Chapter 5

Long-term operability and sustainability

The question of **sustainability** of thermal use of the shallow underground arises in various contexts. There are different definitions and, sometimes, subjective interpretations of sustainable use. Let us first take a technological perspective, which refers to the prolonged production ability. The issues have to be addressed separately for systems in relatively impermeable media and systems in prolific aquifers. In the latter case, one has to distinguish between closed and open systems.

The long-term viability of closed systems limits the amount of heat that can be abstracted sustainably, be it by one borehole heat exchanger (BHE) or a whole set of them. If that limit is overstepped, the temperature at the BHE drops below the freezing point of the working fluid and prevents the system from functioning. Already at prefreezing temperature, the efficiency of the system will of course drop considerably.

To assess the long-term development, thermal modeling is a useful tool. One would have to simulate the temperature distribution for a given heat abstraction and operation time, and check the temperature at the exchanger in order to judge the feasibility. The long-term viability depends on the presence of all users combined. The superposition of several users may lead to a nonsustainable heat abstraction, where a single user would still be doing fine. The question of "stealing" heat from others has to be treated in a heat management scheme for a formation. Regulations try to avoid interaction of neighboring users by defining minimum distances between competitive BHEs. In some countries, simply minimum distances to the property line are defined (Hähnlein et al. 2010a). However, by ignoring site-specific characteristics and potential groundwater flow, such constraints can promote but hardly optimize sustainable use.

5.1 SYSTEMS IN LOW PERMEABLE MEDIA

In the strictest sense, **sustainable use** means that a reservoir is exploited at a rate that does not lead to a decline in the resource in the future. Even though the stored energy in the upper hundred meters of the Earth's crust is vast, current technologies only allow uneven, local use. The permanent flux of geothermal heat in Switzerland is maximally about 100 mW m^{-2}. However, if one assumes that a single geothermal heat pump requires about 3 kW of heat power, this would mean that an area of at least 30,000 m^2 would be necessary per BHE. The exclusive use of this energy would allow only for relatively few users in concentrated settlements.

A single BHE, or a larger collection of BHEs, will therefore eventually empty the storage of utilizable heat, while at the same time lowering the temperature over a certain volume of the underground. On the other hand, the decreasing temperature at the BHE will create a gradient, also supplying heat from the surface, which can eventually contribute to a larger heat flux than the geothermal flux. For a sustainable operation in the long run, the system has to rely on the combined heat fluxes from the depth and from the surface. While the geothermal flux can be considered a constant flux boundary condition at depth, the surface can be considered a constant temperature boundary condition for all practical considerations.

The basic situation is shown in Figure 5.1: At steady state, the abstracted heat power at the BHE is provided by two contributions, the geothermal heat flux and the heat flux from the atmosphere. The BHE forms a "heat catchment" from which it draws the abstracted heat flux. Before steady state is reached, the heat flux at the BHE has an additional contribution stemming from cooling the surroundings of the BHE.

With increasing abstraction of heat at the BHE, the "heat catchment" of the exchanger is growing, while the temperature of the exchanger is decreasing. In order to guarantee a long lifetime of a BHE, that is, time

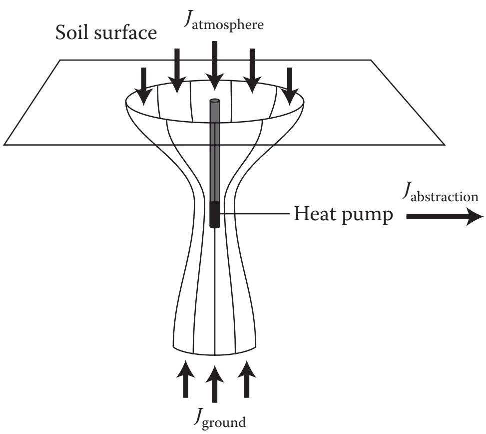

Figure 5.1 Heat catchment and heat balance around a BHE (schematic).

with temperatures at the BHE allowing an efficient production of heat, a proper design of the abstraction in connection with already existing abstractions is required.

