



Subsurface urban heat islands in German cities

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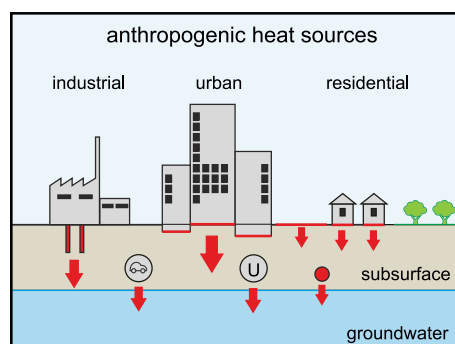
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HIGHLIGHTS

- Positive temperature anomalies under German cities.
- Local heat sources cause hot spots > 30 °C in Frankfurt.
- Superposition of various heat sources leads to a significant regional warming.
- Subsurface urban heat island (UHI) intensities range between 1.9 and 2.4 K.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 30 August 2012

Received in revised form 9 October 2012

Accepted 9 October 2012

Available online xxxx

Keywords:

Urban heat island intensity

Geothermics

Urban hydrology

Groundwater temperature

Urbanization

ABSTRACT

Little is known about the intensity and extension of subsurface urban heat islands (UHI), and the individual role of the driving factors has not been revealed either. In this study, we compare groundwater temperatures in shallow aquifers beneath six German cities of different size (Berlin, Munich, Cologne, Frankfurt, Karlsruhe and Darmstadt). It is revealed that hotspots of up to +20 K often exist, which stem from very local heat sources, such as insufficiently insulated power plants, landfills or open geothermal systems. When visualizing the regional conditions in isotherm maps, mostly a concentric picture is found with the highest temperatures in the city centers. This reflects the long-term accumulation of thermal energy over several centuries and the interplay of various factors, particularly in heat loss from basements, elevated ground surface temperatures (GST) and subsurface infrastructure. As a primary indicator to quantify and compare large-scale UHI intensity the 10–90%-quantile range $UHII_{10-90}$ of the temperature distribution is introduced. The latter reveals, in comparison to annual atmospheric UHI intensities, an even more pronounced heating of the shallow subsurface.

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1. Introduction

The phenomenon of urban heat islands (UHI) in the atmosphere is widely known and has been a focus of environmental research for several decades (Landsberg, 1956; Kratzer, 1956). UHI formation is caused by the manifold changes in cities due to urbanization, such as artificial surface cover and anthropogenic heat loss. These factors cause changes in the atmospheric radiation balance and the urban energy balance, which leads to an urban microclimate and more specifically, to the warming of

Abbreviations: GST, ground surface temperature; GWT, groundwater temperature; UHI, urban heat island; $UHII$, urban heat island intensity; SST, subsurface temperature; $SUHII$, surface urban heat island intensity.

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air temperature (Landsberg, 1981; Oke, 1988). Oke (1973) defined the maximum difference in surface air temperature (SAT) between the urban city center and the rural area as the urban heat island intensity (UHII). The latter is the highest in clear and windless summer nights and can reach values of up to 12 K. He also demonstrates a positive correlation between UHII and city population. Wienert and Kuttler (2005) suggested a relationship between UHII, the geographical latitude and accordingly, the primary energy use of the city. However, Landsberg (1981) pointed out that the UHI effect represents a heterogeneous and site-specific sum of many microclimatic changes. As a consequence, the overall effect can only be inadequately described by a single parameter.

In the subsurface, the temperature (subsurface temperature, SST) is mainly governed by the heat flow from the Earth's interior and the ground surface temperature (GST) (Huang et al., 2009). Variation in GST propagates into the subsurface mainly by thermal diffusion. Especially close to the ground surface, additional local factors may influence the thermal regime, such as advective heat transport from interaction of aquifers with surface water, and any type of direct anthropogenic stimulation (Molina-Giraldo et al., 2011; Saar, 2011). Many studies used vertical borehole temperature profiles to examine paleoclimate conditions or to back-track recent climate changes (Birch, 1948; Lachenbruch and Marshall, 1986; Pollack et al., 1998; Bodri and Cermak, 1997; Kohl, 1998; Huang et al., 2000; Beltrami et al., 2002). Taniguchi (1993) analyzed temperature-depth profiles for detecting regional groundwater flow systems. Alterations of surface covers also influence the SST and the measured temperature profiles (Taylor and Stefan, 2009). For example, increases in soil temperature of several degrees after deforestation were found by Taniguchi et al. (1999) and Nitoui and Beltrami (2005).

In the urban subsurface environment, the temperature regime is more complex than in rural, less disturbed environments. Similar to the UHI in the atmosphere, urbanization leads to a warming of the subsurface environment (Taniguchi et al., 2007), and the observed thermal conditions are always revealed to be specific. Increased SST in fast growing Asian megacities are well documented by numerous studies (e.g. Taniguchi and Uemura, 2005; Taniguchi et al., 2009). Others scrutinized the UHI effect in the subsurface of Northern American cities (e.g. Changnon, 1999; Ferguson and Woodbury, 2007), and elevated SST are reported from several large European cities. Yalcin and Yetemen (2009) inspected shallow soil temperatures at different points in time in two districts of Istanbul. It was revealed that temperatures rise by 3.5 K in built-up areas. However, shallow soil temperature varies seasonally following GST oscillation, and thus fixed-time measurements are not representative for an annual average temperature. In London, Headon et al. (2009) identified regional temperature differences of up to 5 K. However, this temperature anomaly is apparently triggered by variations in the natural geothermal heat flux. Zhu et al. (2010) investigated the spatial distribution of groundwater temperatures below Cologne, Germany, with the highest temperatures under the city center. Similar to the experience from Asian megacities and in North America, intensified vertical heat flux due to urbanization was suspected the main reason.

The factors and processes that cause the subsurface urban warming are not yet comprehensively understood. Taniguchi et al. (2007) and Huang et al. (2009) explored the relationship between SST and SAT. However, the temperature anomalies in the subsurface cannot be explained only by the increase of urban air temperatures. Ferguson and Woodbury (2004) calculated the heat loss from non-insulated buildings in an urban area. This effect is only noticeable within hundred meters from the heated structure. Thus, it cannot fully explain the vast regional increase in SST. In addition, the urban subsurface environment is influenced by a vast amount of other anthropogenic structures, such as subway networks or injections of thermal wastewater, which were not considered in previous studies.

The objective of this study is to evaluate the spatial distribution of groundwater temperatures (GWT) under several German cities, to find

commonalities and differences, and to identify the main influencing factors that stimulate warming of urban aquifers. As most investigations of UHIs in the subsurface were conducted in Asian megacities, the question remains if extensive warming of GWT is a phenomenon characteristic mainly for fast growing cities with a large population, or if also smaller cities with nearly constant populations and a different history share similar thermal features. In contrast to related work on borehole climatology that uses subsurface temperature to assess the effects of climate change, this study focuses on the present state and potential sources of subsurface warming in urban areas.

