IOP Publishing Environmental Research Letters
Environ. Res. Lett. **5** (2010) 044002 (6pp) doi:10.1088/1748-9326/5/4/044002

The geothermal potential of urban heat islands

Ke Zhu[1], **Philipp Blum**[2], **Grant Ferguson**[3], **Klaus-Dieter Balke**[1] **and Peter Bayer**[4]

[1] Center for Applied Geoscience (ZAG), University of Tübingen, Sigwartstrasse 10, Tübingen 72076, Germany
[2] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstraße 12, Karlsruhe 76131, Germany
[3] Department of Earth Science, St Francis Xavier University, Antigonish, NS, B2G 2W5, Canada
[4] ETH Zürich, Engineering Geology, Sonneggstrasse 5, Zürich 8092, Switzerland

E-mail: k.zhu@uni-tuebingen.de

Received 22 July 2010
Accepted for publication 28 September 2010
Published 12 October 2010
Online at stacks.iop.org/ERL/5/044002

Abstract
The urban heat island effect and climate change have not only caused surface temperature increase in most urban areas, but during the last hundred years also enhanced the subsurface temperature by several degrees. This phenomenon yields aquifers with elevated temperature, which are attractive though underestimated thermal energy reservoirs. Detailed groundwater temperature measurements in Cologne (Germany) and Winnipeg (Canada) reveal high subsurface temperature distributions in the centers of both cities and indicate a warming trend of up to 5 °C. The case-specific potential heat content in urban aquifers and available capacities for space heating are quantified. The results show, for example, that, by decreasing the 20 m thick urban aquifer's temperature by 2 °C, the amount of extractable geothermal energy beneath Cologne is 2.5 times the residential heating demand of the whole city. The geothermal potential in other cities such as Shanghai and Tokyo is shown to supply heating demand even for decades.

Keywords: geothermal, urban heat island, groundwater, climate change

1. Introduction

Numerous studies and meteorological records have revealed a dramatic warming trend in most megacities in the last century (Ferguson and Woodbury 2007, Perrier *et al* 2005, Taniguchi *et al* 2007). This phenomenon is not only due to the climate change, but, in particular, a result of non-climatic perturbations, which are mainly caused by local warming due to urbanization (Oke 1973, Kataoka *et al* 2009). This urban heat island (UHI) effect is recognized as a major environmental issue for most cities (Rizwan *et al* 2008). The increased temperature in an urban area compared to the surroundings is known as UHI intensity (Oke 1973, Magee *et al* 1999). The work by Tran *et al* (2006) revealed large UHI intensity values through satellite data in most Asian megacities, such as Tokyo (12 °C), Bangkok (8 °C), and Shanghai (7 °C). Various other researches (Cermak *et al* 2000, Ferguson and Woodbury 2004, Huang *et al* 2009) demonstrate that the UHI effect also has a strong influence on the underground temperature. Regional studies in urban areas from North America (Ferguson and Woodbury 2007, Wang *et al* 1994), Europe (Bodri and Cermak 1997, Perrier *et al* 2005, Yalcin and Yetemen 2009), and Asia (Taniguchi *et al* 2007, Wang *et al* 2009) have indicated 2–5 °C increase of the subsurface temperature. The results from the research of Beltrami (2001) indicated that the heat flux into the ground increased by an average of 24 mW m^{-2} over the last 200 years in Canada. At a large spatial scale the anomaly trends of ground surface temperature (GST) agree with those at the surface (Pollack *et al* 1998, Huang *et al* 2000), and GST directly influences subsurface temperature by thermal conduction. Factors that cause the urban heat island effect in the subsurface are similar to the ones that increase surface air

1748-9326/10/044002+06$30.00

temperature, such as indirect solar heating by the massive and complex urban structures, anthropogenic heat losses, and land use change. In addition, the anthropogenic thermal impacts are more persistent in the subsurface (Huang *et al* 2009), because rather than radiation and advection, slow conduction plays the most important role in underground heat flow, and it is influenced by both surface and subsurface processes.

Although in many cases it is still not clear what the driving forces of enhanced underground temperature are, whether climate change, land use change, sewage leakage or groundwater flow (Balke 1977, Beltrami *et al* 2005), the wide existence of aquifers with elevated temperature is an indisputable fact (Ferguson and Woodbury 2007, Taniguchi *et al* 2007, Yalcin and Yetemen 2009). The extra heat stored in urban aquifers is sometimes considered as a kind of underground thermal pollution. However, as a result of increasing interest in geothermal use, these high yielding aquifers are attractive thermal reservoirs for space heating and cooling. In addition to the general advantages of geothermal usage, such as minor environmental impact and reduced greenhouse gas emissions (Blum *et al* 2010, Saner *et al* 2010), urban aquifers with higher temperature can improve the sustainability of geothermal systems. In essence, higher temperatures mean a higher amount of energy stored, that is, an increased geothermal potential.

