02.14 Groundwater Temperature (2014 Edition)

Overview

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

The temperature measurements of the near-surface groundwater of the State of Berlin carried out since the 1980s show that the average temperature has increased to a level more than 4°C above that in the thinly populated surrounding areas outside the city. They also indicate that this temperature rise is increasingly apparent even at depths greater than 20 m.

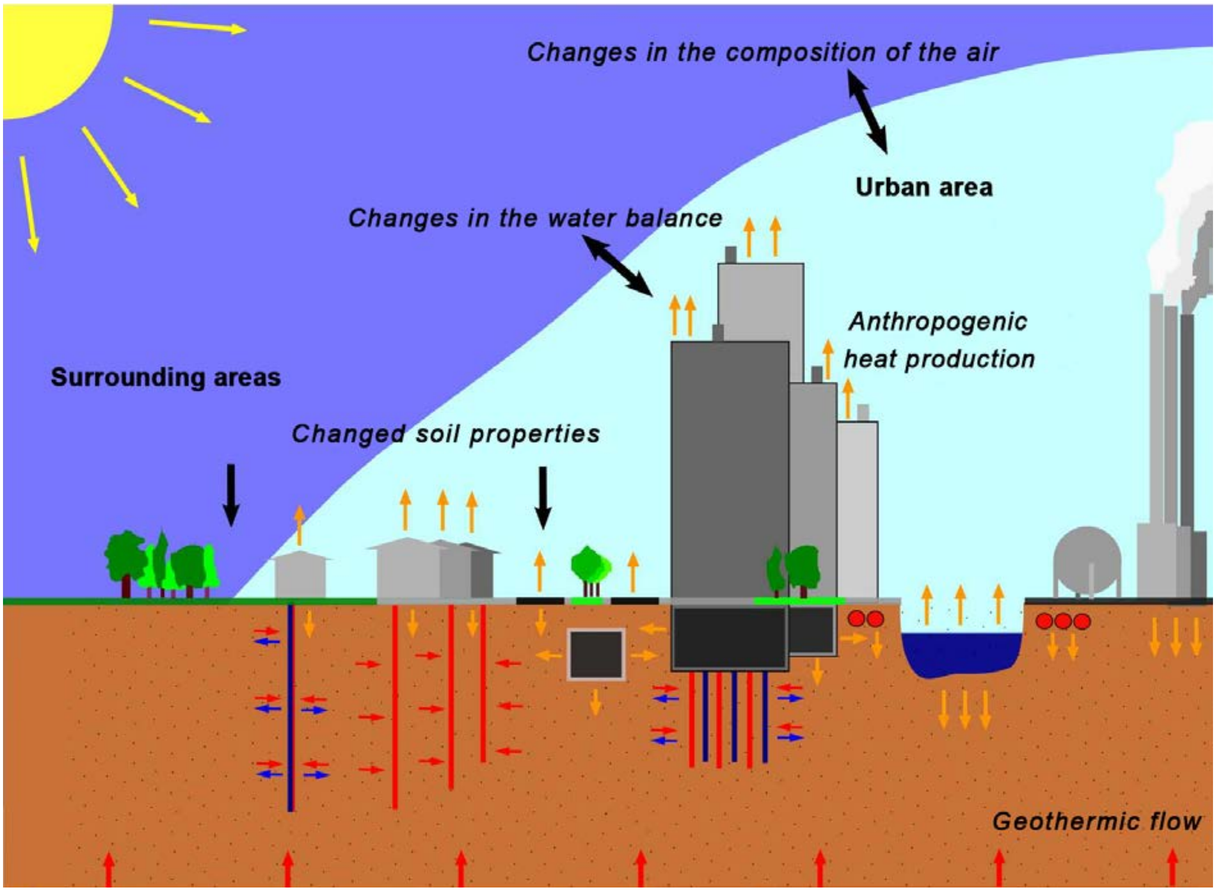

Fig. 1: Schematic diagram of the factors that affect groundwater temperature

The causes of 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.
- **Indirect influences** on groundwater temperature processes of urbanization connected with the change in the heat balance of 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 thermic surface characteristics, such as surface heat conductivity and heat capacity due to surface imperviousness and concentration of structures
- Changes in the irradiance balance due to changes in the atmospheric composition
- Anthropogenic heat generation (domestic heating, industry and transport).

These differences cause changes in the heat balance by comparison with the areas surrounding the city.

The city is gradually heating itself up, storing ever more heat overall, and gradually passing it on again 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 temperatures (cf. Map of long-term mean air temperatures, 1961-’90; Map 04.02).

The long-term warming also leads to a heating of the groundwater. The physical qualities and the chemical and biological nature of the groundwater are temperature-dependent. As a result of such warming, 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 a significant increase in groundwater temperature, is of great importance – especially in the interests of sustainable water management.

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

The purpose of the present map is:

- The extrapolation of the existing documentation on temporal change of the groundwater temperature beneath the municipal area
- To serve as a basis for the authorization of measures which could cause changes in the groundwater temperature, and
- To provide input data for the planning and evaluation of facilities for the use of geothermal energy.

In addition, it can, in combination with other topical maps, such as the Geological Outline Map (Map 01.17), the Groundwater Levels and Catchment Areas Map (Map 02.12), or the Geothermal Potential Map (Map 02.18), be used as an aid for decision-making and for preliminary planning for energy management of the groundwater. The underground temperature is an important quantity for the installation of ground heat exchangers.

