02.14 Groundwater Temperature (Edition 2011)

Overview

The groundwater temperature in the Berlin metropolitan area is significantly anthropogenically influenced.

The temperature measurements carried out since the 1980s for the near surface groundwater of the State of Berlin show that the average temperature has increased more than 4 °C over the thinly populated surroundings outside the city. They also indicate that this temperature is increasingly apparent even at depths greater than 20 m.

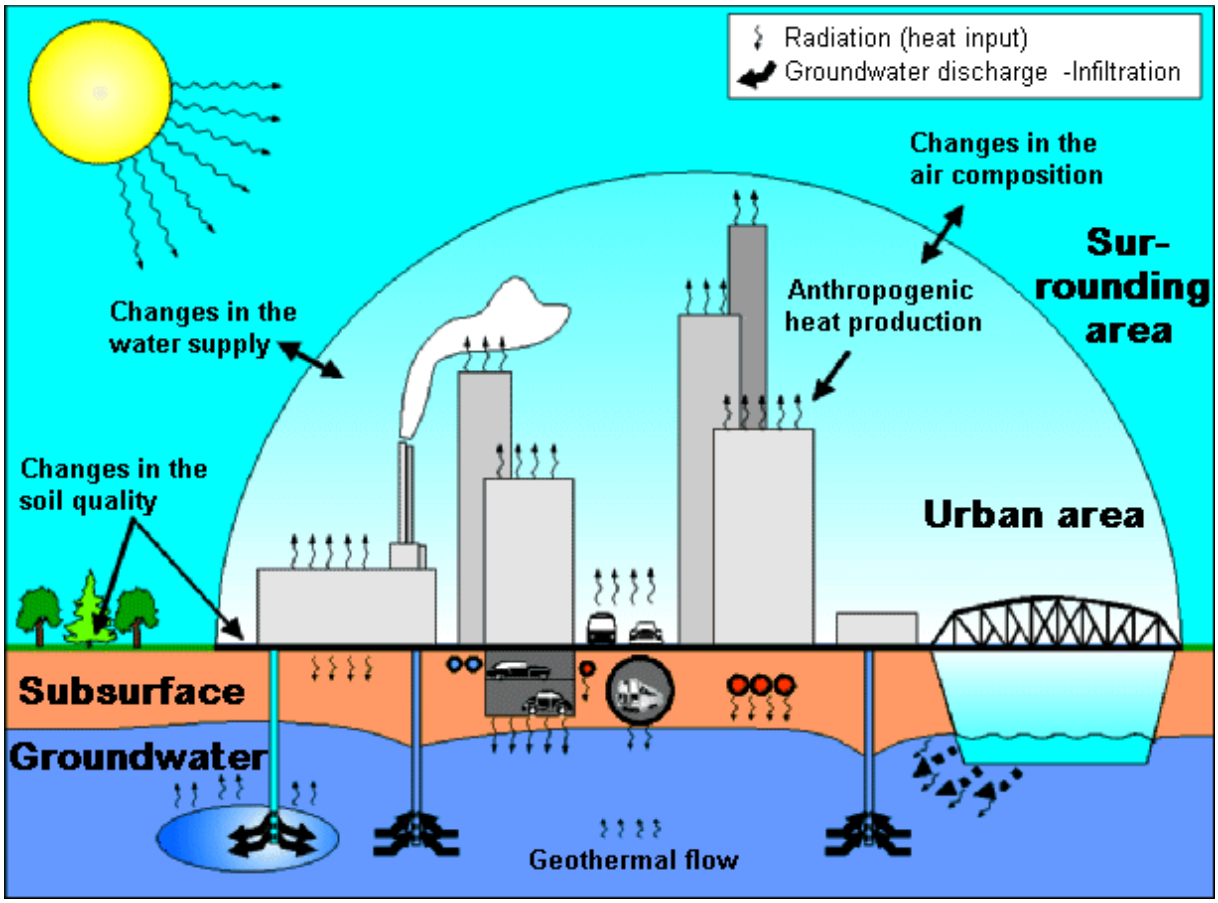


Fig. 1: Schematic Diagram of the Factors that Affect Groundwater Temperature

The causes for the temperature rise are various, and are directly connected to the continuing structural developments and the existing uses at the earth's surface. There, the distinction is made between direct and indirect influences on the groundwater temperature (see Fig. 1).

- **Direct influences** on the groundwater temperature includes all heat inputs to the groundwater through the sewage network, district-heat pipes, power lines and such underground structures as auto and metro tunnels, underground garages etc.
- Other such sources are those connected with the use and storage of groundwater heat.
- **Indirect influences** on groundwater temperature processes connected with urbanization connected with the change of in the heat balance in the near-surface atmosphere. According to Gross (1991), the most important factors are:

- The disturbance of the water balance due to a high degree of surface imperviousness
- The change of soil characteristics caused by an aggregation of structures (differences in the near surface heat input and heat capacity)
- Changes in the irradiance balance by changes in the atmospheric composition
- Anthropogenic heat generation (domestic heating, industry and transport).

