European Geothermal Congress 2016
Strasbourg, France, 19–24 Sept 2016

Influence factors in the depth domain of borehole heat exchangers – global warming and urban heating

Ladislaus Rybach[1], Peter Bayer[2], Jaime A. Rivera[2], Philipp Blum[3]

[1] Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland

[2] Geological Institute, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland

[3] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstraße 12, 76131 Karlsruhe, Germany

rybach@ig.erdw.ethz.ch

Keywords: Temperature anomalies, Urban Heat Island, land use changes.

ABSTRACT

Nowadays in urban areas a deviation is found in borehole temperatures logs (T-logs) from a regular increase with depth (“geothermal gradient”): in the top ~ 100 meters the deviation increases towards the land surface. Two main effects cause this deviation: global warming and urban heating. In order to distinguish and quantify the two effects in the ground thermal regime, a novel model simulation method is used to invert the temperature logs. The inversion is demonstrated on a characteristic T-log measured near Zurich, Switzerland. The logging was performed in a borehole heat exchanger (BHE) U-tube by a wireless measuring device. The two influencing contributions are separated by the modeling; the results reveal that in the investigated depth range top the urban heat island (UHI) effect can be significant or even dominant.

1. INTRODUCTION

The thermal conditions and processes in the shallow subsurface (<400 m depth) are of paramount importance in utilizing the geothermal resources prevailing there. They are essential for space heating/cooling by ground source heat pumps (GSHP). Especially in the top 100 meters, the heat input of atmospheric urban heat island (UHI) and global warming effects are dominant. This heat surplus and its resupply is a decisive and highly welcome addition to the natural resources in this depth range.

The UHI is the rise in air temperature of man-made areas, resulting in a well-defined, distinct "warm island" among the "cool sea" represented by the lower temperature of the surrounding natural landscape. Such UHI also exists in the subsurface of many cities. A subsurface UHI exhibits additional heat that accumulated over the entire life cycle of a city. The heat originates from heated buildings, sun-warmed pavements, buried infrastructures, etc. (Menberg et al. 2013ab, Benz et al. 2015, Rivera et al. 2015). Several previous studies pointed out the relevance of such subsurface UHIs for ground source heat pump applications (Zhu et al. 2010, Herbert et al. 2013, Spadoni et al. 2013, Luo & Asproudi 2015). They represent an increased reservoir for geothermal heating but may impede the utilization of urban ground for cooling.

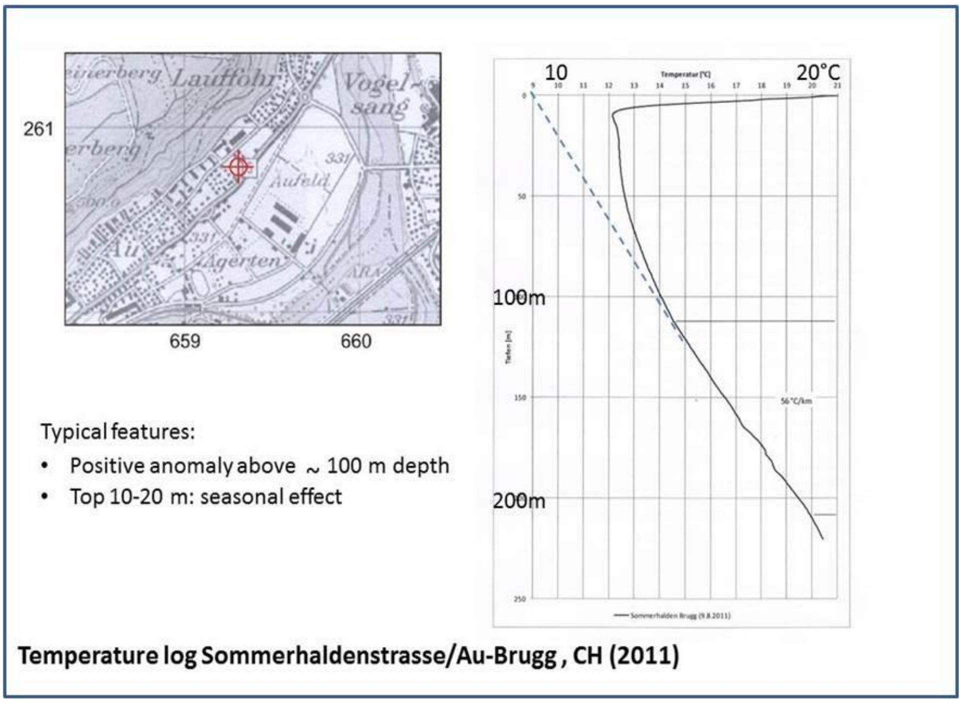
In this study the ground temperature distribution and the influences shaping subsurface UHIs are investigated by field measurements and by model-based simulations. Special emphasis is given to differentiate and quantify the effects of changed land use types and global warming on urban ground heating (Bayer et al. submitted). The results are directly relevant for dimensioning, especially of large GSHP systems in densely populated areas.

