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Sustainability and policy for the thermal use of shallow geothermal energy

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HIGHLIGHTS

- We provide an overview of consequences of geothermal systems in shallow aquifers.
- Static regulations for heating or cooling groundwater are not recommendable.
- Temperature limits should be flexible and orientated on background values.
- Suggestions for a sustainable policy for shallow geothermal systems are provided.
- A potential legal framework for a sustainable use is presented.

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ABSTRACT

Shallow geothermal energy is a renewable energy resource that has become increasingly important. However, the use has environmental, technical and social consequences. Biological, chemical, and physical characteristics of groundwater and subsurface are influenced by the development of this resource. To guarantee a sustainable use it is therefore necessary to consider environmental and technical criteria, such as changes in groundwater quality and temperature. In the current study a comprehensive overview of consequences of geothermal systems in shallow aquifers is provided. We conclude that there is still a lack of knowledge on long-term environmental consequences. Due to local differences in geology and hydrogeology as well as in technical requirements, it is not recommendable to define only static regulations, such as fixed and absolute temperature thresholds. Flexible temperature limits for heating and cooling the groundwater and subsurface are therefore advisable. The limits should be oriented on previously undisturbed temperatures, and chemical, physical and biological conditions of aquifers. Based on these findings, recommendations for a sustainable policy for shallow geothermal systems are provided including a potential legal framework for a sustainable use.

1. Introduction

Geothermal energy is one of the rising renewable energies. Low-enthalpy shallow geothermal energy (<400 m depth) is an attractive alternative to fossil resources, especially for the heating and cooling of buildings. The number of geothermal installations has been continuously rising for the past 15 years (Bayer et al., 2012; Lund et al., 2011, 2004; Rybach, 2010; Sanner et al., 2003). In general, it can be distinguished between open and closed geothermal systems, with the latter being mainly ground source heat pump (GSHP) systems. GSHP systems have commonly one or more vertical borehole heat exchangers (BHE) with a circulating heat carrier fluid inside one or more closed pipes that are operated in a closed loop. By continuous circulation, the fluid transports the heat from the subsurface to the heating system of the building, where a heat pump is often applied. If the hydrogeological and hydrochemical conditions are suitable, the energy can also be extracted in an open loop, directly using the groundwater. These applications are called groundwater heat pump (GWHP) systems. Another categorization can be found, which is based on the operation mode and whose variants are distinguished from GSHPs and GWHPs, which are specifically utilized for heat or cold storage. Borehole thermal energy storage (BTES) systems, equivalent to GSHP systems, and aquifer thermal energy storage (ATES) systems, equivalent to GWHP systems, are sub-groups of underground thermal energy storage (UTES) systems, which use the same technology, but are mainly designed to store energy (e.g., Palmer et al., 1992).

The geothermal use of the shallow subsurface can result in local temperature anomalies in the subsurface and the groundwater

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(e.g., Ferguson and Woodbury, 2006; Hähnlein et al., 2010b; Palmer et al., 1992; Pannike et al., 2006; Rybach and Eugster, 2010). These anomalies are often referred to as cold plumes in case of heat extraction, or heat plumes in case of heat injection (e.g., Hähnlein et al., 2010b; Pannike et al., 2006).

Decreasing or increasing temperatures influence chemical (Arning et al., 2006; Brons et al., 1991; Griffioen and Appelo, 1993), biological (Brielmann et al., 2009, 2011; Hall et al., 2008) and physical properties of groundwater (Balke, 1978; Bonte et al., 2011b). Such interventions into the environment may become critical and substantially alter the natural conditions. According to the European environmental policy, these impacts should be minimized on a low level that no detrimental effects can occur (EU-WFD, 2000). At the same time, worldwide energy demand is rising and the popularity of renewables is spurred on by the need of saving or reducing greenhouse gas emissions. Thus, a balance between these interests, i.e. minimizing detrimental effects of renewable energy technologies and rising energy demand, is desirable.

Groundwater has many functions for the biosphere. For example, in Europe about 75% of the habitants and estimated 50% of the world's population are dependent on groundwater as drinking water resource (Brandt and Henriksen, 2003; Danielopol et al., 2008; European-Commission, 2008). In addition, aquifers are habitats for flora and fauna, and is the Earth's largest reservoir of liquid fresh water (Boulton, 2005; Danielopol et al., 2003). For humans, groundwater offers a broad spectrum of ecosystem services and probably the most important one is its role as a fresh water resource. Therefore, the use of the subsurface as a fresh water and energy reservoir has to be well managed. This makes it necessary to design a sustainable use of shallow geothermal energy (Axelsson et al., 2010; Bonte et al., 2011b; Ferguson and Woodbury, 2006), which is also declared by the European Geothermal Energy Council (EGEC, 2006). This may be an intricate task, especially when different system types have to be integrated or even compete with each other. For example, in land planning of urban areas, where aquifer remediation is required, infrastructure such as transportation tunnels and sanitation are foreseen and geothermal energy systems are integrated (Brandl, 2006; Schädler et al., 2011). Bonte et al. (2011b) elaborates on the possible conflicts of use between subsurface functions and groundwater, such as ATES versus water supply or gas storage. In Bonte et al. (2011a) they focus on the effects on groundwater as drinking water source. They conclude that ATES systems have impacts on groundwater and that risk management strategies have to be developed for shallow geothermal storage systems.

In our study, environmental and technical, as well as social and policy aspects are reviewed, which are relevant for the entire spectrum of sustainable thermal use of the shallow groundwater and subsurface. Subsequently, different definitions of sustainability are discussed, and then a possible policy framework is developed that is based on the precautionary principle. Finally, recommendations for a legal policy are deduced.

2. Definition of sustainability

Geothermal energy is regarded as an environmentally friendly (Axelsson and Stefánsson, 2003; Blum et al., 2010), renewable and sustainable energy (Rybach and Mongillo, 2006). *Environmental friendliness* of a potentially green technology is commonly quantified within a life cycle assessment (LCA) framework, including, for example, a CO_2 balance (Bayer et al., 2012; Saner et al., 2010). *Renewable* refers to the natural state of the energy and describes a characteristic of the resource (Rybach and Mongillo, 2006). *Sustainable* applies to the way of how the resource is used (Axelsson, 2010). However, there are diverse and controversial definitions of sustainability (e.g., Mihelcic et al., 2003; Wright, 1998). In fact, the terms renewable and sustainable are dependent on each other, and the difference is not that apparent, for instance, when the geothermal resource is overexploited. In such a case, the extracted energy cannot naturally be replenished, and through this unsustainable use, the geothermal source becomes exhaustible, which is typical for non-renewables. Consequently, the use-mode defines the renewability of the source. Further, the environmental performance is often included in definitions of sustainability, which is expanded to include environmental impacts or merits (e.g., Preene, 2008; Younger, 2008). This reflects that the way a resource is used, and the applied technology and strategy, are determining for the associated primary or secondary environmental impacts. This overlap, therefore, is inevitable and a combined view of sustainability and renewability is reasonable, as a technology with poor environmental performance can hardly be evaluated as sustainable. In the following we categorize technical, ecological and social sustainability. Technical sustainability refers to the production ability and ecological sustainability to the effect of primary environmental consequences. The original idea of social sustainability refers to the social life of state or society. This can be broken down to the level of direct neighborhood and then includes neighborhood dissent, potentially caused by interferences between geothermal systems. This can also be expanded to all social effects, such as financial, caused by the use of shallow geothermal energy.

