CONTRIBUTION OF GEOSTATISTICS IN MAPPING SUBSOIL TEMPERATURE EVOLUTION IN URBAN AREAS

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Belfast, 5th july 2018

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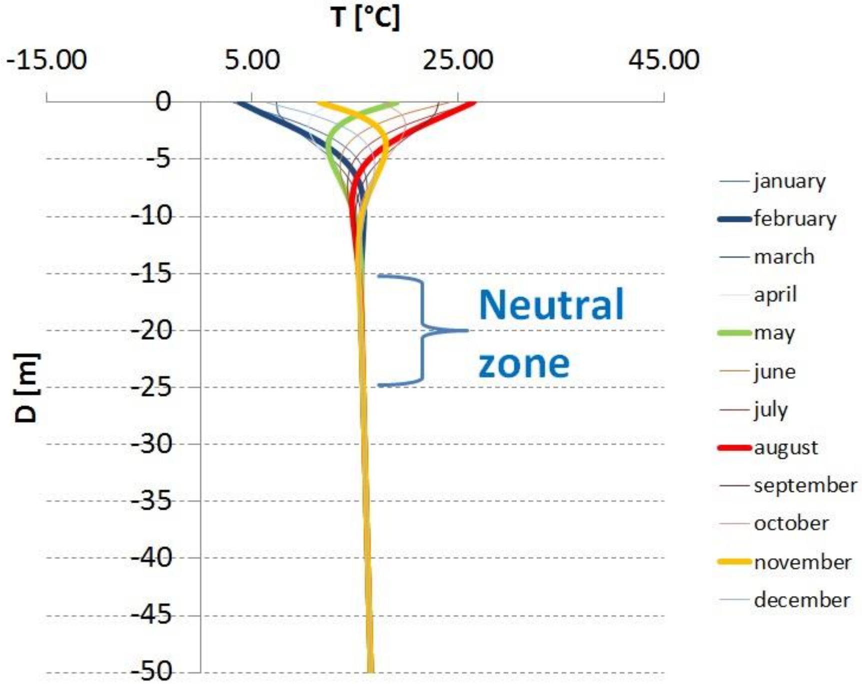
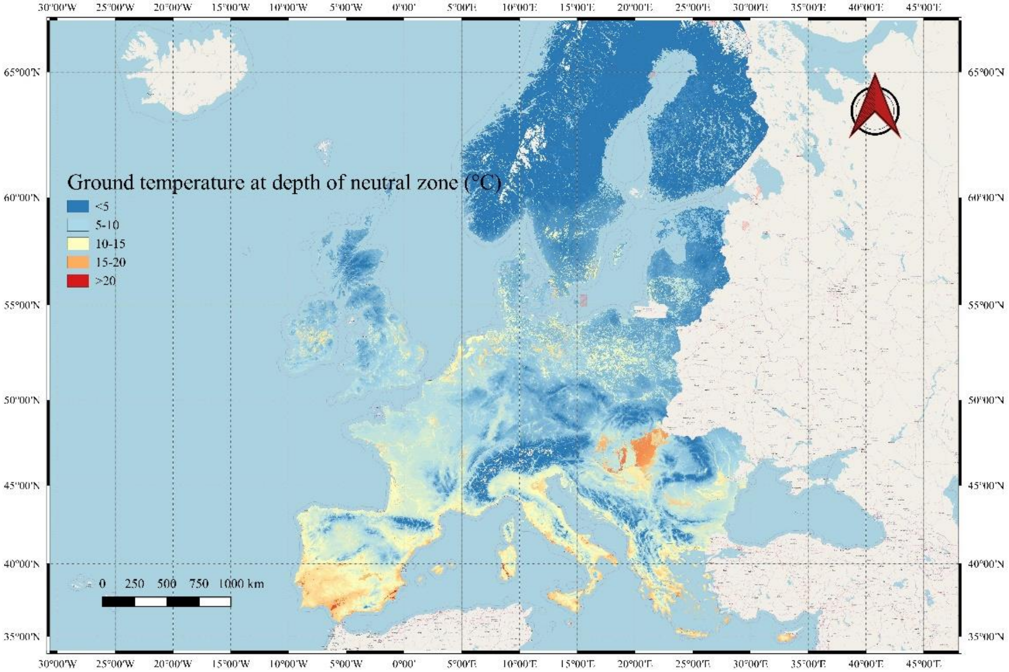
1. The context: ground temperature evolution and its importance for recovery of ambient heat



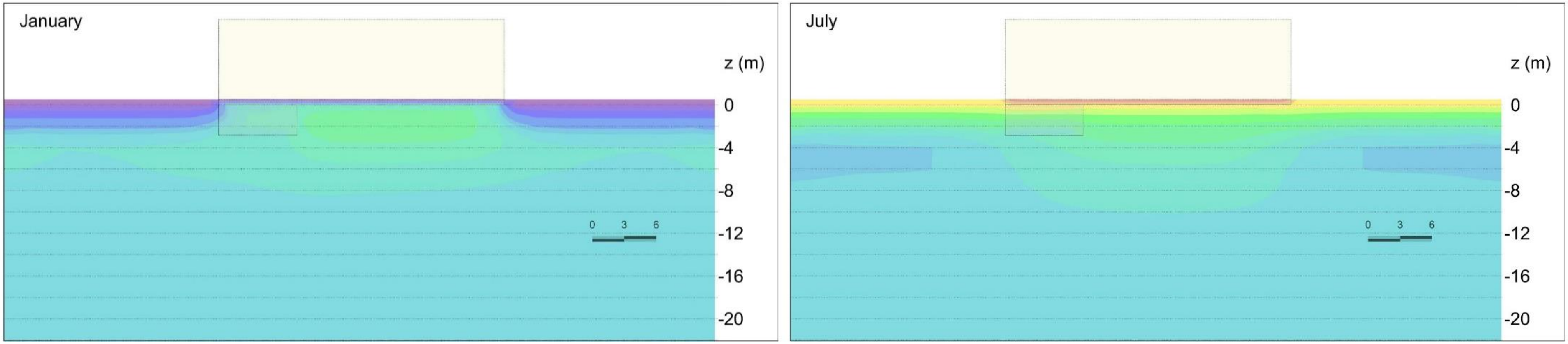


Tinti et al., 2018, *Suitability Evaluation of Specific Shallow Geothermal Technologies Using a GIS-Based Multi Criteria Decision Analysis Implementing the Analytic Hierarchic Process*, Energies, 11(2), 457

Recovery of ambient heat:

Recovery of heat energy at a useful temperature level by means of heat pumps, and which can be stored in the ambient air, ***beneath the surface of solid earth (geothermal energy)*** or in surface water.

1. The context: ground temperature evolution and its importance for recovery of ambient heat



Key points:

- Temperature variations in space and time at very shallow depth depend on many different factors, such as ground thermal properties, groundwater presence, but also heat losses from single buildings and impact of urban heat island on the ground;
- Ground is a renewable reservoir of ambient heat, with many applications.

Objective → Improvement of design of ambient heat recovery systems through a more accurate estimation of ground temperature evolution.

2. Deterministic methods and the influence of urbanization

Underground thermal properties

$$\vec{\lambda}_g(\tilde{x}) = \text{ground thermal conductivity } \left[\frac{W}{mK}\right]$$

$$c_g(\tilde{x}) = \text{ground volumetric heat capacity } \left[\frac{J}{m^3K}\right]$$

$$\vec{\alpha}_g(\tilde{x}) = \frac{\vec{\lambda}_g}{c_g} = \text{ground thermal diffusivity } \left[\frac{m^2}{s}\right]$$

Ground thermal diffusivity determines the dampening of climatic wave into the ground. It varies for different layers.

