A comparison of reduced-order techniques for complex interconnects modeling

Assessment and mapping of the shallow geothermal potential in the province of Cuneo (Piedmont, NW Italy)

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Abstract

Ground Source Heat Pump (GSHP) is a low carbon heating and cooling technology which can make an important contribution for reaching the ambitious CO_2 reduction targets set by the European Union. The economic and technical suitability of this technology strongly depends on the thermal and hydrogeological properties of the ground at the installation site, which need to be assessed in detail. A common indicator adopted to define such suitability is the geothermal potential, i.e. the thermal power that can be exchanged with the ground through a GSHP with a certain setup. In this paper, we present the assessment and mapping of the shallow geothermal potential in the province of Cuneo, a 6,900 km^2 wide county in NW Italy. Geological, hydrogeological and climatic information are collected and processed to estimate the relevant ground properties. The shallow geothermal potential is then estimated with different methods for closed-loop installations (Borehole Heat Exchangers, BHEs) and open-loop installations (Ground Water Heat Pumps, GWHPs) systems in order to identify the most suitable areas for different technologies. The maps of the geothermal potential are an important planning tool for the installation of GSHPs and for the growth of this renewable energy source.

Keywords: geothermal potential; Ground Source Heat Pump; Borehole Heat Exchanger; Ground Water Heat Pump; Cuneo; heat pump

1 Introduction

The European Union recently set three ambitious objectives for its energy policies: by the year 2020, the total energy consumption and the Greenhouse Gas emission have to be cut by 20%, and 20% of the total energy consumption should be covered by Renewable Energy Sources (RES) [1]. Italy has already achieved its national target in 2014, with 38.6% of the electricity and 18% of the heat production provided by RES [2], one of the best performances among EU Member States [1]. To achieve further improvements in alignment with Roadmap 2050 [3], efforts should now concentrate on heat production, for which the most adopted RES are ligneous biomass (68.9%) and heat pumps (25.8%) [2]. A further expansion of biomass heating is hardly sustainable, due to its impact on air quality [4, 5]. On the other hand, heat pumps have zero emissions on site and reduce GHG emissions up to 90% compared to fossil fuel burners, depending on the energy mix adopted for the production of electricity [6, 7]. In Italy, about 60% of the total production of electricity is covered by fossil fuels, with an emission factor of 326.8 g CO_2/kWh [8]; the consequent reduction of CO_2 production, according to Saner et al. [7], is of about 50% compared to a methane boiler.

Heat pumps are divided into two main categories: Air Source (ASHP) and Ground Source (GSHP). The main advantage of GSHPs compared to ASHPs is the higher COP, thanks to the lower temperature difference between the heat source (ground or groundwater) and sink (heating/cooling terminals) [9]. GSHPs have proved to be a cost-effective solution for a wide range of buildings, despite the additional expense for the installation of the ground heat exchangers .

GSHPs in Italy still account for only 0.1% of the total thermal energy production [2]. However, a continuously increasing trend has been observed in recent years (+13% in 2013), and a strong rise is expected for the next 10-15 years [10, 11]. The high cost of installation is widely acknowledged as a limiting factor for the increase of heat pump installations and, particularly, for geothermal heat pumps. In Italy, another major barrier is the high cost of electricity for domestic supply, compared to the relatively low cost of methane [12]. As a consequence, compared to other countries, a lower saving margin is achieved for heat pumps against fossil-fuelled boilers. The problem of the higher cost of installation has been addressed introducing a strong tax refund (65%) on energy retrofit works of existing buildings, among which GSHPs are included [13].

The lack of homogeneous and targeted regulation is another barrier for the growth of shallow geothermal energy in Italy [14]. This absence of regulation has been partially filled with voluntary schemes and standardization [15], such as the recent UNI standards for GSHPs [16-18].

A final problem is that the technology and the potential of shallow geothermal energy are still little known in most EU countries. A number of EU-funded projects have been conducted in recent years to disseminate knowledge on GSHPs with training events, workshops, and case studies [19-21]. These projects raised the different stakeholders' awareness of the potential applications of shallow geothermal energy.

However, the suitability of different territories for GSHPs needs to be studied on the small scale, since it depends on site-specific parameters and on the technology adopted [22-24]. A commonly adopted indicator is geothermal potential, which is defined in different ways, but can generally be identified as the capacity of the ground/aquifer to provide heating and/or cooling [25-31]. Some projects have already been conducted in Italy to assess shallow geothermal potential. Busoni et al. [26] assessed and mapped the suitability for the installation of BHEs of the province of Treviso (Veneto, NE Italy). Their work took into account ground thermal conductivity, geothermal gradient and groundwater velocity. The VIGOR project [28, 29] addressed both shallow and deep geothermal energy potentials of four regions in Southern Italy (Campania, Apulia, Calabria and Sicily). In situ measurements of the thermal conductivity of rocks [28] were conducted over the mapped territory, and the potential for GSHPs was mapped for both heating and cooling purposes [29]. Gemelli et al. (2011, [30]) assessed the shallow geothermal potential of the Marche region (Central Italy), evaluating the required BHE length to cover a standard thermal load. Fewer studies have been performed for open loop Ground Water Heat Pumps (GWHPs), such as the works of Arola et al. in Finland [25]. Lo Russo and Civita provide an overview of the hydrodynamic properties of shallow unconfined aquifers in Piedmont (NW Italy) [31].

The aforementioned studies provide a methodological basis for the work presented in this paper. Here, the shallow geothermal potential in the province of Cuneo (Piedmont, NW Italy) is assessed and mapped. The geological and hydrogeological setting of this territory is studied, and a conceptual model is provided to correlate this setting with ground thermal parameters. These are the input for the estimation of the closed-loop geothermal potential with model G.POT [27]. The geothermal potential for open-loop systems was evaluated by estimating the maximum extractable and injectable flow rates of the shallow aquifers of the Cuneo plain, based on a dataset of well tests results. Conclusions are drawn on the suitability of different areas of the province of Cuneo for closed and open loop geothermal heat pumps.

2 The territory surveyed

The province of Cuneo is a 6,900 km^2 wide area located in the south-western edge of Piedmont. It can be subdivided into three main parts (Fig. 1): the Alpine valleys (Cotian and Maritime Alps) on the western and southern edges, covering about 51% of the total surface, the plain in the centre of the Province (22%) and the hills of Langhe and Roero in the East part (27%).