In the sense of the European Groundwater Act, the aim of sustainable use of shallow geothermal energy is maintaining a good status of the resources (subsurface and groundwater) (EU-GWD, 2006). This leaves considerable freedom for the selection of indicators that measure a satisfactorily "good status". The original definition of a "good status", given by the Brundtland Commission (World Commission on Environment and Development, 1987) is: "Meeting the needs of the present generation without compromising the needs of future generations". This definition also includes economical, ecological and social aspects (UN, 2002). However, referring to geothermal energy, an eminent definition is related to the production ability and thus, represents a technical perspective: "sustainability means the ability of the production system to sustain production levels over long periods" (Rybach, 2003; Rybach and Mongillo, 2006). Preene (2008) adds to this definition the requirement of flexibility in response to any future changes in operation. Rybach and Eugster (2010) suggest 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 possible to maintain constant energy production from the system for a very long time (100–300 years)". This technical interpretation of sustainability is oriented at the extractable energy of the natural system and is suitable especially for deep production systems. In Axelsson (2010), four modes for sustainable deep and/or high enthalpy geothermal utilization, based on the definition above, are presented: (i) constant production on the sustainable level, where sustainability is related to the production ability of the system over a long period; (ii) stepwise increasing of production until sustainable level is achieved; (iii) cyclic production (with an alternation of excessive production and periods of dormancy to allow for recovery); and (iv) an excessive production followed by a reduced, steady production. In principle, these modes can be adapted to the production of shallow geothermal energy with shorter production cycles and lifetimes.

Above mentioned descriptions of sustainability are all focused on reaching and maintaining a high efficiency by a technically robust geothermal system (technical sustainability). For a specific case, this requires energy-balance calculations, consideration of normal, peak demand and paused operation mode, and reliable predictions for the entire lifetime of a system. Social and ecological aspects are not covered in this definition. According to Rybach and Eugster (2010), this is due to the time-variability of these criteria, having in mind that shallow geothermal installations usually operate for decades. Another reason is that productivity and

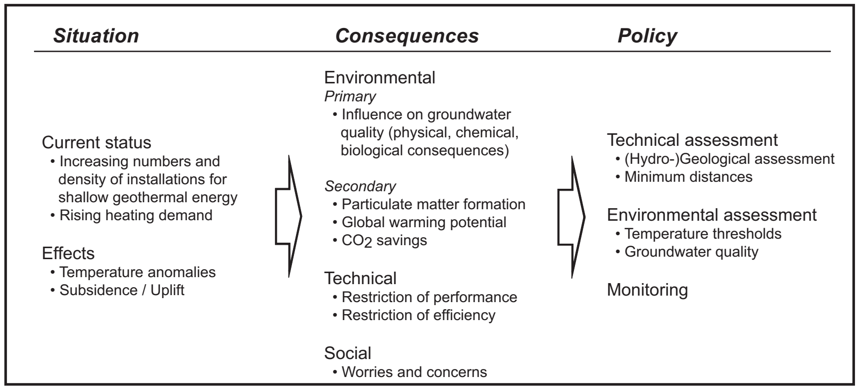

Fig. 1. Situation, consequences and recommendations for a policy on the sustainable thermal use of shallow geothermal energy.

technical performance can be quantitatively measured and predicted by engineers, based on standard simulation techniques or rules of thumb. Long-term productivity has a direct economic meaning, as it directly influences the profit and thus, is crucial for system design. Social criteria appear much more difficult to specify. They may vary significantly between different communities and finally, are not of primary importance for cost–benefit calculations. This also applies to ecological aspects, which are rarely discussed in the context of shallow geothermal energy.

3. Consequences of shallow geothermal energy use

Assessment of the application or renewability of the resource, with respect to sustainability, means putting values and weights on identified consequences of shallow geothermal energy development (Fig. 1). There are many different ways to classify these consequences, and the most primary ones at the place of operation are environmental consequences, which are of physical, chemical and biological nature. Although the underlying processes are strongly coupled, this differentiation is considered the most suitable one. Bonte et al. (2011b), who focused on underground thermal energy storages (UTES) in Europe, particularly in the Netherlands, considered various environmental risks using similar categories, such as hydrological, thermal, chemical and microbiological impacts. They provided a qualitative overview of the negative effects of UTES, also including an estimation of the probability of occurrence.

3.1. Physical consequences

The use of geothermal systems results in local temperature anomalies in the subsurface and groundwater (e.g., Banks, 2009; Ferguson and Woodbury, 2006; Molina-Giraldo et al., 2011a; Palmer et al., 1992; Warner and Algan, 1984). In UTES systems, injection temperature can reach up to 150 °C, or it is chilled (6–12 °C) (Bridger and Allen, 2005). Almost all ATES systems in the Netherlands have a temperature range of 5–25 °C (Bonte et al., 2011a), which in comparison is very low. For most seasonal aquifer thermal energy storage (SATES) (injecting in summer, recovery in winter or vice versa) only limited temperature changes ($\Delta T < 9$ K/6 K) between warm (< 20 °C) and cold well (around 5 °C) for an undisturbed groundwater temperature of around 11 °C occur (Zuurbier et al., 2013). Field applications with a GWHP system like the Royal Festival Hall in London showed temperature differences of 15 K, with an average temperature of 22 °C, therefore 8 K above the undisturbed groundwater temperature (14 °C). Another example of a GWHP system is a Belgian hospital. The ATES system (one warm and one cold well) has a maximum temperature difference of 4 K for heating/6 K for cooling (injection temperature cold/warm well: 8 °C/18 °C) with an undisturbed groundwater temperature of 11.7 °C (Vanhoudt et al., 2011). From the Edremit Geothermal District Heating System (GDHS) in Balikesir, Turkey a temperature difference of around 20 K (58–59 °C extraction temperature and 40–42 °C discharge (to the Edremit river) temperature) is reported (Coskun et al., 2009). Ferguson and Woodbury (2006) show a temperature increase of 6 K but also nearly 10 K in an extraction well in an area with multiple GWHP systems and undisturbed groundwater temperature of around 6 °C in Winnipeg, Canada.