Until now, most research on subsurface temperature has focused on tracking long term climate change (Beltrami *et al* 2005, Kataoka *et al* 2009), studying groundwater flow (Cartwright 1979, Taniguchi *et al* 2003), or identifying human impact on urban subsurface environment (Huang *et al* 2009, Taniguchi *et al* 2009). There are few works on estimation of potential and sustainable use of shallow geothermal energy on the large scale. Balke (1977), Kley and Heekmann (1981) used similar methods to quantify the recoverable heat per unit surface and time from 'groundwater bearing strata' in Cologne. Allen *et al* (2003) concluded that using hydrogeothermal source for space heating has high development potential in urban heat islands with high yielding aquifers. Their calculation was based on data from a single borehole, and regional groundwater conditions and associated heat content were not considered. The current study presents extensive field studies in two cities, Cologne (Germany) and Winnipeg (Canada), and additional case studies for other cities such as London and Tokyo. The major objective is to estimate the regional potential geothermal energy contents in contrast to available capacities for space heating. Subsurface conditions are interpreted on the basis of the findings from comprehensive field measurement campaigns in both city centers and surrounding rural areas.

2. Aquifer temperature anomalies in Winnipeg and Cologne

The city of Cologne, lying on the River Rhine, is Germany's fourth-largest city with a population of around one million. The average annual air temperature from 1945 to 2009 was 11 °C according to the German weather service (DWD). Cologne is underlain by quaternary terrace deposits that host shallow unconfined aquifers (Klostermann 1992). Major components are sand and gravel with a mean hydraulic conductivity of 1×10^{-3}–5×10^{-3} m s^{-1} (Losen 1984). The main aquifer reaches a depth of 30–70 m and is underlain by a layer of clay and soft coal. Groundwater flows from southwest to northeast to the river Rhine. The groundwater level is between 10 and 15 m below the surface. Groundwater temperature measurements were performed in October 2009 using logging equipment (SEBA KLL-T) with an accuracy of 0.1 K. We measured 72 wells in a total area of around 140 km^2. The area covers business districts, residential districts, industrial areas, green spaces in the city, and rural agricultural areas. The measured wells have a diameter between 0.05 and 0.127 m, and the well depth ranges between 20 and 100 m. Groundwater temperatures were recorded at 1 m intervals in each well.

Winnipeg is located in south central Canada, and it is the capital and largest city of Manitoba with more than 0.6 million inhabitants. According to the climate record of Canada Environment, the average daily temperature in Winnipeg from 1971 to 2000 is around 2.6 °C. The Winnipeg area is underlain by the Carbonate Rock Aquifer, which can be divided into two parts, namely the Upper Carbonate Aquifer and the Lower Carbonate Aquifer (Ferguson and Woodbury 2005). Below the carbonate aquifer is a continuous layer of shale. The Upper Carbonate Aquifer occurs at a depth of 15–30 m and is overlain by silt and clay. The thickness of this layer is between 5 and 15 m, and the transmissivities range from 2.9×10^{-2} to 2.9 m^2 s^{-1} (Render 1970). Because it generally has much higher hydraulic conductivities than the Lower Carbonate Aquifer, it is the primary water supply aquifer in Winnipeg area (Render 1970). Temperature measurements were performed in August 2007 in 40 monitoring wells in Winnipeg and the surrounding areas (Ferguson and Woodbury 2007). Measurement accuracy is 0.1 K and equal to that for Cologne. Diameter and depth ranges of wells are 0.05–0.125 m and 20–150 m, respectively. Temperatures were measured at 1–2 m intervals in the water-filled portion of the well.

Collected temperature data for both cities were contoured by kriging (figure 1). As the reference depth, for the Winnipeg case 20 m below ground surface was selected. At this depth, approximately the center of the Upper Carbonate Aquifer, borehole data are most exhaustive while noise from seasonal air temperature change is low. In Cologne, for the same reason, temperatures measured at about 15 m were used to construct isolines, which were smoothed, and only the ones on the western side of the river Rhine were considered here. The measurement results indicate that in both cities the shallow aquifers in the center are several degrees (3–5 °C) warmer than in the surrounding rural areas. Like the experience with urban air temperature, the observed subsurface temperature is correlated with the population density and land cover (Ferguson and Woodbury 2007). The subsurface beneath green spaces in the cities has lower temperatures than business districts in the city centers, and the agricultural areas always have the lowest underground temperatures.