The above differences cause changes in the heat balance by comparison with the areas surrounding the city. The city heats itself up slowly, stores more heat overall, and passes it on again slowly to the surrounding areas, i.e., it can generally be considered a huge heat storage unit. Over the long term, this process leads to an increase in the annual mean air and soil temperatures (cf. Map 04.02, SenStadt 2001).

The long-term warming of the near surface soil also leads to a heating of the groundwater. Since the temperature affects the physical qualities as well as the chemical and biological nature of the groundwater, a deterioration of groundwater quality and an impairment of the groundwater fauna may result.

One hundred percent of Berlin's drinking water comes from groundwater, which is extracted almost exclusively from the territory of the State of Berlin. The groundwater also supplies a large share of the water for industrial use. Therefore, the protection of the groundwater from serious change, such as an increase in groundwater temperature, is of great importance – specifically in terms of sustainable water use.

Since 1978, **temperature profiles** have increasingly been recorded at deep groundwater measurement points distributed throughout the area of the city, and processed and evaluated to develop a chronological and spatial depiction of the groundwater temperature structure.

The purpose of the present map is:

- the extrapolation of the existing documentation on chronological change of the groundwater temperature beneath the municipal area, and
- to serve as a basis for the authorization of measures which could cause changes in the groundwater temperature.

In addition, it can, in combination with other topical maps, such as those of the geological or hydrological structures, be used as an aid for decision making and preliminary planning for energy management of the groundwater. The underground temperature is an important quantum for the installation of geothermal energy probe systems.

In recent years, a sharply growing demand for geothermal energy probes in combination with heat pumps for heating and other thermal uses of the subsoil, e.g. the air conditioning of buildings, has been observable. Especially in urban areas, a wide variety of thermal uses compete in very small areas. To monitor the effects of these uses, regular supervision of the groundwater temperature is of increasing significance.

Groundwater Temperature and Annual Temperature Curve

The significant heat source for the near-surface subsoil to a depth of approx. 20 m is solar irradiance which reaches the earth's surface. This is substantially responsible for the surface temperature.

The near-surface soil is heated by irradiated solar energy, and passes the heat on to the atmosphere and the subsoil. The annual total of that part of the solar irradiance which impacts onto a horizontal surface, the so-called global irradiance, averages approx. 1000 kWh per sq. m and year in the State of Berlin. How much energy is ultimately passed into the subsoil from the surface is very strongly dependent on nature of the surface. Here, such factors as colour, humidity content and type and degree of ground cover are play important factors.

Basically, the temperatures of the earth's surface, and hence, too, the heat entry or exit, are subject to periodic fluctuation, during a cycle of one year, corresponding to the progression of the seasons.

The surface temperature penetrates with decreasing intensity into the soil. The penetration depth and the speed with which the heat is transported depend on the heat transfer capacity of the soil.

Subsoil **heat transfer** can be distinguished as either conductive and convective heat transfer.

While convective heat transfer, the movement of the heat is accomplished by moving material, such as groundwater or seepage water, conductive transfer results from the transmission of energy through the successive impact of molecules.

Compared with solar irradiance, the **geothermal flow** caused by the decay of radioactive isotopes in the subsoil is of much less importance as a source of surface heating.

In the continental crust of the earth, the geothermal flow density, which is defined as the thermal flow per unit of area perpendicular to the standard area, varies regionally. According to Hurtig & Oelsner (1979), and Honarmand & Völker (1999), the mean thermal flow density is in the State of Berlin is between approx. 80 and 90 mW/sq. m. Based on this, an energy total of approx. 0.75 kWh per sq. m and year can be calculated, which is only approx. 1/1000 of the global irradiance.

The near surface groundwater temperature is therefore essentially determined by the exchange of heat between the sun, the earth's surface and the atmosphere, with a much lesser degree by the geothermal flow towards the surface.

The regional average annual temperature at the surface in Berlin, given no anthropogenic effects, is approx. 8.0 to 8.5 °C.

While daily fluctuation affect the soil only to a depth of approx. 1.0 m, seasonal fluctuations reach depths of between 15 and a maximum of 25 m. Below this depth, in the so-called neutral zone, where seasonal effects can no longer be ascertained, the temperatures rises depending on the heat transfer capability of the rock and the regional geothermal flow density (Fig. 2).

In the Berlin area, the average temperature increase to a depth of approx. 300 m is 3 °C per 100 m.