The present study carefully analyzes the GWT beneath six German cities with different population numbers in order to detect the diverse anthropogenic and natural heat sources. While most previous studies focused on individual factors, we consider the interplay of various potential heat sources. For the evaluation of the UHI effect in the subsurface specific city characteristics, such as population and population density are correlated against the UHII and the spatial relationship between GWT and SAT is examined. In the following, first the cities are introduced with special focus on the geological conditions, and the utilized temperature information is shown. Then the thermal subsurface conditions and the dominant urban heat sources are compared for the different cases. This is complemented by contrasting the subsurface conditions with the above ground UHI in two selected cities, Karlsruhe and Berlin.

2. Material and methods

2.1. Study areas

The locations of the studied German cities are shown in Fig. 1. In Table 1 various data are listed providing an overview on the studied cities and showing available geographical, hydrogeological and statistical information. In order to cover a certain range of different population numbers, the selected cities include both large cities with more than one million inhabitants, as well as smaller cities with a population of less than half a million people (Table 1). All cities have a moderate climate and share a similar urban design, with densely built-up city centers, suburban/residential areas and separated industrial areas. Furthermore, below all studied cities, shallow aquifers are present that are prone to be heated by intensified downward heat fluxes. In the following, the hydrogeological and geological conditions for each city are explained in more detail. Then the findings from case-specific temperature measurements and spatial analyses are reported.



Fig. 1. Geographical locations of the studied German cities.

Table 1

Characteristics of the studied German cities. The annual mean SAT values are given for the time period 1961–1990. The hydrogeological parameters refer to the topmost aquifer, where the temperature measurements were conducted, v_a is the groundwater flow velocity. The denoted range accounts for the heterogeneity of the aquifer materials. Temperature measurements were preferably done at an equal depth. Due to data availability in some cities, a certain depth interval was chosen.

| City | Geogr. coordinates ^a | Mean altitude [m asl] ^a | Population ^a | Pop. density [# / km ²] ^a | Total area [km ²] | Annual mean SAT [°C] ^b | Shallow aquifer material | Average v_a [m/d] | Number of observation wells | Investigated area [km ²] | Measurement density [wells/km ²] | Measurement depth [m blg] |
|-----------|---------------------------------|------------------------------------|-------------------------|--|-------------------------------|-----------------------------------|---|--|-----------------------------|--------------------------------------|--|---------------------------|
| Berlin | 52°31' N 13°24' E | 75 | 3,442,675 | 3861 | 891.5 | 8.9 | Gravel, sand, silt, clay, till ^b | 0.03–1.4 ^c | 123 | 835.9 | 0.1 | 20 |
| Munich | 48°08' N 11°34' E | 518 | 1,330,440 | 4282 | 310.7 | 9.2 | Gravel, sand ^d | 10–15 ^d | 492 | 278.6 | 1.8 | 2–20 |
| Cologne | 50°56' N 6°57' E | 53 | 998,105 | 2463 | 405.2 | 10.0 | Gravel, sand ^e | ca. 1.0 ^e | 52 | 119.3 | 0.4 | 15 |
| Frankfurt | 50°07' N 8°41' E | 112 | 679,664 | 2737 | 248.3 | 10.1 | Limestone, clay, marl, sand ^f | 0.1–1.0 ^f | 27 | 27.2 | 1.0 | 20 |
| Karlsruhe | 49°00' N 8°24' E | 115 | 291,959 | 1683 | 173.5 | 10.7 | Sand, gravel ^g | 0.5–3.5 ^j | 82 | 75.1 | 1.1 | 9–12 |
| Darmstadt | 49°52' N 8°39' E | 144 | 143,332 | 1174 | 122.1 | 10.2 | Crystalline rock, sand, gravel ^h | 8.6×10^{-4} –0.9 ⁱ | 16 | 25.7 | 0.6 | 20–25 |

^a Federal Statistical Office (Destatis) (2012).

^b Hannappel and Limberg (2007).

^c Calculated with values from SenStadtUm (2012).

^d Seiler (1979) and Zosseder (2007).

^e Zhu et al. (2010).

^f Kümmerle and Seidenschwann (2009).

^g Geyer and Gwinner (2011).

^h Beier (2008).

ⁱ Calculated with values from Schäfer et al. (2007) and Geyer and Gwinner (2011).

^j German Weather Service (DWD) (2012).

2.2. Geology and hydrogeology

2.2.1. Berlin

The capital city of Berlin is situated in the Northeast German Basin. The shallow subsurface down to a depth of 250 m is composed of Quaternary and Tertiary glacial and fluvial sediments. The glacial valley with mainly sandy deposits separates the Barnim-Plateau in the North from the Teltow-Plateau, which both are primarily built up of marly till. Due to the heterogeneous character of the sediments, several confined and unconfined aquifers can be found below the city of Berlin. The groundwater level varies between 1 and 10 m below the surface in the glacial valley and up to 40 m below the surface in the plateau areas (Hannappel and Limberg, 2007).

2.2.2. Munich

The geological and hydrogeological settings of the Munich area are comprehensively described by Kerl et al. (2012). Munich is built on Tertiary sedimentary deposits of the Southern German Molasse Basin, which consist of alterations of alluvial sand and silt–clay with varying contents of carbonate. These are overlain by an extensive glacial gravel and cobble plain with a thickness between 2 and 20 m. The plain contains a shallow unconfined porous aquifer with high hydraulic conductivities between 5.0×10^{-4} and 5.0×10^{-1} m/s (Seiler, 1979). Underneath in the tertiary sediments several confined aquifers are present. The groundwater flow direction is generally to the North, with minor variations near to the river Isar. The level of the groundwater decreases from around 18 m in the South to about 1 m below the surface in the North (Dohr and Gruban, 1999).

2.2.3. Cologne

The shallow subsurface in Cologne is composed of Quaternary terrace deposits of predominantly gravel and sand. The main unconfined aquifer in these gravels reaches a depth of 30–70 m and is underlain by an aquitard, which is made of clays and soft coals. Our focus is on the western side of the Rhine River. The groundwater level here is between 10 and 15 m under the surface, and the groundwater flow direction is from Southwest to Northeast, in the direction to the Rhine River (Zhu et al., 2010).

2.2.4. Frankfurt

The city of Frankfurt is located in the geological transition zone between the Upper Rhine Valley and the Main–Nidda-depression (Kümmerle and Seidenschwann, 2009). The formation of the Upper Rhine Valley caused the Tertiary rocks in this area to break up into a mosaic of tectonic blocks. The Tertiary rocks are dominated by Miocene limestones, marls and clays and reach a thickness of > 200 m. In the western part of the city area, these sediments are overlain by Pliocene sand deposits with a varying thickness of up to 60 m. In the whole area, the Tertiary sediments are overlain by Quaternary deposits. Confined aquifers (also artesian confined in the western part of the city) exist in the Miocene limestone layers, and a shallow unconfined aquifer is hosted in the Pliocene and Quaternary sands (Kümmerle and Seidenschwann, 2009).

