Chapter 1

Introduction

The **thermal use of shallow subsurface systems** is increasingly discussed, promoted, and implemented as one of many promising measures to reduce fossil fuel use. The energy extracted from such systems is referred to as shallow geothermal energy or low-enthalpy energy. These systems may consist of groundwater abstraction by pumping wells, energy generation, or abstraction with the support of heat pumps such as groundwater heat pump (GWHP) systems, and the reinjection of the cooled or warmed water into the aquifer (open system, Figure 1.1b). On the other hand, thermal use may also include pumping of groundwater for cooling purposes and reinjection of warm water. Both systems may even be seasonally combined. A related topic is heat storage (Dinçer and Rosen 2011). Since temperature in undisturbed shallow aquifers is around annual mean air temperature at a given location outside the range of influence of infiltrating rivers or lakes, energy production by ground-source heat pumps and GWHPs is attractive also at low air temperatures in winter. Thermal use of shallow underground (saturated or unsaturated zone) can also be accomplished by low-enthalpy geothermal heat exchanger systems combined again with heat pumps (closed systems or ground source heat pump systems [GSHP], Figure 1.1a). With respect to the thermal management of underground and groundwater systems, a series of questions arise in this context. What is the tolerable temperature increase or reduction of groundwater? What is the long-term usable energy potential of an aquifer? What is the long-term sustainability of the thermal use of groundwater? What are management problems with respect to thermal use? What are the geotechnical risks related with the thermal use of the underground? What harm comes from the thermal use of groundwater? Is groundwater quality and/or groundwater ecology affected? Is there a competition between drinking water production and thermal use? How much does a city heat up shallow groundwater? How can the temperature development be assessed? How is the heat balance affected? In order to answer these questions and to design thermal systems, it is necessary to provide methods to compute their effects on the development of temperature in the

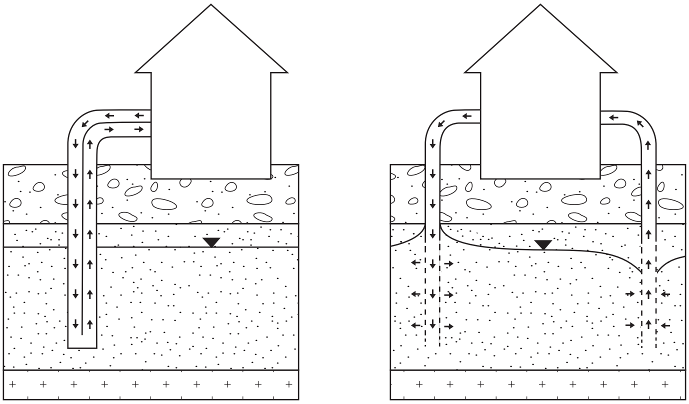

Figure 1.1 (a) Scheme of closed-loop (GSHP system) and (b) open-loop (GWHP system) shallow geothermal systems.

underground and, in particular, the groundwater. Accordingly, the theoretical fundamentals of heat transport in groundwater systems are recalled, and the essential thermal properties and parameters are reviewed and discussed. Hydrogeological–thermal investigations have to be combined with modeling. Therefore, a series of mathematical tools and simulation models based on analytical and numerical solutions are presented and discussed. Case studies are shown for locations in Austria, Germany, and Switzerland. They concern the urban thermal energy use as well as heat storage and cooling.

1.1 MOTIVATION FOR THE THERMAL USE OF UNDERGROUND OR GROUNDWATER SYSTEMS

The prime motivation for the thermal use of shallow underground systems has clearly been the partial substitution of fossil fuel energy by increasing the overall efficiency of thermal power plants. It was seen as an efficient way to transform electricity from nuclear power stations into energy for space heating and thus save a multiple of that amount in fossil fuel. One of the main drivers is, no doubt, the price for energy production. An example is the oil crises between 1973 and about 1982, which led to increased energy prices in this period and triggered, among others, various activities toward thermal use of underground space and groundwater worldwide (e.g., Balke 1974, 1977). The expected long-term exhaustion of fuel reservoirs has been another concern in this context. Therefore, energy safety and independence are important motivations. Recent developments are mainly motivated by the global warming and the debate and discussion about a reduction of the carbon dioxide (greenhouse gases) concentration of the atmosphere (e.g., Blum et al. 2010; Bayer et al. 2012). For example, in 2008, the use of around 879,000 ground-source heat pump (GSHP) systems in nineteen European countries saved 3.7×10^6 t CO_2 (eq.) in comparison to conventional heating practice (Bayer et al. 2012). Hence, the thermal use of underground systems has been considered and discussed as an alternative source of energy.

The thermal use of shallow underground systems comprises the **utilization of the underground** (rock, dry, or unsaturated as well as saturated soil) or **pumped groundwater as heat source** (for heating purposes) **or heat sink** (for cooling purposes). In principle, it is possible to directly use soil air or groundwater together with heat exchangers for heating or cooling depending on the prevailing temperatures. However, **thermal systems combining heat exchangers and heat pumps** are in the focus of current activities.

The extraction of heating or cooling energy or the extraction of groundwater and reinfiltration of cooled or warmed water produces **thermal anomalies**, which propagate in the subsurface environment. One aspect consists of **thermal exploitation** of the resource, which represents thermal mining. In this context, the possible **thermal overexploitation** is of concern, that is, excessive cooling or even freezing and warming of the underground. The other aspect consists of the **induction of thermal fluxes**, which are caused by the thermal anomaly. Main fluxes in shallow groundwater systems are thermal fluxes from the soil surface to the aquifer or from the infiltration of rainwater through the surface and the infiltration of surface water as well as the geothermal flux. In the long run, a **stable thermal yield** can be expected, however, at the cost of long-term shift (increase or decrease) of the temperature in the soil and groundwater system. Care has to be taken that this equilibrium is not reached at a temperature at the extraction point, which is so low that the heat pump system ceases to function.

A well-known phenomenon of urban environments above shallow groundwater systems is the so-called **urban heat island effect** (e.g., Landsberg 1956; Balke 1974; Ferguson and Woodbury 2007; Zhu et al. 2010). As a result of land use change and urban infrastructure, air temperature has increased, typically by 2 to 5 K or even more, compared to rural areas (e.g., Oke 1973). In Ankara, for example, mean soil temperatures in 5–50 cm depths were found to be 1.8–2.1 K higher in the city area than at rural stations (Turkoglu 2010). As a consequence, the temperatures of soil surface, soil, and groundwater have been raised as well (e.g., Balke 1974; Changnon 1999; Ferguson and Woodbury 2007; Taniguchi et al. 2007). Moreover, constructions like **buildings** (including heated basements) or **sewer systems** can heat underground and groundwater significantly, mainly due to heat conduction. All these effects lead to thermal anomalies. Menberg et al. (2013) introduced an indicator, the 10%–90% quantile range of the urban heat island intensity ($UHII_{10-90}$), to quantify and compare different UHI intensities in the groundwater. For the six German cities investigated, the $UHII_{10-90}$ ranged between 1.9 and 2.4 K. The **effect of urbanization on shallow groundwater temperatures** was investigated by Taylor and Stefan (2009). Their analysis showed that groundwater temperature in fully urbanized regions is up to 3 K higher than in agricultural areas. According to Taylor and Stefan (2009), **pavements** (e.g., asphalt strips) are a main cause for the excess temperature. Ferguson and Woodbury (2004) conjectured, for an urban field site in Canada, that temperature changes could be largely attributed to **heat loss from buildings**.

The **heating effect of buildings** on the subsurface depends on a series of factors. It depends on the structure of the building, the foundation, the depth of the foundation, the existence of cellars (basements), the number of underground levels, the building materials, the existence of insulation of walls and floor plates or ceilings, the efficiency of the insulation, the heating of the underground floors (by heating elements or by ventilation), etc. Of course, the physical properties of the underground material and the depth to groundwater are of importance as well. Even in unheated basements, the annual mean temperature is typically higher than the annual mean soil surface temperature.

Within the concept of thermal use of underground systems, this **surplus energy offers an additional potential for energy abstraction**. Allen et al. (2003) emphasized that using a hydrogeothermal source for space heating has high development potential in urban heat islands with high yielding aquifers. They estimated that a well that yields 20 L s^{-1} of 13°C groundwater from an Irish urban aquifer can generate 856 kW of heat, which can satisfy the heating demand of a 12,000 m^2 building with a peak heating intensity of 70 W m^{-2}. On the other hand, the phenomenon may limit possibilities for seasonal heat storage and the use of groundwater for cooling. In the city of Frankfurt, for example, where cooling is of primary interest, the elevated groundwater temperatures (by several degrees, locally up to >30°C in the down-gradient vicinity of a coal-burning power plant) are unfavorable for cooling purposes (Menberg et al. 2013).

