Urban Heat Island in the Subsurface and Geothermal Potential in Urban Areas

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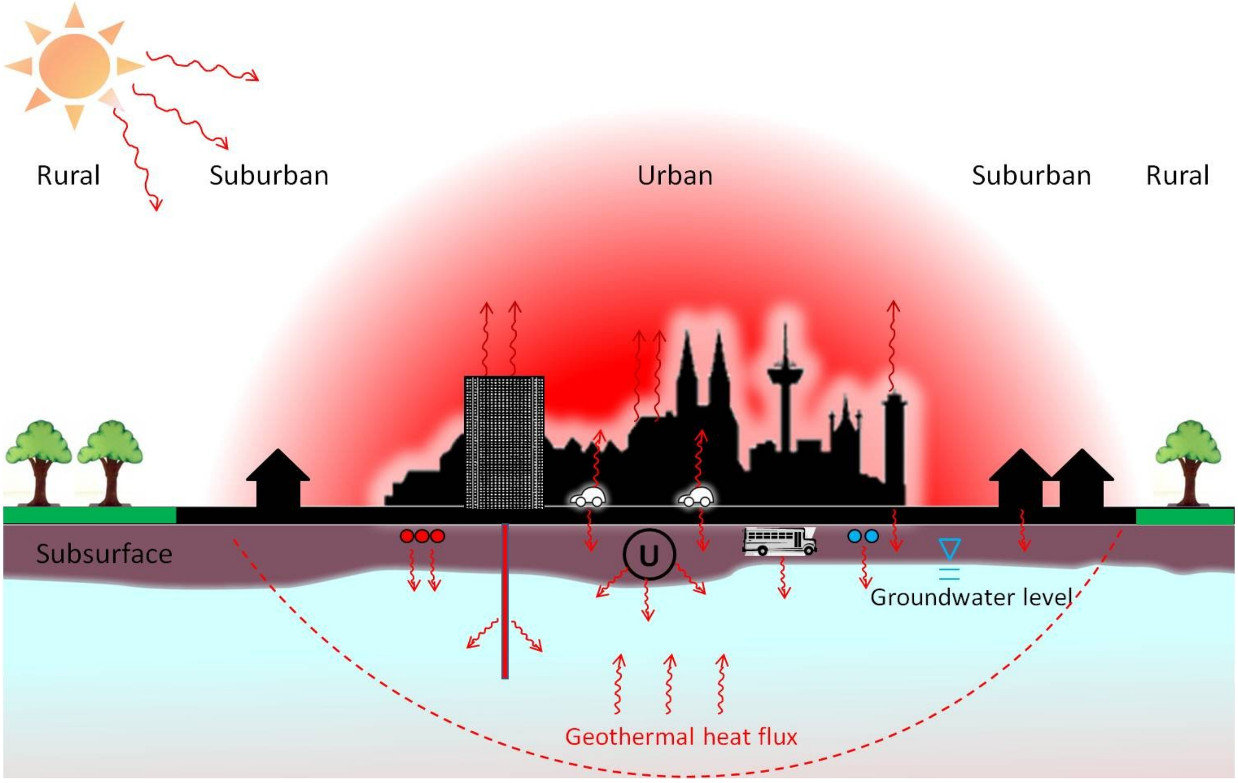
Art and science have their meeting point in method.

— Edward Bulwer-Lytton



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ABSTRACT

Urbanization during the last hundred years has led to both environmental and thermal impacts on the subsurface. The urban heat island (UHI) effect is mostly described as an atmospheric phenomenon, where the measured aboveground temperatures in cities are elevated in comparison to undisturbed rural regions. However, UHIs can be found below, as well as above ground. A large amount of anthropogenic heat migrates into the urban subsurface, raises the ground temperature and permanently changes the thermal conditions in shallow aquifers, which are attractive thermal energy reservoirs. Meanwhile, geothermal energy has become increasingly popular, because it offers a number of advantages over traditional energy sources based on fossil fuels. As a renewable energy source, it is clean and safe for the surrounding environment, and it also contributes to reduction of CO_2 emissions. Therefore, to estimate the regional potential geothermal energy content in densely populated urban areas is necessary. This PhD study presents extensive field studies in the city of Cologne, Germany. The results reveal high subsurface temperature distributions in the city center and indicate a warming trend of up to 5 °C. The case-specific potential heat content in urban aquifers and available capacities for space heating are quantified. The results show, for example, that by decreasing the 20 m thick urban aquifer's temperature by 2 °C, the amount of extractable geothermal energy beneath Cologne could be used for residential heating of the whole city for at least 2.5 years. The geothermal potential in other cities such as Shanghai and Tokyo is shown to supply heating demand even for decades. In this study, different types of shallow geothermal systems that could be used to extract the geothermal energy in urban aquifers are also discussed. In order to study the effects of urbanization and groundwater flow on subsurface temperature evolution in Cologne, and to improve our understanding of the dynamics of subsurface energy fluxes in urban hear island, two and three-dimensional coupled numerical flow and heat transport models were developed. The simulation results indicate that the main thermal transport mechanisms are long-term vertical diffusive heat input, horizontal advection and transversal dispersion. Instead of groundwater recharge, the influence of horizontal flow on heat transport needs to be addressed. Vertical transverse dispersion causes additional vertical heat fluxes, and thermal anomalies have migrated into the local urban aquifer system and they reach a depth of about 120 m. The results also show that groundwater temperature-depth profiles in urban aquifers are strongly related to the relative distance and location (upstream or downstream) to the anthropogenic heat source. In this context, the influence of the regional groundwater flow on the subsurface heat transport and the necessity of long-term temperature development assessment are comprehensively discussed. Our findings will contribute to strategic and more sustainable geothermal use in urban areas.

ZUSAMMENFASSUNG

Die Urbanisierung der letzten hundert Jahre führte zu Veränderungen der Umwelt, wie zum Beispiel die Temperatur des Untergrundes. Die Entwicklung des Stadtklimas wurde bisher hauptsächlich als Atmosphären verursacht betrachtet. Dabei wurden bei Messungen der Oberflächentemperaturen häufig ein Anstieg der Untergrundstemperatur in städtischen Regionen verglichen zu ländlichen Regionen festgestellt. Allerdings beeinflussen nicht nur Faktoren auf der Erdoberfläche das Stadtklima, sondern auch Faktoren des Untergrundes. Der größte Teil der anthropogenen Wärme gelangt in den städtischen Untergrund, wodurch die Temperatur des Untergrundes und somit auch des Grundwasserleiters steigt. Beide sind geeignete thermische Speicher. In der jetzigen Zeit stellt sich die geothermische Energie als zunehmend populär heraus, weil es eine Vielzahl von Vorteilen gegenüber herkömmlicher fossiler Energieresourcen gibt. Als erneuerbare Energiequelle bietet die geothermische Energie eine saubere und sichere Form dar, die zusätzlich zur Reduktion von CO_2 Emissionen beiträgt. Daher ist eine Bestimmung des Potenzials der geothermischen Energie in dicht besiedelten städtischen Regionen notwendig. Im Zuge dieser Doktorarbeit wurde in Köln, Deutschland, eine umfassende Feldstudie durchgeführt. Die Ergebnisse weisen auf eine Erhöhung der Bodentemperaturverteilung im Stadtkern um bis zu 5 °C hin. Die Fallspezifische Wärmemenge in städtischen Grundwasserleitern und verfügbaren Kapazitäten der Raumerwärmung wurden quantifiziert. Anhand der Ergebnisse kann gezeigt werden, dass beispielsweise durch ein Absenken der Temperatur des 20 m dicken Grundwasserleiters um 2 °C ein Plus an geothermischer Energie gewonnen werden kann, mit dem die Stadt Köln für 2,5 Jahre beheizt werden kann. Daneben wird nachgewiesen, dass das geothermische Potential anderer Städte, wie Shanghai oder Tokio, den Wärmebedarf für

Jahrzehnte bereitstellen könnte. In dieser Studie werden verschiedene Arten von oberflächennaher Geothermie-Systemen vorgestellt, mit welchen die geothermische Energie in städtischen Grundwasserleitern gewonnen werden kann. Um sowohl die Effekte der Urbanisierung und des Grundwasserflusses auf die Temperatur-entwicklung des Kölner Untergrundes zu untersuchen als auch unser Verständnis der Dynamik von UHI verursachten Energieflüssen zu verbessern, wurden zwei und drei dimensionale numerische Model mit gekoppelten Grundwasserfluss und Wärmetransport entwickelt. Die Simulationsergebnisse deuten an, dass die wichtigsten thermischen Transportparameter folgende sind: Der langzeitliche vertikale und diffusive Wärmeeintrag, horizontale Advektion und transversale Dispersion. Anstatt der Grundwasserneubildung muss der Einfluss des horizontalen Grundwasserflusses auf den Wärmetransport untersucht werden. Vertikale Transversaldispersion verursacht zusätzlichen vertikalen Wärmetransport. Thermische Anomalien sind bis in eine Tiefe von 120 m in das urbane Untergrund eingedrungen. Des Weiteren zeigen die Ergebnisse, dass Grundwassertemperaturprofile von urbanen Aquiferen stark von ihrer relativen Distanz und Entfernung (Abstrom oder Zustrom) zu der antrophogenen Wärmequelle beeinflusst werden. In diesem Zusammenhang wird der Einfluss des regionalen Grundwasserflusses auf den unterirdischen Wärmetransport und die Temperaturentwicklung ausführlich diskutiert. Unsere Studienresultate werden beitragen zu einer strategischeren und nachhaltigeren Nutzung der geothermischen Energie im urbanen Raum.

1. Introduction

1.1. Urban heat island

Urban heat island (UHI) is the phenomenon that urban areas are warmer compared to their non-urbanized surroundings (Voogt, 2002) (Fig. 1.1). The main causes of UHI above ground are heat generated from urban infrastructures which consume and reradiate solar energy, lack of evapotranspiration due to surface change, and the heat from other anthropogenic sources (Chen et al., 2006; Oke, 1982; Rizwan et al., 2008). Although some studies indicated that the re-radiation in the city is the major reason for UHI effect, the exact contributions from different sources are difficult to quantify. The global study by Pollack et al. (1998) showed a 1°C increase in the Earth's mean surface temperature over the past five centuries; the analysis by Hansen et al. (2006) shows that the global surface temperature has increased only about 0.2 °C per decade in the past 30 years while the records in four Asian cities show that during the last 100 years air temperature in Tokyo, Osaka, Seoul, and Bangkok has increased by 2 to 3 °C (Taniguchi et al., 2007). The UHI effect has drawn a lot of attention because it does not only have significant impact on urban meteorology, air pollution, and human health, but also on urban planning and energy management. In most previous studies the UHI usually refers to the temperature increase above the ground, such as air temperature and surface temperature (Apolonio Callejas et al., 2011; Li et al., 2004; Peng et al., 2011; Tran et al., 2006; Voogt and Oke, 2003), and only a few research studies refer to the subsurface warming (Ferguson and Woodbury, 2007a; Taniguchi et al., 2007; Yalcin and Yetemen, 2009).

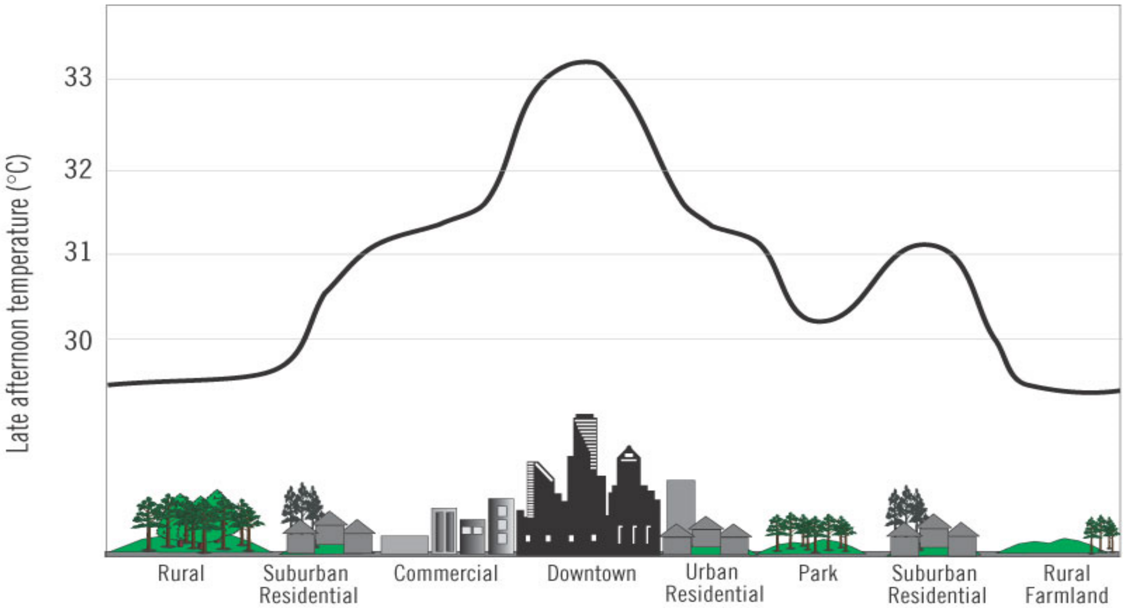

Fig. 1.1 An example of air temperature profile of a large city and surrounding suburban and rural areas. (Source: Natural Resources Canada)

There are different terms used to define the magnitude of UHI effect, such as urban heat island intensity (UHII) and surface urban heat island intensity (SUHII). UHII is normally considered as the difference between measured air temperatures at weather stations located in urban area and rural area. Huang et al. (2005) observed large UHII values in most Asia mega cities, such as Bangkok (8 K) and Shanghai (7 K). SUHII was defined by Peng et al. (2011) as the land surface temperature (LST) difference between urban area and suburban area. LST can be obtained by satellite remote sensing, which has high resolution to determine urban and rural area. According to Peng et al.'s (2011) analysis of 419 large cities all over the world, the average annual daytime SUHII is 1.5 ±1.2 °C and the value of nighttime SUHII is 1.1 ±0.5 °C.

Air temperature (or surface air temperature, SAT), land surface temperature (LST), soil temperature, and groundwater temperature are the terms that are often mentioned in the study of UHI. Air temperature (SAT) is normally measured at 1.5 to 2 m above the ground by weather stations. Since the stations are usually not evenly distributed and the measured data are strongly influenced by local conditions, measured air temperature alone cannot fully represent the UHII on the city scale (Peng et al., 2011). In Liu et al. 's (2011) study, the temperature sensor was fixed at 0.1 m above the ground, and the measured air temperature still showed a strong relation with the wind speed. Surface temperature and air temperatures are correlated at night and generally bare soil surface temperatures are 1 to 2 °C higher than air temperatures during low temperature periods, but in midday, the difference could reach 4 to 7 °C. Dettwiller (1970) showed that the temperature of urban asphalt pavement is 15 to 20 °C higher than air temperature during summer days. Smerdon et al. (2003) studied the relationships between air and surface temperatures by analyzing two decades of air temperature and shallow soil temperature (0.01 to 11.7 m) measured at Fargo, North Dakota. Their results show that ground surface signal is attenuated closely to 20% relative to the air temperature. The heat transfer between air and ground depends on many factors, such as the thermal properties of the soil and the atmospheric conditions (Oke, 1982). The study of (Huang et al., 2000) proved that at a large spatial scale, the anomalous trends of surface air temperature and the surface temperature match well. Though SAT has been proved by many studies as the primary driving force of LST (Ferguson and Woodbury, 2005a; Putnam and Chapman, 1996; Taniguchi et al., 1999), other impacts such as snow cover and land use changes can also influence the LST. The study of Mareschal and Beltrami (Mareschal and Beltrami, 1992) illustrated that in eastern Canada, the insulation of the ground by snow causes a difference of 1.5 to 6 °C between air and ground temperature.

1.2. UHI in the subsurface and geothermal energy

Previous and recent research on the subsurface temperature field indicates that UHI effect does not only appear above the ground but also in the subsurface. A worldwide subsurface warming trend has been observed in the last century (Ferguson and Woodbury, 2007a; Huang et al., 2009; Pollack et al., 1996). Most of the studies are aimed to track long-term climate change (Beltrami et al., 2005; Bodri and Cermak, 1995; Pollack and Huang, 2000; Pollack et al., 1998) or to study groundwater flow (Cartwright, 1979; Taniguchi, 2002), and recent work is more focused on human impact on urban subsurface environment (Ferguson and Woodbury, 2007a; Taniguchi et al., 2008; Yalcin and Yetemen, 2009; Yamano et al., 2009).

Regional studies from North America and eastern Canada (Ferguson and Woodbury, 2004; Wang et al., 1994), Europe (Balke, 1977; Bodri and Cermak, 1995; Bodri et al., 2001; Perrier et al., 2005; Zhu et al., 2010a), and Asia (Kataoka et al., 2009; Taniguchi et al., 2008; Taniguchi et al., 2007) all indicated several degrees temperature increase in the urban subsurface (e.g. Fig. 1.2). The magnitude of subsurface warming is not only related to the factors which determine SUHII, but is also influenced by the urbanization period of the city (Taniguchi et al., 2007).

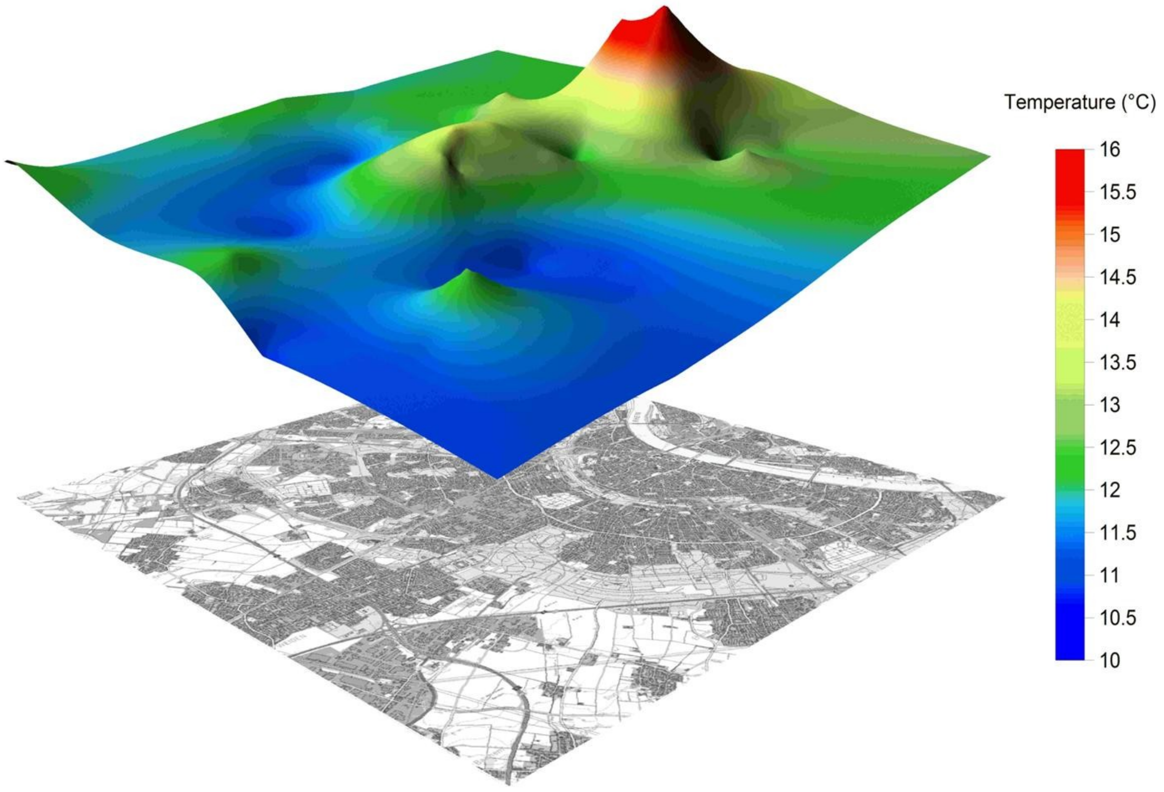

Fig. 1.2. Groundwater temperature at about 15 m depth beneath city of Cologne in 2009.

Geothermal energy is the form of energy stored below the surface of the solid earth as heat (VDI 4640, 2000). It is available in almost every place and depending on the specific geological and thermal properties; it can be applied in various ways such as for electricity generation and space heating. As one of the sustainable energy sources, geothermal energy has become increasingly popular due to the increasing energy demand and environmental concerns. By the end of 2009, the number of installed small and large shallow geothermal systems worldwide was about 2.94 million (Lund et al., 2010), and in Europe, more than 1 million installations were reported in 2011(Bayer et al., 2012). Geothermal energy is able to replace conventional energy sources, and therefore represents an option to reduce environmental pollutions, in particular greenhouse gases. Saner et al. (2010) showed that using a ground source heat pump (GSHP) system to supply an average European single family house saves 35 % of additional CO_2 emissions in comparison to conventional oil fired boilers. Geothermal energy systems are recognized as one of the most efficient heating and cooling systems on the market. Geothermal systems are able to transfer heat to and from the ground with minimal use of electricity, and the energy output is of the order of four times its input (Lund 2004). The U.S. Environmental Protection Agency has called geothermal the most energy-efficient, environmentally clean, and cost-effective space conditioning systems available (EPA report, 1993). Therefore, in most large cities, which require much more energy than the surrounding rural areas, low-enthalpy geothermal resources are of primary interest (Allen et al., 2003).

