Subsurface urban heat island investigation in Debrecen, Hungary based on archive and recently measured data

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ABSTRACT

Analysing the subsurface urban heat island phenomenon including groundwater temperature has become increasingly common and has been described in the case of several cities in the world. It has not only a theoretical role in geothermal energy utilization, since it has effect on designing the heating and cooling systems of buildings. The temperature distribution can be determined by archive and recently measured temperature data, but these datasets must be harmonised. Although the accuracy and reliability of archive data are significantly worse than the recently measured values, the temporal changes can be analysed with them, in addition they may give information on locations or depths from where recent measurements are not available.

Subsurface temperature data of Debrecen, Hungary are presented from 1960 to nowadays. Measurements were carried out for different goals and with different tools for instance meteorological data (soil temperature), bottomhole temperature of drinking water wells, monitoring system of borehole heat exchangers. The determined characteristic temperature-depth profiles suggest an energy surplus beneath the city compared to rural areas, however, to prove this further temperature data collection would be necessary. In addition some of the installed monitoring systems, their prospective development and the applied data management are also described.

1. INTRODUCTION

Subsurface temperature distribution of a given location can determine the possibilities of geothermal energy utilization besides the geological and hydrogeological conditions by the well-head temperature and/or theoretical potential.

This temperature distribution changes when the boundary temperature conditions change: e.g. by magma emplacement or by temperature fluctuation of the surface (Carlsaw and Jaeger 1957, Smerdon et al. 2003). The latter phenomenon could be periodic such as the daily or annual changes or trends such as the warming of the surface. While periodic changes have limited effects in deeper zones (in this case deeper than 20 m) and the averaging over time can hide the changes, surface warming or cooling trends can reach deeper zones and change subsurface temperature.

Based on air temperature measurements two main types of changes are determined: global climate change (nowadays mean warming, e.g. Cermak 1971, Huang et al. 2000, Pollack et al. 2000) and local climatic warming in the urban area. The latter is addressed as urban heat island, and the subsurface temperature increase due to this phenomenon is addressed as subsurface or underground heat island world (e.g. Taniguchi et al. 2006, Ferguson and Woodbury 2007, Zhu et al. 2010, Menberg et al. 2012, Bayer et al. 2019).

In addition several residential, industrial or transport related processes can also change the subsurface temperature distribution including the ground coupled heat pump systems, however, the subsurface temperature distribution reacts with the operation of these systems.

2. STUDY AREA

Debrecen, the second largest city of Hungary with a population of about 200000 is located in East Hungary. Geological setting of its surroundings has been determined by sedimentation since the Miocene (Haas 2012). In the early phase marine and shoreline environments were typical in this area. Due to the progradation of the shoreline of the Pannonian Lake the palaeoenvironment changes to terrestrial and fluvial landscape evolution becomes general.

Based on the stratification of boreholes the investigated depth zone (0–200 m) consists of Pleistocene and Holocene fluvial sediments (Püspöki et al. 2013). In the lower 100 m thick sandy beds of channel-fill deposits dominate the column, above this aquiclude layers of fine grained sediments deposited, while in the upper part of the column the sandy beds also appeared. The surface sediment of the area is loess in the western part and wind-blown sand in the eastern part of the city.

Earlier the shallow sandy aquifers were used for drinking water supply and for irrigation as well. Nowadays the deeper (Lower Pleistocene) sandy aquifers are used for drinking water supply. In and around Debrecen more than 2500 registered wells were drilled in the last 150 years, however, the number of the non-registered wells is similar (or higher). A low portion of the registered wells are in appropriate condition (in which temperature measurements can be made), and most of them are in continuous operation, thus temperature logging in static state cannot be performed.

Drinking water wells are located in the NW edge, the N edge, the E edge and the SE edge of the city. Unfortunately this means that there are not enough logging-books and temperature data from the inner part of the city.