The natures of typical vertical temperature profiles depend on location and depth. This is illustrated by selected wells

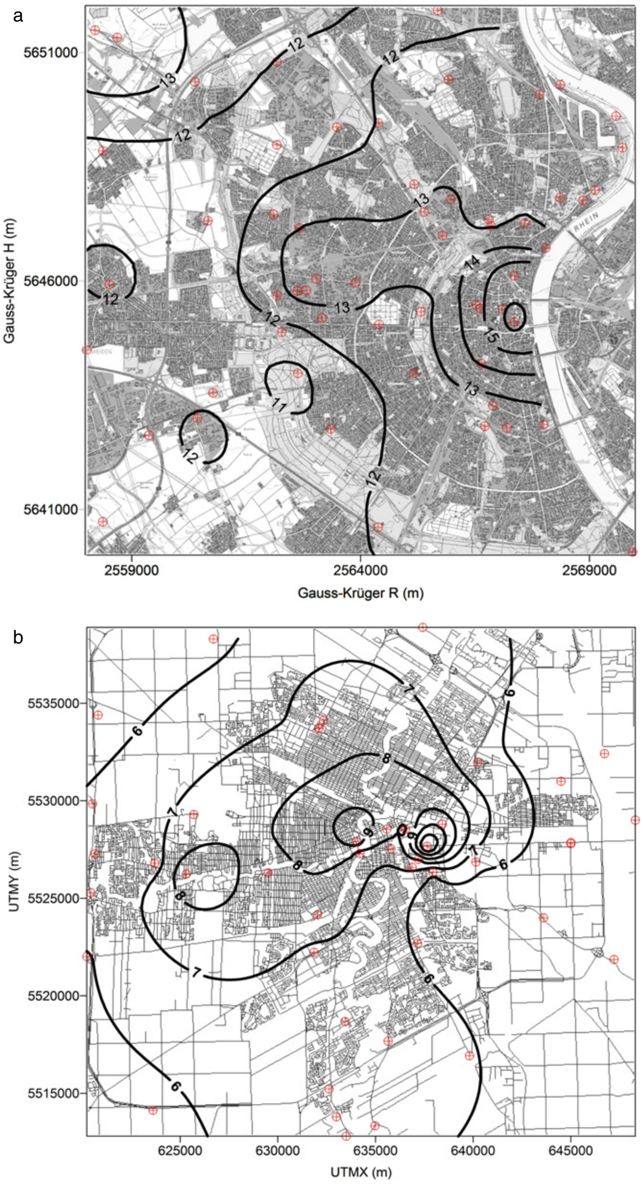

Figure 1. Groundwater temperature contour map. (a) Groundwater temperature contour map at about 15 m depth beneath Cologne in 2009; (b) groundwater temperature contour map at 20 m depth beneath Winnipeg in 2007.

in Cologne (figure 2). The lowest temperatures prevail beneath the agricultural area. Values of 10.8 °C at 17 m depth were measured. The green spaces in the city have higher temperature, and apparently below 10 m depth the temperature increases slightly. In the city center, much higher temperature prevails and profiles vary substantially from well to well. And in most observation wells, temperatures at 15 m depth are above 12 °C. The highest temperatures appear in two observation wells, one of which is near a large underground parking lot and the other next to a dining hall. Similar patterns of temperature distributions were also found in Winnipeg (Ferguson and Woodbury 2007), with higher and more variable subsurface temperatures in the city center and cooler underground for the green spaces and agricultural land. Since natural geothermal anomalies are not known for both Cologne and Winnipeg, the underground anthropogenic thermal loss appears to be the primary cause of the heightened subsurface temperature.