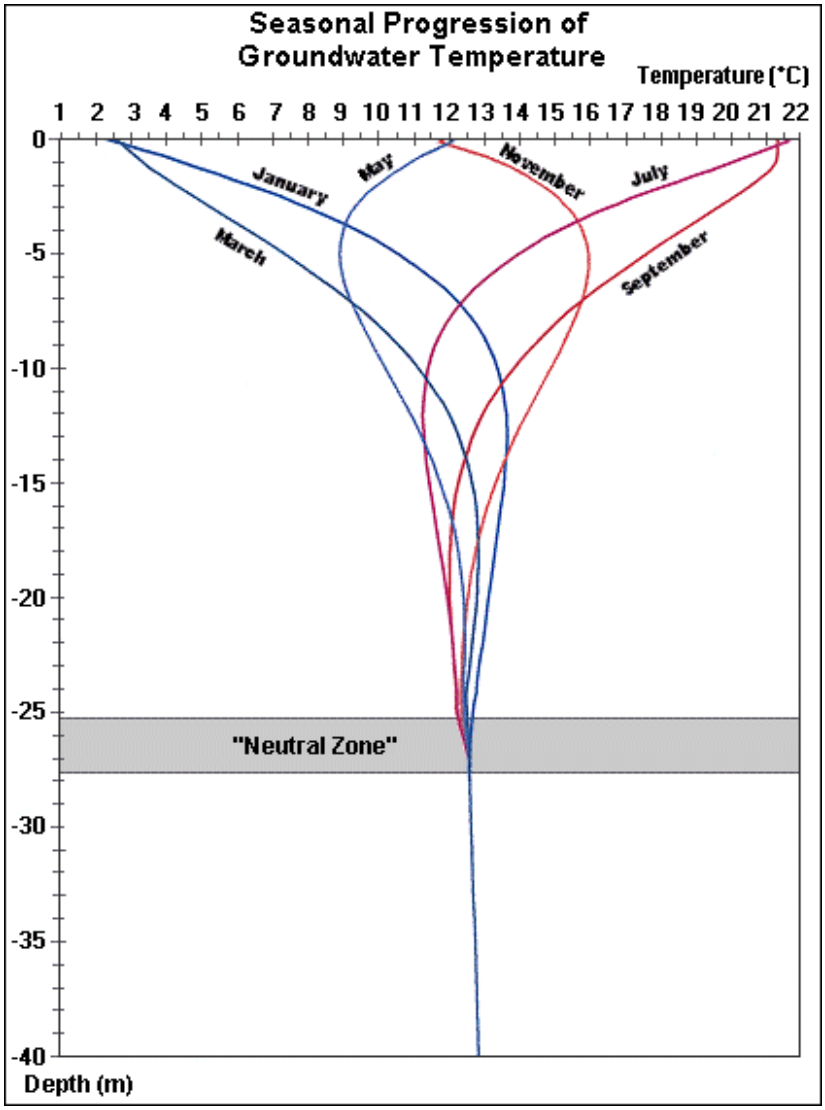


Fig. 2: Schematic Seasonal Progression of Groundwater Temperature

The Surface Structure and the Groundwater Situation

The Warsaw-Berlin glacial spillway runs in a nearly east-westerly direction, separating the Barnim Plateau in the north of the city from the Teltow Plateau and the Nauen Plate in the south (Fig. 3). The terrain elevation of the spillway is 30 to 40 m above sea level, while the plateaus average 40-60 m above sea level. Several elevations rise to over 100 meters above sea level (cf. Map 01.08, SenStadt 2010a).