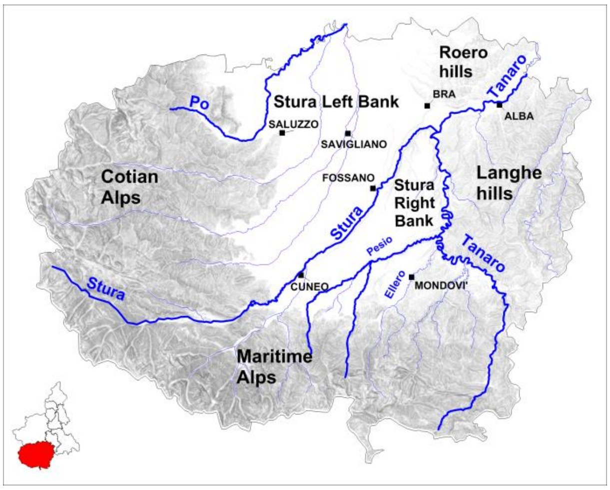


Fig. 1 – Map of the province of Cuneo. Scale: 1:1,500,000.

The total population is 592,060 inhabitants, of which 35% live in the county seat Cuneo (56,113 inhabitants) and 6 other main towns in the plain (Alba, Bra, Fossano, Mondovì, Savigliano and Saluzzo) of 15,000 to 30,000 inhabitants. The rest of the population mostly lives in rural villages on the plain, while a small part lives in the mountains and the hills.

In this chapter, the province of Cuneo is described from the climatic, geologic and hydrogeological points of view, and data is provided for the assessment of the shallow geothermal potential.

2.1 Climate

Cuneo is characterized by a continental climate with a cold winter and a mild summer, as reported in Fig. 2A. Although the distance from the sea is quite short (30÷100 km), a weak influence of the Mediterranean sea is observed, due to the isolating effect of the Alpine chain. The total rainfall varies widely, from 700÷900 mm/y in the hills of Langhe and Roero to 900÷1200 mm/y in the plain and in the mountains [32]. The annual mean air temperature is strongly correlated with the ground elevation, as shown in Fig. 2B, ranging from -3.1°C to +13.2°C [33]. The climate of Cuneo and its province is therefore one of the coldest in Italy, thus influencing the distribution of the heating degree-days (Italian DPR 412/1993 [34]). 66% of the population lives in climate zone E (2400÷3000 heating DD) and 34% lives in climate zone F (>3000 DD). As a consequence, the expense for house heating is one of the highest in Italy, while almost 90% of homes have no chilling plant [35].

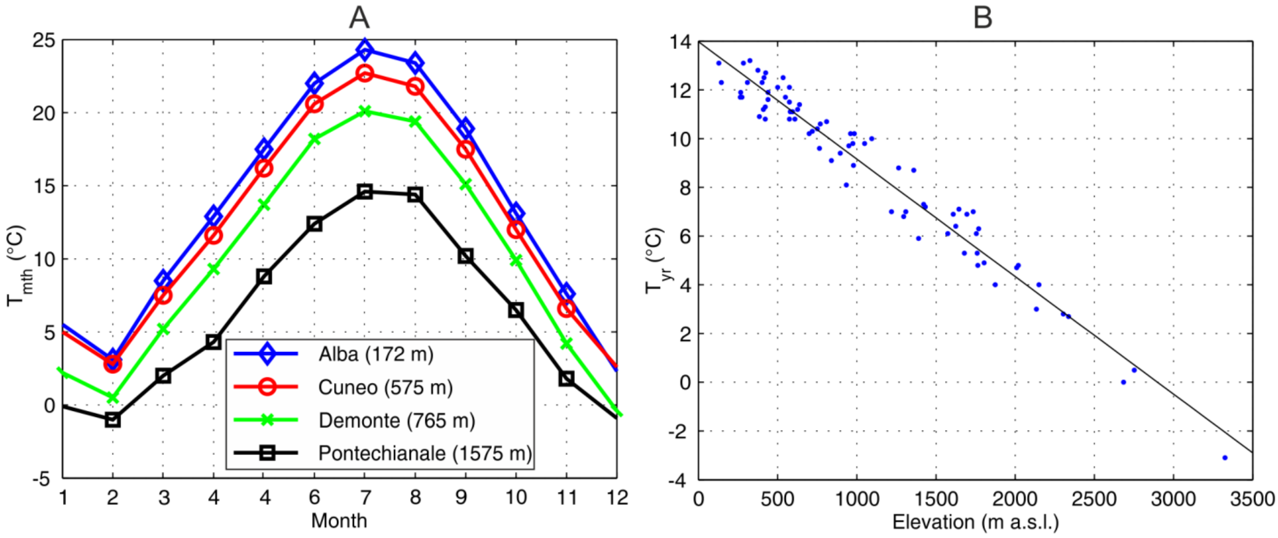


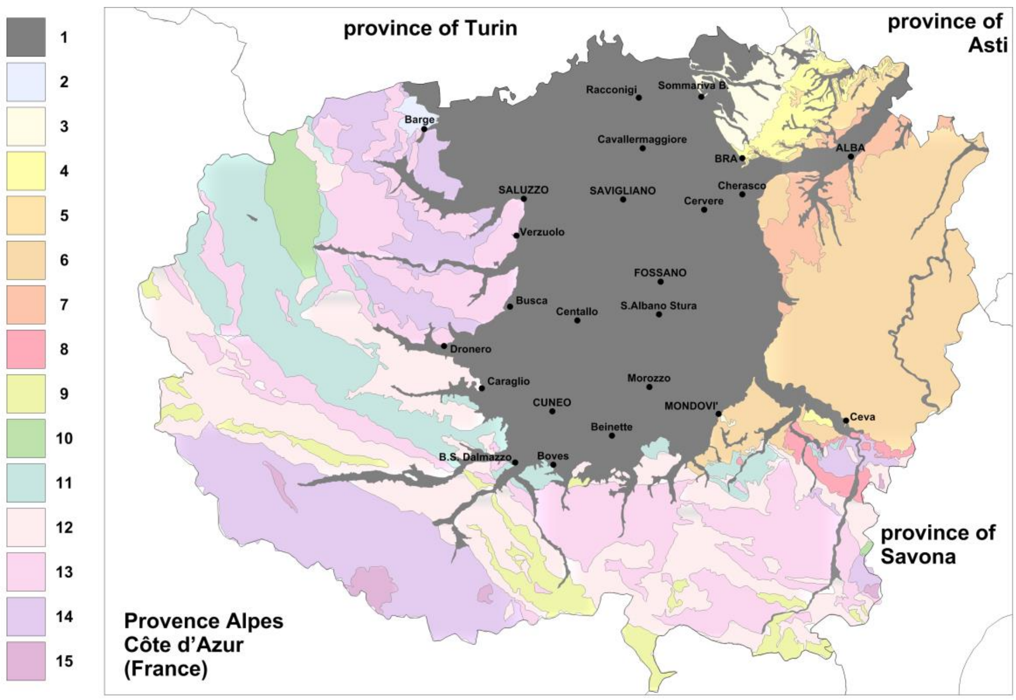
Fig. 2 – Climate of the province of Cuneo: (A) monthly mean temperatures in different locations; (B) correlation between elevation and mean annual air temperature.

