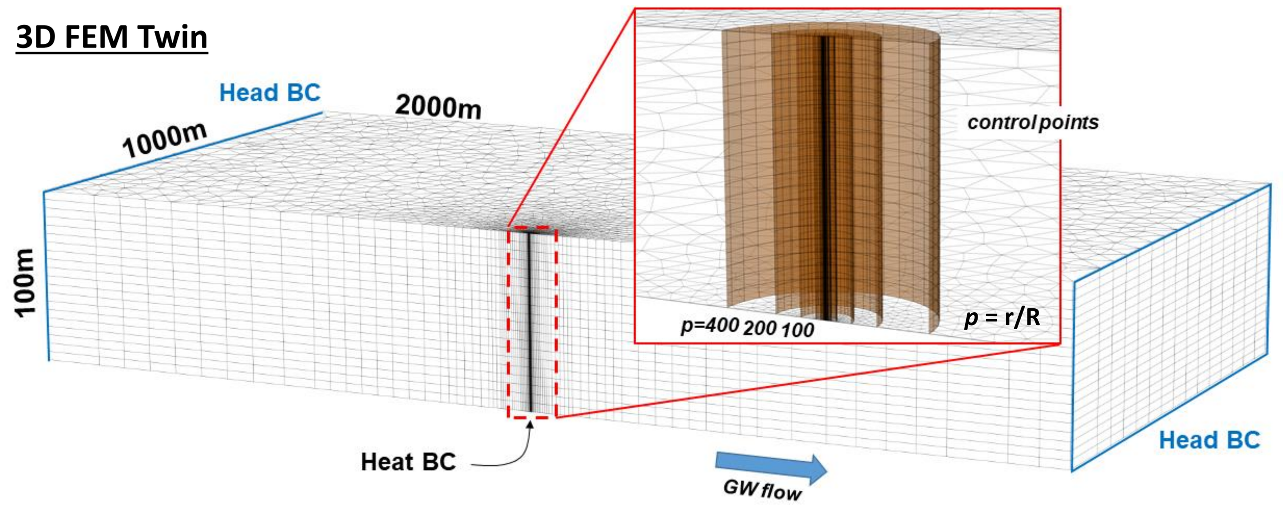
A numerical twin of the ILS/ICS method

$$\Delta T(r,t) = \frac{q}{\lambda} * G(Fo, p)$$

Integral equation to derive the T° perturbation around a cylindrical heat source as a function of the Fourier number *(Ingersoll et al., 1954)*

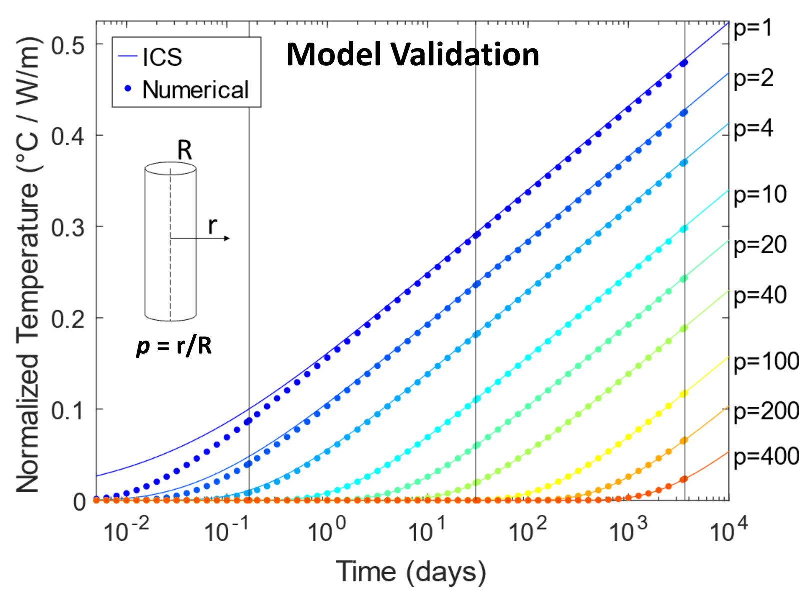
$$Fo = \frac{\alpha\, t}{R^2}$$

3D FEM Twin



Assumptions:

- The heat source is an infinite line
- heat propagates radially by conduction
- Homogeneous ground
- Constant thermal load



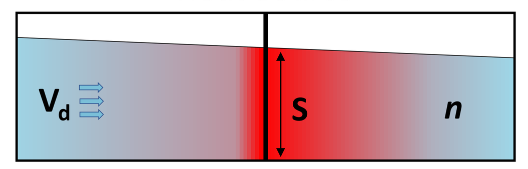
Derivation of G-functions for groundwater flow regimes

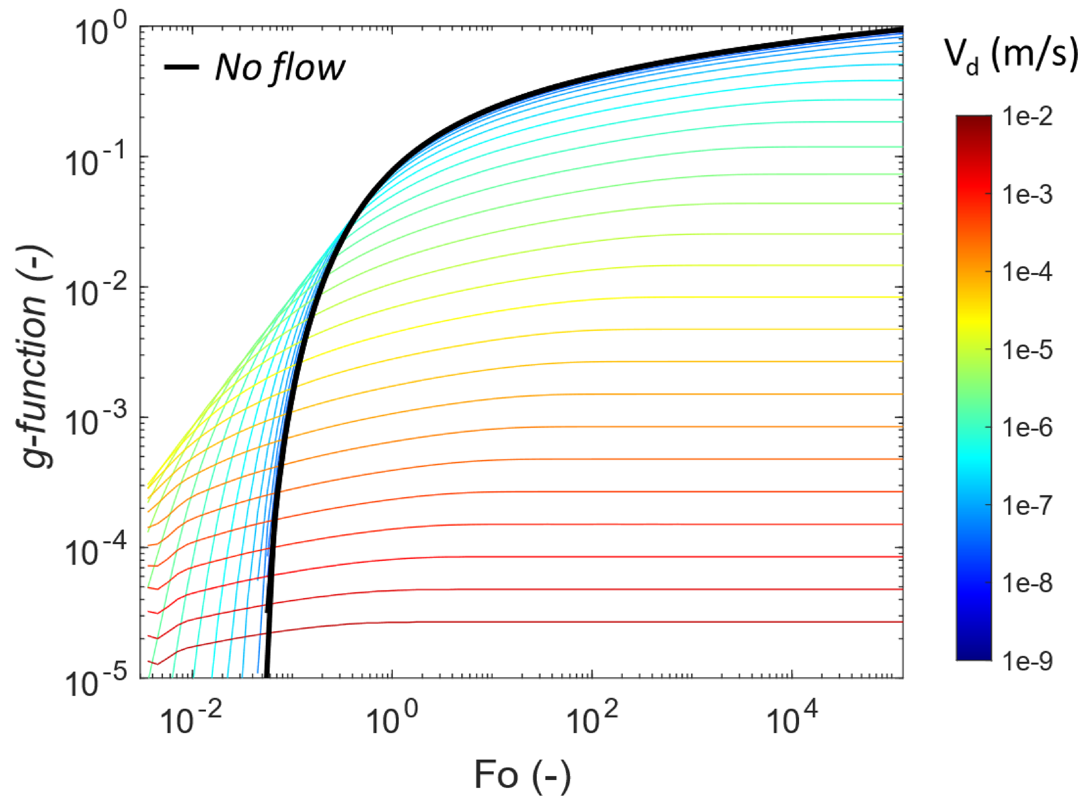
$$G(Fo, p) = \frac{\lambda * \Delta T(r,t)}{q}$$

Parameters

- Thermal parameters (*n*) $\rho c_{eq} = \rho c_f * n + \rho c_s * (1-n)$
- Groundwater velocity (V_d) $\lambda_{eq} = (\lambda_f)^n * (\lambda_s)^{(1-n)}$
- Saturation (S) $V_d = K * i$

Heat Source





Calculation of the thermal exchange potential

Extraction rate → How much thermal energy can be exchanged over time per unit length?

Evaluation of the ground thermal resistance (R_g) to three thermal pulses from the resulting g-function values. The borehole thermal resistance (R_b) is neglected.