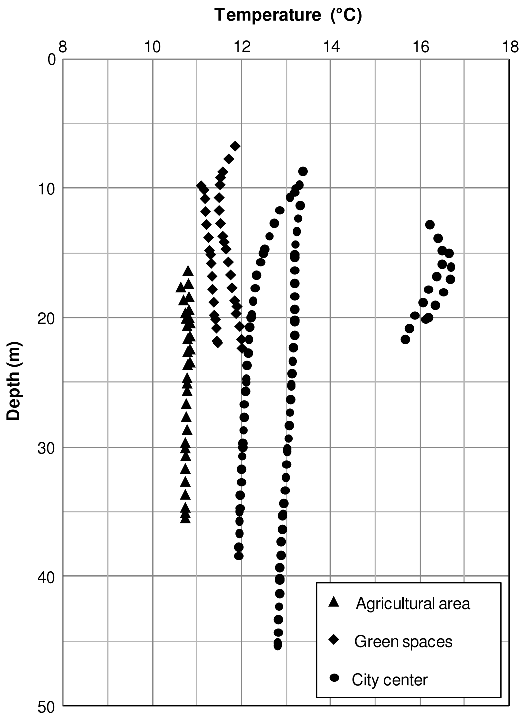

Figure 2. Temperature profiles of selected wells in Cologne in 2009.

3. The geothermal potential

Geothermal energy use of shallow aquifers is on the rise, and anthropogenic anomalies represent increased thermal energy reservoirs. This is of even more importance for highly urbanized cities with higher heating demand compared to the surrounding countryside. The theoretical geothermal potential (i.e. the potential heat content) below Cologne and Winnipeg can be estimated. The three-dimensional non-uniform subsurface temperature distribution is simulated by measurement data interpolation and extrapolation, at a grid size of 500 m × 500 m in east–west and north–south directions and 1 m in the vertical direction. On the basis of the temperature field and known hydrogeological conditions (table 1), the potential heat content can be estimated using the following equation, after Balke (1977):

$$Q = Q_w + Q_s = VnC_w\Delta T + V(1-n)C_s\Delta T \qquad (1)$$

in which Q (kJ) is the total theoretical potential heat content of the aquifer, 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, Q_w and Q_s (kJ) are the heat content stored in groundwater and solid respectively, ΔT (K) is the temperature reduction of the whole aquifer. According to the German engineering guideline VDI 4640/1 (2000), C_w, for water, is 4150 kJ m^{-3} K^{-1}, and C_s has a range depending on sediment types, and for Cologne and Winnipeg ranges between 2100 and 2400 kJ m^{-3} K^{-1}. To cover all possible conditions, maximum,

Table 1. Heat content estimation of the aquifer in Cologne and Winnipeg.

	Cologne			Winnipeg		
	Min	Max	Average	Min	Max	Average
Aquifer thickness (m)	10	30	20	5	15	10
Volume of urban aquifer (m^3)	1.4×10^9	4.3×10^9	2.8×10^9	2.2×10^9	6.5×10^9	4.3×10^9
Porosity	0.15	0.25	0.20	0.05[a]	0.095[a]	0.06
Volume of water (m^3)	2.1×10^8	1.1×10^9	5.7×10^8	1.1×10^8	6.1×10^8	2.6×10^8
Heat content in water (kJ K^{-1})	8.8×10^{11}	4.4×10^{12}	2.4×10^{12}	4.5×10^{11}	2.5×10^{12}	1.1×10^{12}
Volume of solid (m^3)	1.2×10^9	3.2×10^9	2.3×10^9	2.0×10^9	5.9×10^9	4.1×10^9
Volumetric heat capacity of solid (kJ m^{-3} K^{-1})[b]	2100	2200	2150	2100	2400	2250
Heat content in solid (kJ K^{-1})	2.5×10^{12}	7.0×10^{12}	4.9×10^{12}	4.3×10^{12}	1.4×10^{13}	9.1×10^{12}
Temperature reduction (K)	2	6	4	2	6	4
Potential underground heat content (kJ)	6.8×10^{12}	6.9×10^{13}	2.9×10^{13}	9.5×10^{12}	1.0×10^{14}	4.1×10^{13}
Potential underground heat content (kJ km^{-2})	4.8×10^{10}	4.8×10^{11}	2.0×10^{11}	2.2×10^{10}	2.3×10^{11}	9.5×10^{10}
Space heating demand (kJ km^{-2} $year^{-1}$)	1.9×10^{10}[c]			4.1×10^{10}[d]		
Capacity for space heating	2.5	25.5	10.7	0.5	5.6	2.3

[a] Ferguson and Woodbury (2005). [b] VDI 4640/1 (2000). [c] Matthess (1994). [d] Data from Natural Resources Canada (2007).

minimum and mean values were chosen for C_s as well as for porosity n. The latter values are based on the literature (Matthess 1994) and field pumping tests conducted by the regional water association called Erftverband (Voigt and Kilian 2007).