2.2 Geology

The mountainous portion of the territory surveyed is located on the boundary between the Helvetic and the Penninic domains of the Alps [36] and, according to the geological map of Piedmont [37] reported in Fig. 3, it is mainly composed of gneiss, and, to a lesser extent, limestone, calceschysts, serpentinites, sedimentary rocks (conglomerates, sandstone, gypsum, consolidated clays) and granite.

The plain is composed of locally cemented sand and gravel sediments deposited in the Holocene (12000 years BP), with small loamy and clayey lenses. This alluvial cover lies on the Tertiary Piedmont Basin, composed of marine sediments settled during the Pliocene and the Villafranchian (5÷1 Ma BP) [31, 38].

The East part of the province of Cuneo is occupied by the hills of the Langhe, on the right bank of the Tanaro river, and of Roero, on the left bank. These hills were formed by the local uplifting of the Tertiary Piedmont Basin (Langhian, 16÷13 Ma BP) [39] and the excavated by the tributaries of the Tanaro river after the capture of this watercourse, occurred in the Riss-Wurm interglacial period (250,000 years BP). Langhe hills are mainly composed of Miocene marls and sandstones (23÷5 Ma BP), while Roero hills are composed of fine sands and clays deposited during the Pliocene (5÷2.5 Ma BP).



LEGEND OF LITHOLOGIES: 1) Alluvial sediments (Quaternary); 2) Moraines (Pleistocene); 3) Clays (Villafranchian); 4) Fine sands (Astian); 5) Clays and clayey marls (upper Miocene - medium Pliocene); 6) Marls (medium Miocene); 7) Marls and siltstones (upper Oligocene-medium Miocene); 8) Sandstone (Oligocene); 9) Alternated clayey layers (Cretaceous-Eocene); 10) Serpentinites of the Piedmontese zone (Jurassic-Cretaceous); 11) Calceschysts of the Piedmontese zone (Jurassic-Cretaceous); 12) Limestones and dolomies (Mesozoic); 13) Fine-grained gneiss of the Dora-Maira Massif (Permian); 14) Coarse-grained gneiss of Monte Rosa and Val d'Ossola (Permian); 15) Granites (Permian)

Fig. 3 – Geological map of the province of Cuneo (adapted from ARPA Piemonte [40]). Scale: 1:1,000,000.

2.3 Hydrogeology

The capture of Tanaro affected not only the morphology of a large part of the territory surveyed, but also the underground water circulation. Indeed, the deepening of the river bed of Tanaro's tributaries transformed them into hydraulic divides of the alluvial unconfined aquifer, which is composed of three main portions [32] (Fig. 4): the *Left Stura Bank* and the *Right Stura Bank*, separated by the river Stura, and the *Tanaro Valley* along the river.

The *Left Stura Bank* is a large aquifer (1117 km^2) in the Western sector of the plain. The subsurface flow is directed from SW to NNE (Fig. 4A,) and the hydraulic gradient gradually diminishes from 10‰ on the West and South edges to 2‰ in the North part of the plain. The transmissivity is very high (up to 0.1 m^2s^{-1}) in the centre and diminishes on the eastern edge, with a concurrent reduction of the saturated thickness (Fig. 4B) of the aquifer [31]. The depth to water table (Fig. 4A) is below 10 m in the central part of the plain, while higher values close to the East and West boundaries, up to 70 m in the South-Western portion.

The *Right Stura Bank* aquifer (523.5 km^2) is divided into a number of sub-sectors due to the influence of the creeks Pesio, Ellero and other smaller water courses [38]. On a narrow strip along the Stura river, the average transmissivity is quite high ($5\cdot10^{-3}\div5\cdot10^{-2}$ m^2s^{-1}) [31], while in the rest of this area is much lower ($<10^{-3}$ m^2s^{-1}). The saturated thickness is about 50 m in the SW portion along the Stura and it decreases to 5÷10 m elsewhere, with a sharp transition; a similar trend is observed for the depth to water table.

The narrow aquifer of *Tanaro Valley* is scarcely productive [32] and, together with the other small aquifers located in the valleys and on the Langhe and Roero hills, it is not considered in the analysis of the open-loop geothermal potential.

3 Shallow geothermal potential

The spatial distributions of thermal and hydrogeological parameters, reported and described in the previous chapter, were used to assess the techno-economic feasibility of shallow geothermal systems in different parts of the province of Cuneo. The geothermal potential has different definitions depending on the technology adopted, i.e. closed-loop (BHE) or open-loop (GWHP).

For closed-loop systems it is defined, according to G.POT [27], as the yearly average thermal load that can be exchanged with the ground by a BHE with a length L, coping with a minimum/maximum temperature threshold of the heat carrier fluid. A limit is therefore imposed to the thermal alteration of the heat carrier fluid, which mostly depends on the thermal parameters of the ground and, to a lesser extent, on the characteristics of the BHE itself [22].

On the other hand, heat transport in GWHPs mostly depends on the hydrodynamic parameters of the aquifer, while thermal conductivity has a minor impact on the heat diffusion into the aquifer [41]. The efficiency of these systems can be impaired by thermal recycling, which should be considered in the design phase using analytical or numerical models [24, 42]. Another important aspect of the design of GWHPs is the propagation of thermal plumes downstream the injection well, with a negative impact on drinking water wells or other geothermal installations. These issues are more likely in large cities with a high density of GWHPs [43, 44], rather than in a scarcely populated territory such as the province of Cuneo. Both the issues of thermal recycling and thermal plume interference should be evaluated with consideration to specific plants and setups, and hence a large-scale assessment is not feasible. On the other hand, the alteration of hydraulic heads due to water extraction and injection mainly depends on the aquifer's properties. A point-wise evaluation was therefore performed, based on available data on the hydrodynamic parameters of the unconfined aquifers. The maximum flow rate to be sustainably abstracted and injected was estimated and, from this value, the peak thermal power was derived. Differently from G.POT, the evaluation of open-loop geothermal potential did not consider a thermal load profile, but a peak value. Indeed, the evaluation of time-varying thermal loads would require complex and time-consuming numerical simulations for each point reported on the map, which is not feasible at this scale.