Groundwater Temperature and the Annual Temperature Curve

The major heat source for the near-surface subsoil to a depth of approx. 20 m is the 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 to the subsoil. The annual total of that part of the solar irradiance which impacts upon a horizontal surface, the so-called global irradiance, averages approx. 1000 kWh per sq. m and year in the State of Berlin. A number of parameters at the air-surface interface affect the local thermic climate. Colour, composition, surface roughness, degree of ground cover, the water balance and the orientation of solar irradiation upon urban surfaces determine how much energy is absorbed and “stored” in the building structures, and how much of that is passed on to the atmosphere or the subsoil.

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

The surface temperature penetrates the soil with decreasing intensity. 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 or convective heat transfer.

While convective heat transfer involves the movement of the heat via moving medium, 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 main heat source for the near-surface area, the **geothermal flow** caused by the decay of radioactive isotopes in the subsoil is of much less importance.

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 in the State of Berlin is between approx. 80 and 90 mW/sq. m. Based on this, an energy total of between 0.7 and 0.8 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 essentially determined by the exchange of heat between the sun, the earth's surface and the atmosphere, and to 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 the daily fluctuations affect the soil only to a depth of approx. 1.0 m, the 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.

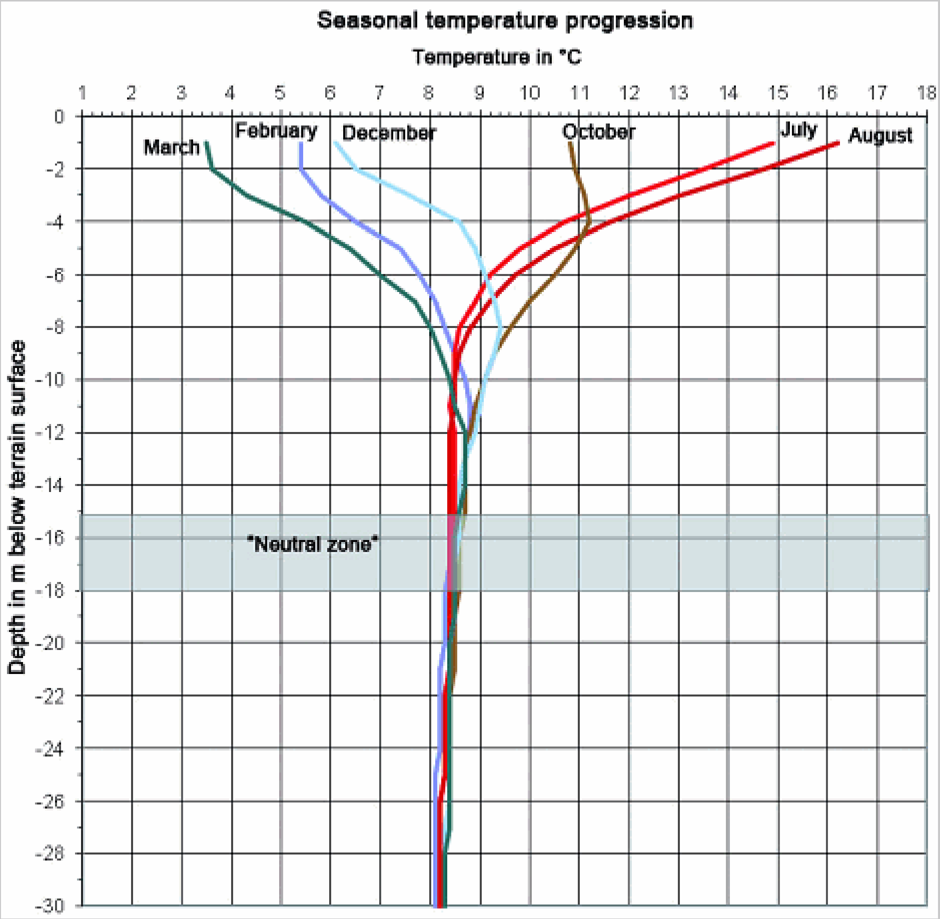

Fig. 2: Seasonal Progression of Groundwater Temperature

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 of Terrain Elevations, Map 01.08).