1.3. Objectives

The main objective of this study is to conduct extensive field investigations in a typical UHI in Germany, the city of Cologne, to discover the temperature distributions and current thermal conditions under the city and quantify potential heat content. Furthermore, the combined effect of urbanization and groundwater on subsurface temperature evolution has been discussed. The two and three-dimensional coupled numerical flow and heat transport models were constructed to improve our understanding of the dynamics of subsurface energy fluxes and the influences of different hydrogeological conditions on heat transport in UHIs. The influence of long-term development of Cologne's subsurface UHI on sustainable geothermal use in the city was also discussed. The findings of this study will hopefully provide useful information for further research on strategic and sustainable subsurface energy use in urban areas.

1.4. Thesis outline

This thesis contains six chapters. Chapter 1 includes a general introduction about research background, objective of this PhD study and, thesis outline. In Chapter 2, a detailed introduction of subsurface temperature and the utilization of urban shallow geothermal energy are given. Chapter 3 is based on the extensive field studies in the city of Cologne, in which the subsurface temperature distributions and current thermal conditions are presented and the case-specific potential heat content in urban aquifers and available capacities for space heating are discussed. Chapter 4 addresses the dynamics of subsurface temperature evolution in UHIs. By running the two and three-dimensional coupled numerical flow and heat transport models we developed, the influence of regional groundwater flow, thermal dispersion, surface warming and recharge are discussed. In Chapter 5, previous studies on sustainable geothermal use are reviewed and the case study of geothermal use in Frankfurt is discussed. Chapter 6 contains the conclusions and recommendations for future work.

2. General overview of subsurface temperature and urban geothermal utilization

2.1. Temperature below the ground

The temperature below ground is mainly influenced by two parts of heat flow: one from the Earth's interior and the other from surface which is directly related to LST. Besides natural geothermal flux, subsurface temperature is generally determined by similar factors that influence LST, such as solar radiation, air temperature, wind speed, land cover, groundwater recharge, and soil properties (Liu et al., 2011). In the absence of anthropogenic disturbances and groundwater flow, the temperature of the upper part (approximate 10 m) of the subsurface has regular seasonal variations due to seasonal heating and cooling of the ground surface (Fig. 2.1), and below a certain depth, it normally follows the geothermal gradient with an increase of 1 °C per 20 to 40 m of depth (Anderson, 2005).

The past energy changes on the surface slowly propagate into the subsurface, leading to significant spatial variation similar to the surface air temperature (Beltrami et al., 2005). The propagation of surface disturbance to the underground is a slow process, which depends on the thermal properties of the underground, and thermal diffusivity plays an important role. Based on the theory of heat conduction, a thermal wave with a period of 100 years can be detected to a depth of 150 m (Beltrami et al., 2005; Huang et al., 2000), and the amplitude diminishes exponentially with depth.

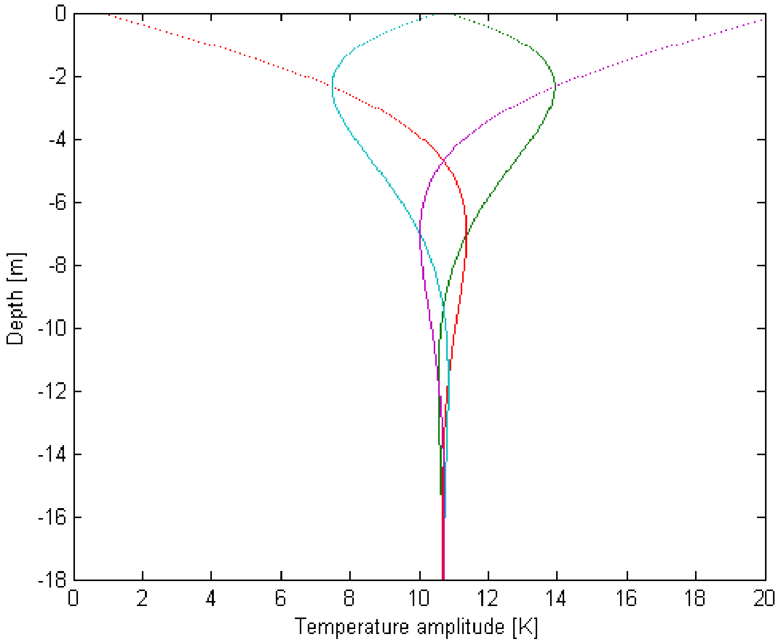

Fig. 2.1. Simulated seasonal variation in the upper part of a temperature-depth profile.

However, vertical ground water flow may curve the geothermal gradient by infiltrating relatively cool water in recharge areas and upward flow of warmer groundwater in discharge areas (Taniguchi et al., 1999) (Fig. 2.2). Research shows there is a positive correlation between the depth of the minimum temperature in the temperature-depth profile and recharge rate. Other research also observed that horizontal groundwater flow also has an effect on vertical temperature distribution. For example, Taniguchi et al. (2008) concluded that human activities, climate change, and character of urban development and social policies are the main factors which determine subsurface temperature.

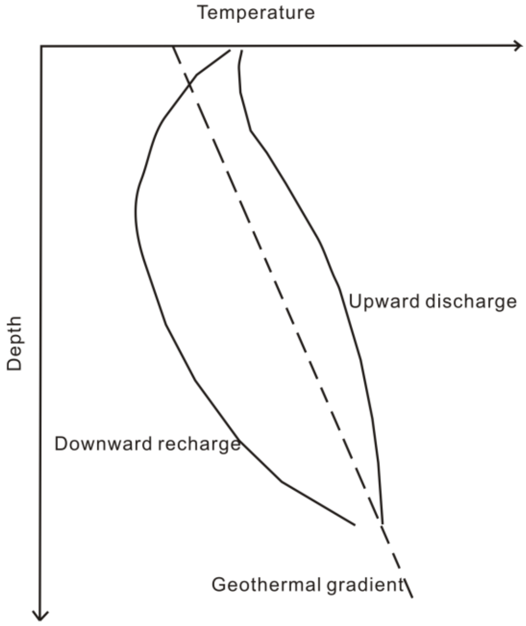

Fig. 2.2. Scheme of typical temperature-depth profiles in recharge and discharge area, showing deviations from the geothermal gradient caused by surface warming and groundwater flow (modified from Taniguchi et al. 1999).

Because of less influence from meteorological variables such as seasonal and diurnal radiation change and wind speed, the anthropogenic thermal impacts on the subsurface can be more persistent and profound than the impacts on the atmosphere. The study by Huang et al. (2009) indicated that the SAT records alone might underestimate the full extent of UHI effects on the subsurface environment. Although comparing to air and surface temperature, subsurface temperature is more consistent. There are other sources which might cause the temperature anomaly in urban areas. For instance, hot pavement and rooftops transfer their excess heat to stormwater, which then drains into underground and increases the thermal amplitude of urban groundwater at event and seasonal scales. The temperature variation can reach 3 °C and is controlled by the difference in temperature between stormwater and groundwater and the amount of runoff (Foulquier et al., 2009), and generally due to attenuation, the thermal effect of stormwater infiltration is limited to the shallow part of the groundwater. Other underground heat sources such as heat losses from buildings, sewage leakage, and the thermal wastewater injected to the aquifer can penetrate into deeper layers.

2.2. Soil and groundwater temperature

Soil temperature (Liu et al., 2011; Smerdon et al., 2003; Tang et al., 2011; Turkoglu, 2010) and groundwater temperature (Allen et al., 2003; Taniguchi et al., 2003; Taylor and Stefan, 2009; Yalcin and Yetemen, 2009) are the two main indicators of urban subsurface temperature. The study of Turkoglu (2010) revealed that the soil temperature difference between city and rural area at 5 to 50 cm depth ranges between 1.8 °C and 2.1 °C. Tang et al. (2011) conducted comprehensive measurements of the soil temperature at 600 locations in Nanjing, China, and they observed 1.21 °C increase of urban soil temperature. The measured results from Liu et al. (2011) showed that in Nanjing the average temperature under urban concrete surface is 3.7 °C higher than that of suburban bare soil. Balke's (1977) study showed the shallow (30 m) groundwater temperature in the city of Cologne is several degrees higher than in the rural area, and he concluded that this is mainly because of the anthropogenic impacts. In the case study in Winnipeg, Canada, Ferguson and Woodbury (Ferguson and Woodbury, 2004) found that the underground temperature of the city is significantly higher than that of the surroundings, and groundwater temperatures in a regional aquifer have risen about 5 K in some locations. Taylor and Stefan (2009) compared their analytical solution with collected data in Minnesota, and their results indicate that urban groundwater temperature is nearly 3 °C higher than an undeveloped agriculture area. The study on the local warming of groundwater in Istanbul, Turkey (Yalcin and Yetemen, 2009) also shows that due to UHI effect, the urban groundwater temperature is 3.5 °C higher than the rural.

In Turkoglu's (2010) study, the soil temperatures at depths of 5, 10, 20 and 50 cm below ground surface at 7 am, 2 pm and 9 pm were recorded by two meteorology stations in Ankara. One is located within an urbanized area and the other is 28 km away from the city center. A continuous observation period from 1960 to 2005 was selected for analysis. In Tang et al.'s (2011) study, they measured soil temperature at depth of 10, 20, 30, 40, 50, 60, 100 and 150 cm continuously from June 2009 to June 2010 at two locations, and they also measured soil temperature at selected times at 600 locations within urban and rural areas in the city of Nanjing. Both studies are focused on the shallow part of the subsurface and they lead to similar conclusions that soil temperature differences between urban and rural areas are larger in warmer seasons. In another study in Nanjing conducted by Liu et al. (2011), the temperature sensors were embedded at depths of 10, 20, 30, 40, 60, 200 and 300 cm, and they also observed that urban soil moisture is 13.9 % lower than suburban soil moisture. In comparison to soil temperature measurements, taking readings from observation wells is more common (Balke, 1977; Ferguson and Woodbury, 2004; Taniguchi and Uemura, 2005; Wang et al., 2009; Zhu et al., 2010b). Groundwater temperature profiles are measured by logging equipment with a good accuracy and resolution (Ferguson and Woodbury, 2007b), and readings are normally taken at 1 to 2 m intervals in the fluid-filled part of the well.

2.3. Characterization of thermal conditions in urban subsurface

Without disturbances, at a certain depth (10-15 m), the shallow ground maintains a nearly constant temperature that is close to the local annual air temperature. In the very upper part, it is influenced by atmospheric, mainly seasonal fluctuations. Cities commonly represent areas with their own microclimates and increased temperatures (Ferguson and Woodbury, 2007). In the cities, additional temperature fluctuations at the surface, caused by climatic perturbations, land use change, and other heat discharges from human activities, penetrate into the underground (Huang et al., 2000; Taniguchi et al., 2007). Therefore, aquifers below large cities are 2 to 5 °C warmer than in surrounding rural areas (e.g. Ferguson and Woodbury, 2007; Taniguchi et al., 2007). There are a number of direct and indirect heat sources in the cities, coming from both above and below the ground, such as transportation, heat losses from large buildings, cooling water, sewerage leakage, power lines, and underground structures like subway tunnels and underground parking lots (Fig. 2.3).

Since the anthropogenic heat fluxes into the ground are recorded as deviation from the natural temperature profiles, the underground heat flow history can be discovered by analysing temperature profiles measured in the cities and surrounding rural areas (Taniguchi et al., 2007). However, more attention should be paid when the profiles are significantly influenced by natural or artificial hydrogeological situations such as natural geothermal fluid from deeper geological structures and local groundwater cooling systems. Groundwater flow may curve the geothermal gradient by infiltration of upward flow of warmer groundwater in discharge areas and local discharge of waste cooling water. On the basis of observations at a case study site and numerical modeling, Ferguson and Woodbury (2005b) found out that groundwater temperature in a homogeneous aquifer depends more on spacing of the wells and pumping rates than soil properties. Therefore, a comprehensive investigation and understanding of thermal characteristics of urban subsurface is the basis for correctly interpreting the heat flow systems.

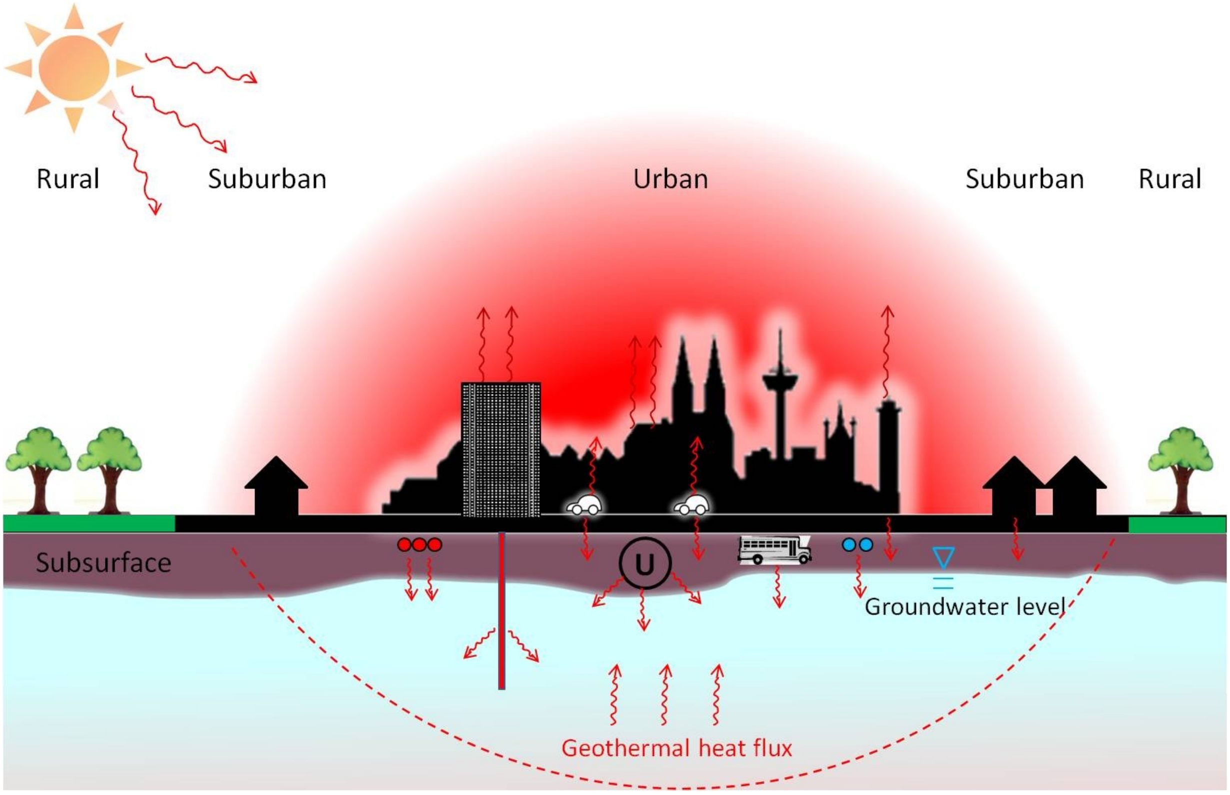

Fig. 2.3. Schematic representation of different heat sources which influence urban subsurface temperature.

2.4. Utilization of geothermal energy in urban areas

In comparison with high-enthalpy (high temperature) geothermal resources (>150°C) which are generally used for electricity generation, low-enthalpy shallow geothermal systems are more common and practical for urban areas. Technically, every city has a certain amount of exploitable energy available in the upper part of the subsurface (i.e. several hundreds of meters), and it is often used for heating and cooling using shallow geothermal systems such as ground source heat pump (GSHP) systems (closed-loop systems) or groundwater heat pump (GWHP) systems (open-loop systems). Among technologies to utilize the shallow geothermal energy, GSHP systems are the most popular ones (Lund et al., 2005). GSHPs use the ground as an energy source or sink for space heating or cooling. A heat pump is often connected to the borehole to change the temperature to reach the required temperature level of the building's energy distribution system. In GWHP systems, groundwater is directly used as heat carrier fluid, and in the doublet system, a production and an injection wells are implemented.

In some large cities, aquifers are mainly used for cooling purposes. In this case, the ground is used as a sink of the heat collected from large buildings like shopping malls and offices. This accelerates subsurface warming and meanwhile decreases the efficiency of using the underground for cooling. In this case, a dual heating/cooling system or aquifer thermal energy storage (ATES) system would be the ideal solution.

3. Geothermal potential of urban heat islands

The urban heat island effect and climate change have not only caused surface temperature increase in most urban areas, but have during the last hundred years also enhanced the subsurface temperature by several degrees. This phenomenon yields aquifers with elevated temperatures, which are attractive though underestimated thermal energy reservoirs. Detailed groundwater temperature measurements in Cologne (Germany) and Winnipeg (Canada) reveal high subsurface temperature distributions in the centers of both cities and indicate a warming trend of up to 5 °C. The case-specific potential heat content in urban aquifers and available capacities for space heating are quantified. The results show, for example, that by decreasing the 20 m thick urban aquifer's temperature by 2 °C, the amount of extractable geothermal energy beneath Cologne is 2.5 times the residential heating demand of the whole city. The geothermal potential in other cities such as Shanghai and Tokyo is shown to adequately supply the heating demand even for decades[1].

3.1. Introduction

Numerous studies and meteorological records have revealed a dramatic warming trend in most megacities in the last century (Ferguson and Woodbury, 2007a; Perrier et al., 2005; Taniguchi et al., 2007). This phenomenon is not only due to the climate change, but in particular, a result of non-climatic perturbations, which are mainly caused by local warming due to urbanization (Kataoka et al., 2009; Oke, 1973). This urban heat island (UHI) effect is recognized as a major environmental issue for most cities (Rizwan et al.,

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[1] Chapter 3 is modified after the author's publication: Zhu, K., Blum, P., Ferguson, G., Balke, K.-D., Bayer, P., 2010. The geothermal potential of urban heat islands. Environmental Research Letters 5(4), 044002.

2008). The increased temperature in an urban area compared to the surroundings is known as UHI intensity (Magee et al., 1999; Rizwan et al., 2008). The work by Tran *et al* (Tran et al., 2006) revealed large UHI intensity values through satellite data in most Asian mega cities, such as Tokyo (12 °C), Bangkok (8 °C), and Shanghai (7 °C). Various other researches (Cermak *et al* 2000, Ferguson and Woodbury 2004, Hung *et al* 2009) demonstrate that the UHI effect has also a strong influence on the underground temperature. Regional studies in urban areas from North America (Ferguson and Woodbury, 2007a; Wang et al., 1994), Europe (Allen et al., 2003; Bodri and Cermak, 1997; Perrier et al., 2005; Yalcin and Yetemen, 2009), and Asia (Huang et al., 2009; Taniguchi et al., 2007; Wang et al., 2009) have indicated 2 to 5 °C increase of the subsurface temperature. The results from the research of Beltrami (2001) indicated that the heat flux into the ground increased an average of 24 mW m^{-2} over the last 200 years in Canada. At a large spatial scale the anomaly trends of ground surface temperature (GST) agree with those at the surface (Huang et al., 2000; Pollack et al., 1998), and GST directly influences subsurface temperature by thermal conduction. Factors that cause the urban heat island effect in the subsurface are similar to the ones that increase surface air temperature, such as indirect solar heating by the massive and complex urban structures, anthropogenic heat losses, and land use change. In addition, the anthropogenic thermal impacts are more persistent in the subsurface (Huang et al., 2009), because, instead of radiation and advection, slow conduction plays the most important role in underground heat flow, and it is influenced by both surface and subsurface processes.

Although in many cases it is still not clear what the driving forces of enhanced underground temperature are, whether climate change, land use change, sewage leakage or groundwater flow (Balke, 1977; Beltrami et al., 2005; Pollack et al., 1998), the wide existence of aquifers with elevated temperature is an indisputable fact (Ferguson and Woodbury, 2007a; Taniguchi et al., 2007; Yalcin and Yetemen, 2009). The extra heat stored in urban aquifers is sometimes considered as a kind of underground thermal pollution. However, as a result of increasing interest in geothermal use, these high yielding aquifers are attractive thermal reservoirs for space heating and cooling. In addition to the general advantages of geothermal usage, such as minor environmental impact and reduced greenhouse gas emissions (Blum et al 2010, Saner et al 2010), urban aquifers with higher temperatures can improve the sustainability of geothermal systems. In essence, higher temperatures mean a higher amount of energy stored, that is, an increased geothermal potential.

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

3.2. Aquifer temperature anomalies in Winnipeg and Cologne

The city of Cologne, lying on the River Rhine, is Germany's fourth-largest city with a population of around one million. The average annual air temperature from 1945 to 2009 was 11 °C according to the German weather service (DWD). Cologne is underlain by Quaternary terrace deposits that host shallow unconfined aquifers (Klostermann, 1992). Major components are sand and gravel with a mean hydraulic conductivity of 1×10^{-3} to 5×10^{-3} ms^{-1} (Losen, 1984). The main aquifer reaches a depth of 30 to 70 m and is underlain by a layer of clay and soft coal (Fig. 3.1). Groundwater flows from southwest to northeast to the river Rhine. The groundwater level is between 10 and 15 m below the surface. Groundwater temperature measurements were performed in October 2009 using logging equipment (SEBA KLL-T) with an accuracy of 0.1 K (Fig. 3.2). We took measurements from 72 wells in a total area of around 140 km^2. The area covers business districts, residential districts, industrial areas, green spaces in the city, and rural agricultural areas. The measured wells have a diameter between 0.05 and 0.127 m, and the well depth ranges between 20 and 100 m. Groundwater temperatures were recorded at 1 m interval in each well.