The applied technologies cause **temperature anomalies** that may exist temporally, stabilize and arrive at steady state, or continuously change and evolve. The strict requirement of arriving at a viable steady state is sometimes relaxed. According to Rybach (2003), sustainability means the ability of the production system to sustain production levels over several decades to a couple of centuries. Similarly, Rybach and Eugster (2010) and Axelsson et al. (2001) state that for each geothermal system and for each mode of production, there exists a certain level of maximum energy production, below which it will be feasible to sustain constant energy production from the system for a very long time (100–300 years). The question of sustainability thus translates into the question of how long can a system operate without significant decline of production (Rybach and Mongillo 2006). As a more elaborate definition of sustainable operation, Hähnlein et al. (2013) suggest adopting the four modes defined by Axelsson (2010) for sustainable deep and/or high enthalpy geothermal utilization: (1) constant production on the sustainable level, where sustainability is related to the production ability of the system over an indefinitely long period; (2) stepwise increase in production until the sustainable level is achieved; (3) cyclic production (with an alternation of excessive production and periods of dormancy to allow for recovery); and (4) an excessive production followed by a reduced, steady production. Apparently, it is common to define a certain time frame, which serves as a premise based upon the assumption that sustainable use is reachable. In the best case, energy deficits are only temporary, of short duration, and, for instance, balanced during seasonal operation throughout each year. In the worst case, after the given time frame, the reservoir is depleted, and it will take a long time for replenishment if it is possible at all. In the ideal case, a viable steady state (or quasi–steady state with seasonal fluctuations) is established.

The **maximum heat flux** to a BHE in equilibrium can be determined by a numerical computation with a temperature boundary condition at the BHE set at the minimum allowable temperature, and applying the geothermal heat flux at the lower boundary, as well as the mean soil temperature at the upper boundary. Of course, the situation can be alleviated by adding heat in times where cooling of buildings rather than heating is required. In the climatic conditions of Switzerland, for example, the cooling requirements in large public buildings are only one third in terms of thermal energy required for heating. In the following, this situation is implicitly covered by considering the average net heat flux, which is the difference between heat abstraction and heat injection, as abstracted heat flux.

The use of the analytical solutions (without aquifer flow) discussed in Chapter 3 is feasible for crude estimates. First, a superposition with image sources, mirrored at the upper (fixed temperature) boundary, and the addition of the natural geothermal temperature gradient are necessary. As the analytical solutions have a flux boundary condition at the heat pump, that is, the abstraction rate of heat, the required temperature in the well has to be transformed to an equivalent heat abstraction rate iteratively (e.g., Hecht-Méndez et al. 2013). The singularity of analytical solutions for point or line sources is avoided by evaluating temperatures at the radius of the borehole (Beck et al. 2013).

Only a few **field studies** exist with long-term monitoring of temperatures. For a 105-m-long coaxial-tube BHE installed near Zurich (Switzerland), in **Elgg**, over 25 years of detailed observations gave insight into the thermal evolution of the ground (Eugster 2001; Rybach and Eugster 2002; Rybach and Eugster 2010; Figures 5.2 and 5.3). The BHE supplies a single-family house at SPF < 3 with peak thermal power of around 70 W m^{-1}. Temperature sensors (accuracy of 0.1 K) are installed at depths of 1, 2, 5, 10, 20, 35, 50, 65, 85, and 105 m at lateral distances of 0.5 and 1 m from the BHE. While at this location there is groundwater at a shallow depth of only a few meters, with a sequence of more or less productive aquifer layers, groundwater flow velocity was considered negligible and the case can be considered as an example for quasi-impermeable media. The temperature profiles recorded during the period of 1986–2001 clearly show the atmospheric influences down to a depth of about 15 m. Within the first few years, the thermal influence from seasonal energy extraction is most pronounced, with about 1–2 K smaller temperatures than in undisturbed ground. It is shown by continuous monitoring and supported by numerical modeling that at short distances from the BHE, the temperature decline continuously decelerates with small fluctuations within 0.5 K that are attributed primarily to the annually slightly varying heating demands (Figure 5.2). By simulation, it is revealed that the thermal anomaly evolves laterally at a very low rate and reaches several decameters within the operation period of 30 years. It is also shown that the heat sink promotes not only lateral heat flux to balance the artificial deficit around the BHE but also vertical heat flux from the atmosphere and geothermal flux from below. No steady state was reached in the 15 years of operation. Long-term simulation was used to examine the effect of abrupt BHE operation stop. Similar to the operation phase, initial thermal response of the ground right after the stop was most significant. Temperatures increased strongly during the first years, but to a lesser extent later. This reflects the effect of conduction, which decreases with thermal recovery as it is driven by the decreasing temperature gradient. Accordingly, about 30 years is needed to arrive at conditions with minor, but negligible, thermal anomalies. This means that about the same amount of time is needed as the system was operated to let it recover. In comparison, for deep geothermal energy use with Engineered Geothermal Systems (EGS), after a similar time of