1.2 IMPORTANCE OF THE LOCAL CONDITIONS

1.2.1 Thermal regime

A principal consideration for the use of shallow geothermal or low-enthalpy energy, besides the identification of the various physical processes involved, is the **thermal regime**. As shallow underground, we define the first few decameters below ground surface. Such systems are highly influenced by the local meteorological conditions. Approximately, the temperature of shallow underground systems at a considered location is close to the mean annual soil temperature. Key information is the vertical above and below ground temperature profile (Figure 1.2). The annual mean air temperature at a location is usually measured at an elevation of 1–2 m above ground surface. It ranges from about 0°C in polar zones to about 24°C in tropical regions. In the temperate climate zone, it is around 8°C to 10°C. This reference air temperature is typically lower than the mean annual ground surface temperature (GST). With increasing depth, the temperature normally increases due to the local geothermal heat flux, which typically ranges between 0.05 and 0.11 W m^{-2} depending on the local geological setting (Pollack et al. 1993). The related vertical temperature gradient is around 0.03 K m^{-1}. Moreover, cryologists observed a thermal offset within the active zone of frozen ground close to soil surface (Williams and Smith 1989). In general, soil temperature depends mainly on latitude, elevation above sea level, exposition of the site, groundwater flow, and the local geothermal heat flow. Seasonal temperature fluctuations are usually perceptible only to a depth of about 10 m below ground surface. Below this depth, the thermal regime is highly damped or even stable. An example of the thermal profile measured close to soil surface at a meteorological station in

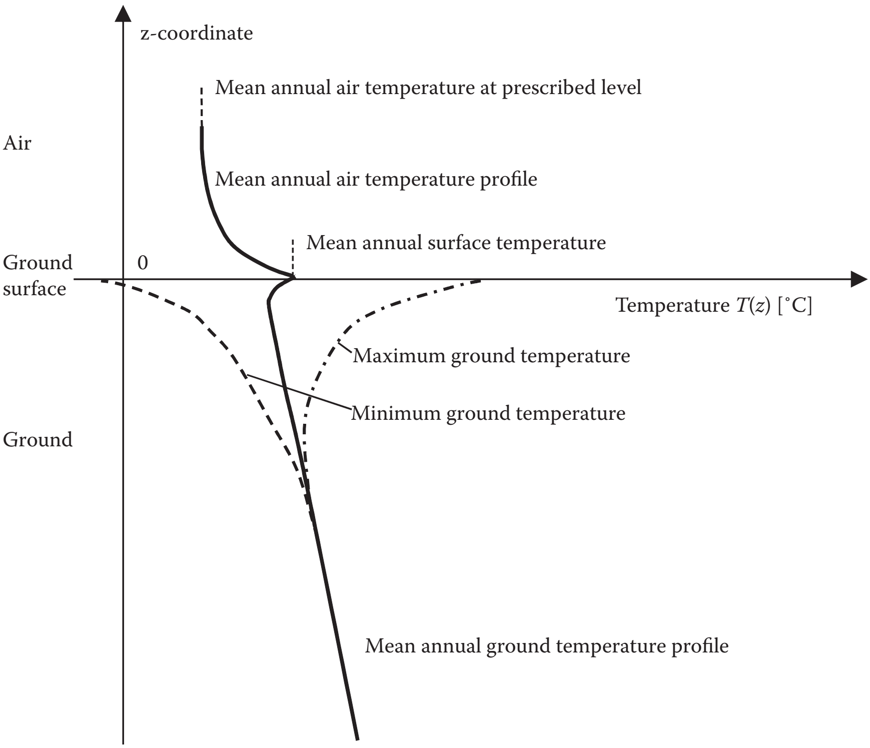

Figure 1.2 Schematic below and above GST profile.

Zurich-Affoltern (Switzerland) is presented in Figure 1.3. It shows that the **annual mean temperature at soil surface is about 2 K** higher than air temperature in this case, with a long-term mean air temperature of 8.5°C and a long-term mean soil surface temperature of about 10.5°C. The monthly average temperature of air (2 m above ground level) and soil (5 cm below ground level) at the meteorological station Zurich-Affoltern (Switzerland) over the period 2000–2010 is depicted in Figure 1.4. Accordingly, a temperature difference of 2 K persists over the year except for the months March and April at this station (mean difference of 1.5 K over the period of 2000–2010).

A similar **difference between mean air and soil surface temperature** was found by Wu and Nofziger (1999) in their investigations of bare soil in northern China. The three-year annual mean surface soil temperature was about 2.0 K higher than that of the air temperature. Similar results for bare soils were already reported by Fluker (1958). While the average annual air temperature was 20.8°C, it was 24.1°C at a soil depth of 5 cm. Moreover, the corresponding maximum average temperatures were 30.0°C and 35.2°C, respectively, and the minimum temperatures were 10.5°C and 11.1°C, respectively. This observation implies corresponding temperature amplitudes of 9.8 and 12.1 K. Measurements of the soil temperature regime in the United States (USDA 1999) showed a typical difference of 1 K between annual air and soil surface temperature. For 14 stations within the United States, this difference ranged between 0.7 and 2.9 K. Putnam and Chapman (1996) inspected a one-year record of ground surface and air temperature measurements in northwest Utah (United States). Mean GSTs were seen to be higher for bare granite (11.3°C) than for partially shaded neolith (9.5°C), and both were above the mean annual air temperature at a height

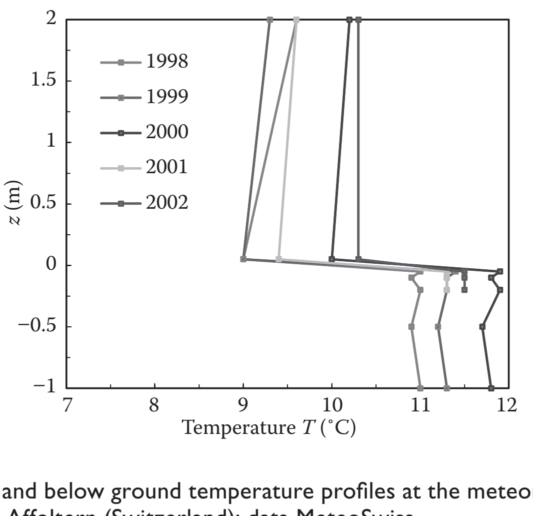

Figure 1.3 Above and below ground temperature profiles at the meteorological station Zurich-Affoltern (Switzerland); data MeteoSwiss.

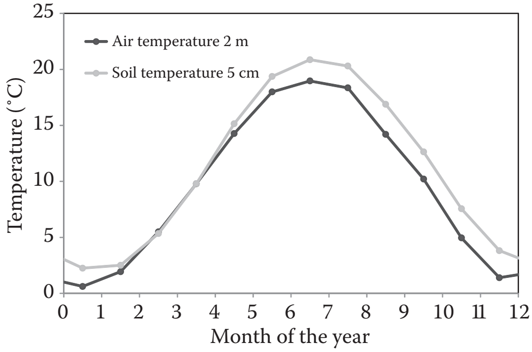

Figure 1.4 Monthly average temperature of air (2 m above ground surface) and soil (in 5 cm depth) at the meteorological station Zurich-Affoltern (Switzerland); period 2000–2010; data MeteoSwiss.

of 2 m above ground (8.8°C). For a soil covered by crops, the temperatures in the profile are expected to be lower than those under a bare surface due to shading and evaporation. Influence of precipitation and snow cover is negligible in the arid environment of this field site.

Lee (2006) found for **urban environments** (City of Seoul, South Korea) that mean annual ground temperatures (13.7°C–13.8°C) were slightly higher than the mean air temperature (12.9°C).

Based on hourly **satellite-derived land surface temperature** (LST) and measured air temperature (T_a) data at 14 stations of the US Climate Network, Gallo et al. (2011) investigated the relationship between air and LST. Vegetation at each station is specified as grass or low vegetation ground cover. LST was greater than T_a for both the clear and cloudy conditions; however, the differences between LST and T_a were significantly less for the cloudy-sky conditions. Mean differences of less than 2 K were observed under cloudy conditions for the stations, as compared with a minimum difference of greater than 2 K (and as great as 7 K) for the clear-sky conditions. The results suggest that the relationship between LST and T_a, even under cloudy conditions, can vary with location. There is a cyclic increase and decrease in the clear-sky hourly difference between LST and T_a, which generally follows the daily and seasonal cycle of solar radiation. Under cloudy conditions, the difference is fairly stable throughout the day. Smerdon et al. (2006) concluded that the main differences between GST and surface air temperature are caused by summer evapotranspiration and winter cryogenic effects (snow, ice).

