# 02.14 Groundwater Temperature 2020

## Introduction

The groundwater temperature in the Berlin metropolitan area has been permanently influenced by humans.

Temperature measurements of the near-surface groundwater in the State of Berlin reveal that the average temperature has increased by more than 5°C compared to the more sparsely populated surrounding areas of the city. Furthermore, the measurements indicate that this rise in temperature has become increasingly apparent also at depths greater than 20 m.

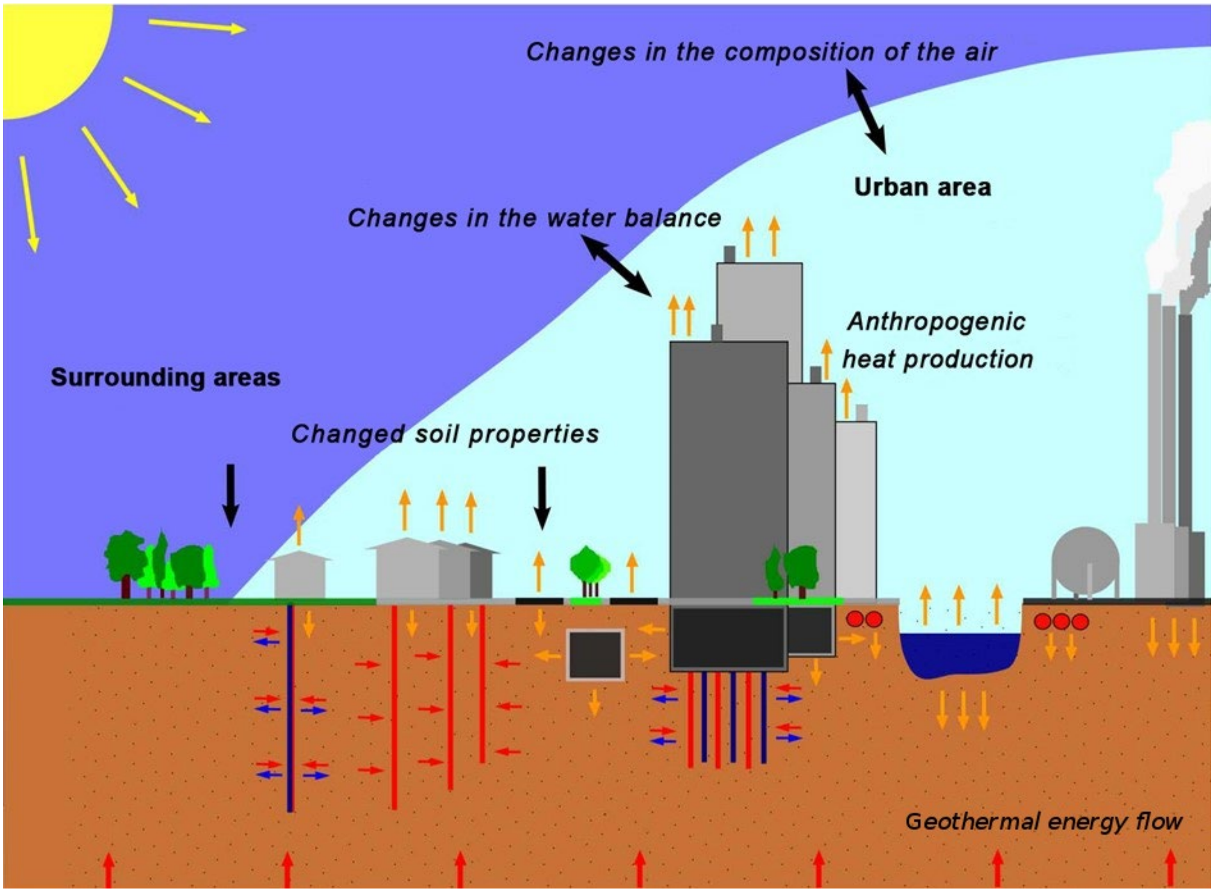



*Fig. 1: Schematic diagram of factors affecting the groundwater temperature (SenUVK 2021)*

There are many causes for this rise in temperature, which are directly related to the progressing building development, how humans utilise the surface of the earth and the effects of climate change. It may be distinguished between direct and indirect influences on groundwater temperatures (cf. Figure 1):

- **Direct influences** on groundwater temperatures include all heat inputs into the groundwater through the sewage network, district heating pipelines, power lines and underground structures, such as tunnels and underground railway systems, underground car parks, etc. They also include heat inputs associated with the thermal use and storage of groundwater heat.
- **Indirect influences** on groundwater temperatures include processes that are part of urbanisation and are associated with changes in the heat balance of the atmosphere near the ground. According to GROSS (1991), important variables are:
  - The disturbance of the water balance due to a high degree of impervious soil coverage
  - The change in thermal surface characteristics, such as surface thermal conductivity and heat capacity due to impervious surfaces and a high density of building structures

- Changes in the energy budget due to changes in the atmospheric composition
- Anthropogenic heat generation (domestic heating, industry and transport).

Compared with the areas surrounding the city, these influencing variables cause changes in the heat balance.

The heat in the city increases gradually; it stores more heat in general, slowly releasing it back into its surroundings. The city may therefore be regarded as a massive heat storage unit. In the long run, this process leads to an increase in the annual mean air temperatures (cf. Map of long-term mean air temperatures 1981-2010, Map 04.02).

This long-term warming also affects the near-surface groundwater. The physical properties and the chemical and biological nature of the groundwater are temperature-dependent. Increasing temperatures may lead to a deterioration in groundwater quality and an impairment of groundwater fauna.

Berlin's drinking water is supplied by groundwater, which is extracted almost exclusively from the State of Berlin. The groundwater also supplies a large share of the water for industrial use. Therefore, it is of utmost importance to protect the groundwater from fundamental change, such as substantial increases or decreases in groundwater temperature – especially against the backdrop of sustainable water management.

Since 1978, **temperature depth profiles** have increasingly been recorded at deep groundwater measurement points and temperature measurement points distributed throughout the State of Berlin, in order to ascertain and observe changes.

The purpose of the present map is:

- To update the existing documentation on how the groundwater temperature changes over time beneath the municipal area,
- To serve as a basis for authorising measures which may cause changes in the groundwater temperature, and
- To provide input data for planning and designing facilities for the use of geothermal energy.