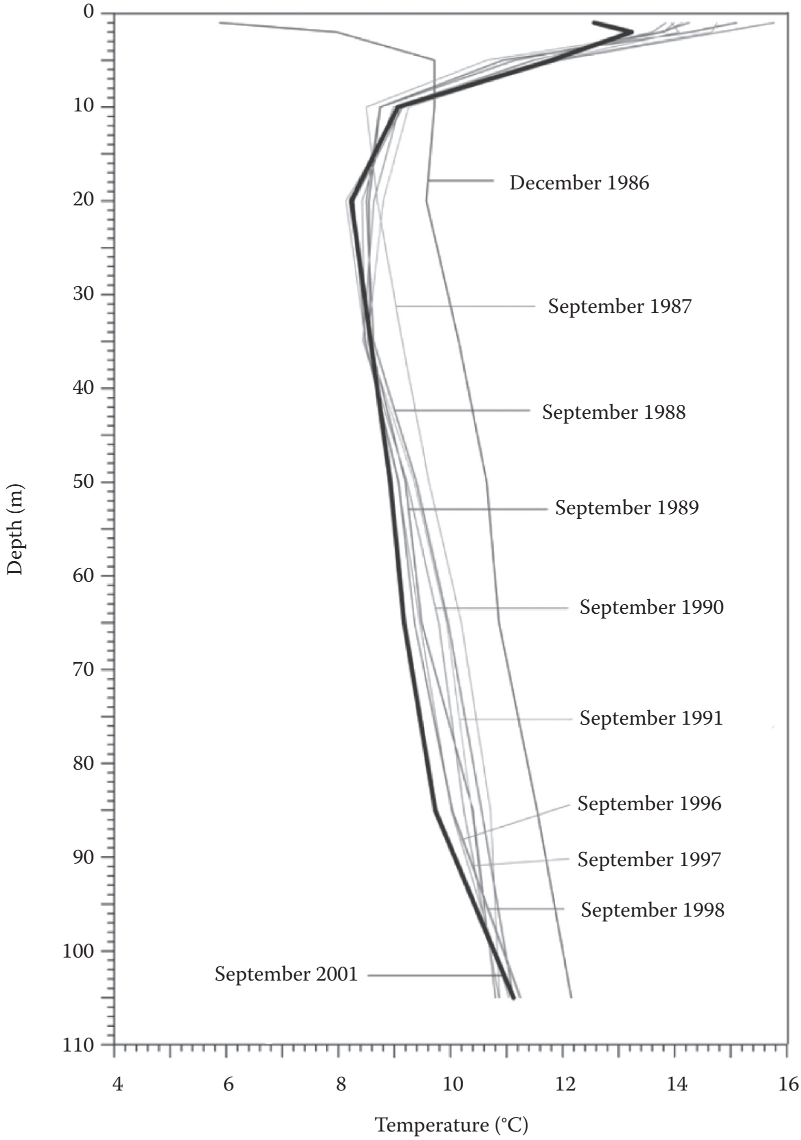

Figure 5.2 **(See color insert.)** Elgg site (Switzerland): measured ground temperature profiles at 0.5 m distance from a 105 m deep operating BHE, repeatedly measured over 15 years. (From Rybach, L. and Eugster, W.J., *Geothermics* 39, 365–369, 2010.)