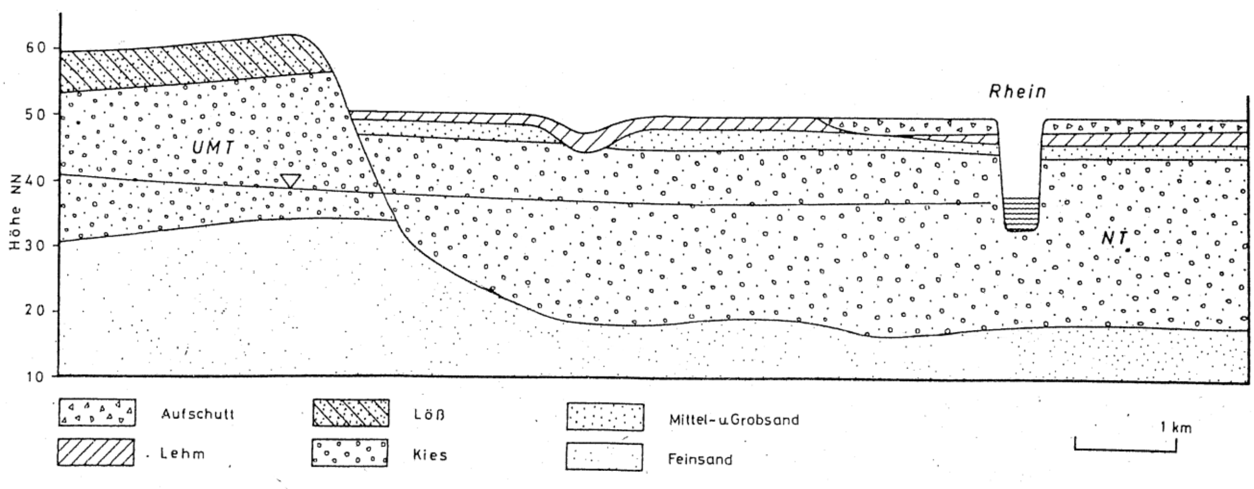

Fig. 3.1. Hydrogeological cross-section of Cologne, from West to East. Modified after Balke (1977b). The legend symbols are from left to right: anthropogenic deposits (Aufschutt), clay (Lehm), loess (Löss), gravel (Kies), coarse and medium coarse sand (Mittel- und Grobsand), fine sand (Feinsand).

Fig. 3.2. SEBA model KLL-T, taken from the official manufacturer prospect from 2010.

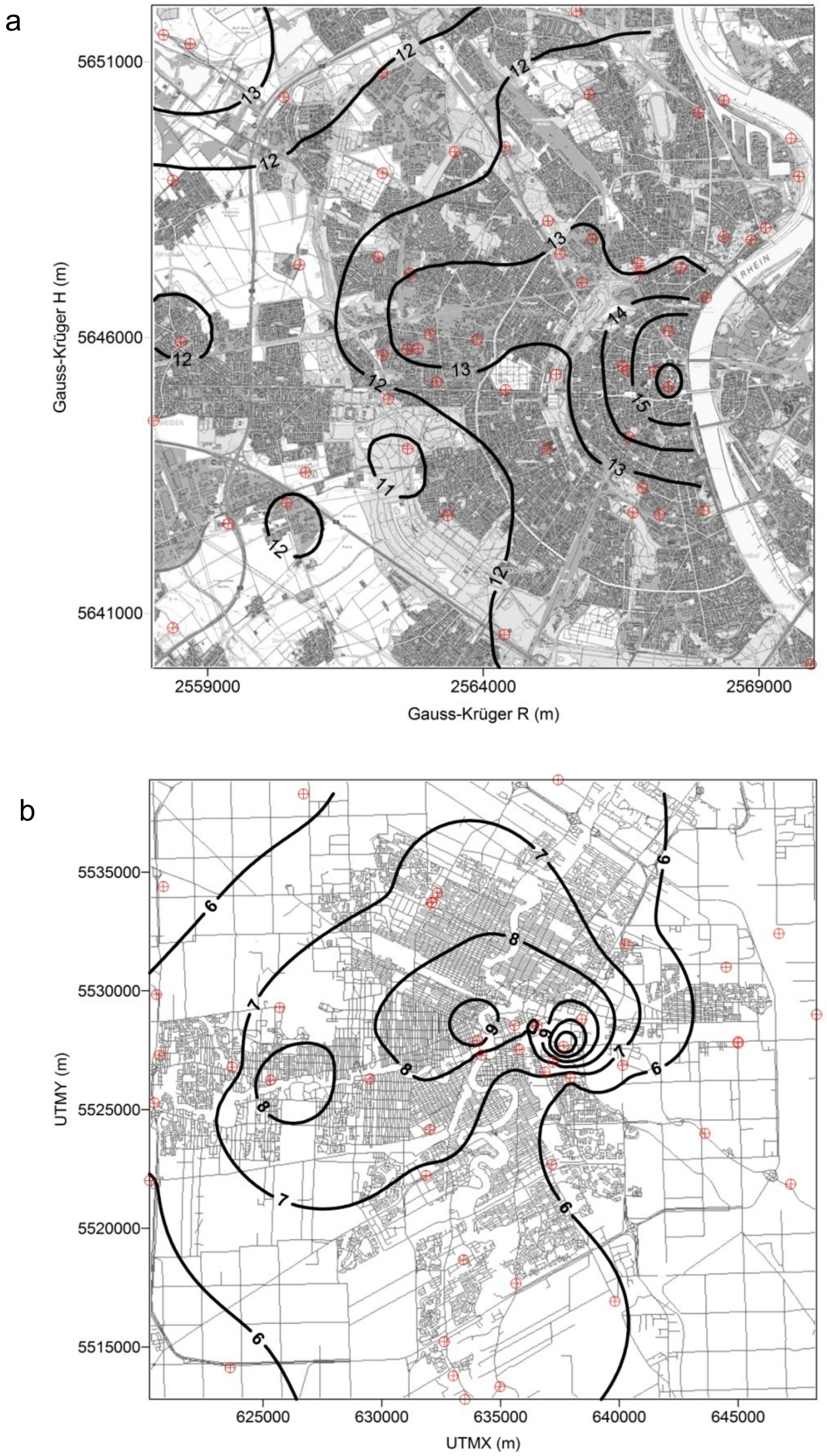

Fig. 3.3. Groundwater temperature contour map. a, Groundwater temperature contour map at about 15 m depth beneath Cologne in 2009; b, Groundwater temperature contour map at 20 m depth beneath Winnipeg in 2007.

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

Collected temperature data for both cities were contoured by kriging (Fig. 3.3). As reference depth, for the Winnipeg case 20 m below ground surface was selected. At this depth, approximately the centre of the Upper Carbonate Aquifer, borehole data is most exhaustive while noise from seasonal air temperature change is low. In Cologne, for the same reason, temperatures measured at about 15 m were used to construct isolines, which were smoothed and only the ones on the western side of the river Rhine were considered here. The measurement results indicate that in both cities the shallow aquifers in the center are several degrees (3-5 °C) warmer than in the surrounding rural areas. Similar to the experience with urban air temperature, the observed subsurface temperature is correlated to the population density and land cover (Ferguson and Woodbury 2007). The subsurface beneath green spaces in the cities have lower temperatures than business districts in the city centers, and the agricultural areas always have the lowest underground temperatures.

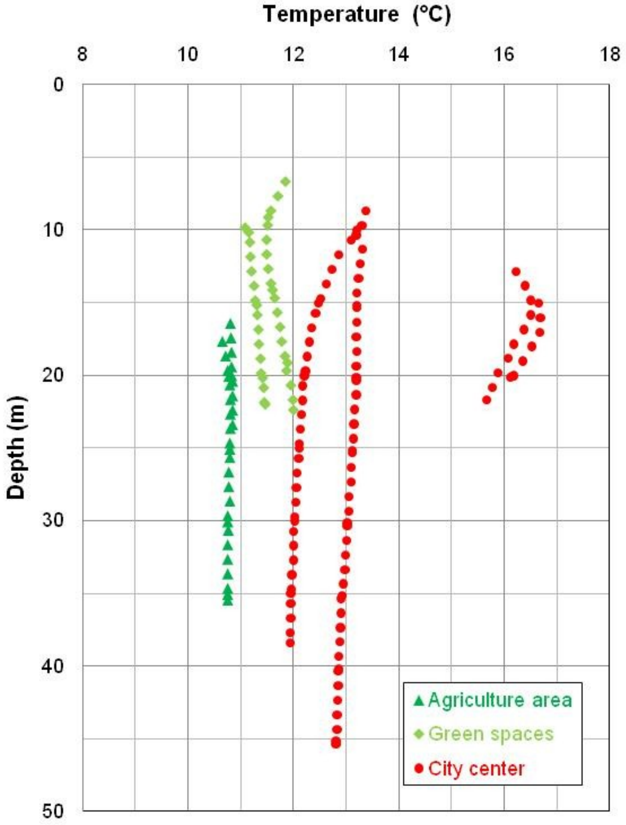

Fig. 3.4. Temperature profiles of selected wells in Cologne in 2009.

The nature of typical vertical temperature profiles depend on location and depth. This is illustrated by selected wells in Cologne (Fig. 3.4). The lowest temperatures prevail beneath the agricultural area. Values of 10.8 °C at 17 m depth were measured. The green spaces in the city have higher temperature, and apparently below 10 m depth, the temperature increases slightly. In the city center, much higher temperature prevails and profiles vary substantially from well to well. And in most observation wells, temperatures at 15 m depth are above 12 °C. The highest temperatures appear in two observation wells, one of which is near a large underground parking lot and the other next to a dining hall. Similar patterns of temperature distributions were also found in Winnipeg (Ferguson and Woodbury, 2007a), with higher and more variable subsurface temperatures in the city center and cooler underground in the green spaces and agricultural land. Since natural geothermal anomalies are not known for both Cologne and Winnipeg, the underground anthropogenic thermal loss appears to be the primary cause of the heightened subsurface temperature.

3.3. Geothermal potential

Geothermal energy use of shallow aquifers is on the rise, and anthropogenic anomalies represent increased thermal energy reservoirs. This is of even more importance for highly urbanized cities with higher heating demand compared to the surrounding countryside. The theoretical geothermal potential (i.e. the potential heat content) below Cologne and Winnipeg can be estimated. The three-dimensional non-uniform subsurface temperature distribution is simulated by measurement data interpolation and extrapolation, at a grid size of 500 m by 500 m in east-west and north-south direction and 1 m in vertical direction. Based on the temperature field and known hydrogeological conditions (Table 3.1), the potential heat content can be estimated by the following equation after Balke (Balke, 1977):

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

in which, Q (kJ) is the total theoretical potential heat content of the aquifer, V (m^3) is the aquifer volume, n is porosity, C_w and C_s ($kJ \cdot m^{-3} \cdot K^{-1}$) are volumetric heat capacity of water and solid, Q_w and Q_s (kJ) are the heat content stored in groundwater and solid respectively, ΔT (K) is the temperature reduction of the whole aquifer. According to the German engineering guideline VDI 4640 (VDI4640, 2000), C_w of water is 4150 kJ m^{-3} K^{-1}, C_s has a range depending on sediment types, and for Cologne and Winnipeg ranges between 2100 and 2400 kJ m^{-3} K^{-1}. To cover all possible conditions, maximum, minimum, and mean values were chosen for C_s as well as for porosity n. The latter values are based on literature (Matthess, 1994) and field pumping tests conducted by the regional water association called Erftverband (Voigt and Kilian 2007).

The total aquifer volume was divided into small units according to the grid size, and the heat content Q of each unit was calculated with specific ΔT by subtracting the local or simulated local temperature by average temperature in agricultural area. The sum of Q for the entire area of the 20 m thick aquifer is between 9.8×10^{12} kJ and 1.1×10^{13} kJ (7.0×10^{10} to 7.9×10^{10} $kJkm^{-2}$ on average in the urban area around 140 km^2), which stands for the increased heat content mainly caused by urbanization effect in Cologne. For geothermal use, in principle, the aquifers’ temperature could be technically decreased to 0 °C, but energy extraction is most efficient at relatively high temperatures. Because of this decrease in efficiency and also due to environmental potential concerns, the extractable energy only reflects a decrease of few degrees. Here, the temperature reduction value was set between 2 to 6 K, the lower value of this range is close to the average temperature increase in Cologne and the upper value is the minimum threshold as recommended in legal regulations such as laws and guidelines of several countries (Hähnlein et al., 2010). Aquifer volume is calculated as the product of approximate aquifer thickness and urban area where the temperature within the depth of the aquifer is higher than the one in the agricultural area. Again, a range of reasonable values, according to field tests and literature, is considered to reflect the uncertainty in specifying this parameter.

Table 3.1. Heat content estimation of the aquifer in Cologne and Winnipeg

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

[a](Ferguson and Woodbury, 2005b); [b]VDI 4640; [c]Matthess, 1994; [d]Data from natural Resources Canada

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

3.4. Discussion and Conclusions

Subsurface warming trends were also discovered in other large cities with rapid urbanization rates all over the world. The potential geothermal energy contents in the various cities are also determined using estimated hydrogeological conditions, and maximum and minimum values of parameters are used in order to cover the possible range and to reflect the uncertainty (Table 3.2). The magnitude of the subsurface temperature reduction is also set to 2-6 K, for the same reason as is applied in Cologne. Due to the difficulty of getting the specific annual space heating demand for each city, the values are preliminary estimates based on national statistical data on space heating, total population, and the city population density (Stulc 1998, Headon 2009). Table 2 indicates that in most cities, with a variety of populations and climates, the large amount of thermal energy stored in the urban local subsurface is capable of fulfilling the annual space heating demand at least for years. Cities with a longer history of urbanization usually have influence on the subsurface temperature at greater depth, due to the early start of additional heat (Taniguchi *et al* 2007). They accordingly have higher potential heat content in the aquifers. In the mega city of Shanghai, the existing heat content in the urban aquifer is at least 22 times the annual heating demand of the city. Considering that aquifers are dynamic systems and that the energy of the subsurface is slowly but continuously replenished, the geothermal potential here is technologically possible to supply space heating for even hundreds of years.

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

Since these technologies are based on energy transfer through closed BHE or open wells, even by dense galleries uniform extraction of the artificially increased heat of the urban subsurface is hardly possible. The ratio between producible and stored thermal energy in a given volume of reservoir is expressed as recovery factor R. The study by Muffler and Cataldi (1978) showed that R may be as much as 0.5 for an ideally permeable hot-water system, while Iglesias and Torres (2003) assumed a constant value of 0.25 for R in their estimation of low- to medium-temperature geothermal reserves. These figures reflect case-specific conditions and there is no generally valid value of R for urban aquifer systems. However, note that the geothermal potential (Table 3.2) in the current study focuses on the component that is artificially increased beneath cities. Therefore, even for recovery factors below 0.5, the technologically utilizable geothermal potential is very high. In order to only exploit the additional energy stored beneath cities, for instance, geothermal systems could be operated that cause more pronounced local temperature anomalies ($> \Delta T$). This also triggers heat conduction to further energy supply and establishes a regional temperature decrease. In many situations it will be possible to recover nearly all of the additional energy due to urbanization with heat pump technologies, but this will require local temperature decreases below background values near the extraction point.

Table 3.2. Heat content and heating demand estimation for selected cities

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

[e] City Population, 2010; [f] Spitz and Moreno, 1996; [g] Zhang et al, 2007; [h] WADE, 2005; [i] Hayashi et al, 2009; [j] Taniguchi et al, 2007; [k] Data from Angency for Natural Resources and Energy (Japan), 2009; [l] Headon et al, 2009; [m] Report: Energy Consumption in the UK, 2007; [n] Yalcin and Yetemen, 2009; [p] Sectoral energy consumption statistics, 2005; [q] Stulc, 1998; [r] Data from Czech statistical office, 2009

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

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

4. Analysis of groundwater temperature evolution in the subsurface urban heat island of Cologne, Germany

Worldwide, long term heating of shallow urban aquifers is observed. Our measurements in the city of Cologne, Germany, revealed that the groundwater temperature measured in the city center is more than 5 K higher than the undisturbed background. In order to explore the role of groundwater flow for the development of subsurface urban heat islands (UHIs), a numerical flow and heat transport model is set up to describe the hydraulic conditions of Cologne and to simulate transient evolution of thermal anomalies in the urban ground. A main focus is on the influence of horizontal groundwater flow, recharge and trends in local ground warming. A local hot spot with a length of 1 km of long term ground heating is defined. In different scenarios, the simulated temperature profiles at upstream, central and downstream of this hot spot reveal that, the main thermal transport mechanisms are long-term vertical diffusive heat input, horizontal advection and transversal dispersion, and groundwater recharge and hot spot size do not play an important role. By comparison between the various hot spot scenarios and measured profiles, the complexity of urban subsurface thermal conditions is better understood.

4.1. Introduction

In the last century, a strong warming trend in urban subsurface has been revealed in many large cities such as Tokyo, Bangkok and Berlin (Taniguchi et al., 2007; Menberg et al., 2013a). Field studies in North America (Ferguson and Woodbury, 2007; Wang et al., 1994), Europe (Allen et al., 2003; Balke, 1977; Bodri and Cermak, 1997; Dědeček et al., 2011; Perrier et al., 2005; Yalcin and Yetemen, 2009, Menberg et al. 2013), and Asia (Taniguchi et al., 2007; Huang et al., 2009; Yamano et al., 2009) have indicated a rise of the regional urban underground temperature by 2 K to 5 K. Higher aboveground temperatures increase the vertical diffusive heat flux into the ground， and thus groundwater temperature is generally closely linked to air temperature. The factors that raise the atmospheric temperature in cities and lead to the evolution of atmospheric urban heat islands (UHIs) are also responsible for ground warming. These factors are, for example, solar heating of massive urban structures such as buildings, and sealed surfaces such as roads and parking lots. UHIs in the subsurface are augmented by further non-climatic perturbations such as in-ground heat losses from buildings, landfills, underground parking lots and subway tunnels, as well as from buried electrical power lines, district heating networks, sewage water canals and leakages (Balke, 1977; Pollack et al., 1998; Menberg et al., 2013b).

Temperature fluctuations at the surface or in shallow depth penetrate further into the ground. They can be seen in borehole temperature logs as deviation from the unperturbed, natural temperature profiles (Huang et al., 2000; Taniguchi et al., 2007). However, even unperturbed profiles do not trace a constant atmospheric temperature from the past. Numerous studies in borehole climatology examined vertical temperature logs that are not suspected of being affected by non-climatic factors. Most of them identified a warming trend and increasing downward heat flux during the last century (e.g. Hopcroft et al., 2009; Huang et al., 2000; Mareschal and Beltrami, 1992; Perrier et al., 2005; Pollack et al., 1998). Only a few focused on perturbed profiles (e.g. Taniguchi et al., 1999; Gunawardhana et al., 2011a, b). Urban ground surface temperature history was interpreted for example by Yamano et al. (2009), who logged more than 100 boreholes of generally 100-250 m depth in the Asian megacities Bangkok, Jakarta, Taipei and Seoul. It was discovered that ground surface temperatures substantially increased during the last century, much more than could be inferred by analytical inversion from logs in rural surroundings. Repeated measurements in some boreholes were carried out by Hamamoto et al. (2008) to inspect the stability of the temperature logs. Instability at greater depths (without seasonal influence) was considered to be an indicator in variability of groundwater flow velocity. Perturbation of the logs by advective heat flow was also assumed to be the reason that unrealistic surface cooling was inferred for the time before 1900, since their forward model assumes vertical conduction only.

Plenty of previous studies to analyze borehole logs and subsurface heat transport are based on the assumption that conduction is the dominant form (e.g. Pollack, 1998; Beltrami, 2002, 2006). The assumption of one-dimensional vertical heat conduction might not be suitable in mixed, conduction-advection controlled systems (Bense and Beltrami, 2007; Ferguson, 2005), which are characteristic in the presence of groundwater. For instance, downward groundwater flow might change temperature profiles into the shape which looks similar to the one caused by surface warming, and the initial and boundary conditions are not always linear (Kurylyk and MacQuarrie, 2013). Accordingly, for subsurface UHIs, applicability of analytical reconstruction methods established in borehole climatology is restricted. Suzuki (1960) and Stallman (1963) provided solutions to solve one dimensional conduction-advection equation, which can be used to estimate vertical groundwater flow rate but require given surface temperature distribution. Even both vertical and/or horizontal advection components and surface temperature changes can be included in analytical solutions (Domenico and Palciauskas, 1973; Lu and Ge, 1996; Reiter, 2001, Taniguchi & Uemura 2005), limitations remain, as for instance, typical layering of aquifers and thermal dispersion are neglected. Furthermore, for many cities, deep boreholes are typically rather scarce. This limits monitoring of continuous temperature profiles down to the undisturbed geothermal gradient. Alternatively, a numerical modeling framework may be adopted (Ferguson & Woodbury 2004, 2007; Liu et al. 2011). While a numerical model can be more flexible and accurate, this comes on the expense of an enormous data requirement. This can be a limiting factor, especially in urban environments, where multiple different factors act and interact, and which can hardly be resolved in all details. Ideally, the selected numerical approach finds a compromise between data requirements and accuracy, which is intended in our study.

The main objective of the present study is to understand the interplay of conductive and advective forces during the evolution of a subsurface UHI, and especially to explore the role of regional horizontal groundwater flow. We focus on the city of Cologne, Germany, where repeated measurements in the shallow groundwater revealed elevated temperatures by more than 5 K in the city center (Zhu et al., 2009; Menberg et al., 2013a). Little is known about the long-term effects that lead to the extensive subsurface UHI reaching a depth of more than 100 m. The currently available information is insufficient for a detailed numerical study including all natural and anthropogenic urban heat sources. Instead, the bulk effect is studied by considering potential long-term trends of increased ground temperatures, which are implemented in a site-specific, simplified numerical ground-water flow and heat transport model.

