ARTICLE IN PRESS

Geothermics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Technologies and environmental impacts of ground heat exchangers in Finland

Pirjo Majuri

Environmental Science, Department of Biology, University of Turku, Finland

A R T I C L E I N F O

Keywords:
Ground heat exchanger
Borehole heat exchanger
Ground source heat pump
Environmental impact
Technology
Damage event

A B S T R A C T

Finland is one of the northernmost countries utilizing ground source heat pumps (GSHPs). In this north European country, GSHPs' operating conditions are characterized by the cold climate, and hard, crystalline bedrock. Environmental risks and technical problems with ground heat exchangers (GHEs) have been much discussed, but the frequency of complications has not been previously studied in Finland. This article examines the types and construction practices of GHEs, and the range of problems in GHEs experienced by the practitioners. The data was collected through a questionnaire study among Finnish GSHP practitioners, and thematic interviews of Finnish heat pump experts. Borehole heat exchangers (BHEs) proved to be the most popular GHE type in Finland with a share of 85%. The questionnaire responses indicate that the most common complications in BHEs are connected to collapsed boreholes, and artesian or otherwise abundant water yields. Also, issues relating to heat transfer fluids, drilling through multiple aquifers, and design errors are discussed.

1. Introduction

Together with Scandinavian countries and Canada, Finland belongs to the northernmost countries utilizing ground source heat pump (GSHP) technology on a large scale (Nowak & Murphy, 2012: 73, 101, 118, 132, 140). According to the Finnish Heat Pump Association nearly 8500 GSHP units were sold in Finland in 2016 (SULPU, 2017). GSHPs are installed in new buildings, and retrofitted in place of oil burners, electrical heating, wood furnaces and district heating. Since 2013 more than half of new detached houses in Finland have had a GSHP installed (Motiva, 2016: 11).

A typical GSHP system in Finland consists of a borehole heat exchanger (BHE) and a vapor compression heat pump with either an inbuilt or a separate domestic hot water tank. Single U-pipes are most commonly used in BHEs. The GSHP system is connected to hydronic heat distribution, which is usually underfloor heating in new buildings and newer retrofit sites, or wall mounted water radiators in older retrofit sites. Horizontal ground heat exchangers (GHEs), in which a single, linear pipe is installed in series, are also used, while slinky or trench collectors are not used (cf. Florides and Kalogirou, 2007; Omer, 2008). Surface water heat exchangers are installed to a lesser extent, mainly in lakes and coastal areas of the Baltic Sea. Open loop heat exchangers are very rare in Finland. Ethanol is the most commonly used antifreeze in the GHEs whereas glycols are rarely used.

Boundary conditions for the sizing and design of GHEs in Finland are set by the northern climate and distinctive geological conditions. The annual average ambient temperature in Finland varies from over 5 °C on the south coast to below −2 °C in parts of northern Finland, where the temperature may drop below −40 °C in wintertime (FMI, 2016a,b). Correspondingly, the annual average temperature of the ground surface varies from 8 °C on the south coast to 2 °C in the far north of Finland (GTK, 2017). The thermal conductivity of Finnish rocks is typically over 3 W/(m*K), and the geothermal gradient is 8–15 K/km (Kukkonen and Peltoniemi, 1998; Kukkonen, 2000).

The bedrock in Finland generally consists of hard crystalline rocks, and sedimentary rocks are rare. Practically all of Finland is located on the Fennoscandian Shield, which is relatively unbroken and tectonically stable (Korsman and Koistinen, 1998; Plant et al., 2005). Due to the hard rocks in Finland, down-the-hole (DTH) drilling method is economically superior, and more efficient than any other method (cf. Rebouças, 2004). In practice, it is the only method applied to drill boreholes for BHEs in Finland. The rotating DTH hammer's percussion is powered by compressed air (typical working pressure 35 bar), and the exhaust air is used to flush the drill cuttings out of the borehole (Jouni Lehtonen, personal communication 12 Nov 2016; Jimmy Kronberg, personal communication 24 May 2017). Another consequence of the hard rocks is that boreholes are mostly left ungrouted and usually remain open. The need for grouting is also decreased by the fact that groundwater table is in most cases within ten meters from the ground surface (Karro and Lahermo, 1999). A completely dry borehole indicates that the rock is solid enough to prevent groundwater movement, in which case the borehole is filled with water.

Environmental and functional issues related to GSHP construction and use have been studied since the 1970s. Aittomäki and Wikstén (1978) and Aittomäki (1983) compared ground, surface water and air as heat sources for heat pumps in Finland, and discussed possible

http://dx.doi.org/10.1016/j.geothermics.2017.08.010
Received 6 March 2017; Received in revised form 25 August 2017; Accepted 27 August 2017
0375-6505/

ecological impacts of heat extraction on lake sediment fauna. Hähnlein et al. (2013) and Vienken et al. (2015) analyzed the sustainability of ground source energy use in general. Environmental risks of heat transfer fluids in GHEs were discussed by e.g. Heinonen et al. (1997, 1998), Klotzbücher et al. (2007), Ilieva et al. (2014) and Schmidt et al. (2016). Ignatowicz et al. (2017) studied the thermophysical properties of ethanol and methanol based heat transfer fluids, and how different denaturing agents affected these properties. Morofsky and Cruickshanks (1997) reviewed procedures for environmental impact assessment in underground thermal energy storage projects. Groundwater flow and potential cross-contamination between aquifers were studied by e.g. Lacombe et al. (1995) and Santi et al. (2006). Bonte (2013) investigated the hydrochemical and geomicrobial effects of GSHPs and aquifer thermal energy storage. Fleuchaus and Blum (2017), and Sass and Burbaum (2010) analyzed damage events relating to BHE construction in Germany. Bleicher and Gross (2016) discussed the unpredictability of hydrogeology in general, and experimental strategies to cope with it in GSHP projects.

Environmental risks and technical problems related to GHEs have been commonly discussed in public, and between authorities and GSHP practitioners in Finland. Yet, little is known about the frequency of complications in GHEs in Finland. Therefore, this article examines 1) the types and construction practices of GHEs in the northern conditions typical of Finland, and 2) the range of problems in GHEs experienced by the practitioners.

2. Materials and methods

I utilized questionnaire responses, thematic interviews of heat pump professionals, and enquiries to insurance companies, to explore the construction practices and environmental impacts of GHEs in Finland. The same questionnaire study and interviews provided data also for Majuri (2016), which presented the questionnaire and interview outlines.

2.1. Questionnaire study

The questionnaire study was conducted between January and March 2014 among GSHP professionals, utilizing the Webropol online survey software (www.webropol.com). The questionnaire contained questions on various GSHP related topics. In this article, I will concentrate on the questions that aimed at 1) gathering information of the technologies and construction practices applied to GHEs in Finland, and 2) approximately quantifying the frequency of complications related to GHEs in Finland. The target groups for the questionnaire were engineering offices, GSHP contractors and borehole contractors, and the aim was to gather company-specific information.

To achieve a broad sub-sectoral and geographical coverage, six organizations associated to the heat pump industry were asked to deliver the questionnaire link to their members. The link was also e-mailed directly to 126 unorganized companies. Since the organizations and their members distributed the questionnaire link freely, the exact number of questionnaire recipients is not known (Majuri, 2016). It is anyway clear that nearly all practitioners in the field received the questionnaire.