The **temperature at soil surface** of a particular site, that is, just within the soil, mainly depends on the net radiation flux and the heat transfer fluxes between soil surface and the air layer above it, as well as energy fluxes into or from the ground. Net radiation is commonly expressed by the **heat balance at the soil surface** (Figure 1.5) as follows (e.g., Williams and Smith 1989; Kollet et al. 2009):

$$J_{\text{net\_radiation}} = J_{\text{sensible\_heat}} + J_{\text{latent\_heat}} + J_{\text{ground\_heat}} \tag{1.1}$$

Note that Equation 1.1 holds for both short- as well as long-term evaluations. The **net radiation** ($J_{\text{net\_radiation}}$) is the incoming shortwave and longwave (IR) radiation minus the outgoing longwave radiation. **Soil surface temperature** is also influenced by the heat transfer between soil surface and air layer, which is composed of the sensible heat flux ($J_{\text{sensible\_heat}}$) due to the movement of air, the latent heat flux ($J_{\text{latent\_heat}}$) due to evapotranspiration and condensation, as well as the ground heat flux ($J_{\text{ground\_heat}}$). Energy fluxes from the surface into the ground (referred to as ground heat flux including negative fluxes from the ground to the surface) comprise heat conduction in solids, soil air and soil water, advective heat flux in soil air (including vapor), and flowing soil water (from rainwater). **Ground heat flux** shows a distinct diurnal and seasonal variability with inflowing and outflowing components, while in the long run, the average ground heat flux is basically identical to the geothermal heat flux.

The thermal use of shallow underground systems will certainly also play a role in the energy balance at soil surface by affecting the soil surface temperature. Taking the resulting **seasonal soil surface temperature**, based on measurement, as reference and thermal boundary condition leads to a pragmatic, simplified formulation of the complex situation.

The unperturbed **temperature of shallow groundwater systems,** with depth to groundwater as well as saturated thickness of up to tens of meters, is often close to the mean annual soil surface temperature. The influence of the geothermal heat flux is usually weak in shallow systems. However, **the thermal regime of shallow groundwater systems can be**, more or less,

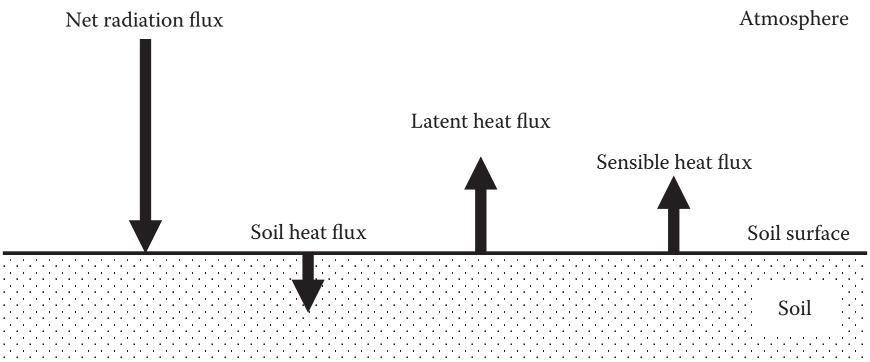

Figure 1.5 Energy fluxes toward soil surface.

strongly influenced by infiltrating surface water from rivers, streams, and lakes. This influence manifests itself by additional temperature fluctuations. Sufficiently far away from infiltrating surface water (order of a few 100 m horizontally), the fluctuations vanish. Moreover, groundwater systems very close to the soil surface exhibit an influence of the seasonal temperature fluctuation at the soil surface.

The fact that temperatures close to the mean annual soil temperature, at a depth of about 10 m or more, are relatively stable provides an important prerequisite for the thermal use of underground systems by heat exchanger systems with the help of heat pumps. This concerns both heating and cooling systems for air conditioning and space heating (Figure 1.6a) as well as cooling. Moreover, direct heat injection from buildings (geo-cooling) without heat pump (Figure 1.6b) is also possible.

1.2.2 Hydrological and hydrogeological conditions

In principle, any underground space may be used thermally. However, the choice of a specific technical system, that is, the installation of borehole heat exchangers (BHEs) or pumping and reinjection of groundwater with heat extraction, strongly depends on the local hydrological and hydrogeological conditions.

For closed systems, low hydraulic conductivity formations are preferred. The main reason is to prevent groundwater pollution caused or enabled by leakage of working fluids of the installation. In this context, highly conductive karst and fractured rock formations are less suited. A prominent example for inappropriate installation due to another reason is the closed system planned

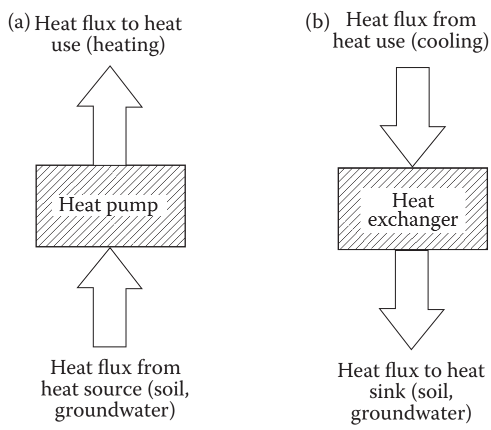

Figure 1.6 Schematic heat flux for (a) space heating with heat pump; (b) space cooling with heat exchanger only.

for the town of Staufen in the Upper Rhine Graben in southwest Germany. Down to a depth of 140 m, seven boreholes were drilled in 2007 into gypsum and anhydrite-bearing Keuper formations (Goldscheider and Bechtel 2009). The boreholes established **hydraulic contact** between confined groundwater and anhydride, and the consequence was substantial volume increase from gypsum swelling. Within a couple of weeks, **uplift of the ground** in the range of 1 cm month^{-1} caused severe damage to the buildings of the town.

Pumping and reinjection of groundwater in **open systems requires that the hydraulic conductivity of the aquifer is sufficiently large** in order to be efficient. Further important parameters are the geologic structure, the porosity, the water content, and the mineral composition of the aquifer material. Important hydrological conditions are the local flow direction, the recharge conditions, the location of surface water bodies, the depth to groundwater, and the fluctuation of the groundwater table. Hydrothermal conditions comprise the soil and water temperature, their fluctuation, and the extent and temperature condition of constructions (buildings, tunnels, sewers, etc.). The relevant hydrothermal properties of soils are their thermal conductivity and thermal capacity. The former can be determined by a thermal response test. While water exhibits an extremely high thermal capacity, soils are neither good insulators nor highly conductive materials. Properties depend to a high degree on the water content. Hydrogeological and hydrothermal investigations required to furnish the relevant parameters are further discussed in chapter 6.

1.3 TECHNICAL SYSTEMS

1.3.1 Heat pumps

A **heat pump** is a technical device that can transfer thermal energy from a “cold” reservoir (a fluid, e.g., air or water mass) at a lower temperature level to a “hot” reservoir with a higher one (again, e.g., air or water) by using an amount of external energy (electrical or fuel energy, waste heat). An overview on ground-source heat pumps is given in Lund et al. (2004). The two main types are the vapor compression and the absorption cycle heat pumps.

A **vapor compression heat pump** (Figure 1.7) consists of a compressor, an expansion valve, and two heat exchangers referred to as an evaporator (heat source) and a condenser (heat sink). The most common type of heat pump is the vapor compression heat pump powered by electricity. Energy is used to mechanically compress the working fluid (vapor). There exist also vapor compression heat pumps, which can be driven by a combustion engine using natural gas or biogas or by directly using solar energy or geothermal energy (Brenn et al. 2010). **Absorption cycle heat pumps**, on the other hand, are thermally driven. Absorption systems utilize the property of liquids or

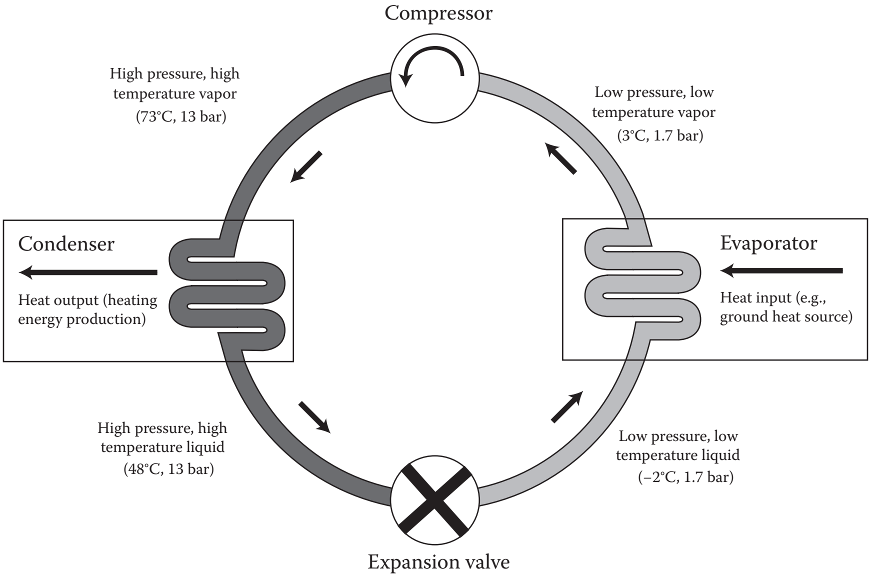

Figure 1.7 Compressor heat pump cycle (schematic).

salts to absorb vapor of the working fluid thus generating heat. Compression of the working fluid is achieved thermally in a solution circuit, which consists of an absorber, a solution pump, a generator, and an expansion valve. Some additional electricity is needed to run a pump. There exist also various hybrid systems. Common to both types is that they use closed cycles with a working fluid. Heat transfer from heat sources and to heat sinks is usually accomplished with the help of heat exchangers. Information can be obtained, for example, at the IEA OECD Heat Pump Centre.