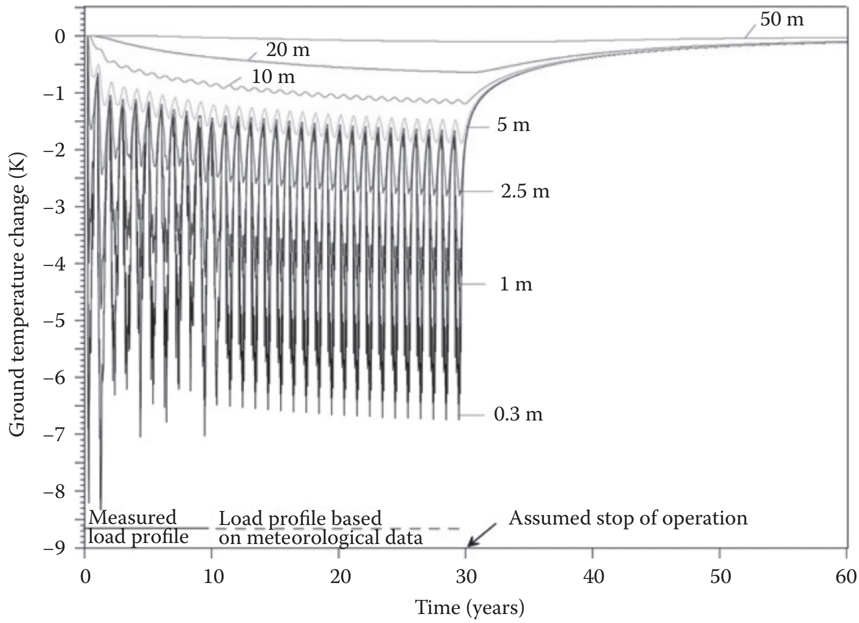

Figure 5.3 **(See color insert.)** Elgg site (Switzerland): simulated ground temperature changes of a BHE relative to the undisturbed situation in December 1986 over 30 years of operation and 30 years of recovery. (From Rybach, L. and Eugster, W.J., *Geothermics* 39, 365–369, 2010.)

operation, much higher recovery periods of up to 100 years (Tester et al. 2006) are needed as only the geothermal flux is available to "heal" the thermal anomaly.

5.2 THERMAL EVOLUTION IN AQUIFERS

There are many factors that influence the **evolution of thermal anomalies around geothermal applications in aquifers**. Among these are the technology type, such as open or closed systems, their size (single or multiple) and installation depth, the operation mode, and the hydraulic and thermal conditions in the subsurface. An additional role is played by the potential hydraulic and/or thermal influence of neighboring or upstream installations (Ferguson 2009). Especially in densely populated areas, competitive use of aquifers by upstream and downstream users is frequent and regulations ideally avoid interaction between adjacent systems. Minimum distances between different BHEs of neighboring installations in a range of 5–20 m are recommended (Hähnlein et al. 2010a).

For **closed systems in aquifers**, the situation in Figure 5.1 is changed, compared to the systems in relatively impermeable media, by additional heat fluxes provided by the advection of heat by the aquifer water flow and by groundwater recharge. On one hand, this increases the available heat flux. On the other hand, a new limitation is introduced by the environmental limits on the downstream temperature reduction, as discussed in the introduction. Now, two temperatures have to be checked for sustainability, the temperature T_b at the BHE (radius of borehole) and the temperature T_d at a given distance in the downstream. T_b should be above the minimum working temperature of the heat exchanger, and the difference between the original temperature and T_d should not be more than the given environmental limit at the location.

The existence of substantial groundwater flow is beneficial. As demonstrated by Hähnlein et al. (2010b), for a synthetic example with a closed system, high groundwater flow velocities, such as observed in gravel aquifers, lead to more elongated thermal plumes than smaller velocities in silty or sandy aquifers. It is also shown that under their assumptions, high groundwater flow velocity can yield thermal recovery within one year in seasonal use mode. This is promoted by combining heating and cooling operations, and for a specific site, recovery will depend on the local thermal and hydraulic conditions as well as the specific heat extraction and injection rates.