In the questionnaire, the respondents were asked to estimate the percentage values of different GHE types in the GSHP projects that their companies had completed in different years (Fig. 1). The questionnaire also included a multiple-choice question: 'When your company constructs or orders the construction of a borehole heat exchanger, how often do you apply or require the application of the following equipment or properties?' This question charted (1) the construction phase practices of BHEs, i.e. how dust and cuttings are handled, and (2) the properties of the completed BHEs, specifically sealing against surface water, the use of manholes, inclined drilling and borehole diameters (Figs. 2–4). For the borehole diameter questions the data was complemented so that if a respondent had ticked 'always' for one diameter and nothing for the two others, option 'never' was added for the other diameters. Similarly, if a respondent had ticked e.g. 'often' for one diameter and 'seldom' for another, 'never' was added for the third one. To determine whether the borehole contractors' experience correlated with their borehole construction practices, Fisher's exact test was used to compare the companies that had up to 10 years of experience with those that had more than 20 years of experience in well drilling. Fisher's exact test is a non-parametric statistical significance test, which can be applied to small sample sizes (Ranta et al., 2012).

In the questionnaire, there were two questions on the occurrence and frequency of complications and environmental problems related to GHEs. In relation to BHEs (Fig. 5), 19 types of possible complications and environmental risks were listed. The items on this list (apart from 'Discharge of artesian water during drilling' and 'Heat exchanger pipes stuck during installation') were derived from Juvonen and Lapinlampi (2013). Correspondingly, in relation to horizontal GHEs and surface water heat exchangers (Fig. 6), 11 types of possible complications and environmental risks were listed. The respondents were asked to estimate the number of cases their company had encountered of each type. They were also asked to describe more closely these situations, their causes and consequences, and how the problems were managed.

There were 64 respondents in total. However, one respondent (a borehole contractor) was excluded from the analyses due to exceptionally aberrant and unrealistic responses. The decision was based on an expert opinion by a borehole and GSHP practitioner. Additionally, another respondent (also a borehole contractor) was excluded from the analysis of complications and environmental problems because the respondent noted that, instead of estimating the number of cases, he or she had marked "1" for each type that the company had encountered.

When examining the questionnaire responses, some potential sources of bias are to be kept in mind: First, relating to some of the numerical questions, the respondents were asked to give estimates as they were not expected to remember exact numbers for incidents that may have occurred over two decades. Second, it is possible that some respondents were reluctant to disclose full details of their companies' failures. It may even be that contractors with the worst problems were less likely to participate in the questionnaire.

2.2. Thematic interviews of heat pump experts

I interviewed seven heat pump experts (Table 1) representing different sectors of the heat pump industry and research. The interviewees were chosen based on their long experience in the GSHP sector in Finland. The interviews recorded their observations of the construction and potential complications of GHEs more broadly than was possible in the questionnaire responses. Since most of them were not contractors in active working life, they could also provide different perspectives compared to the questionnaire respondents. The interviewees were asked how they see environmental conservation within the GSHP industry in Finland, including stakeholders' attitudes towards it, available methods to promote it, and observed environmental problems.

2.3. Insurance companies

I contacted eight Finnish insurance companies to obtain objective information about problems and accidents related to GSHPs. Four of the companies could supply some kind of information whereas the rest of them notified that their data systems did not enable the identification of GSHP claims. Some of the insurance companies provided qualitative data. One company in particular was able to provide more detailed qualitative information and even some general statistics. I interviewed a claim adjuster from this company who is specialized in heat pump claims. None of the companies could provide detailed statistics of different kinds of GSHP damage or accidents.

Table 1
The interviewed heat pump experts, modified from Majuri (2016).

	Background	Interview
Interviewee 1	Professor emeritus from a technical university in Finland, has worked with various heat pump (HP) topics since the 1970s	May 5th 2014
Interviewee 2	One of founders and owners of GSHP factory Suomen Lämpöpumpputekniikka; began his career at Lapuan Yleishiomo, Finland's first GSHP factory	May 5th 2014
Interviewee 3	Engineer, founder of HP design consultancy Enersys; specialist in design of large HP systems, active in HP research projects	May 20th 2014
Interviewee 4	Retired borehole and GSHP contractor, career spanned 1970–2013; drilled one of the first BHEs in Finland in 1983–84	May 20th 2014
Interviewee 5	Borehole and GSHP contractor, the first chairman of the Finnish Well Drillers' Association in the 1990s	June 3rd 2014
Interviewee 6	Executive director of the Finnish Heat Pump Association (SULPU); worked with HP imports until 2011	June 3rd 2014
Interviewee 7	Retired refrigeration contractor, worked with HP service	April 24th 2014

3. Results and discussion

3.1. Technologies applied

3.1.1. Types of ground heat exchangers in Finland

Generally, three types of GHEs are used in Finland: BHEs, horizontal GHEs, and surface water heat exchangers. All of them consist of a plastic pipe made of polyethylene, diameter usually 40 mm (or 50 mm in BHEs deeper than 250 m). The heat transfer fluid is most commonly a 28 wt-% ethanol solution (freezing point −17 °C). Open loop heat pump systems are rare in Finland. Their potential in renewable energy production has been studied by e.g. Arola et al. (2014, 2016).

BHEs have been commonly built in Finland since the 1990s. BHEs are typically 100–250 m deep. Maximum depths of BHEs have increased over the years, and at present BHEs up to 400 m are applied (Jouni Lehtonen, personal communication 12 Nov 2016). Gehlin et al. (2016) discussed this development, and urged designers to evaluate thoroughly the thermal efficiency, actual temperature profiles and increased pressure drop in the BHE when considering the option of deeper boreholes.

In Finland, the recommended minimum distance between boreholes that are intended to be thermally independent is 15 m (e.g. Juvonen & Lapinlampi, 2013: 25), and many contractors aim at 20 m. The BHE typically consists of a single U-pipe or occasionally a double U-pipe. Also three-pipe systems have been installed in which the fluid is pumped down through two pipes and up through one pipe. Generally, groundwater filled BHEs are installed, with no grouting. However, in recent years there has been an increasing interest in grouting for example in designated groundwater areas, where grouting may be a prerequisite for the planning permission.

Horizontal GHEs were the most commonly applied technology when the first wave of GSHPs entered Finland in the 1970s (Interviewees 1 & 2). In a horizontal GHE a single plastic pipe is typically installed in series at a depth of 1.0–1.5 m, with a minimum distance of 1.5 m between the parallel pipes. Compact collectors − such as slinky or multiple pipe systems (e.g. Banks, 2012: 334) – have not been applied to any noteworthy extent in Finland. The practitioners seem to be suspicious of their functionality under the Finnish temperature conditions (Jouni Lehtonen, personal communication 12 Nov 2016). In Sweden, Rosén et al. (2006) studied the properties, installation costs and ground area requirements of compact collectors (a double pipe and a slinky collector) in comparison to a single pipe. They concluded that compact collectors were technically feasible in Swedish conditions, which somewhat compare climatically and geologically to those of Finland. They discovered that the compact collectors require 12–37% less ground area than a single pipe, depending on soil conditions. At the same time, the installation costs are in most cases higher for compact collectors than for single pipes (Rosén et al., 2006:156). Based on these results, possible applications of compact collectors could be studied also in the Finnish natural conditions and business environments.

In Finland surface water heat exchangers, with closed loops that are placed at the bottom of the sea or lake at a minimum depth of two meters, have been built to a lesser extent since the 1970s (Fig. 1). In the Finnish climate, certain precautions are required to manage the effects of ice accumulation around pipes in wintertime: first, the heat exchanger must be sufficiently sized to prevent excessive ice accumulation; second, the heat exchanger must be properly weighted to counterbalance the buoyancy by the ice; and third, rivers are often not suitable as heat sources since the temperature of flowing waters may be close to or even below 0 °C in the winter, which would cause excessive ice accumulation (Aittomäki, 2012).