The total heat flux of a heat pump is, in principle, the sum of the heat flux extracted from the heat source and the heat flux needed to drive the cycle. The performance of a heat pump is represented by the **coefficient of performance** (COP). It is defined as the ratio of useful energy delivered and the total external energy consumed by the heat pump. For an electrical compression heat pump, the COP equals the heat output of the condenser versus the electrical input to the compressor. It can be confronted with the **ideal performance of a Carnot cycle**:

$$\varepsilon_{Carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{1.2}$$

which is defined as the ratio of heat delivered by the heat pump and the energy used by the compressor. It can be considered as a maximum performance, which cannot be exceeded. Typically, a fraction of about 50% of the theoretical ε_{Carnot} can be achieved by a heat pump in practice. The performance is dependent on the heat pump itself (efficiency of heat exchangers, losses in compressor, etc.) and on the temperature difference between the low-temperature medium and the high-temperature medium side. Nevertheless, it becomes clear from Equation 1.2 that a high temperature of the low-temperature medium is more effective. Therefore, ground-source heat pumps and GWHPs usually have a higher COP than air-source heat pumps. This result was demonstrated by, for example, Urchueguía et al. (2008) in their field study in Spain.

Another definition is the **primary energy ratio** (PER), which relates the heat delivered by the heat pump to the primary energy used to generate the external energy supplied. Basically, it is COP times the corresponding efficiency factor. Since COP is often determined for specific operating conditions, the long-term average value in practice is usually smaller. Therefore, a relevant number is the **seasonal performance factor** (SPF), which is an average value over the year. Typical SPF values of GSHP systems are currently around 3 to 4 (Bayer et al. 2012). Miara et al. (2011) evaluated the heat pump efficiency in real-life conditions and found an average SPF value of 3.9 for the 56 GSHP systems studied in Germany. Lund et al. (2011) reported an average COP of 3.5 for GSHP systems. This means that the heat delivered by the heat pump is 3 to 4 times the external energy supplied.

1.3.2 Closed- and open-loop systems

In the thermal use of shallow underground systems, the underground (rock, dry, or unsaturated or saturated soil) or pumped groundwater acts as heat source or heat sink for a heat pump. Various systems exist (Lund et al. 2004; Florides and Kalogirou 2007) for the thermal use of the underground in connection with heat pumps. On one hand, there are ground-coupled **closed-loop systems** (Figure 1.1a) in connection with a heat pump. On the other hand, there are **open systems** with groundwater extraction and injection wells (Figure 1.1b), with or without heat pump. The type chosen in a specific application depends on the operational mode of the system, the soil and rock type, the land available, the groundwater situation, as well as economic and regulatory issues.

In a **closed-loop system**, a closed loop of a pipe (typically high-density polyethylene plastic, or also copper pipe) is installed underground horizontally (at a depth of 1 to 2 m) or vertically (down to a depth of a few tens to about 400 m), acting as a heat exchanger. An environmentally safe heat carrier fluid, for example, a water-antifreeze solution, is circulated through the pipes to collect heat from the ground in winter and/or to inject heat to the ground in summer. The typical **horizontal alignment** of the tube consists of a serial or a parallel connection of pipe sections. According to Florides and Kalogirou (2007), a typical horizontal loop is 35–60 m long for 1 kW of heating or cooling capacity. In horizontal systems, the thermal recharge is provided essentially by solar energy entering the soil surface, which is essentially induced heat from the soil surface. A special variant of horizontal collectors is the direct exchange system. Instead of using plastic pipes, soft copper tubing directly transfers energy between ground and refrigerant. Circulating the heat pump refrigerant instead of the heat carrier fluid in the ground saves one energy transfer step, and the refrigerant temperature is closer to the ground temperature. This is promoted by the copper tubing, which has much higher heat conductivity than plastic. This direct technology raises the SPF by about one unit in comparison to standard practice, however, at the expense of higher installation costs and environmentally critical copper use. Further details on horizontal closed-loop systems can be found in Banks (2008). In **vertical BHEs**, typically plastic pipes (polyethylene or polypropylene pipes) are installed in the borehole. The remaining space is typically filled with a grouting material (backfilling, e.g., concrete–bentonite mixture), which ensures good contact between pipe and undisturbed ground and reduces the thermal resistance. In hard rocks, however, grouting is not needed for stabilization, and if no hydrogeological concerns are raised, no backfilling is applied. Such practice is common in Scandinavian countries such as Sweden. Frequently used types of BHEs are the U-pipe configuration or the coaxial pipe configuration with two concentric tubes (Figure 1.8). In a U-pipe configuration, a pair of straight pipes is connected with a U-bend pipe. One or two U-pipe configurations are typically installed (Figure 1.8a and b). Further configurations exist like the spiral coil or helical configuration. BHEs can be conceived as single systems or as arrays of several to many units (de Paly et al. 2012).

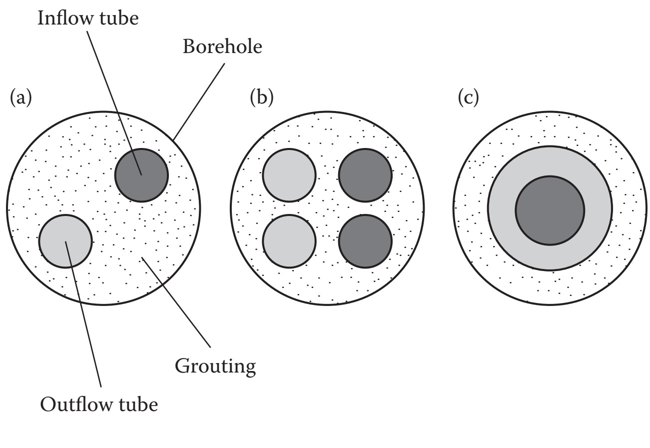

Figure 1.8 Typical BHEs: (a) single U-pipe BHE; (b) double U-pipe BHE; and (c) coaxial BHE.

An **example** is the heat storage project at the Science City Campus (Hönggerberg) of ETH Zurich (Switzerland, Figure 1.9). According to this project, waste heat from the buildings will be dynamically stored underground in summer, with the help of a total of 800 vertical BHE units, and reused in winter for space heating as well as process heat. Two plots of 100 and 130 heat probes have been installed so far and have been operating successfully since 2012 (ETH Life 2012). The vertical probes consist of plastic pipes. They are 200 m long and are arranged in regular intervals of 5 m each horizontally. The local underground consists of unsaturated or quasi-saturated moraine material and molasse rock (sandstone, marl, and conglomerates). The BHEs are connected to a pipe network of the buildings. Space heating is performed in winter with the help of heat pumps using the underground heat of the heat storage. At the end, a total of about 4 millions m^3 of underground volume will be utilized, leading to an expected thermal yield of about 15 GWh per year. **Another example** of borehole thermal energy storage is the facility at the University of Ontario, Institute of Technology (Dinçer and Rosen 2011).

A special combination of closed systems consists of **heat exchangers in geotechnical constructions**. These are foundation constructions like piles, plates, etc., which are equipped with built-in heat exchangers (SIA 2005).

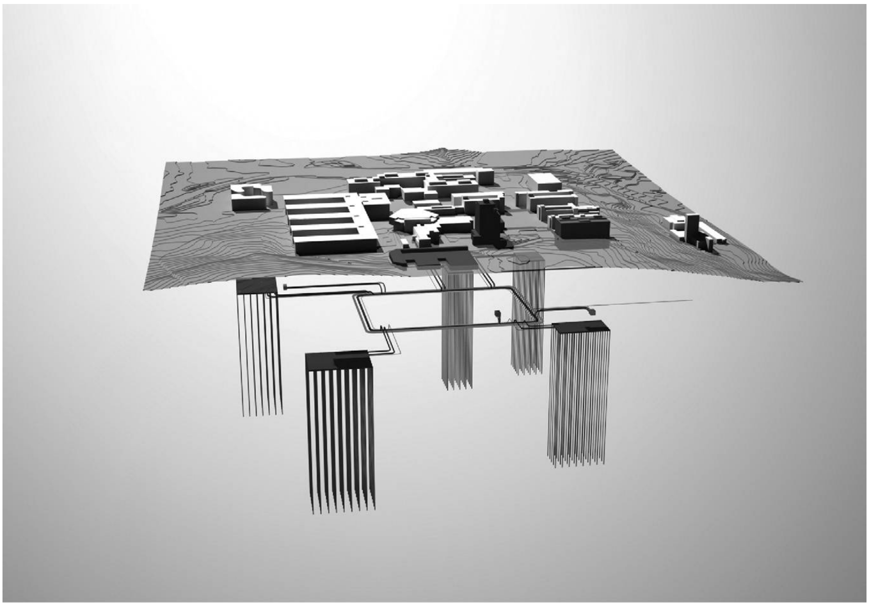

Figure 1.9 **(See color insert.)** Heat storage project (schematic) at the Science City Campus (Hönggerberg) of ETH Zurich (Switzerland). (Courtesy of ETH Zurich, Abteilung Bau, 2011.)