4.2. Methodology

The methodology of this study is shown in a flow chart in Fig. 4.1. First, the case study of Cologne is introduced, and the data survey and measurements in the study area are described. Then, a three-dimensional (3D) groundwater flow model is developed to capture the regional hydrogeological conditions. Based upon the groundwater flow model, first a 3D and then a cross-sectional, two dimensional (2D) flow and heat transport model are derived to examine different scenarios with variable assumptions for elevated ground temperatures, recharges, and advective-dispersive effects from horizontal groundwater flow. By comparison of simulated to measured groundwater temperature-depth (GWTD) profiles, the main factors that influence subsurface UHI heat transport are discussed.

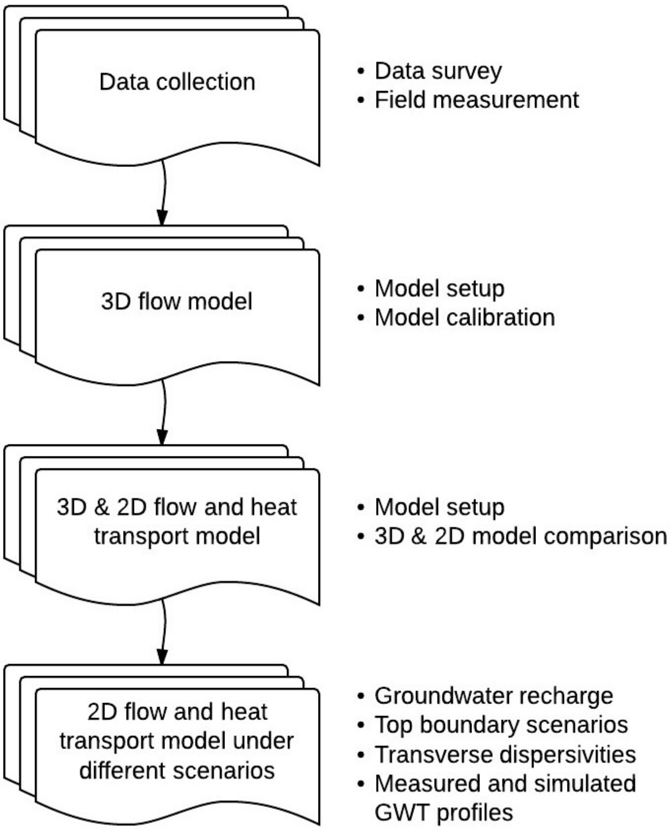

Fig. 4.1. Building blocks for simulation of governing processes for evolution of subsurface urban heat island.

4.3. Data collection

4.3.1. Data survey

This case study is conducted in the city of Cologne, where the climatic, such as past air temperatures (Fig. 4.2), geological and hydrogeological information was collected.

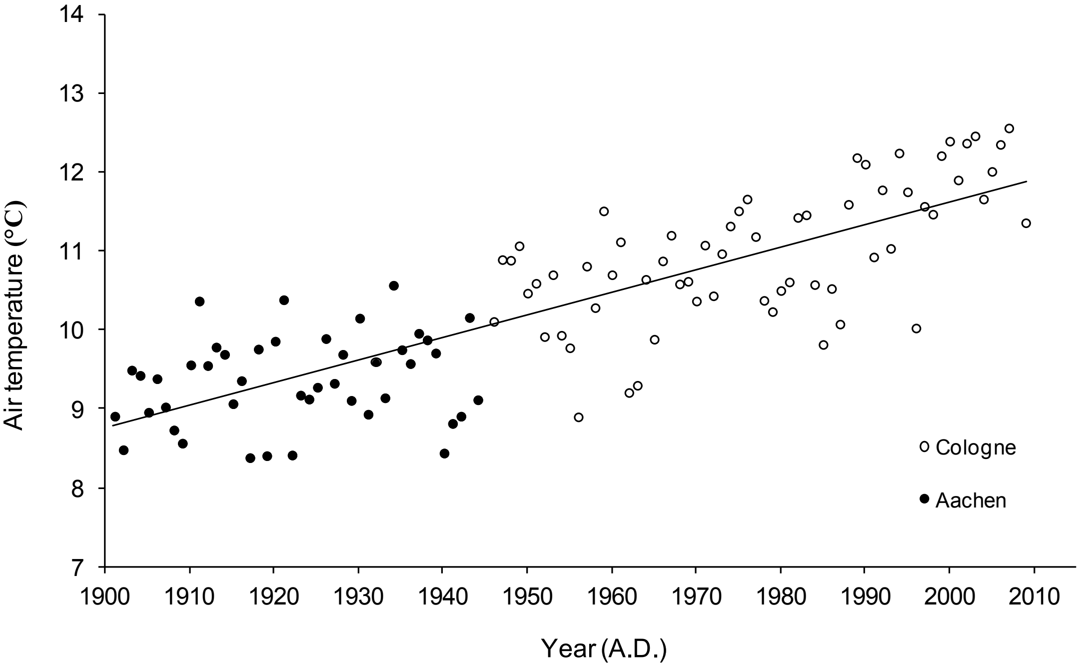

Fig. 4.2. Mean annual air temperature recorded from 1900 to 2010 by a weather station in Stammheim in the north-eastern part of Cologne, and by a weather station in Aachen (DWD, 2010).

The city of Cologne lies on the Rhine River. It is one of the largest cities in Germany, with a population of around one million. We focus on the main city parts, which is located on the western side of the Rhine. The study area is depicted in Fig. 4.3, which also illustrates the subsequent model implementation.

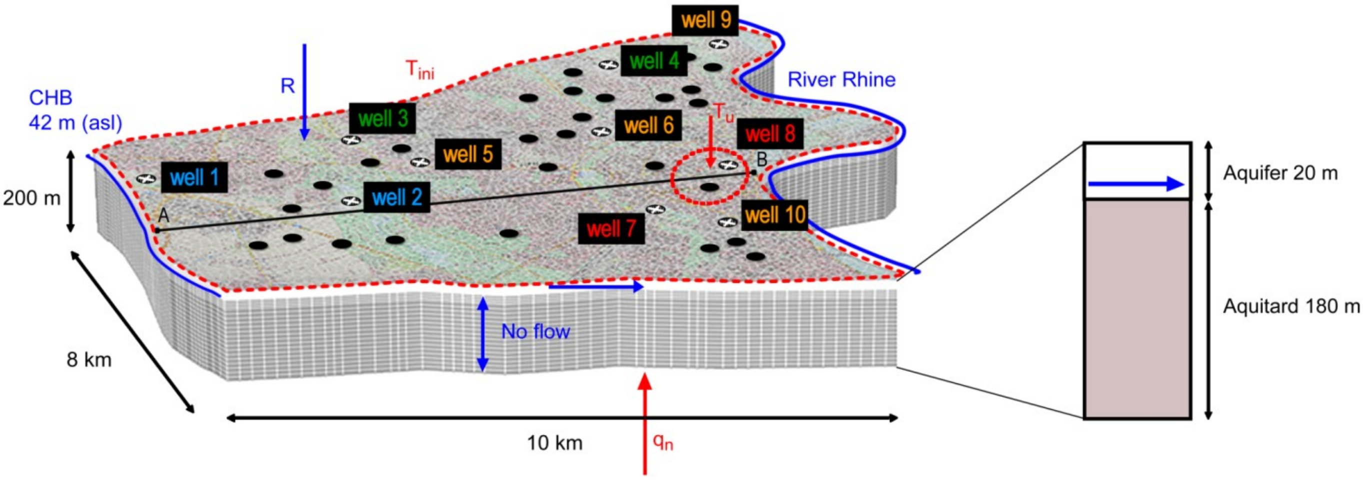

Fig. 4.3. Three-dimensional (3D) conceptual model of the case study of Cologne including hydraulic and thermal boundary conditions, observation wells and a simplified vertical hydrogeological profile (*CHB*: constant head boundary; *R*: groundwater recharge; T_{ini}: initial temperature; T_u: urban temperature; q_n: natural geothermal heat flux). Cross-section A-B indicates the studied two-dimensional (2D) flow and heat transport model.

The mean annual air temperature back in 1900, when the city in Cologne started growing fast, is about 8.7 °C (Fig. 4.2). Since no earlier air temperature measurements are available for Cologne, we added data from 1900 to 1945 recorded in Aachen, which is only 70 km away from Cologne. Linear regression for the whole period since 1900 reveals a mean linear increase of around 0.03 °C per year. The average regional annual precipitation from 1961 to 1990 was around 774 mm (DWD, 2006), with a maximum value of 825 mm recorded in 1966 and a minimum value of 343 mm in 1959. Groundwater recharge in Germany is commonly only about 16% of the precipitation (BGR, 2008) and is mainly concentrated in the winter period, when vegetation is least active.

Cologne is underlain by Quaternary terrace deposits that host a shallow aquifer with a thickness of around 20 m (Klostermann, 1992), and the major components of the urban aquifer are sands and gravels (Losen, 1984). The underlying aquitard consists of clays, silts, lignite and soft coals mixed in with thin sandy layers reaching to a depth of about two hundred meters (Balke, 1973; Hilden, 1988). The groundwater flow velocity in the aquifer is around 1 m per day (Balke, 1973). The groundwater flows towards the north-east and finally discharges into the Rhine River.

4.3.2. Field measurement

In three measurement campaigns in October 2009, September 2012 and December 2012, groundwater levels were measured. In 2009, data from 72 wells in the city, suburban and surrounding rural area were collected (Zhu et al., 2010). Out of these, there are 46 wells located within study area (Fig. 4.3). In 2012, the piezometer levels of 15 wells were repeatedly recorded in the city. The measurements indicate that the water table is relatively stable in most of the wells distant to the river, but especially in the north-eastern part near the river the water levels vary by more than 1 m (data not shown). Despite this local and temporal variability, however, the derived main groundwater flow direction is always from West towards East with a gradient ranging between 5 × 10-4 and 7 × 10-4, and no river infiltrating conditions are observed.

In the present study, we focus on the groundwater temperature data as reported by Zhu et al. (2010). GWTD profiles at 1 meter interval were recorded using SEBA KLL-T logging equipment. Well diameters range from 2 to 5 inch (0.05 to 0.127 m), and the wells reach depths between 20 and 44 m. The positions of these wells are spatially distributed and associated with different types of land use, including built environment, green spaces and agricultural area. Within the temperature measurement of 46 wells, ten wells (see Fig. 4.3) with characteristic GWTD profiles (Fig. 4.4) for undisturbed agricultural area (wells 1, 2), green spaces (3, 4), and built environment in the city (5-10), covering different land use types and the measured temperature ranges, are chosen for further study.

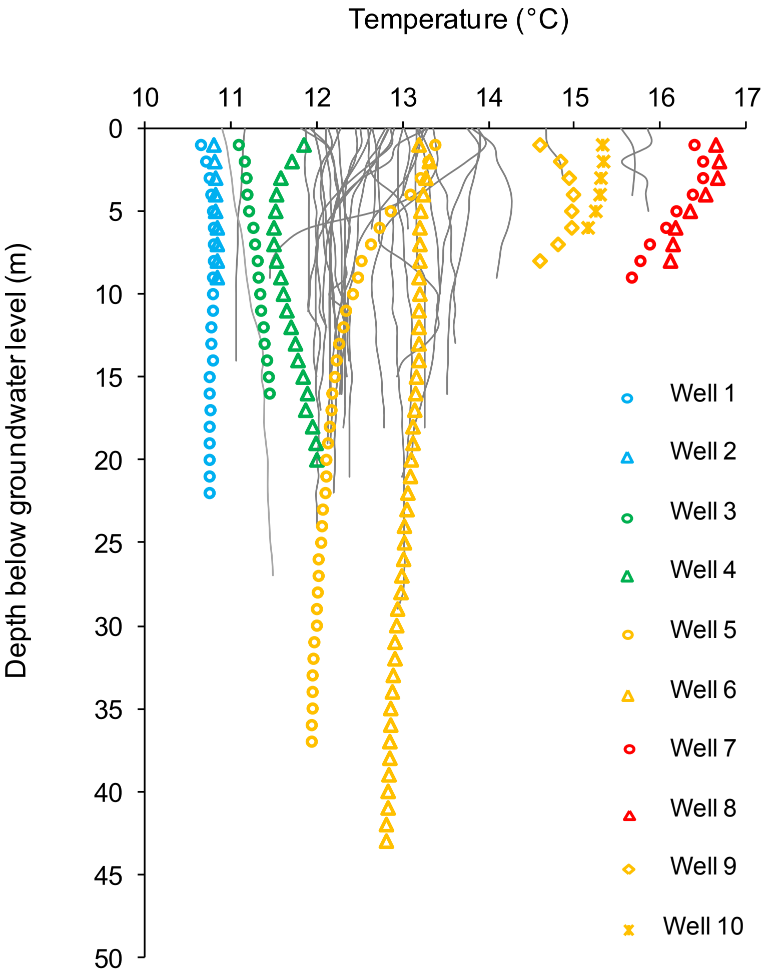

Fig. 4.4. Measured groundwater temperature-depth (GWTD) profiles in Cologne. From the 46 profiles, those from wells 1-10 are selected as representatives for specific urban environments and examined further in Fig. 4.13.

4.4. Regional 3D groundwater flow model

A 3D numerical groundwater flow model that delineates the major hydraulic conditions of the shallow aquifer system was set up with FEFLOW (Version 6.0, Diersch, 2009), a finite element groundwater flow and transport simulator. The modeled area comprises 120.14 km^2 (Fig. 4.3). It covers the main city area on the western side of the Rhine and part of the surrounding suburban areas. The numerical model consists of 40 layers, is about 200 m thick, and has a total of around 260,000 nodes. The upper 20 layers, each with a thickness of 1 m, represent the main aquifer followed by 20 layers with variable thicknesses from 2 to 10 m corresponding to the aquitard below. The aquifer is unconfined, and steady-state hydraulic conditions are simulated. The high resolution of the aquifer is chosen to characterize small-scale vertical temperature variabilities, with steepest thermal gradients expected in the upper part of the model. To limit the computational effort, the vertical grid size in the aquitard increases with depth.

Boundary conditions of the model are obtained from the groundwater level contour map and river head provided by the local water association (Erftverband, 1995). The boundaries at the north and south are oriented perpendicular to the groundwater head contours, and hence no flow boundaries are assigned (Fig. 4.3). The western boundary is chosen by the mean groundwater head isoline of 42 m above sea level (asl) in the countour map, which is far beyond the built urban area. The Rhine River is represented in the model as an eastern head-dependent boundary. The groundwater table, i.e. the upper boundary of the alluvial aquifer, is simulated as a free-surface boundary. Groundwater recharge, which is subsequently be determined by model calibration, enters the aquifer through the top-most active layer.

To obtain a representative model setting, first, value ranges of uncertain hydraulic model parameters are investigated, which are listed in Table 4.1. Hydraulic conductivities of aquifer, porosity and hydraulic gradient of the model domain are obtained from reported values of local groundwater models and pumping tests (Balke, 1973; Voigt and Kilian, 2007). For the aquitard, typical ranges of the hydraulic conductivity and porosity of clays and silts are defined (Freeze and Cherry, 1979; McWhorter and Sunada, 1977). The average observed recharge rates between the year 1971 and 1990 (Erftverband, 1995) rang from 205 to 268 mm/a, the average velue of 237 mm/a is taken as initial maximum value for our study area. As lower bound for the range of recharge rates, we choose 5 % of the average observed precipitation (774 mm/a) from 1961 to 1990 (DWD, 2006), which equals 39 mm/a.

Table 4.1. Reported value ranges, selected and calibrated model parameter values for the 3D groundwater flow and 2D flow and heat transport model

Parameter	Value range	Model input	Calibrated (this study)	Reference
Hydraulic conductivity of aquifer (m s^{-1})	$8.0 \times 10^{-4} – 7.0 \times 10^{-3}$		3.0×10^{-3}	Voigt and Kilian (2007)
Hydraulic conductivity of aquitard (m s^{-1})	$1.0 \times 10^{-8} – 1.0 \times 10^{-6}$		1.6×10^{-7}	Freeze and Cherry (1979)
Groundwater recharge (mm a^{-1})	39 – 237		67.2	Erftverband (1995) DWD (2006)
Porosity of aquifer (-)	0.15 – 0.25	0.2		Balke (1973)
Porosity of aquitard (-)	0.14 – 0.57	0.3		McWhorter and Sunada (1977)
Thermal conductivity of porous media in aquifer (W m^{-1} K^{-1})	1.7 – 5.0	2.1*		VDI 4640/1 (2000)
Thermal conductivity of aquitard (W m^{-1} K^{-1})	1.1 – 5.1	1.9*		VDI 4640/1 (2000)
Water thermal conductivity (W m^{-1} K^{-1})		0.6		VDI 4640/1 (2000)
Heat capacity of minerals (MJ m^{-3} K^{-1})	2.1 – 2.4	2.2		VDI 4640/1 (2000)
Water heat capacity (MJ m^{-3} K^{-1})		4.2		VDI 4640/1 (2000)
Longitudinal dispersivity (m)	5 – 20	10		Gelhar et al. (1992)
Transverse dispersivity (m)	0.05 – 1.0	0.03		Maier and Grathwohl (2006)

* Please note that FEFLOW input values for thermal conductivity of aquifer and aquitard, 2.1 and 1.9 W m^{-1} K^{-1}, refer to the arithmetic mean of solids and water saturated pore space. The corresponding geometric mean values are therefore 2.3 and 2.2 W m^{-1} K^{-1}, respectively.

Porosity values of aquifer and aquitard are fixed in the model domain and based on reported averages (Table 4.1). The values of hydraulic conductivity and recharge rate are adjusted within the given ranges by hydraulic head calibration with support of the parameter estimation software PEST (Version 12, Doherty, 2010). For this, simulated groundwater levels are compared to mean measured groundwater levels at the 46 selected observation wells (data can be seen in Appendix Fig. A-1). The obtained average head difference is 0.13 m, and only two wells near the river showed a discrepancy larger than 0.5 m. The model accuracy is calculated using the root mean square error (RMSE) between actual measurements of hydraulic head and model generated hydraulic head at the end of each model run. The minimal RMSE is about 0.32 m and the normalized RMSE is 5%, which is considered acceptable. The resulting water flow balance of the 3D groundwater flow model is provided in Table 4.2.

Table 4.2. Flow balance of the 3D groundwater flow model of Cologne.

	Inflow (10^3 m^3d^{-1})	Outflow (10^3 m^3d^{-1})
Constant head boundary in the west (CHBW)	81.33	-
Groundwater recharge	19.65	-
Sum of CHBW and groundwater recharge	100.98	-
River boundary in the east	-	101.00

4.5. 3D & 2D flow and heat transport model

The regionally calibrated steady-state 3D flow model describes the hydraulic conditions of the shallow aquifer, such as main flow direction, mean hydraulic gradient and groundwater flow velocity. We choose steady state in order to approximate the long term mean of recurrent and periodic conditions in the flow regime, while keeping the modelling effort on a reasonable level. However, urban groundwater temperature are expected to follow long-term trends, and thus transient conditions are favored in the subsequent coupled 2D flow and heat transport model.

The values of the thermal properties are chosen based on previous studies in the Cologne area (Balke, 1977) and further literature sources (Gelhar et al., 1992; Maier and Grathwohl, 2006; VDI-4640/1, 2000) (Table 4.1). In order to eliminate the vertical influence of seasonal temperature fluctuation, the groundwater level, which is around 10 to 12 m below the surface, is taken as top boundary for the heat transport simulation. The simulation is initiated in the year 1900 with an initial temperature at the top boundary (T_{ini}) with 8.7 °C according to measured mean air temperature in the region (Fig. 4.2). The upward geothermal heat flux value in Cologne region of q_N = 59 mW m^{-2} (Balke, 1977) is expressed by a constant flux boundary at the bottom of the model (Fig. 4.3). Unspecified heat boundaries are assigned to the sides, with the river at the east having the same initial temperature as in the atmosphere (8.7 °C). The initial undisturbed temperature distribution is obtained by running the model for a burn-in phase of 10^8 days. Within this period, the model reaches quasi-steady state conditions, with a maximum temperature change of less than 10^{-5} K for 100 years.

The developed model describes undisturbed thermal conditions. By selecting such settings for 1900, we presume that more than one century ago, main potential anthropogenic heat sources such as reinjections of thermal wastewater and tunnels were absent (Menberg et al., 2013). This assumption is also discussed later. Although, it is hard to pinpoint the exact starting time of subsurface warming in Cologne, a large amount of heat flowing into the underground since the beginning of last century can be expected. As a consequence of urban industrialization the subsurface temperature significantly increased in the last century. Hence, various scenarios of inceasing temperatures at the top are investigated, including background temperature rise (linear increase as air temperature in Fig. 4.2), linear and step increase from 1900, 1955 and 1975 (Fig. 4.5). The total simulation time is set to 110 years, from 1900 to 2010. Among the studied scenarios, linear increase from 1900 (8.7 °C) to 2010 (15 °C, measured in the groundwater in the city center of Cologne) is considered as the urban reference case here. While this linear increase is the most straightforward option, we might also expect much more dynamic evolution of thermal inputs in the ground. As alternatives, thus step-functions are defined, which for example could reflect the instantaneous effect of heat loss from additional new buildings. Comparison between the simulated results for these different trends will facilitate to judge their sensitivities.