Using directly pumped **groundwater from wells** for heat extraction influences the hydraulic conditions in aquifers, and proper planning requires a hydrogeological analysis. For such open systems, which typically use multiple groundwater pumping and injection wells, thermal feedback between the wells is of major concern (Ferguson and Woodbury 2006). This may be avoided or mitigated by increasing the distance between wells or by general spatial rearrangement, by lowering the pumping rates, and/or by considering the viability of a balanced, seasonally reversible scheme (Banks 2008). The condition for sustainability in the open case is more easily applied. Now the legal limit on cooling applies (at most 3 K in a distance of 100 m downstream of the infiltration in Switzerland). This means that the maximum extractable heat flux J (W = J s^{-1}) can be estimated by the formula

$$J = \rho_w c_w Q \Delta T \tag{5.1}$$

where ΔT is the allowed temperature reduction of the reinfiltrated water and Q (m^3 s^{-1}) is the infiltration rate. The application of analytical solutions for rough design purposes is more limited, as the modification of the flow connected to the reinfiltration does not allow for a closed solution of the temperature field. In a crude approximation, injections, which are not too close to each other, can be represented by line sources (transverse to flow) with a width corresponding to the asymptotic width of the injected water flow. This width can be determined analytically with the tools described in Chapter 3.2.1.

In general, numerical simulations have to be applied to inspect the thermal evolution and support optimal design. A challenge will be to capture transient hydraulic conditions of aquifers, such as dynamic changes in flow velocity or flow direction. This is particularly important in the vicinity of surface water bodies. Highly dynamic systems add complexity. At the same time, in comparison to sluggish conduction-dominated conditions, higher groundwater flow velocity means amplified heat or cold transfer by advection. As a consequence, a seasonal system can recover faster, a thermal anomaly can evolve less far into the downstream, and thermal conditions can more easily reach a steady state. As an example, for the Paris Basin, where doublet well systems have been successfully operated since the 1970s, no reduction in production temperature or substantial water level drawdowns has been reported (Rybach and Mongillo 2006). In contrast, Bonte et al. (2011) reported on a survey of 67 aquifer thermal energy systems (ATES) operated in the Netherlands that revealed that none of these systems was in thermal equilibrium. From the perspective of sustainable use, however, sufficient productivity may still be feasible. This is shown, for example, by Mégel and Rybach (2000) for a doublet system operated at a thermal capacity of 15 MW for district heating close to Basel. Numerical simulation revealed that an acceptable temperature decrease of 1.4 K will occur during the first 20 years. This rate substantially declines and much smaller values of 0.15 K in 10 years are expected after 300 years of operation.

5.3 FURTHER CRITERIA OF SUSTAINABILITY

Apart from criteria based on long-term performance of a shallow geothermal system and renewability of the thermal reservoir in the ground, sustainability is often also evaluated from environmental or economic points of view.

The **environmental aspects** concerning the temperature change have been discussed already in Chapter 1. However, the quality of the groundwater can also be influenced when the working fluid of a heat pump leaks out and consequently pollutes groundwater. For this reason, some regional agencies are reluctant to give any licenses for heat pumps in aquifers at all. The potential of polluting the downstream can be estimated by simulating the pollutant cloud forming in the downstream after complete working fluid loss. The potential depends on the type and quantity of cooling fluid used and can be kept small by regulating the allowable fluids.

Secondary effects on groundwater chemistry and biology are considered uncritical in most cases, when operating within the temperature limits of common guidelines (Tables 5.1 and 5.2). In open systems, wells are operated. The most critical (bio-)chemical consequence, which is often observed, is that clogging occurs in reinjection wells, and thus periodic back-flushing may be necessary to maintain long-term operability. In the aquifer, induced thermal gradients influence mixing processes. Furthermore, increase in temperature accelerates chemical reactions and modifies geochemical equilibria of minerals, oxygen saturation, and gas solubility. Through drilling of boreholes or installation of wells, new connections and flow paths in the subsurface can be created, and thus careful attention has to be given to potential effects, such as gypsum swelling. Likewise, cross-aquifer flow between contaminated and pristine aquifers needs to be avoided.