Regarding the quantities of different GHE types, the presumption before this study was that the proportion of BHEs has increased over the years. This was supported by the questionnaire responses (Fig. 1).

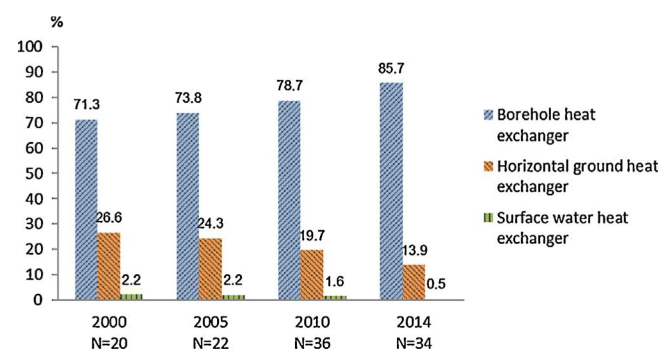

Fig. 1. The proportions of different GHE types (new installations) from 2000 to 2014 in the respondent companies' GSHP projects. To avoid statistical bias in favor of BHEs, responses from GSHP contractors were included in the data while responses of those who only drill and install BHEs were omitted. The figures are mean values of the percentages given by the respondents, as the exact numbers of GSHP systems delivered by them each year were not available.

3.1.2. Borehole heat exchanger construction practices in Finland

Fig. 2 summarizes the questionnaire responses on how dust and drill cuttings are handled at the construction phase of BHEs. Approximately 87% of the companies always or often use dust suppression. Drill cuttings are in rural areas often deposited on site, while in built-up areas they are usually collected and transported off the property. For collecting drill cuttings, a sealed container is more popular than a skip. A skip here refers to an unsealed container, which may be open-topped or covered with e.g. a tarpaulin. Sealed containers enable better control of dust and slurry.

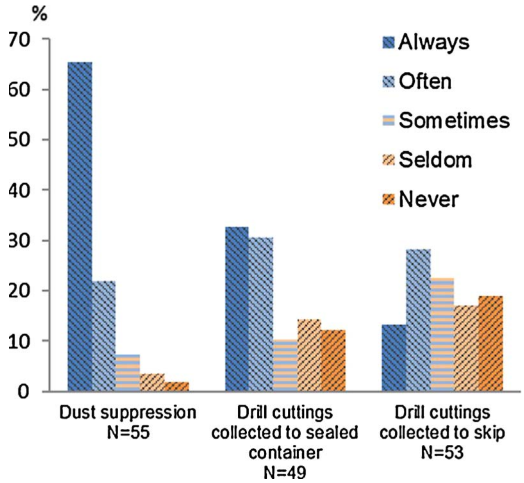

Fig. 2. BHE construction phase practices in the questionnaire respondent companies.

Drill cuttings consist mostly of dust-like material, mixed with stone chips of a few millimeters in diameter. It is possible to re-use drill cuttings for example for soil improvement in agriculture, although in some areas this may be limited by naturally elevated concentrations of harmful substances such as arsenic in the bedrock (Jarva, 2016: 39). It is not known how common re-use and recycling of drill cuttings are compared to landfilling, and a further study would be needed on their treatment practices and re-use potential.

Since almost all BHEs in Finland are constructed without grouting, surface water sealing is of utmost importance. It is also listed in the Normheatwell criteria, which is a BHE construction guideline developed by the Finnish Well Drillers' Association (Poratek, 2016). Surface water sealing in the borehole may be implemented in different ways: in addition to the surface casing (steel or plastic), an additional casing (usually HDPE or PVC) may be installed and sealed against the borehole wall, or a plastic plug or cuplike plate may be installed into the borehole along with the collector pipes. Some companies also fasten the surface casing to the bedrock using beading or cementing. The questionnaire enquired whether the respondent companies use a surface water sealing in addition to the surface casing, and 41% of the respondent companies reported that they always apply such sealings in their BHE projects (Fig. 3). Six GSHP contractors did not respond to this question, possibly implying that when delivering a GSHP system, they take no stand on and responsibility for groundwater protection. Overall, the various methods of surface water sealing, their effectiveness and functionality are a central topic for further research.

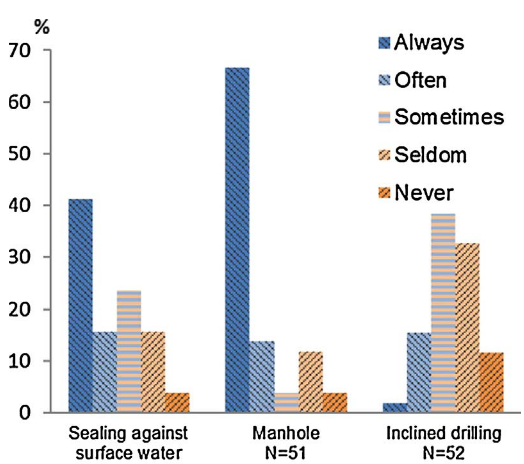

Fig. 3. Properties of BHEs in the questionnaire respondent companies.

A manhole here refers to a concrete or plastic ring with a cover of concrete, plastic or steel, placed on top of the borehole. Both the diameter and depth of the ring are usually 50 cm or larger. Fig. 3 shows that a clear majority of the respondent companies prefer to have the boreholes, and the connections between the collector pipes and the transfer pipes accessible by using a manhole instead of covering them directly with soil.

Over the past ten years the borehole diameters have presumably shifted increasingly from 5½ towards 4½ inches. 40% of the questionnaire respondent companies use only 4½ inch boreholes, 24% 5½ inch boreholes and 4% 6½ inch boreholes (Fig. 4).

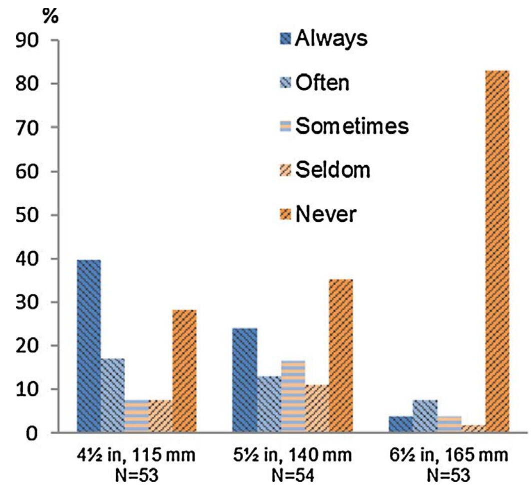

Fig. 4. Diameters of boreholes in the questionnaire respondent companies. Due to wide use of inches within the drilling industry, the sizes are given in both inches and millimeters.

Interviewee 4 strongly supported borehole diameters of 5½ inches or larger. He gave three reasons for this: (1) He prefers the surface water sealing with an additional casing, which is only possible in 5½" or larger boreholes. (2) The 4½" drilling hammer has so little weight that it lacks the capacity to draw a casing of sufficient thickness to a sufficient depth into the bedrock. (3) During drilling, the drill cuttings are more easily removed from the 5½" borehole than the 4½" borehole.

Only in one respect did the borehole contractors' construction practices correlate with their experience: The 4½" borehole diameter (Table 2) was clearly more popular among the companies that had 10 years or less experience compared to those that had more than 20 years of experience in well drilling (Fisher's exact test, two-tailed $P = 0.0114$). There are several possible reasons for this pattern. For example, the older contractors may have shifted to larger borehole diameters after having learnt their superiority. It is also possible that the larger diameters are only a relic from the past that older contractors have not been able to abandon. Furthermore, it is possible that newcomers in the field respond more easily to the severe competition within the Finnish borehole industry by lowering prices, thus having to decrease expenses in every possible way.