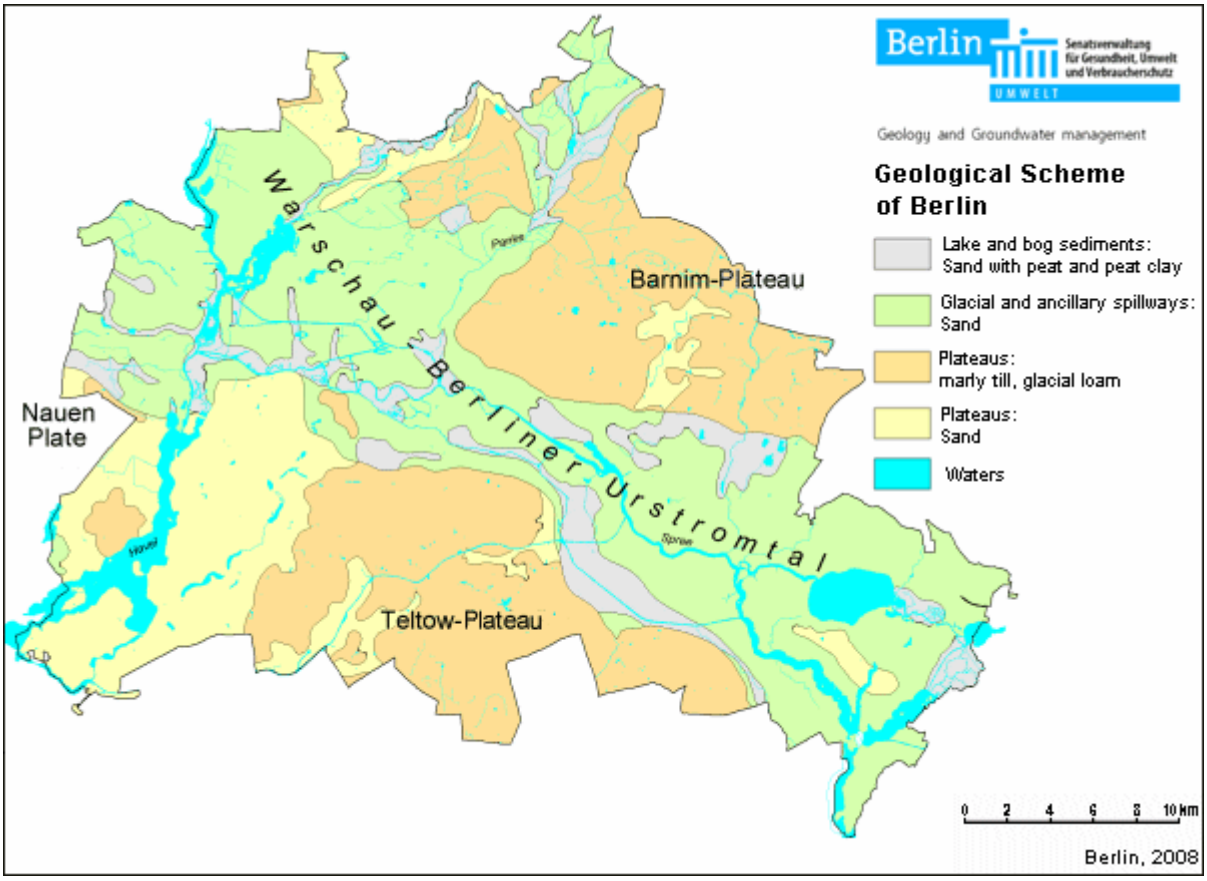


Fig. 3: Geological Scheme of Berlin

In Berlin the pore space in the upper 150-200 meters of the predominantly sandy and gravelly sediments is completely filled until just below the surface with groundwater, which is used as the drinking water supply for the city. The depth to groundwater fluctuates depending on the morphology and geology, between 0 m and a few meters in the glacial valley, and from five to over 30 meters on the plateaus (cf. Map 02.07, SenStadt 2010b).

Groundwater removal for the extraction of drinking and industrial water has led to the formation of broad funnel-shaped depressions in the surface of groundwater. This changes the natural depth and flow velocity of the groundwater, as well as the natural flow direction of the groundwater. For that reason influent conditions have been created in the areas where well galleries extract groundwater near rivers and lakes, which means the surface water infiltrates as bank filtrate into the groundwater. Since the surface water is in addition warmed throughout the year, e.g. in the area of the Spree, by the intake of cooling water from of heating and power stations, this infiltration necessarily causes heating of the groundwater in the watershed area of such surface bodies of water.

Population Structure and Climatic Relationships

The city of Berlin has a polycentric settlement structure characterized by the existence of two main centres, several smaller urban centres, and the close proximity of residential areas, green space and commercial and industrial districts. Major commercial and industrial areas are generally located on residential and development axes extending radially from the city centre towards the outskirts, and along the canalized surface waters.

A very simplified view of the city allows the following rough categories (Fig. 4):

- without built-up areas, primarily vegetation
- built-up areas of low to medium density
- high density built-up areas, city centres and
- industrial areas

