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Review

Assessment and Minimization of Potential Environmental Impacts of Ground Source Heat Pump (GSHP) Systems

Alessandro Casasso * and Rajandrea Sethi

Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy
* Correspondence: alessandro.casasso@polito.it; Tel.: +39-320-4213-886

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Abstract: Ground source heat pumps (GSHPs) gained increasing interest owing to benefits such as low heating and cooling costs, reduction of greenhouse gas emissions, and no pollutant emissions on site. However, GSHPs may have various possible interactions with underground and groundwater, which, despite the extremely rare occurrence of relevant damages, has raised concerns on their sustainability. Possible criticalities for their installation are (hydro)geological features (artesian aquifers, swelling or soluble layers, landslide-prone areas), human activities (mines, quarries, landfills, contaminated sites), and groundwater quality. Thermal alterations due to the operation of GSHPs may have an impact on groundwater chemistry and on the efficiency of neighboring installations. So far, scientific studies excluded appraisable geochemical alterations within typical ranges of GSHPs (±6 K on the initial groundwater temperature); such alterations, however, may occur for aquifer thermal energy storage over 40 °C. Thermal interferences among neighboring installations may be severe in urban areas with a high plant density, thus highlighting the need for their proper management. These issues are presented here and framed from a groundwater quality protection perspective, providing the basis for a discussion on critical aspects to be tackled in the planning, authorization, installation, and operation phase. GSHPs turn out to be safe and sustainable if care is taken in such phases, and the best available techniques are adopted.

Keywords: geothermal energy; water-energy nexus; geochemistry; groundwater; heat pump; water resources protection; web GIS; regulation

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1. Introduction

Global warming trends are fostering the replacement of fossil fuels with low-carbon renewable energy sources (RES), and this also applies to buildings' heating and cooling systems, which account for about 40% of the world's energy total demand [1]. Renewable heat production is growing all over the world and is currently mostly based on wood biomass, with a noticeable impact on air quality, and hence on human health [2,3]. Heat pumps, the other main contributor to renewable heat, are also growing at a fast rate, for example, 14% yearly in Europe between 2005 and 2016 [4].

Heat pumps are grouped into two main categories, air-source and ground-source, with less common types using low-grade waste heat, surface water, and solar heat as heat sources [5]. Ground-source heat pumps (GSHPs) are further divided into two categories: closed-loop systems (Figure 1A–C), exchanging heat with the ground through the circulation of a heat carrier fluid in a closed-loop pipe; and open-loop systems also known as groundwater heat pumps (GWHPs) (Figure 1D), exchanging heat with groundwater that is usually reinjected into the same aquifer after the heat exchange.

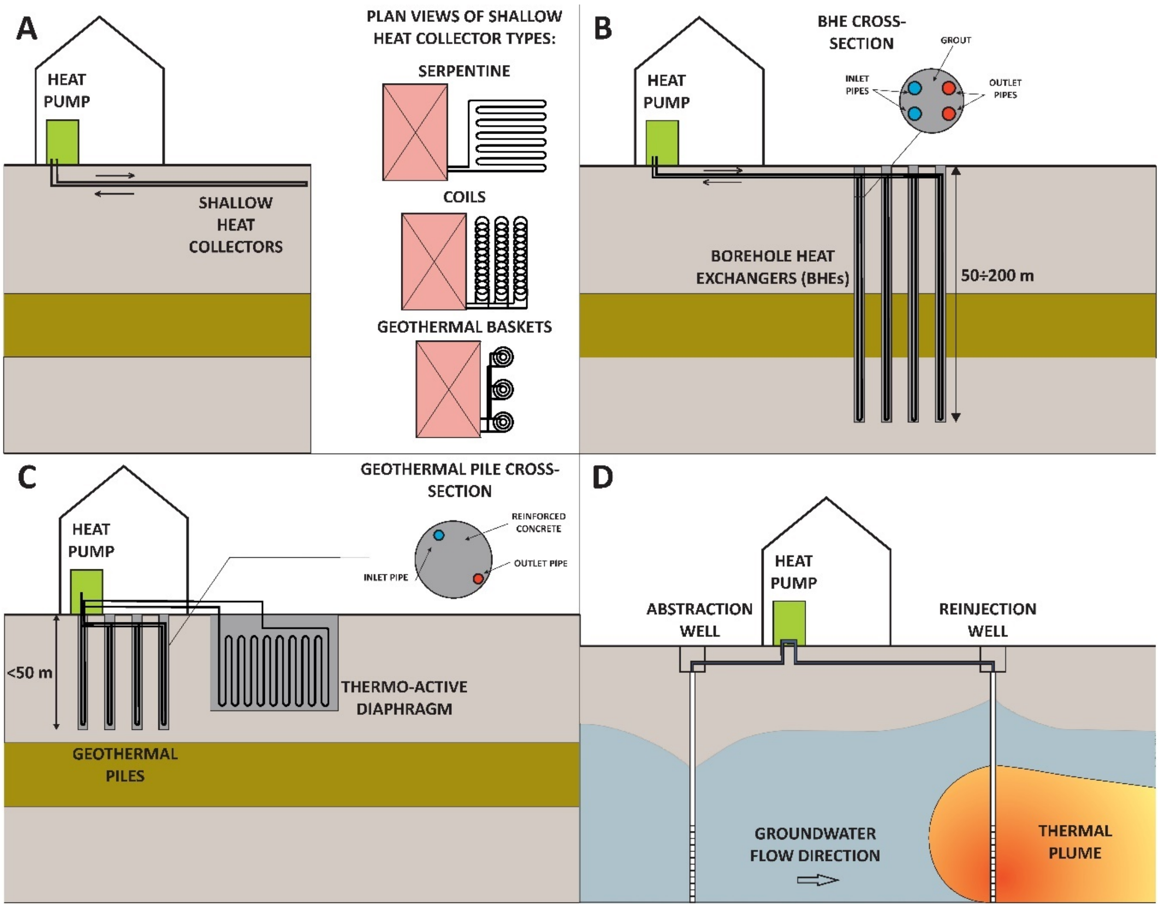

Figure 1. Classification of ground source heat pump (GSHP) systems: closed-loop horizontal heat exchangers (**A**), borehole heat exchangers (BHEs) (**B**), geo-structures (**C**), and open-loop systems (**D**). Modified from the work of [6].