The total aquifer volume was divided into small units according to the grid size, and the heat content Q of each unit was calculated with specific ΔT by subtracting the local or simulated local temperature from the average temperature in agricultural area. The sum of Q for the entire area of the 20 m thick aquifer is between 9.8×10^{12} and 1.1×10^{13} kJ (7.0×10^{10}–7.9×10^{10} kJ km^{-2} on average in the urban area around 140 km^2), which stands for the increased heat content mainly caused by the urbanization effect in Cologne. For geothermal use, in principle, the aquifers' temperature could be technically decreased to 0 °C, but energy extraction is most efficient at relatively high temperatures. Because of this decrease in efficiency and also due to environmental potential concerns, the extractable energy only reflects a decrease of few degrees. Here, the temperature reduction value was set between 2 and 6 K; the lower value of this range is close to the average temperature increase in Cologne and the upper value is the minimum threshold as recommended in legal regulations such as laws and guidelines of several countries (VDI 4640/4 2004). Aquifer volume is calculated as the product of approximate aquifer thickness and urban area where the temperature within the depth of the aquifer is higher than the one in agricultural areas. Again, a range of reasonable values, according to field tests and literature, are considered to reflect the uncertainty in specifying this parameter.

The space heating demand in Cologne is around 1.9×10^{10} kJ km^{-2} $year^{-1}$, with an average annual unit heating demand of 50 kWh m^{-2} and average living space of around 43 m^2 (Timm 2008). For long term geothermal use, besides the potential heat content of the aquifer, natural geothermal flux from the Earth's interior has to be considered. For instance, the natural heat flux density in Cologne is 0.059 W m^{-2} (Balke 1977), which represents an annual heat supply of around 1.9×10^9 kJ km^{-2} and equals 10% of the annual heating demand in Cologne. However, the annual natural heat supply is less than 3% of the calculated increased heat content due to urbanization (7.0×10^{10} kJ km^{-2}); therefore in this case it is not included in the space heating capacity estimation. The natural geothermal flux for Winnipeg is only 0.035–0.040 W m^{-2} (Jessop and Judge 1971) and would have an even smaller effect on the calculations performed. The results show that the theoretical geothermal potential in the urban aquifer of Cologne has a space heating capacity of 2.5, which means that the minimum potential extractable heat content is at least 2.5 times the total annual residential heating demand. For the most optimistic case, even 25.5 times would be possible. Winnipeg's heating demand is almost twice that of Cologne and its population is smaller. Accordingly, its geothermal potential is at least half of the annual heating demand, and a maximum capacity of 5.6.

4. Discussion and conclusions

Subsurface warming trends were also discovered in other large cities with rapid urbanization rates all over the world. The potential geothermal energy contents in various cities are also determined using estimated hydrogeological conditions, and maximum and minimum values of parameters are used in order to cover the possible range and to reflect the uncertainty (table 2). The magnitude of the subsurface temperature reduction is also set to 2–6 K, for the same reason as is applied in Cologne. Due to the difficulty of getting the specific annual space heating demand for each city, the values are preliminary estimates based on national statistical data on space heating, total population and the city population density (Stulc 1998, Headon *et al* 2009). Table 2 indicates that in most cities, with a variety of populations and climates, the large amount of thermal energy stored in the urban local subsurface is capable of fulfilling the annual space heating demand at least for years. Cities with a longer history of urbanization usually have influence on the subsurface temperature at greater depth, due to the early start of additional heat (Taniguchi *et al* 2007). They accordingly have higher potential heat content in the aquifers. In the megacity of Shanghai, the existing heat content in the urban aquifer is at least 22 times the annual heating demand of the city. Considering that aquifers are dynamic

Table 2. Heat content and heating demand estimation for selected cities.

City	Area[a] (km^2)	Population density[a] (km^{-2})	Aquifer material	Thickness (m)	Porosity[b]	Potential minimal heat content ($kJ\ year^{-1}\ km^{-2}$)	Heating demand ($kJ\ year^{-1}\ km^{-2}$)	Capacity for space heating
Cologne	405	2528	Gravel, sand	10–30	0.15–0.25	4.8×10^{10}–4.8×10^{11}	1.9×10^{10}	2.5–25.5
Winnipeg	5302	1429	Carbonate	5–15	0.05–0.1	2.2×10^{10}–2.1×10^{11}	4.1×10^{10}	0.5–5.6
Shanghai	6200	2646	Sand, clay[c]	10–20[c]	0.2–0.3	5.0×10^{10}–3.5×10^{11}	2.3×10^{9} [d]	22.2–155.1
Tokyo	2187	5874	Sand, clay[e]	30–70[e,f]	0.2–0.3	5.0×10^{10}–7.0×10^{11}	2.5×10^{10} [g]	5.9–48.3
London	1707	4761	Chalk[h]	30–40[h]	0.05–0.2	1.1×10^{11}–5.6×10^{11}	9.5×10^{10} [i]	1.4–6.9
Istanbul	1830	6211	Limestone[j]	10–30	0.05–0.25	4.4×10^{10}–5.0×10^{11}	5.5×10^{9} [k]	8.0–92.9
Prague	496	2504	Sandstone[l]	10–30	0.1–0.3	4.6×10^{10}–5.3×10^{11}	9.6×10^{9} [m]	4.8–55.0