In combination with other relevant maps, such as the Geological Outline Map (Map 01.17), the Groundwater Levels Map (Map 02.12), or the Geothermal Potential Map (Map 02.18), the present map may also be used during decision-making and preliminary planning processes for the energy management of groundwater. Underground temperature as a parameter plays an important role in the design of ground heat exchangers.

### Groundwater Temperature and the Annual Temperature Curve

The main heat source for the near-surface subsoil, down to a depth of approx. 20 m, is the solar irradiance that hits the earth's surface. It has a great impact on the surface temperature.

The near-surface soil is heated by irradiated solar energy, which releases the heat into the atmosphere and the subsoil. The annual total of the proportion of solar irradiance that falls onto a horizontal surface, the global irradiance, amounts to approx. 1,000 kWh per sq. m and year in the State of Berlin. There are many parameters that influence the local thermal climate, where the surface of the earth meets the air. Colour, composition, surface roughness, degree of impervious soil coverage, the water balance and the angle at which the solar irradiation falls upon urban surfaces determine how much energy is absorbed and "stored" in building structures, and how much of it is released into the atmosphere or the subsoil.

Generally, temperatures at the surface of the earth, and therefore also the heat input or output, are subject to the periodic fluctuations of a cycle of a year, as the seasons progress.

The surface temperature penetrates the subsoil with decreasing intensity. The penetration depth and speed at which the heat is transported depend on the thermal conductivity of the subsoil among other things.

**Heat transfer** in the subsoil may be either conductive or convective.

While convective heat transfer involves conducting heat through matter, such as groundwater or seepage water, conductive heat transfer involves transporting energy through the rock without the movement of matter.

Solar irradiance is the main source of heat near the surface. The **geothermal energy flow**, directed from the earth's interior to the surface, originates from the decay of radioactive isotopes in the subsoil. In contrast to solar irradiance, it is only of secondary importance.

Heat flux density, which is defined as the rate of heat flow per unit of area perpendicular to the standard area, varies regionally in the continental crust of the earth. According to HURTIG & OELSNER (1979), and HONARMAND & VÖLKER (1999), the mean heat flux density ranges from approx. 80 to 90 mW/sq. m in the State of Berlin. The annual energy total thus ranges between 0.7 and 0.8 kWh per sq. m and year, which is approx. 1/1,000 below that of the global irradiance.

The near-surface groundwater temperature is essentially determined by the energy exchange between the sun, the earth's surface and the atmosphere, and to a much lesser degree by the heat flow moving from the earth's interior towards the surface.

Berlin's long-term mean air temperatures recorded between 1981 and 2010 range between 9.3°C and 10.4°C, depending on the exact location (SENSTADTWOHN (2021)).

While daily fluctuations affect the soil only to a depth of approx. 1 m, seasonal fluctuations reach depths of between 15 and of 20 m. Below this depth, where seasonal effects can no longer be detected, i.e. in the "neutral zone", temperatures rise depending on the thermal conductivity of the rock and the regional heat flux density (Fig. 2).

Down to a depth of approx. 300 m, the average rise in temperature ranges between 2.5°C and 3°C per 100 m in the Berlin area.

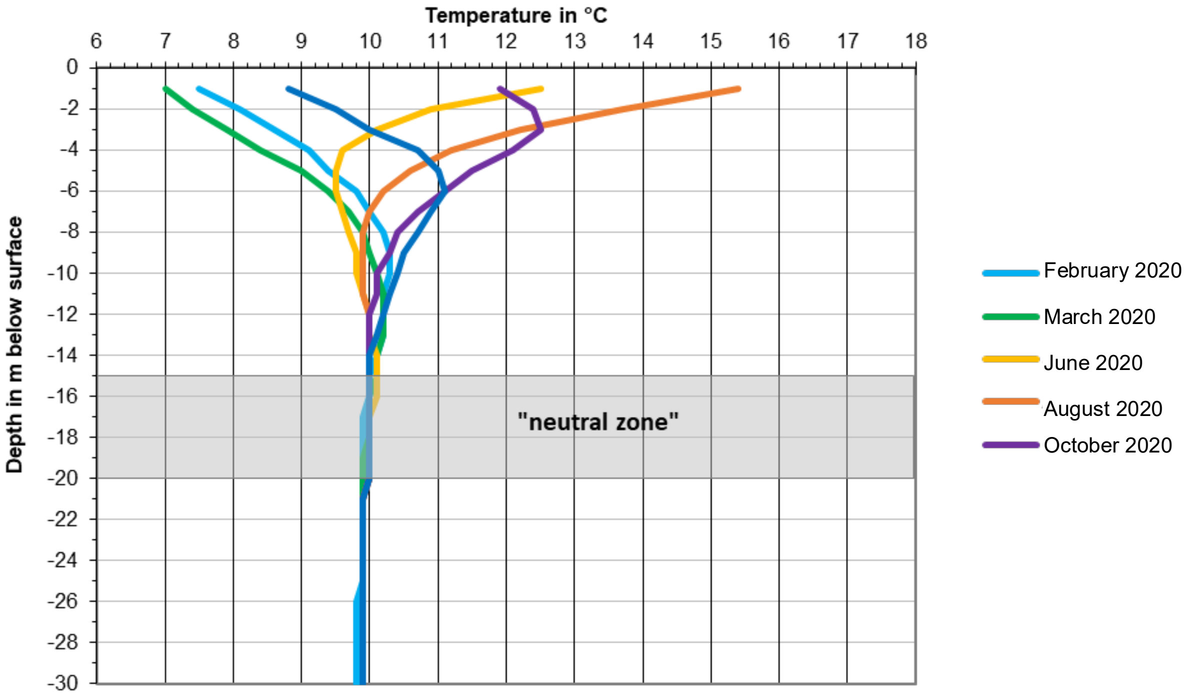



*Fig. 2: Seasonal temperature curves in the subsoil at temperature measurement point 70006 in Schmöckwitz, Schmöckwitzer Damm (SenUVK2021)*

## Surface Structure and Groundwater Situation

The Warsaw-Berlin glacial spillway, running roughly from east to west, separates the Barnim Plateau in the north from the Teltow Plateau and the Nauen Plate in the south of the city (Fig. 3). The terrain elevation of the glacial spillway ranges between 30 and 40 m above sea level, while the plateaus have an average elevation of 40 to 60 m above sea level. Individual peaks rise to 100 meters above sea level and higher.