For GSHP systems with multiple boreholes, long-term temperature changes can be substantial. This is demonstrated in the simulation studies by Beck et al. (2013) and Hecht-Méndez et al. (2013), with strong cooling by more than 10 K when regeneration is not sufficient. For single GSHP systems ground temperature is rarely monitored for years. However, an example is the Elgg site in Switzerland, a single GSHP system, which is located in a setting with negligible groundwater flow (Rybach and Eugster, 2010). The thermal anomaly induced by this GSHP system was examined for about 10 years. At the peak times during the heating period, temperatures initially decreased by more than 8 K in the vicinity of the BHE. However, this strong cooling is only of short time and ground temperatures are much less influenced at a few meters distance. In GWHP systems, groundwater temperature changes are strongly depend on the hydrogeological conditions. Simulations by Zhou and Zhou (2009) identified hydraulic gradient and flow rate of groundwater between injection and extraction well as dominant factor. Numerical simulations by LoRusso and Civita (2009) showed that the thermal dispersivity in the aquifer is an important factor. In case of substantial groundwater flow, thermal anomalies are balanced by advective heat or cold replenishment, and induced temperature changes are expected to be small (e.g. Hecht-Méndez et al., 2013). The physical consequences, such as the impact of changing physical properties of groundwater, changed availability, and the spatial and temporal distribution of the temperature anomalies, for the system design, operation and post-operation (recovery) time, have to be comprehensively understood. Physical properties of groundwater, such as viscosity, density, compressibility and vapor pressure, are temperature-dependent. For the spatial and temporal evaluation of resulting temperature anomalies, which also depend on extraction rates and the thermal properties of the subsurface, various analytical and numerical heat transport models are available (e.g., Carslaw and Jaeger, 1959; Eskilson, 1987; Molina-Giraldo et al., 2010; Mottaghy et al., 2011; Yang et al., 2010). For example, Hecht-Méndez et al. (2010) demonstrated that within a typically small temperature range of the generated anomalies, dependency of thermal properties only marginally influence the heat transport simulations of closed shallow geothermal systems. However, with increasing temperature differences of more than 10 K, such thermal effects have to be considered.

Table 1
Possible processes, effects and their potential impact for open shallow geothermal energy systems.

Process	Effects	Follow-up event	Potential impact	Significance	References
Temperature increase	Enhanced microbiological activity	Mineral precipitation	Clogging	++	Abesser (2007)
			Biofilms	+	Lerm et al. (2011)
		Biofouling		−	Wagner et al. (1988)
		Slime production	Clogging	−	
		Mass explosion		−−	Snijders (1990), Wagner et al. (1988)
		Sedimentation of iron ocher		++	Kolb and Heise (1979)
		Corrosion		−	Wagner et al. (1988)
	Increase of mineral solubility (e.g., iron, manganese)[a]	Increase of mineral concentration in the groundwater (e.g., sedimentation of iron ocher)	Clogging	++	Andersson (1990), Kolb and Heise (1979)
		Mass explosion (algae and bacterial growth)[a]		++	UMBW (2009)
Temperature decrease	Increase of CO_2 solubility	Increased carbonate load	Clogging	++	Abesser (2007), Kolb and Heise (1979)
Algae growth	Lowering pH removing CO_2	Mineral precipitation[a]	Clogging	−	Abesser (2007), UMBW (2009)
Shifting of material (solifluction)	Increase of holes		Changes in flow regime	−	Wagner et al. (1988)
	Accumulation of material			−	
			Clogging	−	

Significance of impact is: (++) high, (+) moderate, (−) low, (−−) very low.

[a] Critical iron concentration > 0.1 mg/l and manganese concentration > 0.05 mg/l (UMBW, 2009).

With regard to technical sustainability, a geothermal system can be seen as sustainable, if long production ability is guaranteed (> 30 years). For closed systems in unconsolidated materials, with little or no groundwater flow, such as clays and silts, the evolving temperature plume does not reach steady-state in one operation cycle (Hähnlein et al., 2010b). This transient cooling effect was also observed, especially in the first 2–3 years for the Elgg site. Afterwards, the temperature in the subsurface decreased until a quasi-steady-state condition, a stable thermal equilibrium of 1–2 K below the initial undisturbed temperature, was reached (Rybach and Eugster, 2010). In contrast, the temperature plume of a GSHP system in soils with sufficient groundwater flow, such as sands and gravels, could achieve steady-state conditions in just one operation cycle (Hähnlein et al., 2010b). Hence, for such systems, a full recovery is possible during the summer, if the system is not operating and/or only used for cooling.

Similar conclusions to those for closed systems can be drawn for open systems. With increasing flow velocity, the temperature plumes quickly reach a steady-state and under these conditions the plumes are shorter. However, with increasing heat extraction rates, the time to reach a steady-state temperature plume also increases. Banks (2009), who studied the thermal and hydraulic feedbacks of open systems in the context of technical sustainability, recommended a way to improve the technical sustainability by avoiding thermal feedbacks in four steps: (1) increase the distance between injection and extraction wells; (2) decrease the pumping rates; (3) reconsider the system design (e.g., rearrangement of well locations); (4) consider the viability of a balanced, seasonally reversible scheme. Analytical solutions, for instance by Tsang et al. (1977) and Lippmann and Tsang (1980), are available to study the risk of a thermal breakthrough (thermal feedback) at the extraction well. For complex designs, such as in heterogeneous aquifers and/or ATES systems with more than two wells, numerical flow and heat transport models are favorable to reliably assess the technical sustainability of open geothermal systems (Banks, 2009; Tsang et al., 1977).

Open systems need extraction and/or injection of groundwater, which affects the subsurface flow regime. Even if injection and extraction are balanced in doublets, a permanent disturbance of the aquifer occurs (Bredehoeft, 2002). Changes in the water budget are most critical if extracted groundwater is not re-injected in the same aquifer and in the most extreme case yield surface subsidence. Well operation may also influence natural groundwater-surface water interaction and/or groundwater dependent ecosystems (GDE). Such changes cannot be avoided, but it is possible to minimize their impacts if attention is given to well placement and extraction/injection rates. These hydraulic consequences are normally dealt with in conventional groundwater regulation.

When the operation of a shallow geothermal system ends, the recovery phase is important for assessment of technical (and ecological) sustainability. Signorelli et al. (2004) presented results of numerical simulations of the recovery phase, illustrating an almost total recovery after 30 years for a production time also of 30 years. Accordingly, the recovery characteristics for closed systems can be summarized as follows: they are strong at the beginning and slow down asymptotically over time, with an infinite amount of time for total recovery. An almost complete recovery is reached after a period similar to the lifetime of the production systems (Rybach and Eugster, 2010; Rybach and Mongillo, 2006). The last two studies showed that for a typical lifetime of 30 years, single systems are technically sustainable. However, it would always be environmentally beneficial for the alternation of heat extraction and injection to be performed, as for example also recommended for open systems (Banks, 2009). In general, increased dynamics, either stimulated by dual use mode or due to natural processes accelerate recovery.

We can conclude that local and spatial temperature changes during the operation and recovery phase of shallow geothermal systems have to be accepted and are indispensable. Therefore, even if reaching centuries, the lifetime of geothermal systems is limited. This is also reflected in a common technical interpretation of geothermal sustainability, which is achieved when a certain production level can be maintained for a desired (long) period (Rybach and Eugster, 2010). For this purpose, appropriate technical design that exploits all degrees of freedom plays a prominent role. This is, for example, demonstrated for the operation of multiple closed systems, where optimization of individual borehole energy extraction rates is suggested (e.g., DePaly et al., 2012).