Table 2
Correlation between the frequency of drilling 4½" boreholes, and the borehole contractors' experience in well drilling.

Frequency of drilling 4½" boreholes	Experience	
	≤10 yr	> 20 yr
Always or often	6	3
Sometimes, seldom or never	0	7

3.2. Environmental impacts and functionality of GHEs

3.2.1. Overview of results

The responses of 62 questionnaire respondents, including 15 borehole contractors, were analyzed for the questions regarding complications in their BHE and horizontal GHE projects. The Finnish Well Drillers' Association estimates that there are 60–70 actively operating borehole contractors in Finland (Timo Rajala, personal communication 28 May 2017). 49 of the analyzed respondents reported that they have had some complications with either their BHE projects, horizontal GHE projects, or both. Three respondents notified that they had not encountered complications. Three respondents had not reported any incidents but either notified that their companies did not build GHEs, or this was otherwise apparent (they were design offices). Seven GSHP contractors did not report any cases, nor commented otherwise, so it remains unclear whether they had encountered any complications in their projects.

Among the 19 types of potential risks and complications related to BHEs, there were two that none of the analyzed respondents reported. These were 'Drilling and excavation on contaminated ground areas' and 'Increased radon concentration due to new channels opened by drilling'. Likewise, among the 11 types of potential risks and complications associated with horizontal GHEs, there were two that none of the analyzed respondents reported: 'Excavation on contaminated ground areas' and 'Changes in level and quality of ground water'. While no cases of drilling and excavation works on contaminated soil areas were reported, it is still possible that for example leakages from private heating oil tanks have been encountered. The respondents may have interpreted the question to refer to contaminated areas that have been registered by the authorities (ELY, 2014).

The questionnaire responses regarding the numbers of complications in BHEs are presented in Fig. 5, and horizontal ground and surface water heat exchangers in Fig. 6. To proportion the numerical questionnaire responses, it was estimated that the responding companies had commissioned altogether 15–20 000 GSHP systems by the time the questionnaire was conducted (corresponding to 15–20% of all GSHP systems commissioned in Finland by that time). The estimate is based on the companies' age, and on the number of GSHP systems they had delivered the year before the questionnaire.

3.2.2. Risks relating to surface and ground waters

In BHEs the most commonly reported ground water related complications were discharge of artesian water during drilling, and flooding caused by artesian water (Fig. 5, Table 3). Interviewees 3 and 4 mentioned the challenge sometimes caused by abundant water yields during borehole drilling. This is often not artesian, but the related problems are similar, i.e. discharge and flooding during drilling. Thus, some of the cases reported by the respondents may belong to this non-artesian category. If the water yield is too large for the compressor to handle, drilling may be prevented, in which case an additional borehole needs to be drilled.

Interviewee 3 mentioned the issue of overflowing artesian water which may continue for years after BHE installation. Unlike in e.g. parts of Germany (Fleuchaus and Blum, 2017), the geological conditions in Finland do not favor very high pressure and yield in artesian bedrock aquifers. Thus, usually cases involving artesian water cause moderate damage at most, and are resolved by for example conveying the overflowing water into a ditch, or by installing a pressure-proof well cap. However, it seems that contractors have not been systematically informed about the risks of pressure-proof well caps, for example the need to have tightly sealed casings with them (Teppo Arola & Jouni Lehtonen, personal communications 27 June 2017).

Questionnaire respondents reported 74 heat transfer fluid leakages in total (Figs. 5 & 6, Table 3). Leakages are much more common in the horizontal transfer pipes (i.e. between the borehole and the heat pump) than in the borehole. The horizontal transfer pipes, as well as horizontal GHEs are prone to damage by excavation work and stones in the ground (Fig. 6). In the Nordic climate conditions upfreezing moves stones

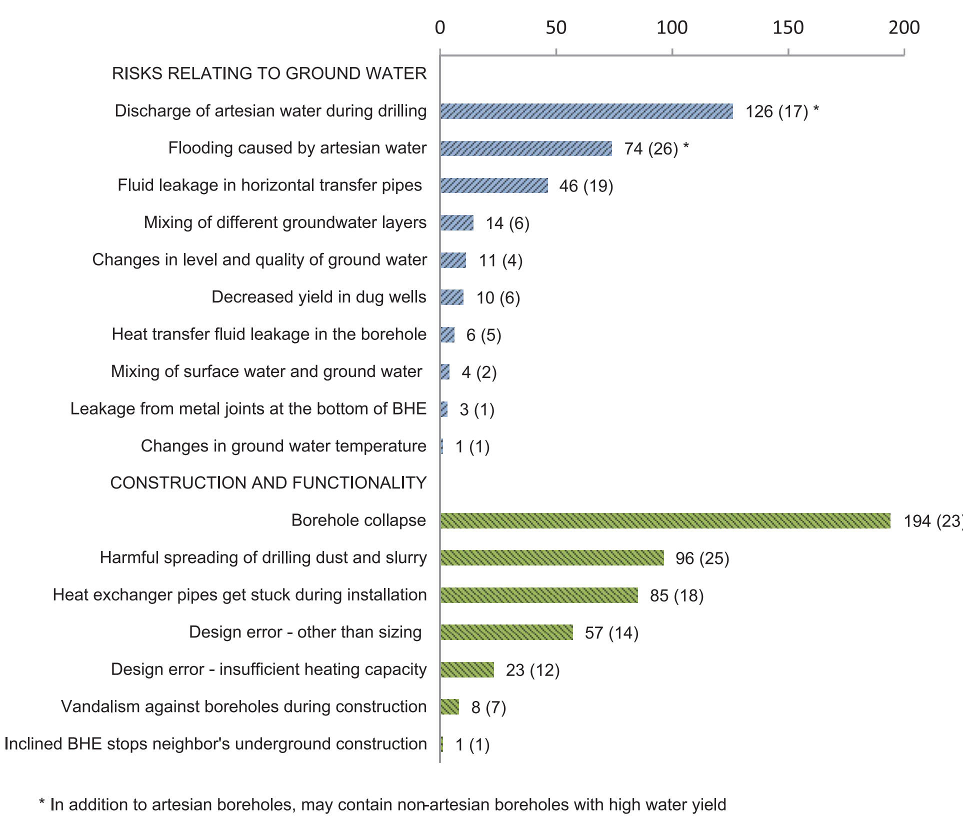

Fig. 5. The number of complications in questionnaire respondents' BHE projects. The respondents were asked to estimate the number of cases that had occurred in all the BHE projects of their company (the figures in brackets refer to the number of respondents reporting each type of complications).

Table 3
Summary of findings.