3. DATA AND METHODS

3.1 Archive data

Temperature data presented in this paper were obtained in two ways. In the first case, referred as archive data, the temperature values were measured by other researchers, the circumstances of the measurement were not exactly documented in each case and the accuracy of the measurement is corresponds to the available techniques at the time of the measurement. In this case data measured continuously or deeper than 20 m are used, since the annual temperature changes in this zone are minimal.

Most archive data were collected from the Hungarian database on geology, geophysics and mining, from hydrogeological log-books of the wells. The sub-regional temperature profile was identified by the bottomhole temperature of the thermal wells and the temperature log of monitoring wells.

Bottomhole temperature of 94 wells for water production can be used to identify the local temperature profile. Numerous log-book of wells drilled before 1980 or drilled to shallow depth contains only well-head temperature with accuracy of 1 °C. In several cases, water was produced from a well defined layer, thus the well-head temperature can also be used for the analysis. In the last two decades the accuracy of the temperature measurement becomes 0.1 °C, and this measurement is occurs in several cases. In addition temperature logging in static state and/or during producing is also more common.

Data form monitoring network of a ground coupled heat pump system (Renewable Energy Application Center, REAC) is also considered as archive data. Around the building borehole heat exchangers with length of 50 m or 100 m were installed with temperature sensors at different depths. Before the first heating season these sensors measured the original temperature around the systems, however, in some cases the temperature perturbing effect of operation can be eliminated by mathematical methods from the daily average values (Buday 2009; Buday 2010).

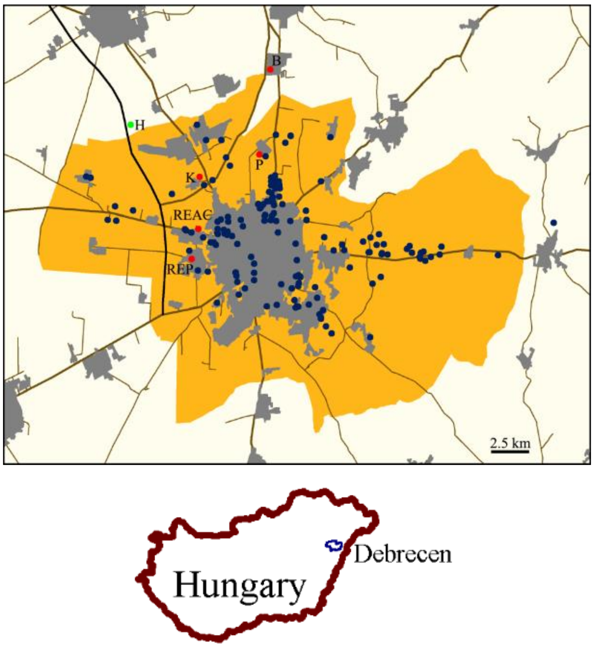

Figure 1: Location of the studied wells (blue dots) and monitoring systems, in and around Debrecen. Legends: REP: Renewable Energy Park Research Center; REAC: Renewable Energy Application Center; K: Kismacs (meteorological station); P: Pallag (meteorological station); B: Bocskaikert (meteorological station; H: Hajdúböszörmény K

3.2 Monitoring data of shallow systems

In the second case, temperature values were derived from current temperature measurements, most of them are controlled by the authors.

In the cooperation of the University of Debrecen and the Renewable Energy Park Research Center (REP) several meteorological stations have been installed in and around Debrecen since 2013. In three cases, soil temperature is also measured at depths of 2 cm, 5 cm, 10 cm, 20 cm, 50 cm, 1 m, 1.5 m and 2 m. In addition soil temperature data of one more meteorological station of the University of Debrecen, located near Debrecen are available (“Kismacs”).

In the area of REP a monitoring system around borehole heat exchangers is also installed temperature data of which from the depths of 5 m, 7.5 m, 10 m, 12.5 m, 15 m, 17.5 m and 20 m can also be used (Buday et al. 2015), while another system was installed in a village near Debrecen (Bocskaikert), with similar depths.