2. GROUND TEMPERATURE DISTRIBUTION IN THE SUBSURFACE

Under conduction-dominated conditions without groundwater flow, the temperature-depth profile in homogeneous ground shows a linear gradient, on which the variations, caused by surface temperature changes, are superposed. Temperature changes at the earth’s surface propagate inexorably down into the ground, which therefore can be considered (and deciphered) as an archive of past changes (Harris & Chapman 1997, Pollack & Huang 2000). The amplitude of seasonal changes, evoked by solar radiation, decrease with depth; below the “neutral zone” at about $z = 15 – 20$ m depth, this effect becomes negligible. The extrapolation of the linear temperature profile to zero depth then gives a value, which corresponds with the mean annual temperature at $z = 0$. In moderate climate this can be a few °C higher than the mean annual air temperature, see e.g. Signorelli & Kohl (2004).

In many urban areas, the temperature-depth profiles (= temperature logs) clearly and significantly differ from a linear temperature-depth trend; a systematic deviation starts at a depth of about 100 meters with a tendency to gradually increase towards the surface. Measurements of temperature profiles in shallow groundwater revealed several degrees higher temperatures beneath cities (Ferguson & Woodbury 2004, Taniguchi et al. 2007, Eggleston & McCoy 2015, Zhu et al. 2015). In this work, however, we focus on temperature depth profiles taken in borehole heat exchangers. Such profiles are rarely investigated and specialized techniques are required for obtaining the vertical temperature trend before geothermal heat extraction starts.

Figure 1 shows a typical example, from a location with numerous buildings in a densely populated area (Au-Brugg, Switzerland). The extrapolation of the temperature log to zero depth gives T(0) = 9°C.



Typical features:

- Positive anomaly above ~ 100 m depth
- Top 10-20 m: seasonal effect

Temperature log Sommerhaldenstrasse/Au-Brugg , CH (2011)

Figure 1: A typical shallow (<400 m) temperature log, with a pronounced deviation from a linear gradient. Red symbol: Borehole location.

Other examples can be found for this characteristic deviation from the linear T(z) trend in many parts of the world. The characteristic temperature profiles appear in groundwater wells as well as in borehole heat exchanger pipes. The deviations from the linear trend below about 20 m can clearly be attributed to the UHI effect, and to global warming, see e.g. Ferguson & Woodbury (2004), Eggleston & McCoy (2015).

In the following, results from quantitative analysis of such deviations from a straight temperature profile will be presented. We ask, what are the contributions from urban ground heating and atmospheric warming that lead to deviations in temperature profiles measured in cities? Several such profiles were recorded and samples (cuttings as well as borehole cores) were taken for thermal conductivity measurements in a campaign in the area of Zurich, Switzerland. The logging was performed in borehole heat exchanger (BHE) U-tubes by a wireless measuring technique (Schärli et al. 2007). The goal of the campaign was to elaborate a data base for regional heat flow mapping as well as for borehole exchanger-coupled GSHP development. The data base consists of temperature logs and rock thermal conductivity profiles at 33 locations, extending over an area of about 2’500 km^2. All measured borehole temperature profiles show deviations from the linear trend. These changes can be attributed to different local conditions like vegetation cover or history of building development. From this data base, a typical temperature profile has been selected.

2.1 Temperature profile at Meilen near Zurich, Switzerland

As an example case, a temperature profile measured in the suburb Meilen southeast of Zurich is chosen (Figure 2). This location is typical for residential agglomerations in the canton of Zurich. Here, a 280 m deep borehole heat exchanger tube installed in consolidated fine sand of the Upper Freshwater Molasse (Tertiary) was logged in October 2005. At this site no groundwater influence could be detected. Figure 3 displays the measured temperature profile T(z).

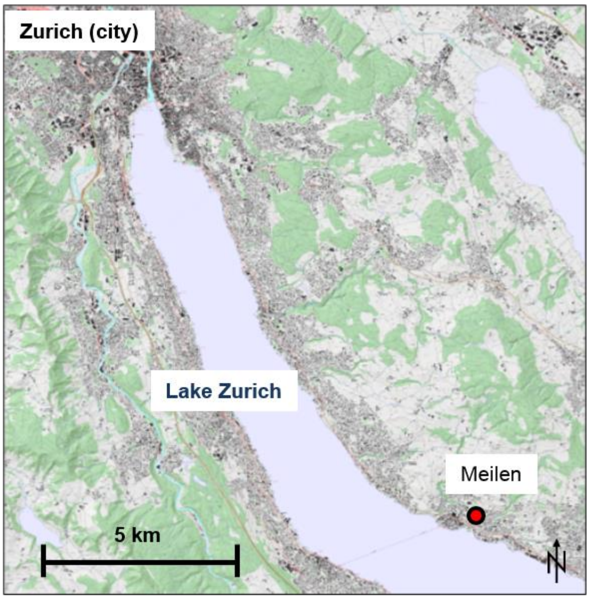


Figure 2: Location of the investigated site Meilen.