The closed pipe loop for heat exchange could be installed in three different configurations:

- Shallow heat collectors are installed at very small depths (1–3 m), and can be arranged in coils, trenches, or heat exchange units such as geothermal baskets (Figure 1A);
- Borehole heat exchangers (BHEs) are installed in vertical boreholes, generally with a depth of 50 ÷ 200 m and a diameter of 15 ÷ 20 cm (Figure 1B);
- Thermally active geo-structures (Figure 1C) are installed into foundation components of the building, such as foundation piles, diaphragms, platforms, or tunnels.

The increase of heat pump installations is motivated by their economic, environmental, and energetic benefits, which can be summarized as (1) the reduction of heating costs compared with fossil fuels, (2) the reduction of greenhouse gas emissions, and (3) the absence of emissions on site. The magnitude of such benefits depends on the characteristics of heat pump systems, on the context of application, and on country-specific factors. The reduction of heating costs mostly depends on the costs of electricity and of the fuel to be replaced [4,7], as well as on the coefficient of performance (COP) of the heat pump, that is, the ratio between the heat delivered to the building and the electricity consumed. The reduction of greenhouse gas (GHG) emissions with heat pumps depends on the COP and on the GHG emission factor of the electrical grid [8,9]; compared with a gas boiler, such reduction exceeds 90% in Sweden, where most electricity is produced by hydropower and nuclear plants, while heat pumps could even exceed gas boilers' GHG emissions if powered with electricity from coal power plants, as occurring in Poland. With the E.U. average GHG emission factor of the electrical grid (444 g CO_2 equivalent per kWh), heat pumps reduce GHG emissions from 38% (air-source with COP = 3) to

63% (open-loop geothermal, with COP = 5), with closed-loop geothermal systems in between. The absence of any pollutant emissions on site related to the operation of heat pumps is one of their major environmental benefits, not only in comparison with wood biomass, but also considering the noticeable contribution of gas boilers to NOx emissions in urban areas [10].

The air-source type accounts for 80.1% of the existing heat pumps stock, according to the European Heat Pump Association (EHPA, 2018 [4]), while the rest is covered by the ground-source type (16.4%) and waste heat recovery (3.4%) heat pumps. Air-source heat pumps prevail as a result of simpler and cheaper installations compared with GSHPs, which require the setting up of ground heat exchangers or wells. However, ground-source heat pumps have a higher COP compared with air-source ones [5] and, thanks to the indoor installation of the heat pump unit, a significant reduction in noise pollution is achieved, which is one of the most severe issues related to these systems [11,12].

The interest raised by GSHPs is partly counterbalanced by concerns on possible adverse impacts of their installation on the underground and on groundwater resources. Several studies have been conducted so far on specific aspects, especially in Europe, where most GSHPs are installed.

Several drilling impacts related to the installation of BHEs were identified in the works of [13–16], with case studies reported in the works of [17–19]. Among them, the most well-known accident is the one that occurred in Staufen (Germany) [19], where the drilling of BHEs caused a differential ground uplift due to the swelling of an anhydrite layer, resulting in serious damages to historical buildings of the town center. The drilling of BHEs is considered as a possible trigger of cross-contamination between aquifers through the formation of preferential migration pathways in defective grouts. A few studies addressed this issue from a theoretical point of view, including Bonte et al. (2015, [20]), while the theme of the quality and durability of borehole filling materials has been addressed by several studies, including those reported in the works of [21–24].

BHEs use water solutions containing anti-freeze compounds as a heat carrier fluid, and this has led to concerns on possible release of such compounds into groundwater in the unlikely event of pipe leaks, which are addressed in the works of [24–26].

Another major concern is the possible (physio-)chemical alterations of groundwater due to temperature changes induced by the operation of GSHPs, in particular the temperature increases due to underground thermal energy storage [27]. Several studies were conducted in the Netherlands [28–31] and in Germany [32–35], where European trials of underground thermal energy storage are concentrated. The studies dealt with laboratory samples because of the complexity of controlling (physio-)chemical parameters of groundwater in the field. The results of these studies highlight how numerous are the factors influencing possible impacts on groundwater chemistry of thermal alterations, but temperature is not the only groundwater parameter that may be altered by GSHPs. Increase of dissolved oxygen may also occur [36,37]. Other studies, such as that reported by Garcìa-Gil et al. (2016, [38]), addressed geochemical alterations at a city scale.

Groundwater (physio-)chemical conditions could be critical for the operation of open-loop systems in the presence of high values of water hardness [39,40] and other critical geochemical parameters that may induce corrosion or scaling of pipes [41].

Besides geochemical impacts, the propagation of subsurface thermal alterations (thermal plumes) is the most important aspect for the management of geothermal systems, especially in densely inhabited areas. An approach called "relaxation factor" was recently proposed [42], which is based on the calculation of the margin for further thermal alteration to be induced by future installations. As the propagation of thermal plumes is a key aspect of the design and management of GSHPs, it has been addressed by several articles on case studies, including the works of [43–46], and a few theoretical studies, including the works of [47,48].

The possible conflicts and impacts of GSHPs led to the issuing of legislation schemes with prescriptions such as operating temperature thresholds and minimum distances [49–53].

The above-mentioned studies provide several points on possible impacts and resource conflicts on the installation and operation of GSHPs. Yet, a comprehensive analysis of potential impacts and resource conflicts of GSHPs is still missing and is the purpose of this paper. The article is structured as follows. Section 2 analyses critical conditions for the installation of GSHPs, due to specific geological and hydrogeological conditions, and possible impacts on groundwater physical, physiochemical, and chemical parameters. Section 3 shows how scientific findings and good practices could be implemented in the different phases (planning, authorization, installation, and operation) of GSHP systems implementation, in order to ensure groundwater protection. Conclusions are finally reported in Section 4.