T_1 = 4h T_2 = 30d T_3 = 10y

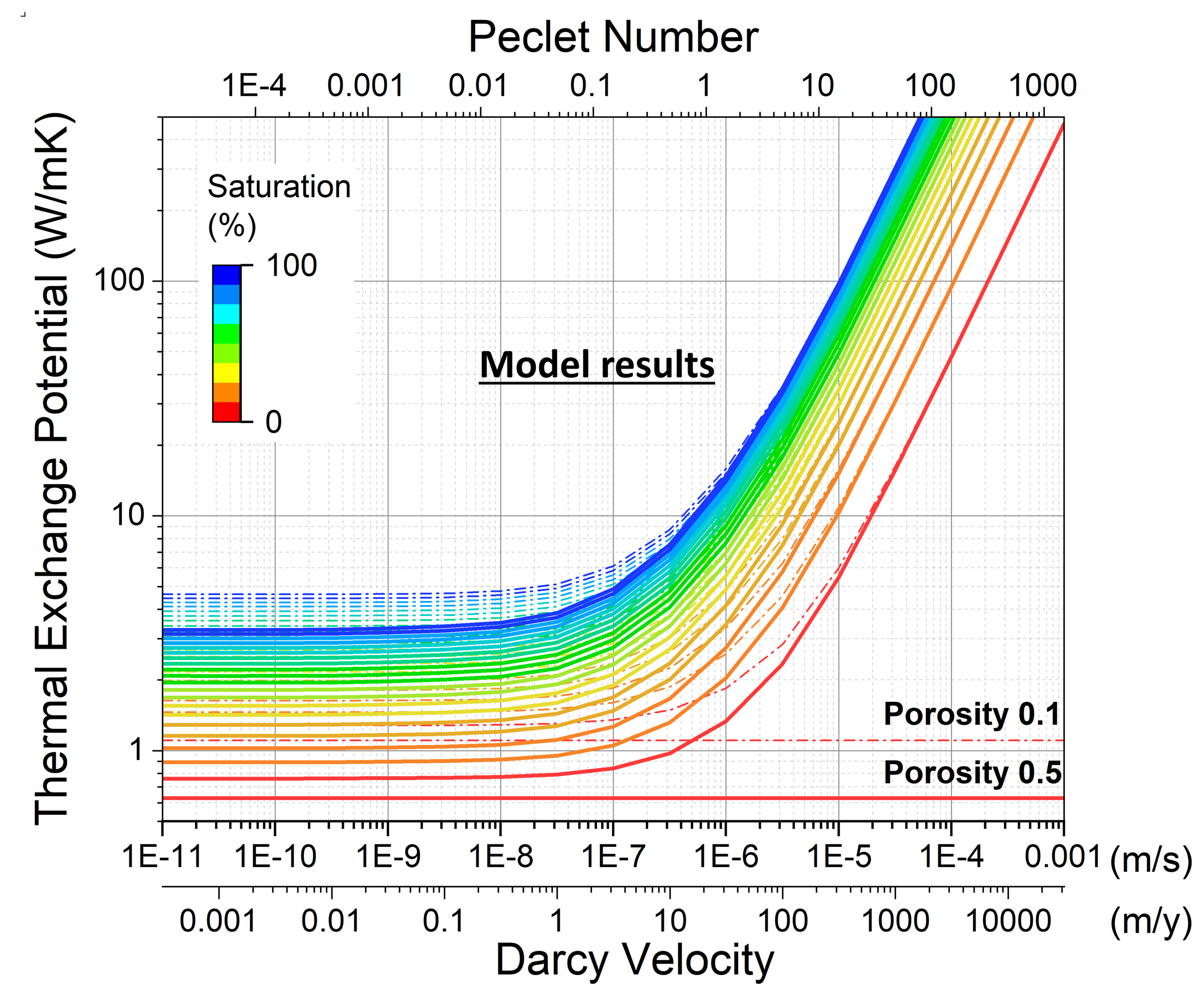
$$R_{g3} = \frac{G_3 - G_2}{\lambda_g} \qquad R_{g2} = \frac{G_2 - G_1}{\lambda_g} \qquad R_{g1} = \frac{G_1}{\lambda_g}$$

$$P = \frac{\Delta T}{\left(\frac{q_h * EFLH_h + q_c * EFLH_c}{8760}\right) * R_{g3} + q_{h/c} * (R_b + a\, R_{g2} + b\, R_{g1})}$$