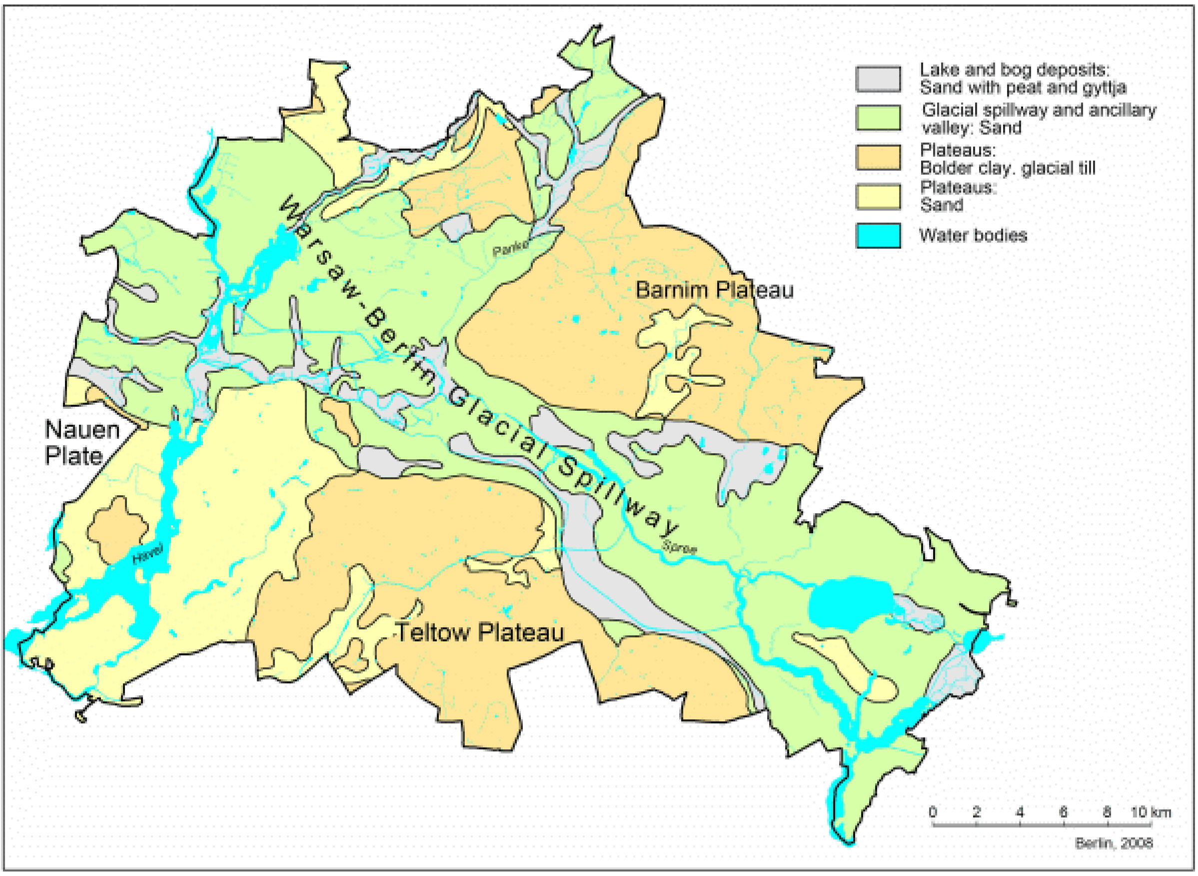

Fig. 3: Geological Scheme of Berlin

In Berlin, the pore space in the upper 150-200 m 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 spillway, and from five to over 30 m on the plateaus (cf. Map 02.07, Depth to Groundwater).

Groundwater removal for the extraction of drinking and industrial water has led to the formation of broad funnel-shaped depressions in the groundwater surface. This changes the natural depth and flow velocity of the groundwater, as well as its natural flow direction. For that reason influent conditions have been created in the areas where well galleries extract groundwater near rivers and lakes, which means that 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 Conditions

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

- Green and open spaces
- Residential areas (low to medium density), and
- Mixed-use areas, core areas, commercial/industrial areas (high density)