	Reported cases in questionnaire (N of respondents in brackets)	N of questionnaire respondents who took up the topic in open-ended questions	N of interviewees who took up the topic
COMPLICATIONS AND RISKS			
Heat transfer fluid leakages	74 (28)		2
Composition of anti-freeze solutions			2
Groundwater risks from drilling through multiple aquifers	39 (14)	1	2
Problems caused by artesian water or otherwise abundant water yield	200 (29)		1
Abundant water yield during borehole drilling			2
Collapsed boreholes	194 (23)		
Design errors of BHEs or GSHP systems (insufficient heating capacity)	28 (15)	13	1
Surfacing of submerged pipes	6 (4)		1
REASONS FOR COMPLICATIONS			
Fracture zones in the bedrock		9	
"Customer related reasons" that are still under practitioner's control		4	
Customer related reasons – deficient or false information, customer turns on the heat pump		5	
Competence, attitudes, qualifications		10 (Majuri, 2016)	2

vertically in the ground (Anderson, 1988) so that the pipes may be at risk even if stones around the pipe have been removed during installation. Surface water heat exchangers are the most susceptible type since they have no protection against anchors, moving ice and other external factors in the water. Furthermore, the submerged pipes sometimes surface due to excessive ice accumulation (Fig. 6), which is a constructional and functional problem as such, and may also cause leakages. Interviewee 3 described two cases in the 1980s that resulted in leakages in large surface water heat exchangers, comprising several kilometers of pipes. In both cases the problems resulted from excessive cooling, ice buildup around the pipes and consequent partial surfacing of the pipes. According to interviewee 3, regarding large GSHP systems, during the 2000s leakages have been tackled with e.g. pressure alarms in the ground loops.

Interviewee 3 pointed out that if a ground loop or surface water heat exchanger leaks, only those parts get drained that are above the groundwater or water level. If the ground loop is pressurized, the additional leakage would approximately correspond to the volume of the expansion tank, which is usually 3–4% of the entire ground loop volume (Jouni Lehtonen, personal communication 12 Nov 2016). However, a slow, seeping leakage of heat transfer fluid is not always easy to detect, and serious attention should be paid to systems that require repeated fluid additions.

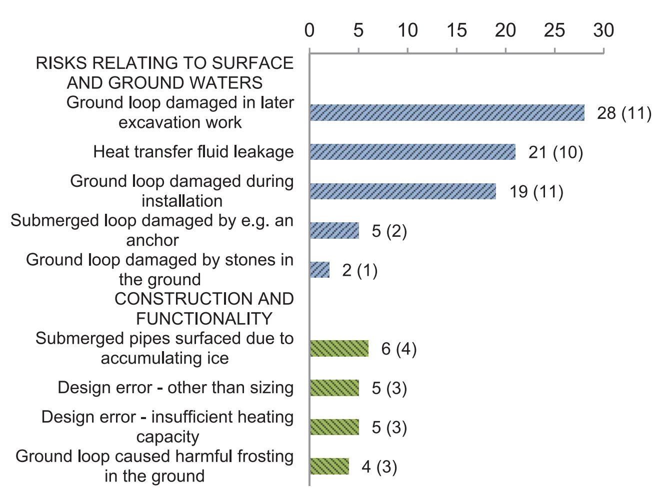

Fig. 6. The number of complications in horizontal GHEs and surface water heat exchangers reported by the questionnaire respondents (the figures in brackets refer to the number of respondents reporting each type of complications).

Central issues relating to heat transfer fluid leakages are for example toxicity of the fluid constituents or their degradation products, and oxygen depletion caused by biodegradation of the fluid constituents. These questions have been studied in relation to glycol, betaine and potassium formate based fluids (Klotzbücher et al., 2007; Ilieva et al., 2014; Schmidt et al., 2016). Similar studies have not been conducted in relation to the ethanol based heat transfer fluids commonly used in Finland. The most frequently used commercial fluid (Naturet by Altia PLC) contains 28 wt-% ethanol, and methyl isobutyl ketone (0.8 wt-%) and methyl ethyl ketone (0.6 wt-%) as denaturants (Naturet Safety Protocol, 2017). The fluids are available with and without corrosion inhibitors. The composition of corrosion inhibitors is not publicly accessible information. In their studies Klotzbücher et al. (2007) and Schmidt et al. (2016) discovered that the commercial glycol based heat transfer fluids are less biodegradable and more ecotoxic, respectively, than glycol solutions without additives. This implies that further research is needed also on the environmental impacts of the ethanol based heat transfer fluids.

Interviewees 4 and 6 took up potentially hazardous heat transfer fluids. Interviewee 4 described a suspicious case at the beginning of the 2000s when a small importer marketed an anti-freeze solution of unknown composition to GSHP contractors. The suspicions later proved justified, when it was reported that an importer had sold methanol solution with false product information to some GSHP contractors, who had used it in more than a thousand GHEs in Finland in 2012–2015 (Blencowe, 2016). Due to methanol's toxicity, neither the general public, nor the authorities, nor the majority of Finnish practitioners consider it acceptable as a heat transfer fluid. Interviewee 6 expressed his concern over the fact that Finnish legislation still does not explicitly prohibit the use of methanol in GHEs. The Chemical Act (2013: 19§) leaves some room for interpretation by stating that "out of the available chemicals or techniques must be chosen the one that poses the least danger". As methanol is known to have higher health hazard risks than ethanol (Heinonen et al., 1997, 1998), the ambiguity in legislation could be eliminated by setting a legal precedent. This would also resolve liability issues in case of accidents.

Problems relating to drilling through multiple aquifers are commonly discussed in environmental GSHP studies (e.g. Hähnlein et al., 2013; Haehnlein et al., 2010; Dehkordi and Schincariol, 2014; Buday, 2014). Four of the potential complications listed in the questionnaire went under this topic: mixing of groundwater layers, mixing of surface water and ground water, changes in level and quality of ground water, and decreased yield in dug wells. The respondents reported altogether 39 cases of these types (Fig. 5, Table 3). Interviewees 4 and 5 mentioned the risk of surface waters for groundwater deterioration, which is of particular concern for companies that drill also water wells for their customers. Interviewee 4 emphasized the importance of proper sealing against surface water, and in his opinion this should be done using the surface water casing method described in Section 3.1.2. He objected to plugging the borehole with a plug-like or cup-like seal: As such it does not provide adequate protection against surface waters, and if complemented with a backfill of concrete or some other material, it becomes impossible to remove and makes the BHE non-serviceable and thus single-use. On the other hand, the technical functionality of such partial grouting should also be properly investigated e.g. in cases of borehole freezing. This situation is in some ways similar to that described by Nordell and Ahlström (2007) in relation to flattening of collector pipes in freezing boreholes.

When interpreting the numbers reported in Figs. 5 & 6, it should be kept in mind that, apart from discharge and flooding of artesian water, most of the other problems with ground water are rather difficult to detect. As one respondent pointed out, for example mixing of surface water and groundwater, mixing of groundwater layers, or changes in level and quality of ground water are usually revealed only if there are water wells nearby. When drilling on designated groundwater areas, Juvonen and Lapinlampi (2013) recommended regular monitoring of chloride concentrations or electrical conductivity of the water to detect possible saline aquifers. Apart from this, there are no instructions on monitoring the impacts of BHE construction. Moreover, subsequent inspections and monitoring of the borehole are possible only if it has been constructed with a manhole.

One insurance company reported that from 2009 to January 2014 they received approximately 30 claims from companies concerning liability damages in relation to GSHP projects. This included cases like damages to neighbors' water wells, flooding caused by excessive water yield during drilling or discharge of artesian water, damages caused by drilling vibration and apparently also increased radon concentrations. A more detailed categorization of the numbers of cases was not available. However, it is noteworthy that while there have been some claims concerning repairs of broken GHEs, no claims have been notified for damages caused by heat transfer fluid leakages. The other insurance companies could provide even less statistics. Some of them also mentioned claims regarding repairs of broken GHEs but did not mention any specific liability insurance claims regarding environmental damage.