The considerations reported above are the conceptual basis for the assessment and mapping of the geothermal potential for BHEs and GWHPs, which is described in this chapter.

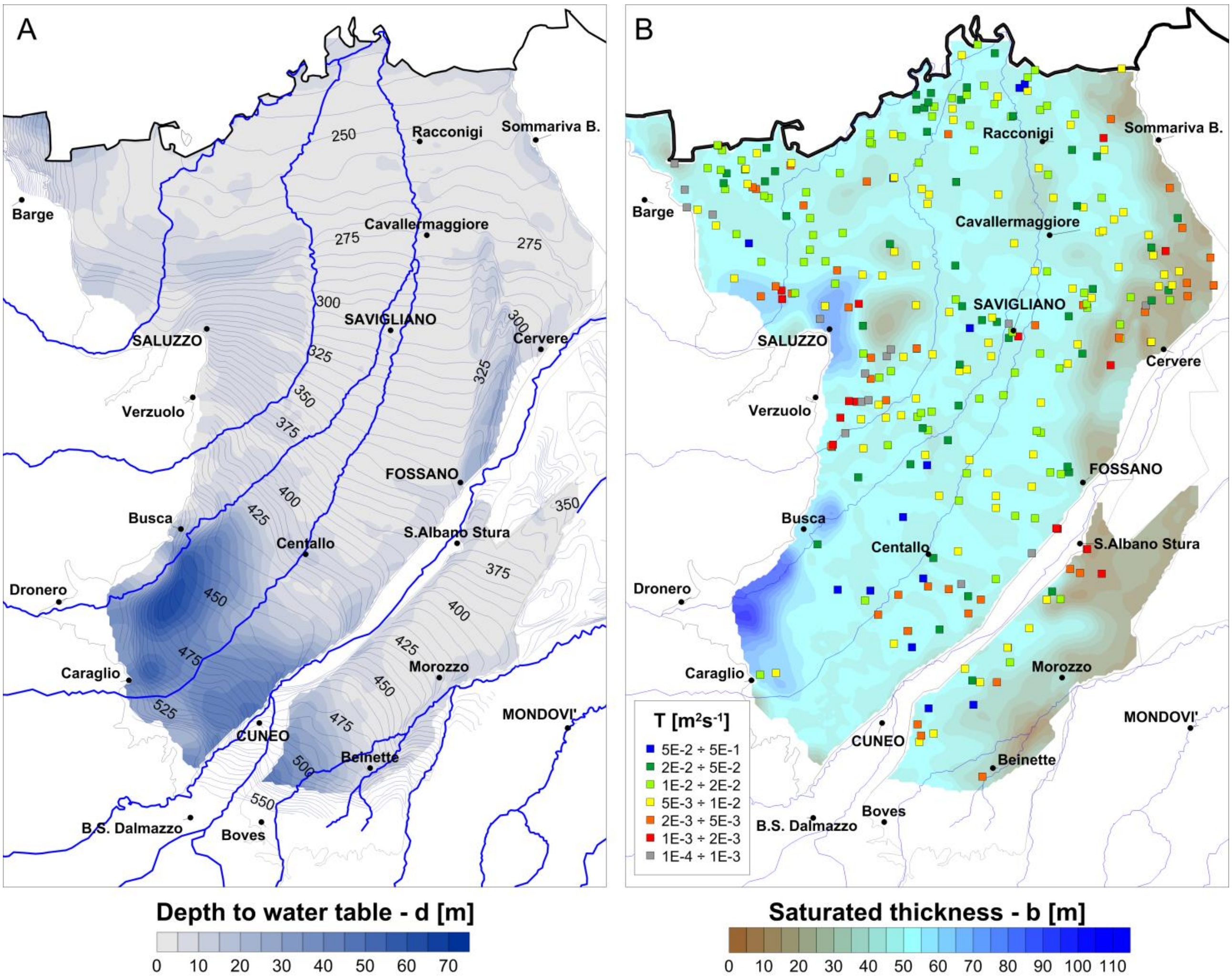


Fig. 4 – Maps of the hydrogeological parameters of the unconfined aquifers of Left Stura Bank and Right Stura Bank: (A) hydraulic heads and depth to water table; (B) transmissivity and saturated thickness. Scale 1:500,000.

3.1 Closed-loop geothermal potential

Closed-loop geothermal heat pumps can be installed virtually everywhere, since they do not require the abstraction of groundwater. However, the techno-economic feasibility of these systems varies substantially depending on a wide range of factors, namely:

- usage profile: the GSHP can be used in heating or cooling mode, or for both purposes in different proportions, depending on the building type (i.e. residential, commercial, public building…) and on the climate;
- thermal properties of the ground: thermal conductivity (λ), thermal capacity (ρc), undisturbed ground temperature (T_0);
- BHE and plant properties: length (L), minimum/maximum threshold fluid temperature ($T_{\lim}$) and thermal resistance (R_b). The value of R_b is function of the geometry (borehole radius r_b, pipe

radius r_p, number of U-pipes n) and of the thermal conductivity of the backfilling (geothermal grout λ_{bf}).