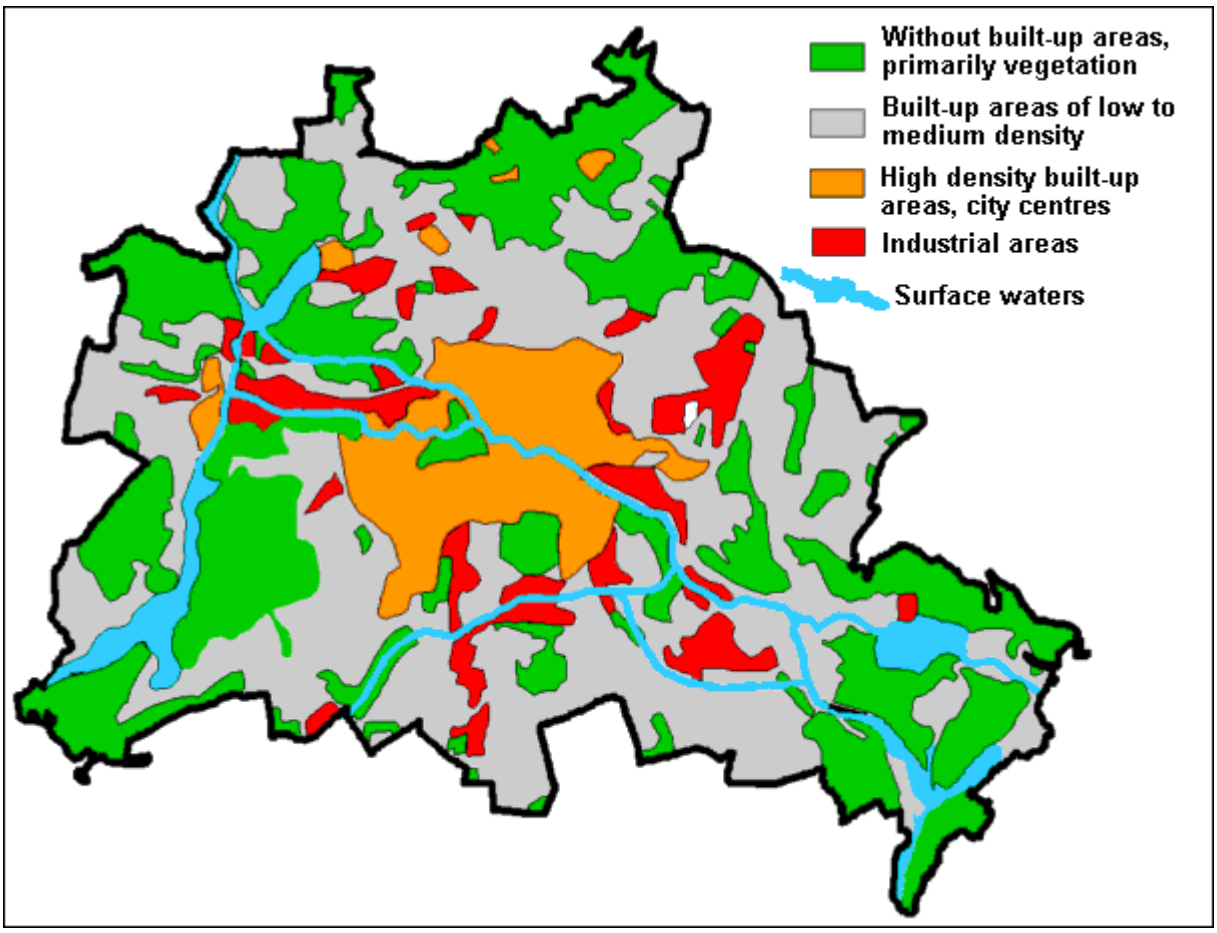


Fig. 4: Simple Diagram of the Urban Structure of Berlin

A look at the local climatic situation in Berlin reveals first and foremost that the structurally high-density city centre shows profound changes in the heat balance compared with surrounding areas. Anthropogenic activities cause energy to pass as heat into the city's atmosphere. Thus, the mean annual air temperature in the outlying neighbourhood of Dahlem is to 8.9 °C, while the average temperature in the city centre has already risen to above 10.5 °C (cf. Map 04.02, SenStadt 2001).

Statistical Base

The present map of groundwater temperature distribution is based on current measurements at 124 groundwater measurement points in the State of Berlin. These temperature measurements were carried out in **2010,** and complemented with temperature data from the Senate Department's data base.

In addition, temperature measurements have been carried out regularly every 2 months February 2008 at specially established unfiltered groundwater measurement points, which have the special feature that they can be filled with water almost to ground level, which permits monitoring of the annual temperature progression even in subsoil not saturated by groundwater.

As a rule, the temperature profiles of the groundwater level up to the measurement depth are ascertained with a measurement point interval of 1 m. The measurement error which arises from calibration inaccuracy and measurement inaccuracy of the device, as well as measurement inaccuracy of the object of measurement (e.g., due to heat convection at the measurement points) can be assumed at at least ±0.3°C.

Update on the Data as of 2010

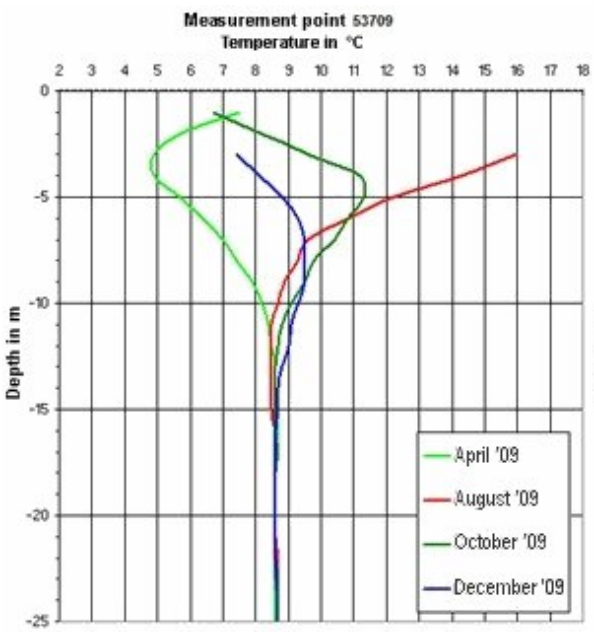
The temperature measurements carried out over the past 30 years at 124 selected measurement points indicate changes Towards a warming of the groundwater, starting near the surface and increasingly extending into the deeper subsoil to a depth of 20 m.

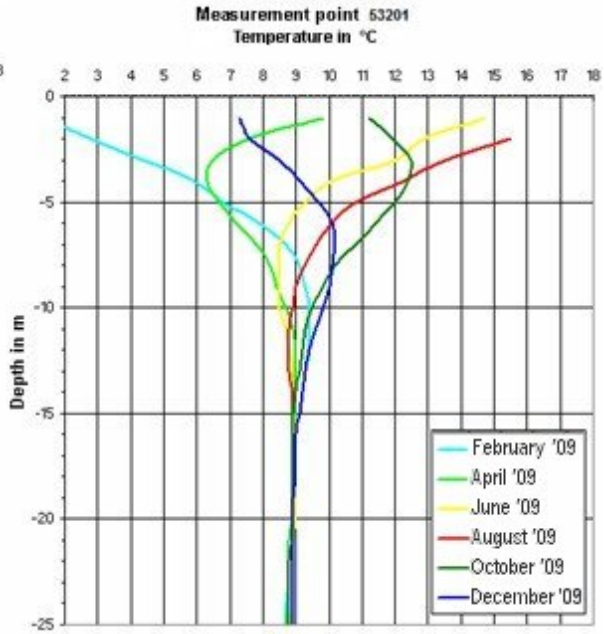
Methodology

In order to obtain a statement regarding the groundwater temperature distribution over a large area, a **Kriging interpolation** based on a variogram analysis was carried out. The prerequisite for this analysis is that the groundwater temperature be a regionalized – i.e., a locality dependant – variable which can be seen as the realization of a coincidence function. A regionalized variable is e.g. characterized by the fact that neighbouring points are more similar to each other than are mutually remote points (Akim & Siemes, 1988). The purpose of a **variogram analysis** is to characterize these structural characteristics and to depict them mathematically. The results thus obtained are integrated as input parameters into the Kriging interpolation. The interpolation provides a freely selectable grid, the junction points of which represent the calculated groundwater temperatures.