2.2.5. Karlsruhe

Karlsruhe is situated in the Upper Rhine Graben, a Cenozoic continental rift valley filled with Tertiary and Quaternary sediments. In the study area, the Quaternary sediments are dominated by sands and gravels with minor contents of silt, clay and stones and reach a thickness of around 150 m (Geyer and Gwinner, 2011). Due to sporadic layers with lower permeability, up to three aquifer levels can be separated. The water table in the upper unconfined aquifer ranges between 2 and 10 m below ground. The groundwater flow direction is Northwest to the Rhine River.

2.2.6. Darmstadt

The city of Darmstadt is located on the Eastern border fault of the Upper Rhine Graben. The subsurface of the Eastern part is composed of Mesozoic sandstones and Palaeozoic crystalline rocks, which contain fractured rock aquifers. The Western part of the city is underlain by Quaternary fluvial deposits of the Upper Rhine Graben, which reach a thickness of up to 100 m in the Southern part and 30 m in the Northern part. The sand and gravel sediments form up to three aquifers with inconsistent interlayers of silt and clay. The groundwater flow direction in this area is from east to west. The level of the water table ranges from 10 to 30 m below the surface in the entire area (Beier, 2008).

2.3. Spatial analysis

2.3.1. Spatial distribution of groundwater temperatures

For the spatial analysis of groundwater temperatures (GWT), mainly pre-existing data of temperature measurements in observation wells are used. Usually, dense networks of wells are maintained by the German city authorities for monitoring the level of water table and the 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. An overview on the number of measured wells and the depth of measurements in the studied cities is given in Table 1.

The temperature measurements in Berlin were conducted by the Senate Department for Urban Development and the Environment in 2010 (SenStadtUm, 2012). In the city of Munich, temperature data from a measurement campaign in 2009 was used. Measurements of GWT were carried out 1 m below the water table. Accordingly, the depth below the surface varies between about 2 m in the northern parts and 20 m in the southern parts. Due to the annual variation of SAT, shallow GWT in the upper 15 m of the subsurface usually show similar annual variations depending on the thermal diffusivity of the ground (e.g. Taylor and Stefan, 2009). Thus, the arithmetic mean of several measurements at different times during one year was used for the present analysis. Zhu et al. (2010) explored the spatial distribution of Cologne's GWT in 2009, and the information of their measurement campaign is adopted for the present study. In Frankfurt, the Hessian State Office for Environment and Geology (HLUG) delivered temperature data from 27 wells from 2009. For the examination of groundwater temperatures in Karlsruhe, we use daily temperature data from data loggers installed in 82 monitoring wells, which are operated by the Public Works Service Karlsruhe. Due to the shallow installation depth (9–12 m) of the data loggers the GWT data is again influenced by the annual variations of air temperatures. The arithmetic mean of the seasonal cycle is therefore taken here as it represents the annual mean GWT. In Darmstadt, the GWT was measured during a study on urban hydrochemistry performed by Beier (2008). These measurements were conducted with depths ranging between 5 and 25 m, and so, only 16 wells with a depth of at least 20 m were selected for the present study.

To visualize the GWT spatially, the temperature data is interpolated using kriging in GIS (ESRI® ArcInfo™ 10.0). The method is described in detail by Kitanidis (1997). We use a K-Bessel model for the semi-variogram analysis and optimize the model parameters by cross validation.

2.3.2. Urban heat sources

Potential natural and anthropogenic heat sources in the urban subsurface environment are manifold. Previous studies have discussed increased GST and heated basements as potential causes for increased SST (Taylor and Stefan, 2009; Taniguchi et al., 2007; Ferguson and Woodbury, 2004). However, there are other urban constructions in the subsurface that can act as heat sources, because they are seasonally or permanently warmer than the surrounding subsurface, such as road and subway tunnels, sewage systems, and buried district heating networks. In addition, shallow groundwater is often utilized for cooling in industrial processes and re-injected several degrees warmer into the aquifer (Fig. 2). Likewise, the shallow subsurface in many cities is used thermally by geothermal energy systems, such as ground source heat pump systems (Blum et al., 2011), aquifer thermal energy storage applications or energy piles (Brandl, 2006).

In this study, we offer a qualitative analysis of these potential heat sources by comparing the isotherm maps with land-use plans, town plan maps, positions of district heating networks, underground railway systems and locations of thermal wastewater injections.

2.3.3. Influencing factors for subsurface urban heat islands

City characteristics, such as population and population density, correlate, to some extent, with local concentration of certain urban

heat sources, like basements and sewers. Thus, they could be used as simple surrogates for density of buildings and infrastructures, assuming that the urbanization development in the different cities is similar. A comparable approach was used by Taniguchi (2006), who employed the exponential decrease in population density with the distance from the city center as a proxy for the change in air temperature. Population density data is available for the individual districts of the studied cities covering urban, suburban and rural areas. However, industrial areas and inner-city green spaces are disregarded in this data. Nevertheless, we would expect a relation between the city characteristics and the magnitude of subsurface warming. To test this hypothesis, we correlate the spatial distribution of population densities within the studied cities with the spatial distribution of GWT. In addition, we correlate the GWT with the spatial distribution of mean annual SAT in the city of Berlin. SAT are also strongly influenced by urbanization effects and are closely linked to GST, which are assumed to be a major driver for the warming of GWT (Taniguchi et al., 2007; Huang et al., 2009).

In atmospheric science, the magnitude of the UHI is usually described as a temperature difference between urban and rural areas by the UHI Intensity (UHII) (Oke, 1973). In accordance with this atmospheric UHII, a method to quantify the UHII in the subsurface is needed to enable a comparison. For the calculation of the atmospheric UHII most studies use temperature data from single points (e.g. weather stations, meteorological observatories, etc.) (e.g. Landsberg, 1956; Oke, 1973; Landsberg, 1981; Kim and Baik, 2004). However, in the subsurface, single point measurements are not very applicable for calculating UHII. GWT and SST measurements at single points can yield extremely high or low temperature values if they are in the vicinity of a local heat source (Fig. 2) or heat sink (e.g. reinjection of cool water from a groundwater heat pump system). Due to the slow heat conduction in the subsurface compared to heat advection in the air, heat accumulates locally near permanent heat sources or sinks in the subsurface. As a consequence, a high density network of measurement points is required to capture local extremes, but commonly the number of boreholes or observation wells is limited.

Since temperature in the ground is more heterogeneous than above-ground and balancing heat anomalies from local heat or cold sources is a comparably slow process, the standard indicator of intensity is not expressive for this environment. Values for UHIIs that reflect only extreme local temperatures hardly represent a robust regional parameter. As an alternative to the maximum temperature, we introduce as measure for subsurface UHII, an inner quantile range, $UHII_{10-90}$, of the temperature distribution that cuts the extremes. The cumulative temperature distribution can be plotted as city-specific characteristic curve by pixel-based interpolation between measurement points. We then extract the values of the 10%- and 90%-quantiles and calculate their difference to quantify the UHII in the subsurface. The impact of observed very local heat anomalies is therefore mitigated, while they are still reflected in the cumulative curves. In principle, the $UHII_{100}$ of the subsurface is equivalently determined like the atmospheric UHII or surface urban heat island intensity (SUHII), respectively. Commonly, however, atmospheric UHII or SUHII is not interpolated over the city area. Only few studies provide a 2-dimensional thermal characterization, for instance, based on satellite data (Schwarz et al., 2011; Peng et al., 2012; Schwarz, 2012) or model results (Balázs et al., 2009).

