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# Exploring the Geothermal Potential of Waste Heat Beneath Cities

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## ABSTRACT

Anthropogenic alteration in the urban environment causes an increase in atmospheric temperatures, which is known as the urban heat island (UHI) effect. However, this is not only an atmospheric phenomenon. We also find significant warming of the urban subsurface and shallow groundwater bodies. Besides potential negative effects on groundwater quality, thermal anomalies in aquifers also represent attractive shallow geothermal energy reservoirs for space heating. In this study, we inspect aquifer temperatures in several German cities, such as Berlin, Munich, Cologne and Karlsruhe. A significant increase in groundwater temperature by more than 4 K was detected close to the city center of all studied urban areas. Even locally, hot spots of up to +20 K can be found in the vicinity of insufficiently insulated power plants or reinjection sites of cooling water. This yields a highly variable spatial and temporal pattern of increased ground temperatures. Furthermore, the geothermal potential of the subsurface was calculated for the studied cities. In the city of Cologne, the calculation of the potential heat content in the 20 m thick aquifer shows that by decreasing the aquifer's temperature by 2 K, the extractable geothermal energy could supply the space heating demand of the whole city for at least 2.5 years.

## 1. INTRODUCTION

Numerous studies and meteorological records have shown that the climatic conditions in large cities differ from those in the rural background (Oke 1973; Kataoka et al. 2009). Various anthropogenic alterations in the urban environment lead to increased atmospheric temperatures. However, this urban heat island (UHI) effect is not limited to the atmosphere, but also in the subsurface urban aquifers exhibit increased groundwater temperatures. Extensive thermal anomalies in urban aquifers, which spread laterally from the city centre, were reported from many fast growing Asian megacities (e.g. Taniguchi et al. 2007) and North American cities (Ferguson and Woodbury 2007). Also in several German cities a warming of shallow urban aquifers by up to 6 K was found (Zhu et al. 2010, Menberg et al. 2013). However, these thermal anomalies are not limited to the shallow subsurface. Temperature deviations from the geothermal gradient can be found in depths of 100 m and more (Taniguchi et al. 2007). Thus the anthropogenic subsurface warming can affect a considerable volume of urban groundwater bodies.

This warming of urban aquifers has positive as well as negative implications for groundwater use. First, the anthropogenic temperature increase modifies the microbiological activity in the groundwater and influences the groundwater ecology with possible negative consequences for water quality (Brielmann et al. 2009). On the other hand, these extensive temperature anomalies form a vast amount of stored thermal energy. As a consequence, the warm urban aquifers represent attractive reservoirs of thermal energy for geothermal use such as space heating (Zhu et al. 2010). In addition to the general advantages of geothermal usage, such as reduction of greenhouse gas emissions (e.g. Blum et al. 2010, Bayer et al. 2012), aquifers in urban areas with increased temperatures can enhance the sustainability of geothermal systems. The elevated temperatures in urban aquifers also improve the efficiency of the heat pumps used for space heating. However, at the same time, elevated temperatures curb the use of groundwater for cooling purposes. Therefore, attuned management of the regional geothermal energy content in densely populated urban areas is necessary. In this study, the spatial distribution of groundwater temperatures in several German cities, such as Berlin, Munich, Cologne and Karlsruhe, is analysed. Furthermore, the case-specific additional heat content in these urban aquifers is calculated and the resulting capacity for space heating is quantified.

## 2. MATERIAL AND METHODS

### 2.1 Spatial analysis of groundwater temperatures

A detailed spatial analysis of groundwater temperatures (GWT) is performed for four German cities: Berlin, Munich, Cologne and Karlsruhe. The selected cities cover a certain range of different city sizes with population numbers ranging from more than one million to less than 300,000 inhabitants (Table 1). In addition, the subsurface of all the chosen cities is for the most part composed of sedimentary deposits hosting unconfined shallow aquifers, which are prone to be affected by intensified downward heat fluxes. Furthermore, the municipal authorities in the listed cities maintain a rather large number of groundwater wells for the monitoring of water table and groundwater quality. This large number of monitoring wells enables a regional evaluation of GWT in each of the selected urban, as well as surrounding suburban areas.