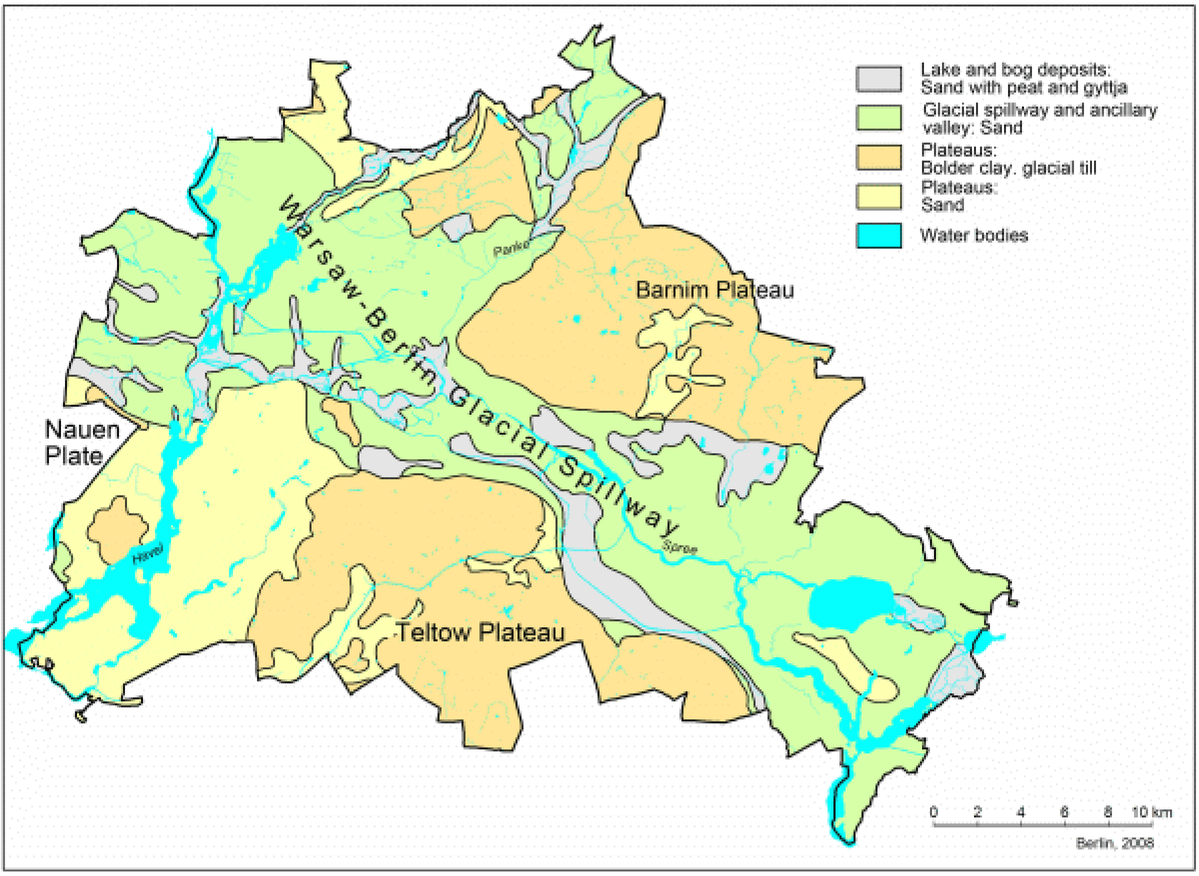



*Fig. 3: Geological Outline of Berlin (SenUVK 2021)*

In Berlin, the porous space of the predominantly sandy and gravelly sediments located 150-200 m below surface is completely saturated with groundwater, which extends almost to the terrain surface. It is used for the city's drinking water supply. The depth to groundwater (depth to the water table) fluctuates, depending on the morphology and geology, between 0 m and a few metres in the glacial spillway, and between 5 to over 30 m on the plateaus (cf. Depth to the Water Table, Map 02.07).

**Groundwater removal** for the extraction of drinking and industrial water has led to the formation of depression cones in the groundwater surface. This increases the natural depth to the water table and the groundwater's flow velocity, as well as its natural flow direction. Influent conditions therefore developed in areas in which well galleries extract groundwater near rivers and lakes. The surface water therefore infiltrates into the groundwater as bank filtrate. Combined heat and power plants frequently discharge cooling water into surface waters, which increases their temperature all year round (e.g. around the Spree). Due to infiltrating surface water, the temperature of the groundwater inevitably rises in the catchment area of the surface water.

## Settlement Structure and Climatic Conditions

The State of Berlin has a polycentric settlement structure characterised by the presence of two main centres, several smaller urban centres, and a dense arrangement of residential areas, green space and commercial and industrial areas. Larger commercial and industrial settlements are generally located along residential and development axes extending radially from the city centre towards the outskirts, and along the canalised surface waters.

Simplified, the following categories may be identified (cf. Fig. 4):