3. Results and discussion

3.1. Spatial distribution of groundwater temperatures

Fig. 3 shows the results of the GWT measurements as interpolated annual mean isotherm maps for Berlin, Munich, Cologne and Karlsruhe. Due to the low number of sampled wells with no seasonal noise in Frankfurt and Darmstadt, contour maps are considered too speculative. Hence, only single data points are shown. In all six cities, the spatial distribution of the GWT is very variable with a clear warming trend towards the inner cities. In all studied areas, the lowest temperatures of

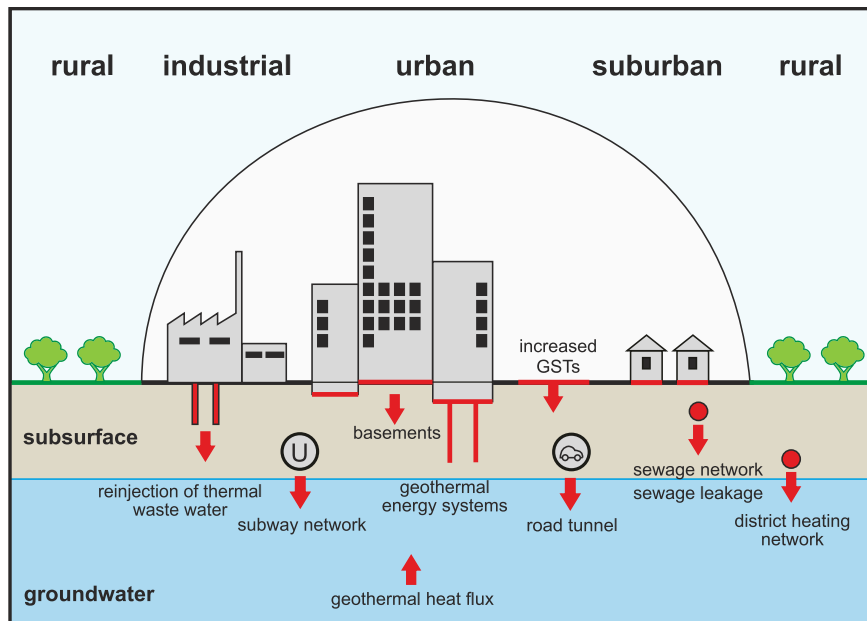


Fig. 2. Potential anthropogenic and natural heat sources in urban areas.

8–11 °C were measured in the rural parts, mostly under forests or agricultural land. “Cold” locations, for example, are found in the south-eastern part of Berlin and the south of Munich. Apparently, direct anthropogenic impact on the GWT is minimal in these regions, and the observed temperatures are interpreted as a proxy for undisturbed background conditions. In the shallow subsurface in each region these resemble the annual average SAT (Table 1).

In suburban and residential areas, the GWT is slightly higher than the background value. The same applies to inner-city green spaces, such as parks or conditions found in airport areas. In almost all cities, the highest GWT of 13–18 °C are detected close to the city centers, which are usually the oldest and most densely built-up urban areas. However, the relatively small cities of Karlsruhe and Darmstadt are exceptions. Highest temperatures are found in industrial areas and outside the city, respectively, where known local heat sources are present (Fig. 3).

In general, the derived annual mean temperature distribution in the urban subsurface turns out to be heterogeneous, strongly depending on the depth of GWT measurements (Table 1). In Berlin and Cologne, where GWT measurements were carried out at 15 and 20 m below the surface, respectively, the obtained spatial distribution of GWT is represented by smooth contours. The same applies to Karlsruhe, where daily GWT measurements were used to calculate the annual mean GWT. In contrast, the interpolated Munich isotherm map indicates a more restless pattern. Main reasons here are the spatial and temporal measurement density. The comparable high density of wells (1.8 wells/km²) with often slightly distinct temperature values next to each other strongly influences the visualization and interpolation. Here, especially the shallow GWT measurements in the upper meters (entire range 2–20 m) of the subsurface appear strongly influenced by local heat sources. Aside from this, the annual mean GWT in the shallow subsurface was interpolated from a few measurements during the year, and the non-uniform contours may also be affected by non-resolved seasonal variability.

3.2. Urban heat sources

When discussing potential heat sources, which could cause urban temperature anomalies, one must distinguish between natural and anthropogenic temperature variations. Natural causes for GWT fluctuations are, for example, spatial variability in the geothermal heat flux

or the existence of local groundwater recharge and discharge zones, as identified in several cities in Japan (Taniguchi and Uemura, 2005; Taniguchi et al., 2005). According to the geological and hydrogeological settings, potential variability of the natural background geothermal regime can be neglected in Berlin, Munich, Cologne and Karlsruhe. The cities of Frankfurt and Darmstadt are both partially located on the main border fault of the Upper Rhine Graben. Thus, in both cities spatial differences in the geothermal heat flux and the upwelling of thermal water are likely to influence the spatial distribution of the GWT (Beier, 2008; Seithel, 2010; Schmid, 2010). In Frankfurt, some wells with unusually high GWT correlate with the zone of tectonic disaggregation in vicinity to the main border fault. The identified potential natural and anthropogenic heat sources in all studied cities are depicted in Fig. 4.

In all cases, the city center exhibits the absolute (Berlin, Munich, Cologne, Frankfurt) or in some cases a local (Karlsruhe, Darmstadt) GWT maximum. Simultaneously, this is usually the area with the highest density of buildings (and therefore also basements), underground car parks and with the highest percentage of sealed surface cover. Kottmeier et al. (2007) showed that there is a direct link between the percentage of sealed surfaces and increasing GST using the example of Berlin. As the density of basements and the percentage of sealed surfaces decrease in suburban and residential areas, so does the GWT. This observation supports the hypothesis that basements and increased GST are dominant heat sources in urban areas. This is also consistent with findings from related studies by Ferguson and Woodbury (2004) and Taylor and Stefan (2009).

Some of the local heat anomalies in the cities of Berlin, Munich and Karlsruhe are correlated to industrial areas and especially to combined heat and power stations. In the presence of shallow aquifers, groundwater is often used for cooling purposes and then re-injected into the aquifer at a temperature of up to 20 °C, which is the recommended maximum temperature in Germany (Hähnlein et al., 2010). In areas with several reinjections of thermal wastewater, widespread shallow thermally affected zones can develop (e.g. Lo Russo et al., 2012). In the examined cities, installations of geothermal energy systems are also widespread and used for both heating and cooling purposes. Especially in Frankfurt, a great part of the large office buildings in the city center are equipped with energy piles used for cooling (Fig. 4).