ASHRAE method by *Kavanaugh and Rafferty (2014)*

A machine learning regression-based surrogate model

5670 combinations of input parameters (V_d, n and S)

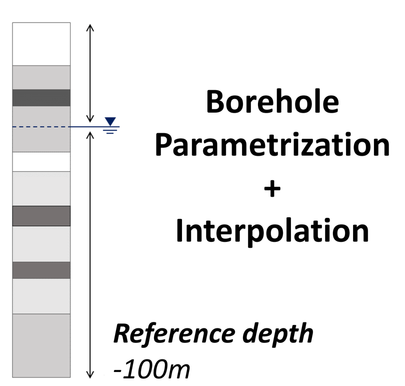


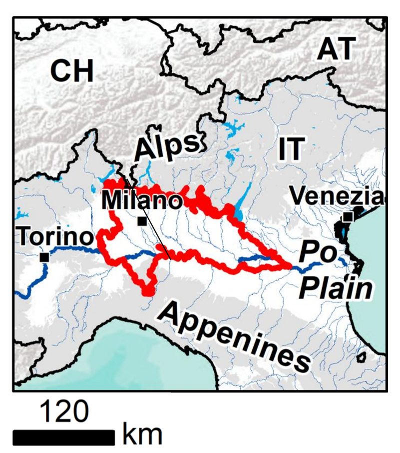
Model Type	RMSE (V)	RMSE (T)	R^2 (V)	R^2 (T)
ANN	2.0E-03	2.0E-03	1.00	1.00
Decision Tree	3.3E-02	1.5E-02	1.00	1.00
SVM	1.3E-01	1.3E-01	0.99	0.99
Kernel	1.9E-01	3.9E-01	0.98	0.93
Linear Regression	1.2E+00	1.3E+00	0.30	0.13
Stepwise Linear Regression	1.4E+00	1.3E+00	0.10	0.16

Training set → 70%
V = validation (15%)
T = test set (15%)

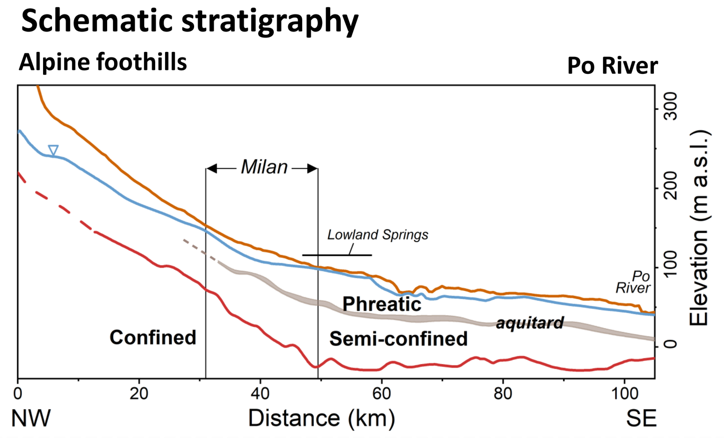
Case Study

Po alluvial plain (northern Italy)