- Green and open spaces
- Built-up areas

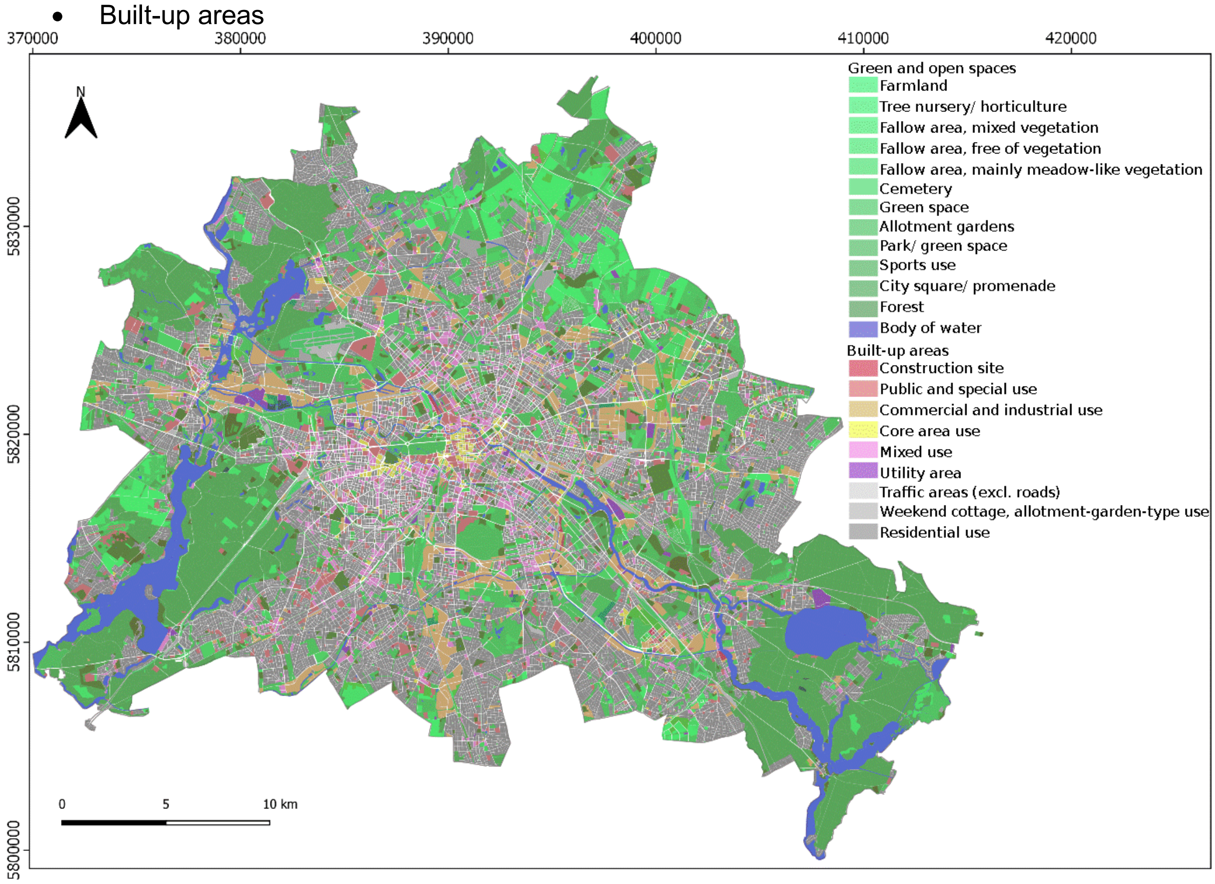



*Fig. 4: Representation of land use in Berlin from Matthée (2021), based on Map 06.01 Actual Use of Built-up Areas (Edition 2016).*

A look at the local climatic situation in Berlin primarily reveals the profound temperature changes in the structurally high-density city centre compared with the surrounding areas. The long-term mean air temperature recorded between 1981 and 2010 (cf. map Long-term Mean Air Temperature 1981 - 2010 Map 04.02) was thus 9.5 °C on the north-eastern outskirts of the city in Buch, whereas long-term means of up to 10.4 °C where measured in the inner-city area.

# Statistical Base

The present maps of groundwater temperature distribution are based on the evaluation of measurement data from the years 2015 to 2020, which was recorded at more than 200 measurement points in the State of Berlin. It should be noted that for measurement depths of more than 60 m below terrain surface, the number of available measurement points decreases considerably. In some parts of the city, there are relatively large areas where temperature measurements cannot be obtained from greater depths.

In addition to single measurements, temperatures have been measured at groundwater measurement points specifically designed for that purpose at regular intervals since February 2018. These measurement points consist of a full pipe without a filter, allowing it to be filled with water to just below terrain surface. This enables the observation of the seasonal temperature development even in the subsoil not saturated with water.

In areas without current measurement data from 2020, temperature measurements recorded between 2015 and 2019 were drawn upon. In these cases, the temperature data was adjusted to the 2020 measurements by area. As a rule, temperature profiles are recorded from the water table to the excavation depth with a measuring point spacing of 1 m.

Measurement error arising from calibration and measurement inaccuracy of the device or measurement inaccuracy of the measured object (e.g., due to heat convection at the measurement points) is estimated to be ±0.1°C.

# Methodology

The values measured between 2015 and 2019 were extrapolated by area. The adjustment factors were determined based on temperature changes emerging from long-term measurement series (2015-2020) at temperature measurement points. Figure 5 presents the mean temperature changes over 5 years, for all depths, categorised into green/ open spaces and built-up areas.

For the first 20 m below terrain surface, a temperature increase of 0.28 K (in 5 years) emerges for open and green spaces. The temperature change for built-up areas is slightly higher at 0.41 K (in 5 years), due to anthropogenic factors. For 40 m below terrain surface, the adjustment factor is lower at 0.16 K (in 5 years) for built-up areas and only 0.05 K (in 5 years) for green and open space. The latter is too small for the measurement device to detect. For this horizon, only values measured for built-up areas are therefore adjusted.

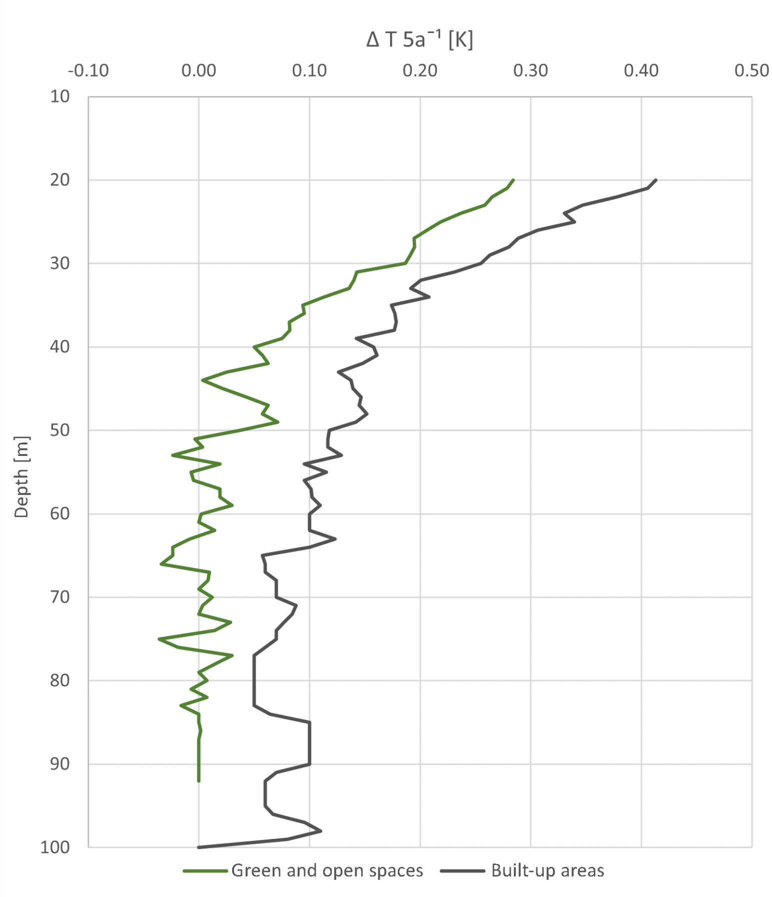



*Fig. 5: Comparison of the mean temperature change in five years, for green and open spaces and built-up areas, based on the measurement series from 2015 to 2020 (Matheé, H. K. (2021)).*

In order to obtain a comprehensive overview of the temperature distribution in the subsoil, an inverse distance weighted (IDW) interpolation was carried out subsequently. With the help of this deterministic interpolation method, surfaces are generated using measured points based on the degree of similarity. To be able to use this method, the variable of groundwater temperature needs to be regionalised, i.e., it should be dependent on its location. Neighbouring points of a regionalised variable, for example, are typically more similar to each other than they are to points that are further away.