Map Description

The penetration depth of seasonal temperature fluctuations, and hence the depth position of the neutral zone, is determined by such geological factors as the depth to groundwater, the thermal conductivity and heat capacity of the rocks, and the formation of new groundwater. In Berlin, the **neutral zone** is located in depths between approx. 15 and a maximum of 25 m, depending on the conditions mentioned above (Henning & Limberg; 1995).





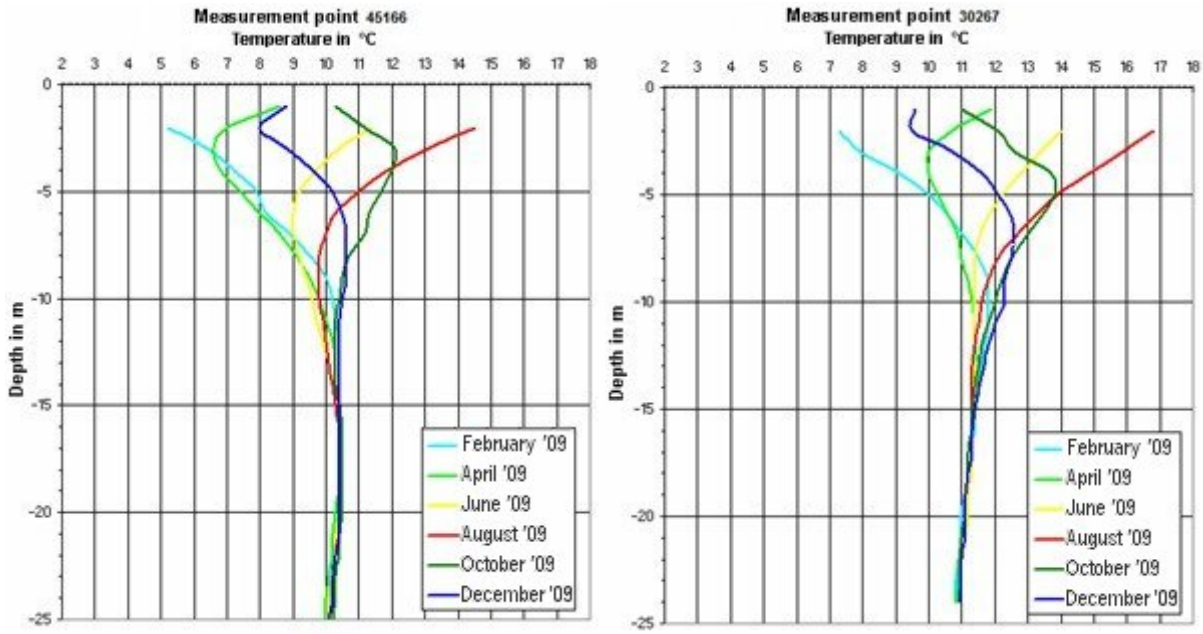


Fig. 5: Seasonal Change of Groundwater Temperature

Fig. 5 shows the variation over time of the temperature progression for four groundwater measurement points at roughly identical geological positions, but for different urban structural situations, in the first 25 metres under the surface, in groundwater saturated and non-saturated subsoil. The first ten metres of soil are predominantly characterized by the occurrence of cohesive soils, primarily marly till. The depth to groundwater amounts is 5 to 10 m, depending on the geomorphological situation.

Depending on the location of the groundwater measurement point, considerable differences can be seen in the observed temperatures, as well as in the temperature progression at increasing depth below the neutral zone, in approx. 15 m depth.

In the near-surface area (< 5 m depth), the **lowest subsoil temperatures** as a rule appear in the spring (February through May), and **the highest** in late summer (September through October).

Table 1 shows a comparative overview of the key temperature values obtained from selected measurement points with different urban structural situations, in measurements taken in February, April, June, August, October and December 2009 (Henning Energie- und Umweltberatung, 2010).

Site	Urban structure as per Map 06.08, Urban Structure-Differentiated	Urban climatic zone	Min. temp. at 3 m depth, 2009	Max. temp. at 3 m depth, 2009	Mean temp. in neutral zone, 2009
53709	Outskirts; green and open areas/ woods	**"very minor"** changes	-	12.5°C	8.7°C
53201	Outskirts; predominately green and open areas, non-dense residential areas	**"very minor"** to **"minor" changes**	4.4°C	13.5°C	9.3°C
45166	Dense residential areas, built post-1945	**"minor" changes**	6.4°C	13.1°C	9.7°C
30267	Inner city, dense residential areas; built pre-1945	**"major" changes**	7.9°C	15.9°C	11.3°C

Tab. 1: Table of Selected Temperature Characteristics in Various Urban Areas

Table 1 shows that in general, with increasing density of structures, an **increase in groundwater temperature** (cf. Fig. 5) can be ascertained.