3.2. Chemical consequences

Chemical consequences are especially important for open systems, where groundwater is directly used. The cooling or heating of groundwater can affect chemical reaction times. For instance, according to the rule of Van't Hoff, the rise of the groundwater temperature by 10 K results in a 2–4 times faster chemical reaction (Balke, 1978). Furthermore, temperature variations also influence mixing processes in groundwater (Bonte et al., 2011b). These variations change geochemical equilibria of minerals, such as carbonate precipitation (Griffioen and Appelo, 1993), they control the solubility of salts (Balke, 1978; Willibald, 1979) and dissolution of silicate minerals (Arning et al., 2006). They change the mobilization of organic compounds from sediments (Brons et al., 1991), as well as oxygen saturation and gas solubility (Balke, 1978; Danielopol et al., 2003). A common observation due to these processes is clogging in the re-injection well of open systems, which is routinely moderated by periodic backflushing.

In Table 1 selected biological and physical processes and their possible chemical and biological effects for open systems are listed. Their impacts on the geothermal system or the influenced aquifer are also evaluated. Table 2 gives a general overview how open and closed shallow geothermal systems and their temperature affected areas (TAA) can be affected. Apparently there are several chemical (and biological) processes that promote clogging and therefore can result in decreased production ability and compromise technical sustainability. So clogging is an important effect for open geothermal systems (Table 2). In contrast, for example, corrosion by enhanced microbiological activity shows only very low significance (Wagner et al., 1988).

A further chemical aspect is the potential input of contaminants and/or creation of contaminant transport pathways. This can be caused by incautious installation or hydrological short circuit through boreholes that connect contaminated and pristine aquifers. Even if boreholes of closed systems are backfilled, there is a risk of deficient installations with inadequate backfilling, e.g., due to debonding of the backfilling (Avci, 1992), which may promote cross-aquifer flow (Santi et al., 2006). Debonding can also result in lower heat conduction, particularly when it happens between backfilling and pipe (Philippacopoulos and Berndt, 2001).

Table 2
Consequences and the affected systems.

Follow-up event	Affected system			
	Open system		Closed system	
	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]	

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.

3.3. Biological consequences

There exist several potential biological consequences of shallow geothermal energy use on subsurface and groundwater fauna, groundwater dependent organisms and ecosystems (e.g., Hancock et al., 2009). Aside from these, biologically induced fouling and clogging, which has been discussed above, is a common effect in wells such as those used in open systems (Table 2).

The influence by shallow systems on the surface ecosystem, aboveground flora and soil fauna, seems to be minor and with increasing depth of the geothermal installation the influence becomes smaller (Adinolfi et al., 1994; Kolb and Heise, 1979). However, any alteration of vertical heat flux, which leads to unnatural local heating or cooling up to the surface, generates changes in microclimate (Kolb and Heise, 1979). In particular near surface geothermal collectors (at approximately 2 m), which directly use the seasonally recharged shallow geothermal energy and which —in contrast to more common vertical installations—cover relatively large areas, play a role here. Their influence can be observed, for example, in delayed development of snow cover (Adinolfi et al., 1994). For soil fauna and flora, rather than the changes of seasonal temperature trends, the modification and conditioning of the soil has to be considered relevant. Artificial sand layers imbed the collector tubes and thus hamper capillarity and fauna mobility. Also the injection of cooled or heated (ground-)water to surface waters by open systems has biological effects. Significant heating of surface water modifies the diversity of fishes, and also a sudden reduction of heating back to undisturbed temperature regime influences the ground storey (Verones et al., 2010; Wunderlich, 1979).

Table 3
Overview of four studies on the influence of temperature change on microbiology by the use of shallow geothermal energy systems.

Aim	**Test site and system**	**Results**	**Conclusion**	**References**
Dieback and growth of microorganisms	Bremen (North Germany)	No significant influence of temperature on the amount of microorganisms above the freezing point. Only for −20 °C a decrease of living cell number was detectable, potentially caused by speed defrosting	The use of shallow geothermal energy has no influence on the amount of microorganisms in the subsurface	Schippers and Reichling (2006)
Change on bacterial cell number, faunal abundance and water chemistry	Bavaria (South Germany), Oligotrophic shallow quaternary aquifer in with a mean depth of 8–15 m GWHP system	Composition of bacterial and faunal community changes and the diversity increases with rising temperatures, but no significant impacts on bacterial or faunal abundance	Reaction intensity of different species is variable. Tolerance towards temperature changes is obvious for a few days. For undisturbed aquifers a maximum temperature of 20 °C and temperature difference of ±6 K is acceptable	Brielmann et al. (2009, 2011)
Potential of suspected population explosions and subsequent plugging	Stuttgart (South Germany) model of ATES heat storage system	Confirmed field observations on further ATES systems, where no mass explosions could be noticed	Mass explosion is not important as expected	Adinolfi et al. (1994)
Influence of bacteria on operability of the system	Berlin (North Germany; Parliament), quaternary sand aquifer in the North German Basin ATES cold and heat storage system	Formation of iron-sulfide deposits by metabolism support filter clogging	Shifts in microbial community composition can influence lifetime and production ability of ATES systems	Lerm et al. (2011)

Microbes such as bacteria and groundwater invertebrates are essential components of groundwater ecosystems, which offer crucial ecosystem services, such as water purification and filtration. To protect this functionality an intact ecosystem is desirable. Shifts in microbe community due to temperature changes appear only favorable, if it results in an improvement of functionality. Microbial diversity in groundwater ecosystems is directly or indirectly controlled by numerous abiotic and biotic parameters, such as habitat size, biogeography and contaminations (Griebler and Lueders, 2009). Additional important factors are temperature, pH and the availability of water, light and oxygen (Brunke and Gonser, 1997; Yates et al., 1985). Thus, temperature changes in subsurface and in the groundwater influence the bacterial community composition (Hall et al., 2008). For more insight, four studies analyzing the influence of temperature changes by shallow geothermal systems on groundwater microbes, are presented in Table 3.

Psychrophilic microbes are of particular interest when examining the effects of shallow geothermal energy, which have a preferred habitat temperature similar to that found in natural aquifers. Psychrophilic microbes grow at 0 °C and have their temperature optimum at 15 °C or lower. Above 30 °C these microbes are not able to survive (Adinolfi et al., 1994), and thus substantial anomalies can have harsh effects. If groundwater temperatures are raised to 15 °C or 20 °C, this already supports the growth of mesophilic species (Brielmann et al., 2011), and thus temperature anomalies can yield locally altered microbial communities and specific reaction intensity. In these laboratory experiments, tolerance towards temperature increase is obvious for a few days and a groundwater temperature of 20 °C appears to be the critical maximum temperature for groundwater invertebrates (Brielmann et al., 2011). We can conclude that there exists a tolerable range of temperature variations due to a heating or cooling, however, this should be minimized in intensity, expansion and duration. Until now, the studies of Brielmann et al. (2009, 2011) hypothesize that for undisturbed aquifers a maximum temperature of 20 °C and temperature difference of ± 6 K, as recommended by the VDI 4640 (VDI, 2001, 2010), is acceptable and should not be exceeded (Brielmann et al. 2009, 2011). This is comparable to earlier thresholds such as those recommended by Kolb and Heise (1979). They interpreted from the results of a workshop on “heat pumps and water protection” that a maximum cooling of 5 °C for pumped water is acceptable. It can be summarized that the use of shallow geothermal energy, especially the effect of temperature change influences bacterial diversity and community composition in groundwater. However, it does not have high impact on the amount of microbes (Brielmann et al., 2011; Lerm et al., 2011). Thus, in the sense of European environmental policy, for protecting the natural state and functionality of the ecosystems, it is necessary to keep temperature anomalies within a range of a few degrees.