In the case of temperature measurements, however, this is true only to a limited extent, as local climatic conditions near the ground influence the temperature distribution in the layers just below the surface and increasingly also in the deeper layers of the subsoil. In some cases, it has been observed that the temperature changes are confined to very small areas. Furthermore, it has been established that existing temperature measurement sites, especially those that access the deeper subsoil at depths of more than 50 m, are not evenly distributed across the State of Berlin. In some cases, measuring points that access the deeper layers are more than 5 km apart.

When developing the map, measurement points that were largely unaffected by the influence of local temperatures were therefore selected. This is especially important for urban developments, such as that of the State of Berlin, where the distribution of building structures varies greatly and where pervious green areas and highly impervious urban areas alternate often. The temperature distribution in the subsoil is more homogeneous in a rural environment, however, due to less variable surface conditions that impact on the local climate and therefore the near-surface temperature conditions in the subsoil. It should be noted that temperatures recorded by a measurement point in the urban area often reflect conditions within a radius of a few 10 to 100 metres of the measurement site. Potential small-scale temperature changes in the near-surface subsoil may therefore not be recorded, which may render temperature isolines rather inaccurate.

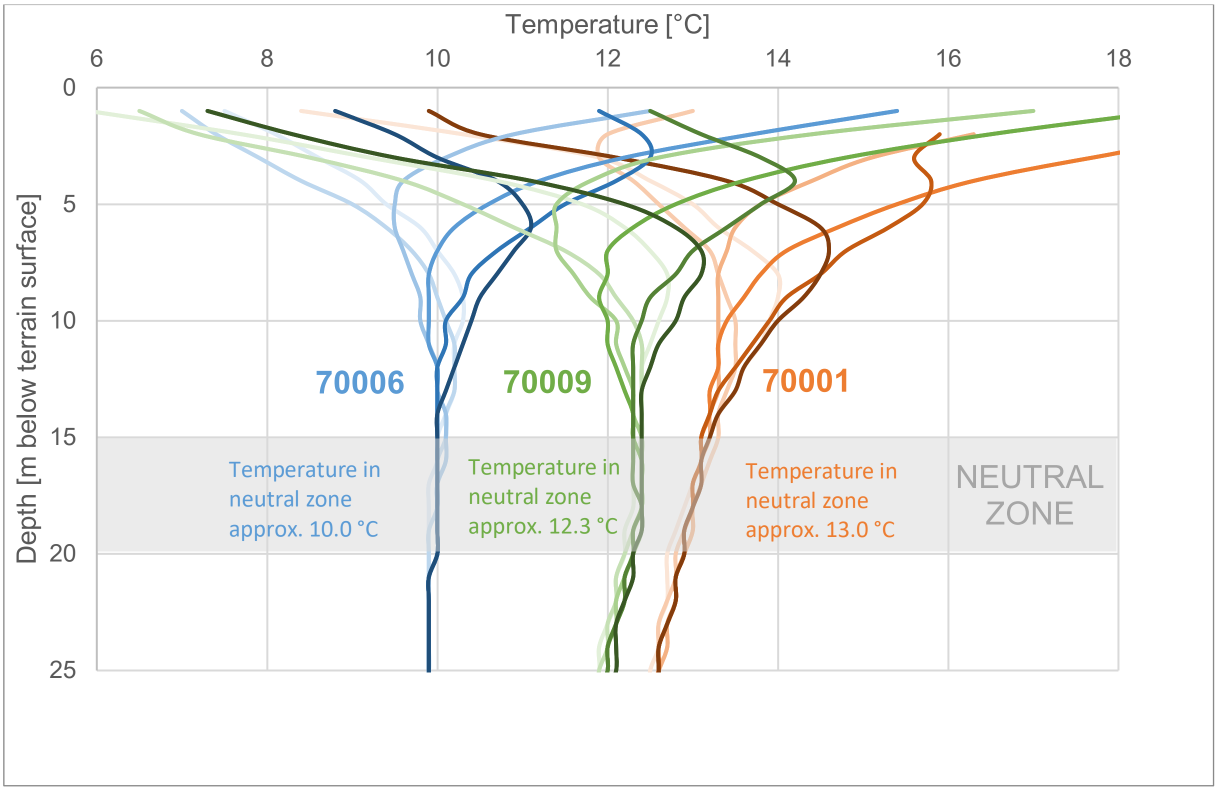
It is important to note that, due to the spacing of the measurement points, not all spatial structures at the surface and in the subsoil could be recorded, and thus taken into account in terms of their effect on temperature conditions. Measurement points that represent small-scale temperature anomalies were therefore largely removed before interpolation.

# Map Description

## Temperature Profiles

The penetration depth of the seasonal temperature fluctuations, and hence the depth of the neutral zone, is largely determined by geogenic factors. These include depth to the water table, the thermal conductivity and heat capacity of rocks, and the formation of new groundwater. In Berlin, the **neutral zone** is located at a depth of between approx. 15 and 20 m, depending on the conditions mentioned above (HENNING & LIMBERG, 2012).

Fig. 6 illustrates how temperatures develop over time in the first 25 m below terrain surface in the unsaturated zone and the groundwater-saturated zone for three temperature measurement points in different urban climatic zones. For each measurement point, 6 measurements are displayed from the year 2020. The colour intensity increases as the year progresses. The measurements are usually carried out in February, April, June, August, October and December. The depth to the water table ranges between 5 and 20 m, depending on the geomorphological position.