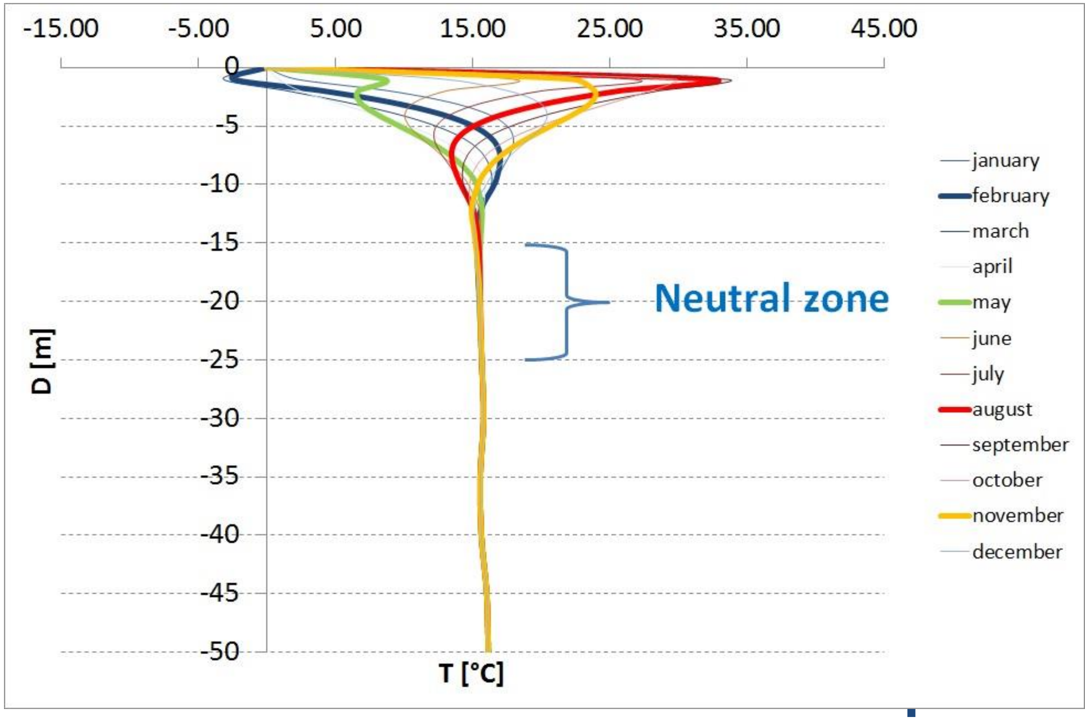
Ground thermal conductivity influences the impact of geothermal heat flow density on the ground temperature. It varies for different layers.

2. Deterministic methods and the influence of urbanization

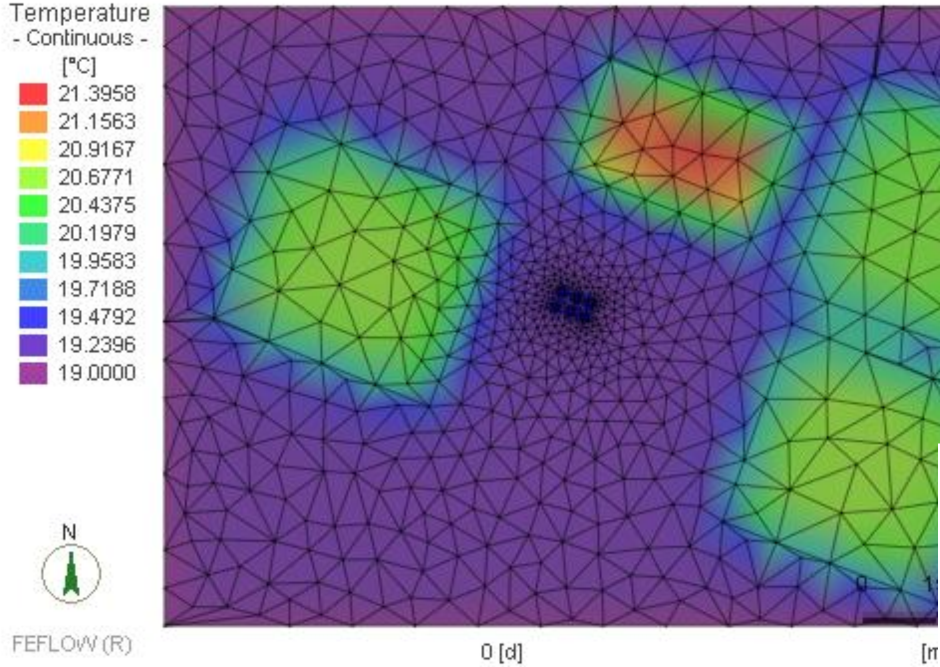
Underground temperature distribution assessment

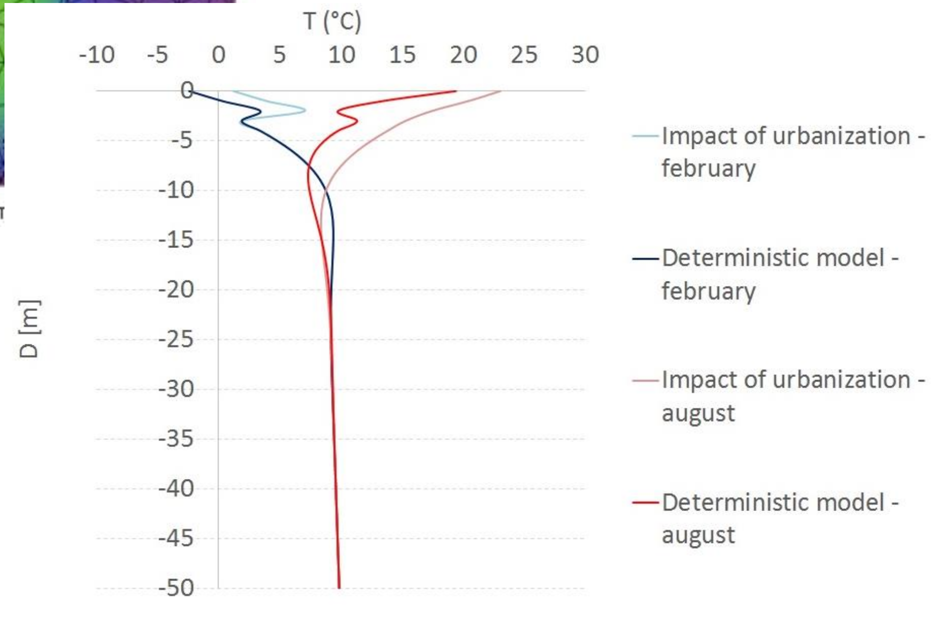
$$T_g(d,t) = T_m - A\cdot\exp\left[-d\cdot\sqrt{\left(\frac{\pi}{\mathrm{T}\cdot\alpha_g}\right)}\right]\cdot\cos\left[\frac{2\pi}{\mathrm{T}}\cdot\left(t - t_{T_0} - \frac{d}{2}\cdot\sqrt{\left(\frac{\mathrm{T}}{\pi\cdot\alpha_g}\right)}\right)\right] + \vec{\nabla}T_{geo}(h,\lambda_g)\cdot d$$