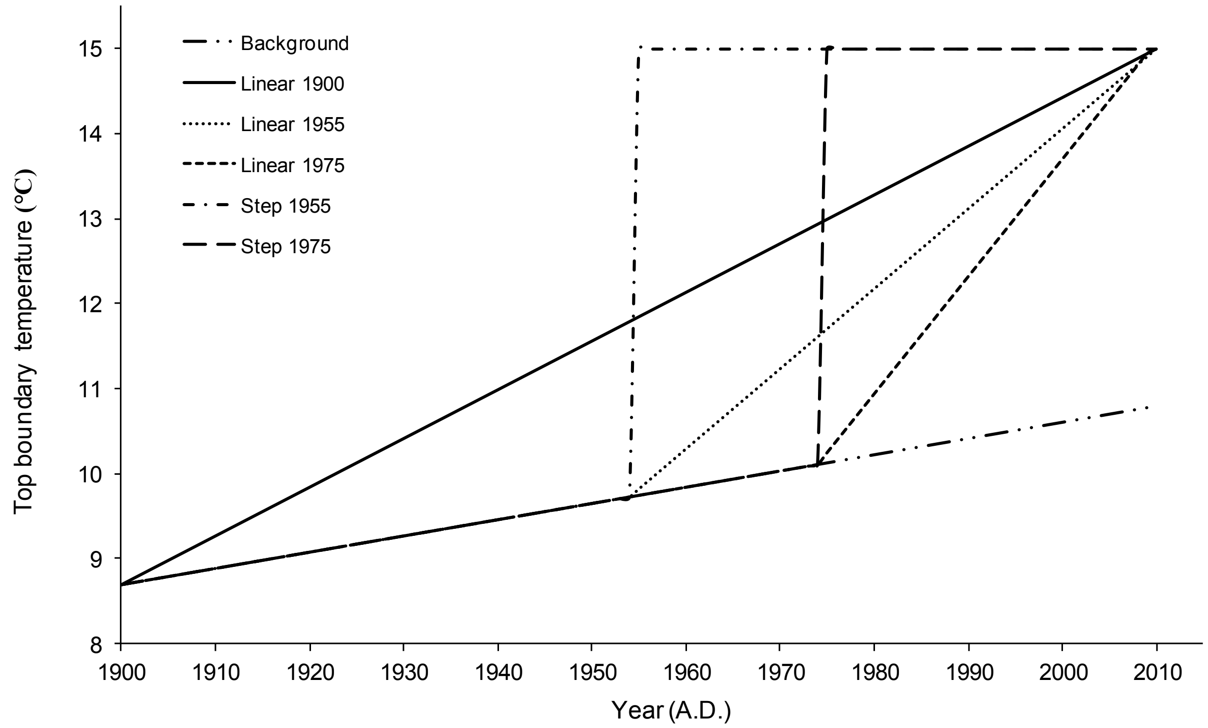

Fig. 4.5. Scenarios of transient temperature boundary conditions (from 1900 to 2010) applied to control groundwater temperature at hot spot of the model.

Detailed simulations of spatial development of potential heat sources over time as a consequence of city growth is beyond the scope of this study. Instead, an idealized hot spot of fixed size is initially defined, which is located at the city center. It encompasses a circular area with 1 km diameter, where the effect of the different transient top boundaries are assessed. The hot spot can be interpreted as a cutout of the city, an urban district with elevated temperature, which is separately examined. This means, potential lateral interaction, such as different adjacent heat sources, or large scale expansion of the area of increased ground heat flux is currently not accounted for in the model, which is also consequently discussed. At the hot spot, we are primarily interested in the evolution of the induced thermal anomaly in the vertical and groundwater flow direction (along A-B, Figs. 4.3 and 4.6), and thus specifically inspect the cross section through the center (Fig. 4.3). To simplify the model and shorten simulation time, for this cross section A-B, an equivalent 2D vertical steady state flow and transient heat transport model is constructed and, for validation, compared with the 3D model results (Fig. 4.6). Analogous to the 3D model, the hydraulic boundary on the western side (A) of the 2D model is a constant head of 42 m and on the eastern side (B) is the river of a depth of 20 m, with a head of 36.5 m. The 2D model has a length of 10 km and a thickness of 200 m. Same spin-up simulation was applied and results show the same initial vertical temperature distribution as the 3D model. To emulate the hot spot, different increasing temperature scenarios were assigned at the top boundary of the 2D model, from 9 km to 10 km. After 110 years simulation time (1900-2010), the difference of temperature distribution between 2D (Fig. 4.7) and 3D cross section reveals to be minor with a maximum temperature difference along the profile with < 0.2°C. With this accuracy, the computationally much more efficient 2D model is taken for the subsequent simulations.

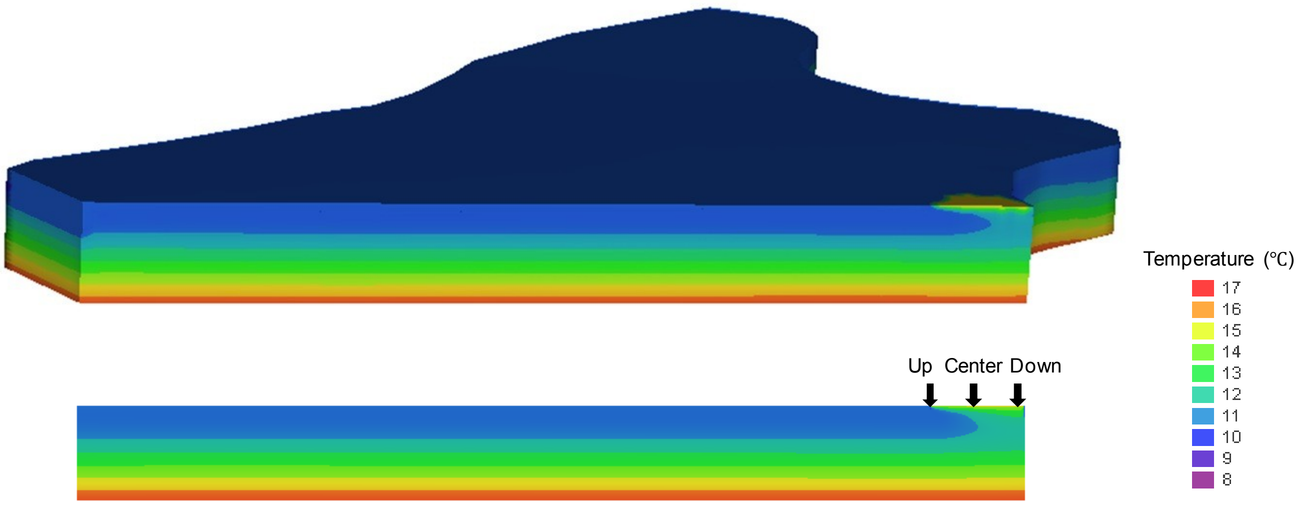

Fig. 4.6. Temperature distribution after 110 years simulation (reference case with linear temperature increase at hot spot) for selected cross section of 3D model and of emulated vertical 2D model.

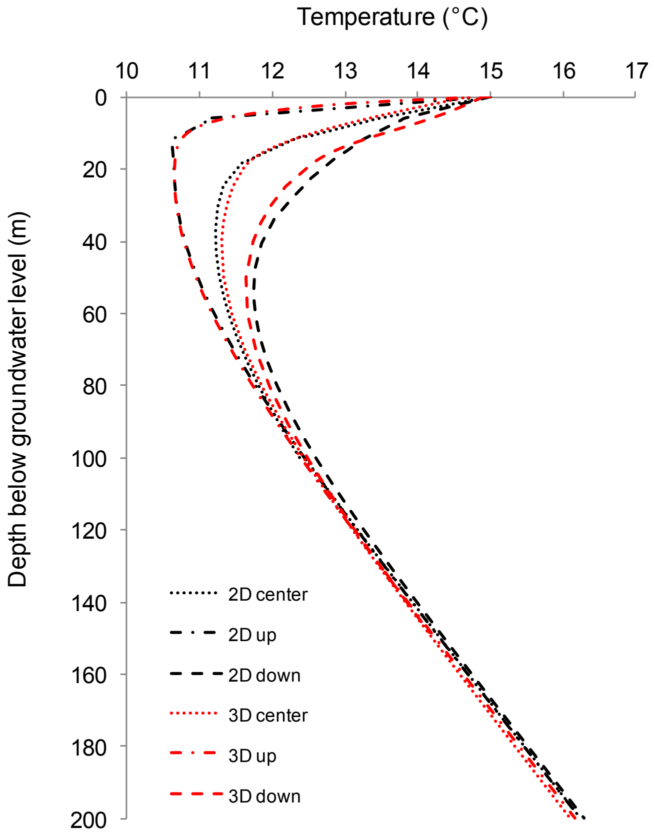

Fig. 4.7. Comparison of simulated ground temperature vertical profiles at different locations (upstream, center, and downstream) of the hot spot in 3D and 2D models.

First, the focus is set on the sensitivity of some potentially crucial model parameters. Thus, we envisage the role of the calibrated recharge value, and then analyse the impact of mechanical thermal dispersion, as quantified by the dispersivity, on the thermal evolution in the aquifer. With this insight, additional scenarios with different hydraulic-thermal conditions are compared to study the evolution of the groundwater temperature under undisturbed condition and with hot spots. In addition, the influences of different temperature top boundaries and hot spot size are discussed. The model results are juxtaposed to measured GWTD profiles in order to discuss the expressiveness of the hot spot based findings for Cologne.

4.6. Results and discussion

4.6.1. Influence of groundwater recharge on heat transport

Automatic calibration of the hydraulic conductivities and the groundwater recharge specified in the 3D flow model reveals that the inversion problem is not well posed, and a range of parameter value combinations produce equally satisfactorly predictions. However, the small given range of plausible hydraulic conductivity values constrains the associated range of reasonable groundwater recharge values ranging between 36 and 70 mm a^{-1}. The best fit is however obtained with 67.2 mm a^{-1} (Table 4.1), although several other close-optimal solutions exist. The essential question here is how sensitive this model specification and especially the recharge value is for the simulated results. Several previous studies indicated that vertical groundwater fluxes can cause temperature anomalies, and that in recharge areas geothermal gradients are smaller (e.g. Domenico and Palciauskas, 1973; Ferguson et al., 2006; Taniguchi et al., 2003). Furthermore, groundwater recharge can also accelerate shallow subsurface warming (Kurylyk and MacQuarrie, 2013).

Since around 70% of the study area is highly urbanized with sealed concrete surfaces, it is reasonable to expect such a small local effective recharge, 67.2 mm a^{-1}, from precipitation. The horizontal groundwater flow rate is orders of magnitude (10^3) higher than the recharge, thus it can be anticipated that for the study site the effect of recharge for the heat transport process is only minor. This is supported by trial simulations with negligable differences in subsurface temperatures for variants with and without recharge, which are not shown here. Under steady-state conditions and for constant surface temperature (i.e. initial undisturbed temperature distribution), the simulated GWTD profiles with recharge result in minor differences (< 1 % relative discrepancy) compared to the ones with no recharge (data not shown). A similar outcome was observed, for instance by Molina-Giraldo et al. (2011b), who could demonstrate the minor impact of groundwater recharge (using 300 mm a^{-1}) for their heat transport model of an infiltrating river in an aquifer. Gunawardhana et al. (2012) also demonstrate that comparing to a recharge of 200 mm a^{-1}, ground surface warming plays a more profound role in the temperature variation in the shallow subsurface.

Furthermore, for the urban reference case of 2D heat transport model, if we ignore the groundwater recharge at the top boundary, the temperature beneath the center of the hot spot only decreases by an average of 0.03 K along the first 50 m depth (data not shown). Nevertheless, in densely populated urban areas with high air and ground temperatures and higher groundwater recharges, more anthropogenic heat might also penetrate into the ground and advective heat transport by recharge has to be considered more carefully.

Foulquier et al. (2009), for example, observed that the thermal amplitude of groundwater can be increased dramatically by stormwater infiltration at seasonal and event scales.

We conclude that recharge is able to warm up groundwater, if the rainfall mainly occurs during warm seasons. Still, in undisturbed rural environments with the similar climatic conditions as Cologne, recharge from precipitation mainly occurs during cold seasons with a small amounts < 70 mm a^{-1}. Hence, recharge from precipitation in urban area is not considered a relevant driver for shallow subsurface warming. In contrast, anthropogenic heat sources such as leakage of sewage or water distribution networks might play a more prominent role. For example, the study by Lerner (1990) showed that urbanization reduces the groundwater recharge, but creates new and additional sources for recharge, such as leaking from water mains and sewers. Yang et al. (1999) observed in the city of Nottingham that only about 63 mm a^{-1} of total precipitation (700 mm a^{-1}) contributed to total urban recharge with 211 mm a^{-1}, of which the most originates from mains and sewer leakage.

4.6.2. Influence of groundwater flow for undisturbed condition

4.6.2.1. Vertical and horizontal groundwater flow

In the study site a shallow aquifer with substantial groundwater flow velocity of around 1 m d^{-1} exists, and thus horizontal advection is expected to play an important role for the evolution of the groundwater temperatures. Lu and Ge (1996) demonstrated that when the horizontal heat and fluid flow is greater than 30 % of the vertical one, it has a significant effect on the vertical temperature distribution. Ferguson et al. (2006) concluded that when the downward Darcy flux is smaller than 2.0×10^{-8} m s^{-1} (0.63 m a^{-1}), it does not significantly change the temperature profile under steady-state thermal conditions. In our study area, which is in a river valley, the dominant flow direction in the urban aquifers is horizontal, with significant flow rates about 1 m per day; while the vertical groundwater flux due to recharge is only around 1.9×10^{-4} m d^{-1} (0.07 m a^{-1}). And simulation results show that consistent with the criterion set by Ferguson et al. (2006), it only has a minor influence on the temperature profile with a temperature change < 0.03 °C.

4.6.2.2. Influence of transverse thermal dispersion

A mechanism, which has not been studied in this context, is the impact of the transverse thermal dispersion. Mechanical thermal dispersion in porous media is caused by moving heat carrying fluid, such as groundwater. The different flow pathways on the pore-scale create differential advection, and the mixing of the pore-scale interstitial water causes thermal dispersion. Macroscopic scale heterogeneity of a permeability field also contributes to thermal dispersion, and increases uncertainty of the transverse and longitudinal spreading of heat plumes in the subsurface (e.g. Ferguson 2007; Molina-Giraldo et al., 2011a).

In our high-velocity case, transversal dispersion can be expected to influence the vertical heat flow and the GWTD profile. The value of transverse dispersivity is however not exactly known and has not been especially examined for the Cologne area. In general, there are only few studies specifically dedicated to experimental or model-based estimations of thermal dispersivity (Molina-Giraldo et al., 2011a; Rau et al., 2012). Hence, we approximate the field-scale transverse dispersivity by Maier and Grathwohl (2006) with $\alpha_t = 0.03$ m, which was derived for a similar aquifer. Even higher values might occur in more heterogeneous environments. To examine the role of this uncertain parameter value in more detail, ground GWTD profiles simulated for undisturbed conditions are compared for different transverse dispersivities (α_t = 0 m, 0.03 m, 0.1 m and 1 m). With increase of dispersivity, the simulated vertical temperature gradient along the aquifer becomes smaller in the aquifer (Fig. 4.8). This is a similar effect as that from vertical groundwater flow, such as described, for example, by Taniguchi et al. (2003). Thus, macroscale mechanical dispersion reveals to be an important process, which accelerates vertical penetration of surface temperature variations in (sub-) horizontal groundwater flow regimes.

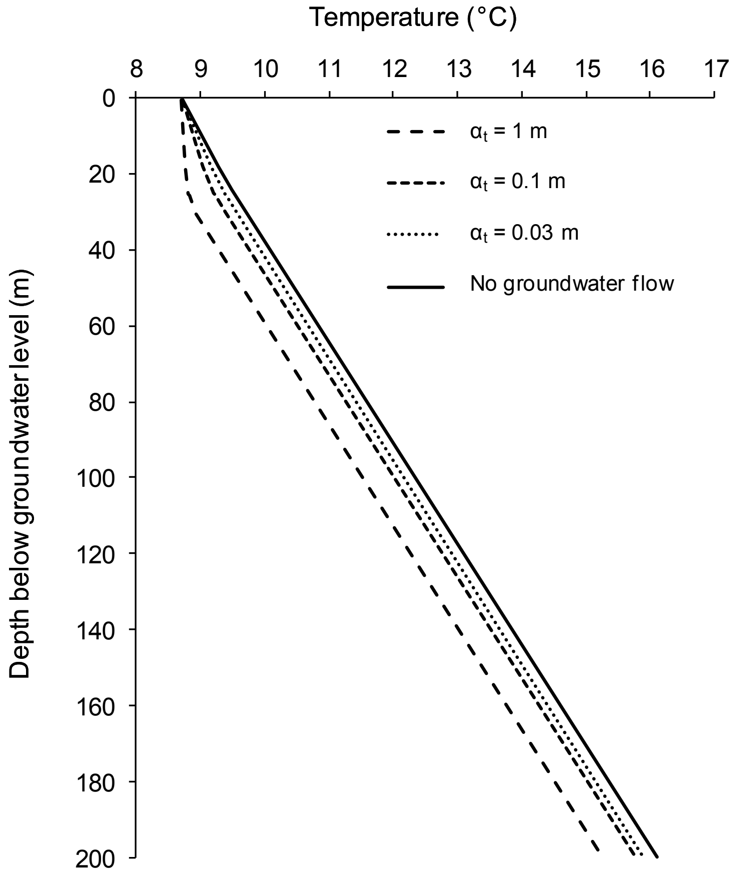

Fig. 4.8. Simulated initial undisturbed GWTD profiles under conduction-dominated condition (solid line) and flow conditions with different transverse dispersivity (α_t) values.

4.6.3. Influence of groundwater flow with local heat sources

4.6.3.1. Different temperature top boundaries

As illustrated in Fig. 4.8, the effect of horizontal groundwater flow under steady-state thermal conditions on ground temperature evolution is governed by the transversal dispersion. In comparison, Fig. 4.9 shows simulated GWTD profiles at different locations (upstream, center, and downstream) of the hot spot, given transient conditions with different top boundary temperature increasing scenarios (Fig. 4.5). The dispersivity is not varied here and set the default value of $\alpha_t = 0.03$ m. The simulated profiles are comparable in the upper part, down to the aquifer basis at 20 m, as well as in a depth of more than 100 m below the water table. Even if slightly increased temperatures are simulated at greater depth than 100 m, all curves converge to a linear trend representing undisturbed conditions. Due to horizontal groundwater, all the simulated profiles at upstream are almost the same (Fig. 4.9a), and at center and downstream the differences become larger. As expected, temperature increasing scenarios with earlier onset of the hot spot generate deeper penetration, and for the different linear trends start in 1900 generates more pronounced anomaly than the scenario initiated in 1955 (Fig. 4.9b, c). Due to thermal diffusion and dispersion, step functions assigned to the top boundary also induce smooth profiles. Temperatures are higher for step-wise than linear increase starting from the same point in time (Fig. 4.9b, c), and this can be easily explained by the higher amount of heat introduced in the subsurface. In all profiles, because of groundwater flow, the influence of different increasing temperature top boundaries in 0-20 m depth is not directly visible in the profiles.

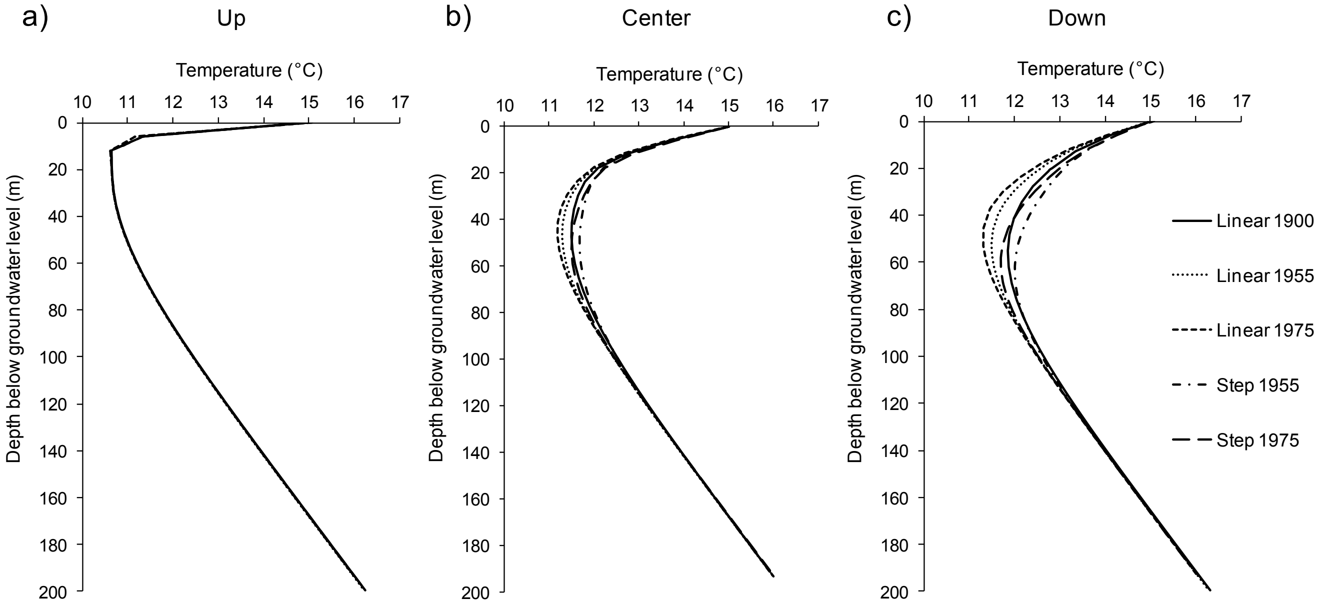

Fig. 4.9. Simulated GWTD profiles at different locations (upstream, center, and downstream) of hot spot for five different scenarios of top boundary temperature increase.