2. Analysis of Potential Interferences of GSHPs with Subsurface and Groundwater

Ground source heat pumps exploit a virtually ubiquitous renewable energy source characterized by few possible interferences and impacts. Some of these potential impacts, however, have raised concerns about GSHP system sustainability [54]. These concerns have led some European jurisdictions to issue restrictive regulations, including the definition of areas in which the installation of GSHP systems is forbidden or subject to onerous requirements [49–51].

In this section, possible interferences and impacts of GSHP installations are described, reporting evidence and good practices from the literature and case studies. Section 2.1 analyses potentially critical (hydro)geological conditions that can interfere with the installation and/or operation of a GSHP installation, such as sensitive ground layers, land uses, and groundwater chemistry. Section 2.2 analyses two specific concerns related to BHEs, that is, possible spills of heat carrier fluid into the ground and the possible formation of contaminant preferential migration pathways owing to defective grout filling. Section 2.3 explains how the operation of a GSHP, which produces a local temperature alteration of the subsurface (thermal plume), can impact the operation of other GSHPs. Section 2.4 explains how temperature changes can affect physiochemical and chemical characteristics of groundwater.

2.1. Potential Interferences with Specific (Hydro)geological Conditions

Regulations on GSHPs provide several restrictions on their installation, motivated by concerns that usually deal with groundwater protection. On the basis of previous works [15,16,55], the following risks are hereby addressed: (1) artesian aquifers, (2) soluble or swelling underground layers, (3) landslide-prone areas, (4) mining and quarry areas, (5) shallow gas layers, (6) landfills and contaminated sites, (7) groundwater chemistry unsuitable for open-loop systems, (8) groundwater resources protection areas, and (9) coastal aquifers.

GWHPs generally draw on shallow unconfined aquifers, but artesian aquifers may complicate the installation of BHEs. When reaching the top of an artesian or confined aquifer, the rising of water levels may impair or even impede drilling and grouting operations, as recently reported in some cases in Switzerland and France [18]. Stober and Bucher (2013 [55], pp. 87–93) explain how an artesian aquifer could be drilled, using denser grout and a packer to contrast its pressure.

Another risk connected with the interception of aquifers lies in the potential for water to come into contact with swelling or soluble layers, which were previously hydraulically isolated from them. A well-known swelling phenomenon is the transformation of anhydrite into gypsum, with an increase of volume that can be as high as 61% [19]. This occurred in Staufen im Breisgau (SW Germany) and resulted in a differential ground uplift, which damaged several historical buildings in the town center [19] and in a few other sites in Land Baden-Württemberg, Germany [17], and in Alsace, France [18]. Although it may be possible to avoid the contact of swelling layers with groundwater ([55], pp. 90–91), swelling layers represent a major risk for the drilling of wells and BHEs.

A few episodes of local-scale subsidence due to salt layer dissolution are reported in literature [17,18] and, like the previously cited ground swelling episodes, they are thanks to the groundwater infiltration triggered by the installation of BHEs.

The accidents described above have a very low frequency as areas where these sensitive layers could be found at typical BHE depths are rather limited; with more than 350,000 GSHPs installed since 1990 in Germany, the number of reported cases of serious damages (i.e., higher than 500 k€) is as low as nine according to Fleuchaus and Blum (2017, [17]). The authors also highlight that the probability of serious damages is much lower than that of other commonly used energy sources. The damage events are concentrated in a a few small areas, thus confirming the need for the thorough mapping layers that could be sensitive to BHE and water well drilling.

The excavation of wells and installation of BHEs is unlikely to trigger landslides. BHEs, however, can be damaged even by small ground movements. For this reason, the installation of BHEs in landslide-threatened areas is subjected to ex-ante authorization or banned [13,14].

Underground mines could potentially interfere with the installation of borehole heat exchangers, but BHEs are unlikely to be installed in such sites. On the other hand, active or former underground mines are exploited in several cases for heating purposes through the extraction of warm water from the mine dewatering systems [56]. A more concrete possibility of interference among extraction activities and GSHPs is represented by sand and gravel pits, which can transform parts of shallow aquifers into lakes, thus locally altering groundwater flows and temperatures [57].

Relatively shallow gas layers (methane and other hydrocarbons, hydrogen sulphide, and so on) can be intercepted by wells or BHEs drillings, as documented in the works of [18,58], with the potential risks of explosion, suffocation, or poisoning. As for artesian aquifers, packers could also be used to avoid gas leakage [55].

The installation of GSHPs is generally forbidden in landfills and contaminated sites because of the potential risk of triggering the dispersion of pollutants into groundwater. However, GSHPs can positively interact with landfills and remediation activities, for example, with Pump & Treat [59] or former mine dewatering systems [60], exploiting the heat generated by the degradation of waste in municipal solid waste landfills [61], or fostering the natural attenuation of contaminants [28,32,33].

Groundwater chemistry is a key aspect in evaluating the feasibility of GWHPs as high hardness, strong mineralization, or other characteristics can lead to clogging or corrosion of the heat exchangers between the primary (groundwater) and the secondary (heat pump refrigerant) circuits. Rafferty [39,40] suggests that the direct heat exchange between water and refrigerant in the heat pump's evaporator or condenser could be performed only in the presence of a lowly mineralized water with hardness below 12°F. However, higher water hardness values are very common in groundwater, hence, an intermediate heat exchanger is strongly advisable to ease periodic maintenance and, if necessary, replacement [62]. Recently, the French geological survey (BRGM) developed a comprehensive set of suitability criteria based on chemical and physiochemical parameters (dissolved CO_2, salinity, electrical conductivity, pH, chlorides, and so on), which affect corrosion, clogging, and encrustation [41].

BHE installation poses risks of anti-freeze release in the case of pipes leakage, and of triggering contaminants propagation between different aquifers in the case of borehole filling voids or cracks. These two issues are addressed in Section 2.2 and are listed among the motivations for BHE drilling bans or limitations in well-head protection areas, deep aquifer recharge areas, and other kinds of water protection zones. As well-head protection areas are often not identified, numerous regulations impose minimum distances from wells [49,51].