Based on the aforementioned parameters, the closed-loop shallow geothermal potential $\bar{P}_{BHE}$ (MWh/y) was estimated with the G.POT method [27]:

$$\bar{P}_{BHE} = \frac{0.0701 \cdot (T_0 - T_{lim}) \cdot \lambda \cdot L \cdot t'_c}{G_{max}(u'_s, u'_c, t'_c) + 4\pi\lambda \cdot R_b}$$

Eq. 1

where T_0 (°C) is the undisturbed ground temperature, T_{lim} (°C) is the threshold minimum fluid temperature, λ (Wm^{-1}K^{-1}) is the ground thermal conductivity, L (m) is the borehole depth, and R_b (mKW^{-1}) is the borehole thermal resistance. $G_{max}(u'_s, u'_c, t'_c)$ is function of three non-dimensional parameters t'_c , u'_c and u'_s:

$$G_{max}(u'_s, u'_c, t'_c) = -0.619 \cdot t'_c \cdot log(u'_s) + (0.532 \cdot t'_c - 0.962) \cdot log(u'_c) - 0.455 \cdot t'_c - 1.619$$

Eq. 2

with:

$$t'_c = t_c / t_y$$

Eq. 3

$$u'_c = \rho c \cdot r_b^2 / (4\lambda t_c)$$

Eq. 4

$$u'_s = \rho c \cdot r_b^2 / (4\lambda t_s)$$

Eq. 5

where t_c (s) is the length of the heating season (set to 183 days), and t_y is the length of the year; ρc (Jm^{-3}K^{-1}) is the thermal capacity of the ground; t_s (s) is the simulated lifetime of the plant (set to 50 years). The G.POT method is implemented in an electronic spreadsheet available at http://goo.gl/Pm93JT.

An only-heating usage profile was set, as most of residential buildings in Piedmont do not have a chilling plant [35]. This is a conservative assumption, since the operation in cooling mode during summer would partially compensate the heat extraction during winter, and hence reduce the thermal drift of the ground. The thermal load has a sinusoidal trend and a typical duration of the heating season has been chosen, from October 15th to April 15th (183 days), as foreseen by DPR 412/93 for the climate zone "E" [34]. A typical double-U pipe BHE (Tab. 1) was considered, with a length $L = 100m$. The thermal properties of the ground were therefore evaluated on the same depth.

Tab. 1 – Geometrical and physical properties of the BHE adopted for the geothermal potential analysis.

Parameter	Symbol	Value
Borehole length	L	100 m
Borehole radius	r_b	0.075 m

Pipe radius	r_p	0.016 m
Pipe number	n	4 (2-U pipe)
Thermal conductivity of backfilling	λ_{bf}	2 $Wm^{-1}K^{-1}$

For thermal conductivity and thermal capacity, two different approaches were adopted:

- homogeneous values were adopted for compact rocks, both metamorphic (gneiss, serpentinite) and sedimentary (marls, sandstones, limestones);
- a depth-averaged value has been chosen for alluvial aquifers in the plain, considering the different thermal conductivity of the vadose and the saturated zone (see Tab. 2). The depth to water table was used to determine the thickness of these two layers.

The maps of ground thermal conductivity and capacity are reported in the Supporting Information.

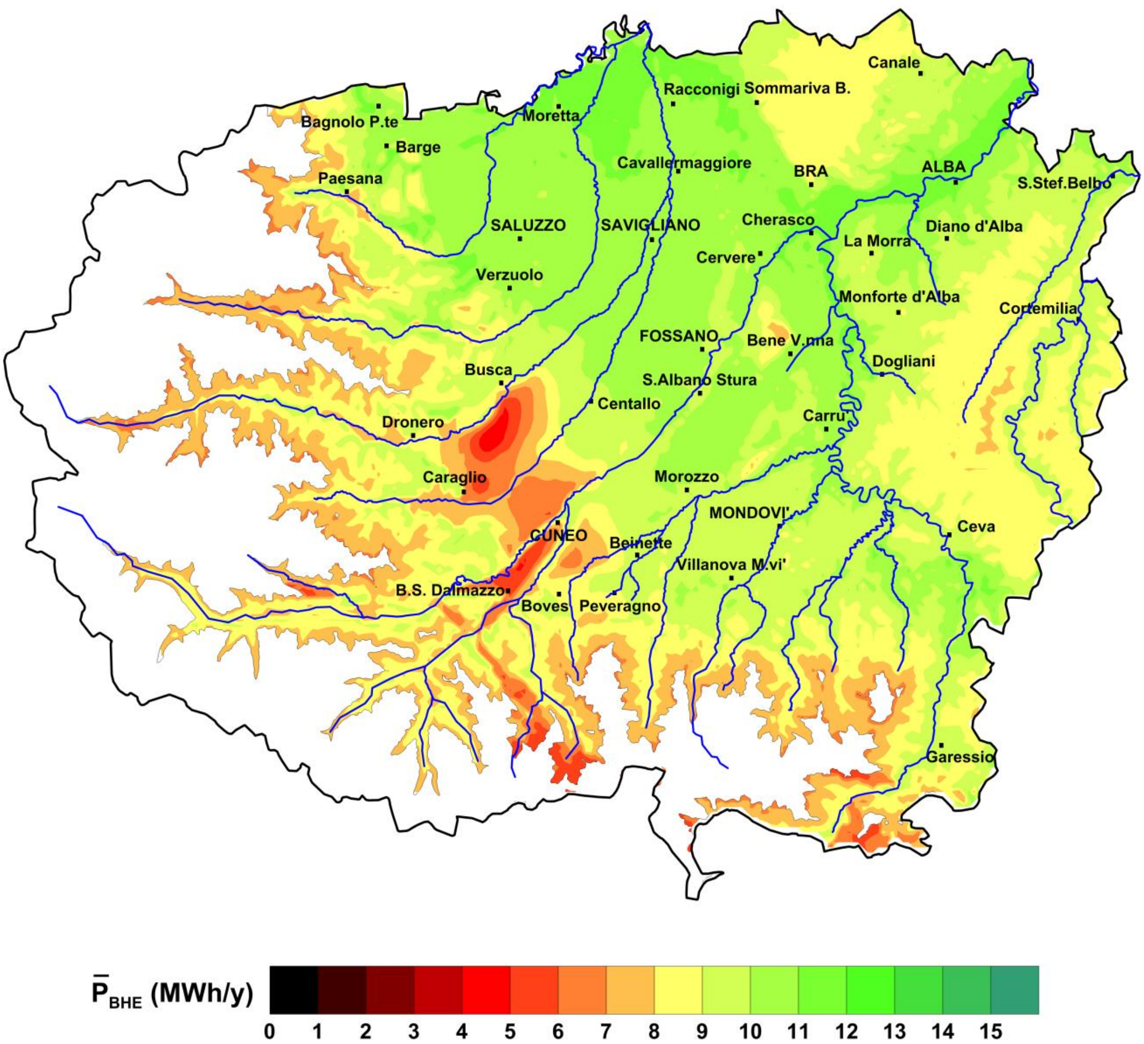


Fig. 5 – Map of the closed-loop geothermal potential calculated with the G.POT method [27]. Scale 1:750,000.