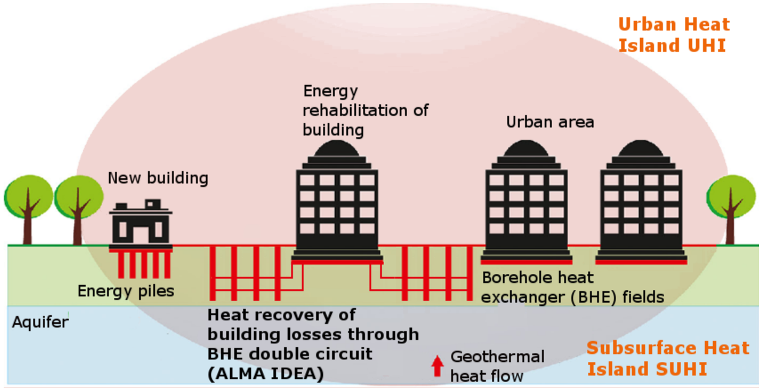
T_g → Underground temperature (°C)
T_m → Annual average temperature (°C)
A → Wave amplitude (°C)
T → Wave period (d)
t_{T0} → Day of minimum temperature (days)
α_g → Ground thermal diffusivity (m^2/days)
λ_g → Ground thermal conductivity (W/(mK))
C_g → Ground heat capacity (J/(kgK))
ρ_g → Ground density (kg/m^3)
d → Depth (m)
$\vec{\nabla}T_{geo}$ → Geothermal gradient (°C/m)
h → Geothermal heat flow (W/m^2)



2. Deterministic methods and the influence of urbanization







2. Deterministic methods and the influence of urbanization

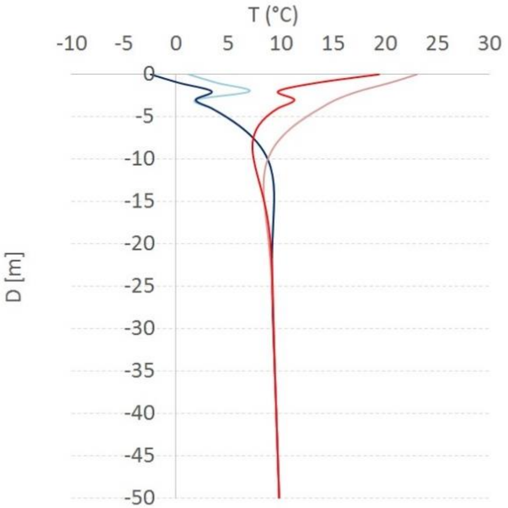
City	**Area (km^2)**	**Population density (inhab./km^2)**	**Aquifer geology**	**Thickness (m)**	**Porosity (-)**	**Potential heat content (kJ/m^2)**	**Heating demand (kJ/year)**
Cologne	405	2528	gravel, sand	15-30	0.15-0.25	4.8×10^{10} - 4.8×10^{11}	1.9×10^{10}
Winnipeg	5302	1429	carbonate	5-15	0.05-0.10	2.2×10^{10} - 2.1×10^{11}	4.1×10^{10}
Shanghai	6200	2646	sand, clay	10-20	0.20-0.30	5.0×10^{10} - 3.5×10^{11}	2.3×10^{9}
Tokyo	2187	5874	sand, clay	30-70	0.20-0.30	5.0×10^{10} - 7.0×10^{11}	2.5×10^{10}
London	1707	4761	chalk	30-40	0.05-0.20	1.1×10^{11} - 5.6×10^{11}	9.5×10^{10}
Istanbul	1830	6211	limestone	10-30	0.05-0.25	4.4×10^{10} - 5.0×10^{11}	5.5×10^{9}
Prague	496	2504	sandstone	10-30	0.10-0.30	4.6×10^{10} - 5.3×10^{11}	9.6×10^{9r}

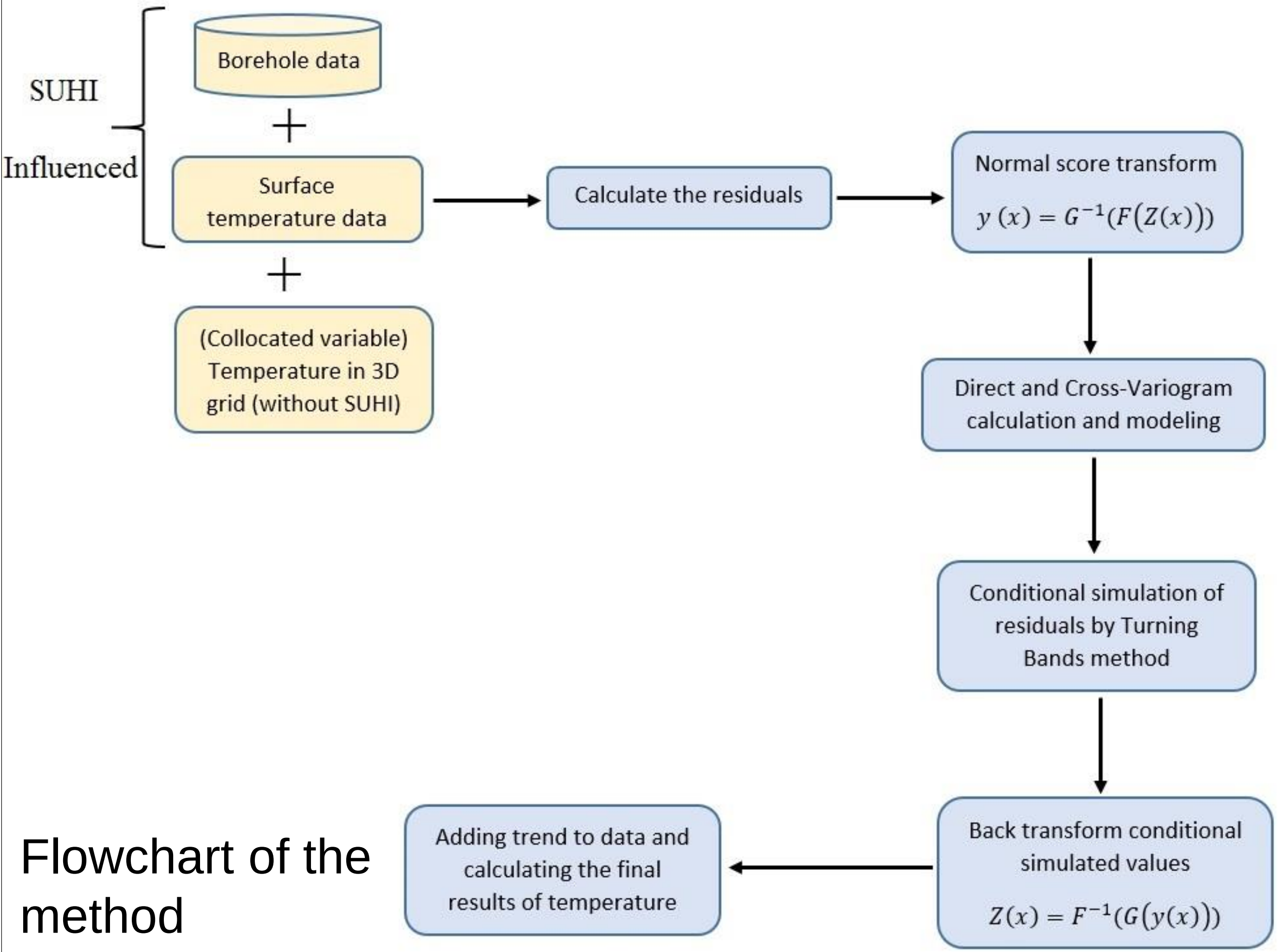
Zhu K., 2013 Urban Heat Island in the Subsurface and Geothermal Potential in Urban Areas PhD Thesis, University of Tubingen, Germany

- Deterministic calculation based on climate data and ground properties
- Statistical correlations between population density and temperature increase