As a result, the following categorization of residential areas can be made:

Areas	Temperature in the neutral zone
No structures, predominately vegetation	< 9°C
Low to medium structural density	9 -11°C
High structural density, city centre and industrial areas	> 11 °C

The exceptions are areas located in the vicinity of dense industrial parks with major waste heat producers, or in the immediate proximity of warmed surface waters.

Figure 6 shows an extreme example. This groundwater measurement point is located in the middle of a dense industrial park with several major waste heat producers in the immediate proximity of surface waters. In this case, the highest groundwater temperatures can be found in winter, and the lowest in summer. Since the surface waters are warmed strongly by the input of cooling water, particularly during the winter months, the groundwater temperature also rises, particularly due to infiltrating surface water. In 1991, a temperature anomaly with seasonal temperature fluctuations throughout the entire year of only approx. 1 K, between 14.5.and 15.50°C, was observed at depths of between 10 and 20 m below the surface.

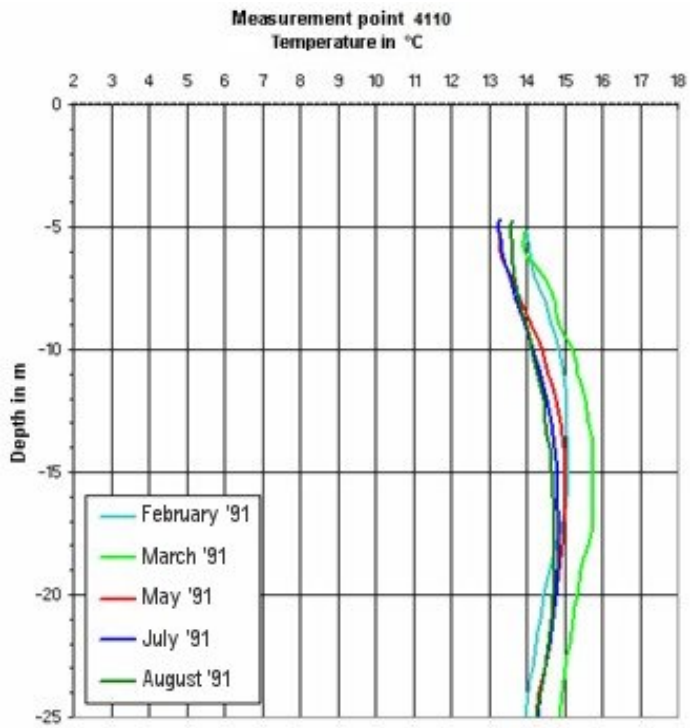


Fig.6: Seasonal Temperature Fluctuations of the Groundwater in the Immediate Proximity of Surface Waters Warmed Year-round

An evaluation of long-term investigations at measurement points in the inner-city area show (Henning Energie- und Umweltberatung, 2010) that over the long term, effects on groundwater temperatures even at greater depths should be assumed. Fig.7 shows this by means of an example at temperature profiles taken at groundwater measurement points at various times.

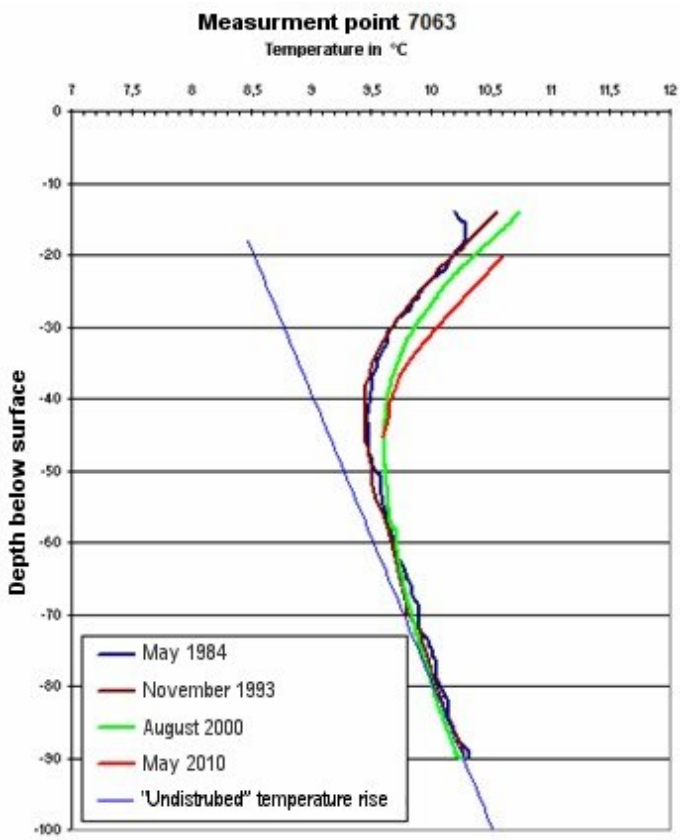


Fig.7: Results of a Long-term Analysis at one Measurement Point

The measured temperature profiles taken in 1984 and 1993 show approximately the same temperature progression for the neutral zone in approx. 18 m of depth and for the deeper subsoil at greater than 20 m depth. A comparison with the assumed "undisturbed" temperature progression shows a considerable increase in the underground temperature up to approx. 70 m depth. At 40 m depth, this temperature difference is still approx. 0.5 °K. This temperature increase, which was ascertainable until the beginning of the 1990s, can presumably be attributed to changes in the local climate caused by the construction of a large housing estate in the immediate proximity during the 1960 and 1970s.