Coastal shallow aquifers are problematic for GWHPs installations because of corrosion or incrustation of heat exchangers risks; however, heat exchangers specifically developed for saline water could be used. Also, if wells are properly arranged, GWHPs can help to reduce saltwater intrusion [63].

2.2. Specific Issues Related to BHEs

Although BHEs do not use groundwater for heat exchange, they could pollute aquifers through two mechanisms: the possible release of anti-freeze additives from leaking pipes and the possible leakage of contaminants from an aquifer to another through defective borehole filling.

The heat carrier fluid circulating in closed-loop geothermal systems is generally composed of water and anti-freeze additives to allow the system to operate below 0 °C in heating mode. Concerns on groundwater quality are based on the experience gained with road de-icing with propylene glycol and other substances [64], which, however, imply the use of much larger quantities compared with the case of closed-loop ground heat exchangers. The hypothetical release of heat carrier fluids poses a much smaller threat compared with its use in road de-icing, nevertheless some local regulations have banned anti-freeze additives for BHEs, thus limiting the diffusion of BHEs in cold areas where anti-freeze measures are necessary [51]. To our knowledge, only one case of leakage from BHE pipes is reported in literature, and it resulted in the contamination of wells within 200 m of distance ([18], p. 64).

The comparative analysis of anti-freeze additives concluded that propylene glycol is the most environmentally sustainable anti-freeze additive owing to its low toxicity [25,65]. Yet, besides direct effects on human health, possible alterations on groundwater chemical and physiochemical parameters need to be considered. Klotzbücher et al. (2007, [26]) discovered that pure propylene and ethylene glycol are rapidly biodegraded under both oxic and anoxic conditions without inducing formation of toxic intermediates, but the addition of corrosion inhibitors may hamper such degradation. Bucci et al. (2018, [24]) observed an increase of Fe, Mn, and Ni concentrations carrying out in vitro tests on aquifer samples in contact with pure propylene glycol; yet, the dilution occurring downstream the release point is likely to greatly reduce this impact.

From a hydraulic point of view, BHEs could be modelled as a concrete column installed vertically in the subsurface, with a different hydraulic conductivity (K_{fill}) compared with the surrounding ground. If the grout is more permeable than a certain layer crossed, or pipes do not adhere well to the grout, the borehole could become a preferential conduit for the migration of contaminants. Such conditions are depicted in Figure 2, showing a BHE crossing both a shallow (contaminated) and a deep (clean) aquifer, these two separated by an aquitard or aquiclude with a hydraulic conductivity K_A; if not properly sealed (i.e., if $K_{fill} \gg K_A$), the BHE may trigger the propagation of contaminants from the shallow to the deep aquifer. Cross-contamination may also from a contaminated deep aquifer (e.g., with a high salinity) with a higher hydraulic head compared with the shallow aquifer.

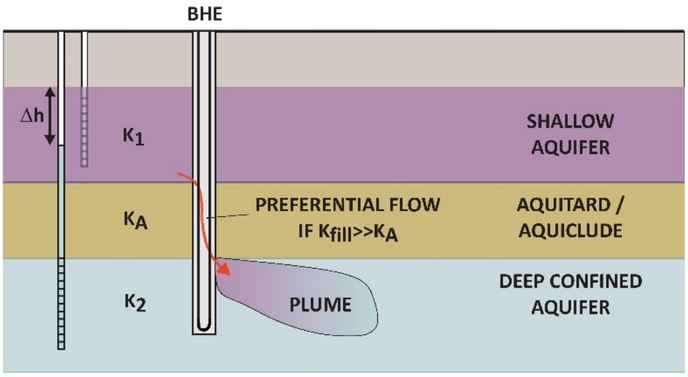

Figure 2. Possible contamination due to anti-freeze leakage from a BHE.

So far, a few studies have been performed to quantitatively assess this phenomenon, focusing on the flow rate that could cross a badly grouted BHE [20,24]. As expected, such a flow rate is proportional to the hydraulic conductivity of the borehole filling.

Laboratory measurements substantially confirm the sealing quality of the grout adopted for BHE filling (geothermal grout). These materials have been developed since the 1990s, combining cement, bentonite, silica sand, and other additives (graphite flakes etc.) to find a trade-off between low hydraulic conductivity, high thermal conductivity, and good mechanical resistance [66]. Tests on cement-sand grout samples conducted by Allan and Philippacopoulos (1998, [21]) reported hydraulic conductivities in the order of 10^{-12} m/s, while higher values in the order of 10^{-10} m/s were measured for grout-pipe specimens where the interface between the pipe and the grout is a weak point for the hydraulic sealing [22,23]. Geothermal grouts are thus less permeable than most of clayey and silty aquicludes, as shown in Figure 3, but increases in hydraulic conductivity are possible in the case of grouts injected with a very high water/cement ratio subjected to extreme thermal (freeze-thaw) or hydraulic (wet-dry) alternated stresses [21,23].