The used database contains the average temperature of every 10 minutes, based on which daily average values were calculated. If the sensors operated all the year the annual average temperature was calculated as the average of daily average values, in other cases best-fitting sinusoidal curves were calculated with Solver add-in of Microsoft Excel and their parameters are used for the further calculations (see details in Buday et al. 2015).

4. RESULTS

4.1 General relationships based on archive data

Depth range of bottomhole temperature measurements is 40–220 m, however, the upper part of it contains only a few data (5 values in the depth zone of 40–90 m). Linear temperature-depth profile fitted to the values, the geothermal gradient is 0.053 °C/km, while the extrapolated surface temperature is 10.93 °C (Fig. 2). Wells with one screening are also studied, the geothermal gradient is 0.044 °C/km and the extrapolated surface temperature is 11.36 °C, while the correlation between the variables is lower. The main advantage of this analysis is that temperature of the upper 50 m can be estimated based on this.

In the right part of Fig. 2 continuous temperature log of two wells located in the rural area are also presented. There is a significant difference between the temperature values at a given depth (up to 3 °C) but the values are similar to those in the middle part of Fig. 2.

Additional information can be seen in Fig. 2: the static water level of the wells is different based on the depth of the screening, and temperature measurements can be made between the bottomhole depth and static (or dynamic) water level. Generally in drinking water wells the static water level is deeper than 20 m, thus the temperature of the upper 20 m is not measurable with temperature logs in these wells.

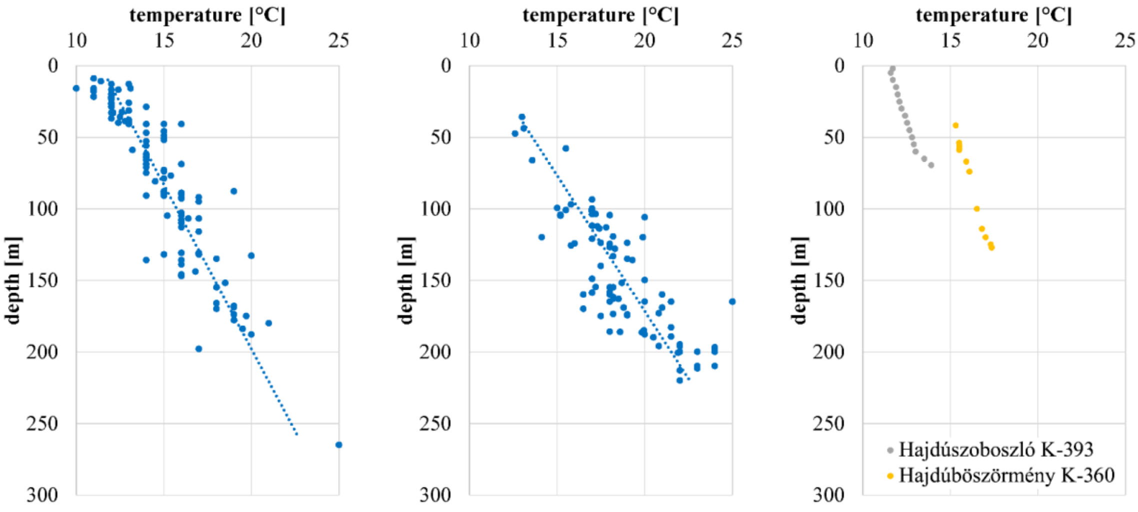

Figure 2: Bottomhole temperature values by depth (left), well-head temperature values by the depth of screening (middle) and temperature logs (right) around Debrecen.

4.2 Temporal and spatial temperature pattern below the depth of 20 m based on archive data

Temperature data of drinking water wells were analysed in spatial and temporal relation as well. Only a few and questionable relations were determined.

It seems in the case of the well in the eastern part of Debrecen, that the well-head temperature at a given depth is lower in the outer regions than in the inner part of the city by 1-2 °C (Fig. 3). Unfortunately this value is around the accuracy of the measurements and the number of obtained temperature values is low. There were not enough archive data in the other parts of the city to make similar calculations.

In the NW part of Debrecen the later installed wells have higher well-head temperatures than the older well’s values. In other areas this relation cannot be detected.