Another potential heat source is the infiltration of warm stream water into urban aquifers as discussed for Switzerland by Kiefer (2011) in the

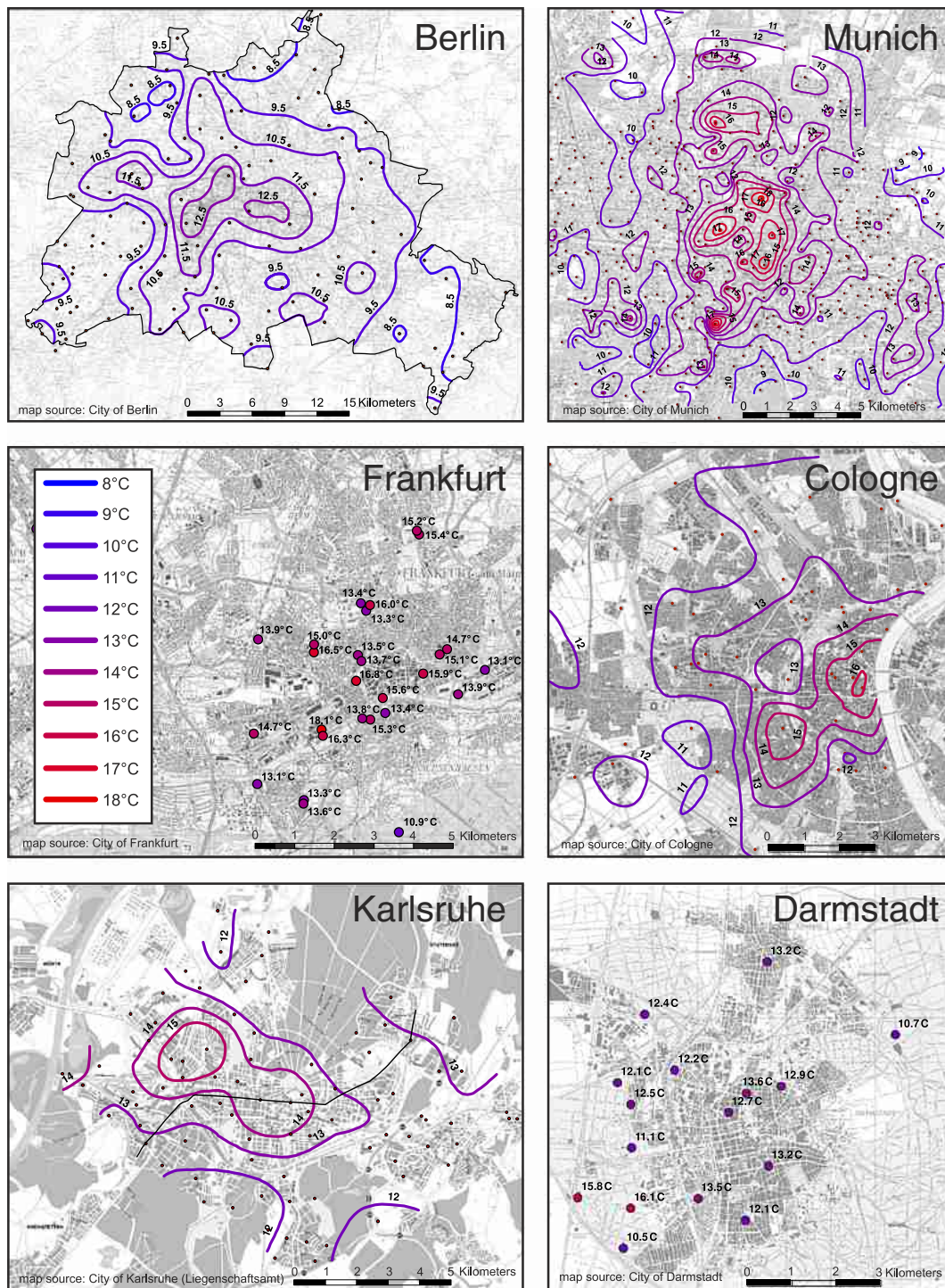


Fig. 3. Isotherm maps of groundwater temperatures (GWT) in the studied German cities, including locations of observation wells. The measurement depths in the individual cities are listed in Table 1. The black line on the map of Karlsruhe indicates the profile section in Fig. 5.

area of Zurich, and for the city of Basel by Epting and Huggenberger (2012). In the city of Karlsruhe, one shallow observation well next to the Rhine River is clearly influenced by the stream water, as it shows high GWT (Fig. 3), which follows a seasonal trend. In Munich, infiltration of stream water from the Isar River takes place in some shallow parts of the aquifer. As influences of cold and warm water infiltration throughout the year counteract with each other, only a minor effect on the annual mean GWT can be seen. In the other cities no such effects could be observed, because large-scale infiltrating streams do not exist

(Darmstadt, Berlin) and/or because measurements are not in adequate distance of the river.

Another potential heat source in the urban subsurface is the subway system. Ampofo et al. (2004) monitored tunnel and station temperatures in London, which were higher than ambient temperatures by several degrees. In addition, they calculated the heat loss from the subway train system in London and concluded that only 70% of the heat is dissipated by the ventilation. The rest is conducted to the subsurface. Four of the studied cities have differently constructed subway systems (Fig. 4), so it