Lankia and Kleiman (2009) described an extreme case, which exemplifies problems that may follow from oxygen depletion when heat transfer fluid leaks, and from drilling through multiple aquifers: Several deep BHEs were drilled on a property close to seashore in southern Finland. Some time after that the inhabitants of the neighboring property detected a strong smell of solvent and alcohol in their domestic water that came from a drilled water well. Analyses revealed iron, manganese and chloride concentrations that exceeded the recommended levels. Later on, heat transfer fluid (alcohol) leakages were detected in the BHEs, but after these had been repaired the neighbor's well water turned black, started to foam and developed a sulphury smell. Iron, manganese, and humus concentrations rose considerably. The black deposit proved to be iron sulphide, which is oxidized into e.g. sulphuric acid. Large corrosive damage had appeared in the water pipes and the water had become unusable.

A newspaper article described another case from southern Finland, where the drilling of eleven energy wells for an industrial hall pierced the clay aquitard below an upper aquifer. During the drilling work, the domestic water wells of several nearby households dried up. One of these was almost a kilometer away from the drilling site. The wells remained dry for several weeks after which water returned to at least some of them (Mattsson, 2010). Also, a case of gross negligence has been reported: In Helsinki, drilling slurry had been conveyed into a rainwater sewer, which in turn discharged it into a creek. The creek had earlier been restored into a breeding habitat for trout, and it was feared that the slurry had destroyed the breeding grounds and would expel the trout from the restored creek (Sippola, 2011).

3.2.3. Complications with construction and functionality

Collapsed boreholes are clearly the most common type of complication relating to BHEs (Fig. 5). According to the respondents, these are usually resolved by drilling the borehole open and possibly extending the casing, or by drilling an additional borehole. A collapsed borehole is clearly detectable during construction, whereas a collapse thereafter is not easily detected unless the heat exchanger pipes are blocked or broken. Other relatively common complications with BHE construction and functionality are harmful spreading of drilling dust and slurry, and heat exchanger pipes getting stuck during installation.

The questionnaire respondents reported 23 design errors with insufficient heating capacity for BHEs, and 5 for horizontal heat exchangers (Figs. 5 & 6). On the other hand, the respondents reported only 4 cases of harmful frosting around horizontal ground heat exchangers. These are also related to under-designed GHEs, and were much discussed during the first heat pump boom in the 1970s and 1980s. It seems that this lesson has been learnt well enough to eliminate the most blatant design errors.

However, all design errors are not as obvious and are sometimes detected much later. Interviewee 3 described the insufficient design of BHEs as a time bomb: he had encountered numerous boreholes that were frozen year-round, and believed that design errors may be quite common. One questionnaire respondent criticized the heat pump supplier's design program for too short BHE designs, and 13 respondents expressed their concern about the design practices of GSHP systems in general, or BHEs in particular. Interviewee 3 pointed out that some regeneration occurs if the BHE is used for summertime cooling, but this is an insufficient remedy when the BHE is clearly too short. Thus, according to interviewee 3, the continuous cooling of the ground over the years increasingly impairs the efficiency and increases the electricity consumption of the GSHP system. The role of the supplementary heating system (usually electricity or oil) increases, and further complications may arise especially regarding the sufficiency of electrical heating capacity in detached houses. Also, the Finnish Heat Pump Association has identified the problem and has set up a working group to investigate and give instructions on BHE sizing (Jussi Hirvonen, personal communication October 2016).

3.2.4. Reasons for and prevention of complications

The questionnaire respondents were also asked to describe in their own words possible reasons for the complications they had reported. These are summarized in Table 3, along with the encountered complications. Geological conditions, in most cases fracture zones in the rock, were given as a reason for collapsed boreholes and stuck heat exchanger pipes. One respondent suggested that the diameter of the borehole would be an important factor when heat exchanger pipes get stuck during installation. The numbers given by the respondents do not contradict with this notion: Companies (N = 21) that use only 4½" boreholes reported on average 2.24 cases of stuck pipes, whereas companies (N = 15) that use only 5½" or 6½" boreholes reported on average 0.53 cases.

Several respondents also gave customer related reasons for the complications they reported. It seems that in some of the cases the contractors could save a lot of trouble by using their professional judgement in a firm manner, and by delivering information clearly. On the other hand, in some cases the contractors and designers have less control over the complications. The following examples clarify this:

- *The customer demands that the borehole length should be halved to save money, or does not want to pay for a long enough casing.* In these cases the borehole contractors have the choice of refusing to drill. Based on their superior experience they know that in such conditions functional and environmental problems are to be expected: the heating capacity will be insufficient and the borehole will freeze, or the borehole will have a high risk of collapsing.

- *The customer does not understand how much drill cuttings come out of the borehole.* Prior to drilling, the contractor should describe the amount of cuttings realistically. The customer and contractor may have different interpretations of what is "harmful spreading" of drilling dust and slurry, but it is up to the contractor to implement sufficient measures to at least prevent damages to the customer's and neighbors property, and to the environment.
- *The customer gives deficient or false information about the building and its heating demand.* Here responsibility issues are more ambiguous, and the sizing of a GSHP system relies on both the customer and the designer: the customer is expected to give accurate and correct information, while the designer must use professional judgement to evaluate the accuracy of provided information.
- *The customer or someone else at the construction site turns on the heat pump without the GSHP contractors permission.* This is beyond the control of the GSHP practitioner, and usually against the conditions of the contract. Contractors generally want to start up the systems themselves to run some tests and to adjust the system. This kind of initiative by non-professionals may have various consequences, such as damage to the system, and, as one respondent reported, freezing of boreholes if the insulation of the building has not been completed.

Interviewee 4 emphasized the significance of expertise and experience in borehole drilling: "You can learn to operate the drill rig in a relatively short time, but learning to really drill, to know what happens down inside the rock, that takes time. —And managing the more challenging situations is a whole different story. If someone else must try and fix them afterwards, it is incredibly difficult. The one who drills should know what the borehole is like, and what kind of ground and rock there is around it."

Carelessness, e.g. neglecting pressure tests of pipes as one questionnaire respondent mentioned, also inevitably leads to problems. As a general observation, Interviewee 6 underlined the importance of disseminating responsible environmental attitudes among the GSHP and borehole contractors. As examples he mentioned the handling of heat transfer fluids and refrigerants, and recycling. His observation was that some contractors may not take environmental issues as seriously as they could, since they feel they are already promoting environmental protection enough by selling renewable energy systems.

In connection to expertise and attitudes, proper training and qualifications are a precondition for the development of the GSHP sector. Ten questionnaire respondents expressed their concern about training and qualifications within the GSHP sector in Finland (Majuri, 2016). Voluntary training and qualification programs have been set up for well drillers in Finland (Poratek, 2015), and heat pump installers at the European level (EHPA, 2017). However, the refrigerant qualification requirement for GSHP installers was abolished from the Finnish legislation at the end of 2016, and currently no qualification requirements are in effect for GSHP practitioners.

4. Conclusions and recommendations

This study has investigated the types and construction practices of GHEs in Finland, a north European country, and the kinds of problems GSHP practitioners have encountered in their GHE projects. BHEs were found to be the most common GHE type with a proportion of 85%. The most frequent complications in BHEs are collapsed boreholes, and artesian or otherwise abundant water yields. Hazardous heat transfer fluids (mainly methanol), and removing them from the market, have been topical in Finland. Another threat for the ground water is drilling through multiple aquifers, and neglecting proper sealing to prevent surface water from entering the borehole.

Sufficient regulations, applicable to the Finnish conditions, are needed to ensure that environmental conservation and functionality are duly considered in the design and construction of GHEs. Such regulations include adequate qualification requirements and mandatory training programs for drillers, installers and designers, and binding criteria for GHE and borehole construction. In the construction criteria, the use of for example surface water sealing and manholes in borehole construction should be considered.