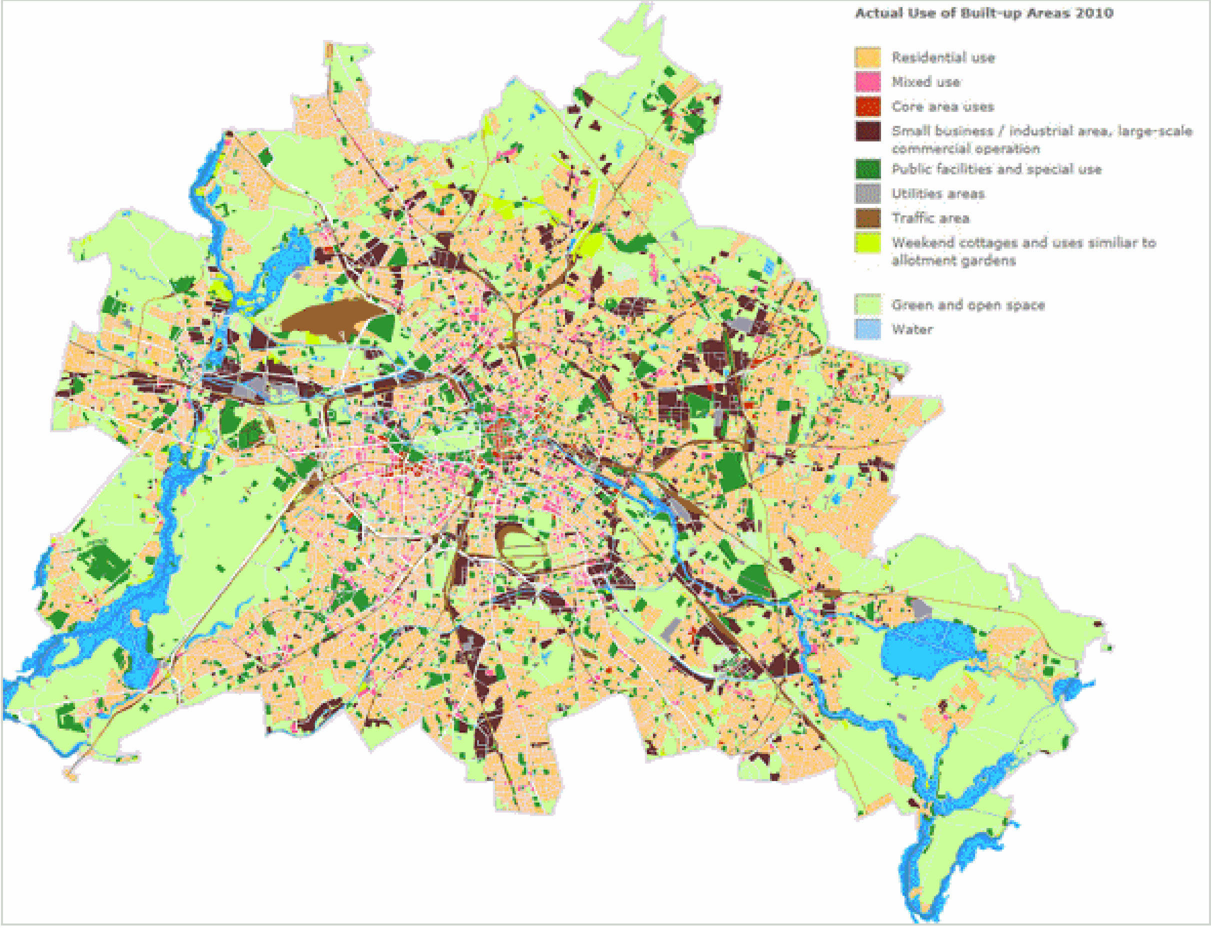

Fig. 4: Excerpt from Environmental Atlas Map 06.01, Actual Use of Built-Up Areas (2011 Edition)

A look at the local climatic situation in Berlin reveals first and foremost that the structurally high-density city centre shows profound temperature changes compared with surrounding areas. Thus, the Map of Long-Term Mean Air Temperatures (Map 04.02) shows that the long-term mean air temperature from 1961-1990 in the north-eastern outlying neighbourhood of Buch was between 7.0 and 7.5°C, while the average temperature in the city centre had already risen to above 10.5°C.

Statistical Base

The present map of groundwater temperature distribution is based on measurements from more than 350 temperature measurement points in the State of Berlin carried out between 1999 and 2013**.** For the near-surface area down to 20 m below terrain surface, current temperature data taken in 2010 and 2012 were largely used.

Since February 2008, in addition to single measurements, temperature measurements have been carried out regularly every two months at groundwater measurement points especially established for that purpose. They consist of a full pipe with no filter, so that they can be filled with water almost to ground level, which permits monitoring of the annual temperature progression even in subsoil not saturated with groundwater.

As a rule, the measurement of the temperature profiles of the groundwater level up to the measurement depth is carried out with a measurement point interval of 1 m.

The measurement error which arises from calibration and measurement inaccuracy of the device, as well as the measurement inaccuracy of the object of measurement (e.g., due to heat convection at the measurement points) is estimated to be at least ±0.3°C.

The existing temperature measurement points, particularly those which measure the deeper subsoil at depths greater than 50 m, are not equally distributed across the territory of the state of Berlin. There are frequently large gaps, with horizontal intervals between measurement points of more than 3000 m.

Local climatic conditions at the surface can greatly influence the temperature distribution in the near-surface area, and increasingly, too, in the deeper subsoil. To some extent, it is apparent that the local representation of temperature measurement values at certain temperature measurement points can be very different, which has to be taken into account in data evaluation.

The representative range of a temperature measurement point varies according to the site environment. In an urban situation such as that in the state of Berlin, with its varying distribution of buildings and its alternation between uncovered green surface areas and highly impervious urban areas, the representative range is more strongly limited than it is in rural areas with less variable surface conditions which strongly affect the local climate and, as a result, the temperature conditions in the near-surface subsoil.

It is evident that temperature measurement values of a certain measurement point in an urban area often represent the conditions in the radius of less than 10 to 100 m around that measurement point.

Methodology

In order to obtain a statement regarding the groundwater temperature distribution over a large area, a **Kriging interpolation** was first of all carried out. The prerequisite for the use of this method is that the groundwater temperature has been regionalized, i.e., it is a locality dependant variable. Such a variable is e.g. characterized by the fact that neighbouring points are more similar to each other than are mutually remote points.

The temperature distribution in the near-surface subsoil is very greatly influenced by the local climatic conditions at the surface, and the intervals between measurement points are in some cases very great in the state of Berlin. Potential small-scale temperature changes in the near-surface subsoil are hence often not registered, so that the progression of the temperature isolines may be subject to great imprecision.

Basically, a check of local representation should be carried out for each measurement point. However, the cost of testing would be very high, and the results would include areas in which the spatial representation of a measurement point would be insufficient to permit precise statements on temperature distribution in the subsoil of an area.

In order to increase the precision of statements for temperature distribution down to a depth of 40 m below terrain surface without a test of representation, the manual spatial interpolation of measurement values additionally took into account the local climatic conditions and the type of utilization at the terrain surface.

The basis for the qualitative processing was provided by the maps 04.02 Long-Term Mean Air Temperature, 1961-1990 (2001 Edition), and 06.01 Actual Use of Built-Up Areas (2011 Edition).

In addition, for larger areas in which no temperature data were available for the deeper subsoil between 50 and 100 m depth below terrain surface, synthetic temperature profiles and virtual boreholes at an interval of 1000 m were generated based on similar site characteristics, and using the known structure of the geological subsoil. These synthetic temperature profiles were used for the prognosis of the temperature distribution. Here too, it was evident that based on the intervals between synthetic measurement points, not all spatial structures at the surface and in the subsoil could be ascertained, and thus taken into account in terms of their effect on temperature conditions.