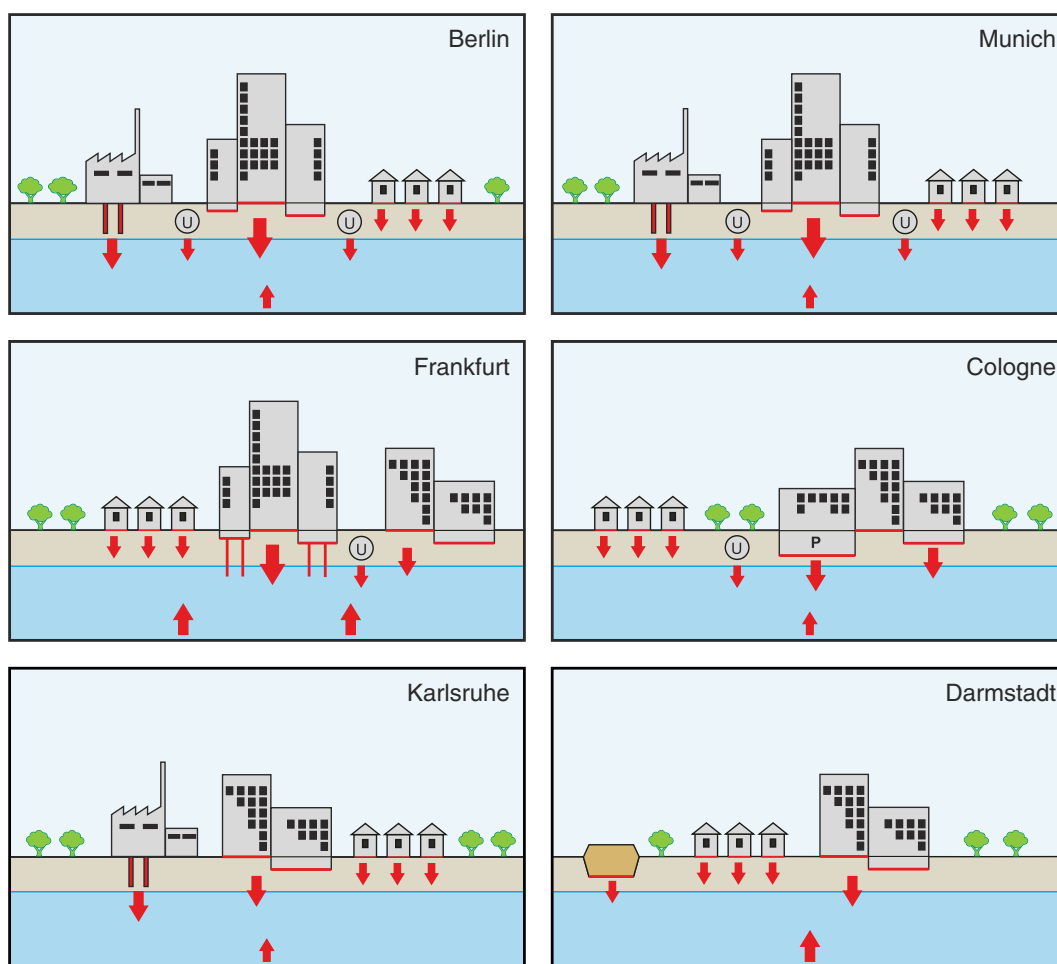


Fig. 4. Schematic drawing of the identified dominant anthropogenic and natural heat sources in the subsurface of the studied German cities. The thicknesses of the arrows indicate the strength of the heat source.

is most likely that some part of the heat in the subsurface of these cities emerges from the subway systems. A considerable influence of the subway system on the GWT was found in Munich by [Dohr \(1989\)](#), who measured GWT along the tunnels during the construction works of the subway system. However, due to the coarser distribution of measured wells in this study, we were not able to localize effects of the subway system on GWT.

The same applies to other anthropogenic structures in the subsurface, such as high-voltage cables, district heating networks and sewage systems. Although high-voltage cables and the pipes of the district-heating network are usually insulated, there is still a certain loss of energy in the form of heat from these networks ([Rink, pers. comm.](#)), which is conducted into the subsurface. The average temperature of the domestic wastewater circulating in the sewage system is likely to be higher than the ambient subsurface temperature. This also stimulates conductive heat loss from the sewage system. [Hoetzel and Makurat \(1981\)](#) calculated a mixing temperature of wastewater for the entire sewage system, including domestic and industrial wastewater, of 20 °C for the city of Karlsruhe. Even if the heat loss from these linear structures might be minor, these heat sources are omnipresent in the urban subsurface and therefore might contribute to the UHI effect. However, their local effect on the GWT is difficult to detect.

A very special anthropogenic heat source, which influences the local GWT, was identified in the city of Darmstadt. The high temperatures in the southwest, outside the city, are measured in wells close to a landfill site ([Fig. 3](#)). Exothermic degradation processes can lead to a warming of landfill bodies of up to 60 °C ([Krümpelbeck, 2000](#)) and thus to a warming

of the surrounding subsurface. Another example for a very local, but nevertheless quite significant heat source was found in Frankfurt, where measurements in an observation well showed temperatures of nearly 20 °C, which were first thought to be caused by upwelling thermal water. Rapidly decreasing temperatures with increasing depth revealed a different heat source. The observation well is located down gradient to a heated public swimming pool, which was not insulated at the bottom. More common heat sources that cause local GWT to rise extremely are power plants. In the city of Frankfurt, several shallow observation wells revealed $GWT > 30$ °C in depths between 6 and 20 m. All wells are located in the down-gradient vicinity of a coal-burning power plant.

Finally, we examined the influence of elevated SAT in urban areas on the GWT by comparing both temperatures in Karlsruhe and Berlin. In Karlsruhe, the comparison is made along a cross section through the city ([Figs. 3, 5](#)). The SAT was measured on a tram on over 2000 trips along the line in the year 2011 ([Rinke et al., 2010](#)). The mean annual SAT in the inner-city center in Karlsruhe is about 1 K higher than in the suburbs and 1.8 K higher than in the rural areas. The maximum annual GWT along this line is at the same location, yet the GWT are continuously 3–4 K higher than the SAT. The dots in [Fig. 5](#) represent the wells in the vicinity to the profile section, from which the interpolated GWT was calculated. Despite being measured at similar depths between 9 and 12 m below the surface, they show very dissimilar magnitudes of seasonal temperature variability, which cannot be explained only by the variation of measurement depth. The composition of the sedimentary deposits and the groundwater level also show only minor variations along the profile section. Thus, it can be assumed that local factors and infrastructure in

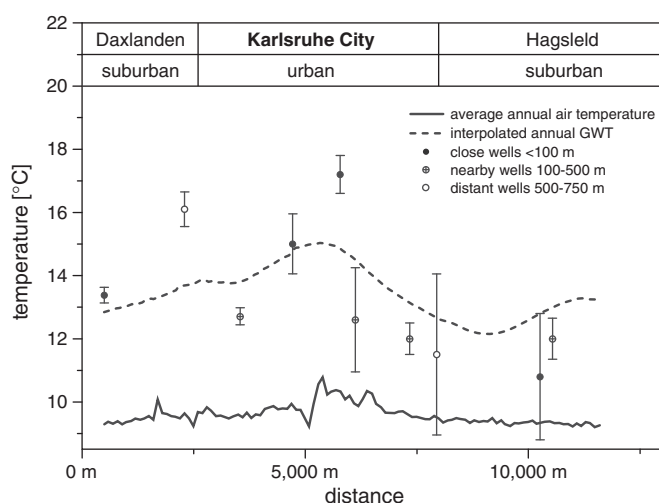


Fig. 5. Relationship between the mean annual SAT and annual GWT along a profile section through the city center of Karlsruhe and two suburbs. The error bars indicate the annual variation of GWT. The origin of the profile lies in the Southwest of Karlsruhe and the end point in the Northeast of the city (Fig. 3).

the urban environment additionally influence the local heat flux into the subsurface.

3.3. Correlation between influencing factors and subsurface urban heat islands

Spatial correlation of GWT and population density is quantified by correlation coefficients for the studied cities (Table 2). When calculated for the whole city area, the coefficients, γ , indicate only small correlations for the larger cities and no correlation for the small city of Karlsruhe. Apparently, population density only is not a good proxy for elevated GWT. Locally specific heat sources dominate the GWT distribution and several elements in the urban environment cannot be captured. Commercial and industrial areas, for instance, only share naturally low population densities, but often exhibit high GWT stimulated by heat loss from buildings, basements, deep parking lots, focused reinjection of thermal wastewater, etc. Furthermore, population density here is given as average value for city districts, that is, at much less resolution than the interpolated thermal conditions. Local features can therefore hardly be correlated, such as inner-city green spaces with typically low temperature, which are in central districts with high population density.