Environmental (and also other) consequences can be distinguished into primary (direct) and secondary (indirect) effects. The described physical, chemical and biological consequences reflect the direct effects. Most apparent indirect effects stem from the continuous energy consumption by heat pump operation, which, depending on the electricity consumed, results in greenhouse gas emissions and particulate matter formation at power plants. Saner et al. (2010), who studied the environmental effects, including health effects, during the entire life cycle of average European GSHP system, concluded that 55% of the environmental effects are related to climate change, 34% by fossil depletion and only 8% by the formation of particulate matter due to the burning of fossil fuels. These negative effects are mostly compensated by the achieved CO_2 savings and even reductions (Blum et al., 2010). This mainly depends on the provided energy supply and type of installation, i.e. installation in a new building (potential savings) or replacement of an existing energy system for heating or cooling (potential reductions). Saner et al. (2010) and Bayer et al. (2012) show that for Europe, in comparison to fossil fuel based conventional heating or cooling systems, the CO_2 savings or reductions of shallow geothermal systems can be rather high. For the year 2011, the installed geothermal heat pumps (about 1.25 Mio.) are expected to save about 5.5 Mio. t CO_2.

Morofsky (2007) suggests a checklist of potential environmental concerns, which should be addressed through thermal storage system design and monitoring. In addition to environmental risks, consequences on the production ability and social consequences also cause concern, which is ideally considered by a policy for sustainable use (Fig. 1). In the present study, the technical consequences, such as the restrictions of performance and efficiency, are discussed in context of physical consequences and technical sustainability of shallow geothermal systems. As indicated above, social aspects are rarely emphasized. One example is the market analysis by Kölbel et al. (2009). They showed that in the state of Baden-Württemberg in Germany, most owners of shallow geothermal systems are satisfied with their GWHP or GSHP systems. The majority switched from heating oil to GSHP systems because of rising energy costs and potential energy savings, which shows that the people agree to these systems and that an ecological awareness exists.

4. International policy and legislations

In the following, the fundamentals of current environmental policy and international legislations for shallow geothermal energy are presented. Two main principles, risk based and precautionary principle, are applied to manage groundwater and subsurface contaminations worldwide (Rügner et al., 2006). The precautionary principle means taking anticipatory action in the absence of complete proof or scientific uncertainty of harm. The present tendency is to become more precautionary, and to change from a reacting to a more formative policy (EU-COM, 2011; TFEU, 2010). This includes the possibility of creating a totally new policy. In contrast, risk-based attitude is reflected in a reacting and passive policy. For example, Butscher et al. (2010) presented a risk-oriented licensing for the Canton Basel-Landschaft in Switzerland. Thereby, the licensing procedure is dynamic and oriented on potential risks, related to geology and hydrogeology.

For the European Union, the Treaty on the Functioning of the European Union (TFEU, 2010) (Article 191, paragraph 2) arrogate precautionary as one of the leading principles for European environmental policy and therefore, it is also imbedded in the European Water Framework Directive (EU-WFD, 2000). In the USA, contaminated land and groundwater management is usually risk-based (Rügner et al., 2006). For deeper geothermal systems (>400 m depth), most countries apply existing mining laws, which are not originally based on precautionary principle. For example, in Germany a gentle handling is stated as convention for mining (BBergG, 1980). It is apparent that if sustainable use of shallow geothermal energy is desirable, it is necessary to incorporate the precautionary principle in the many mining laws worldwide. Nevertheless, for a legislation ensuring a sustainable use, further aspects have to be regarded. For more insight, we subsequently review the findings from three recent studies that examined existing national legislations (Bonte et al., 2011b; Goodman et al., 2009; Hähnlein et al., 2010b). The European Project, GeoThermal Regulation—Heat (GTR—H), inspected existing regulatory frameworks for the use of geothermal energy with the main focus, however, on deep geothermal systems. In the final report additional issues, such as clear definition and classification of geothermal energy, resource ownership and licensing system, are discussed. These should be stated and included in each national and European geothermal legislation. These measures are grouped as follows: legal, financial and flanking measures (e.g., market penetration). It is concluded that effective national regulations need a well-founded

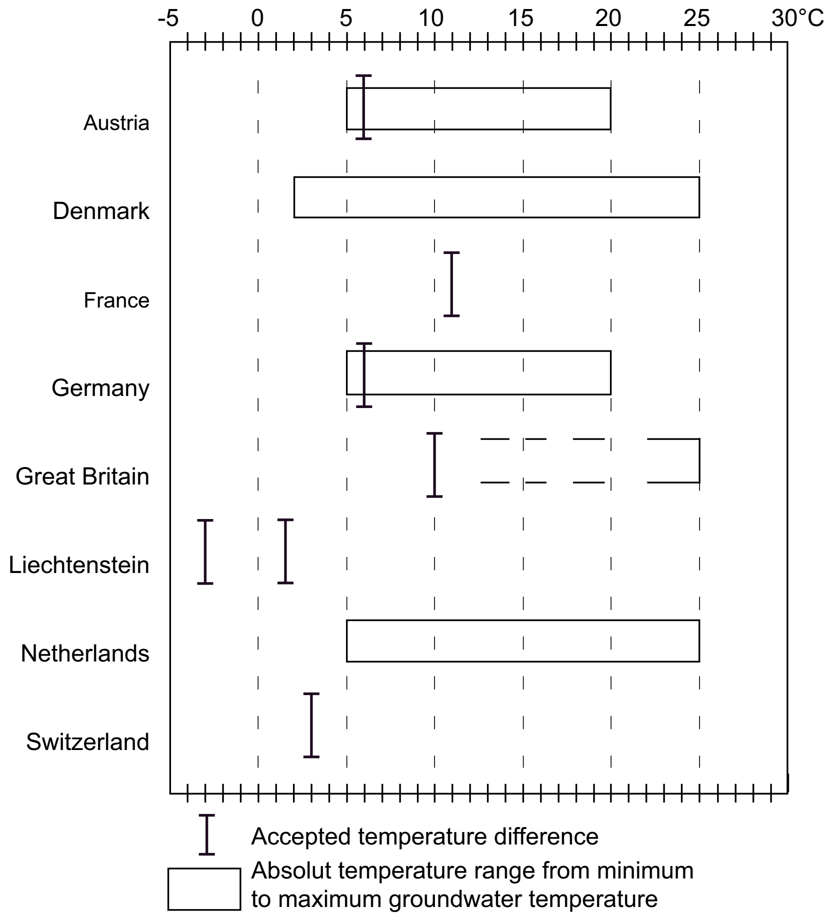

Fig. 2. Nationally regulated threshold values for groundwater temperatures. In Great Britain, until recently, no limit for cooling of groundwater was defined. The negative value for Liechtenstein indicates that a different threshold applies for cooling and for heating.

legislation. The focus here is on economic aspects, and no environmental consequences are considered (Goodman et al., 2009).