Thermal use of shallow aquifers may directly affect groundwater and groundwater-dependent ecosystems. In aquifers, microbes and groundwater invertebrates are important components of the ecosystem, and their

Table 5.1 Possible processes, effects, and their potential impact for shallow open geothermal energy systems

Process	*Effects*	*Follow-up event*	*Potential impact*	*Significance*
Temperature increase	Enhanced microbiological activity	Mineral precipitation	Clogging	++
			Biofilms	+
		Biofouling		–
		Slime production	Clogging	–
		Mass explosion		––
		Sedimentation of iron ocher		++
		Corrosion		–
	Increase in mineral solubility (e.g., iron, manganese)[a]	Increase in mineral concentration in the groundwater (e.g., sedimentation of iron ocher)	Clogging	++
		Mass explosion (algae and bacterial growth)[a]		++
Temperature decrease	Increase in CO_2 solubility	Increased carbonate load	Clogging	++
Algae growth	Lowering pH Removing CO_2	Mineral precipitation[a]	Clogging	–
Shifting of material (solifluction)	Increase in holes		Changes in flow regime	–
	Accumulation of material			–
			Clogging	–

Source: After Hähnlein, S. et al. (2013), Sustainability and policy for the thermal use of shallow geothermal energy. *Energy Policy*, 59, 914–925.

[a] Critical iron concentration 40.1 mg/l and critical manganese concentration 40.05 mg/l.

Table 5.2 Physical, chemical, and biological consequences on open and closed systems and the thermally influenced area of ground-source heating pump systems (i.e., soil, ground, aquifer)

	Affected System			
	Open System		*Closed System*	
Follow-up event	*System*	*TAA*	*System*	*TAA*
Algae growth	+	+	−	+
Appearance of temperature anomalies	−	+	−	+
Changes in bacterial and faunal community		+		+
Changes in microbiological activity	+	+	−	+
Debonding	−	−	+	−
Gas solubility	−	++	−	+
Hydrological circuit/perforation of separating layers	+	−	+	−
Hydrological feedback	+		−	
Influence on surface ecosystem	−	+	−	++
Solifluction	−	+	−	−
Thermal feedback	+		−[a] / +[b]	

Source: After Hähnlein, S. et al. (2013), Sustainability and policy for the thermal use of shallow geothermal energy. *Energy Policy*, 59, 914–925.

Note: Follow-up event: (−) does not impact, (+) impact, (++) more pronounced impact on the system or temperature affected area (TAA).

[a] For single GSHP systems.
[b] For multiple GSHP systems.

diversity, composition, and functionality are influenced by the temperature. However, groundwater microbiology is a very young area of research, and general conclusions are hard to obtain. Hähnlein et al. (2013) reviewed four studies on the effect of temperature by shallow geothermal systems. It was found that there exists a tolerable range of temperature variations, which should be minimized in intensity, expansion, and duration. In the literature (Brielmann et al. 2009, 2011), we find acceptable ranges of ±6 K, and therefore, it is concluded that within the regulated temperature thresholds, impact of shallow geothermal energy use is only minor.

In addition to the direct site-specific consequences, **secondary environmental impacts** that are associated with the life cycle of a technology may be integrated in sustainability assessment. As pointed out by Saner et al. (2010), these are mainly controlled by the primary power consumption of the heat pump and thus the seasonal performance factor (SPF). The most common applications are closed systems, with far more than 1 million applications in Europe. An average European system that has been operating for

20 years would generate carbon dioxide (equivalent) emissions of 63 t at the present electricity mix (Saner et al. 2010). This is still less than traditional space heating technologies. Average savings are 35% in comparison to oil-fired boilers and 18% to gas-furnace heating systems. These figures refer to standard one-family houses. The use of shallow aquifers for combined heating and (passive) cooling, as it is common in bigger applications such as office buildings or district heating systems, is even more environmentally attractive.

Technical criteria and productivity can be quantitatively measured and predicted, and they have direct economic implications. In contrast, environmental or ecological criteria are often considered of secondary importance. They are sometimes difficult to evaluate, with distinct results depending on the assessment concept employed, the geological and groundwater conditions, the location of the system, and finally, the social environment involved (Hähnlein et al. 2013).

REFERENCES

Axelsson, G. (2010). Sustainable geothermal utilization—Case histories; definitions, research issues and modelling. *Geothermics* 39, 283–291.

Axelsson, G., Gudmundsson, A., Steingrimsson, B., Palmason, G., Armansson, H., Tulinius, H., Flovenz, O., Björnsson, S., Stefansson, V. (2001). Sustainable production of geothermal energy: Suggested definition. *IGA-News, Quarterly* 43, 1–2.