Map Description

Temperature Profile

The penetration depth of seasonal temperature fluctuations, and hence the depth position of the neutral zone, is determined by such geogenic 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 at depths between approx. 15 and a maximum of 25 m, depending on the conditions mentioned above (HENNING & LIMBERG; 2012).

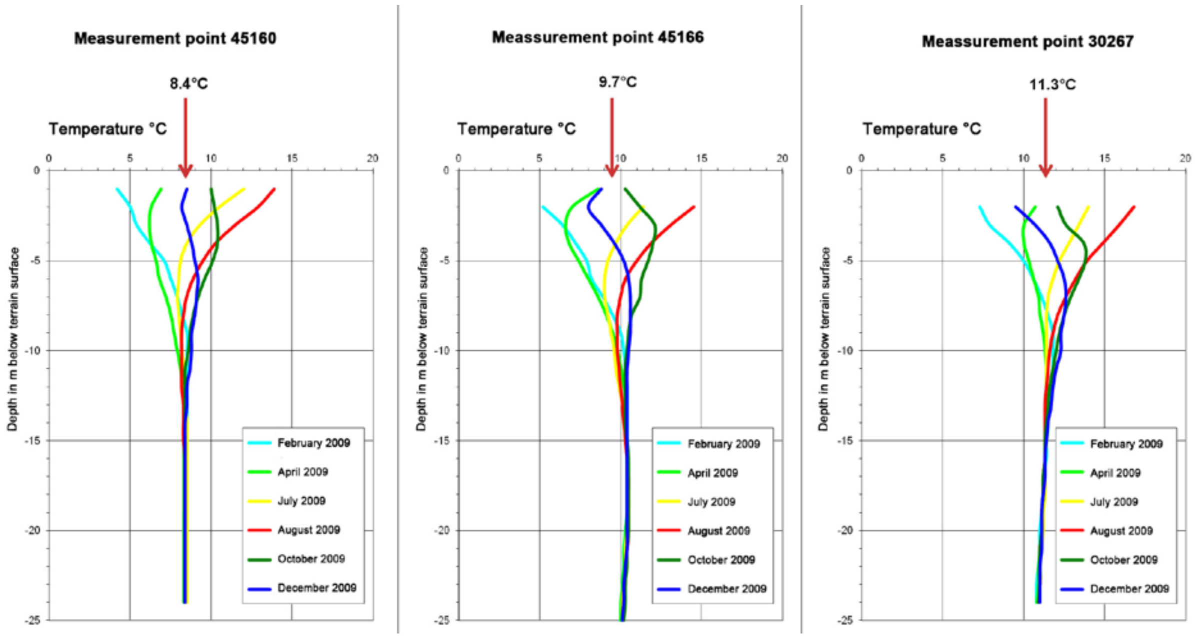

Fig. 5: Seasonal Change of Temperature of the Subsoil in the Groundwater Saturated and Unsaturated Soil Zone

Fig. 5 shows the variation over time of the temperature progression for three special temperature measurement points for different urban climatic zones, in the first 40 m under the terrain surface, in groundwater saturated and unsaturated subsoil. The depth to groundwater amounts is 5 to 10 m.

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, between 10 and approx. 15 m below terrain surface.

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 the autumn (September through October).

Table 1 shows a tabular overview comparing the key temperature values obtained from the above measurement points during the observation period of February 2008 through March 2010 (HENNING & LIMBERG; 2012).

Site	Urban structural location	Urban climatic zone	Min. temp. at 3 m depth,	Max. temp. at 3 m depth,	Mean temp.
45160	Outskirts; green and open areas/ woods Less than 10% impervious surface	**“very minor”** changes	5.4°C	11.5°C	8.4°C
45166	Residential areas, approx. 50% impervious surface	**“minor”** to **“medium”** changes	6.4°C	13.1°C	9.7°C
30267	Inner city, dense residential areas; over 60% impervious surface	“**major”** changes	7.4°C	15.9°C	11.3°C

Tab. 1: Comparison of Selected Temperature Values in Various Types of Urban Areas

Table 1 shows that in general, with increasing density of structures, as expressed by the urban structural location, an **increase in groundwater temperature** (cf. Fig. 5) can be ascertained.

As a result, the following categorization of residential areas can be made (Tab. 2):

Areas	**Temperature in the neutral zone**
Outskirts, green/open space, woods	< 9°C
Residential area (low to medium density)	9 -11°C
City centre; commercial/industrial areas (city centre; high density)	> 11 °C

Tab. 2: Temperatures in the Neutral Zone, Depending on Various Structural Densities

Figure 6 shows an extreme example for a temperature progression in the middle of a dense industrial park with several major waste heat producers. Moreover, in the immediate proximity, there is a surface body of water. 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 15.5°C, was observed at depths of between 10 and 20 m below the surface.