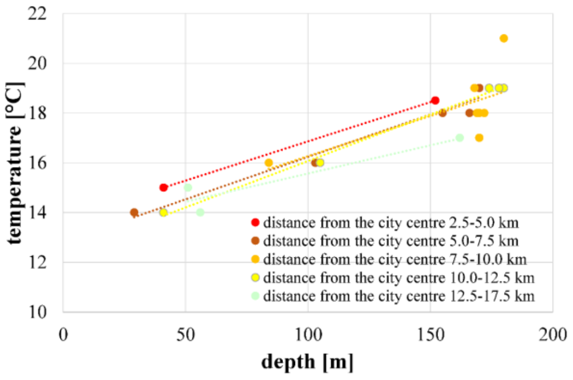

Figure 3: Well-head temperature values by depth in different distances from the city centre, East-Debrecen.

4.3 Temporal and spatial temperature pattern above the depth of 20 m

Only 3 monitoring systems serve data from the depth of 2 to 20 m (Fig. 4). In the Renewable Energy Application Center several measuring subsystems exist, some of the annual average temperature values are presented in Fig. 5. In the zone of 20 to 100 m the annual average temperature values of monitoring boreholes of Borehole 10 is averaged in each depth and linear temperature-depth profile fitted to the values: the geothermal gradient is 0.030 °C/km, while the extrapolated surface temperature is 11.72 °C. In the zone of the 0 to 10 m 14 average temperature values were determined, 12 of them are higher than the calculated surface temperature, in addition, the highest value is 13.65 °C (Fig. 5). Analysing all of the measured values in the depth of 0 to 20 m a temperature-depth profile is also presented (Fig. 4, green line).

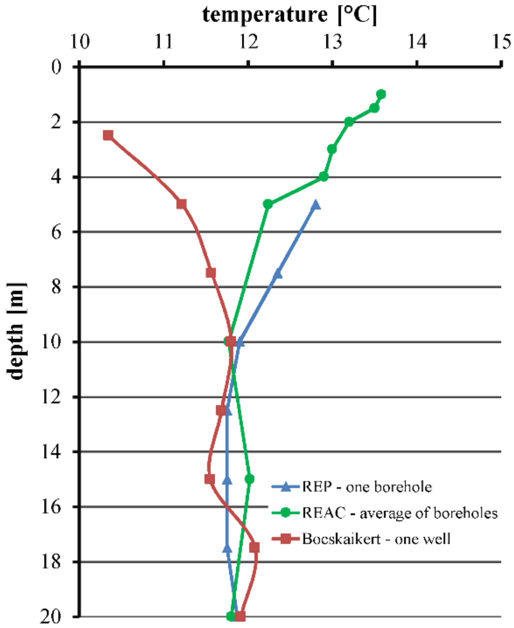

Figure 4: Annual average temperature values in the depth zone of 2 to 20 m, Debrecen.

The main difference between the three curves of Fig. 4 appears in their upper part, the rural temperature profile has no temperature surplus in the shallow depth, while measurement points of Debrecen have increasing temperatures, since the temperature in the shallow depth are higher than the extrapolated surface temperature based on the presented descriptions above. Each temperature function has a depth-independent part between 10 and 20 m, where the temperature of the medium is about 12 °C.

The annual changes of the subsurface temperature is also can be studied in this shallow-depth systems. Fig. 6 shows the daily average temperature values of Bocskaikert site in a 2-year-long period. Sinusoidal curves are stand out in the upper part, the amplitude of the annual changes decreases notably. The difference between the annual maximum and minimum temperature is 12.67 °C at the depth of 2.5 m, lower than 1 °C at the depth of 10 m and lower than 0,1 °C at the depth of 17.5 m.