3. Uncertainty issues and the use of geostatistical simulation

Geostatistics applied to the topic





SUHI

Influenced

Borehole data

+

Surface temperature data

+

(Collocated variable) Temperature in 3D grid (without SUHI)

Calculate the residuals

Normal score transform

$$y(x) = G^{-1}(F(Z(x)))$$

Direct and Cross-Variogram calculation and modeling

Conditional simulation of residuals by Turning Bands method

Back transform conditional simulated values

$$Z(x) = F^{-1}(G(y(x)))$$

Adding trend to data and calculating the final results of temperature

Flowchart of the method

3. Uncertainty issues and the use of geostatistical simulation

Choice of an area of intervention

Data to get

Temperature direct measurements – Direct variable

Borehole temperature data (measured)

Surface temperature data (measured)

Values affected by the presence of urbanization

3D temperature calculation – Collocated variable

Deterministic calculation of ground temperature in 3D from estimated parameters and indicators at macro scale (geological layers, thermal conductivity, thermal diffusivity, climate data, heat flow density)

3. Uncertainty issues and the use of geostatistical simulation

Procedure for geostatistical analysis of data (1/2)

Removal of the trend in the vertical direction and work on the residuals as fluctuation of the variables: target variable (T meas) and collocated variable

Normal score transform of residuals

$$y(x)=G^{-1}\left(F\left(Z\left(x\right)\right)\right)$$

Variograms on the residual of the target variable

Variograms on the residual of the collocated variable (T det. calculation)

Cross-variograms between the residual of the target variable and the residual collocated variable

3. Uncertainty issues and the use of geostatistical simulation

Procedure for geostatistical analysis of data (2/2)

Conditional simulation of residuals of direct variable by Turning Bands method

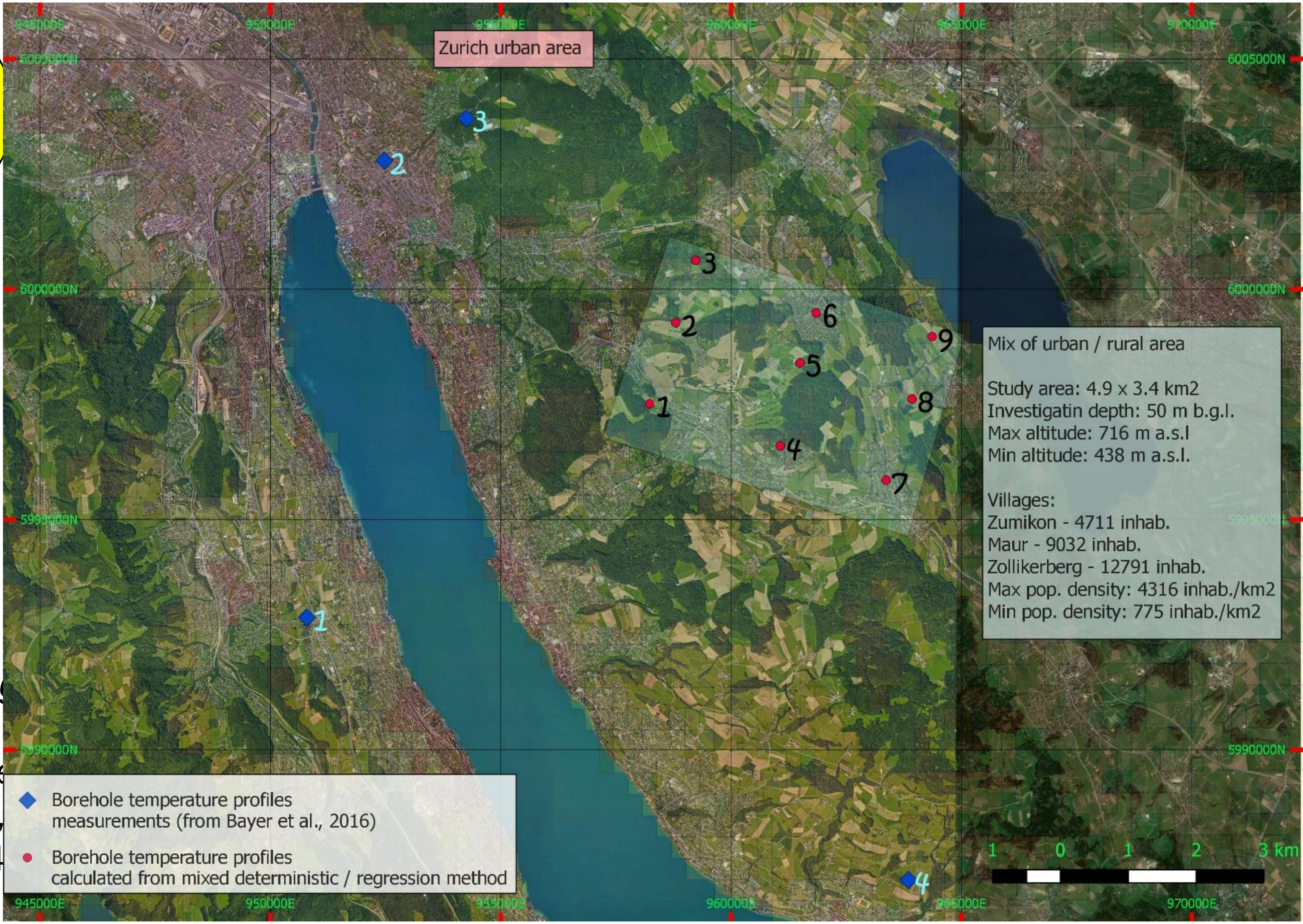
Back transform of conditional simulation results $Z(x)=F^{-1}\left(G\left(y(x)\right)\right)$

Addition of trend to results

Calculation of final 3D temperature in the area of interest, after considering the effective temperature measurements, affected by presence of urbanization

3. An application of geostatistical simulation on a case study area

Area of interest: Zurich City Area



Mix of urban / rural area

Study area: 4.9 x 3.4 km2
Investigatin depth: 50 m b.g.l.
Max altitude: 716 m a.s.l
Min altitude: 438 m a.s.l.

Villages:
Zumikon - 4711 inhab.
Maur - 9032 inhab.
Zollikerberg - 12791 inhab.
Max pop. density: 4316 inhab./km2
Min pop. density: 775 inhab./km2

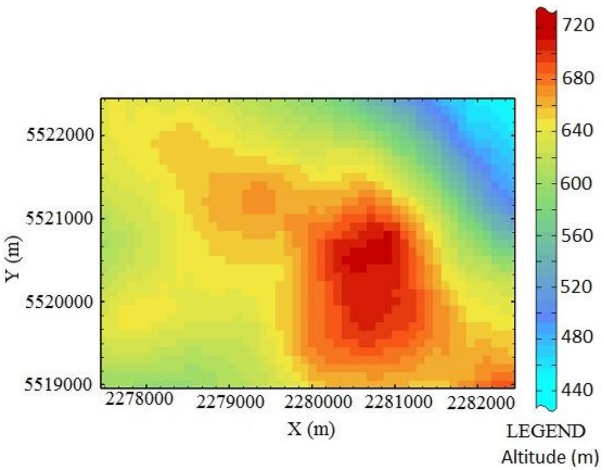
Information from:
Bayer et al.., 2016
Extracting past atmospheric warmin and urban heating effects from borehol temperature profiles,
GEOTHERMICS, 64
289-299