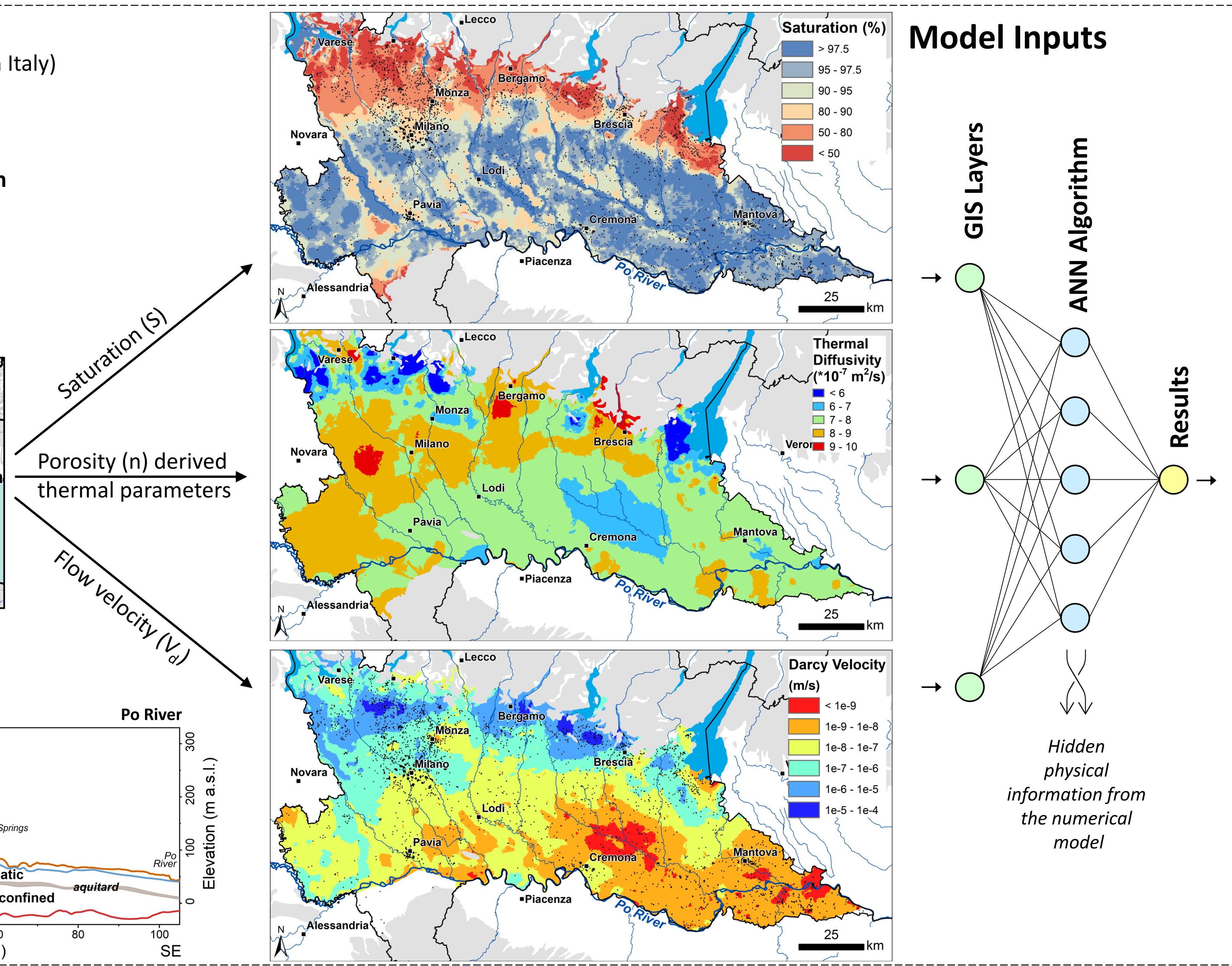




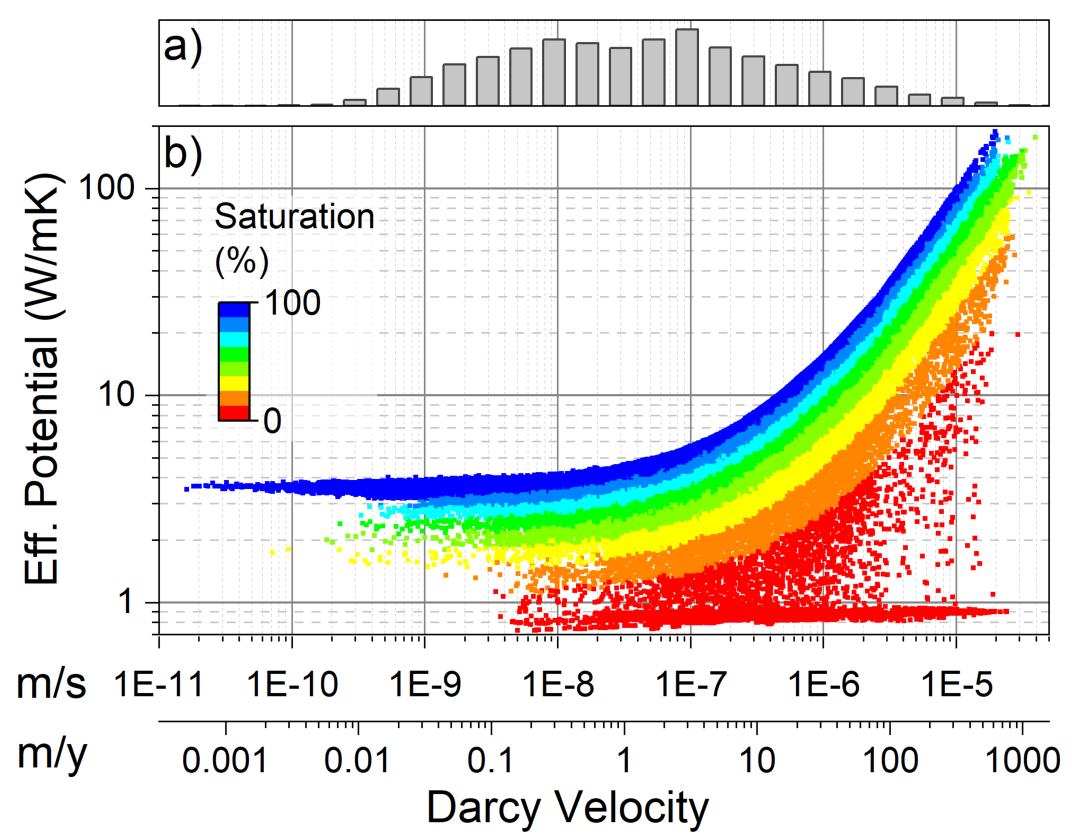
Schematic stratigraphy



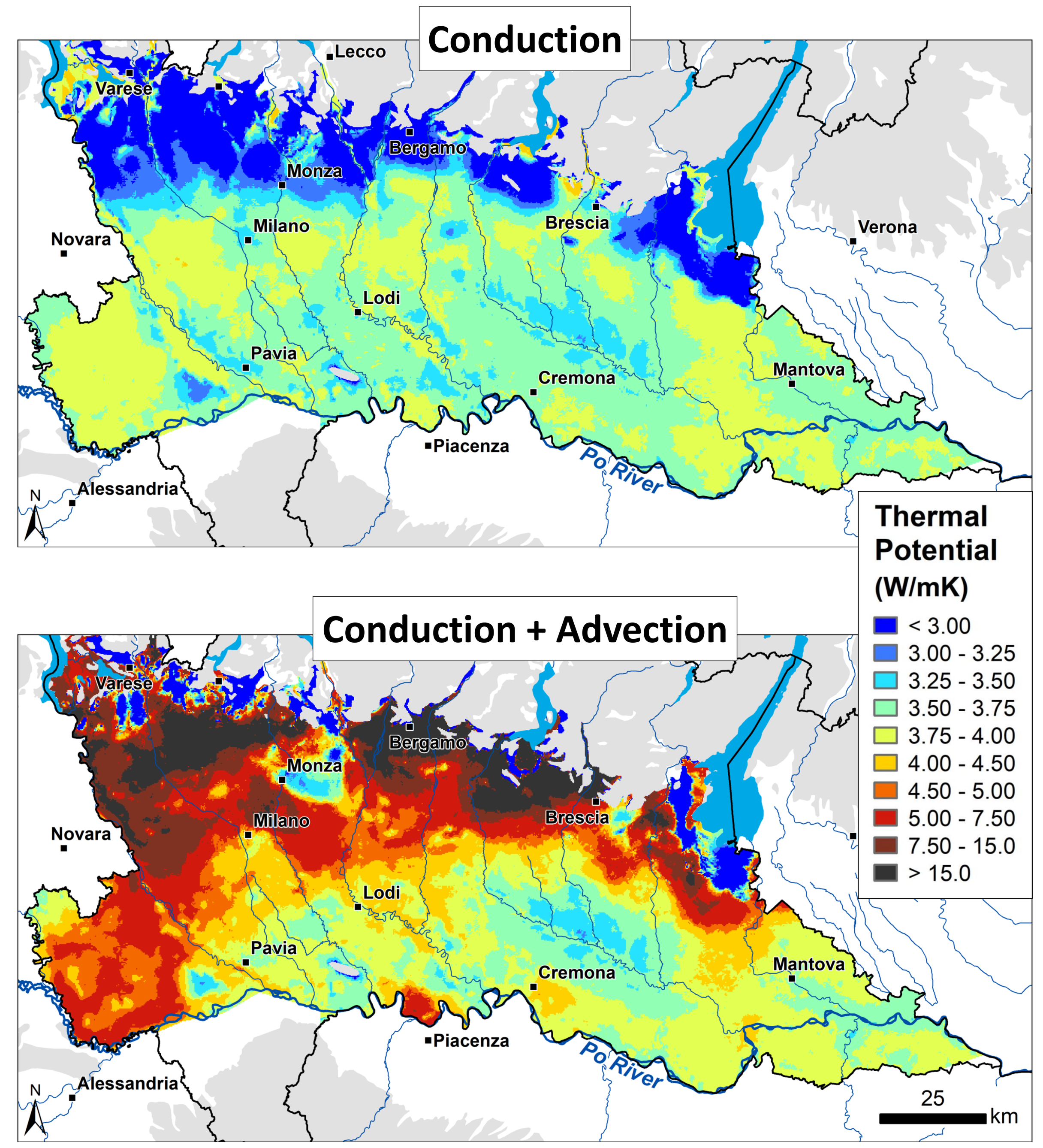
Model Inputs



Model Results

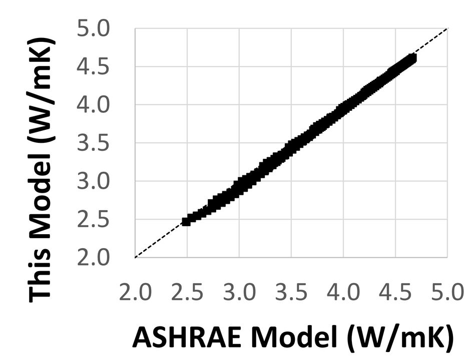


GIS Visualization

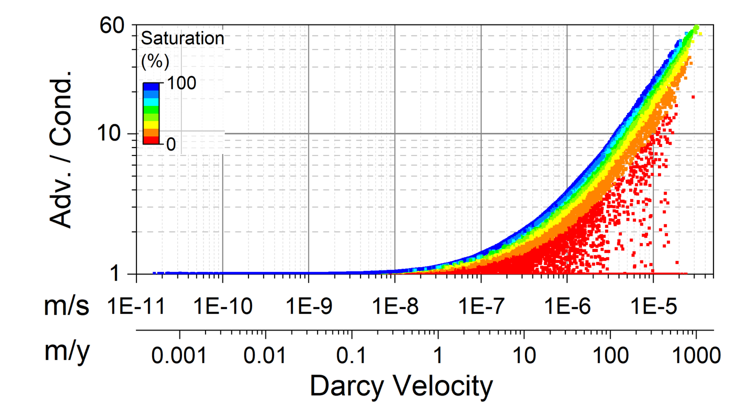


Conclusions

A **new large-scale solution** to estimate the low temperature geothermal potential covering a great variability of **groundwater flow** regimes was presented. The model was tested against known approaches such as the ASHRAE method for static groundwater in unsaturated and saturated conditions showing perfect reproducibility.



Going beyond the conductive solution and including the effects of thermal transport by groundwater a significant increase of the geothermal potential was predicted by means of a machine learning-based surrogate model as a function of the Darcy velocity. Considering the parameters investigated in this study, the **thermal potential was expected to increase from 10 to 50 times** for groundwater velocities higher than 100 m/y.



PRO

- Physically based (energy conservation)
- Heat conduction + advection
- Fast method - large scale solution
- Scalable for any reference depth
- Range of hydrogeological parameters

CONS

- Lack of field scale validation (laboratory experiment under design)
- Neglect interactions for multiple BHE arrays (implementable)