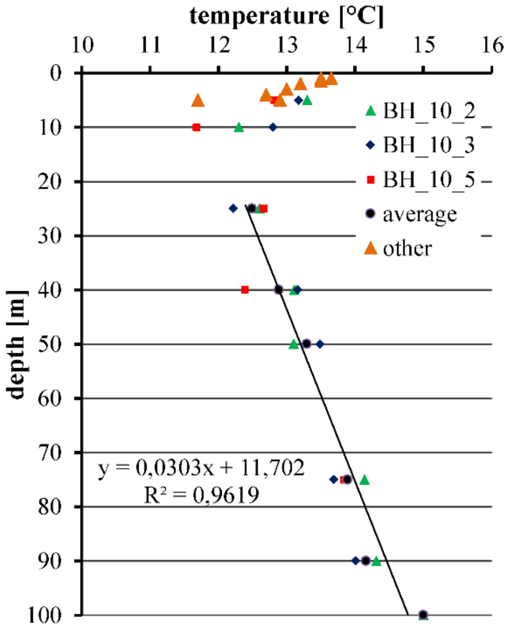

Figure 5: Average temperature values around borehole heat exchangers of Renewable Energy Application Center, Debrecen.

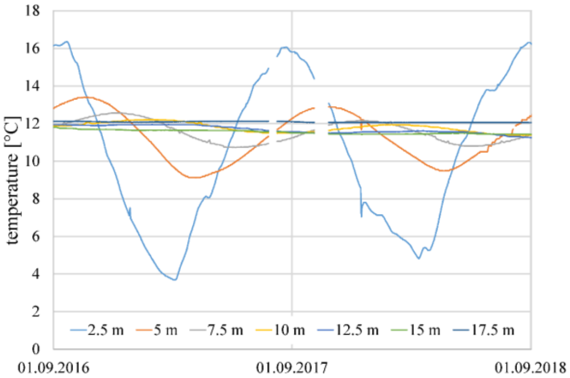

Figure 5: Annual temperature changes at different depths, Bocskaikert.

In the four meteorological stations the soil temperature profile was determined in each year. For soil climatology the main parameter is the average temperature at 50 cm depth, so these values are presented here. Two of the stations have higher average temperatures than the extrapolated surface temperature. One of them (Pallag) is around this average while and the Bocskaikert station has lower temperature. Surprisingly only one of the stations is located in Debrecen, the others can be found in rural areas, suggesting a general temperature increase besides the subsurface urban heat island effect.

These values are the most sensitive to climatic fluctuations, microclimatic effects compared to the other presented sets, thus long time temperature data series are required for more accurate analysis.

5. CONCLUSIONS

Presence of subsurface urban heat island effect in the urban area of Debrecen is confirmed by shallow temperature measurements and analysis of well-head temperature data of drinking water wells. However, determination of the detailed spatial subsurface distribution of the temperature archive temperature data alone is not suitable due to the spatial and vertical distribution.

The latter problem can be eliminated if temperature logging in monitoring wells occurs or similar type of archive data appears in data stores, therefore cooperation is forming with the waterworks of Debrecen. Unfortunately the deep static water levels cannot allow the measurement of the temperature distribution in the whole vertical section, thus temporarily not used irrigation wells also should be included in the investigation. Both measurements will be run with portable temperature sensor strings.

Another important aim is to install monitoring networks in new buildings with ground coupled heat pump systems, collecting temperature and geological data during installation and operation as well. In this case, the upper 100 m of the studied zone can be logged in one phase with standard methods. The presented investigations involved several places in Debrecen, such as in the downtown, where usable temperature data is rare at the present time.

Installation of meteorological stations with subsurface temperature measurement in the downtown are in progress, but harder to get permission when drilling procedures are connected to the installation is more difficult than without drilling procedures. Although the depth of these systems is typically lower than the depth of the minimum temperature in the log, but urban heat island (e.g. Szegedi et al. 2014) and subsurface heat island in Debrecen can be measured parallel.

Since temperature distribution has effects on the heat transport processes between the natural and artificial substances, such as heat loss of building, in addition on the efficiency of ground coupled heat pump systems. Consequently the subsurface urban heat island has effects on technical, economical and sustainable geothermal potential of the area as well, thus all the presented developments are required in any case.

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