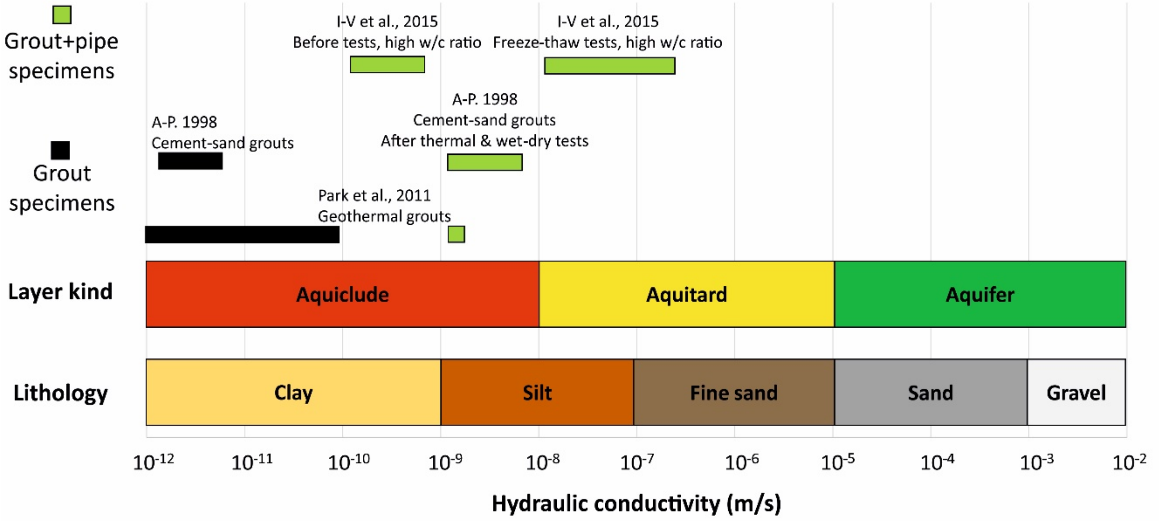

Figure 3. Comparison between hydraulic conductivities of geothermal grouts from laboratory tests (refer to the works of [21–23] for details of the references cited on the figure) and of typical aquifer, aquitard and aquiclude lithologies (see the works of [67]).

The results of these studies highlight that geothermal grouts available in the market can ensure suitable protection against aquifer cross-contaminations, but they need to be injected properly, in particular by avoiding the use of excess water for the sake of workability since this would impair the hydraulic sealing properties of the injected mixture.

2.3. *Underground Temperature Alterations*

GSHPs generally operate without a net groundwater withdrawal, except for the cases of GWHP systems accessing a very shallow water table, where reinjection is not advised and thus groundwater is disposed in surface water bodies after the heat exchange. The limited resource to be managed is the temperature of the ground (for closed-loop systems) or of groundwater (for open-loop systems), the alteration of which limits the possibility for further thermal uses in the surroundings. As the thermal anomaly (also known as "thermal plume") propagates, its intensity is reduced, and the geothermal resource is recharged through the heat exchange with the atmosphere and the underlying layers.

The design of GSHPs must ensure sustainable operating temperatures for both the projected installation ("internal" sustainability) and the neighboring ones ("external" sustainability). The internal sustainability is achieved with a correct plant sizing, with different methods for closed-loop and open-loop systems. The number and length of BHEs are sized to distribute the thermal load along the borehole depth and avoid the excessive thermal alteration of the ground; sizing methods are tables and nomograms [68,69], semi-analytical methods such as the ASHRAE [70] and the g-functions [71], and numerical modelling software such as FEFLOW [72] and MODFLOW with MT3D or SEAWAT [73]. BHEs are sized to cope with fluid temperature constraints, which could be prescribed by regulations [49], by the heat pump manufacturer, or by the designer. The design of open-loop geothermal systems should consider three main constraints: the drawdown in abstraction well(s), the level rise in injection well(s), and thermal recycling [74]. Thermal recycling is the return of part of the reinjected water to the abstraction well, resulting in a progressive alteration of the abstracted water's temperature. The occurrence and the strength of this phenomenon depends on well distance and depth, hydraulic conductivity, and gradient of the aquifer [75] and, in particular, wells should be placed far enough to avoid or limit this phenomenon. Quantitative assessment of thermal recycling can be performed with analytical formulae [76], with numerical modelling and, more recently, with the free code Thermal Recycling Simulator [77].

The thermal impact on other installations is assessed in the authorization procedures to preserve existing rights on thermal use of groundwater ("external" sustainability), generally determining the size of the thermal plume with numerical software, among which FEFLOW [72], MODFLOW with MT3D [78], and Groundwater Energy Designer [79] are the most used.

Recent studies [47,48] identified flow velocity as the most influential subsurface parameter for thermal plume dimensions; to a lesser extent, thermal conductivity and thickness of the vadose zone can also influence the propagation of thermal plumes. The modelling of thermal plumes from GWHPs is a complex 3D phenomenon, involving also the layers underlying and overlying the aquifer. Two-dimensional (2D) models, which neglect such thermal exchanges, lead to an overestimation of the thermal plume size and are thus to be considered as conservative models [47].

Several studies have addressed the numerical modelling of potential interference between adjacent GWHP systems in urban areas [43–46], but numerical studies with general validity are still lacking. Verda et al. (2012, [80]) addressed this issue in a planning study on the possible integration of district heating and GWHPs, focusing on the COP reduction induced by the interference of other installations. More recently, Attard et al. (2019, [81]) developed two mathematical methods, one for closed-loop and one for open-loop GSHP systems, for assessing the thermal impact of neighboring installations.

The most constraining limitation on further uses of GSHPs lies in groundwater temperature variations, especially regarding minimum temperatures with the risk of groundwater freezing. García-Gil et al. (2015, [42]) developed a new indicator called "relaxation factor", which imposes a margin on groundwater temperature alteration, which should be left for future installations, thus providing an alternative to the present approach of "first come, first served".

Finally, the operation of GSHPs in urban areas could also be influenced by the subsurface urban heat island, that is, the presence of higher temperature in the city center compared with the outskirt areas owing to both higher air temperature (i.e., the above-surface urban heat island) and heat inputs in the ground other than GSHPs (heat from building basements, sewers, district heating networks, etc.), which can be in the order of 1 W/m^2 [82,83]. The urban heat island reduces the available margin for the operation of cooling-dominated GSHPs, but it increases the possibility of exploiting the subsurface for heating purposes [84].

2.4. Underground Chemical and Microbiological Alterations

Thermal plumes may not only affect the operation of neighboring plants, but also groundwater quality. Several parameters related to microbiological activity, dissolved gas, metal solubility, and contaminant degradation are correlated to groundwater temperature and have complex interrelations among each other. Not all these alterations are harmful and most of them are not appraisable at GSHPs' typical operating temperature ranges, but research in this field is still in progress.