3. An application of geostatistical simulation on a case study area

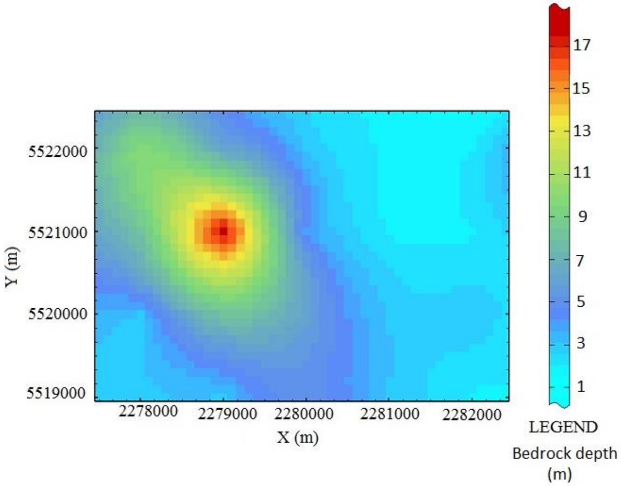
Area of interest: Zurich City Area

Reasons of area selection:

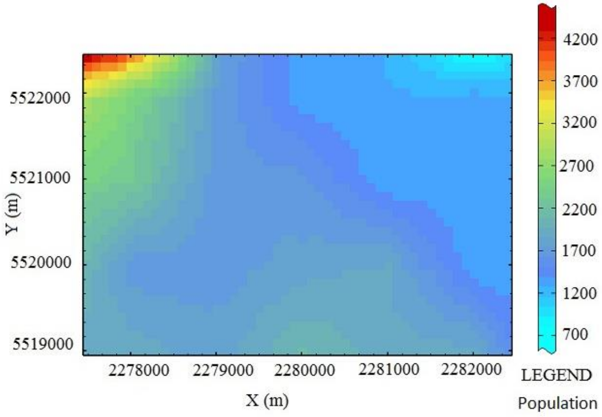
- No presence of groundwater bodies;
- High geological variability: presence of valleys and mountains;
- High population density variability: presence of urban (villages) and rural areas.



Altitude
m a.s.l.

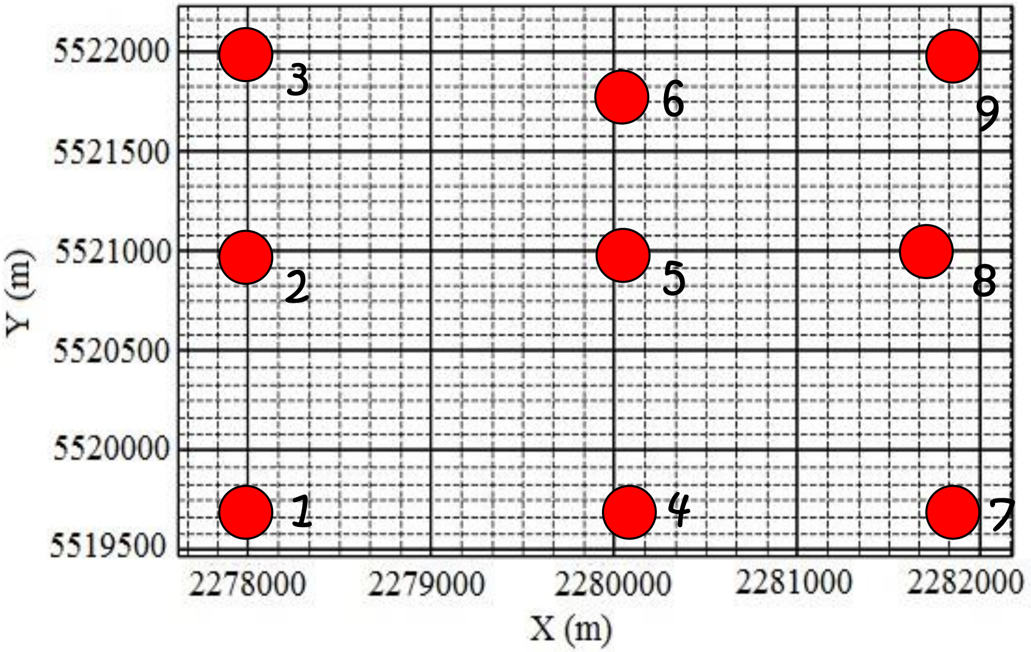


Bedrock depth
m b.g.l.

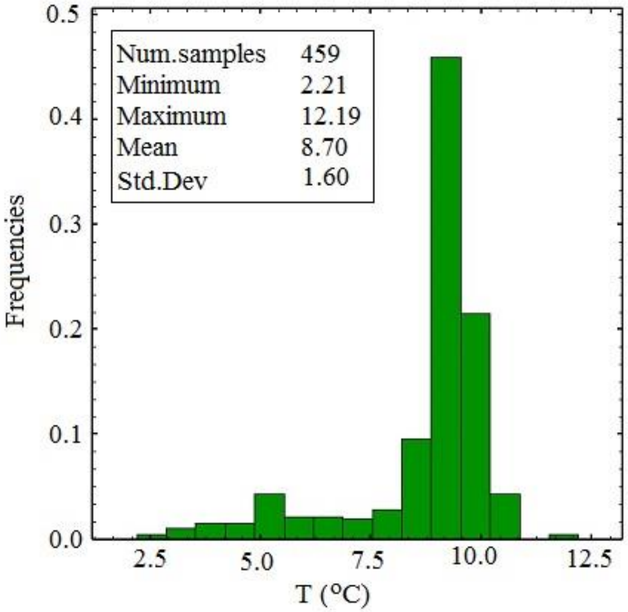


Population density
Inhab./km^2

3. An application of geostatistical simulation on a case study area



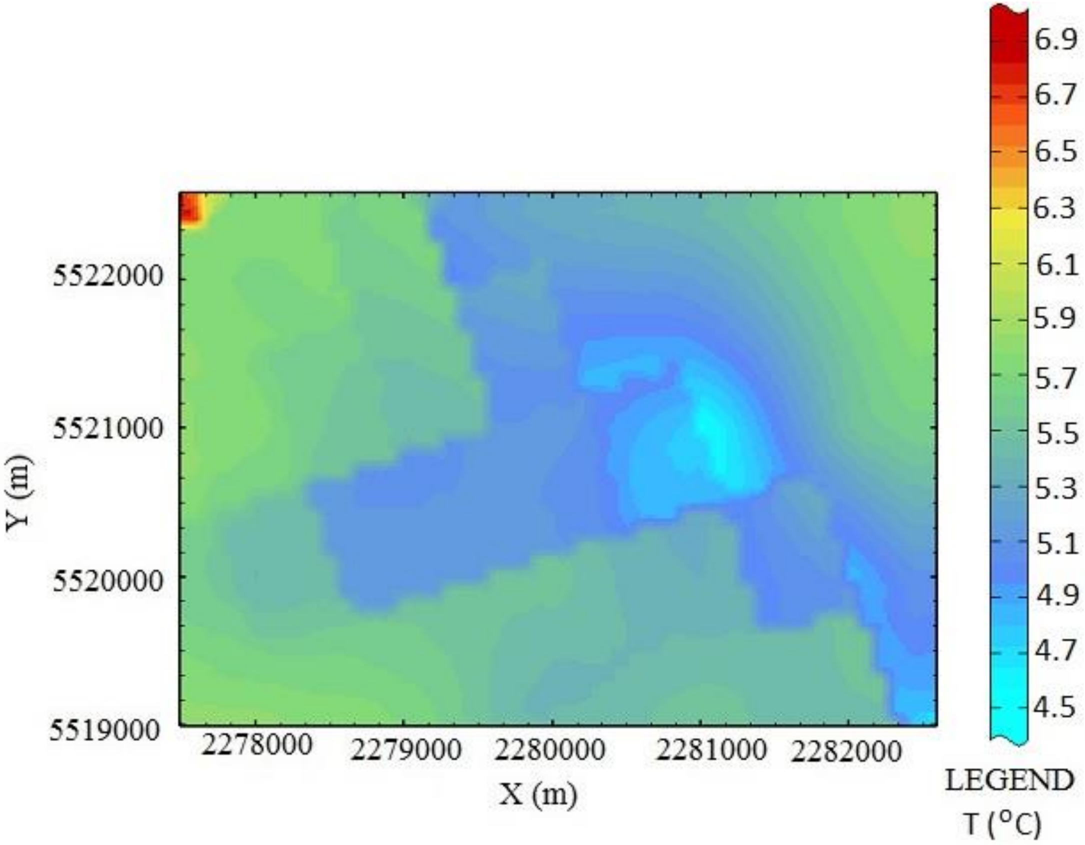
Location of 9 artificial boreholes in the study area, with CRS: ED50 / UTM Zone 28