4.6.3.2. Dispersion effects at different locations

The simulated profiles show that the footprint of elevated urban heat flux can be tracked to a maximum of about 120 m, which is similar to the deviation depth observed in other cities, such as Winnipeg (Ferguson and Woodbury, 2004) and Tokyo (Taniguchi et al., 2007). The different trends of past temperature increase obviously do not have substantial impact on the shallow part of temperature profiles, given that the initial (T_u = 8.7 °C) and final (T_u = 15 °C) conditions are known. In the following thus we stick to the linear increase from 1900 (urban reference case), and concentrate on the role of transversal dispersion. This is investigated by visualizing the thermal conditions beneath the hot spot, and by comparing the temperature profiles simulated at the central as well as up- and downstream fringe position (Figs. 4.10, 4.11).

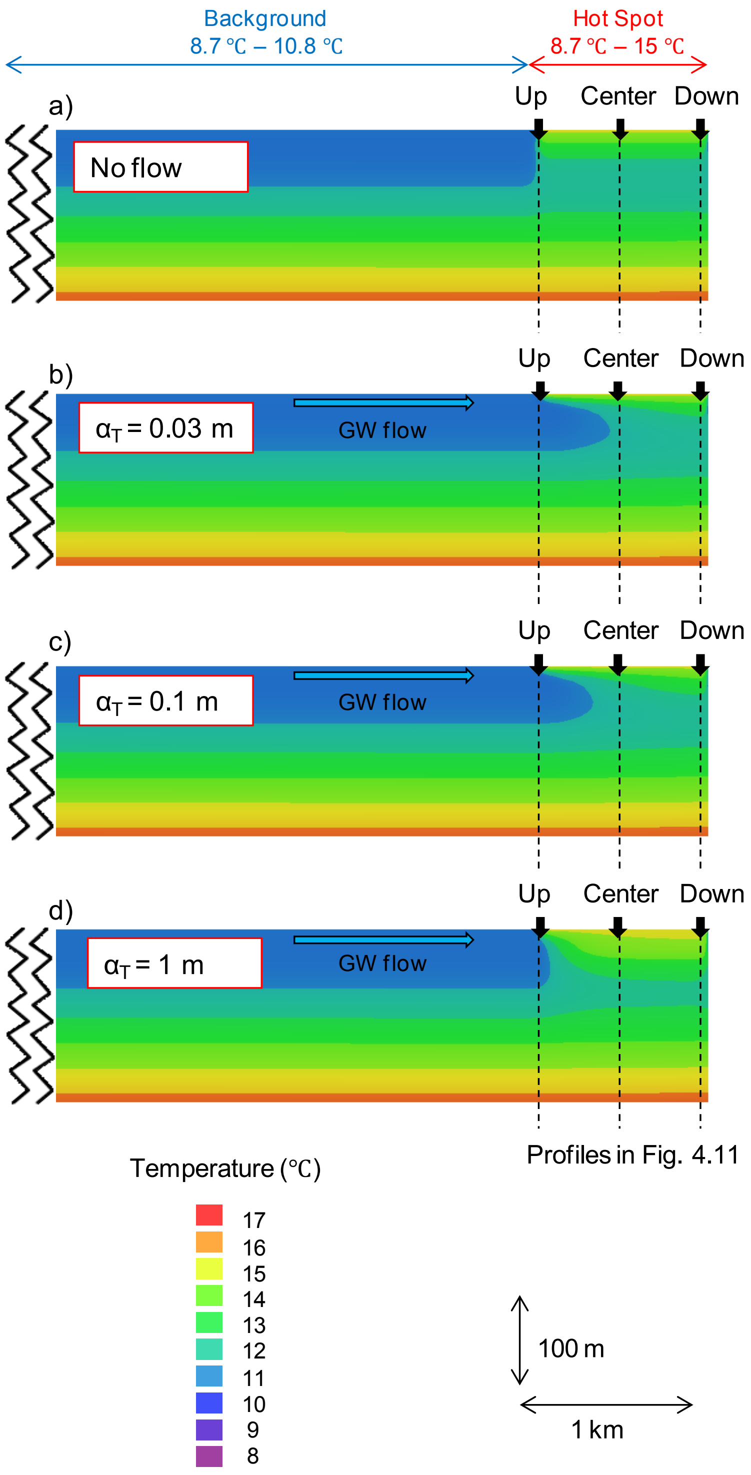

Fig. 4.10. Simulated temperature distribution after 110 years (urban reference case) of vertical 2D models with no horizontal groundwater (GW) flow (a) and flow from left to right (1 m/d) with different transverse dispersivity (α_t) values (b-d). The cold plume moves below the hot spot. Temperature profiles at upstream, center and downstream position of the hot spot of each scenario are compared and shown in Fig. 4.11.

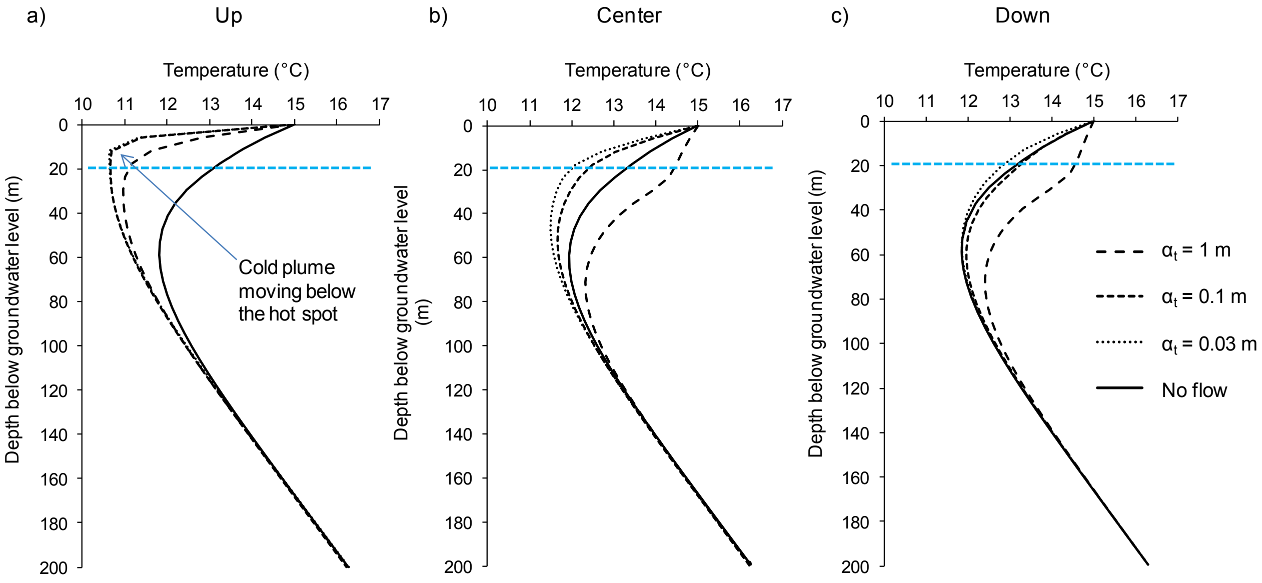

Fig. 4.11. Simulated GWTD profiles with different transverse dispersivity (α_t) values at different locations (upstream, center, and downstream) beneath the hot spot (see Fig. 4.10). The doted blue line indicates the lower boundary of the aquifer. Additionally, the profile derived for no horizontal groundwater flow in the aquifer is shown.

Fig. 4.10 shows that horizontal groundwater flow in the shallow aquifer deviates the thermal anomaly, evolving beneath the hot spot, in downstream direction. This is reflected in the vertical temperature profiles in Fig. 4.11. In the upstream position (Fig. 4.11a) horizontal groundwater flow therefore prevents the evolution of deeper alterations. In comparison, for conduction dominated conditions, simulated by switching off groundwater flow in the model, the thermal anomaly is not deviated and vertical thermal diffusion is most effective. Still, despite the high flow velocity of 1 m/d, horizontal advection does not act as a thermal barrier. In downstream direction conduction-induced profiles become similar to those conditions with small to moderate values of the dispersivity, that is $\alpha_t \leq$ 0.1 m (Fig. 4.11c).

Figs. 4.10 and 4.11 illustrate that most pronounced effects occur for conditions with very high transversal dispersion (α_t = 1 m). This scenario could represent substantial macro-dispersive effects as a consequence of aquifer heterogeneity. For simulating the aquifer of Cologne we assume α_t = 0.03 m, a small value which however is highly uncertain and not validated. In fact, the formation hosting the aquifer consists of terrace deposits with interbedding gravels and sands. This are not resolved in our simplified model, which assumes homogeneous aquifer and aquitard layers. Hence, in the field, macrodispersion may play a more prominent role than simulated by the reference model.

4.6.3.3. Size of hot spots

The 1 km hot spot scenario is based on the 15 °C temperature isolines and is just an approximation of local conditions in the city of Cologne. In fact, the distribution of heat sources in the city is very heterogeneous, and thus the integrated heat source could cover larger area. If, for example, we extend the hot spot to 3 km, the simulated temperature profile in the upstream is the same as for the 1 km case, but the profiles at the center and downstream show higher temperatures for 3 km (Fig. 4.12). However, for the case study here, the difference between the 3 km center and downstream profiles is only minor, which indicates that the size of hot spot has a limited influence until 1.5 km from the upstream.

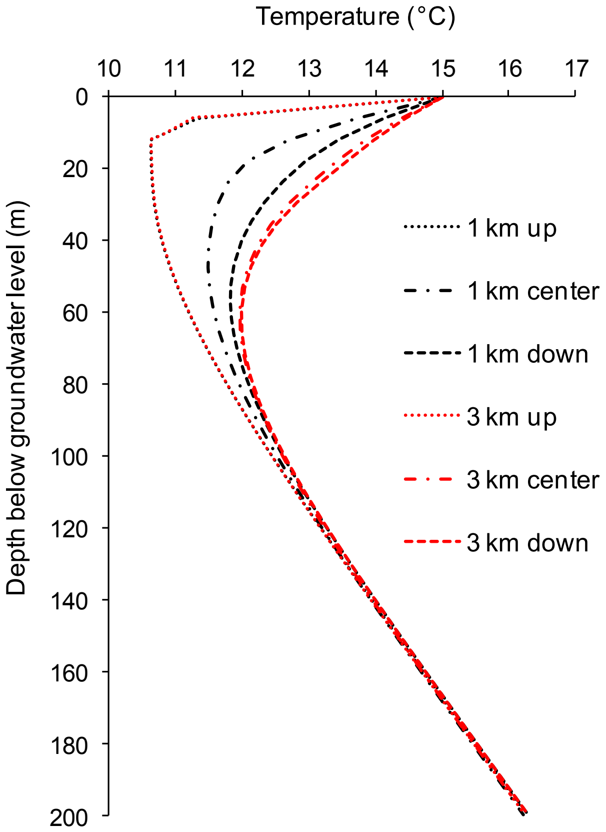

Fig. 4.12. Comparison of simulated GWTD profiles at different locations (upstream, center, and downstream) with 1 km and 3 km hot spot, respectively.

4.6.4. Comparison between simulated and measured temperature-depth profiles

During the 2009 field campaign, GWTD profiles were recorded at 46 wells in the study area. Due to spatial variation in land-use type, differences in heating history, the local presence of different heat sources, and hydrogeological influences, temperature profiles in the city show pronounced spatial variability. Thus, ten wells with characteristic temperature profiles covering all different land use types and the measured temperature ranges are chosen (Fig. 4.3). And GWTD profiles under synthetic conditions with dfferent final temperatures are simulated, in order to identify governing factors and to study in general the consistency of our modelling approach. Simulated profiles are compared seperately for the measured profiles at given land use types. Again, a hot spot of 1000 m extension is implemented. In the four modeled temperature variants (10.8 °C, 13.5 °C, 15 °C, 17 °C), a standard linear trend since 1900 is assumed with the final temperature at the hot spot oriented at average values characteristic for different land use types. These are 10.8 °C in 2010 for undisturbed conditions, 13.5 and 15 °C for built envorinment, and 17 °C as observed in the highly urbanized city center.

Undisturbed conditions are found in measurements in the surrounding rural area of Cologne: Wells 1 and 2 are located in agricultural land, and the vertical measured GWTD profiles are very similar with a nearly constant temperature of 10.8 °C. The measured profiles at these wells are well reproduced by the model, which shows that the model is accurately calibrated to these undisturbed conditions. The measured temperautre in urban green spaces show about 1 °C higher than the simulated undisturbed temperature. When moving towards the city center, measured groundwater temperatures increase and the temperature-depth profiles are perturbed, which reveals to be specific for each well. When simulating the hot spot with different temperatures in 2010, the profiles that are found in upstream, center or downstream position may fit in the uppermost, shallow profile, but not in the deeper parts of the wells. Here, typically measured temperatures remain high and the profiles appear less inclined than the simulated ones (Fig. 4.13 b, c, d). Based on the previous analysis on crucial model and scenario configurations, we can identify several potential reasons for this discrepancy.

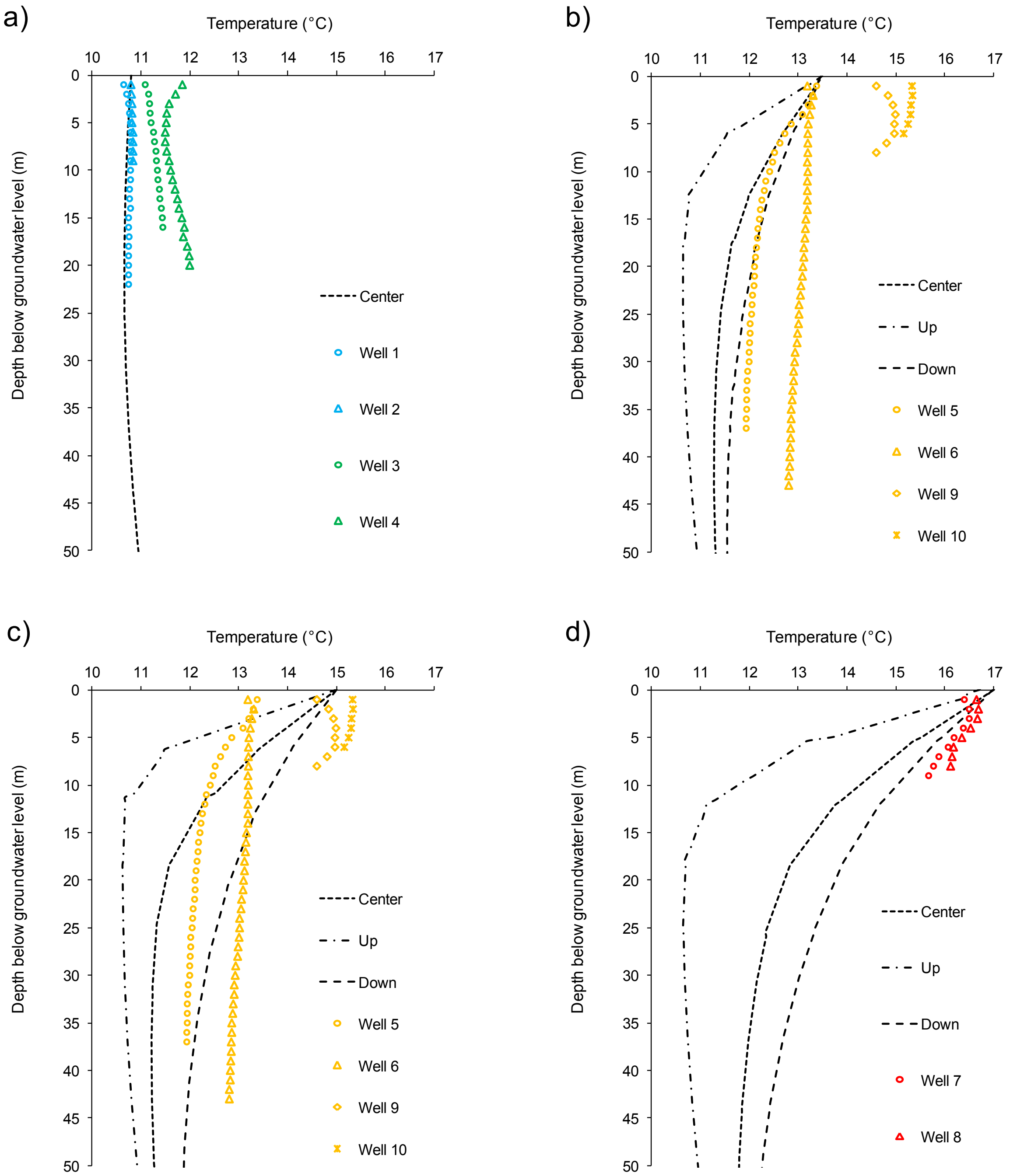

Fig. 4.13. Simulated and measured GWTD profiles from different land use types in Cologne.

One principal reason is that the generic hot spot scenario is only an approximation of the site-specific and local conditions of the city of Cologne. The heterogeneity on the spatial and temporal dimensions of urban thermal environment exist, and it is unrealistic to simulate subsurface heat transport with simple scenarios in large city scale. The comparison to measured profiles confirms that for a city a much more extensive hot spot or, on fine resolution, multiple overlapping hot spots existing in the entire city area can be expected. Downstream of an area with elevated heat flux, groundwater temperature profiles tend to be more vertical as a consequence of transversal mixing. This also means that in this case, transversal dispersion may play an important or even dominant role. Alternatively, merely assuming more intense macrodispersion than specified in our reference model would lead to more realistic temperature profiles. This could be an indication that the role of subsurface heterogeneity is underestimated. Finally, an apparent reason for higher temperatures in the deeper wells are higher vertical heat fluxes in the past than estimated by the linear trend, and which might date back before the year 1900, i.e. time zero in the currentmodel. However, this is very challenging to examine in more detail. The first settlements in Cologne are even dated before christ (B.C.), and since then there may have been many urban sources of heat, such as heat loss from besements and reinjection of thermal wastewater, which are now found fossilized in the deep temperature logs.

4.7. Conclusions

During the past hundred years, because of urbanization, a large amount of anthropogenic heat has entered the subsurface of cities. The anthropogenic heat discharge elevated the temperature of a local urban aquifer beneath the city of Cologne, Germany, by up to more than 5 K. Based on simulation results from site-specific flow and heat transport modelling, we can conclude that, for humid climate urban conditions such as in Cologne, average groundwater recharge does not play a significant role in urban groundwater temperature evolution. Since the dominant flow direction in the Cologne urban aquifers is horizontal, with significant flow rates, the influence of horizontal flow on subsurface temperature evolution needs to be addressed.

It is shown that vertical transverse dispersion causes additional vertical heat fluxes, which perturbes the GWTD profiles. The influence of this mechanism substantially depends on the effective transverse dispersivity and is more pronounced in more heterogeneous media, especially with local heat sources, than under undisturbed conditions. In the Cologne case, the chosen transverse dispersivity of $\alpha_t = 0.03$ m is already more influential than vertical heat transport by groundwater recharge for both undisturbed conditions and hot spot scenarios. Our study also shows that, under undisturbed condition, the transverse dispersion could lead to a concave upward temperature distribution, which is similarly caused by surface warming or downward groundwater. In urban regimes, neglection of transverse dispersion in aquifers with high horizontal groundwater flow velocity when analysing GWTD profiles may result in wrong estimations of surface warming rate or groundwater recharge.

When horizontal advection is the dominant heat transport process, a subsurface UHI might be moved downstream. Concequently, the GWTD profiles in urban aquifers are strongly influenced by the relative position and distance (upstream or downstream) to the anthropogenic heat source. It is shown by numerical modeling that different increasing temperature trends and the size of heat source (simulated as hot spot) also play a role on temperature evolution, especially at center and downstream location. (In order to investigate all possible conditions, another scenation of a 2 km local hot spot with a constant temperature of 15 °C to represent the built environment, while assuming a constant undisturbed temperature of 8.7 °C along the remaining top boundary are shown in the appendix, Fig. A-2 and A-3). The comparison of measured and simulated GWTD profiles also indicates that it is difficult to capture the driving subsurface heat transport mechanisms with streamlined scenarios. The heat flow in urban subsurface depends on many local and site-specific parameters, and thus a more detailed resolution of underground geological structures and the temporally variable heat urban sources would be desirable.

5. Sustainable geothermal use in urban areas

5.1. Geothermal sustainability and renewability

Geothermal energy is considered as a renewable and sustainable energy source. Renewable energy can be defined as “an energy removed from a resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological societal systems” (Axelsson et al., 2005; Rybach et al., 2000). The sustainable development was officially defined for the first time in the Brundtland Commission Report (1987) as ‘‘development that meets the need of the present without compromising the ability of future generations to meet their own needs’’. The term ‘‘renewable’’ concerns more about the nature of a resource while ‘‘sustainable’’ addresses the way of utilization for a certain resource (Axelsson et al., 2002). A more specific definition of sustainable geothermal production was suggested by Axelsson et al. (2001) as ‘‘for each geothermal system, and for each mode of production, there exists a certain level of maximum heat production, below which it will be possible to maintain constant energy production from the system for a very long time (100 - 300 years)’’. According to the International Energy Agency (IEA) Geothermal Implementing Agreement, sustainable development was identified as the one of the most important issues for geothermal industry.