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| *Fig. 6:* | *Seasonal temperature fluctuations of the subsoil at three temperature measurement points (70001, 70006, 70009) in different urban climatic zones; the colour intensity increases as the year progresses (February, April, June, August, October and December) (SenUVK 2021).* |

Depending on the location of the groundwater measurement point, considerable differences can be seen in the observed temperatures, as well as in the temperature development at increasing depths below terrain surface. In the near-surface area (< 5 m depth), the **lowest subsoil temperatures** generally occur in spring (February to May), whereas **the highest** temperatures occur in autumn (September to October).

Table 1 compares characteristic values of temperature in a tabular overview, based on measurements recorded during the observation period from January 2020 to December 2020 (HENNING & LIMBERG; 2012) for the measurement points presented above.

| Site | Location in urban structure | Urban climatic zone | Min. temp. at 3 m depth | Max. temp. at 3 m depth | Temperature in the neutral zone |
|---|---|---|---|---|---|
| 70006 | Schmöckwitzer Damm, Treptow / Köpenick, outskirts; green and open spaces/ forest, less than 10% impervious soil coverage | **"very minor"** changes | 7.9°C | 12.5°C | approx. 10.0°C |
| 70009 | Poelchaustraße, Marzahn-Hellersdorf, residential areas, approx. 50% impervious surface | **"minor to medium"** changes | 8.5°C | 14.8°C | approx. 12.3°C |
| 70001 | Rügener Straße, Mitte, inner city, dense residential areas; over 60% impervious soil coverage | "**major**" changes | 11.9°C | 17.7°C | approx. 13.0°C |

*Tab. 1: Comparison of selected characteristic values of temperature, recorded at temperature measurement points in various types of urban areas in the year 2020*

Table 1 shows that with an increasing structural density, represented by "location in urban structure", the **groundwater temperatures in the neutral zone** generally also **increase** (cf. Fig. 6).

Based on the available temperature maps (cf. Table 2), a rough temperature range can be derived for different settlement areas and different points in time. It is evident that all areas have experienced a rise in temperature over the period studied.

| Areas | Temperature in the neutral zone (2020) | Temperature in the neutral zone 2015) | Temperature in the neutral zone (2010) |
|---|---|---|---|
| Outskirts, green and open spaces/ forest | < 11.5°C | < 10.5 °C | < 9.5 °C |
| Residential area (low to medium structural density) | 11.5°C - 12.5°C | 10.5 °C - 12.5 °C | 9.5 °C – 11.5 °C |
| City centre; commercial/industrial areas (city centre; high structural density) | 12.5°C - 15.9°C | 12.5 °C - 15.6 °C* | 11.5 °C – 13.7 °C* |

*maximum temperature measured 20 m below terrain surface

*Tab. 2: Temperature development in the neutral zone, depending on various structural densities*

The analysis of long-term investigations carried out at measurement points in the inner city indicates that **groundwater temperatures will** likely **be influenced** also **at greater depths** in the long run. Figure 7 illustrates this using the example of temperature profiles, which were recorded at a groundwater measurement point between 1984 and 2021.