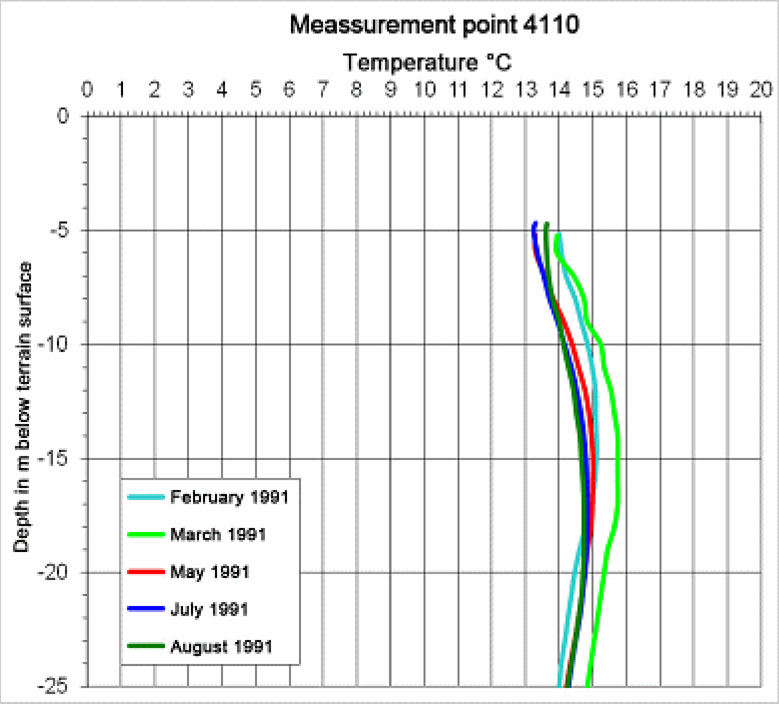

Fig.6: Seasonal Temperature Fluctuations of the Groundwater at Measurement Point 4110, in the Immediate Proximity of Surface Waters Warmed Year-round

In Figure 7, the temperature profiles of selected measurement points in the borough of Mitte are shown for an area of approx. 3 x 3 km, with data obtained in 2012 and 2013. The figure shows a clear effect on the underground temperature to a depth of more than 100 m below terrain surface. The measured temperatures range between 11 and 15°C. The measurement point showing the greatest influence on the temperature is located near a surface body of water (here, the purple line in Figure 7).

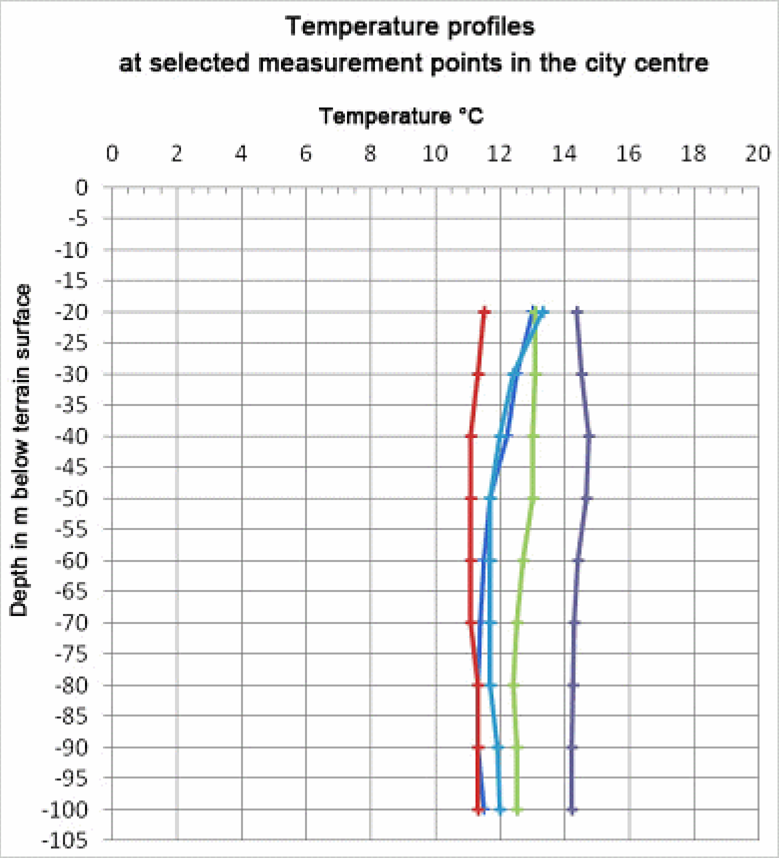

Fig.7: Temperature Profiles of Selected Measurement Points in Central Berlin (Borough of Mitte)

The evaluation of a long-term investigation at measurement points in the inner-city area have, according to HENNING ENERGIE- UND UMWELTBERATUNG (2010), showed that even over the long term, an effect on groundwater temperatures at great depths must be assumed. Figure 8 shows this clearly using the example of temperature profiles recorded at a groundwater measurement point at various points in time.