Tab. 2 – Values of thermal conductivity and thermal capacity adopted for different lithologies (elaboration on data from [28, 45].

N°	Lithology	λ [$Wm^{-1}K^{-1}$]	ρc [10^6 $Jm^{-3}K^{-1}$]
1, 2	Alluvial/moraine sediments (dry)	2.4	1.5
1, 2	Alluvial/moraine sediments (saturated)	0.5	2.4
3, 9	Clay/Alternated clayey layers	1.8	2.5
4	Fine sand	1.8	2.5
5	Clay and clayey marl	2.1	2.25
6	Marl	2.3	2.25
7	Marl and siltstone	2.1	2.25
8	Sandstone	2.8	2.2
10	Serpentinite	2.5	2.8
11	Calceschyst	2.5	2.4
12	Limestone and dolostone	2.7	2.25
13	Fine grained gneiss	2.5	2.1
14	Coarse grained gneiss	2.9	2.1
15	Granite	3.2	2.5

The ground temperature is almost constant through the year and slightly higher than the annual mean air temperature [30, 46], which is strongly correlated with the elevation (Fig. 2). A few data are available on the subsurface temperature in the province of Cuneo, measured in a number of water wells in the plain [31, 47], while no measures are available for the hilly and mountainous parts. An empirical correlation with the ground elevation was therefore used, which was calibrated against ground temperature measured in Switzerland [48]. The regional DTM of Piedmont was used as an input for ground elevations [49]. Ground temperatures were not estimated above 1500 m a.s.l. where, according to Ref. [48], the correlation is not valid since the snow cover alters the thermal exchange between the air and the ground. About 25% of the total area of the province of Cuneo, but less than 1% of the total population, was therefore excluded from the evaluation of the ground temperature and hence of the geothermal potential.

The map of the closed-loop geothermal potential is shown in Fig. 5**Errore. L'origine riferimento non è stata trovata.**. This indicator varies from 5 to 12 MWh/y, depending on the thermal conductivity and the temperature of the ground. In the central and northern part of the *Left Stura Bank* plain and in the *Tanaro Valley*, the thermal conductivity is quite high ($\lambda = 2 \div 2.3\ Wm^{-1}K^{-1}$) due to the shallow water table, and the ground temperature are the highest in the territory surveyed ($T_0 = 12 \div 14°C$). The highest geothermal potentials ($\bar{P}_{BHE} = 10 \div 12\ MWh/y$) are therefore observed in this part of the plain, which accounts for about 20% of the total area and 40% of the total population. The hills of Langhe and Roero and the southern portion of the *Right Stura Bank* plain, which account for about 50% of the total population, are slightly less suitable for BHEs ($\bar{P}_{BHE} = 8 \div 10\ MWh/y$) due to the lower thermal conductivity ($\lambda = 1.2 \div 2.1\ Wm^{-1}K^{-1}$) and temperature ($T_0 = 10 \div 12°C$) of the ground. Less than 10% of the population lives in areas with very low suitability for BHEs, where the geothermal potential falls to $\bar{P}_{BHE} = 5 \div 8\ MWh/y$. The causes of such a low geothermal potential are different:

- in the valleys, the outcropping rocks are generally very conductive ($\lambda > 2.5\ Wm^{-1}K^{-1}$) but the ground temperature is very low ($T_0 = 7 \div 10°C$);
- in the SW of the *Left Stura Bank* (Cuneo, Caraglio, Busca and Centallo) the water table is very deep (up to 70 m from ground surface) and hence the thermal conductivity is very low ($\lambda = 1 \div 1.5\ Wm^{-1}K^{-1}$). Borehole Thermal Energy Storage (BTES) can be installed here to take advantage of the poorly conductive ground, storing large quantities of heat during Summer with low heat losses [50].

3.2 Open-loop geothermal potential

While the design of closed-loop GSHPs is generally performed with standard sizing methods based on ground thermal parameters which can be derived from large-scale geological maps, GWHPs require a thorough hydrogeological characterization of the installation site. Indeed, the hydrodynamic properties of the aquifer are site-specific, may vary in large ranges over short distances and should therefore be evaluated with *in situ* tests. A spatially continuous map of the open-loop geothermal potential cannot be developed unless a high spatial resolution database is available, which is not the case. A point-wise evaluation was therefore performed. The maximum allowed flow rate was estimated for both extraction and injection. The minimum of these two values was then used to calculate the open-loop geothermal potential, i.e. the maximum thermal power that can be exchanged with the aquifer, if water is disposed into the same aquifer after the heat exchange, which is the most commonly adopted practice.

Misstear and Beeson (2000, [51]) defined the potential well yield as the maximum flow rate that can be extracted by a well respecting a low-level threshold called Deepest Advisable Pumping Water Level (DAPWL). The variation of the hydraulic head in the well is calculated with the equation of Cooper and Jacob (1946, [52]):

$$s_w(Q) = \frac{Q}{4\pi T} \cdot log\left(2.25\frac{Tt_{pump}}{Sr_w^2}\right) + CQ^2$$

Eq. 6

where Q (m^{3}s^{-1}) is the well flow rate, T (m^{2}s^{-1}) is the transmissivity of the aquifer, t_{pump} (s) is the pumping time, r_w(m) is the well radius, and C (s^{2}m^{-5}) is the coefficient of the quadratic term of the Rorabaugh equation.

The drawdown in the production well and the rise in the reinjection well are calculated without considering their mutual interference. This is a conservative assumption, since the drawdown induced by the extraction well partially compensates the level rise due to the injection well, and vice versa.

The maximum allowed abstracted (Q_{abs}) and injected (Q_{inj}) flow rates were calculated with Eq. 6 imposing, respectively, a maximum drawdown (Eq. 7) and a maximum level rise (Eq. 8).

$$s_w(Q_{abs}) = \alpha \cdot b$$

Eq. 7

$$s_w\left(Q_{inj}\right) = d - d_{min}$$

Eq. 8

where α is a fraction of the saturated thickness (b), d and d_{min} are respectively the initial and the minimum possible depth of water table from ground surface. A 50% reduction of the initial saturated thickness ($\alpha = 0.5$), was set as suggested by Ref. [51], while a minimum water table depth $d_{min} = 3m$ was imposed to provide a safety margin against groundwater flooding.