They are typically applied in building constructions under difficult soil conditions, like silt, fine sand, marl, mud, unconsolidated deposits, etc. Often these are fine-grained soils. The tight relationship to the building makes them suitable for combined space heating and cooling with seasonal heat charging and extraction. It is indispensable for these systems that the thermal recharge is guaranteed by proper design in order to avoid excessive cooling or heating of the ground. Particularly, soil freezing has to be prevented in order to preserve the geotechnical functioning of the construction.

The **open-loop system** uses pumped groundwater directly in the heat exchanger and then discharges it to the aquifer, to a stream or lake, or on the soil surface (e.g., infiltration or irrigation), depending upon local regulations. A typical configuration consists of a **well-doublet scheme** in a shallow aquifer with extraction well, which pumps water to the heat exchanger of the heat pump (Figure 1.10). The cooled or warmed water is injected back, either in an injection well or via an infiltration facility (pond, pit, ditch, gallery, well), where water infiltrates toward the groundwater table. Care has to be taken that the distance between extraction well and infiltration facility or injection well is large enough to prevent a hydraulic short circuit, thus avoiding the recycling of cooled or warmed water, respectively. Configurations with several pumping wells and injection facilities are also in use. It is further possible to pump groundwater and to discharge it to a surface water body. The depth of the wells is typically less than 50 m.

Further schemes exist. For example, in the **standing column well**, water is pumped from the bottom of the well to the heat pump. The injected water is percolated through a gravel pack in the annulus of the well in order to absorb heat. Standing column wells are typically 15 cm in diameter and may be as deep as 500 m (Florides and Kalogirou 2007). A detailed description of standing column wells can be found in Banks (2008). A related concept consists of the **vertical double well** after Jacob (Banks 2008). It

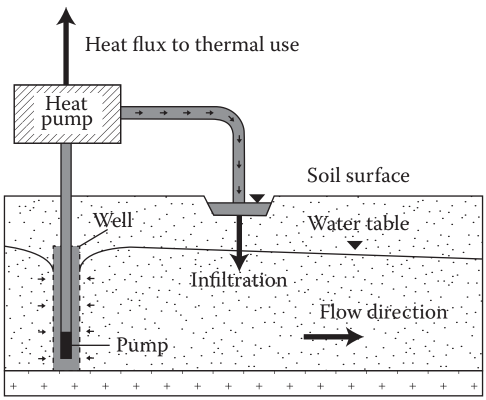

Figure 1.10 Well doublet with pumping well, heat pump, and infiltration facility.

consists of inflow and outflow sections of a well, which are separated by packers and a pump.

1.4 ENERGY DEMAND AND ENERGY PRODUCTION

Basic information needed for the design of technical installations for thermal use of buildings, settlements, and industrial installations is the seasonal energy demand. This comprises both heating and cooling energy. In the discussion about energy demand in the context of heat pumps, it is important to define the **temperature range**, since it affects the selection of the heat pump system:

- Low energy space heating uses water temperatures in the range of about 35°C to 55°C.
- Hot water for domestic use has temperatures in the range of 60°C to 70°C.
- Process water for industry is supplied at the requested temperature (heating or cooling).
- Space cooling requires coolant temperatures in the range of 22°C to 25°C.

A schematic seasonal energy demand profile is shown in Figure 1.11.

Bayer et al. (2012) presented an overview on the current **energy demand** for space heating for selected countries. Except in North European countries, the relative portion of ground-source heat pumps and GWHPs is still small and often supplies less than 1% of the total energy demand.

An overview of the **energy production by ground-source heat pumps in shallow underground systems** (Bayer et al. 2012) is given in Table 1.1 for selected countries (status in 2008). For comparison, the total heating

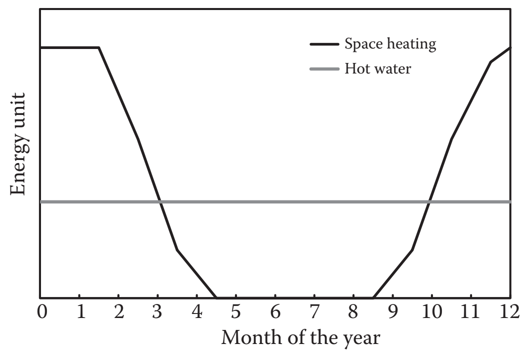

Figure 1.11 Seasonal energy demand (schematic).

Table 1.1 Energy production by GSHPs in shallow underground systems and heating demand in 2008 in European countries

	GSHPs (TJ)	*Heating demand (TJ)*	*Population* $\times 10^6$
Austria	3,229	209,000	8.2
Belgium	495	295,000	10.4
Czech Republic	927	186,000	10.2
Denmark	1,859	173,000	5.5
Finland	9,852	139,000	5.2
France	7,784	1,268,000	63.7
Germany	11,237	2,044,000	82.4
Italy	1,157	816,000	58.1
Netherlands	1,080	298,000	16.6
Norway	8,588	91,000	4.6
Poland	1,193	615,000	38.5
Slovenia	387	30,000	2.0
Spain	408	286,000	40.4
Sweden	52,251	257,000	9.0
Switzerland	7,403	138,000	7.6
United Kingdom	783	1,152,000	60.8

Source: After Bayer, P. et al., *Renewable and Sustainable Energy Reviews* 16(2): 1256–1267.

demand and the population are presented as well. For Switzerland, the total energy demand in 2010 was 911,550 TJ, the energy production by closed ground-source systems was 5321 TJ, and the energy production by open systems was 737 TJ (FOE 2011).

In practice, **back-of-the-envelope** calculations are often useful for first tier screening. A common approach is to predict the specific heat extraction rate $q_{\mathrm{tb}} = J/H$ of a closed-system borehole depending on operating hours and ground conditions (Table 1.2). By also assuming that the SPF can be anticipated, the required total borehole length H is estimated for an annual energy demand E and operating time t:

$$H = \frac{E - \dfrac{E}{\mathrm{SPF}}}{t q_{\mathrm{tb,given}}} \tag{1.3}$$

As an example, consider the heating of a single family house by a closed system with SPF = 4.25. The annual demand of the house is 21,350 kWh (~2000 kg of fuel oil). The system is operated for t = 2160 h during the heating season with a specific heat extraction of q_{tb} = 50 W m^{-1}. The question is, what is the needed installation depth H of the BHE to supply the required heat demand? The primary power consumption of the heat pump is governed

Table 1.2 Specific heat extraction rates for single closed system BHEs (W m^{-1}) of 40–100 m length (only heating) for given total annual operation times

Rock and soil material		VDI 4640 (VDI 2001a) 1800 h/a	VDI 4640 (VDI 2001a) 2400 h/a	MCS (2011) 2400 h/a	Numerical Simulation (Erol 2011) 2400 h/a
Unconsolidated soils (dry conditions)	Sand	<25	<20	n. a.	38–48
	Gravel	<25	<20	n. a.	34–43
Unconsolidated soils (saturated)	Clay	35–50	30–40	22–35	27–32
	Loam (silt)	35–50	30–40	22–35	32–39
	Sand	65–80	55–65	23–46	38–49
Unconsolidated soils (with high groundwater flow)	Sand	80–100	80–100	n. a.	55–82
	Gravel	80–100	80–100	n. a.	67–114
Sedimentary rocks	Sandstone	65–80	55–65	22–55	40–52
	Limestone	55–70	45–60	n. a.	32–39
Magmatic rocks	Basalt	40–65	35–55	n. a.	32–39
	Granite	65–85	55–70	32–48	33–40
Metamorphic rocks	Gneiss	70–85	60–70	n. a.	37–48

by the SPF, and related to the heat demand we obtain 21,350 kWh/4.25 = 5024 kWh. The fraction of geothermal energy thus is 21,350 kWh – 5024 kWh = 16,360 kWh. With the given operation time, the required power of the heat pump results in 16,360 kWh/2160 h = 7559 W. This means, with the given specific heat extraction, a borehole length of 7559 W/50 W/m = 151 m is needed. However, this is only a very approximate value, and the assumed value of the specific heat extraction is uncertain and governed by the hydrogeological, geothermal, and technological conditions. Apart from this, the value of the SPF is not only determined by the efficiency of the heat pump but also strongly influenced by the operating conditions.

Specific heat extraction rates are given by the VDI 4640 guidelines (VDI 2001a) and are commonly used in practice. For these values, however, no quantitative basis is provided. The values are pertinent for double-U-tube or coaxial pipes and for boreholes of 40–100 m length. In comparison, a detailed numerical simulation with a range of different scenarios was conducted by Erol (2011) for typical rock and soil in Germany, given realistic ranges of thermal conductivity and heat capacity. Resulting values of the specific heat extraction rates after 30 years of operation (at 2400 h $year^{-1}$) are comparable to VDI values for some unconsolidated sediments such as clay and loam, but are higher for sand. For most other scenarios, the computed ranges are below the VDI values. One reason could be the role of groundwater flow, which means additional advective heat provision and thus higher specific heat extraction rates. For the VDI values, this may be accounted for, whereas the simulation was done without. In comparison, as a specific case of unconsolidated material, soils with “high groundwater flow” are distinguished by the VDI with similar values as the simulated ones (seepage velocity of 0.5–5 m day^{-1}). Groundwater flow does not only increase the specific heat extraction rate; it also promotes regeneration. As a result, typical performance decline, reflected in the simulation by decreasing heat extraction rates, is mitigated (Erol 2011). Table 1.2 also lists values taken from a British guideline (MCS 2011), which are comparable to those ranges obtained by simulation.