In a modified correlation analysis, such areas were clipped out of the raster dataset containing the GWT and population density (Table 2). The resulting partial correlation coefficients, γ' , are considerably higher. Significant correlations between 0.6 and 0.8 can be found in the cities of Berlin, Munich and Cologne. Depending on the city the excluded area accounts for 10–16% of the whole area. However, the correlation analysis is constrained by the relative spatial resolution of the given population density data. This particularly affects the results for smaller cities,

Table 2

Pearson's correlation coefficients γ with an uncertainty of 5% between groundwater temperature and population density (spatially defined for the city districts) for the studied German cities.

| City | Correlation between GWT and population density | | | Ratio between district area/city area |
|-----------|--|--|-----------------------------|---------------------------------------|
| | γ total area | γ' without parks and industrial areas | Excluded area [γ'] | |
| Berlin | 0.60 ± 0.005 | 0.76 ± 0.005 | 12% | 0.01 |
| Munich | 0.54 ± 0.01 | 0.63 ± 0.005 | 10% | 0.01 |
| Cologne | 0.61 ± 0.01 | 0.72 ± 0.005 | 16% | 0.01 |
| Karlsruhe | 0.33 ± 0.005 | 0.52 ± 0.01 | 14% | 0.03 |

such as Karlsruhe, with only a few districts. This is listed in Table 2 by the ratio between the individual district areas and the whole city area.

In Berlin spatially resolved SAT data is available from the Urban and Environmental Information System (ISU) of the Senate Department for Urban Development and the Environment (SenStadtUm, 2012) as annual mean from 1961 to 1990. For this period, SAT data from multiple observation stations is extrapolated to the whole area of Berlin and compared to local land use in Fig. 6. In the rural areas, SAT and GWT are comparable. In some rural places, GWT is up to 0.5–1 K higher than SAT due to the difference in thermal diffusivity of air and ground materials, as well as a consequence of meteorological effects (e.g. snow cover and solar irradiation) (e.g. Putnam and Chapman, 1996; Smerdon et al., 2006; Taylor and Stefan, 2009). Both mean GWT and SAT are the highest in the city center of Berlin, but the maximum GWT is higher than the maximum SAT. The annual SAT covers a range of about 3 K for the area of Berlin; in contrast, the GWT varies by about 4 K. Thus, as observed for Karlsruhe in Fig. 5, the UHI in the subsurface is more pronounced than the UHI of annual mean SAT in the atmosphere. A spatial comparison of both temperature datasets for the whole Berlin area yields a correlation coefficient of 0.71. This correlation suggests that there is a close link between the SAT and GWT development in urban areas. Similar conclusions were drawn for several large Asian cities such as Tokyo, Osaka, Seoul and Bangkok by Taniguchi et al. (2007).

Fig. 7 shows the cumulative GWT distribution over the investigated area for those four studied cities, where a 2-dimensional interpolation of GWT data was possible (Fig. 3). The difference between the 90%- and 10%-quantiles yields the following values for the $UHII_{10-90}$: Berlin 2.4 K, Munich, 2.4 K, Cologne 2.1 K and Karlsruhe 1.9 K. Though the number of investigated cities is rather small, a certain tendency in the subsurface UHI is obvious. Elevation of GWT increases with both population and average population density (Table 1). Berlin and Munich provide the same subsurface UHI, as Berlin has the larger population and Munich the higher population density. As discussed above, both parameters have a strong influence on the alteration of GWT.

Examination of the form of the cumulative temperature curves in Fig. 7 confirms that the interval between the 90%- and 10%-quantiles demarcates a mostly linear section of the curves. Extremely positive or negative local GWT anomalies in the investigated areas control the neglected marginal upward and downward parts. The $UHII_{10-90}$ accordingly reveals to be an appropriate indicator of regional subsurface UHI. It is less biased by the spatial resolution and accuracy of the measured and interpolated temperatures than that of measured extremes. This becomes obvious by the temperatures peaks (i.e. denoting $UHII_{100}$) of the individual graphs in Fig. 7. The cumulative GWT curve for Berlin follows a rather constant rise, whereas a sharp peak for high GWT characterizes the conditions of Munich. In Munich, an average number of 1.8 wells/km² was available, in Berlin only 0.1 wells/km² was inspected.

To enable a comparison to the atmospheric UHI values, the annual urban and rural SAT (from meteorological observatories) are also displayed in Fig. 7. As explained above, comparability between the UHIs is restricted due to the different calculation procedures. However, comparison shows that GWT are almost always higher than SAT. Atmospheric annual mean UHI from the single SAT values are 0.4–1.8 K and thus substantially smaller than subsurface UHI with 1.9–2.4 K. Both observations are already apparent in Figs. 5 and 6 for the cities Karlsruhe and Berlin.

4. Conclusions

We examined the shallow groundwater temperatures (GWT) under six German cities and found pronounced positive temperature anomalies. The regional differences in GWT between urban and rural areas range from 3 to 7 K. Shallow GWT in rural areas correspond to the annual SAT, which causes the GWT in Cologne, Karlsruhe and Darmstadt to be generally higher than in Berlin or Munich. The maximum temperature elevation in large cities, such as Berlin, Munich, and Cologne, is

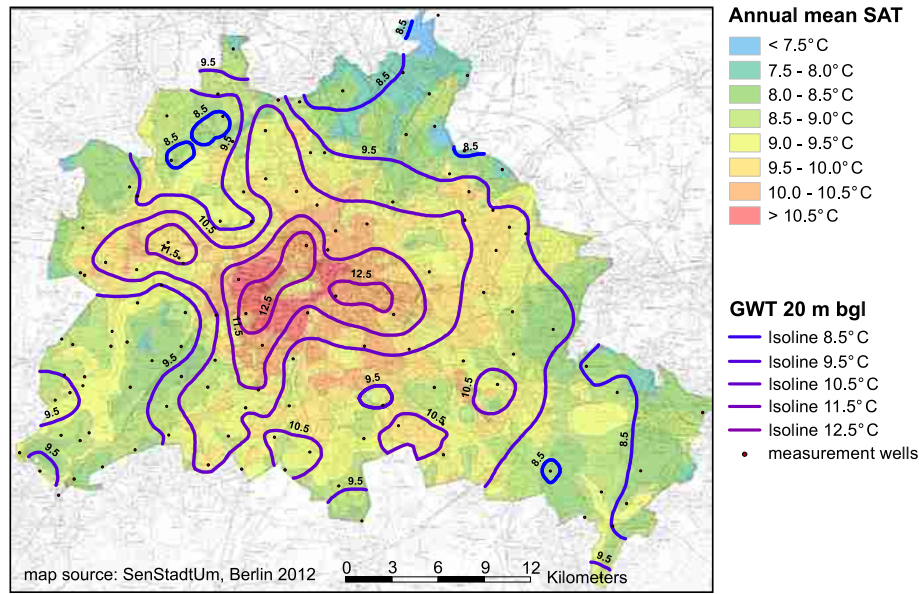


Fig. 6. Comparison of the annual mean SAT (1961–1990) and the GWT 20 m below surface in Berlin. The method of SAT data acquisition is described in detail by [SenStadtUm \(2012\)](#). Data source for the annual mean SAT is the Urban and Environmental Information System (ISU) of the Senate Department for Urban Development and the Environment, Berlin.