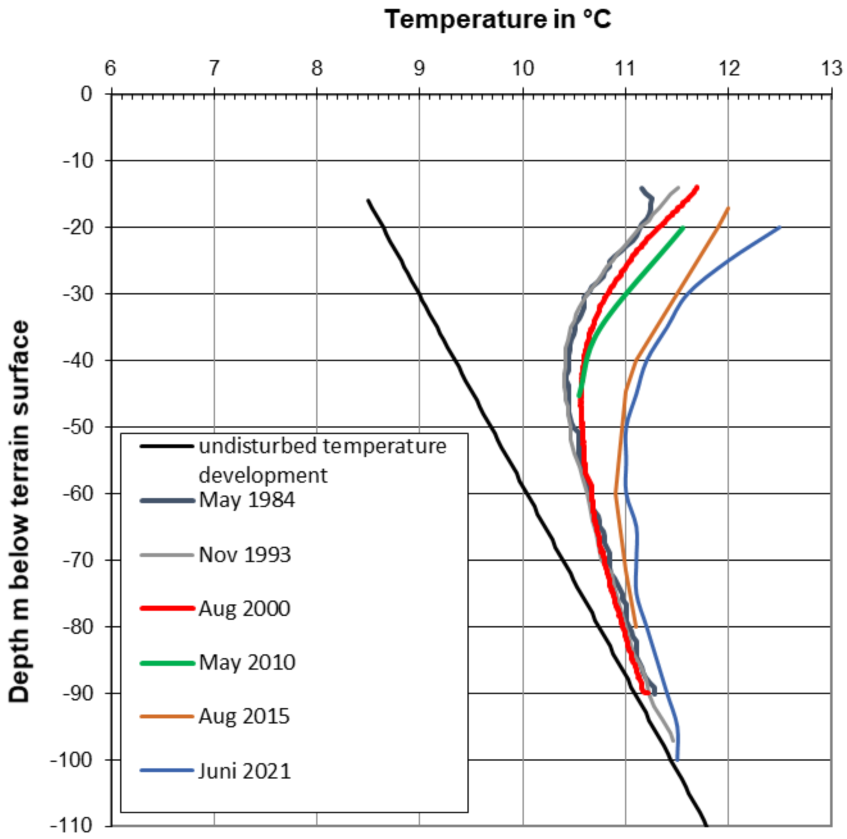


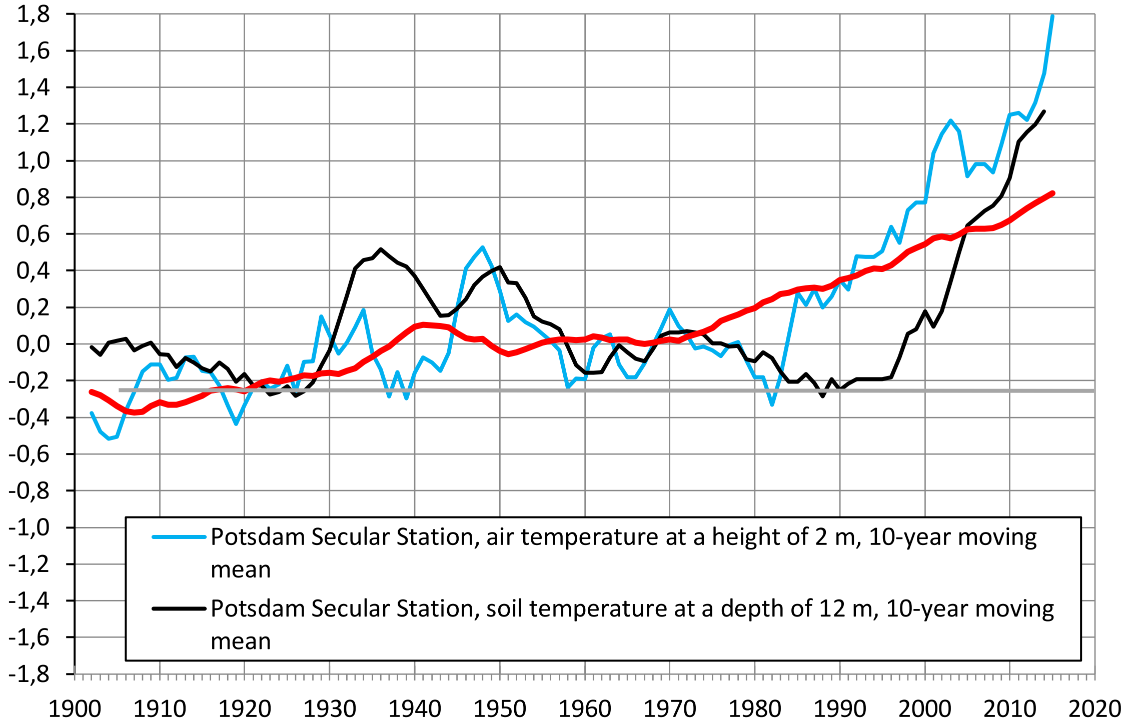

*Fig. 7: Results of a long-term temperature investigation at measurement point 7063 (Dieselstraße, in Neukölln) (SenUVK 2021).*

The temperature profiles recorded in 1984 and 1993 exhibit roughly the same temperature development from a depth of approx. 20 m. Subsequent measurements in 2000, 2010, 2015 and 2021 indicate an increase in near-surface temperatures, which decrease as depths increase.

Compared with the temperature development that is assumed to be “undisturbed”, there is a clear increase in the temperature of the subsoil down to a depth of about 70 m. At a depth of 40 m, there is a temperature difference of about 1 K compared to the 1993 measurement. This observed temperature increase may be attributed to a change in the local climate, presumably caused by a large residential development built in the immediate vicinity during the 1960s and 1970s. The “undisturbed” temperature development was derived theoretically based on the borehole profile, the mean heat flux density assumed for the site and the undisturbed annual mean surface temperature (HENNING ENERGIE- UND UMWELTBERATUNG (2010).

The measurements from 2015 and 2021 show a further increase in temperature. This temperature increase may be observed down to depths of around 80 m.

During this period, no major changes were observed in the vicinity of the measuring point, e.g., due to building development/ impervious soil coverage, which could have affected the local climate. Hence, it seems likely that this increase is connected to the effects of the global climate change.

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| *Fig.8:* | *Air and soil temperature fluctuations at a depth of 12 m at the Potsdam Secular Station, compared with the global temperature development for the period from 1901 to 2001 (SenUVK 2021)* |

Figure 8 reveals that, since the beginning of the 1980s, there has been a clear increase in air temperatures in the State of Berlin and its surrounding areas, as well as at a global level (red line). As a consequence of this temperature increase, about 0.5 K in 1995 and more than 0.8 K in 2010, the temperature balance in the near-surface subsoil is noticeably disrupted. This may also be observed at numerous measuring points below the neutral zone in the State of Berlin, an example of which is presented in Figure 9. In the period between 1984 and 2019, the soil temperature rose by approx. 1.4 K at a depth of 12 m in Potsdam (blue line). At groundwater measurement point 7063 (green line) in Berlin Neukölln, the temperature also rose by 1.4 K at a depth of 20 m in the reference period from 1984 to 2021. Soil temperature measurements at a depth of 12 m were discontinued at the Potsdam Secular Station in 2019.

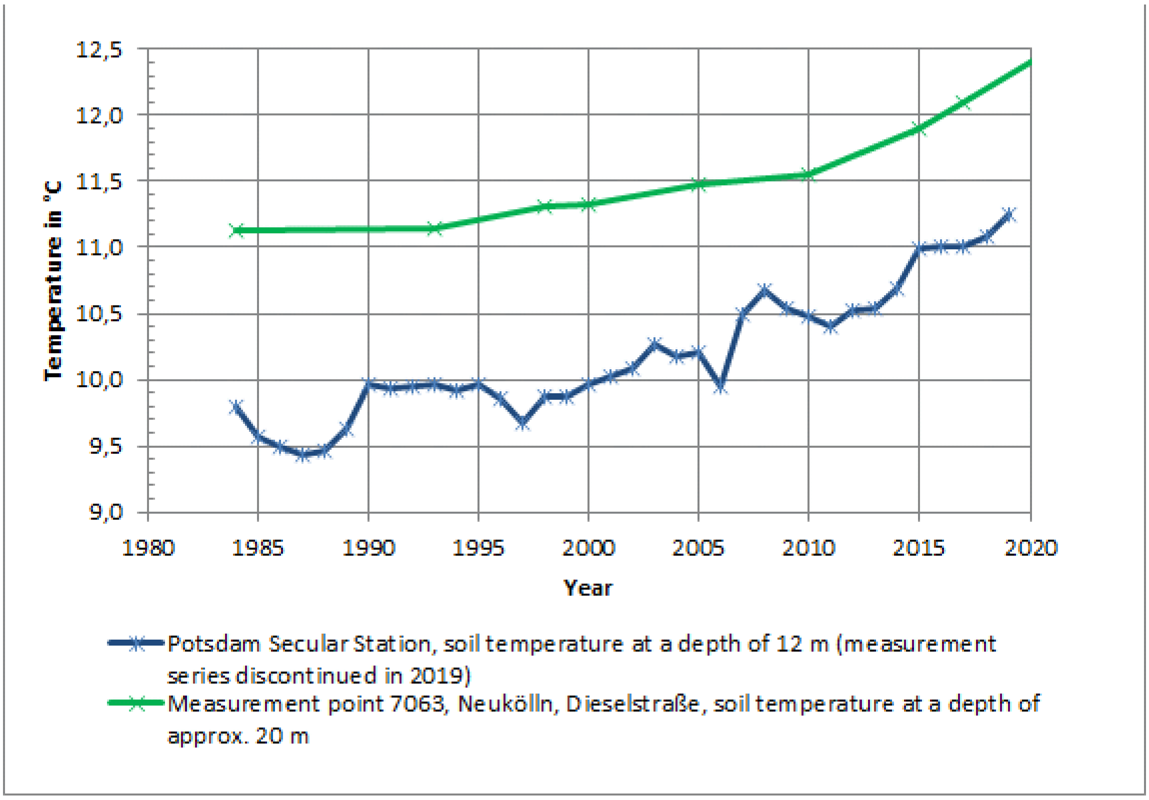


*Fig. 9: Soil temperature development at the Potsdam Secular Station at a depth of 12 m and at measurement point 7063 in the borough of Neukölln Dieselstraße, at a depth of 20 m, between 1984 and 2021 (SenUVK)*