Bleicher and Gross (2016) have argued that, due to the unpredictability of the hydrogeological conditions, the construction of each GSHP system may be viewed as a real world experiment. These experiments produce valuable knowledge on problems and solutions, which should be collected and shared systematically to promote the development of the industry and the administrative practices. To accomplish this, openness from the practitioners' side is needed in sharing their experiences.

Additionally, further research on GHEs in Nordic conditions would support the development of the industry. For example, in the course of this study the following topics emerged: ecotoxicity and biodegradation of ethanol based heat transfer fluids; frequency and consequences of undersized BHEs in Finland, or more largely in the Nordic countries; and comparison of different borehole designs (e.g. surface water sealing and its design, borehole diameter) and their functionality in an experimental setup. Clarifying these issues would give valuable information for future recommendations.

Acknowledgements

I warmly thank the interviewees and questionnaire respondents for providing the data for this study, and the organizations that were involved in data gathering. I am grateful to Timo Vuorisalo for support and valuable comments; to Timo Saarinen and Timo Kilpeläinen for comments; to Tero Klemola for statistical advice; to Jouni Lehtonen (GSHP and borehole contractor) for comments and clarifying the technical practices of GSHP construction in Finland; and to Jussi Hirvonen (Finnish Heat Pump Association Sulpu), Timo Rajala (Finnish Well Drillers' Association Poratek), Jimmy Kronberg (GSHP and borehole contractor) and Teppo Arola (Geological Survey of Finland) for delivering information on the Finnish GSHP sector and geology. I gratefully acknowledge the funding provided by Kone Foundation and Fortum Foundation (201300205).

References

Aittomäki, A., Wikstén, R., 1978. Maaseudun asuinrakennusten lämmitys lämpöpumpulla. Finnish, Heat Pump Heating of Residential Buildings in the Countryside. State Technical Research Centre, Laboratory of HVAC Technology, Report, pp. 38.

Aittomäki, A., 1983. Maaperä ja vesistöt lämmönlähteinä. Finnish, Ground and Surface Water as Heat Sources. Tampere University of Technology, Department of Mechanical Engineering, Thermal Engineering, Report 37, Tampere.

Aittomäki, A., 2012. Lämpöpumput. Finnish, Heat Pumps. Chapter 14. In: Aittomäki, A. (Ed.), Kylmätekniikka, 4th edition. Suomen Kylmäyhdistys ry, Helsinki, pp. 336–359.

Anderson, S.P., 1988. The upfreezing process: experiments with a single clast. Geol. Soc. Am. Bull. 100, 609–621.

Arola, T., Eskola, L., Hellen, J., Korkka-Niemi, K., 2014. Mapping the low enthalpy geothermal potential of shalow Quaternary aquifers in Finland. Geother. Energy 2 (9).

Arola, T., Okkonen, J., Jokisalo, J., 2016. Groundwater utilisation for energy production in the Nordic environment: an energy simulation and hydrogeological modelling approach. J. Water Resour. Prot. 8, 642–656.

Banks, D., 2012. An introduction to thermogeology. Ground Source Heating and Cooling, 2nd edition. Wiley-Blackwell.

Bleicher, A., Gross, M., 2016. Geothermal heat pumps and the vagaries of subterranean geology: energy independence at a household level as a real world experiment. Renew. Sustain. Energy Rev. 64, 279–288.

Blencowe, A., 2016. Ministeriöt varoittavat: Maalämpöjärjestelmiin asennettu vaarallista nestettä – Kiinteistönomistaja, toimi näin. Finnish, A Warning from The Ministries: Dangerous Fluid Has Been Installed into GSHP Systems – Instructions for Property Owners. YLE -the Finnish Broadcasting Company. 8.9.2016. (Accessed 8 September 2016 http://yle.fi/uutiset/ministeriot_varoittavat_maalampojarjestelmiin_asennettu_vaarallista_nestetta_kiinteistonomistaja_toimi_nain/9151767).

Bonte, M., 2013. Impacts of Shallow Geothermal Energy on Groundwater Quality. A Hydrochemical and Geomicrobial Study of the Effects of Ground Source Heat Pumps