typically close to or in the city center. In Karlsruhe and Darmstadt, the highest GWT were found in industrial areas and close to landfill sites, respectively. The temperature distribution under the urban areas is generally rather heterogeneous. Especially in Munich due to the shallow measurement depth and the high density of observed wells, the isotherm map reveals plenty of local hot spots. Accordingly, the heat input into the urban subsurface is likely to be controlled by many local and

site-specific parameters. At the same time, it is difficult to differentiate between the individual heat sources causing the warming of GWT found at local measurement wells.

A spatial comparison of SAT and GWT in Karlsruhe and Berlin showed that both parameters are closely linked, and similar processes control the evolution above and below ground surface. As higher GWT occur in more densely built-up areas, one can suspect that buildings/basements and

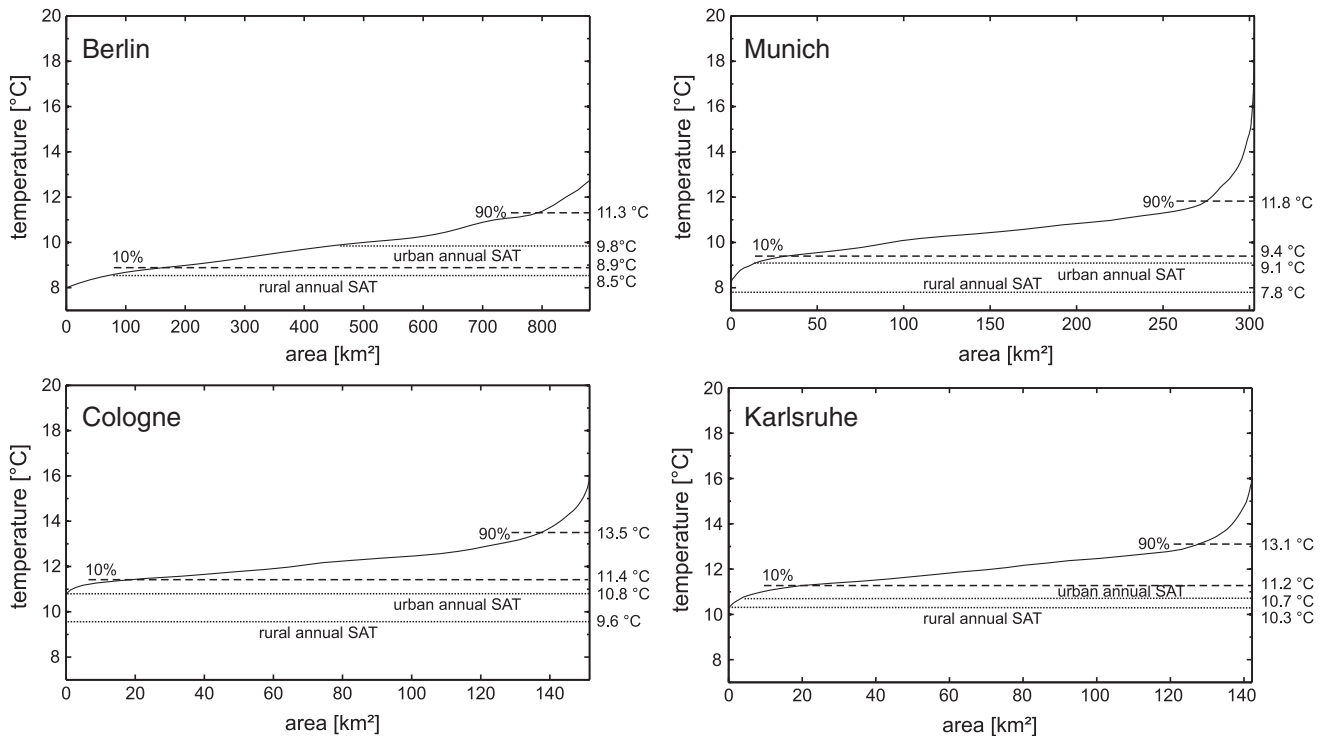


Fig. 7. Cumulative groundwater temperature curves over the investigated area for four studied cities. The investigated area is delimited by the distribution of the observation wells in [Fig. 3](#). In each graph, the 10%- and 90%-quantiles for the temperature distribution are displayed as dashed lines. The dotted lines represent the rural and urban mean annual SAT, respectively.

increased GST act as dominant heat sources. These heat sources also affect a large part of the urban area. For the subsurface, additional factors, such as sewage networks, high-voltage cables and district heating networks might also be important. Other heat sources such as reinjections of thermal wastewater affect the GWT only very locally, but often causing local temperature anomalies of high magnitude. In summary, it can be stated that the superposition of various heat sources results in an extensive groundwater temperature increase by several degrees in the long-term.

In order to evaluate the regional magnitude of urban GWT warming, we developed an inner-quantile based method to calculate the subsurface urban heat island intensity, $UHII_{10-90}$. The values of the subsurface $UHII$ cover a range from 1.9 to 2.4 K, with an increasing trend that depends on city population and average population density. In comparison to the atmospheric $UHII$, warming of the subsurface is more pronounced. This finding is also supported by the spatial comparison of SAT and GWT in Karlsruhe and Berlin. Furthermore, the shown spatial correlation between the GWT and the population density supports the hypothesis of increased GST, buildings/basements and subsurface infrastructure as important urban heat sources. Their individual roles and long-term heat contribution, however, appear to be controlled by many site-specific aspects, and can therefore only be quantified by a more detailed case study.

Acknowledgments

The financial support for Kathrin Menberg from the Scholarship Programme of the German Federal Environmental Foundation (DBU) is gratefully acknowledged. Peter Bayer was supported by the EU FP7 ECO-GHP project. Furthermore, we would like to thank Susanne Reimer (Public Works Service Karlsruhe), Annette März (Environmental Service, City of Karlsruhe), Alexander Limberg and Thomas Schneider (Senate Department for Urban Development and the Environment, Berlin), Andreas Henning (Henning Umwelt) and Folker Dohr (Environmental Department, Munich) for the valuable support with data and additional information. For the preparation of the AERO-TRAM data we would like to thank Rayk Rinke and Christoph Kottmeier (Institute for Meteorology and Climate Research IMK-TRO, KIT). Special thanks are also given to Axel Schaffitel for the help with the data management and field work and to Ke Zhu (University of Tübingen) for the inspiring discussions. We also thank the two anonymous reviewers for their comments.

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