1.5 MANAGEMENT OF UNDERGROUND RESOURCES

The thermal use of soil and groundwater resources has to be embedded in a holistic view of the management of the water resource. Soil water and groundwater environments are, in principle, **part of an ecosystem with related ecosystem services**. The **management of groundwater resources** essentially comprises its use for **water supply for domestic and industrial use**, as well as the **thermal use**. While questions of the impact of the thermal use on groundwater quality and ecology are treated in Section 1.6, specific questions related to the management of underground resources are briefly discussed here. One management aspect is the **seasonal operation of technical installations for the thermal use of the underground**. Another management aspect is the **possible antagonism between water supply and thermal use**.

1.5.1 Seasonal operation of technical installations

The **seasonal operation of technical installations** for the thermal use of soil and groundwater can be conceived as

- Solely extracting heat from the underground or groundwater, that is, for space heating in winters
- Solely injecting heat into the underground or groundwater, that is, for space cooling in summers
- Combined seasonal heat extraction and injection

Technical systems **solely extracting or injecting heat** only work in a satisfactory, long-term manner if thermal recharge or recovery of the cooled or warmed underground space is assured. Otherwise, undesired soil cooling or soil warming, or even soil freezing, occurs. Efficient heat recharge happens if sufficient advective heat transport by soil water or groundwater flow is present. For a typical field situation, the related minimum Darcy velocity is of the order of 1 m day^{-1}. Otherwise, the thermal recovery is restricted to mainly heat conduction from the soil surface. Proper design of the layout is decisive.

Combined seasonal heat extraction and injection with heat storage enable thermal recharge by the system itself. However, the efficiency might be severely reduced in this case by too high influence of advective heat transport due to water flow. If possible, the technical design should pursue thermal layering instead of mixing of warm and cold water.

1.5.2 Water supply and thermal use

Groundwater resources, which are suited for drinking water supply, often receive highest priority in national regulations for groundwater protection (see Section 1.8). Still the **simultaneous use of groundwater resources for water supply and for thermal use** is possible and desired. However, it deserves some attention with respect to the overall energy balance.

Imagine substantial pumping from an aquifer for water supply at temperature T_0 with the water being delivered to domestic users and industrial plants and installations in buildings. Depending on the residence time of the water and the type of technical installation in the buildings (e.g., non-insulated containers and vessels like water toilets, boilers, and reservoirs) and on the prevailing room temperature in the building, a certain energy flux will result (warming or cooling). This energy flux may have to be compensated by the local climate control systems. Now, if simultaneous thermal use of the aquifer is introduced, this results in a change ΔT of the groundwater temperature (warming or cooling) and therefore in the temperature of the delivered water. In this case, the expected temperature of the pumped and delivered water is essentially changed to $T_0 + \Delta T$, and a compensating energy flux in the buildings and installations may be needed. For an aquifer, the temperature of which is decreased, a compensating positive energy flux within the buildings will be needed in winter. This represents an energy loss. Similar considerations are applicable for increase in groundwater temperature for cooling purposes in summer. Therefore, depending on the water and energy fluxes and the temperature difference ΔT, **short-circuit effects and thus a loss of the overall thermal efficiency** may occur. Such effects should be avoided or at least be reduced.

1.6 IMPACT ON GROUNDWATER QUALITY AND ECOLOGY

Water quality can be affected by heat extraction or injection by **directly influencing water temperature**. It can be indirectly influenced by **temperature-dependent physical, chemical, and biological processes** and their interaction.

Most physical properties are temperature dependent (e.g., water viscosity or water density). Temperature can **affect the thermodynamic equilibrium of species and the chemical milieu**. All chemical reactions are, in principle, temperature dependent. Recall the van-'t-Hoff rule, which states that for a temperature rise of 10 K, the velocity of chemical reactions doubles. Lowering the temperature can change the equilibrium constants of dissolved minerals and gases. A consequence can be, for example, increased solubility of carbon dioxide and a subsequent increase in carbonate hardness. An increase in temperature can lead to increased solubility of minerals or to increased growth of undesired bacteria. Furthermore, undesired desiccation of soils may occur, thus leading to undesired soil cracks. Temperature change may **affect the self-purification ability of soils and groundwater systems**. **Plant growth in ecosystems including agriculture** is sensitive to temperature changes. The **effect of thermal energy discharge on shallow groundwater ecosystems** was investigated by Brielmann et al. (2009). For their investigation site in Germany, they found no likely threat to ecosystem functioning and drinking water quality by the thermal use of the aquifer. **Shallow soils** may be strongly thermally affected by horizontal closed heat exchanger systems. Therefore, care has to be taken in the design of such systems in order to avoid negative effects. The same holds true for the neighborhood of vertical closed systems.

Water quality can further be negatively affected by **pollutants** entering soil and groundwater via installations for thermal use, for example, via boreholes or via infiltration facilities. Potential pollutants are the working fluid of heat pumps, the heat carrier fluid in closed systems, or any further pollutant entering soil and groundwater via BHE, pumping well, or infiltration facilities. This concerns mainly GWHP systems and those ground-source heat pump systems, which are situated in groundwater supply areas.

1.7 GEOTECHNICAL ISSUES

Due to the development of geothermal systems **malfunctioning**, **direct damages** of the systems or even **third party damages** may occur. Causes for such damages are numerous and might be related to the technical heat pump systems, site-specific conditions of the subsurface, and/or the development by the geothermal systems, such as drilling of the wells or installation of BHEs. Bassetti et al. (2006), for example, investigated causes of damages by ground-source heating pump (GSHP) systems in Switzerland. They concluded that many causes are related to the incorrect design of GSHP systems, resulting mainly in malfunctioning of the GSHP system. Blum et al. (2011), who studied 1100 GSHP systems in Germany, also showed that subsurface characteristics are often not adequately considered during the planning and design, which results in an undersizing or oversizing of GSHP systems.

In addition to such deficiencies during the planning and design, **geotechnical issues** such as **subsidence** or **uplift** and resulting damages may occur due to the installations of geothermal wells or BHEs. For example, **inadequate backfilling** of the annular space between the BHE and the borehole wall may cause severe damages due to the rise of artesian groundwater or the artificial hydraulic connection between aquifers. The latter, for example, resulted in severe third party damages due to land subsidence and uplift in South Germany. In 2007, a heave of more than 10 cm per year triggered by anhydritic swelling caused a severe damage in the historic town of Staufen (Goldscheider and Bechtel 2009; Sass and Burbaum 2010; LGRB 2010, 2012). The total damage of more than 250 houses including the historical town hall (Figure 1.12) is currently estimated to be around 50 million euros. The site is currently remediated by pumping groundwater from the lower Triassic limestone aquifer.

In contrast to the damage in Staufen, one year later in 2008, an artificial hydraulic connection between two aquifers due to the installation of a GSHP system caused a local subsidence in the town of Schorndorf (Germany), and particularly, one grammar school house showed numerous cracks and one spring fell dry. In 2009, the BHEs were successfully remediated by overcoring and grouting, using a concrete–bentonite suspension. The costs incurred in this case were only about 300,000 euros. Both cases, however, clearly demonstrate the potential damages that might be triggered due to geothermal installations. Such third party damages due to installations of GSHP systems in the state of Baden-Württemberg (southwest Germany) are site specific and mainly occurred by drilling in the Triassic Gipskeuper Formation and the Triassic limestones (Muschelkalk). Furthermore, both acute damages in the towns of Staufen and Schorndorf were caused by inadequate backfilling of the BHE, and hence damages could have been avoided by adequate and rapid on-site measures. After these incidents, a **technical guideline** for the quality assurance for GSHP systems was introduced by the Environmental Ministry of Baden-Württemberg (Germany) in 2011 (LQS 2012).

Nevertheless, future damage due to the installations of a geothermal system can never be ruled out; however, it can be comprehensively addressed by improved locally adopted license systems (e.g., Butscher et al. 2011) and **quality standards and quality assurances** (QS/QA). On the other hand, such damages might also be only locally restricted, site- and country-specific. For example, in Scandinavia, boreholes are typically drilled in crystalline rocks and are not grouted, leaving the space between the BHE pipes and the borehole wall filled with groundwater (e.g., Gustafsson et al. 2010). Under such conditions, the geotechnical and third party damages, which occurred in southwest Germany, are not feasible.

Figure 1.12 Damaged town hall of the historic town of Staufen, which was triggered by geothermal installations that resulted in the swelling of clay-sulfate rocks in the Gipskeuper Formation. (Courtesy of Christoph Butscher, 2013.)