To our knowledge, most GWHPs in Europe are installed in aquifers with undisturbed temperatures between 8 °C and 14 °C, at which psychrophilic and psychrotolerant prokaryotes prevail [35]. As the temperature shifts for GWHPs remain within the limits of a ±6 K alteration recommended by the German norm VDI 4640 [69], no relevant change of microbial communities is thus expected. Mesophilic bacteria start appearing at 20 °C, and thermophilic bacteria appear at temperatures above 40 °C, which are typical of Aquifer Thermal Energy Storage (ATES) systems [27], where solar heat is injected during summer for its use during winter.

On the basis of their laboratory and field studies, Brielmann et al. [34,35] found that no significant changes in groundwater bacterial activity and biodiversity within the ±6 K boundaries to the thermal alteration compared with background temperature, although Griebler et al. (2016, [32]) point out that this may occur in abundance of dissolved organic carbon and other nutrients.

Regarding concerns on pathogenic bacteria in groundwater, Jesußek et al. (2013, [33]) stated that they could proliferate around 40 °C. Yet, García-Gil et al. (2018, [85]) observed a reduction in waterborne pathogen bacteria in an area intensively exploited for cooling with GWHPs, where groundwater temperatures exceeded 30 °C, attributing this change to "thermal shocks" induced by the heat exchange.

Besides microbial activity, groundwater chemical and physio-chemical parameters are the main concerns when dealing with GSHPs. Water temperatures over 40 °C may promote the dissolution of organic carbon [29,30,32,33], but these values are common only in ATES systems, but not with the usual GSHP setups. Jesußek et al. (2013, [33]) analyzed geochemical alterations in lignite sand samples between 10 °C and 70 °C, finding that a temperature increase may promote the release of metals such as iron (III) from the solid matrix that, besides possible impacts on water quality, may cause the clogging of reinjection wells. On the other hand, the available literature agrees on the positive effect of temperature increase on the natural attenuation of different kinds of contaminants such as chlorinated solvents [28,32,33].

A concern raised by various studies lies in the possible reduction of dissolved oxygen (DO) at increased temperatures, which may switch the aquifer conditions from oxic to anoxic. However, DO may also increase if groundwater is put into contact with the atmosphere between abstraction and injection. While this could have a possible positive effect on the degradation of contaminants, it can also trigger the clogging of reinjection wells [36] and the dissolution of gypsum and halite bedrocks [37]. For this reason, the loop from extraction to reinjection should be kept close and tight, avoiding free-fall reinjection in favor of a submerged pipe.

Regarding the impact of temperature variations on metals concentrations, Bonte et al. (2013, [31]) observed increased arsenic mobility when heating from 11 °C to 25 °C in laboratory column measurements, while cooling to 5 °C does not impact As concentrations. By contrast, in a city-scale groundwater monitoring program in Zaragoza, García-Gil et al. (2016, [38]) observed no variation of harmful elements concentrations (As, Ni, Cd, B) directly attributed to groundwater heating by GWHPs. Yet, they also observed that alterations in physiochemical parameters (pH, oxidation reduction potential, DO, EC) could trigger the mobilization of such elements, thus confirming the importance of avoiding any contact between groundwater and air from the abstraction to the reinjection, as this is the most likely altering factor on non-thermal parameters.

3. Discussion: How to Ensure Groundwater Protection with GSHPs at Different Implementation Stages

The studies described in the previous sections highlight possible environmental impacts of the installation and operation of GSHPs, which could be prevented by applying appropriate procedures at different stages, which are hereby discussed: planning (Section 3.1), authorization (Section 3.2), installation (Section 3.3), and operation (Section 3.4). A summary of the literature review of Section 2 and of the suggestions presented in this Section is reported in Table A1 (Appendix A).

3.1. Planning

As highlighted in Section 2.1, a few negative interferences may potentially arise when installing BHEs or water wells, and hence open data on potentially critical (hydro)geological features are key to reduce the occurrence of such issues.

The state-of-the-art approach is represented by dynamic maps loaded on Web Geographic Information System (GIS), adopted in some of the most mature market countries, such as Germany, Switzerland, and France [15]. In these cases, drilling risks are mapped by public authorities, thus reducing time-consuming research for geologic data on the installation site and avoiding unsuccessful attempts to get authorizations for installations in unsuitable areas. Two main approaches have been followed so far: the provision of georeferenced data on drilling risks and the statutory zones, that is, the identification of areas where drilling BHEs or wells is allowed, forbidden, or allowed with certain prescriptions. The former one has been followed, for example, by local environmental agencies of Land Bayern [86] and Baden-Württemberg [87] in Germany, which show which areas have drilling risks described in Section 2.1 up to 100 m from ground surface, as this is a typical depth for most BHEs. More recently, the GRETA project delivered a similar web GIS for the Alpine area [88]. The statutory zone approach was adopted in France [89], where the national geological survey BRGM has divided the national territory into small pixels of 500 × 500 m, where the installation of GSHPs below certain thresholds (500 kW of power; 200 m of depth; and, for open-loop systems, 80 m^3/h of flow rate) is subject to different authorization regimes:

- allowed with no ex-ante authorization (green areas);
- allowed, requiring an expert consultancy (orange areas);
- subject to a thorough impact assessment studies as the installations exceeding the above-mentioned thresholds (red areas).

A combination of both approaches could represent the optimal decision support tool. A few critical geological conditions could be considered by legislation as no-go areas for GSHPs, for example, the inner well-head protection areas [49,51]. In this case, spatial information on these areas would avoid unfruitful applications for GSHP authorization. Conditions such as swelling clay or anhydrite layers, soluble halite layers, and artesian aquifers could theoretically be addressed by expert and skilled installers [55], but the risks might not be worth the attempt. On the other hand, providing a "traffic light" for GSHP installations could result in a dangerous excess of confidence in the case no drilling risk is highlighted. A web GIS, even when based on a thorough assessment on large geological datasets, could never provide the same certainty as the case-by-case expert judgement, but it is a support to such judgement.