[a] City Population (2010). [b] Spitz and Moreno (1996). [c] Zhang *et al* (2007). [d] The Climate Group of WADE (2005). [e] Hayashi *et al* (2009). [f] Taniguchi *et al* (2007). [g] Data from Agency for Natural Resources and Energy (2009). [h] Headon *et al* (2009). [i] Report: Energy Consumption in the UK (2007). [j] Yalcin and Yetemen (2009). [k] Sectoral Energy Consumption Statistics (2005). [l] Stulc (1998). [m] Data from Czech Statistical Office (2008).

systems and that the energy of the subsurface is slowly but continuously replenished, the geothermal potential here has the technological possibility to supply space heating for even hundreds of years.

In order to extract the geothermal energy in urban aquifers, two kinds of shallow geothermal systems, closed and open systems, are commonly used. Closed systems are typically represented as ground source heat pumps (GSHP). A heat carrier fluid is circulated within buried vertical or horizontal borehole heat exchangers (BHE) that exchange heat with the surrounding underground. In open systems such as groundwater heat pump (GWHP) systems, groundwater is directly circulated between production and injection wells. Depending on the local hydrogeological conditions, national legislation (Haehnlein *et al* 2010) and groundwater utilization, different systems can be chosen. In order to reduce the detrimental environmental impacts, groundwater temperature change limits for both heating and cooling and minimum distances between different geothermal systems have been defined in some national regulations and recommendations. According to the study of Haehnlein *et al* (2010), these worldwide regulations and recommendations show a wide range of temperature limits and minimum distances, and most of them are still in an early stage.

Since these technologies are based on energy transfer through closed BHE or open wells, even with dense galleries, uniform extraction of the artificially increased heat of the urban subsurface is hardly possible. The ratio between producible and stored thermal energy in a given volume of reservoir is expressed as the recovery factor (R). The study by Muffler and Cataldi (1978) showed that R may be as much as 0.5 for an ideally permeable hot-water system, while Iglesias and Torres (2003) assumed a constant value of 0.25 for R in their estimation of geothermal reserves with low to medium temperature. These figures reflect case-specific conditions and there is no generally valid value of R for urban aquifer systems. However, note that the geothermal potential (table 2) in the current study focuses on the component that is artificially increased beneath cities. Therefore, even for recovery factors below 0.5 the technologically utilizable geothermal potential is very high. In order to only exploit the additional energy stored beneath cities, for instance, geothermal systems could be operated that cause more pronounced local temperature anomalies ($>\Delta T$). This also triggers heat conduction to further energy supply and establishes a regional temperature decrease. In many situations it will be possible to recover nearly all of the additional energy due to urbanization with heat pump technologies, but this will require local temperature decreases below background values near the extraction point.

In numerous cities, such as Winnipeg, aquifers have mainly been used for cooling purposes since the early 20th century (Ferguson and Woodbury 2005). This accelerates subsurface warming and meanwhile decreases the efficiency of using underground for cooling. In this case, a dual heating/cooling system or aquifer thermal energy storage (ATES) system will be more environmentally and economically efficient. In particular in summer, the large difference between air temperature and the underground temperature makes the GSHP systems very efficient for space cooling.

As a result of rapid urbanization, particularly in Asian megacities, the magnitude of temperature increase in the subsurface becomes even greater and so does the influenced depth. Consequently, the potential heat content stored in these urban aquifers is growing. Efficiently and sustainably extracting this large amount of energy will not only fulfill part of the energy demand in urban areas, but also play a positive role in slowing down urban warming, because of the reduction of greenhouse gas emissions. Detailed research according to specific hydrological/geological and urbanized conditions, such as subsurface temperature profiles, land use and specific heating and cooling demands in megacities, is therefore necessary to further improve our understanding of the dynamics of energy fluxes in urban heat islands.