Banks, D. (2008). An Introduction to Thermogeology: Ground Source Heating and Cooling. Blackwell Publishing, Oxford, UK.

Beck, M., Bayer, P., de Paly, M., Hecht-Méndez, J., Zell, A. (2013). Geometric arrangement and operation mode adjustment in low-enthalpy geothermal borehole fields for heating. *Energy* 49, 434–443.

Bonte, M., Stuyfzand, P.J., Huismann, A., Van Beelen, P. (2011). Underground thermal energy storage: Environmental risks and policy developments in the Netherlands and European Union. *Ecology and Society* 16(1), 22.

Brielmann, H., Griebler, C., Schmidt, S.I., Michel, R., Lueders, T. (2009). Effects of thermal energy discharge on shallow groundwater ecosystems. *FEMS Microbiology Ecology* 68, 273–286.

Brielmann, H., Lueders, T., Schreglmann, K., Ferraro, F., Avramov, M., Hammerl, V., Blum, P., Bayer, P., Griebler, C. (2011). Oberflächennahe Geothermie und ihre potenziellen Auswirkungen auf Grundwasserökosysteme. *Grundwasser* 16, 77–91.

Eugster, W.J. (2001). *Langzeitverhalten der EWS-Anlage in Elgg (ZH)—Spotmessung im Herbst 2001*. Swiss Federal Office of Energy, Bern, Switzerland, 14 pp.

Ferguson, G. (2009). Unfinished business in geothermal energy. *Ground Water* 47(2), 167.

Ferguson, G., Woodbury, A.D. (2006). Observed thermal pollution and post-development simulations of low-temperature geothermal systems in Winnipeg, Canada. *Hydrogeology Journal* 14, 1206–1215.

Hähnlein, S., Bayer, P., Blum, P. (2010a). International legal status of the use of shallow geothermal energy. *Renewable and Sustainable Energy Reviews* 14, 2611–2625.
Hähnlein, S., Bayer, P., Ferguson, G., Blum, P. (2013). Sustainability and policy for the thermal use of shallow geothermal energy. *Energy Policy*, 59, 914–925.
Hähnlein, S., Molina-Giraldo, N., Blum, P., Bayer, P., Grathwohl, P. (2010b). Ausbreitung von Kältefahnen im Grundwasser bei Erdwärmesonden. *Grundwasser* 15, 123–133.
Hecht-Méndez, J., de Paly, M., Beck, M., Bayer, P. (2013). Optimization of energy extraction for vertical closed-loop geothermal systems considering groundwater flow. *Energy Conversion and Management* 66, 1–10.
Klotzbücher, T., Kappler, A., Straub, K.L., Haderlein, S.B. (2007). Biodegradability and groundwater pollutant potential of organic anti-freeze liquids used in borehole heat exchangers. *Geothermics* 36, 348–361.
Mégel, T., Rybach, L. (2000). Production capacity and sustainability of geothermal doublets. *Proceedings World Geothermal Congress 2000*, International Geothermal Association, Beppu-Morioka, Japan, pp. 849–854.
Rybach, L. (2003). Geothermal energy: Sustainability and the environment. *Geothermics* 32, 463–470.
Rybach, L., Eugster, W.J. (2002). Sustainability aspects of geothermal heat pumps. *Proceedings 27th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, pp. 50–64.
Rybach, L., Eugster, W.J. (2010). Sustainability aspects of geothermal heat pump operation, with experience from Switzerland. *Geothermics* 39, 365–369.
Rybach, L., Mongillo, M. (2006). Geothermal sustainability—A review with identified research needs. *Geothermal Resources Council (GRC) Transactions* 30, 1083–1090.
Saner, D., Juraske, R., Kübert, M., Blum, P., Hellweg, S., Bayer, P. (2010). Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable and Sustainable Energy Reviews* 14, 1798–1813.
Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksöz, M.N., Veatch, R.W. (2006). *The Future of Geothermal Energy—Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*. Massachusetts Institute of Technology and US Department of Energy, Cambridge, MA, USA, 332 pp.