The values of transmissivity (T) were drawn from a dataset of specific flow rates q_{sp} derived from 304 wells in the *Left* and *Right Stura Bank* [53], adopting the equivalence $T = q_{sp}$ suggested by Refs. [54-56]. The storage coefficient was set to $S = 0.2$, i.e. the average value of the range ($S = 0.1 \div 0.3$) provided for unconfined aquifers [54]. The well radius was set to $r_w = 0.25m$ and the quadratic loss coefficient of the Rorabaugh equation was set to $C = 1900 s^2 m^{-5}$, i.e. the highest value for a non-deteriorated well [57]. The pumping time was set to $t_{pump} = 200d$, as suggested by Ref. [51].

The maximum allowed extracted/injected flow rates are used as input to calculate the open-loop geothermal potential according to two operating modes:

- without reinjection, thus avoiding possible groundwater flooding issues in the reinjection wells:

$$P_{GWHP,max,noinj} = Q_{abs} \cdot \rho_f c_f \cdot \Delta T$$

Eq. 9

- with reinjection, which is the most commonly adopted solution:

$$P_{GWHP,max,inj} = \min\left(Q_{abs}, Q_{inj}\right) \cdot \rho_f c_f \cdot \Delta T$$

Eq. 10

where $\rho_f c_f = 4.2 \cdot 10^6 J m^{-3} K^{-1}$ is the thermal capacity of water and $\Delta T = 5K$ is the temperature difference between injection and abstraction well.

The maps of the open-loop geothermal potential with and without reinjection are reported in Fig. 6. Reinjection can be avoided if a surface water body (rivers, channels, lakes) is available close to the installation site. The open-loop geothermal potential in this case achieves values higher than 1000 kW in most of the *Left Stura Bank* plain, as shown in Fig. 6A, while lower values are observed on the western and eastern edges, due to the lower transmissivity of the aquifer (Fig. 4B). However, reinjection is usually required for GWHPs in Piedmont, in order to avoid additional consumptive uses of the aquifer, and hence the open-loop geothermal potential with reinjection was calculated ($P_{GWHP,max,inj}$, see Eq. 10). Reinjection proves a strong limiting factor for the installable thermal power of GWHPs, as shown in Fig. 6B, due to the low depth to water table of the northern and eastern sectors of the *Left Stura Bank*, and of most of the the *Right Stura Bank (*Fig. 4A). A clear decreasing trend from west to east is therefore observed for open-loop geothermal potential in the *Left Stura Bank* (Fig. 4B) due to the progressive reduction of the water table depth and hence of the injectable flow rate. This issue can be overcome adopting multiple injection and extraction wells, or other reinjection techniques such as ponds or trenches [58].

Groundwater chemistry is another important design issue for of GWHPs. According to Rafferty (1999, [59]), scale formation can occur in the thermal exchange circuit for water carbonate hardness higher than 10°F. This threshold is usually not respected in the unconfined aquifer in the province of Cuneo, with most values ranging between 20°F and 40°F [38, 60], and hence the use of secondary heat exchange circuit is strongly advised.

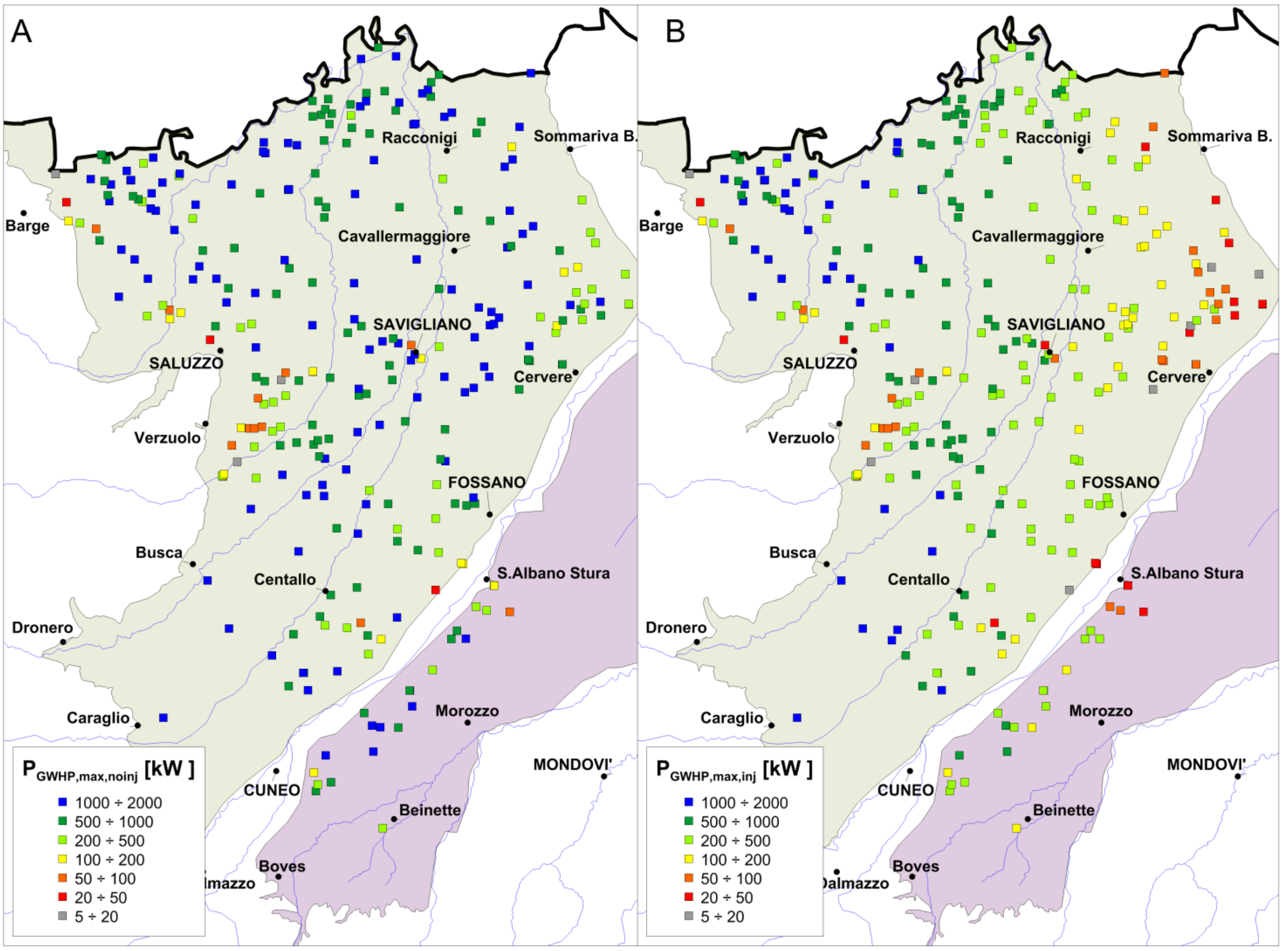


Fig. 6 – Map of the open-loop geothermal potential in the alluvial shallow aquifers of the province of Cuneo with water disposal in surface water bodies (A) and in the same aquifer (B).