1.8 REGULATORY ISSUES

As a rule, groundwater resources, which are suited for **drinking water supply, receive highest priority in groundwater protection**. Therefore, parts of the regulations concerning thermal use are based on groundwater protection principles, which primarily concern water quality issues (e.g., Stauffer 2011). Of course, quality can be affected by temperature, directly and indirectly. **Drinking water quality targets** may comprise temperature ranges, which can be exceeded or undercut by thermal use (warming and cooling). Water quality is indirectly influenced by **temperature-dependent physical, chemical, and biological processes** and their interaction. Therefore, regulations **limit the temperature change** caused by thermal use with respect to the initial, unaffected state. It is sometimes argued that admissible temperature changes should be smaller than climatically caused deviations from seasonal temperature variations. Some uncertainty exists with respect to the initial thermal state, which is the basis for evaluating the permissible temperature change. Regulations may also concern the energy abstraction rate (energy load).

Water quality can further be negatively affected by **pollutants** entering soil and groundwater via installations for thermal use. Therefore, regulations may concern technical and operational requirements in order to minimize or limit pollution.

Further regulations concern **soil and ecosystem protection**. Plant growth and agricultural activities should not be deteriorated by thermal use. These requirements affect mainly horizontal closed-loop systems. Some regulations limit the admissible temperature range.

Regulations also concern the heat pumps. One of the most important items concerns the choice of the **working fluid of heat pumps**. Working fluids principally have to fulfill the requirement of protecting the atmospheric ozone layer. Moreover, they have to fulfill the requirements of soil and groundwater protection.

Thermal use of soils and groundwater represents the **exploitation of a renewable resource**. This may affect neighboring stakeholders. Any thermal use results in temperature anomalies, which propagate within the underground. Since the temperature change should not exceed a predescribed limit, the thermal use of an individual abstractor can be strongly affected by upstream or neighboring users. Therefore, regulations may concern the **prevention of disadvantage** by, for example, limiting the distance of open and closed systems to neighboring property lines, wells, and surface water bodies.

Regulations may also prescribe **thermal monitoring** of groundwater resources and possibly of soils. Long-term thermal monitoring allows the surveillance of efficient use and of measures to ensure the quality standards.

Main regulatory issues and recommendations may comprise the following items, depending on the responsible agency:

- **Need for a concession** or license for thermal use of underground space or groundwater issued by the responsible agency
- Definition of permissible maximum modification of the seasonal ground and groundwater temperature
- Definition of **minimum** (e.g., 5°C) and **maximum** (e.g., 25°C) **groundwater temperature**
- Prevention **of disadvantage** to neighboring property owners by thermal use
- Prevention of groundwater pollution by thermal use systems
- Licensing of **working fluids** for heat pumps
- **Thermal monitoring** of groundwater resources

Haehnlein et al. (2010) presented an overview on the **international legal status** of the thermal use of shallow aquifer systems. They showed that the legal situation is quite diverse. Extensive national regulations exist only in a few countries such as Denmark or Sweden. European countries are, in general, more regulated. In addition, guidelines and technical recommendations exist in several countries, somehow defining the state of the art. A wide range for minimum required distances of thermal installations from property lines was observed (5–30 m). The same holds true for the temperature limits for groundwater. Specific ecological and environmental criteria are rarely reported. The authors observed that the highest inconsistency occurred in values for the acceptable maximum temperature change for groundwater, which is 3 K in Switzerland, 6 K in Austria, and 11 K in France.

On the **European Community level**, the use of energy from renewable sources is promoted by the directive 2009/28/EC (EC 2009). The directive includes the thermal use of shallow geothermal systems. An overview of the current European regulations for geothermal energy can be found in the EGEC (2007) report. Accordingly, the relevant national legislation is spread throughout the mining, energy, environmental, water management, and geological acts, sometimes in a contradicting way, and the licensing authority framework for geothermal facilities is rather complex in most countries.

In the following, a few **examples of national regulations** on the use of shallow geothermal energy are described.

1.8.1 Swiss regulation

According to the **regulation of Switzerland** (FOEN 2004), the power of allocating water resources, including groundwater, is basically a privilege of the cantons (provincial level). Based on federal and cantonal law, rights can be further transferred to beneficiaries (communities, corporations). In general, these authorities decide upon the permission or license for thermal use of groundwater resources by applicants (communities, companies, private persons). Based on federal and cantonal law, soils can generally be thermally used, for example, by horizontal closed-loop systems by property owners. On the other hand, BHEs and installations with pumping well and infiltration device for thermal use are, in general, not permitted in aquifers that are suitable for drinking water supply. Therefore, priority is clearly given to drinking water supply. Exceptions can be made by the authority, which issues the corresponding concession or license. Measures have to be taken in order to prevent groundwater pollution, for example, by leaking heat exchangers. Moreover, it has to be ensured that no further pollutants can enter the subsoil.

Based on federal law, the thermal use of an aquifer may not change the seasonal groundwater temperature by more than 3 K with respect to a situation with “natural” or “close to natural” conditions. However, in the immediate neighborhood of infiltration facilities, the temperature change may be higher, but has to reach the 3 K limit within a distance of maximally 100 m from the infiltration facility. The limit has to be fulfilled under consideration of all installations for thermal use within the aquifer. Outside of usable groundwater resources, the thermal use with closed heat exchanger systems (horizontal or vertical loops) is generally acceptable. Further restrictions can be formulated by the cantons. The regulation of admissible cooling and warming of groundwater directly limits its thermal use.

The definition of **natural conditions** represents a challenge since such conditions do not exist anymore. They can be approximated at best. We have to keep in mind that mainly in urban areas, with relatively small depths to groundwater, the groundwater temperature is often increased due to the settlements, factories, and technical installations, as well as increased air temperature, and therefore also mirrors the typical heat island effect. Thermal effects are present, in principle, also for agricultural and horticultural areas. These anthropogenic temperature changes have to be taken into consideration in the thermal management of aquifers (Figure 1.13). The limitation of temperature change with respect to “natural” conditions is mainly meant to limit undesired physical, chemical, and biological effects on the groundwater quality.

The Swiss Federal Government issued the implementation tool “Use of heat from soil and subsoil” (in German and French; FOEN 2009). It is intended to ensure harmonization of the approval practice of the cantons for shallow geothermal heat probes, GWHPs, soil recorders, and geothermal energy cages and piles in Switzerland. It also defines the necessary conservation measures, on the basis of the environmental protection legislation. Technical standards exist for the installation of shallow geothermal heat probes (SIA 2010).

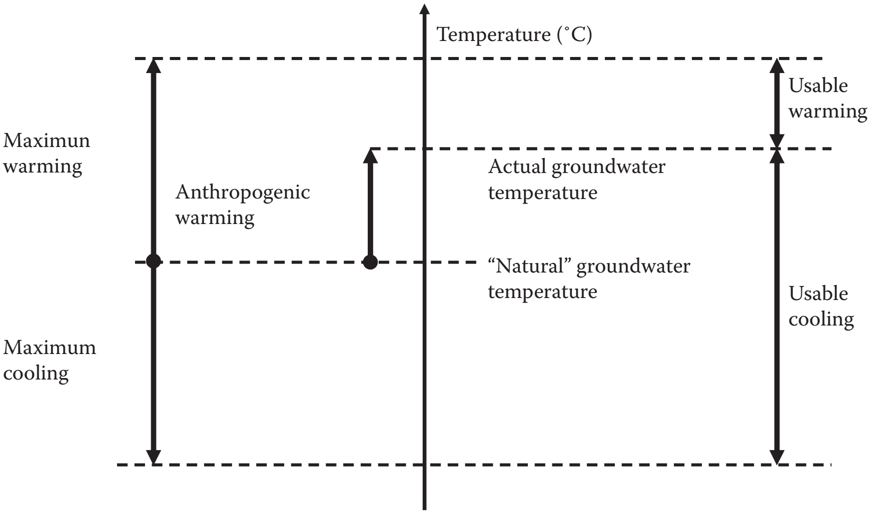

Figure 1.13 Usable warming and cooling range in regulations, which allow maximum deviation from "natural" conditions (schematic).

Concerning the **installation of vertical geothermal heat probes**, the Swiss Federal regulation (FOEN 2009) lists the regions where such installations are prohibited. These regions concern (1) aquifers, which are suitable for drinking water supply, (2) geological formations with high hydraulic conductivity and therefore large flow velocities, like karst formations or highly conductive fractured rock formations, and (3) potential landslide areas. Furthermore, situations are listed where the installation can be approved after detailed investigations, like installations in confined aquifers or multiaquifer systems, or the existence of contamination at the site, or the existence of highly mineralized groundwater. Exceptions are possible and need specific investigations and the approval by the cantonal authorities. The main motivation is to prevent groundwater pollution.