For the present study, mainly pre-existing GWT data from temperature measurements campaigns in observation wells is used. The groundwater temperature measurements in Berlin were carried out by the Senate Department for Urban Development and the Environment in 2010 at the level of 0 m asl, which corresponds to a depth of about 30–60 m below ground level (Henning and Limberg 2012). Dohr (1989) conducted a measurement campaign of the shallow groundwater temperature in 1983 in a dense network of observation wells along the subway system of Munich. In Karlsruhe, data loggers recording the daily groundwater temperature are operated by the Public Works Service. The data loggers are installed in over 80 observation wells in depths of about 9-12 m. The groundwater temperatures in this shallow depth exhibit variable seasonal variations. Therefore, the arithmetic annual mean for the year 2012 is used for the analysis. Zhu et al. (2010) explored the spatial distribution of groundwater temperature in Cologne in 2009, and the data of their measurement campaign is adopted for the present study. To visualize the spatial distribution of the groundwater temperature, the data is interpolated using kriging in GIS (ESRI® ArcInfo™ 10.0).

**Table 1: Characteristics of the studied German cities. The annual mean air temperature values are given for the time period 1961–1990.**

| City | Population[a] | City area [km²][a] | Annual mean air temperature (SAT) [°C][b] |
|---|---|---|---|
| **Berlin** | 3,515,473 | 891.5 | 8.9 |
| **Munich** | 1,330,440 | 310.7 | 9.2 |
| **Cologne** | 998,105 | 405.2 | 10.0 |
| **Karlsruhe** | 291,959 | 173.5 | 10.7 |

[a] Federal Statistical Office (2013), [b] German Weather Service (2013).

### 2.2 Geothermal potential of urban heat islands

Zhu et al (2010) applied a method to estimate the theoretical geothermal potential by quantifying the potential heat content in urban aquifers with elevated groundwater temperatures. If the thermo-physical and hydrogeological parameters of the aquifer are known, the heat content can be calculated by:

$$Q = Qw + Qs = V\ n\ Cw\ \Delta T + V\ (1 - n)\ Cs\ \Delta T \quad (1)$$

in which $Q$ (kJ) is the total theoretical potential heat content of the aquifer, $Q_w$ and $Q_s$ (kJ) are the heat contents stored in groundwater and solid, respectively, $V$ (m$^3$) is the aquifer volume, $n$ is porosity, $C_w$ and $C_s$ (kJ m$^{-3}$ K$^{-1}$) are the volumetric heat capacity of water and solid, and $\Delta T$ (K) is the temperature reduction of the aquifer. The aquifer thickness, porosity $n$ and heat capacity of the solid content $C_s$ of the shallow aquifers for the investigated cities are listed in Table 2. The approx. aquifer volume $V$ can thus be calculated as the product of aquifer thickness and urban area.

To account for the variability in the parameters above due the heterogeneous geological settings in the investigated city areas, parameters ranges and a respective mean value were defined for aquifer thickness based on hydrogeological data from literature (Table 2). Likewise parameter ranges and mean values were assigned for $C_s$ and $n$ based on the material composition of the subsurface and respective literature values for porosity and thermal properties (Table 2). For the heat capacity of water a fixed value of 4150 kJ m$^{-3}$ K$^{-1}$ was taken (VDI 4640/1 2010). According to the analysis by Zhu et al. (2010) the temperature reduction was set to $\Delta T$ = 2-6 K, with a mean value of $\Delta T$ = 4K. In order to estimate the capacity for space heating, the potential heat content is contrasted to the space heating demand of the individual cities. The latter can be estimated by the average living space and the average annual unit heating demand of 50 kWh m$^{-2}$ (Zhu et al. 2010). Timm (2008) provides average living space values for different regions in Germany: Berlin 40 m$^2$, Munich 44 m$^2$, Cologne 42 m$^2$ and Karlsruhe 43 m$^2$.