Acknowledgments

The financial support for Ke Zhu from the BMBF program for International Postgraduate Studies in Water Technologies (IPSWaT) is gratefully acknowledged. This work was also supported by Erftverband and RheinEnergie and the EU funded FP7 project GWAT-LCA (PIEF-GA-2008-220620). Furthermore, we would like to thank Peter Grathwohl for his suggestions and valuable support.

References

Agency for Natural Resources and Energy 2009 *FY 2009 Annual Energy Report* (in Japanese)

Allen A, Milenic D and Sikora P 2003 Shallow gravel aquifers and the urban 'heat island' effect: a source of low enthalpy geothermal energy *Geothermics* **32** 569–78

Balke K D 1977 Das Grundwasser als Energieträger *Brennstoff-Wärme-Kraft* **29** 191–4

Beltrami H 2001 Surface heat flux histories from inversion of geothermal data: energy balance at the Earth's surface *J. Geophys. Res.* **106** 21979–93

Beltrami H, Ferguson G and Harris R N 2005 Long-term tracking of climate change by underground temperatures *Geophys. Res. Lett.* **32** L19707

Blum P, Campillo G, Münch W and Kölbel T 2010 CO_2 savings of ground source heat pump systems—a regional analysis *Renew. Energy* **35** 122–7

Bodri L and Cermak V 1997 Climate changes of the last two millennia inferred from borehole temperatures: results from the Czech Republic 2 *Glob. Planet. Change* **14** 163–73

Cartwright K 1979 Measurement of fluid velocity using temperature profiles: experimental verification *J. Hydrol.* **43** 185–94

Cermak V, Safanda J, Kresl M, Dedecek P and Bodri L 2000 Recent climate warming: surface air temperature series and geothermal evidence *Stud. Geophys. Geod.* **44** 430–41

City Population 2010 www.citypopulation.de/

Czech Statistical Office 2008 Heat energy balance between 2000 and 2008 www.czso.cz/csu/2009edicniplan.nsf/engt/1F003A8B75/$File/81100916.pdf

Energy Consumption in the UK 2007 www.berr.gov.uk/files/file11250.pdf

Ferguson G and Woodbury A D 2004 Subsurface heat flow in an urban environment *J. Geophys. Res.* **109** B02402

Ferguson G and Woodbury A D 2005 Thermal sustainability of groundwater-source cooling in Winnipeg Manitoba *Can. Geotech. J.* **42** 1290–301

Ferguson G and Woodbury A D 2007 Urban heat island in the subsurface *Geophys. Res. Lett.* **34** L23713

Haehnlein S, Bayer P and Blum P 2010 International legal status of the use of shallow geothermal energy *Renew. Sustain. Energy Rev.* **14** 2611–25

Hayashi T, Tokunaga T, Aichi M, Shimada J and Taniguchi M 2009 Effects of human activities and urbanization on groundwater environments: an example from the aquifer system of Tokyo and the surrounding area *Sci. Total Environ.* **407** 3165–72

Headon J, Banks D, Waters A and Robinson V K 2009 Regional distribution of ground temperature in the Chalk aquifer of London UK *Q. J. Eng. Geol. Hydrogeol.* **42** 313–23

Huang S, Taniguchi M, Yamano M and Wang C H 2009 Detecting urbanization effects on surface and subsurface thermal environment—a case study of Osaka *Sci. Total Environ.* **407** 3142–52

Huang S P, Pollack H N and Shen P Y 2000 Temperature trends ever the past five centuries reconstructed from borehole temperatures *Nature* **403** 756–8

Iglesias E R and Torres R J 2003 Low- to medium-temperature geothermal reserves in Mexico: a first assessment *Geothermics* **32** 711–9

Jessop A M and Judge A M 1971 Five measurements of heat flow in southern Canada *Can. J. Earth Sci.* **8** 711–6

Kataoka K, Matsumoto F, Ichinose T and Taniguchi M 2009 Urban warming trends in several large Asian cities over the last 100 years *Sci. Total Environ.* **407** 3112–9

Kley W and Heekmann W 1981 Waste heat balance in aquifers calculated by a computer programme *Ground Water* **19** 144–8

Klostermann J 1992 *Das Quartär der Niederrheinischen Bucht—Ablagerungen der Letzten Eiszeit am Niederrhein* 4. Auflage (Krefeld: Geologisches Landesamt Nordrhein-Westfalen)

Losen H 1984 Grundwasserstände und Grundwasserbeschaffenheit im südlichen Teil der linksrheinischen Kölner Scholle—Eine hydrologische und statistische Analyse *Dissertation RWTH Aachen*