In a second study, Hähnlein et al. (2010a) show the current status of international regulations for shallow geothermal energy systems in 48 countries, with special interest in threshold values for groundwater temperatures and minimum distances between installations. It is revealed that, in order to prevent detrimental changes in groundwater characteristics, regulations are embedded in national laws of some countries such as Netherlands, Denmark and Germany. In other countries, for example in Canada, until now, regulations are primarily provided on a provincial level. In most countries, still there are no regulations. The few existing ones typically include threshold values for groundwater temperatures and/or minimum distances. The most commonly used minimum and maximum absolute groundwater temperatures for heating and cooling of groundwater are 5 °C and 25 °C, respectively (Fig. 2). The acceptable temperature difference (ΔT) ranges between 3 K in Switzerland and 11 K in France (Hähnlein et al., 2010a). These threshold values for groundwater temperatures are typically defined to mitigate any impact on the groundwater ecosystem (e.g., Brielmann et al., 2009, 2011).

Minimum distances between different points of reference vary between 2.5 m in Austria and 300 m in Denmark. As point of reference mostly serves the next property line, but for example in Denmark the next drinking water well is also suggested as point of reference. Often, even national regulations such as in Austria or Germany are inconsistent (Hähnlein et al., 2010b), and frequently regulations are recommendations and therefore not legally binding.

Bonte et al. (2011b) investigated the environmental risks and policy developments for UTES systems. In their study, they identified various impacts such as chemical, biological, thermal and hydrogeological. They examined the Dutch Water Act and presented case studies from different Dutch provinces. For example, for the protection of the deep groundwater in the province of Noord-Brabant, extraction and injection wells of ATES systems are not allowed to be deeper than 80 m. They also concluded that there is currently no international consistent legislation and that there are partially major differences between countries and minor differences even within countries. Furthermore, it is revealed that a scientifically based risk management strategy is lacking. More research on the impacts of UTES systems, cross-sectoral subsurface planning of different subsurface installations, European wide guidelines and standards are recommended for quality assurance and control.

These recent reviews highlight that legislation for the sustainable thermal use of groundwater and the shallow subsurface are recommendable worldwide. These regulations have to be adjusted to climatic conditions, stages of development, financial resources and/or dissimilar decision boards in politics and policy. Ideally they follow a similar policy and the national legislations are harmonized with each other or at least with neighboring countries.

5. Synthesis and discussion

The number of production systems for shallow geothermal energy is on a continuous rise, and this increases the pressure from especially direct environmental consequences, such as the development of temperature anomalies. Available ecological studies indicate that permanent changes by more than 5 or 6 K could potentially have detrimental effects on groundwater and

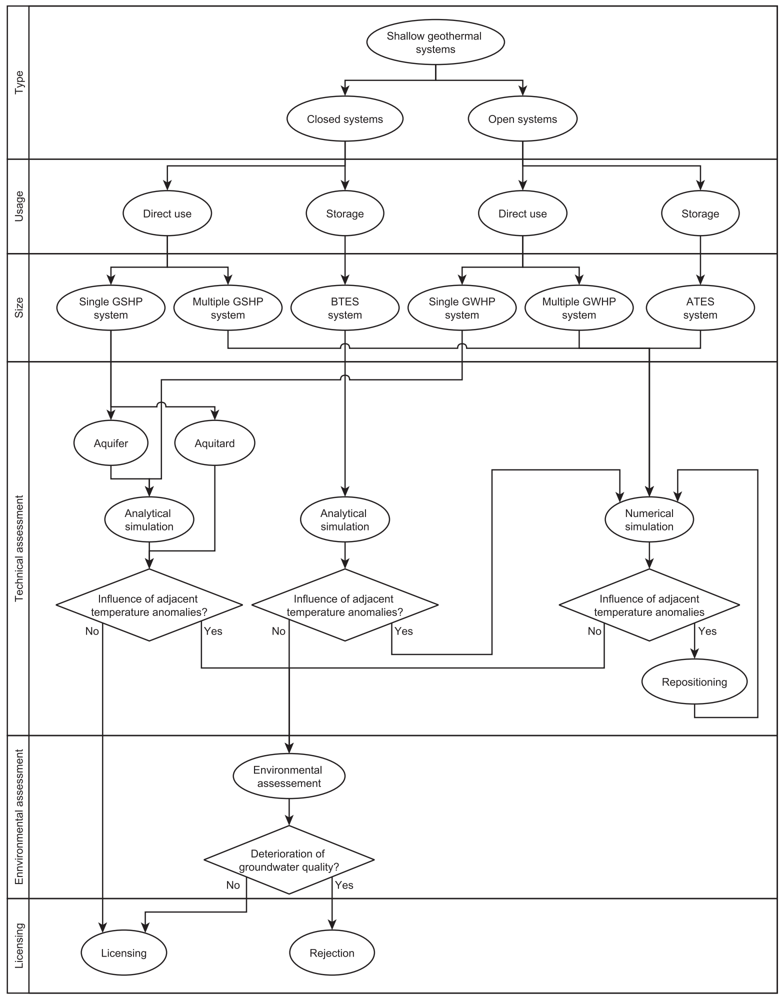

Fig. 3. Suggested legal framework for a sustainable use of shallow geothermal energy. The workflow of the legal framework is divided in six levels: (1) type, (2) usage, (3) size, (4) technical assessment, (5) environmental assessment, and (6) licensing.

subsurface ecosystems, and also change the natural chemical and physical conditions. Detrimental effects of groundwater heating may even be amplified in cases where the ground is already heated from climate change, urbanization (e.g., Zhu et al., 2010) and/or neighboring geothermal installations. To conserve the functions of groundwater for nature, animals and humans, especially to save it as source for drinking water, it is necessary to develop a sustainable geothermal energy use strategy. Preferably, this is based on the precautionary principle such as that recommended in the European water framework directive (EU-WFD, 2000). At the same time, there are technical reasons such as to guarantee the operability of the systems (Rybach and Eugster, 2010) and to avoid conflicts between different interests, that make it necessary to define sustainability-based regulations (Bonte et al., 2011b). Furthermore, there are social and political arguments that support well controlled long-term shallow geothermal energy use: Renewable energies and energy independency become increasingly important; and there is a world-wide interest to reduce greenhouse gas emissions. Finally, regulations cannot only abet sustainable use, but it is also essential to avoid uncontrolled growth, to provide confidence in a new technology, to support market penetration and ultimately achieve economically attractive conditions (Blum et al., 2011). So far, there is no general and international policy for evaluating or planning sustainable geothermal systems. Based on the current situation and the identified potential consequences of shallow geothermal energy use, we suggest an inclusive legal framework as shown in Fig. 3.