**Table 2: Hydrogeological and thermo-physical parameters of the studied cities.**

| City | Aquifer thickness [m] min – max (mean) | Porosity [-][e] min – max (mean) | Volumetric heat capacity of solid [MJ m$^{-3}$ K$^{-1}$] min – max (mean) |
|---|---|---|---|
| **Berlin** | 30 – 50 (40)[a] | 0.15 – 0.25 (0.20) | 2.0 – 2.2 (2.1)[f] |
| **Munich** | 5 – 20 (10)[b] | 0.20 – 0.25 (0.23) | 2.3 – 2.5 (2.4)[f] |
| **Cologne** | 10 – 30 (20)[c] | 0.15 – 0.25 (0.20) | 2.1 – 2.2 (2.15)[f] |
| **Karlsruhe** | 10 – 50 (30)[d] | 0.15 – 0.25 (0.20) | 2.2 – 2.6 (2.4)[f] |

Hydrogeological data and values for porosity and thermal properties taken from: [a] Limberg and Thierbach (2007), [b] Kerl et al. (2012), [c] Zhu et al. (2010), [d] Schäfer et al. (2007), [e] Prinz and Strauß (2006), [f] VDI 4640/1 (2010).

## 3. RESULTS AND DISCUSSION

### 3.1 Spatial distribution of groundwater temperatures

The results of the spatial GWT analysis are displayed in Fig. 1 as interpolated isotherm maps. The GWT in the rural background of each city ranges between 8 and 11°C and resembles the annual mean air temperature (Table 1). The anthropogenic impact on the GWT in these agricultural and woodland areas is apparently very low. According to changes in land cover and building density in suburban and urban areas, GWT shows an increasing trend towards the city centres. In almost all cities, the highest GWT of 13-18°C are detected close to the city centres, which are usually the oldest and most densely built-up urban areas. However, in Karlsruhe the highest temperatures are found in an industrial area in the western part of the city, where several reinjections of thermal waste-water are situated (Menberg et al. 2013). In individual wells in the city centre of Munich close to underground buildings, temperatures of up to 20°C were measured (Dohr 1989). In contrast, inner-city green spaces, such as parks or also airport areas, exhibit lower GWT close to background values.

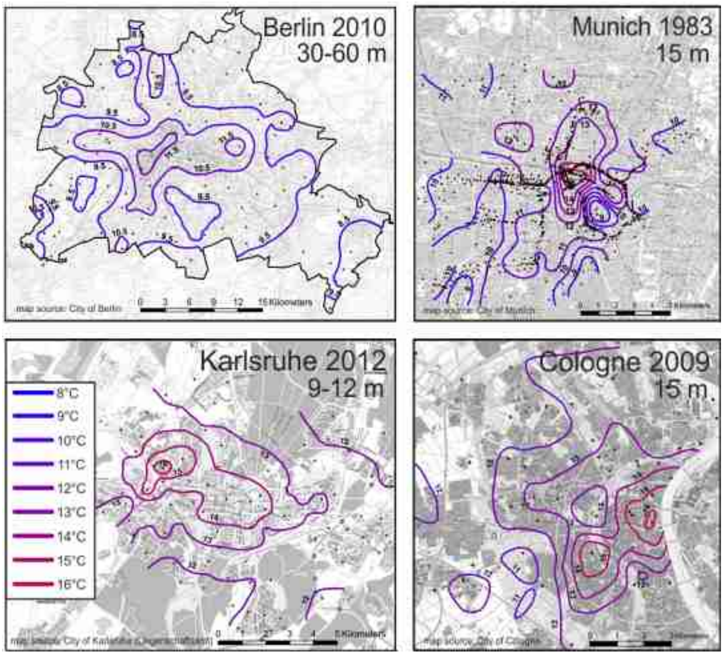


**Figure 1: Isotherm maps of groundwater temperature under the studied cities. The dots represent the location of the observation wells.**

The observed patterns of groundwater temperature under urban areas are generally heterogeneous, which is on the one hand caused by the spatial density and depth of the temperature measurements. This effect is quite apparent in Munich, where the density of observation wells is significantly higher than in the other cities (Fig. 1). Another reason for the heterogeneity of the spatial temperature distribution is the various local heat sources that cause the subsurface warming. In addition to possible natural triggers, such as variations in the geothermal heat flux and regional groundwater flow systems (Taniguchi and Uemura 2005), there exist numerous anthropogenic heat sources that interact with the subsurface urban environment. Increased air and surface temperatures (e.g. Taniguchi et al. 2007, Taylor and Stefan 2009), as well as heat losses through basements of buildings (Ferguson and Woodbury 2004), are discussed as potential heat sources. Menberg et al. (2013a) examined further heat sources in the context of city and building development, such as subway systems, sewers, district heating networks and reinjections of thermal waste water.