An additional temperature rise of approx. 0.4 °K could be observed in the neutral zone between 1993 and 2010; it can currently be ascertained to depths of approx. 40 m. Since in this case, there were no significant changes, such as construction, in the area around the measurement point during this time period, which could have caused changes in the local climate, there is presumably a connection with the effects of general climate warming. During the same time period, the mean air temperature in 2 m height measured at the secular station in Potsdam has increased by approx. 0.5 °K (Henning Energie- und Umweltberatung 2010).

Groundwater Temperature Distribution Map for the Reference Horizon 20 m Below Surface

In the present map, the groundwater temperature distribution at the reference horizon area 20 m below surface in the area of the so-called neutral zone for the State of Berlin is shown. Generally, no effect of seasonal temperature fluctuations is ascertainable at such depths. The distance between the isolines is 1 °C.

The groundwater temperatures fluctuates between <8.5°C in the outskirts and >12.5°C in the densely built-up inner city area and in the industrial areas. Generally, a **tendency towards higher temperatures from the outskirts to the city centre** can be observed. The temperature progression shows a continuous increase from the northeast toward the city centre, while in the other areas of the city, the appearance of several smaller positive and negative temperature anomalies is characteristic.

The densely built-up city centre with its highly impervious surface is enclosed by a 11.5 °C isoline. The

heat island with temperatures of more than 12.5 °C which is apparent in the city centre, is interrupted by the Great Tiergarten, a large green space in the centre of the city. Within this heat island, isolated anomalies with temperatures above 13.0 °C can be observed, as local examinations have shown. The highest temperatures have been measured near **cooling water inflows near heating and power stations**.

Outside of the city centre, too, positive temperature anomalies correlate with highly impervious areas (cf. Map 01.02, SenStadt 2007), such as secondary centres and industrial areas.

Below the extensive woodlands on the outskirts to the southeast, the north, the northwest and the southwest, the temperatures are in the area of 9 °C or less. Negative temperature anomalies of less than 10 °C in the municipal area correlate with areas characterized by a high proportion of vegetation, e.g. the Britz Gardens.

Groundwater temperatures in the densely populated inner urban area are generally more than 4°C higher than in the open countryside.

Groundwater Temperature Distribution Map for the Reference Horizon 0 m Above Sea Level

The second map shows groundwater temperature distribution for the reference horizon 0 m above sea level in the State of Berlin. This corresponds top edge to a depth between approx. 30 to max. approx. 70 m into dependence of the situation in the glacial valley or on the high areas under area (cf. Fig. 3). In these depths an influence of the daily and seasonal temperature fluctuations is excluded. In these depths continuous temperature variations which e.g. are caused by a changed structural development or climatic changes can, however, manifest themselves in the long run.

The distance between the individual isolines is 1 °C on this map. A direct comparison of this map with the 1999 Edition is not possible, due to the different data basis with regard to the measurement point density, and because a less precise temperature gradation has now been chosen.

On this map too, groundwater temperatures fluctuate between < 8.5 °C in the outskirts and > 11.5> °C in the densely built-up inner city area.

In the densely built-up and highly impervious city centre, the area enclosed by a 11.5 °C isoline (depth position approx. 30 m below surface) has been considerably reduced. On the other hand, there has been a considerable enlargement of the areas in the temperature range between 8.5 and 9.5 °C, which is to some extent due to the depth position of the reference horizon (between> 30 m and < 70 m). This is particularly true of the south-eastern, northern and north-western outskirts areas.

A comparison with the groundwater temperature distribution map for the 20 m reference horizon under area top edge shows that particularly the smaller positive and negative temperature anomalies be watched in the southern and south-eastern municipal area do not appear any more.

In summary, it can be ascertained that groundwater temperature increases in the densely populated inner city area of more than 4 °C compared with the open countryside can occur, which is thus a considerable degree of warming. There is a clear connection with urban climatic conditions at the surface. The results of regular investigations at selected temperature measurement points in locations of varying urban structures also confirm this.

Overall, the near-surface groundwater temperature distribution in the State of Berlin generally shows a connection with the distribution of industrial facilities, waste heat producers, impervious surfaces, open spaces and surface waters warmed due to anthropogenic activity (see also Henning1990). Taking the groundwater flow field into consideration, it can be assumed that these factors have a substantial influence on the change in groundwater temperature. Since there is generally an accumulation of such factors in the city, these factors are mutually reinforcing (Blobelt 1999).

On basis of data from long-term investigations, it can be shown that due to progressive structural development and also to general climate change, a further very considerable warming of the near-surface (< 20 m depth) and deeper (to 100 m depth) subsoil, and hence also of the groundwater, can be assumed.

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