Magee N, Curtis J and Wendler G 1999 The urban heat island effect at Fairbanks, Alaska *Theor. Appl. Climatol.* **64** 39–47

Matthess G 1994 *Die Beschaffenheit des Grundwassers* 3 (Germany: Auflage Gebrüder Bornträger) p 499

Muffler P and Cataldi R 1978 Methods for regional assessment of geothermal resources *Geothermics* **7** 53–89

Natural Resources Canada 2007 *Energy Use Data Handbook Tables* (Canada: Energy Publications Office of Energy Efficiency)

Oke T R 1973 City size and the urban heat island *Atmos. Environ.* **7** 769–79

Perrier F, Le Mouel J L, Poirier J P and Shnirman M G 2005 Long-term climate change and surface versus underground temperature measurements in Paris *Int. J. Climatol.* **25** 1619–31

Pollack H N, Huang S P and Shen P Y 1998 Climate change record in subsurface temperatures: a global perspective *Science* **282** 279–81

Render F W 1970 Geohydrology of the metropolitan Winnipeg area as related to groundwater supply and construction *Can. Geotech. J.* **7** 243–74

Rizwan A M, Dennis Y C L and Liu C H 2008 A review on the generation, determination and mitigation of Urban Heat Island *J. Environ. Sci.* **20** 120–8

Saner D, Juraske R, Kübert M, Blum P, Hellweg S and Bayer P 2010 Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems *Renew. Sustain. Energy Rev.* **14** 1798–813

Sectoral Energy Consumption Statistics 2005 *Sectoral Energy Consumption Statistics 2005* Turkish Statistical Institute, Prime Ministry, Republic of Turkey

Spitz K and Moreno J 1996 *A Practical Guide to Groundwater and Solute Transport Modeling* (New York: John Wiley & Sons) pp 342–3

Stulc P 1998 Combined effect of topography and hydrogeology on subsurface temperature—implications for aquifer permeability and heat flow. A study from the Bohemian Cretaceous basin *Tectonophysics* **284** 161–74

Taniguchi M, Burnett W C and Ness G 2009 Human impacts on urban subsurface environments *Sci. Total Environ.* **407** 3073–4

Taniguchi M, Shimada J and Uemura T 2003 Transient effects of surface temperature and groundwater flow on subsurface temperature in Kumamoto Plain Japan *Phys. Chem. Earth* **28** 477–86

Taniguchi M, Uemura T and Jago-on K 2007 Combined effects of urbanization and global warming on subsurface temperature in four Asian cities *Vadose Zone J.* **6** 591–6

The Climate Group of WADE (World Alliance for Decentralized Energy) 2005 *Building Integrated Cooling, Heat & Power—2005 Status and Prospects for Canada, China, India and the USA*

Timm U 2008 *Wohnsituation in Deutschland 2006—Ergebnisse der Mikrozensus—Zusatzerhebung, Wirtschaft und Statistik 2/2008*

Tran H, Uchihama D, Ochi S and Yasuoka Y 2006 Assessment with satellite data of the urban heat island effects in Asian mega cities *Int. J. Appl. Earth Obs. Geoinf.* **8** 34–48

VDI 4640/1 2000 *Thermal Use of the Underground—Fundamentals, Approvals, Environmental Aspects* VDI (Verein Deutscher Ingenieure)

VDI 4640/4 2004 *Thermal Use of the Underground—Direct Uses* VDI (Verein Deutscher Ingenieure)

Voigt J and Kilian L 2007 *Grundwassermodell für das Rheinische Braunkohlenrevier* Modellbericht, RWE Power AG, Köln

Wang C H, Lin W Z, Peng T R and Tsai H C 2009 Erratum to 'temperature and hydrological variations of the urban environment in the Taipei metropolitan area, Taiwan' *Sci. Total Environ.* **407** 3233–8

Wang K, Lewis T J, Belton D S and Shen P Y 1994 Differences in recent ground surface warming in eastern and western Canada: evidence from borehole temperatures *Geophys. Res. Lett.* **21** 2689–92

Yalcin T and Yetemen O 2009 Local warming of groundwaters caused by the urban heat island effect in Istanbul, Turkey *Hydrogeol. J.* **17** 1247–55

Zhang Y, Xue Y Q, Wu J C, Ye S J, Wei Z X, Li Q F and Yu J 2007 Characteristics of aquifer system deformation in the Southern Yangtse Delta, China *Eng. Geol.* **90** 160–73