### 3.2 Geothermal potential

The maximum ranges and mean values of the potential heat content in the aquifers of the studied cities are shown in Table 3. As all studied cities exhibit a similar dimension of groundwater temperature increase (Fig. 1) and share similar hydrogeological parameters, the values for the potential underground heat contents vary within one order of magnitude. In order to enable comparison to the potential underground heat content, the annual space heating demand was also averaged to the city area. Differences in the space heating demand in the studied cities arise from the individual average living spaces and the varying city characteristics, such as population number and covered city area (Table 1).

The results in Table 3 indicate that the amount of thermal energy stored in the urban aquifers would suffice to cover the space heating demand in the individual cities for at least 1.3-5.6 years. Estimations with more optimistic values, such as higher heat capacities of the subsurface material or a larger temperature reduction of the aquifer, yield capacities of up to 17.1-31.4 years. However, the approach used here is a rather conservative one, which only considers the actual heat content in the aquifer that has accumulated over a long time. As shown by Menberg et al. (2013b), heat sources, such as heated basements of buildings and increased ground surface temperatures, cause a considerable anthropogenic heat input in the shallow urban aquifer that is one order of magnitude higher than the natural heat gain. Under consideration of this continuous replenishment of thermal energy in the urban subsurface, a certain part of the heating demand in the cities could be fulfilled sustainably by heat extraction from the shallow aquifers. However, this urban subsurface thermal environment is a highly heterogeneous and dynamic system, in which the local changes in groundwater temperatures would result in alterations in the site-specific heat gain of the aquifer. Also technical factors, such as limitation in the spatially distributed placement of geothermal system, are likely to curb the exploitation of the overall geothermal potential that is indicated in Table 3.

**Table 3: Geothermal potential of the studied cities.**

| City | Potential underground heat content [$\times 10^{12}$ J km$^{-2}$] min – max (mean) | Space heating demand [$\times 10^{12}$ J km$^{-2}$ year$^{-1}$] | Capacity for space heating [years] min – max (mean) |
|---|---|---|---|
| **Berlin** | 155 – 874 (440) | 27.8 | 5.6 – 31.4 (15.8) |
| **Munich** | 26.7 – 350 (112) | 20.5 | 1.3 – 17.1 (5.5) |
| **Cologne** | 48.2 – 484 (204) | 19.2 | 2.5 – 25.1 (10.6) |
| **Karlsruhe** | 46.5 – 806 (301) | 36.4 | 1.3 – 22.1 (8.3) |

## 4. CONCLUSIONS

In all studied cities, pronounced positive temperature anomalies with up to 16°C are present in the shallow urban aquifers. The presented detailed spatial examination reveals that the distribution of groundwater temperatures in urban areas is quite heterogeneous, because the heat input is controlled by various site-specific factors. Dominant local heat sources, such as reinjections of cooling water in the aquifer, can cause local thermal anomalies of up to 20°C. In the long term, the superposition of diverse heat sources, such as heat loss from underground buildings and increased temperatures on artificial surfaces, yields urban aquifers with temperatures several degrees higher than rural background values.

Due to this accumulated heat content in the subsurface, urban aquifers can act as attractive and easily accessible reservoirs for thermal energy. The estimation of the space heating capacity reveals that the theoretical geothermal potential could fulfil the residential heating demand in all studied cities for at least several years and assuming more optimistic values even for a few decades. Considering the permanent anthropogenic heat input from the urban structures into the shallow aquifer the heating demand of the cities could also be partly satisfied for a longer period, when this heat resource is exploited in a more sustainable way. However, to meet the requirements for such a sustainable management a more detailed examination of the transient behaviour of these subsurface urban heat islands under scenarios with geothermal usage would be needed.

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