## Map Descriptions

### General

The maps present the temperature distribution in the subsoil for five different depths, i.e. the reference horizons 20 m, 40 m, 60 m, 80 m and 100 m below terrain surface in the State of Berlin. They also show the average temperatures for depths from 0 m to 50 m and 0 m to 100 m. It should be noted that the isothermal lines may be rather inaccurate, depending on the density of the existing measuring points.

**The map information on temperature distribution should be used in cases where no representative temperature measurements are available for the site.** It should be noted that the results of a temperature measurement apply to the recorded depth profile only. Depending on the variability of the site characteristics, other conditions may well prevail only a few hundred metres away, which could lead to changes in the temperature of the subsoil. Without taking these changes into account, applying the data even to a site very close to the measurement point could seriously distort the assessments of temperature conditions. **In general, however, the maps presented may be used to obtain initial insight into the temperature conditions of a site and its potential use for geothermal energy.**

The influence of bank filtrate in the vicinity of multiple well galleries of the Belin waterworks (Berliner Wasserbetriebe) on the near-surface temperature field was found to be substantial. Due to seasonal temperature fluctuations of the surface waters, measuring points located between production wells and surface waters are particularly influenced. For this reason, these measurements were disregarded during map development.

### Temperatures 20 m below terrain surface

The current temperature distribution (measurements from 2020) shows considerable differences compared with the previous edition of the map from 2015 for the reference horizon 20 m below terrain surface (Map 02.14.1). This is due to the fact that a lot more measuring points, especially in the east of the city area, were used to determine the temperature distribution, among other things.

Generally, **temperatures tend to increase from the outskirts of the city towards the city centre**. In the north-east, the temperature development is characterised by a continuous temperature increase moving towards the city centre, while multiple smaller positive and negative temperature anomalies occur in the rest of the city.

A contour line of 12.5°C encircles the densely built-up city centre with its highly impervious surfaces 20 m below terrain surface (Map 02.14.1). The heat island located in the city centre has temperatures of more than 12.5°C and is interrupted by the Großer Tiergarten, a large green space in the centre of the city. Temperature anomalies exceeding temperatures of 14.5°C may be observed within this heat island.

Outside of the city centre, positive temperature anomalies also correlate with highly impervious areas, such as secondary centres and industrial areas.

Below the extensive woodlands in the south-eastern, northern and north-western outskirts of the city, as well as in the Grunewald area, temperatures are below 10.5 °C. Some temperature anomalies with less than 11.5°C occur in the urban area, such as the Britzer Garten, Tempelhofer Feld or Jungfernheide. These areas have a high proportion of vegetation. A reason for the number of negative temperature anomalies that have now been detected/ proven, in contrast to that of the previous map edition from 2015, is the higher density of measuring points. In general, the groundwater temperature in the densely populated inner-city area is more than 5 K higher than that of the surrounding areas.

**Temperatures 40 m, 60 m, 80 m and 100 m below terrain surface**

The other maps (02.14.3 – 02.14.6) show the groundwater temperature distribution for the reference horizons 40 m, 60 m, 80 m and 100 m below terrain surface in the State of Berlin. At these depths, daily and seasonal fluctuations can be ruled out. However, long-lasting and, for example, anthropogenic changes in temperature, that may have been caused by changes in building development or the climate, may manifest themselves at these depths.

Such temperature anomalies can be observed particularly in the inner-city areas in the borough of Mitte, but also at the southern edge of the city, in Berlin Lichterfelde along the Teltowkanal, with a history of construction use and intensive industrial use (groundwater temperature distribution for the reference horizons of 80 m and 100 m).

Other temperature anomalies, such as those in the south-west of Berlin on the border with Potsdam, in the northern portion of the Grunewald forest, in the area of the natural gas storage area, and in Lübars, on the northern border of Berlin, are linked to geological structures in the deeper subsoil. These temperature anomalies are assumed to be connected to the salt dome structures in the deep subsoil that exist in the Berlin area.

The presented temperature distributions in the deeper subsoil at more than 80 m below terrain surface, e.g. in the boroughs of Lichtenberg, Marzahn and Hellersdorf in the east of Berlin, may be rather inaccurate, due to the small number of measurements available.

**Average temperature 20 m to 100 m below terrain surface**

In addition to the groundwater temperature distribution maps covering the different reference horizons, another map was developed focussing on average temperatures at depths between 20 m and 100 m. This map may also be used as a tool in the design of geothermal plants.

The map reveals that the densely built-up inner-city area in particular exhibits average temperatures of more than 11 °C. The average temperature is approx. 10 °C in the outer boroughs, and approx. 9°C in the non-built-up periphery.

In the context of this map, it should be noted that the average temperatures presented may deviate to a small extent, due to local climatic conditions and the density of measurement points. For example, the average temperature may be lower in areas with a lot of vegetation, whereas it may be higher in areas that are largely impervious.

**Summary**

In summary, it was found that the groundwater temperature may more than 5 K higher in the densely populated inner-city area compared to the non-built-up surrounding areas. There is a clear connection between groundwater temperatures and the urban climatic conditions above ground. Regular measurement results at temperature measuring points, which are located in areas with different urban structures, prove this further.

In general, the groundwater temperature distribution near the surface is directly related to the land use in the State of Berlin. The influence of industrial settlements, larger buildings, waste heat producers, impervious soil coverage, and anthropogenically heated surface waters is clearly reflected in the temperature distributions. These aspects have a major influence on the temperature change in the subsoil. It was also demonstrated that green spaces cause negative temperature anomalies in the subsoil, which then contribute to lowering the temperature of the subsoil and to counteracting further temperature rises.

The results of long-term studies indicate that, based on the progressing building development and the global climate change, it seems inevitable that the temperature of the subsoil near the surface as well as the groundwater will continue to rise substantially.

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