Rybach and Mongillo (2006) concluded in their paper that more research for sustainability of geothermal production is needed, and they recommended following investigations: to determine sustainable production level and techniques for various geothermal resources; to analyze existed reservoirs with stable performance; to re-examine the regeneration time scales of numerically modelled production technologies; to model enhanced geothermal system with long-term strategies under different scenarios and to derive dynamic recovery factors. Among these investigations, defining the production rate in a sustainable way is one of the most important tasks. For each geothermal system (deep or shallow / open or closed), the sustainable production rate is determined by different factors, such as the undisturbed fluid and/or heat content, temperature gradient, thermal properties and the recharge rate. For example, the energy content decline, which can be indicated by temperature drop, constrains the production rate of closed geothermal systems; while for open systems, sometimes instead of the temperature decrease, the pressure (hydraulic head) decline or corrosion and scaling problems (Lopez et al., 2010) are the factors which limits the production rate (Axelsson et al., 2005). Therefore, specific studies, both on local and regional geothermal characteristics and utilization technology, are required for the determination of production strategy.

Numerical modeling has been widely used as a useful tool to simulate the change of production rate over time. Lopez et al. (2010) applied numerical modeling to forecast the thermal breakthrough of open doublet geothermal systems in Paris Basin. They considered different options for the Dogger aquifer and based on their results the current geothermal energy can still contribute to district heating in Paris Basin for at least another 40 years. Rybach and Eugster (2000) studied the long-term production behavior of borehole heat exchanger based GHPs, and the result of a single borehole showed cylindrically shaped thermal isolines near the heat exchanger after a couple of years of operation. And the calculated ground temperature at 50 m depth showed a quick drawdown in the first couple of years and the decrease slowed down to a quasi-steady level after 10 years. The recovery period of the same system takes as long as operation period.

As a renewable energy, geothermal energy can always be replenished, though in some cases the recovery rates are very slow. The stakeholders are more concerned about the long-term sustainable production of geothermal systems, and to determine the sustainable production rate is one of the most important requirements (Rybach and Mongillo, 2006). A number of case studies on sustainability modeling have been performed (Axelsson, 2010), however, most of these studies focus on deep and open geothermal systems, and water level and pressure change are the main concerns.

For closed shallow geothermal systems, which are more feasible in urban area, only a few models have been presented (Axelsson et al., 2005; Eugster and Rybach, 2000). And the background temperatures are generally considered as undisturbed, no other heat sources are included in the system except the ground source heat pumps. Based on our case studies in the city of Cologne, anthropogenic and/or natural heat sources cannot be neglected when implementing shallow geothermal systems in urban areas. In some locations with high groundwater flow velocity and intense artificial heat flow, a detailed numerical model that integrates local and site-specific parameters is needed. Only in this way, the accurate sustainable production rate can be defined for such complex and dynamic urban systems with high geothermal potential.

5.2. Investigation of local thermal conditions: case study in Frankfurt

Due to the simplification of installation and application, shallow geothermal systems are much more common in urban areas. The production of geothermal energy in both open and close shallow systems decreases fluid and/or heat content of the subsurface and meanwhile increases both natural and anthropogenic recharge rate. Strategies should be made according to the type of the system and the site-specific thermal and hydrogeological features, such as thermal conductivity, groundwater flow, natural heat flux and other artificial heat sources. From our comprehensive study in the city of Cologne, it can be seen that underground thermal conditions in urban areas are more complicated than rural areas; the heat flow in the urban subsurface is controlled by multi local sources and groundwater flow. Thus, a comprehensive investigation of local thermal conditions is necessary for the determination of sustainable production level.

The city of Frankfurt is a good example to show the importance of investigating local thermal conditions. Because the urban aquifers in Frankfurt are not only influenced by anthropogenic sources like in Cologne, but also show a perturbation from natural sources. Frankfurt is Germany's fifth-largest city with a population of more than 0.6 million, and it has an annual mean air temperature about 10.9 °C (DWD). The groundwater temperature profiles we measured in April 2009 and March 2010 (Table 5.1 and Fig. 5.1) show that the elevated groundwater temperature caused not only by heat conduction from the surface, but also the highly mineralized warm groundwater from the bottom of some observation wells.

Table 5.1. Groundwater temperature measurements in Frankfurt.

Well name	Well depth (m)	Temperature at 20 m (°C)	Temperature at 80 m (°C)
Well S	105	15.4	17.8
Well G	100	18.2	22.2
Well F	145	15.2	17.0
Well D	100	16.5	21.2
Well R1	141	13.7	18.3
Well R2	85	13.8	18.7
Well U1	92	13.5	17.8
Well U2	140	13.5	17.9
Well RB	100	13.2	15.3
Well H	130	13.4	17.7

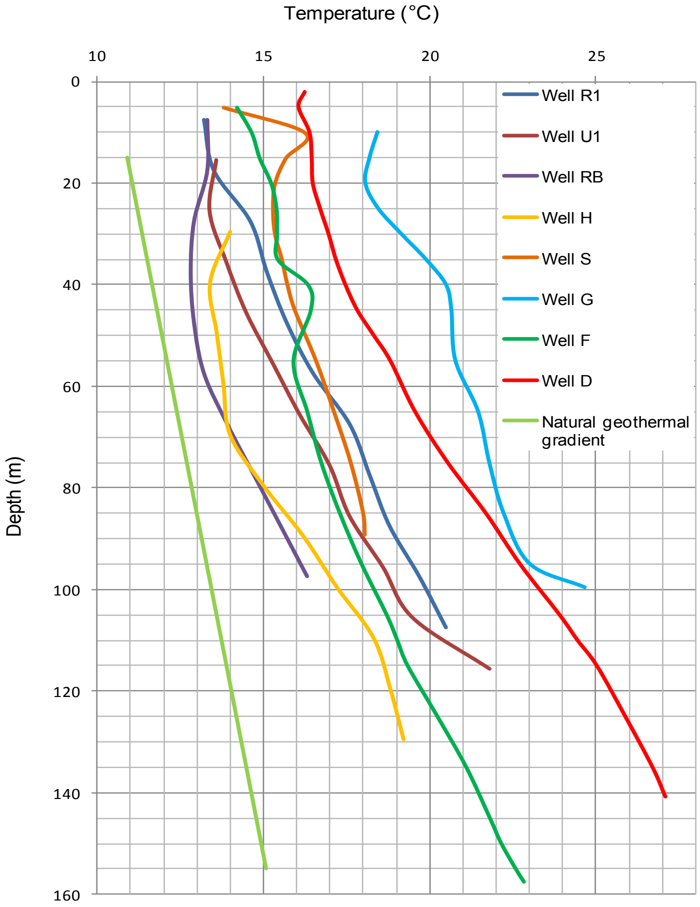

Fig. 5.1. Temperature profiles of observation wells Frankfurt.

This phenomenon can be explained by the geological structure of the city: Frankfurt is underlain by Pliocene and Pleistocene terrace deposits, which are represented by three main sedimentary formations (Fig. 5.2). A thin layer of sand and gravel is on the top, underlain by clay ("Frankfurt Ton") in a depth from 30 to 80 m, and beneath this is an up to hundred meters thick limestone formation called the "Frankfurt Kalk". The central clay formation is interbedded by several thin layers of limestone. This limestone layer is very heterogeneous with high conductivity fluid pathways (Fig. 5.3). The upward flow of warm groundwater from the Frankfurt Kalk aquifer beyond 80 m has a strong influence on the subsurface temperature. Warmer groundwater from deeper aquifers flow up through the cracks and fractures in the limestone layer and then form a natural thermal anomaly in shallow depth. This is supported by highly mineralized groundwater that was detected at several high temperature wells. Both the downward anthropogenic urban warming in the shallow subsurface and the upward natural groundwater flow increase the subsurface temperature beneath Frankfurt and consequently increase the geothermal potential of the aquifer.

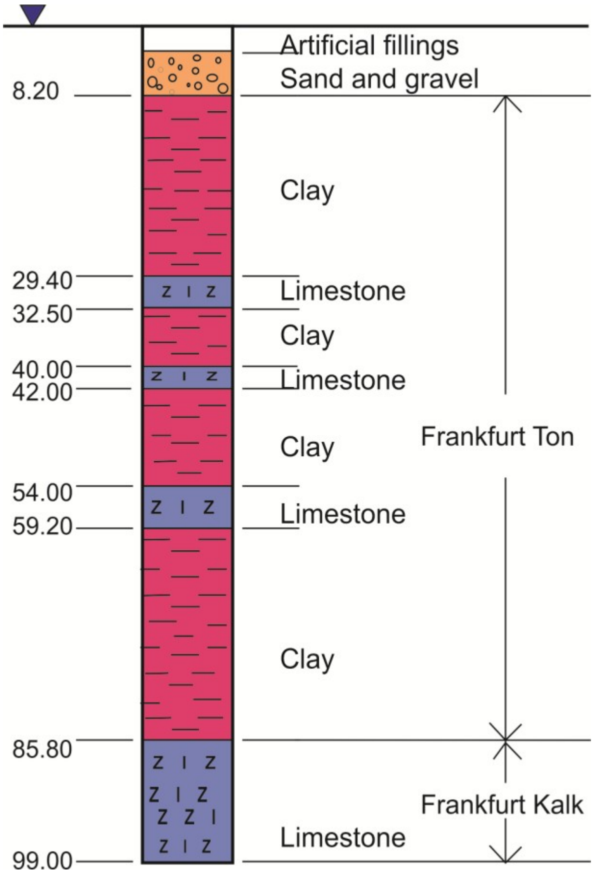

Fig. 5.2. General geology of Frankfurt using an exemplary borehole profile.

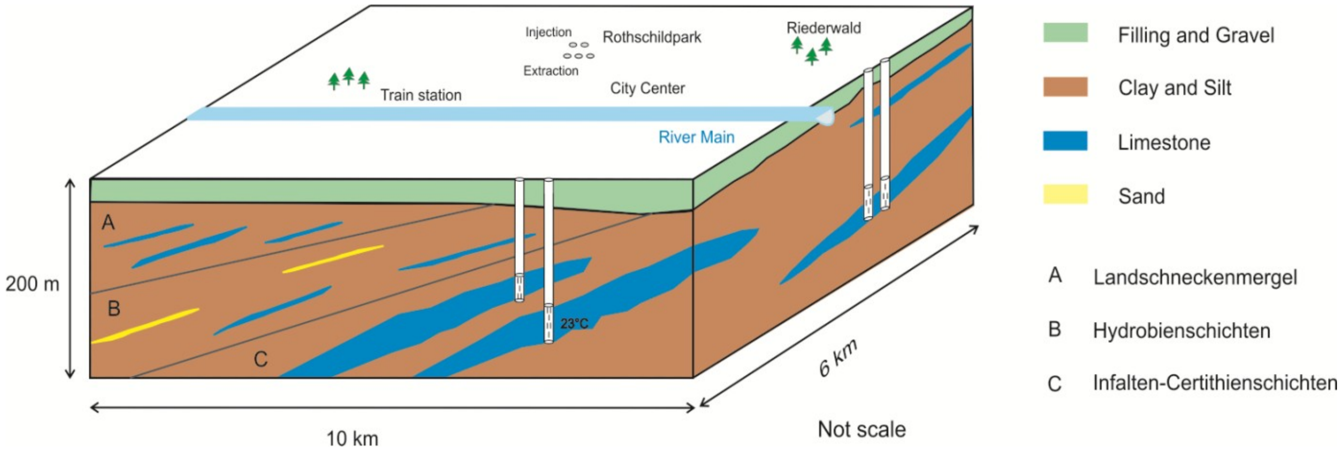

Fig. 5.3. An hydrogeological conceptual model of Frankfurt.

In cities like Frankfurt, temperature anomalies in the subsurface do not only stem from anthropogenic sources such as observed in other urban heat islands, but also from naturally occurring hydrothermal waters that cause substantially increased temperatures and augment the exploitable renewable energy content in the shallow subsurface beneath this city. Therefore, analytical solutions or a simplified regional scale 3D model will not be applicable to catch all the local conditions and thus it is difficult to estimate geothermal potential and urban heat fluxes in Frankfurt. The local specific thermal conditions determine how much energy can be technically extracted in an optimal way and how it can be sustainably managed.

Furthermore, in many large cities like Frankfurt, groundwater is extensively used for cooling purposes, which on one hand increases local groundwater temperature and on the other hand decreases the efficiency and sustainability of cooling. An elaborate investigation of local thermal conditions is fundamental before conducting a geothermal project, either for heating or cooling.

6. Conclusions and recommendations for future work

6.1. Conclusions

During the past centuries, because of urbanization, a large amount of anthropogenic heat has flowed into the subsurface of cities. The urban heat island (UHI) effect and climate change have not only caused surface temperature increase in most urban areas, but have also enhanced the subsurface temperature. In Chapter 1 and 2, an introduction on UHI, subsurface temperature and utilization of shallow geothermal energy are given.

In Chapter 3, a case study in a typical UHI in Germany, the city of Cologne, is presented. Our comprehensive field investigations show that anthropogenic heat discharge elevated the temperature of a local urban aquifer beneath Cologne by up to more than 5 K. In some other mega cities, the magnitude of temperature increase in the subsurface becomes even greater. High temperature is an indicator of large potential heat content stored in these urban aquifers. The preliminary estimation in Cologne shows that, by decreasing the 20 m thick urban aquifer’s temperature by 2 °C, the amount of energy that needs to be taken away is about 2.5 times the annual residential heating demand of the whole city. The geothermal potential in other cities such as Shanghai and Tokyo is even higher. And we conclude that sustainably extracting this large amount of energy, will not only fulfill part of the energy demand in urban areas, but also contribute to slow down urban warming by the reduction of greenhouse gas emissions.

In order to further improve our understanding of the dynamics of underground energy flow in Cologne, a coupled three-dimensional groundwater flow and heat transport model is developed. Regional hydrogeological conditions, site-specific thermal parameters are captured in this model. In Chapter 4, the simulation results under different scenarios are discussed. According to the results, for humid climate urban conditions, such as in Cologne, average groundwater recharge does not play a significant role in urban groundwater temperature evolution, instead, the influence of horizontal flow on heat transport need to be addressed. Vertical transverse dispersion influences groundwater temperature-depth profiles, and it could lead to a concave upward temperature distribution, which can also be caused by surface warming or downward groundwater. Our study also shows that, the temperature-depth profiles in urban aquifers are strongly related to the relative distance and location (upstream or downstream) to the anthropogenic heat source. The comparison of measured and simulated profiles indicates that, the heat flow in urban subsurface is related to many local and site-specific parameters, thus detailed underground structures and temperature-depth profiles from a large number of wells are needed in order to demonstrate the underground thermal condition and provide a clear insight into the UHI in the subsurface.

Detailed case studies could provide important information to make strategies for sustainable geothermal use. In Chapter 5, previous studies on sustainable geothermal use are reviewed and discussed. Since groundwater temperature changes also impair groundwater quality, additional attention need to be paid when drafting strategies to implement shallow geothermal system in cities, where underground temperature is strongly influenced by locally hydrogeological and anthropogenic heat sources. Due to the complexity of thermal and ecological conditions in urban areas, a comprehensive understand of locally dynamically thermal and ecological conditions is required.

6.2. Recommendations for future work

In order to build up representative local or regional numerical models to study the urban geothermal potential, urban development, such as land use changes and air and groundwater temperature variation over a long period have to be well known. And further, the temporal and 3D spacial changes in urban subsurface need to be included in the model. Fig. 6.1 shows changes in the urban land use in Cologne from 1850 to 2000, these changes, or by another word – expansions, in horizontal direction, also induce changes on the groundwater temperature-depth profiles by several degrees in the vertical direction.

The snapshots at different time steps show that, in the city scale, the most pronounced changes happened in the year of 1955 and 1975. However, if we have a closer look at local scale, there might be various changing patterns. For example, some locations experienced land use change in 1930th or during some other period. Even in recent years, when the urbanization is already ceased, the observed temperature at 5 m depth still shows an increase from 2009 to 2012 (Fig. 6.2), which cannot be explained only by air temperature changes. Well locations near the city center generally have larger temperature increase, which indicate that anthropogenic sources are the main drivers for subsurface UHI, and heat flow is controlled by many local and site-specific parameters. Without knowing the long-term development of urban subsurface temperature, it is almost impossible to differentiate individual heat sources and therefore makes it difficult to provide accurate background temperature for the implementation of shallow geothermal system.

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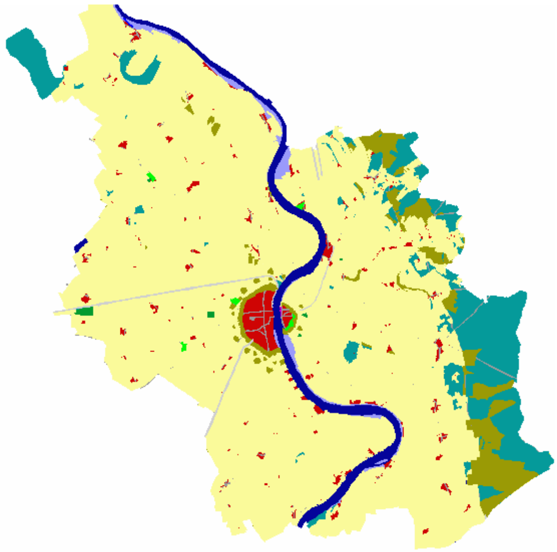

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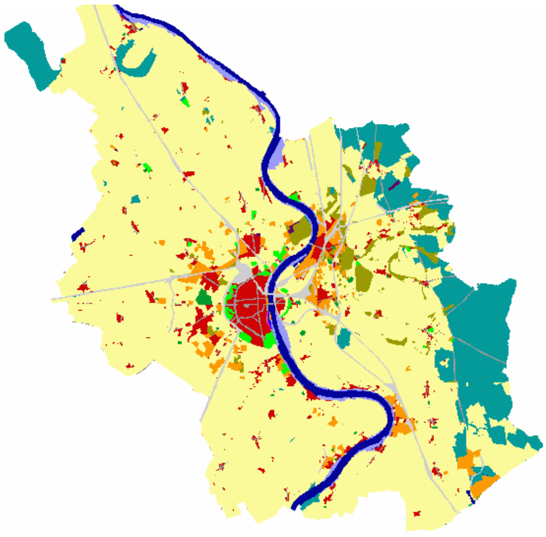

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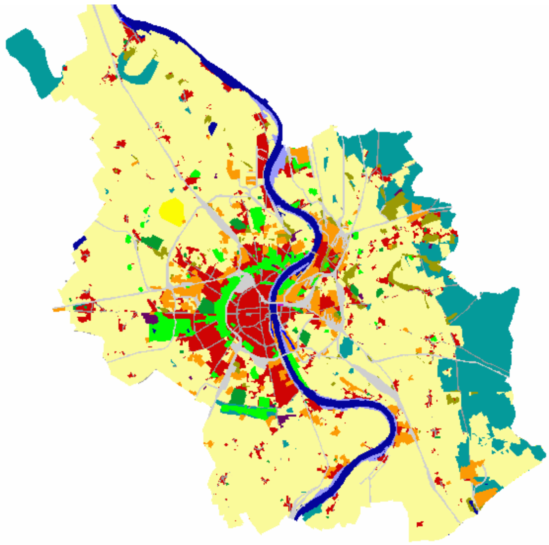

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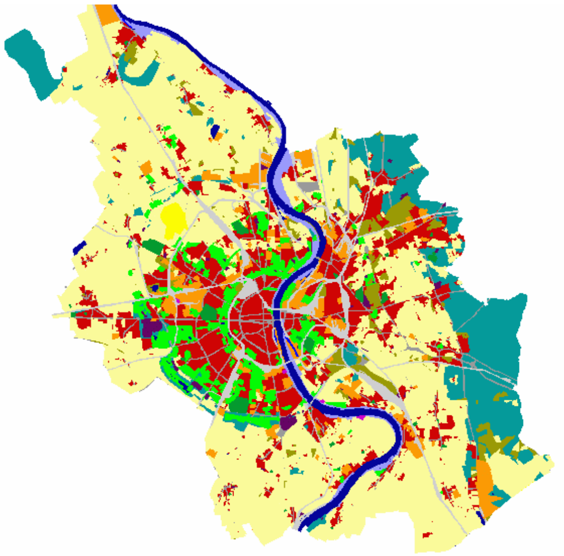