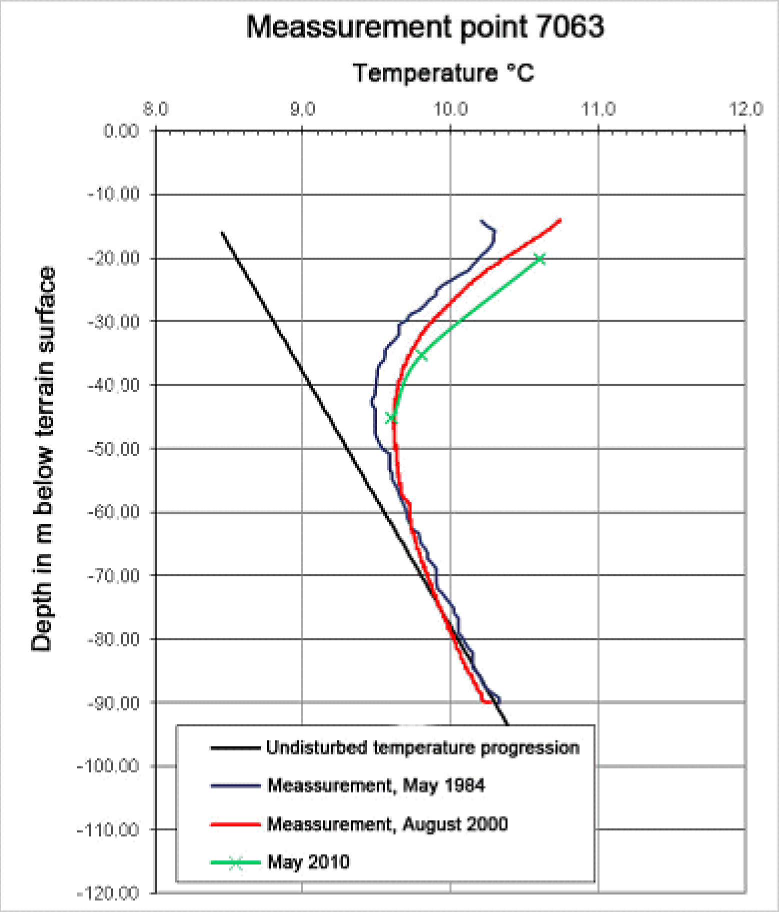

Fig.8: Results of a Long-term Temperature Investigation at Measurement Point 7063

The measured temperature profiles taken in 1984 and 1993 show approximately the same temperature progression for the neutral zone in approx. 18 m 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 the construction of a large housing estate in the immediate proximity during the 1960 and ‘70s. The “undisturbed” temperature progression was calculated theoretically from the borehole profile, the mean flow density assumed for the site, and the undisturbed mean annual surface temperature.

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 probably a connection with the effects of general climate warming.

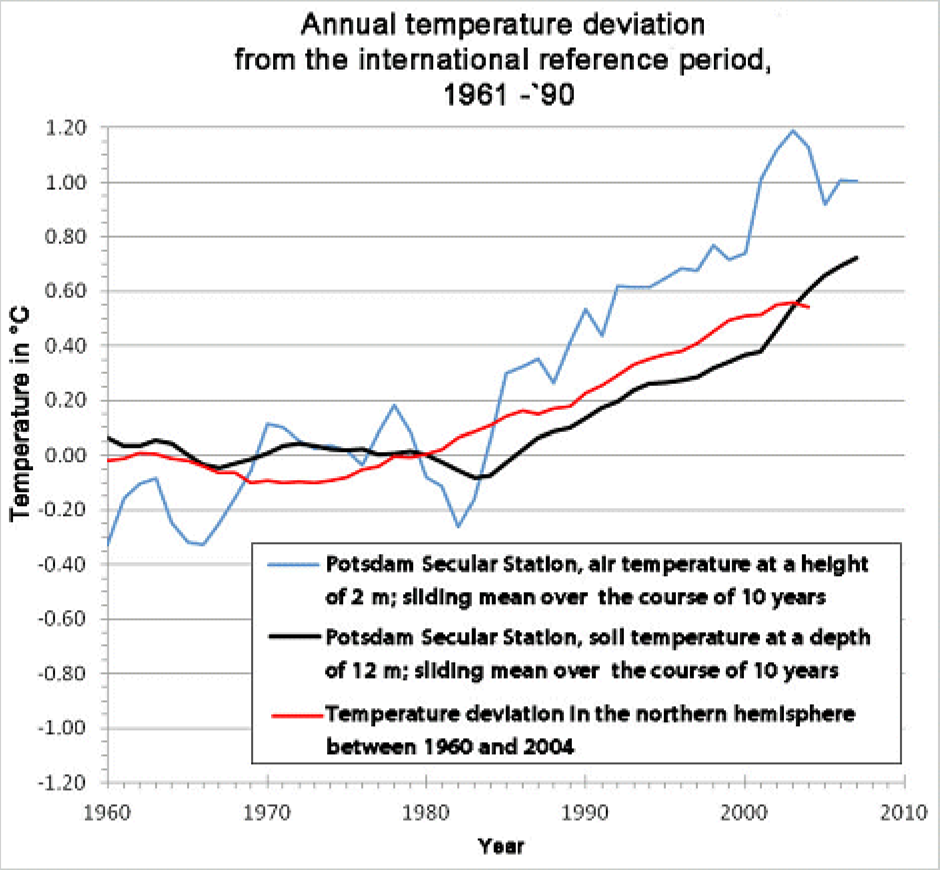

Fig.9: Temperature Deviation of the Air Temperature and the Soil Temperatures at a Depth of 12 m at the Potsdam Secular Station, by Comparison with the Temperature Progression in the Northern Hemisphere from 1922-2004, with Reference to the Period 1961-1990 (HENNING & LIMBERG, 2012).

Figure 9 shows that since the beginning of the 1980s, a clear rise in air temperatures has been observable in the state of Berlin and surrounding areas, as has been the case for the entire northern hemisphere. This temperature rise of approx. 0.5 K leads to a noticeable disturbance of the temperature balance in the near-surface subsoil, which can also be observed below the neutral zone at numerous measurement points in the state of Berlin. One example for this is shown in Figure 10.