5.1. Type

On the first level, the type of system is defined. Due to the different primary environmental and social consequences by open and closed systems as well as fundamental differences in technical design, it is necessary to distinguish from the beginning between these types of systems.

5.2. Usage

The second level accounts for the different use, storage or direct use. For instance, for high-enthalpy systems UTES systems are typically used and not GWHP or GSHP systems (e.g., Sanner et al., 2005).

5.3. Size

The dimension and size of storage systems are usually larger than average GWHP or GSHP systems (e.g., Bonte et al., 2011b). Thus, the usage level is a preliminary decision step for the third one, which concerns the size (single system or multiple) of the system. This is analogous to standard guidelines such as the German VDI 4640, where the distinction is only made based on power of the systems, e.g. power of more or less than 30 kW (e.g., VDI, 2010). Hence, the system size generally determines the extent of impact intensity, required space and therefore overall consequences. The number of boreholes (BHEs or wells) is of primary importance for the environmental impact, because a higher number of boreholes means a greater volume of the ground or aquifer is exploited and therefore also impacted. Moreover, the temperature anomalies from multiple boreholes might interfere and have superimposed intensity. UTES systems and multiple GWHP and GSHP systems typically require more space in the subsurface than single systems for direct use (e.g., Katsura et al., 2008). In general, the risk of mistakes rises with increasing number of boreholes and BHEs. Thus, we can assume that single systems need less effort for the planning and design and therefore should also be treated differently in comparison to larger scale systems.

5.4. Technical assessment

After the third level, the technical assessment should be performed to avoid and evaluate potential consequences in size and intensity. In general, the main objective is to realize a system that operates sustainably for decades (> 30 years), which has to be adjusted to the specific conditions in the ground, while generating an often temporally variable heat and/or cold demand. A broad range of commercial software applications are available that support site-specific optimal planning (e.g., Schmidt and Hellström, 2005). For a given energy extraction or cold injection, standardized planning tools assist in adjusting borehole configurations, layout of multiple borehole fields or well doublets, as well as their operation mode. Simple BHE installations to supply Central European single family housings can be configured based on empirical rules of thumbs such as the commonly used heat extraction rate of 50 W/m (e.g., Blum et al., 2011). The total required borehole length is calculated based on the type of ground (i.e. its expected thermal conductivity) and energy demand (e.g., VDI, 2010). More sizeable and complex applications may require analytical or numerical modeling, which is in particular suitable to predict the evolving temperature anomalies in the ground. While appropriate technological planning, which also means technologically efficient and sustainable design and maintenance, is guided by cost-effectiveness, policy focuses on the associated long-term disturbances of nature and on concerted regulation of neighboring installations. However, before the planning and specific design of a specific system, several prerequisites are needed, which are typically defined in national and international guidelines and standards (e. g., Hähnlein et al., 2010a; Hähnlein et al., 2011; Sanner, 2008).

Geological prerequisites include the geological assessment of the subsurface at the potential location of the BHEs or wells, respectively. Thus, the potential of swelling (i.e. anhydrite swelling) or subsidence of the geological layer, which will be penetrated, has to be carefully evaluated, which could result in local depth restrictions (e.g., Blum et al., 2010). For example, in the city of Staufen in South Germany an inadequate backfilling of BHEs caused an uprising of groundwater, which resulted in the swelling of anhydrite and finally a massive damage of houses in the city center (e.g., Goldscheider and Bechtel, 2009; Sass and Burbaum, 2010). Hence, any drilling in such sensitive rock formations like the Gipskeuper (Triassic) should be avoided and/or strictly regulated.

Besides, hydrogeological requirements have to be assessed such as the location of the site in context of adjacent groundwater supplies and in particular groundwater protection zones. For example, in the German state of Baden-Württemberg, no license is given for systems inside the catchment of a groundwater supply. Only in outer groundwater protection zones GSHP systems might be approved (UMBW, 2005). In addition, hydraulic shortcuts between different aquifers such as short circuits by drilling of boreholes or during the backfilling of a BHE, as well as unwanted hydraulic effects from operating GHWP have to be avoided (Fry, 2009).

One main physical consequence from geothermal installations are temperature anomalies in the ground. For the sake of long-term technological efficiency, there is often an interest in keeping the temperature anomalies within a certain range, that is, for example significant long-term cooling of aquifers is not desirable since this also mitigates the seasonal performance factor of the heat pump used in the heating mode. Ideally a self-regulative mechanism therefore applies that compensates significant anomalies by combined heating/cooling or limits the heat extraction rates for given aquifer volumes. Even so, temperature anomalies may evolve that are not acceptable. Under these conditions, analytical or numerical simulation is suggested to inspect the long-term evolution of underground temperature. This reveals the expected intensity of anomalies, and potential interception of neighboring installations can be anticipated. If an analytical simulation is sufficient or a numerical simulation is necessary, depends on type, size of the system, as well as hydrogeological conditions such as degree of heterogeneity. In our proposed legal framework for a single GSHP system in an environment with negligible groundwater flow, i.e. in an aquitard, reference values from previous studies might be consulted. In Pannike et al. (2006) and Hähnlein et al. (2010b) temperature anomalies for GSHP systems in aquitards are simulated using numerical and analytical solutions for different uses (e.g., heating in winter, cooling in summer). The results of Pannike et al. (2006) show that for an accepted temperature difference of <1 K and heating demand of 4.5 kW for middle to coarse sand a minimum distance of 5 m is sufficient. For clay and silt and heat capacity of 3 kW a minimum distance of 8 m is necessary (Pannike et al., 2006). In Hähnlein et al. (2010b) it is demonstrated that the maximum length of plumes after 100 days for the most extreme case, that is, permanent heat extraction, has a mean value for solid materials of 4.8 m (with sandstone 5.1 m, limestone 0.7 m, crystalline 0.4 m). Both studies conclude that the length depends on heat extraction rates and subsurface conditions and therefore regulations for minimum distances should always be a case-by-case decision.

For a small single GWHP and GSHP systems, simple analytical solutions such as presented by Ingerle (1988) for open systems and by Yang et al. (2010) or Hähnlein et al. (2010a) for closed systems might be adequate. The latter presents an analytical solution for GSHP systems, in which conduction, advection and dispersion are considered (Molina-Giraldo et al., 2011b). Therewith, the maximum length of plumes for steady-state conditions and constant heating extraction can be calculated. The results show that the analytical solution can be used for a primary estimation of maximal plume length and that anomalies in an aquifer become longer after one heating period than in an aquitard, but regenerate faster.