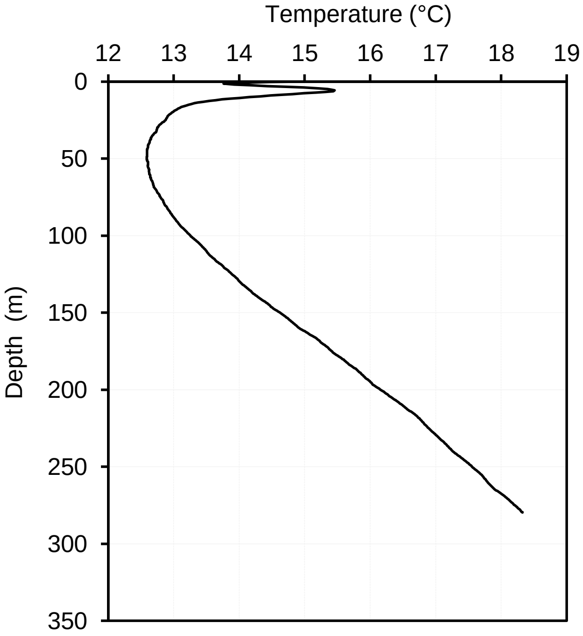


Figure 3: Temperature log at the locality Meilen (measured on 27/10/2005).

2.2 Analysis of the temperature profile

For the analysis, an analytical simulation tool was applied in order to invert the measured temperature profiles. In essence: the possible surface heat sources within a circle with 200 m radius around the investigated borehole are identified and discretized, and their heat input into the ground and the corresponding temperature profiles are calculated. Two main surface types are distinguished for the UHI effect: heating (buildings, pavements), and neutral (green surfaces). The ages of buildings and asphalt is also considered. By taking the temperature trend of the outdoor urban ground surface temperatures, the expected ground thermal conditions due to climatic forcing are calculated. The modelling procedure is described in detail in Bayer et al. (submitted).

3. RESULTS

Figure 4 displays the results for the investigated site. It shows the measured temperature profile along with the modelled profile with error bands (Root Mean Squared Error, RMSE), the extrapolated linear trends, and the climatic forcing. In the uppermost 20 meters of the ground, the temperatures usually vary over the year and are therefore not considered.

At the Meilen site, at 20 m depth, the total warming is by 2.2 °C. Of this amount, global warming contributes 0.9 °C and urban warming 1.3 °C (59 % of total).

The simulation properly reproduces the measured profile. Given the influence from climate forcing alone, however, the significant deviation from the linear trend cannot be explained. Atmospheric warming has caused an additional power of around 20 MW/m^2 stored in the ground beneath our reference depth of 10 m. In comparison, the contribution by urban structures such as buildings and asphalted streets, is around 100 MW/m^2. Both factors, atmospheric heating and urban structures, together accelerate the heat flux into the ground and their combined influence causes the typical bending of the temperature profile.

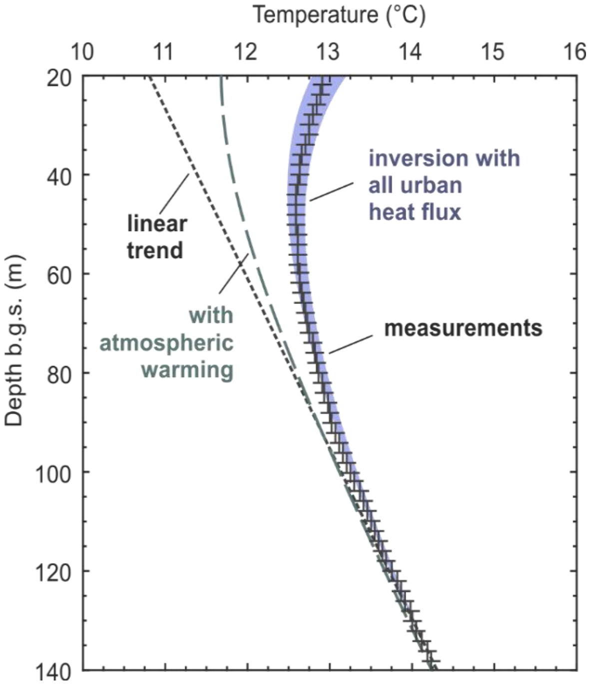


Figure 4: Measured temperature profile in depth of 20-140 m in Meilen (+ signs) with modeling results (error band for RMSE = ±0.1 °C). Also shown are the undisturbed linear trend (29 °C/km) and the expected profile due to climate forcing alone.

