Elevated temperatures beneath cities: An enhanced geothermal resource

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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 phenol-menon. 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 centre 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.

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 [km^2][a]	Annual mean air temperature [°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).

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).

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:

$$Q = Q_w + Q_s = V\, n\, C_w\, \Delta T + V\,(1 - n)\, C_s\, \Delta T \qquad [1]$$

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 ΔT (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 can thus be calculated as the product of aquifer thickness and urban area. To account for a certain variability in the parameters, maximum, minimum and mean values were assigned for aquifer thickness, C_s and n (Table 2). For the heat capacity of water a value of 4150 kJ m^{-3} K^{-1} was taken (VDI 4640/1). According to Zhu et al (2010) the temperature reduction was set to ΔT = 2 K for the minimum case, 4 K for the mean and 6 K for the maximum case. 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^3.

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

City	Aquifer thickness [m][a, b, c, d]	Porosity [-][e]	Volumetric heat capacity of solid [kJ m^{-3} K^{-1}][f]
Berlin	30	0.15	2000
	40	0.20	2100
	50	0.25	2200
Munich	5	0.20	2300
	10	0.23	2400
	20	0.25	2500
Cologne	10	0.15	2100
	20	0.20	2150
	30	0.25	2200
Karlsruhe	10	0.15	2200
	30	0.20	2400
	50	0.25	2600

[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 (2000).

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.

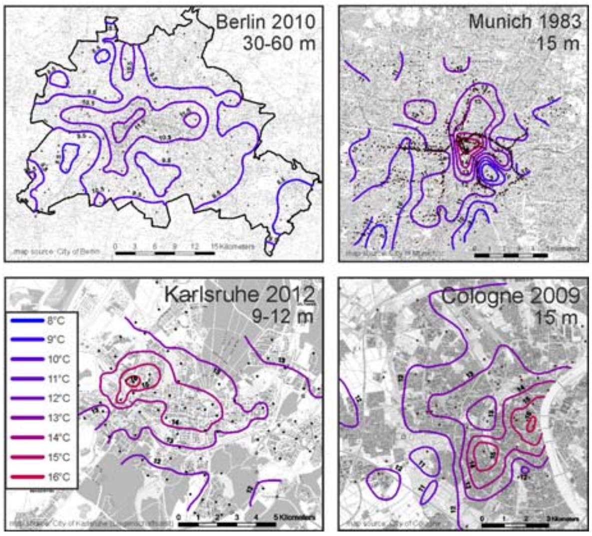

Figure 1: Isotherm maps of groundwater temperature under the studied cities. The red black dots represent the location of the observation wells.

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 (2013) 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 minimum, mean and maximum 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 annual space heating demand in the individual cities for at least 1.3-5.6 years. Estimations with more optimistic values yield capacities of up to 17.1-31.4 years.

Table 3: Geothermal potential of the studied cities.

City	Potential underground heat content [kJ km^{-2}]	Space heating demand [kJ km^{-2} year^{-1}]	Capacity for space heating [years]
	1.55×10^{11}		5.6
Berlin	4.40×10^{11}	2.78×10^{10}	15.8
	8.74×10^{11}		31.4
	2.67×10^{10}		1.3
Munich	1.12×10^{11}	2.05×10^{10}	5.5
	3.50×10^{11}		17.1
	4.82×10^{10}		2.5
Cologne	2.04×10^{11}	1.92×10^{10}	10.6
	4.84×10^{11}		25.1
	4.65×10^{10}		1.3
Karlsruhe	3.01×10^{11}	3.64×10^{10}	8.3
	8.06×10^{11}		22.1

3. CONCLUSIONS

In all studied cities, pronounced positive temperature anomalies are present in the shallow urban aquifers. The detailed spatial examination revealed that the distribution of groundwater temperatures in urban areas is quite heterogeneous. In the long term the superposition of various heat sources yields urban aquifers with temperatures several degrees higher than rural background values. Dominant site-specific heat sources can cause local thermal anomalies of up to 20°C. Thus, urban aquifers can act as attractive reservoirs for thermal energy. The estimation of the space heating capacity revealed that the theoretical geothermal potential could fulfil the residential heating demand in all studied cities for at least several years.

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