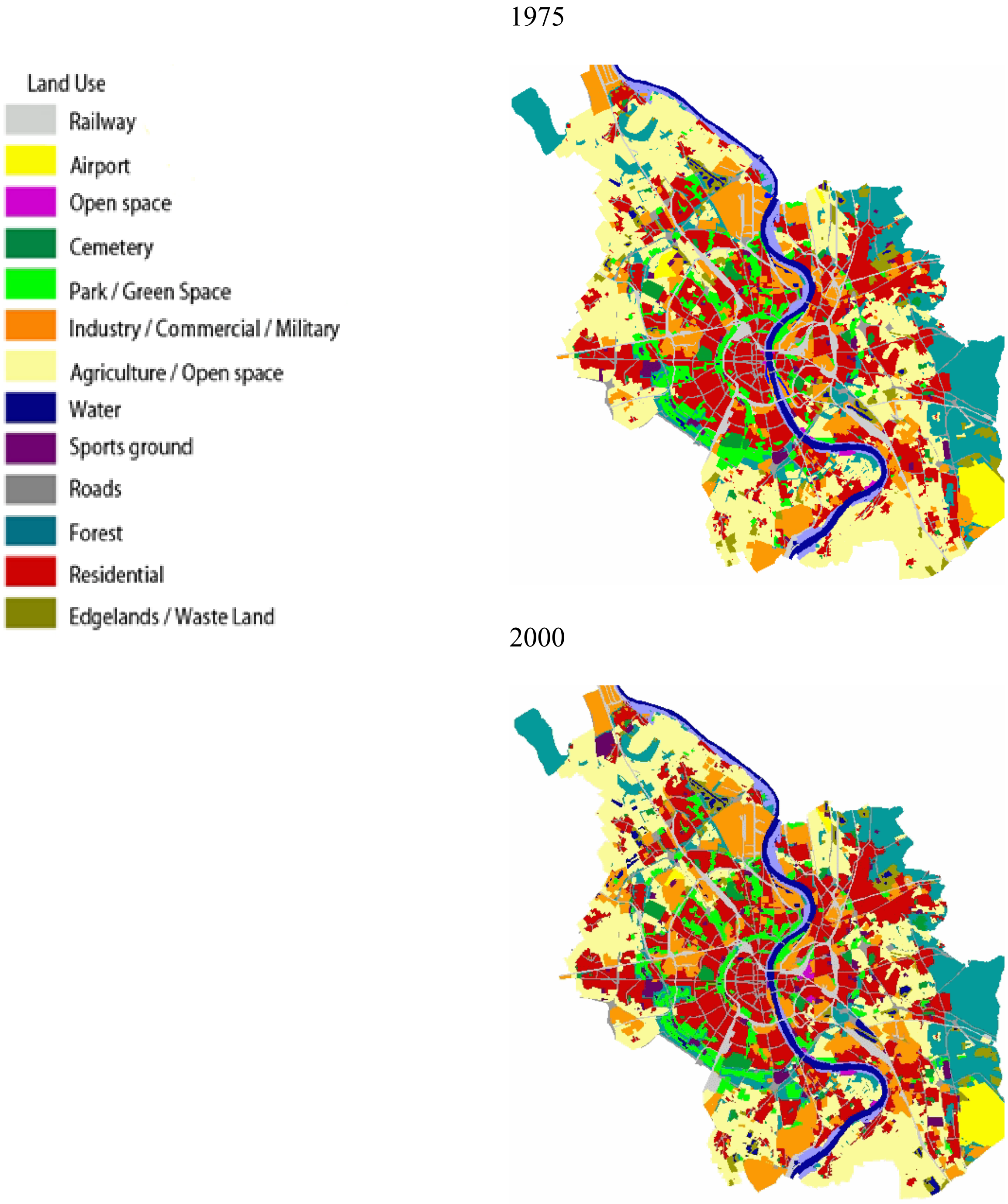


Fig. 6.1. Changes in the urban land use in Cologne from 1850 to 2000. (Modified after Hennig, 2011)

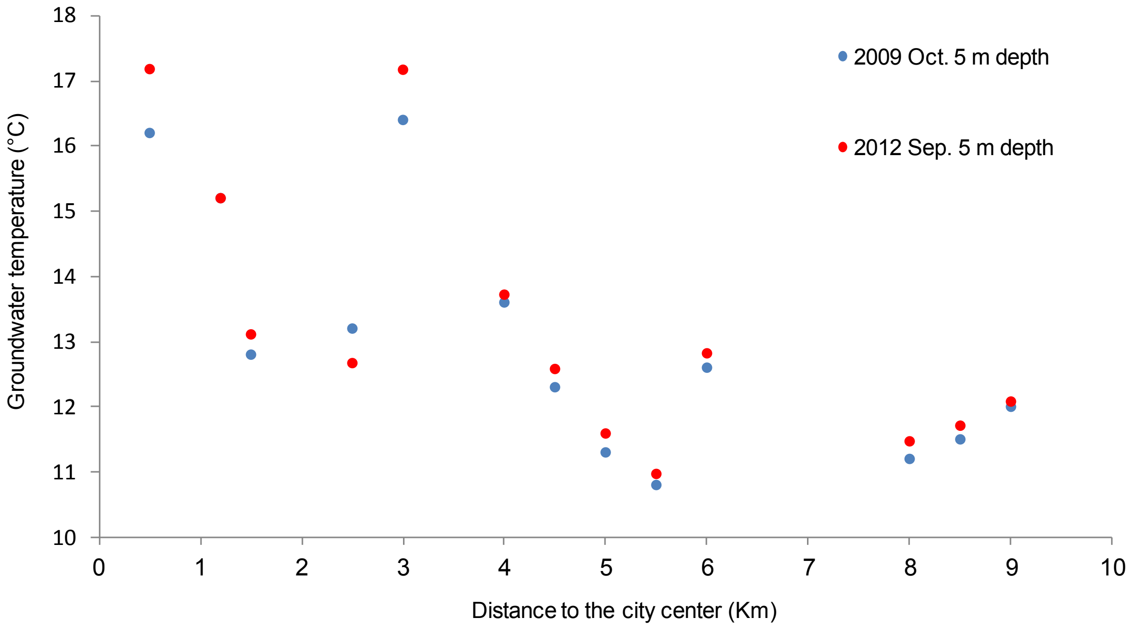


Fig. 6.2. Groundwater temperature measured at 5 m depth below groundwater level in 13 observation wells in Cologne in October 2009 and September 2012.

Though production rate is considered to be the most essential aspect for sustainable geothermal utilization, there are other important aspects that also need to be concerned, such as surface disturbances, bacteria growth and discharge of chemicals. Foulquier et al. observed that (2009) elevated subsurface temperature decreases oxygen solubility and stimulates microbial respiration in the soil and thus lower dissolved oxygen concentration in groundwater. However, as Hähnlein et al. (2010; 2013) mentioned in their studies, there is still a lack of knowledge on the validation of the available heat transport models, long-term environmental impacts, and the system optimization. This is because in many countries, the use of shallow geothermal energy is not as popular as other renewable energy resources. There is not enough experience with shallow geothermal systems, and the related regulations also need to be completed. The case studies on Cologne and Frankfurt also support the conclusions by Hähnlein et al. (2013) that static regulations such as fixed and absolute temperature thresholds are not recommendable, especially in urban areas, where local differences in hydrogeological and anthropogenic heat sources occur. In order to make strategies for sustainable urban geothermal use, a comprehensive understand of locally dynamically thermal and ecological conditions is required, and flexible temperature limits for heating and cooling the groundwater or subsurface are recommended.

Appendix

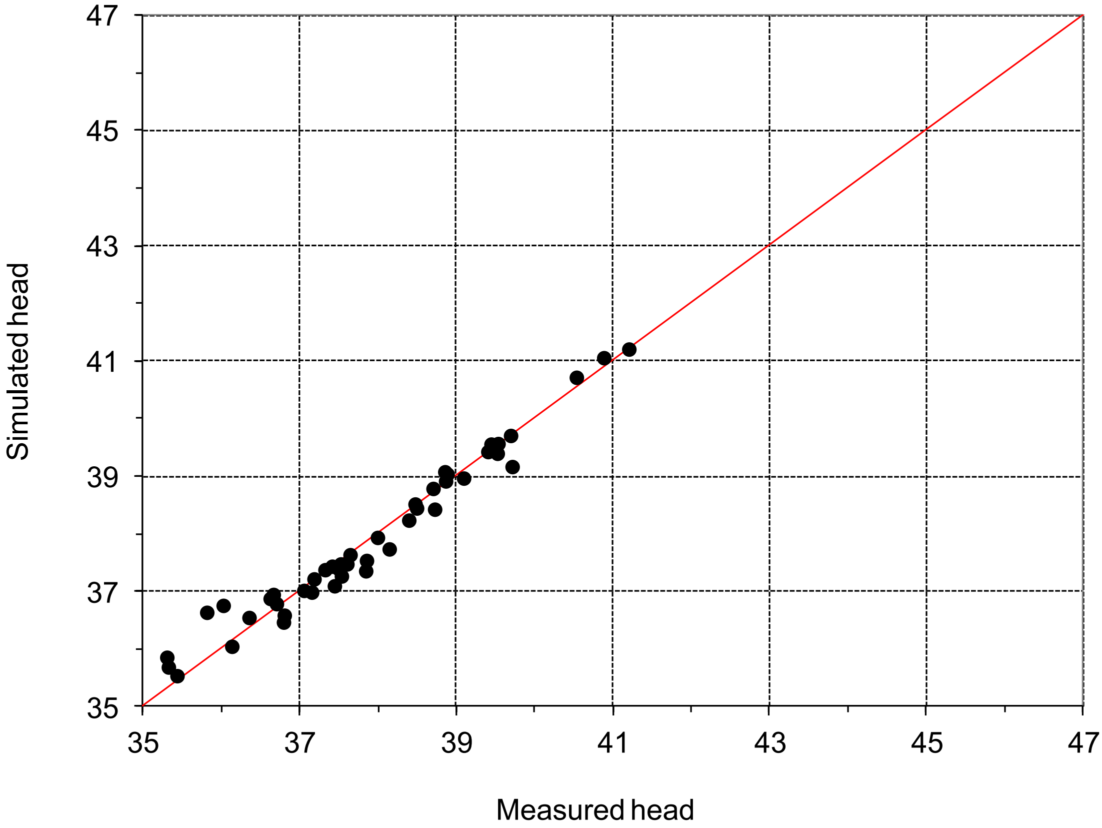


Fig. A-1. Measured and simulated groundwater heads of 46 observation wells in Cologne.

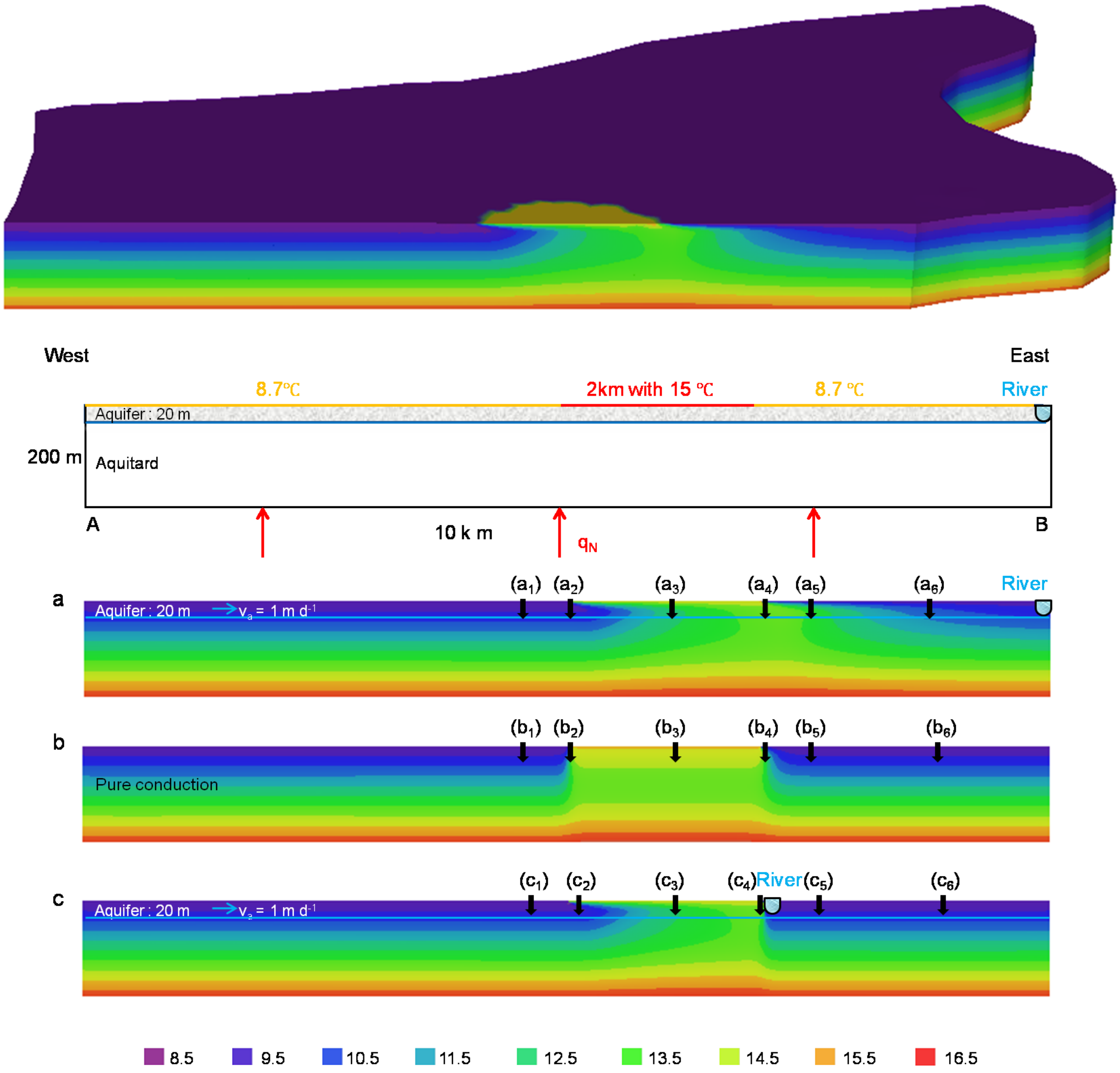
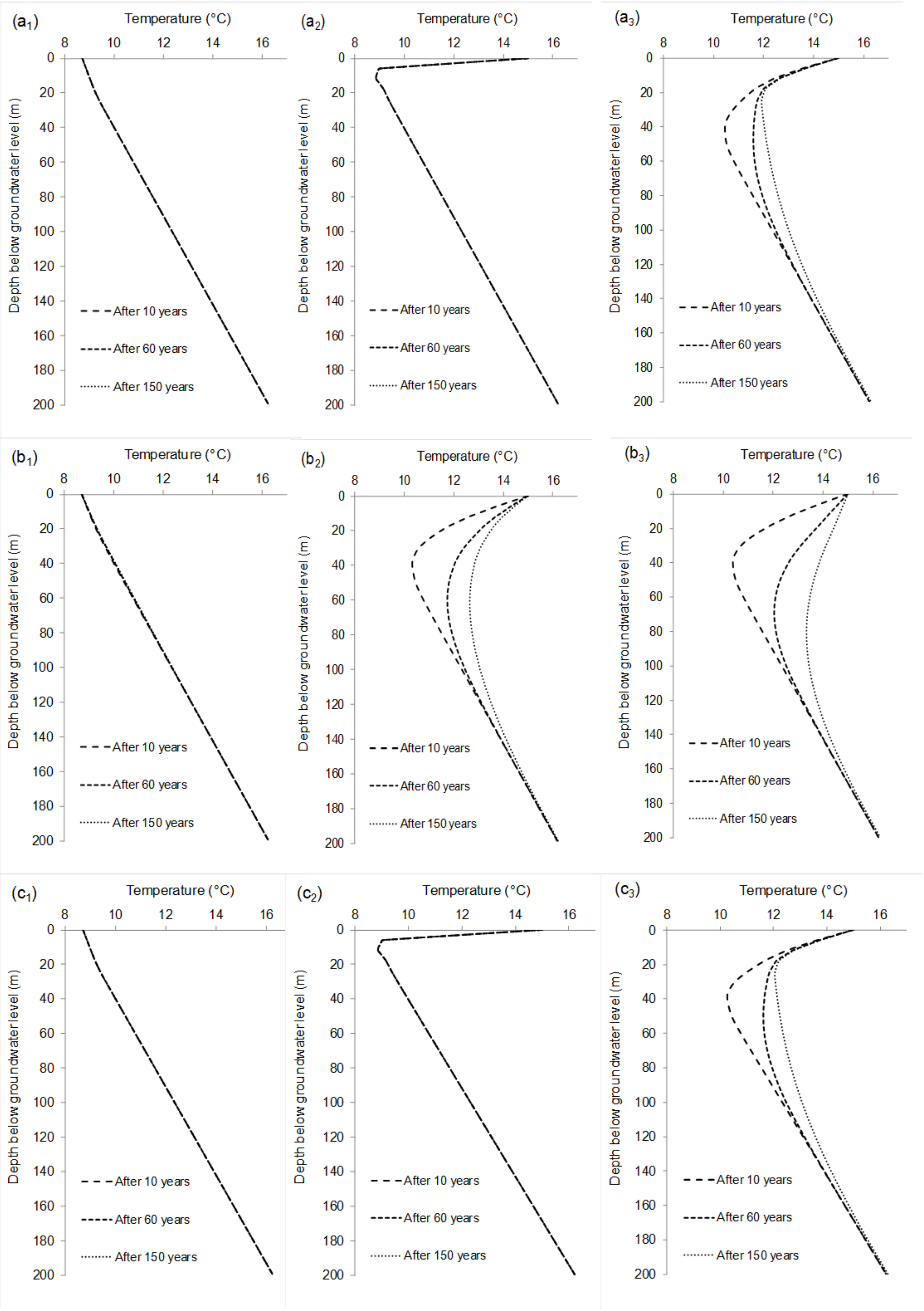


Fig. A-2. Temperature distribution for selected 3D cross section and three different scenarios in vertical 2D model: (a) shallow aquifer with 20 m thickness (a1-a6, b1-b2 and c1-c6 are the locations for temperature profile comparison in Fig. A-3; va is flow velocity in the aquifer); (b) pure conduction, i.e. no aquifer only aquitard; (c) with river close to the heat source. Location a3 (b3 and c3) is in the centre of the 2 km high temperature zone, a1 (b1 and c1) is sited 500 m upstream, and a5 (b5 and c5) is 500 m downstream from the centre. Locations a2 (b2 and c2) and a4 (b4 and c4) are at the up- and downstream edge of the high temperature zone, and a6 (b6 and c6) is 2.5 km away downstream from the hot spot zone.


(a1)
Temperature (°C)
8
10
12
14
16
Depth below groundwater level (m)
0
20
40
60
80
100
120
140
160
180
200
After 10 years
After 60 years
After 150 years
(a2)
(a3)
(b1)
(b2)
(b3)
(c1)
(c2)
(c3)

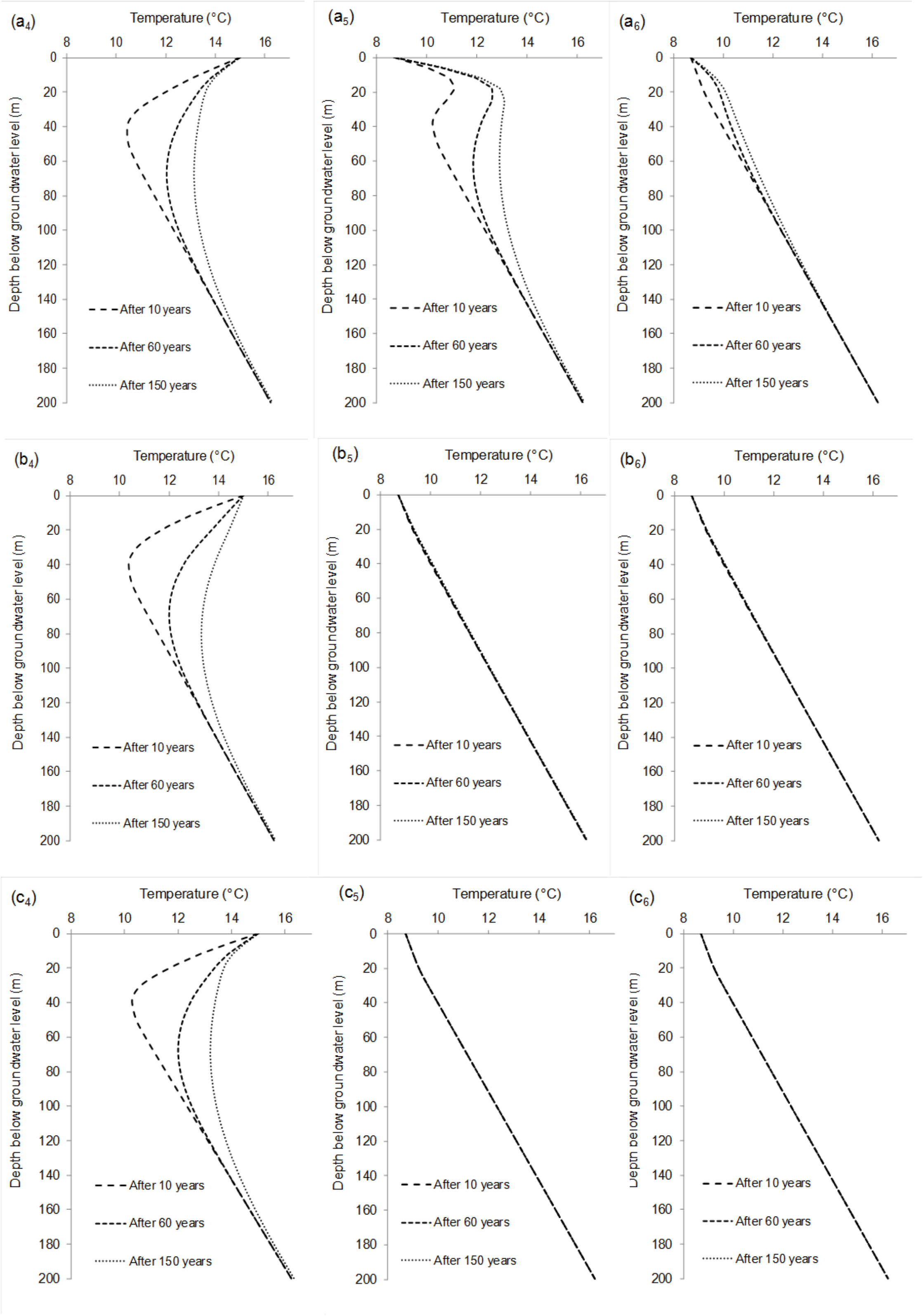


Fig. A-3. Temperature profiles at different time periods and different locations for three scenarios (i.e. shallow aquifer with 20 m thickness). See Fig. A-2 for locations of the vertical temperature profiles.

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