3. CONCLUSIONS

The anomalous curvature in the top 100 meters of the observed borehole temperature profiles can fully be explained by heat input from global warming and urban heating. The modelling separates and quantifies the two effects. In urban areas the accelerated heat flux from buildings and streets can be significant or even dominant.

The heat surplus provided by the subsurface UHI and its resupply is a decisive and highly welcome addition to the natural resources in this depth range. It is directly relevant for dimensioning, especially of large GSHP systems in densely populated areas.

The applied modelling framework does not allow only backtracking of past changes, but could be used for local and even city-wide predictions of the future thermal conditions in the ground. This is of interest to envisage the long-term evolution of subsurface UHIs, and especially their spatial development and associated geothermal potential.

REFERENCES

Bayer, P., Rivera, J.A., Schweizer, D., Schärli, U., Blum, P., Rybach, L. 2016. Extracting past atmospheric warming and urban heating effects from borehole temperature profiles, submitted.

Benz, S. A., Bayer, P., Menberg, K., Jung, S., Blum, P., 2015. Spatial resolution of anthropogenic heat fluxes into urban aquifers: Science of the Total Environment, v. 524, p. 427-439.

Eggleston, J., McCoy, K.J., 2015. Assessing the magnitude and timing of anthropogenic warming of a shallow aquifer: example from Virginia Beach, USA. Hydrogeology Journal, 23(1), 105-120.

Ferguson, G., Woodbury, A.D., 2004. Subsurface heat flow in an urban environment: Journal of Geophysical Research-Solid Earth, v. 109.

Harris, R. N., Chapman, D.S., 1997. Borehole temperatures and a baseline for 20th-century global warming estimates: Science, v. 275, p. 1618-1621.

Herbert, A., Arthur, S., Chillingworth, G., 2013. Thermal modelling of large scale exploitation of ground source energy in urban aquifers as a resource management tool: Applied Energy, v. 109, p. 94-103.

Luo, Z., Asproudi, C., 2015. Subsurface urban heat island and its effects on horizontal ground-source heat pump potential under climate change. Applied Thermal Engineering, 90, 530-537.

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., Blum, P., 2013. Subsurface urban heat islands in German cities: Science of the Total Environment, v. 442, p. 123-133.

Menberg, K., Blum, P., Schaffitel, A., Bayer, P., 2013. Long-Term Evolution of Anthropogenic Heat Fluxes into a Subsurface Urban Heat Island: Environmental Science & Technology, v. 47, p. 9747-9755.

Pollack, H. N., Huang, S.P., 2000. Climate reconstruction from subsurface temperatures: Annual Review of Earth and Planetary Sciences, v. 28, p. 339-365.

Rivera, J. A., Blum, P., Bayer, P., 2015. Analytical simulation of groundwater flow and land surface effects on thermal plumes of borehole heat exchangers. Applied Energy, 146, 421-433.

Schärli, U., Rohner, E., Signorelli, S., Wagner, R., 2007. Thermische Leitfähigkeit: Eichung von in-situ Messungen (dh „kabellose Temperatursonde “) mit Laborbestimmungen als Grundlage für die geothermische Kartierung des Kanton ZH und der umliegenden Kantone: Bundesamt für Energie, Bern.

Signorelli, S., Kohl, T., 2004. Regional ground surface temperature mapping from meteorological data: Global and Planetary Change, v. 40, p. 267-284.

Soldo, V., Lepoša, L., Boban, L., Borović, S., 2015. Implementation of the Distributed Thermal Response Test at Characteristic Geological Regions throughout Croatia. In Proceedings of the World Geothermal Congress, Melbourne, Australia.

Spadoni, L., Della Pona, L., Magon, M., 2013. Geothermal Heat Pump for A2A District Heating Service in Milan (Italy). Proceedings of the European Geothermal Congress, Pisa, Italy.

Taniguchi, M., Uemura, T., Jago-on, K., 2007. Combined effects of urbanization and global warming on subsurface temperature in four Asian cities. Vadose Zone Journal, 6(3), 591-596.

Zhu, K., Bayer, P., Grathwohl, P., Blum, P., 2015. Groundwater temperature evolution in the subsurface urban heat island of Cologne, Germany. Hydrological Processes, 29(6), 965-978.

Zhu, K., Blum, P., Ferguson, G., Balke, K.-D., Bayer, P., 2010. The geothermal potential of urban heat islands: Environmental Research Letters, v. 5, p. 044002.

Acknowledgements

We thank the Swiss Federal Office of Energy in Berne for financially supporting the campaign in the Zurich area, which provided the borehole temperature data for our study. This work was also supported by the Swiss National Science Foundation (SNSF) under grant number 200021L 144288.