The required **steps for the design of vertical geothermal heat probes** for heating purpose according to SIA (2010) are as follows:

1. Determination of the mean soil surface temperature of the site
2. Determination of the thermal parameters (thermal conductivity)
3. Determination of the standard specific performance of the geothermal heat probe, depending on the thermal conductivity (diagram)
4. Evaluation of the standard annual hours of operation, depending on elevation (Switzerland)
5. Evaluation of annual energy demand of the system
6. Evaluation of the total annual hours of operation of the system

7. Evaluation of standard length of probe (diagram)
8. Correction of length of probe for given probe configuration and total annual hours of operation
9. Correction of length of probe for mean soil surface temperature
10. Evaluation of pressure loss in the pipe of the probe
11. Determination of the total length of the probe

The specifications are valid for Switzerland. With these requirements, the minimum temperature of 0°C/–3°C (outlet/inlet) of the refrigerant fluid of the probe after 50 operating years can be achieved. Another important requirement is to guarantee a professional and tight backfilling of the space between geothermal heat probe and underground material with practically impermeable grout material. This should prevent a hydraulic connection of aquifer layers with differing water quality and also prevent the penetration of pollutants into the subsurface from the soil surface or from leaky tubes.

The Swiss Society of Engineers and Architects (SIA) issued a series of documentations, which provide basic information on the design of installations for seasonal energy storage (SIA 1989, 2003), the use of shallow underground systems for space heating (SIA 1996), and the use of foundation constructions equipped with built-in heat exchangers (SIA 2005). They represent the technical state of the art.

We may look at the **regulations of the Canton of Zurich as an example**. The use of energy from underground systems and groundwater is described in a planning support brochure (AWEL 2010). Besides licensing, the local regulations mainly concern BHEs. The location of BHEs within a property is generally unconstrained by regulations with exceptions. These are as follows:

- If the BHE is located less than 3 m from the property line, the agreement of the neighbor is needed.
- If the BHE is located within a communal restricted area (mainly infrastructure), the agreement of the community is needed.
- If the BHE is located close to a railway line or tunnel, the agreement of the railway company is needed.
- BHEs close to surface water bodies are not allowed within a distance of 20 m from the shoreline. For small creeks, the distance is smaller.

The grouting material of BHEs has to fulfill specific requirements concerning the material composition (a bentonite cement water mixture). Conformity of the materials with water protection requirements has to be observed. Furthermore, a long-term (50 years) assessment of the temperature development has to be provided (if heat extraction capacity is larger than 100 kW).

1.8.2 Austrian regulation

According to the **Austrian standards** (ÖWAV 2009), drinking water supply is clearly prioritized. Thermal use within well-head protection zones is not allowed in protection zone I (the immediate zone around the extraction well) and is limited in protection zones II and III (zone II according to bacteriological protection with groundwater residence time of 60 days and zone III for chemical pollution prevention). Moreover, thermal use of confined aquifers is not allowed. Existing entitlements of thermal use have to be respected.

Based on the observation that temperature in shallow aquifers at a depth of 7 m below ground surface typically ranges between 7°C and 12°C, the temperature at the location of the water injection from thermal use should not fall below 5°C and not exceed 20°C. The maximum warming or cooling is limited to 6 K at the location of the water injection, compared with the existing temperature. Water should be extracted from deep sections of the aquifer, if possible, whereas reinjection should preferably be done at shallow depths.

In BHEs, as well as shallow horizontal heat exchangers, the temperature of the heat carrier fluid should not exceed 30°C (for cooling purposes). The mean temperature (average of inflow and outflow temperature) of the heat carrier fluid should not fall below –1.5°C after reaching equilibrium conditions (expected after 5 to 50 years). Temperature in shallow horizontal heat exchangers should not lead to freezing. Further requirements concern the heat carrier fluid and the working fluid of heat pumps, as well as the design of systems for thermal use.

1.8.3 British regulation

Recommendations and regulations concerning the thermal use of groundwater are based on policy and practice of groundwater protection (EA 2008). **Key issues** are as follows:

- The risk of the pipes or boreholes creating undesirable connections between rock or soil layers. This may cause pollution and/or changes in groundwater flow and/or quality.
- Undesirable or unsustainable temperature changes in the aquifer or dependent surface waters.
- Pollution of water from leaks of polluting chemicals contained in closed-loop systems.
- Pollution of water from heat pump discharge from an open-loop system that contains additive chemicals.
- Impacts of reinjection of water from an open-loop system into the same aquifer, both hydraulic and thermal, as well as any water quality changes induced.

- The potential impact of groundwater abstraction for ground-source heat systems on other users of groundwater or surface water.

Requirements can be summarized as follows:

- It is strongly recommended that GSHP systems are operated sustainably.
- Developers are expected to undertake appropriate prior investigations of the planned systems.
- Drilling through contaminated ground poses a significant risk of groundwater pollution.
- Where it is necessary to prevent pollution of controlled waters, the agency serves a notice under the Groundwater Regulations or Water Resources Act to control the activity.
- A permit is not required for closed-loop systems. It is strongly recommended to not use hazardous substances.
- An abstraction license is required unless the abstraction rate is below the threshold for license control, which is currently 20 m^3 day^{-1}.
- Discharge consent is required unless it can be shown that no deterioration in groundwater quality is caused and that no significant change in ground or groundwater temperature occurs.
- If the GSHP system adversely affects existing systems or other legitimate use of groundwater, the operation of the systems has to be modified.

1.8.4 German regulation

In Germany, the mining law (Bundesberggesetz BBergG) states that shallow geothermal energy belongs to the 16 federal states, and, generally, these states provide individual guidelines. These serve as the basis for adapting local regulations and permission procedure, and they are mainly focused on closed systems. We find suggested minimum distances between 5 and 10 m between two BHEs and 3 and 5 m between property line and BHE (Haehnlein et al. 2010). In addition to the regulatory framework by the states, as fundamental general and technical guidelines, the VDI 4640 (VDI 2001a,b, 2004, 2010), VBI-guideline (VBI 2008), and for quality assurance, state-specific standards (e.g., LQS 2012) are consulted. These include suggestions on how to restrict the temperature difference and maximum temperature for heating and cooling of the heat carrier fluid and for the groundwater. If groundwater is concerned, then the federal Water Act is applicable (Haehnlein et al. 2011). It states that detrimental changes in physical, chemical, and biological characteristics must be avoided. A critical point, however, is that detrimental changes are not further specified. A unique guideline for groundwater injection and extraction systems for thermal use is available from the state of Baden-Württemberg (Bauer et al. 2009). This includes an analytical equation describing heat conduction, which can be applied to approximate thermal conditions evolving in an aquifer with operating wells.

1.9 CHALLENGES RELATED TO DESIGN AND MANAGEMENT

From the discussion above, we can list a few **problems** that are related to design and management of the thermal use of underground space:

- The establishment of closed and open systems for thermal use creates local and regional temperature anomalies of the underground space (rock zone or unsaturated or saturated zones of the aquifer). Regulations may directly refer to expected changes in temperature due to the chosen scheme of thermal management. Therefore, **methods and models are needed to simulate the local and regional temperature development in the underground or aquifer**. Aspects of the investigation can be the short- and long-term behavior, as well as the interference between various installations. The latter is of importance in order to prevent a thermal overuse of the underground space or aquifer and to assess the long-term heat abstraction potential.
- Application of extraction and injection wells in open systems alters both the **thermal and hydraulic conditions** in aquifers. As a consequence, this type of use may compete with installations for freshwater abstraction, and especially in densely populated areas, balanced and concerted management strategies have to be developed.
- In the design of **BHE** systems, an important requirement is to **prevent freezing of the soil and of the circulating fluid**. Therefore, methods and models are needed to simulate the temperature development within and outside of the BHE. Especially the long-term behavior is of importance.
- Additionally to thermal and hydraulic effects, chemical conditions in aquifers change with associated **potential ecological consequences**. Groundwater ecosystems will adapt to thermal, chemical, and hydraulic modifications, which can be of short duration, seasonal, permanent, and even irreversible, slowly evolving or unnaturally abrupt.
- Good characterization of thermally used aquifers is essential to develop efficient management strategies and to make reliable long-term predictions. For this, the repertoire of available hydraulic **field investigation techniques** is extensive. These have to be combined with thermal characterization methods. Still, for being able to predict decades of operation, we also need validation via long-term monitoring programs. We meanwhile have a long-term experience with many applications; however, case studies that provide detailed recorded field and technological performance data are scarce.

1.10 SCOPE OF THE BOOK

The **main objective of the book is to provide and discuss mathematical modeling tool**s, which are useful for the design and management of systems making thermal use of underground. Based on the motivation presented in the introduction, the **theoretical foundations** of heat transport in underground systems are recalled, and the essential thermal properties and parameters are reviewed. An overview over a series of **analytical and numerical methods** and models is presented and discussed. The main focus will be the local and regional modeling of flow and heat transport in open as well as closed systems. Using these concepts and models, the long-term operability of thermal systems is discussed. Since any modeling effort has to be combined with an assessment of the hydrogeological–thermal conditions, a series of **field methods** is presented. Finally, **case studies** for locations in Austria, Germany, and Switzerland will illustrate urban thermal energy use as well as heat storage and cooling.

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