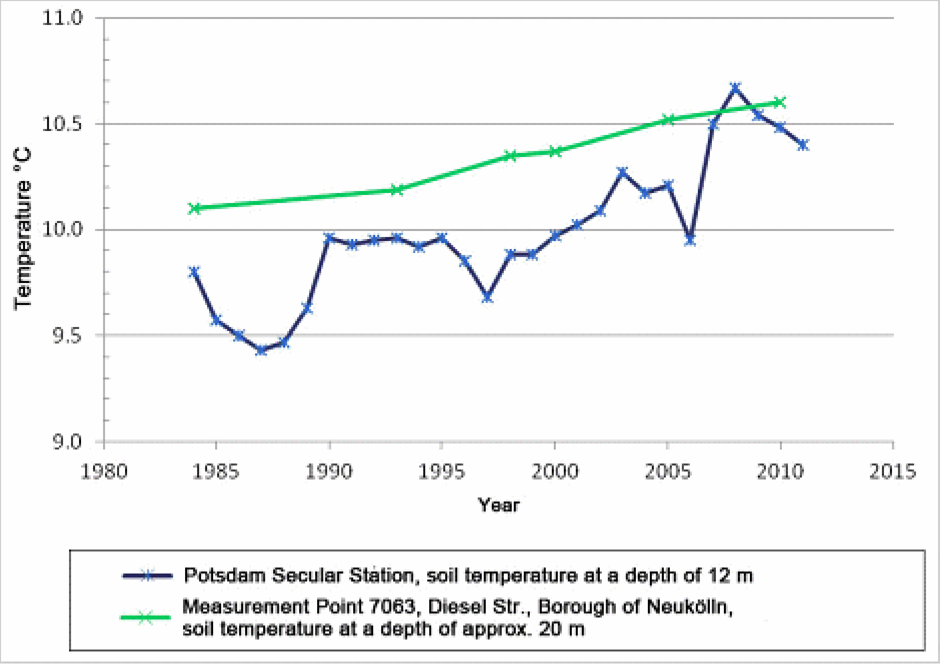

Fig.10: Temperature Deviation at the Potsdam Secular Station, for the Air Temperature at a Height of 2 m, and the Soil Temperatures at a Depth of 12 m, by Comparison with the Temperature Progression in the Northern Hemisphere. The Temperature Deviation is Referenced to the Mean Temperature Value of the International Reference Period 1961-1990 (HENNING & LIMBERG, 2012).

Map Descriptions

The maps show the temperature distribution in the subsoil for five different depths below terrain surface for the state of Berlin. It should be taken into account that the results shown represent the temperature distribution not as point-referenced information, but rather as a tendency.

The map information on temperature distribution should always be used in cases where no representative temperature measurements exist for the site. It should be taken into account that the results of a temperature measurement only apply precisely for the depth profile ascertained. Depending on the variability of the site characteristics, other conditions may well prevail only a few hundred meters away which could lead to changes in the temperature of the subsoil. Without taking these changes into account, a transfer of information even to a site very close to the measurement point could lead to considerable false assessments of temperature conditions.

The updating of the geo-thermic map resulted in differences compared with the 2011 edition of the map for the reference horizon 20 m below terrain surface. This is to some extent due to the fact that considerably more measurement points have been incorporated into the ascertainment process of temperature distribution, and that for several older measurements, measurement value corrections were necessary.

Basically, an initial estimate of temperature conditions at a site which can be used for geothermal energy is possible on the basis of the present maps.

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 an 11.5°C contour line 20 m below terrain surface (Map 02.14.1). 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, temperatures anomalies greater than 13.5°C can be observed.

Outside of the city centre, too, positive temperature anomalies correlate with highly impervious areas, 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 9.5°C or less. Negative temperature anomalies of less than 10.5°C in the municipal area correlate with areas characterized by a high proportion of vegetation, e.g. the Britz Gardens, or the Tempelhof Field.

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

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 continuous temperature variations which e.g. are caused by a changed structural development or climatic changes can, however, manifest themselves in the long run.

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 the Lichterfelde neighbourhood at the Teltow Canal, with its long-term building use and its intensive industrial utilization (groundwater temperature distribution for the reference horizons of 80 m and 100 m).

Other temperature anomalies, such as those in the south-western part of Berlin at the border with Potsdam, in the northern portion of the Grunewald forest in the area of the natural gas storage area, and in Lübars, at the northern border of Berlin, are caused by geological structures in the deep subsoil. These temperature anomalies are assumed to be connected with the salt dome structures known to exist in the Berlin area.

Other temperature anomalies in the deep subsoil more than 80 m below terrain surface, such as in the Rudow/Altglienicke area in south-eastern Berlin, in the Lichtenberg, Marzahn und Hellersdorf neighbourhoods in the east of the city, and in the Spandau City Forest in the west, involve increased subsoil temperatures the reasons for which have not yet been ascertained. In these cases, however, it can be seen that in many of these areas, no temperature measurement data exists, and synthetic temperature profiles have been used for the prognosis of temperature distribution. The temperature statements in these areas therefore involve relatively great uncertainties.

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 thus constitutes a considerable degree of warming. There is a clear connection with urban climatic conditions at the surface. The results of regular investigations at selected special 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, major buildings, waste heat producers, impervious surfaces, open spaces and surface waters warmed due to anthropogenic activity (see also HENNING 1990). 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 overlapping of such factors in the city, these quanta are mutually reinforcing.

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 also in the deeper subsoil (to 100 m depth) subsoil, and hence also of the groundwater, can be assumed.

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