Data available on subsurface are constantly growing as new wells and BHEs are drilled, new infrastructures are built, contaminated sites are remediated, and so on. Making these data publicly available would, inter alia, complement web GIS as a decision support tool for the installation of BHEs or geothermal wells. Several legislations prescribe the provision of all drilling reports, highlighting the stratigraphy identified. For example, Italian legislation prescribes all drilling reports exceeding 30 m of depth to be communicated to the national geological survey ISPRA [90], and a few regional environmental protection agencies release such reports (or simplified versions of them) as open data [91,92].

3.2. Authorization

In the authorization procedure, a trade-off should be inevitably found between the need to guarantee groundwater protection with a thorough assessment of proposed installations and the risk of discouraging the usage of a climate-friendly technology with long authorization procedures, as often complained by practitioners in this field [93].

Public authorities must focus both on minimizing the impacts on other installations and on the subsurface environment. To achieve these objectives, different approaches are adopted for open- and closed-loop systems. Open-loop systems are subjected to an ex-ante authorization by local water authorities, and applicants should provide an evaluation of the expected impacts on groundwater levels and temperatures. On the other hand, closed-loop systems are often not subjected to an approval procedure but, sometimes, to an ex-post communication to a local authority; this is the case, for example, in Region Lombardia (Italy) [94] and in France [95]. Several reviews on regulations have been published recently, among which are those reported in the works of [49–53], comparing prescriptions that mainly deal with operating temperatures and distances among installations and from drinking water wells.

On the basis of the experiences analyzed, the ex-ante authorization procedure of open-loop systems seems unavoidable as water wells are subjected to water use regulations, even with an exclusively geothermal use, which is generally non-consumptive (i.e., water is reinjected after the heat exchange). An exception could be represented by thresholds of flow rate and/or thermal power, below which no authorization is required. This approach has been adopted by Piemonte (Italy) for wells below a flow rate of 2 L/s [96] and, in France, for GSHPs (both closed- and open-loop) below 500 kW of power (i.e., 20 L/s with a temperature difference of ±6 K) and <200 m of depth [95]. In the French case, however, the statutory zones ([89] and Section 3.1) identify the different authorization regimes of such plants, that is, the level of detail of surveys and assessments to be presented to authorities. Besides planning purposes, web GIS on drilling risks, therefore, also serve as a complement to legislation and local regulation and, in the cases in which a drilling permit is required, they can accelerate the decision process.

The authorization of new geothermal installations also aims at avoiding the overexploitation of the resource, sometimes even prescribing design documents and minimum requirements on plant sizing to prove the sustainability of the plant [51]. Still, the main concern is the management of thermally altered areas (thermal plumes), and the proponents of installations are generally asked to provide an estimation of the thermal impact of the plant alone or, sometimes, on neighboring installations too. The usefulness of this important step could be hampered by the lack of datasets and modelling approaches shared among proponents and authorities. The "relaxation factor" approach proposed by García-Gil et al. (2015, [42]) also requires the city-scale modelling of the operation of GSHPs for an overall assessment and mapping of all cumulated impacts. While this operation could be useful in large cities, it is not worth the effort and the expense in most cases. For this reason, general-value research studies such as the one recently proposed by Attard et al. (2019, [81]) are needed on the reciprocal impacts of neighboring GSHPs to provide guidance on the authorization of their installation and on their operation.

3.3. Installation

The installation phase is a critical step for mitigating possible impacts on groundwater resources, both for open-loop GWHPs and closed-loop systems (especially BHEs). While the drilling of water wells is thoroughly regulated in many jurisdictions by legislations and standards to protect groundwater resources, the debate is still open on possible impacts of BHEs on groundwater quality and whether it is possible to avoid them. The main groundwater protection issue that relates to the installation phase is the possibility that BHEs could create preferential pathways for contaminants due to bad grouting. Research presented in Section 2.2 highlights that specific geothermal grouts, if properly mixed, guarantee a good hydraulic sealing of boreholes. Drillers must, therefore, comply with the recommended water/cement ratios provided by grout producers, avoiding the use of excess water for the sake of workability. Grout discontinuities are the other concern regarding BHE filling, and they could be prevented by filling the borehole with high-density grout (1300–1900 kg/m^3 according to the authors of [55]) at a high pressure starting from the borehole bottom with the Tremie pipe method [55,97]. In addition, various grouting monitoring techniques have been introduced in recent years in Germany, which allow to identify discontinuities and inhomogeneities in the borehole filling during the grout injection and to solve the issue before the concrete solidifies [98].

Grouting, pipe installation, and testing are delicate operations that are typical of BHE installations. For this reason, qualification schemes have been implemented in recent years. In a few countries such as France [95], the qualification is compulsory, while in other countries, voluntary programs are available, issued by associations such as the European GEOTRAINET [99] and the American IGSHPA [100].

3.4. Operation

Once the installation is authorized and completed, the main potential impact on groundwater resources lies in the alteration of its chemical and physicochemical parameters due to thermal alteration and, in the case of GWHPs, to the contact between extracted groundwater and the atmosphere. Research in this field is quite new and, as shown in Section 2.4, a consensus on the effect of thermal alterations on groundwater quality has not been reached yet. To date, appraisable impacts have been observed only in laboratory experiments at high temperatures, typical of ATES [31,34], while most authors agree that smaller changes, typical of GWHPs, do not significantly alter groundwater quality [34,35,38]. On the other hand, contact of groundwater with the atmosphere may result in significant alterations in physiochemical parameters such as pH, ORP, DO, and EC, with possible resulting clogging of the injection well, changes in the mobility and solubility of harmful elements, and dissolution of evaporitic bedrocks [36,37].

Most of the analyzed studies were performed on laboratory samples, while a few addressed real-scale installations or urban areas, for which further research is strongly needed. In this view, the current approach of monitoring activities performed by plant owners should be overcome. Despite the prescriptions given by public authorities during the authorization procedure, monitoring of single installations provide patchy and fragmented data, which are often not useful to assess and manage site-specific geochemical impacts of GSHPs. In addition, these monitoring activities represent a high cost for plant owners and achieve limited spatial scales of survey as owners can hardly install and manage monitoring wells outside their properties. A more cost-effective approach could be that of reducing monitoring activities of single installations only to the recording of flow rate and operating temperatures (abstraction and injection), which is quite inexpensive, leaving monitoring well installation and groundwater chemical analyses to be performed on a city-scale monitoring network managed by public authorities (e.g., environmental or water protection agencies) and funded by water permit fees. This would reduce costs especially for small open-loop installations, for which periodic chemical analyses and the maintenance of monitoring wells represent a non-negligible cost. Part of the monitoring network could rely on existing monitoring wells; however, as highlighted by the authors of [16], different purposes of groundwater monitoring networks should also be considered, as these imply different characteristics of wells, devices installed, depths covered, and so on.