and Aquifer Thermal Energy Storage. Doctoral Thesis. Vrije Universiteit, Amsterdam (Accessed 17 March 2015 http://dare.ubvu.vu.nl/handle/1871/49188).
Buday, T., 2014. Reduction of environmental impacts of heat pump usage with special regard on systems with borehole heat exchangers. Landsc. Environ. 8 (2), 66–77.
ChemicalAct, 2013. Kemikaalilaki 2013/599 (In Finnish), Finnish Statute Collection. (Accessed 16 June 2017 http://www.finlex.fi/fi/laki/ajantasa/2013/20130599?search%5Btype%5D=pika&search%5Bpika%5D=Kemikaalilaki#L4P19).
Dehkordi, S.E., Schincariol, R.A., 2014. Guidelines and the design approach for vertical geothermal heat pump systems: current status and perspective. Can. Geotech. J. 51, 647–662.
EHPA, 2017. EUCERT. European Heat Pump Association(Accessed 24 February 2017 http://www.ehpa.org/european-certified-hp-installer/).
ELY, 2014. Tietoa Maaperän tilan tietojärjestelmästä ja maaperän kunnostuksesta. Finnish, Information on the 'Datasystem on the condition of soil', and on soil restoration. Elinkeino-, liikenne- ja ympäristökeskus(Accessed 3 March 2017, http://www.ymparisto.fi/download/noname/%7B40CE320C-7A05-4C13-A49A-223AE1321C2A%7D/103228).
FMI, 2016a. Vuositilastot Suomen keskilämpötila 1981–2010. Finnish, Yearly Statistics. Average temperature in Finland 1981–2010. The Finnish Meteorological Institute (Accessed 27 October 2016 http://ilmatieteenlaitos.fi/vuositilastot).
FMI, 2016b. Kovat pakkaset ja talven kylmimmät lämpötilat. Finnish, The Coldest Winter Temperatures. The Finnish Meteorological Institute(Accessed 27 October 2016 http://ilmatieteenlaitos.fi/kovat-pakkaset-ja-kylmimmat-talvet).
Fleuchaus, P., Blum, P., 2017. Damage event analysis of vertical ground source heat pump systems in Germany. Geother. Energy 5 (10).
Florides, G., Kalogirou, S., 2007. Ground heat − a review of systems, models and applications. Renew. Energy 32, 2461–2478.
GTK, 2017. Geoenergia. Finnish, Geoenergy. Geological Survey of Finland(Accessed 2 March 2017 http://www.gtk.fi/geologia/luonnonvarat/geoenergia/).
Gehlin, S.E.A., Spitler, J., Hellström, G., 2016. Deep boreholes for ground source heat pump systems − Scandinavian experience and future prospects. In: ASHRAE Winter Meeting. Orlando, Florida, Jan 23–27, 2016.
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.
Haehnlein, S., Bayer, P., Blum, P., 2010. International legal status of the use of shallow geothermal energy. Renew. Sustain. Energy Rev. 14, 2611–2625.
Heinonen, E.W., Wildin, M.W., Beall, A.N., Tapscott, R.E., 1997. Assessment of antifreeze solutions for ground-source heat pump systems. ASHRAE Trans. 103, 747–756.
Heinonen, E.W., Wildin, M.W., Beall, A.N., Tapscott, R.E., 1998. Anti-freeze fluid environmental and health evaluation – an update. Proceedings of the Second Stockton International Geothermal Conference 16–17 March 1998.
Ignatowicz, M., Melinder, Å., Palm, B., 2017. Properties of different ethyl alcohol based secondary fluids used for GSHP in Europe and USA. In: IGSHPA Technical/Research Conference and Expo. Denver, March 14–16, 2017.
Ilieva, D., Haderlein, S.B., Morasch, B., 2014. Grundwassergefährdungspotenzial von Additiven in Wärmeträgerflüssigkeiten aus Erdwärmesonden. German, Groundwater Pollution Potential of Additives Used in Borehole Heat Exchanger Fluids. Grundwasser 19, pp. 263–274.
Jarva, J., 2016. Geochemical Baselines in the Assessment of Soil Contamination in Finland. Academic Dissertation. Department of Geography and Geology, University of Turku, Finland.
Juvonen, J., Lapinlampi, T., 2013. Energiakaivo – Maalämmön hyödyntäminen pientaloissa. Finnish, Energy Well -Ground-Source Heat in One-family Houses. Ministry of the Environment, Environment Guide 2013, Helsinki, Finland(Accessed 8 September 2016 https://helda.helsinki.fi/bitstream/handle/10138/40953/YO_2013.pdf?sequence=4).
Karro, E., Lahermo, P., 1999. Occurrence and chemical characteristics of groundwater in Precambrian bedrock in Finland. Geological Survey of Finland, Special Paper 27. pp. 85–96.
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.
Korsman, K., Koistinen, T., 1998. Suomen kallioperän yleispiirteet. Finnish, General features of Finland's bedrock. Chapter 3. In: Lehtinen, M., Nurmi, P., Rämö, T. (Eds.), Suomen kallioperä -3000 vuosimiljoonaa. The Geological Society of Finland, Jyväskylä, Finland, pp. 93–103(Accessed 31 January 2017 http://www.geologinenseura.fi/suomenkalliopera/CH3.pdf).
Kukkonen, I.T., Peltoniemi, S., 1998. Relationships between thermal and other petrophysical properties of rocks in Finland. Phys. Chem. Earth 23 (3), 341–349.
Kukkonen, I.T., 2000. Geothermal energy in Finland. In: Proceedings World Geothermal Congress 2000. Kyushu-Tohoku, Japan, May 28-June 10.
Lacombe, S., Sudicky, E.A., Frape, S.K., Unger, A.J.A., 1995. Influence of leaky boreholes on cross-formational groundwater flow and contaminant transport. Water Resour. Res. 31 (8), 1871–1882.
Lankia, O., Kleiman, H., 2009. Maalämpökaivo voi olla riski pohjaveden ja talousvesikaivojen veden laadulle. Finnish, A ground source energy well may be a risk for water quality of groundwater and domestic water wells. Ympäristö ja Terveys 40 (7), 66–67.
Majuri, P., 2016. Ground source heat pumps and environmental policy − the Finnish practitioner's point of view. J. Clean. Prod. 139, 740–749.
Mattsson, U., 2010. Maalämpökaivojen villi poraaminen voi poikia ongelmia. Finnish, The Wild Drilling of Energy Wells May Create Problems. Turun Sanomat 25 October 2010.
Morofsky, E., Cruickshanks, F., 1997. Underground thermal energy storage. Procedures for Environmental Impact Assessment. Working Report, IEA ECES Program, Annex 8.
Motiva, 2016. Uudisrakentamisen energiatehokkuustaso Suomessa 2013–2015 pientalot. Finnish, The energy efficiency level of new building in Finland 2013–2015, detached houses. Motiva Oy, Report by the Energy Efficient Homes Project. (Accessed 17 February 2017 http://motiva.fi/files/11506/Pientalot_Uudisrakentamisen_energiatehokkuustaso_2013-2015.pdf).
Naturet Safety Protocol, 2017. Accessed 29 May 2017 https://www.altiaindustrial.com/sites/default/files/media/KTT_NATURET%20-maalamponeste%20-17%20oC.pdf.
Nordell, B., Ahlström, A.-K., 2007. Freezing problems in borehole heat exchangers. In: Paksoy, H.Ö. (Ed.), Thermal Energy Storage for Sustainable Energy Consumption. Springer, pp. 193–203.
Nowak, T., Murphy, P., 2012. Outlook 2012-European Heat Pump Statistics. The European Heat Pump Association, Brussels.
Omer, A.M., 2008. Ground-source heat pumps systems and applications. Renew. Sustain. Energy Rev. 12, 344–371.
Plant, J.A., Whittaker, A., Demetriades, A., DeVivo, B., Lexa, J., 2005. The geological and tectonic framework of Europe. In: In: Salminen, R. (Ed.), Geochemical Atlas of Europe. Part 1: Background Information, Methodology and Maps 2005 Geological Survey of Finland, Espoo.
Poratek, 2015. Tutkintotodistus vahvistaa ammattiosaamisen. Finnish, Adiploma Verifies the Professional Competence. Poratek Uutiset December 2015, pp. 28–29(Accessed 24 Feb 2017. http://poratek.fi/wp-content/uploads/2016/01/Poratek-Uutiset-2015_kevyempi.pdf. December 2015).
Poratek, 2016. Normilämpökaivon kriteerit. Finnish, Criteria for the Normheatwell. The Finnish Well Drillers' Association(Accessed 19 Oct 2016 http://poratek.fi/normikaivot-ja-poraukset/normilampokaivo/normilampokaivon-kriteerit/).
Ranta, E., Rita, H., Kouki, J., 2012. Biometria. Gaudeamus Helsinki University Press, Helsinki, Finland.
Rebouças, A., 2004. Well drilling and design methods. In: Kovalevsky, V.S., Kruseman, G.P., Rushton, K.R. (Eds.), Groundwater Studies − An International Guide for Hydrogeological Investigations. IHP-VI, Series on Groundwater No. 3. UNESCO, Paris, pp. 185–215.
Rosén, B., Gabrielsson, A., Hellström, G., Nilsson, G., 2006. System för värme och kyla ur mark -Demonstrationsobjekt över jordvärmeanläggningar. Swedish, Systems for Heating and Cooling from the Ground -Demonstration Objects for Ground Heat Exchangers. Swedish Geotechnical Institute, Varia 556, Linköping, Sweden.
SULPU, 2017. Toimitetut ja laskutetut lämpöpumput Suomessa vuonna 2016. Finnish, Delivered and Invoiced Heat Pumps in Finland in 2016. Finnish Heat Pump Association(Accessed 31 Jan 2017. http://www.sulpu.fi/documents/184029/208772/SULPU%2C%20myydyt%20l%C3%A4mp%C3%B6pumput%202016%2C%20teholuokittain%2C%20f.pdf).
Santi, P.M., McCray, J.E., Martens, J.L., 2006. Investigating cross-contamination of aquifers. Hydrogeol. J. 14 (1-2), 51–68.
Sass, I., Burbaum, U., 2010. Damage to the historic town of Staufen (Germany) caused by geothermal drillings through anhydrite-bearing formations. Acta Carsol. 39 (2), 233–245.
Schmidt, K.R., Körner, B., Sacher, F., Conrad, R., Hollert, H., Tiehm, A., 2016. Biodegradability and ecotoxicity of commercially available geothermal heat transfer fluids. Grundwasser 21, 59–67.
Sippola, A.R., 2011. Maalämpökaivojen porausliete tärvelee puroja. Finnish, The Drilling Slurry from Energy Wells Damages Creeks. Helsingin Sanomat 21 Oct 2011.
Vienken, T., Schelenz, S., Rink, K., Dietrich, P., 2015. Sustainable intensive thermal use of the shallow subsurface — a critical view on the status quo. Groundwater 53 (3), 356–361.