Num.samples	459
Minimum	2.21
Maximum	12.19
Mean	8.70
Std.Dev	1.60

Histogram of temperature data and related basic statistics

3. An application of geostatistical simulation on a case study area



Surface temperature in the area of interest for March

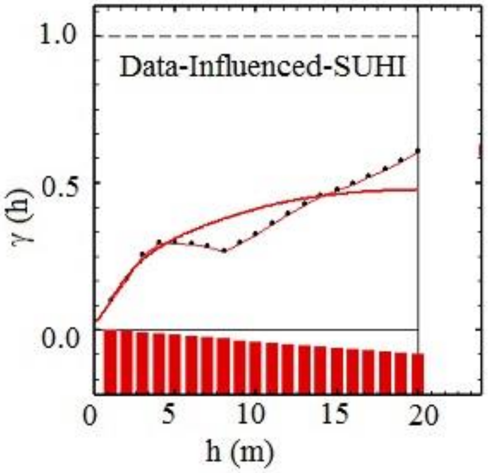
The value integrates climate information with urban effect

3. An application of geostatistical simulation on a case study area

Application on data

- Removing trend $Z(x) = m(x) + Y(x)$
- Normal score transformation with Hermit Polynomials $y(x) = G^{-1}\left(F\left(Z(x)\right)\right)$

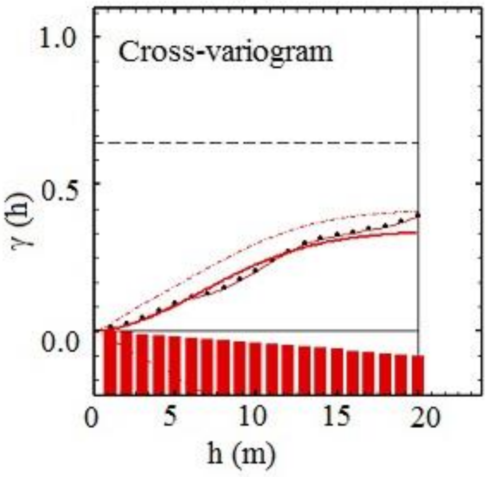
3. An application of geostatistical simulation on a case study area

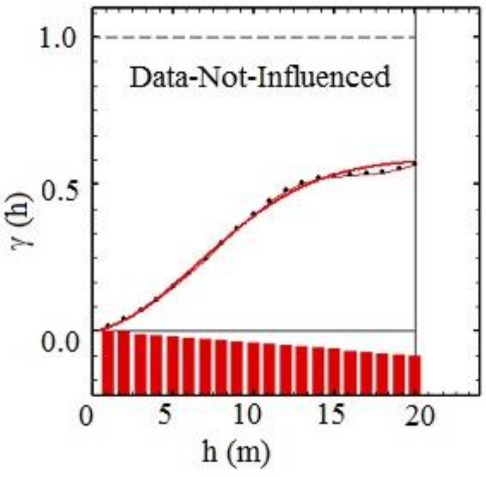


Direct and cross-variograms in vertical direction (sample and models)

$$\begin{cases}\gamma_{K-Bessel}(h) = C\cdot\left[1-\dfrac{\left(\frac{h}{a}\right)^{k}}{2^{k-1}\cdot\Gamma(\alpha)}K_{-k}\left(\frac{h}{a}\right)\right]\\ k>0\end{cases}$$

$$\begin{cases}\gamma_{J-Bessel}(h) = C\cdot\left[1-2^{k}\cdot\Gamma(\alpha+1)\dfrac{J_{k}\left(\frac{h}{a}\right)}{\left(\frac{h}{a}\right)^{k}}\right]\\ k>\dfrac{sd}{2}-1\end{cases}$$

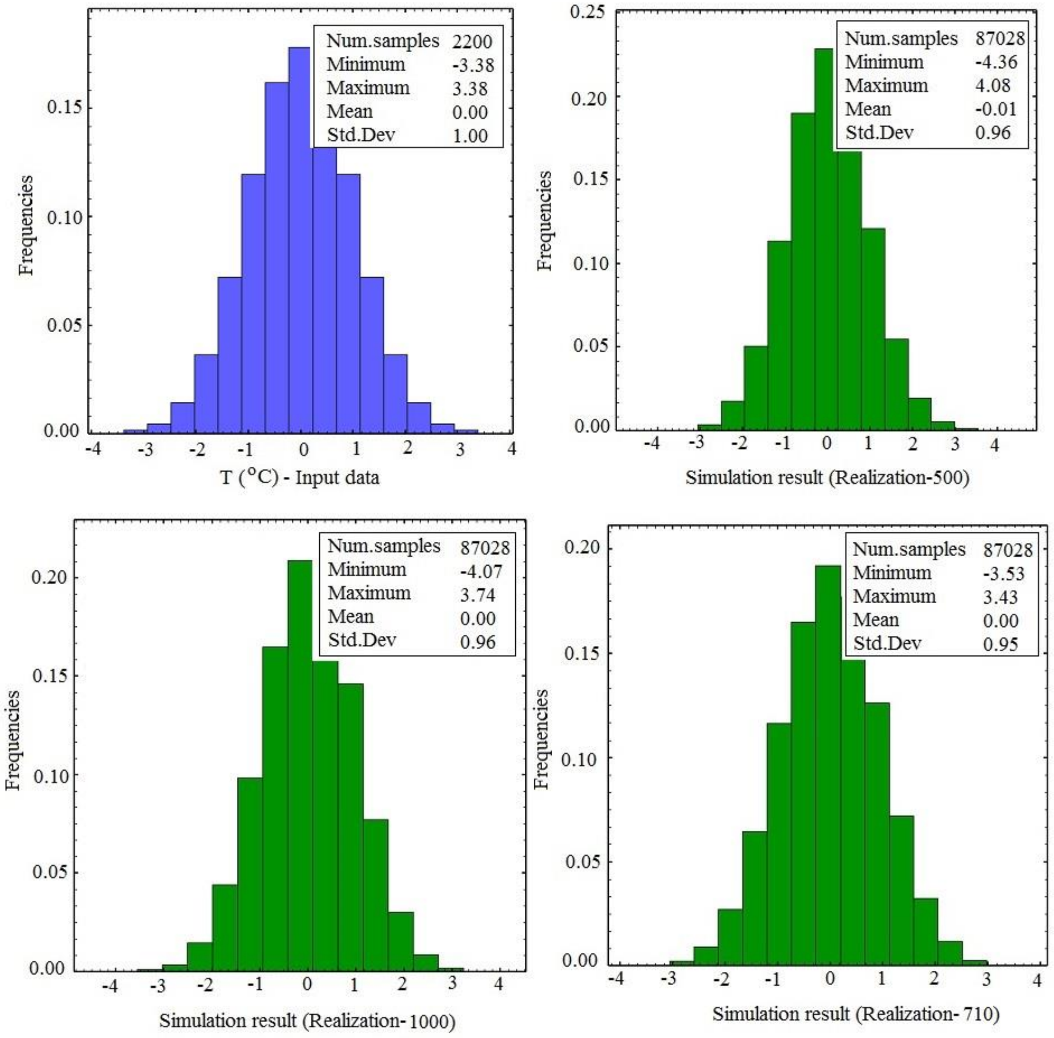




Variogram model of ground T from:

Kasmaee et al., *Use of Universal Kriging as a tool to estimate mountain temperature distribution affected by underground infrastructures: the case of the Brenner Base Tunnel*, in: European Geothermal Congress 2016 Proceedings, Bruxelles

3. An application of geostatistical simulation on a case study area



Conditional simulation with turning bands

Number of turning bands: 400

Number of simulations: 1000

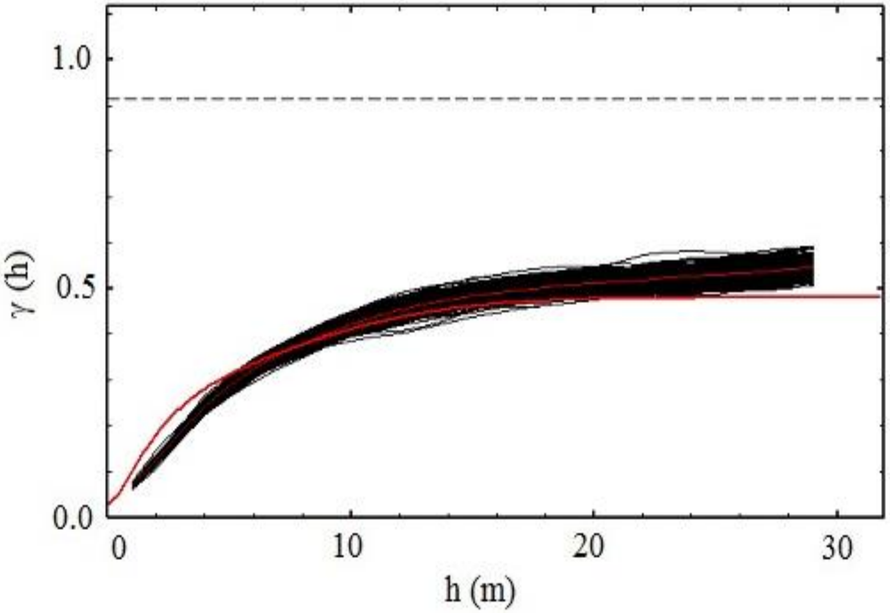
Implementation: ISATIS

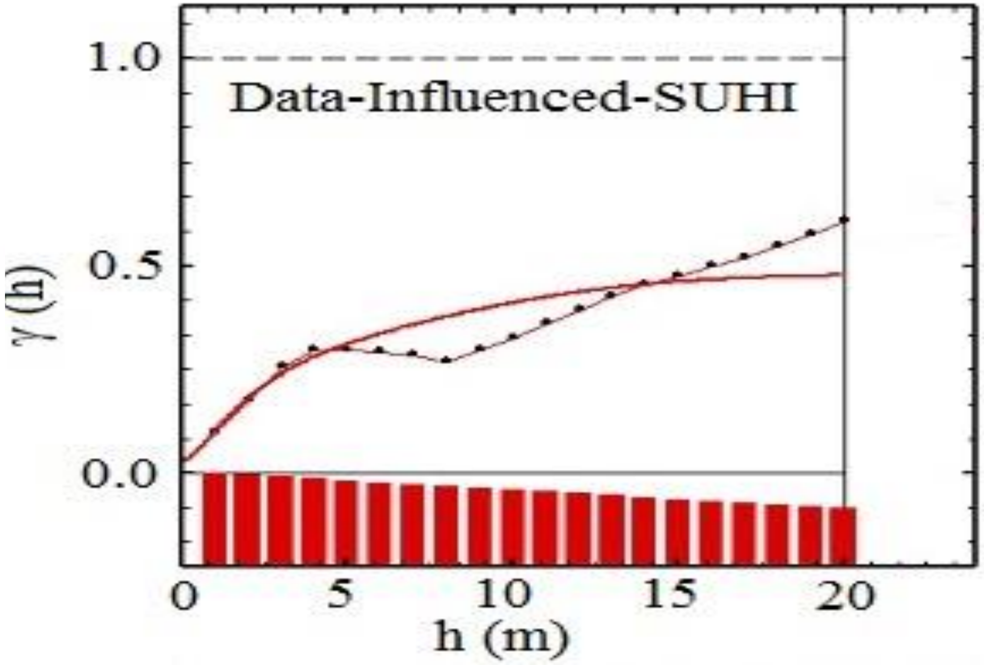
Simulation time: 3 hours

Comparisons of input data (Gaussian distribution) with the distributions of simulation results for three realizations.

3. An application of geostatistical simulation on a case study area

Convergence of the variogram results obtained from all simulation realizations with the initial variogram model used for the simulation (red thick line)





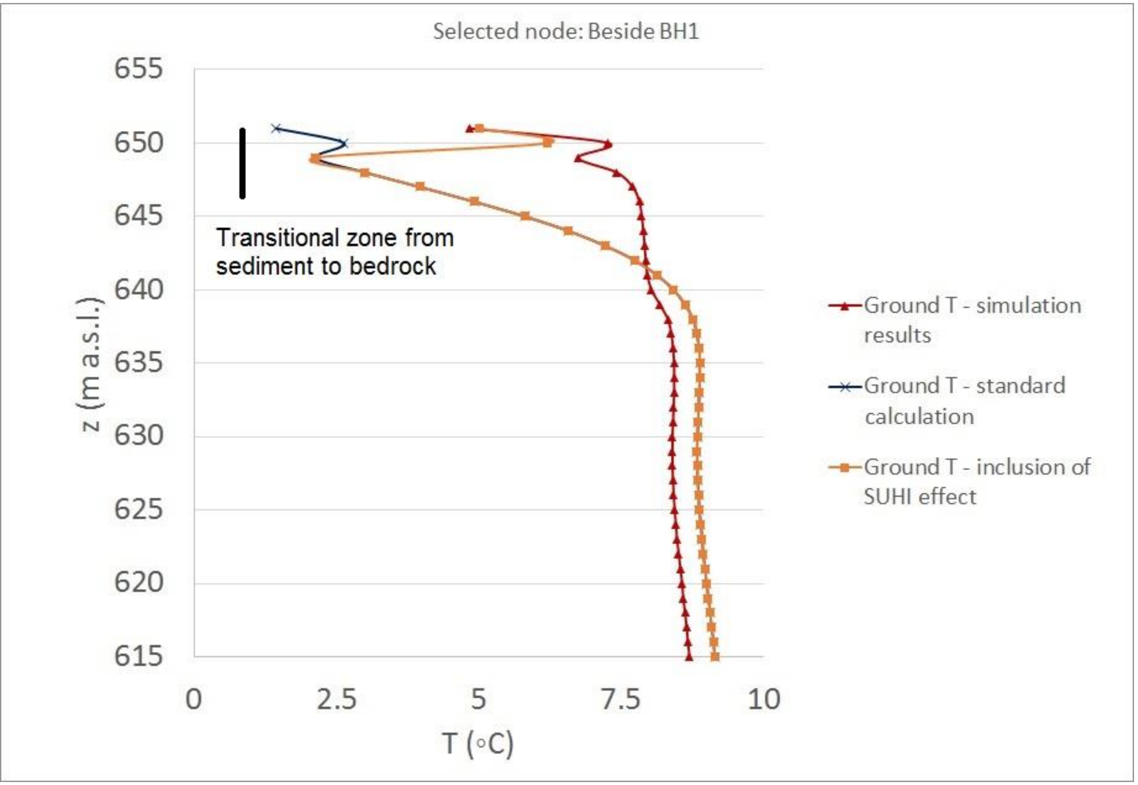
Comparison between the variogram of simulation realisation and the variogram model of residuals of initial temperature data influenced by urban presence