4. Conclusions

Ground-source heat pumps are gaining increasing interest owing to their economic, environmental, and energetic benefits, but concerns have been raised on their compatibility with groundwater resources. In this paper, we analyzed existing literature and good practices on overall management and possible side adverse impacts of the installation and operation of GSHPs, providing suggestions to address such issues.

Critical (hydro)geological conditions for GSHP installations have been identified among swelling anhydrites or soluble halite layers, landslide-prone areas, artesian aquifers, and shallow gas layers. A few others may induce side-adverse effects, which should be evaluated case by case, such as mining and quarrying areas, landfills, contaminated sites, and coastal aquifers. However, the number of cases in which the installation of GSHPs in critical geological conditions led to relevant damages is very limited, and it could be further reduced if open data sets are made available on these (hydro)geological issues, preferably as a Web GIS complemented by open borehole datasets.

Specific possible impacts of borehole heat exchangers on groundwater quality are the release of heat carrier fluid in the unlikely case of pipe leakages and the possible formation of preferential conduits for groundwater contamination through defective borehole filling (grout). Using pure water eliminates the risk of releasing toxic substances to groundwater, but, when anti-freeze is needed, propylene glycol is recommended. As for preferential flows through boreholes, geothermal grouts available on the market guarantee a hydraulic conductivity generally lower than those of any geological layers crossed by BHEs, so this eventuality seems to be avoided. The hydraulic sealing ability of the grout, however, strongly depends on the water/cement ratio, which should be kept as low as possible. Also, the continuity of grouting could be monitored with different tools recently released on the market.

The design of GSHPs must ensure that the thermal alterations are sustainable both at the single installation scale ("internal" sustainability), and, in the broader context, considering neighboring plants ("external" sustainability). In particular, the propagation of thermal plumes from groundwater heat pumps is a complex modelling issue that should preferably be addressed with 3D numerical models, and research still lacks general valuable studies on the interference among neighboring installation to support the management of GSHPs in densely inhabited urban areas.

Most of the available studies in the literature agree that no relevant changes of groundwater chemistry are expected within the ±6 K interval from undisturbed temperature suggested by most standards and regulations and usually adopted in GWHPs. On the other hand, ATES operating at 40 °C or more may trigger the release into groundwater of harmful substances such as arsenic. Evidence from field studies also highlight the importance of keeping a tight hydraulic circuit from abstraction to reinjection to avoid geochemical alterations and well clogging owing to an increase in dissolved oxygen.

Finally, for dense populations of installed GSHPs, groundwater monitoring should switch from a single installation scale to a city scale, thus achieving consistency of sampling times, analytical approaches, and allowing to understand large-scale dynamics of chemical and physiochemical groundwater parameters.

This study identified possible risks in the installation and operation of GSHPs and solutions based on the review of recent literature and best technical practices. Ground-source heat pumps have proven to be a safe and environmentally sustainable solution for the heating and cooling of buildings, as the number of accidents and serious environmental impacts related to their installation is rather low. However, risks could be further reduced by implementing georeferenced information on critical geological conditions, which are already available in a few countries and regions, mainly in the forms of web GIS and open data on stratigraphy from previous drilling activities. Several research gaps still need to be filled, among which the main ones identified in this paper are geochemical alterations of groundwater induced by GWHPs, possible cross-contamination induced by BHEs, and the reciprocal thermal impacts among neighboring GWHP installations.

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Appendix A

Table A1. Summary of environmental concerns for the installation of ground source heat pump (GSHP) systems with related literature references and suggestions to address them. BHE, borehole heat exchanger.

Category	Issue	References	Suggestions
Impacts of drilling	Artesian aquifers	[18,55]	Avoid drilling BHEs and water wells crossing sensitive layers. Provide geo-referenced information (web Geographic Information System, GIS) on areas with these (hydro)geological risks.
	Swelling layers	[17–19,55]	
	Salt layer dissolution	[17,18]	
	Shallow gas layers	[18,55,58]	
Impacts on BHEs and wells	Landslides	[13,14]	
Possible negative conditions for GSHPs	Interference with mining activities	[57]	These areas do not necessarily represent a risk for GSHP installation and operation. A case-by-case evaluation of risks and opportunities is necessary.
	Interaction with groundwater contamination	[28,32,33,59–61]	
	Hardness and mineral content of groundwater	[39–41]	Intermediate exchanger above 12°F [39]. Use threshold values from the work of [41] for GWHPs.
	Saltwater	[63]	Reinject on the coastline [63] and use saltwater-specific heat exchangers

Table A1. *Cont.*

Category	Issue	References	Suggestions
Impacts of BHEs	Heat carrier fluid release from BHEs	[18,24–26,65]	Using pure water in BHEs. Further research is needed on the impact of anti-freeze additives on groundwater quality.
	Preferential flow through BHEs	[20–24]	Use specifically developed, well-mixed and properly installed geothermal grouts. Further modelling and field studies needed for preferential flow.
Impact of GSHP operation	Thermal alterations	[42–47,80–82]	The works of [45,47] for modelling assumptions. City-scale modelling of thermal plumes. Modelling studies on reciprocal impacts of neighboring GWHPs such as the work of [81]. Relaxation factor approach suggested by the authors of [42].
	Microbial alteration	[32,34,35,85]	Keep within ±6 K thermal alteration [69]. Case-by-case evaluation for higher temperatures. Reinject under pressure (no free-fall). City-scale monitoring funded by taxes on GSHPs.
	Geochemical alterations	[30,32,33,36–38]	

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