4 Conclusions

Ground Source Heat Pump is an environmentally and economically viable technology for the heating and cooling of buildings. It exploits a local RES such as the heat stored in shallow ground. This resource is available everywhere, but the techno-economic feasibility depends on the site conditions, i.e. ground thermal and/or hydrogeological parameters. In this work, the potential for the installation of closed-loop and open-loop geothermal heat pumps was assessed in the province of Cuneo, NW Italy. The geology, the hydrogeology and the climate of this territory was studied by harmonizing and homogenizing data from different sources. Based on these data, relevant parameters for the operation of GSHPs were estimated. A mathematical method called G.POT [27] was used to estimate the closed-loop geothermal potential, i.e. the thermal power that can be exchanged by a BHE. The open-loop geothermal potential is defined as the maximum thermal power that can be exchanged by a GWHP composed of a well doublet. The thermal power is limited by hydraulic head alterations induced by groundwater extraction and injection, which depend on the hydrogeological properties of the aquifer.

According to the results, the following conclusions can be drawn:

- the province of Cuneo has a good potential for the installation of closed-loop BHEs, in particular in the central part of the plain, where about 40% of the population lives. In this area, 10÷12 MWh/y can be exchanged with a 100 m-long BHE. The geothermal potential diminishes to 8÷10 MWh/y in the hilly areas of the Langhe and Roero, in the alluvial aquifers at the bottom of the valleys and in the southern part of the alluvial plain of the *Right Stura Bank*, due to lower ground temperatures;
- less than 10% of the population lives in areas with a low suitability for the installation of BHEs, where the geothermal potential falls to $\bar{P}_{BHE} = 5 \div 8\ MWh/y$). In the south-western part of the plain (both *Left Stura Bank* and *Right Stura Bank*), this is due to the presence of a thick vadose zone (up to 70 m) and the consequently low thermal conductivity of the ground. On the other hand, such a thick unsaturated zone makes this area suitable for Borehole Thermal Energy Storage (BTES). The upper part of the Alpine valleys, characterized by a very low ground temperature, is also scarcely suitable for BHEs;
- a large part of the Province of Cuneo is occupied by alluvial aquifers with a high transmissivity, which makes them suitable for the installation of GWHPs. The main limiting factor is the low depth to water table, which is critical for water reinjection. This issue can be overcome by using reinjection techniques such as ponds, trenches, and gabions [58].

Maps of geothermal potential are valuable tools for the evaluation of the suitability for closed-loop and open-loop geothermal heat pumps. Closed-loop BHEs can be installed everywhere, hence the evaluation in this work focused on the efficiency of a possible installation, depending on site-specific ground thermal parameters. On the other hand, the installation of an open-loop GWHP is possible only in the presence of a sufficiently productive aquifer. For this reason, the evaluation focused on the sustainability of groundwater extraction and reinjection, which depends on the hydrodynamic properties of the aquifer, while the efficiency was not evaluated, since it depends on the characteristics of single geothermal systems.

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6 List of acronyms

ASHP	Air-Source Heat Pump
BHE	Borehole Heat Exchangers
BP	Before Present
BTES	Borehole Thermal Energy Storage
COP	Coefficient Of Performance
DD	Degree-Days
DTM	Digital Terrain Model
EU	European Union
G.POT	Geothermal POTential
GSHP	Ground Source Heat Pump
GWHP	Ground Water Heat Pump
RES	Renewable Energy Source

7 List of symbols

7.1 Latin letters

Symbol	Unit	Description
b	m	Saturated thickness of the aquifer
d	m	Depth of the aquifer's water table (depth to water table)
d_{min}	m	Minimum allowed depth to water table
$G_{max}(u'_s, u'_c, t'_c)$	-	Non-dimensional function of the maximum thermal alteration of the ground at the borehole wall
L	m	Depth of the borehole heat exchanger
n	-	Number of pipes
$\bar{P}_{BHE}$	MWh/y	Closed-loop geothermal potential
$P_{GWHP,max,inj}$	kW	Open-loop geothermal potential with water reinjection into the same aquifer
$P_{GWHP,max,noinj}$	kW	Open-loop geothermal potential without water reinjection
Q	m^3s^{-1}	Well flow rate
Q_{abs}	m^3s^{-1}	Maximum allowed abstraction flow rate
Q_{inj}	m^3s^{-1}	Maximum allowed injection flow rate
q_{sp}	m^2s^{-1}	Specific flow rate
r_b	m	Radius of the borehole
R_b	mKW^{-1}	Borehole thermal resistance
r_p	m	Radius of the pipes of the borehole heat exchanger
r_w	m	Well radius
S	-	Aquifer's storage coefficient
s_w	m	Level displacement in the well
T_0	K	Undisturbed ground temperature
t_c	s	Length of the heating season
t'_c	-	Non-dimensional length of the heating season
T	m^2s^{-1}	Aquifer's transmissivity
$T_{\lim}$	K	Minimum or maximum threshold temperature of the heat carrier fluid
T_{mth}	°C	Monthly average air temperature
t_s	s	Simulated operation time
t_y	s	Length of the year
T_{yr}	°C	Yearly average air temperature
u'_c	-	Non-dimensional cycle time parameter
u'_s	-	Non-dimensional simulation time parameter

7.2 Greek letters

Symbol	Unit	Description
α	-	Maximum allowed reduction of the saturated thickness
ΔT	K	Temperature difference between abstraction and injection well
λ	$Wm^{-1}K^{-1}$	Thermal conductivity of the ground
λ_{bf}	$Wm^{-1}K^{-1}$	Thermal conductivity of the borehole filling (grout)
ρc	$Jm^{-3}K^{-1}$	Thermal capacity of the ground
$\rho_f c_f$	$Jm^{-3}K^{-1}$	Thermal capacity of water