3. An application of geostatistical simulation on a case study area

Ex.
Realisation 1

Beside BH1

3. An application of geostatistical simulation on a case study area

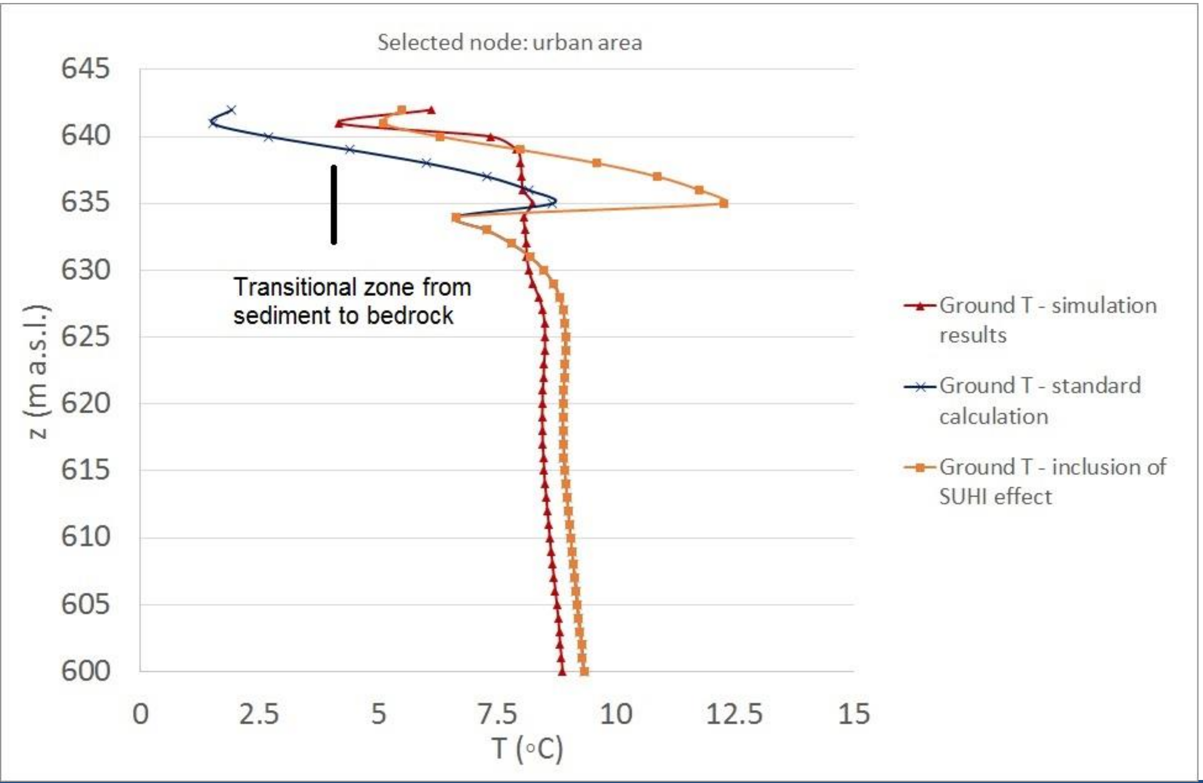


3. An application of geostatistical simulation on a case study area

Ex.
Realisation 2

In urban area

3. An application of geostatistical simulation on a case study area

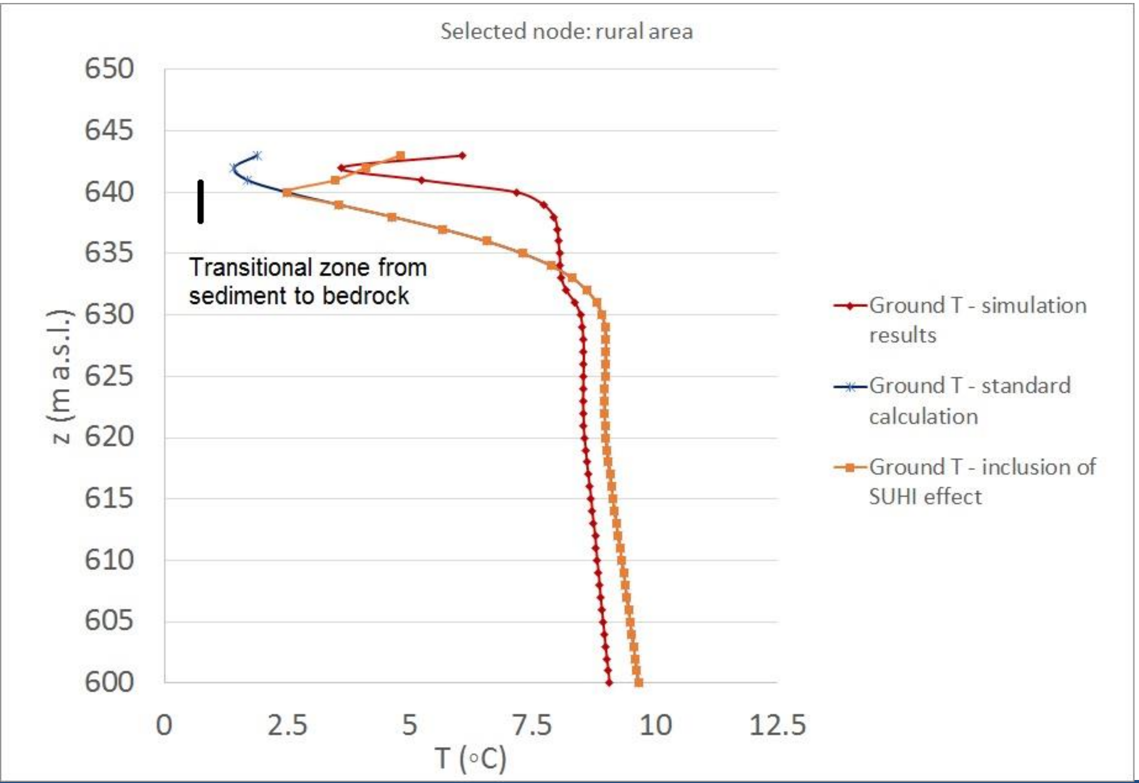


3. An application of geostatistical simulation on a case study area

Ex.
Realisation 2

Out of urban area

3. An application of geostatistical simulation on a case study area



4. Conclusions and next steps

Preliminary results

- Geostatistical conditional simulation can be used to reconstruct in 3D ground temperature, including urban heat island (UHI) effect.
- Sample data are surface temperature, including UHI effect (for example aerial thermography), and temperature measurements in depth at convenient scale (measurements from existing wells, boreholes,…).

Impact for geothermal sector

- Improved characterization of geothermal resource, for its sustainable exploitation at shallow depth (< 50 m) with geothermal heat exchangers

Next steps and future work

- ☐ Adding the fourth dimension (time) in the simulation.
- ☐ Inclusion of geology information as indicator (with transition between sediments and bedrock).
- ☐ Validation of the methodology on a real case with borehole temperature measurements in a defined future area of Bologna (IT), with aerial thermography and borehole and well samples.
- ☐ Inclusion of additional temperature measurements from city underground structures and spaces (cellars, garages, sewer system, channels).

Thank you for your attention

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