For both single borehole applications as well as BTES, analytical solutions or semi-analytical *g*-function based models such as Earth Energy Designer EED (Hellström and Sanner, 2000) or GLHEPRO (2007) might be used. For multiple GSHP systems, GWHP systems, single GWHP systems and ATES systems numerical heat transport models such as SHEMAT (e.g., Mottaghy et al., 2011) or MT3DMS (Hecht-Méndez et al., 2010), FEFLOW (Wasy, 2010), or EED (Hellström and Sanner, 2000) are advisable. If the geothermal use results in substantial temperature anomalies, coupled transport models such as SEAWAT (Langevin et al., 2008) or FEFLOW, in which temperature-dependent fluid density and viscosity can be considered, should be applied. If the results of the numerical simulation identify interference such as overlap of temperature anomalies, superimposing of temperature changes or in case of influences of adjacent installations such as water supplies, repositioning of the boreholes might be necessary and therefore a new and more detailed simulation is required (e.g., Katsura et al., 2008).

5.5. Environmental assessment

If the results show no interferences or low acceptable interferences the next step is the environmental assessment (fifth level). This is necessary to identify the primary environmental consequences of the systems. The general decision on extent and manner of the environmental assessment depends on various aspects such as absolute temperature difference and type and size of the systems, and therefore should always be a case-by-case review. Also due to the fact that there is still a need for research on the environmental consequences (e.g., Brielmann et al., 2011), we conclude that with the current knowledge it is impossible to define a general procedure for the environmental assessment. So far, for open systems the intensity of the effects of mineral precipitation or dissolution, mobilization of organic compounds, oxygen saturation, changes in mesophilic populations and increase of undesirable bacteria are generally recommended as reference points for the environmental assessment. A chemical analysis of the groundwater for open systems should be adapted to the local chemical groundwater character, as defined for example in the context of the European Water Framework Directive (EU-WFD, 2000).

Besides potential alteration of the natural groundwater character also anthropogenic contaminations have to be considered. For example, in contaminated aquifers, it could be even beneficial, if groundwater temperature is elevated to intensify microbiological degradation as supporting aspect for enhanced natural attenuation (Slenders et al., 2010). However, possible positive effects depend on manner of contamination (Zuurbier et al., 2013). In the Netherlands, the combination of groundwater plume treatment (e.g., pump and treat system) and shallow open geothermal systems is considered to be beneficial (Pijls and Boode, 2011). In addition, it is necessary to be aware of the difficulties arising with groundwater flow. For heat extraction groundwater flow is advantageous, whereas for groundwater remediation minimal flows can be favored to avoid distribution effects. Thus, novel management concepts and legislation might be required (Slenders et al., 2010), which also enables the reinjection of minor contaminated water. Thereby, the concepts of sustainable energy (geothermal energy) and remediation are combined. If necessary, additional nutrients for an enhanced remediation can be added. However, such combined heat extraction and remediation concepts need a comprehensive planning to avoid any uncontrolled spreading of contaminants. For foresighted groundwater protection the reinjection of heavily contaminated water without previous remediation should not be permitted.

For closed systems the extent of the environmental assessment is minor. However, the composition of the heat carrier fluids and in particular the commonly used additives should be carefully addressed to avoid any environmental risk due to a potential leakage of the BHE. Although, Saner et al. (2010) could demonstrate that in context of the entire life cycle of a GSHP system the environmental impact of a total leakage of such heat carrier fluids is minor. Klotzbücher et al. (2007) found out that commonly used heat carrier fluids such as ethylene and propylene glycol are readily biodegradable under both oxic and anoxic conditions. Other critical and toxic chemical additives, which are also commonly applied such as corrosion inhibitors or biocides (e.g., borates and sodium nitrite), might pose an environmental threat. Current studies on the biodegradability of some additives showed that the corrosion inhibitors, benzotriazole and tolyltriazole are persistent under various redox conditions (Ilieva et al., 2011). A comprehensive environmental assessment of these additives is however currently not available.

If there is no thermal influence of small adjacent closed systems, in our opinion no environmental assessment is necessary and the licensing procedure can begin (Fig. 3). On the other hand, more pronounced impacts from large scale systems should be studied in detail. If the outcome of the environmental assessment is negative and in particular a degradation of groundwater quality is anticipated, permission should be rejected.

5.6. Licensing

A positive outcome of the technical and environmental assessment facilitates licensing. The details of the application and licensing procedure strongly depend on the country-specific standards and guidelines. A comprehensive overview of currently available standards and guidelines is provided by Sanner (2008) and Hähnlein et al. (2011). Although there are country-specific differences, a license application should include a drilling notice, the site plan with the location of the planned systems, dimensions of the planned installation and results of technical assessment, and if necessary, the outcome of the environmental assessment.

Based on this application the public authorities have to check the proposed location of the system, if there are any protected areas such as nature reserve or drinking water protection zones. Furthermore, the authority has to evaluate the provided results of technical and environmental assessment. Parriaux et al. (2004) presented an organigram showing a methodology for the identification of potential sites for geothermal systems. This framework fits to our fourth level (technical assessment). However, it does not consider the potential hydraulic circuit between two aquifers or environmental aspects, and it focuses on the interaction between buildings and so called geothermal structures.

Finally, during the operation of larger geothermal systems (e.g., multiple GWHP systems, multiple GWHP systems ATES, BTES) monitoring should be performed, which controls the size of temperature anomalies over time and especially temperature differences between natural and disturbed subsurface.

6. Conclusion

For the sustainable thermal use of shallow geothermal energy, technical, economical, environmental and also social aspects should be integrative considered. We conclude that a shallow geothermal system is sustainable, if the following aspects are principally fulfilled:

- From technical aspects:
  - The system operates without any major technical failures;
  - Other adjacent systems are not impacted;
- From economical aspects:
  - The system implies no main financial disadvantage in comparison with other renewable or conventional heating and cooling systems;
- From ecological aspects:
  - The generated energy is mainly renewable energy;
  - CO_2 emissions and particulate matter emissions are saved or even reduced;
  - Impacts on groundwater quality, quantity and ecology are negligible;
  - Temporary changes during the operation are reversible;
- From social aspects:
  - The owner has a user-friendly and controllable heating system;
  - The system contributes to environmental protection and climate change;
  - The user obtains or feels a social prestige;
  - No interferences with adjacent installations exist (e.g., possible conflicts with the neighbor).

Currently, there is still a lack of knowledge, especially on the validation of the available heat transport models and design tools with long-operating systems, the long-term environmental impacts, the functions of the groundwater ecosystems, and the optimum integrated system and operation. Due to local differences in geology and hydrogeology as well as in technical requirements, it is not recommendable to define only static regulations such as fixed and absolute temperature thresholds. Advisable are flexible temperature limits for heating and cooling the groundwater and subsurface, based on previously long-term undisturbed and locally observed groundwater temperatures such as anthropogenic caused temperature anomalies (i.e. urban heat islands in the subsurface; (Menberg et al., 2013)), chemical, physical and biological aquifer conditions. Furthermore, already existing groundwater usages for heating and cooling should always be carefully considered, because this might be locally beneficial. Thus, for example geothermal systems for heating in the centers of urban areas results in cooling of anthropogenic locally warmed up aquifers. The proposed legal framework follows a systematical procedure, in which more criteria might be gradually included in the decision making process providing profound basis for drafting a country-specific legislation of sustainable shallow geothermal energy utilization. In the future, the proposed framework offers the possibility to be adopted and extended according to the advancing knowledge and innovation.

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