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A methodology for lithology-based thermal conductivities at a regional scale for shallow geothermal energy – Application to the Brussels-Capital Region

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ABSTRACT

A methodology for the determination of lithology-based thermal conductivities at a regional scale is proposed, assigning a saturated and unsaturated thermal conductivity to each stratigraphic unit encountered in the region. Such a methodology is paramount for GIS-supported mapping of shallow geothermal energy at a regional scale. The analysis is primarily based on the interpretation of thermal response tests (TRT), assuming that the thermal conductivity determined during TRT is a thickness-weighted average of the individual thermal conductivity of each stratigraphic unit constituting the ground along a ground heat exchanger (GHE). Enhanced thermal response tests, reference geological material-based thermal conductivities and laboratory optical scanning tests achieved on remolded specimen from drilling cuttings are used to validate the results. The relevance of the methodology is illustrated through its application to the Brussels-Capital Region (Belgium), and consistent saturated and unsaturated thermal conductivities are obtained for each stratigraphic unit. An uncertainty analysis on the thermal conductivity is proposed, and its impact on the design of GHE is discussed. In most cases, the relative error on the ground thermal conductivity is lower than 10 %, and its impact on GHE length remains limited.

1. Introduction

A Ground Source Heat Pump (GSHP) is a low carbon heating and cooling technology which can make an important contribution for reaching the ambitious CO2 reduction targets defined by the European Union. Amongst GSHP techniques, ground heat exchangers (GHE) are the most widespread shallow geothermal installations. GHE are introduced in a borehole and thermal energy can be exchanged between the ground and the heat transfer fluid circulating within the pipes. The thermal efficiency of GHE systems depends on a number of factors including the type of GHE (Bidarmaghz et al., 2013; Batini et al., 2015), its thermal properties (Delaleux et al., 2012; Erol & François, 2014; Alberti et al., 2017), the thermal properties of the surrounding ground (Di Donna & Barla, 2016; Woloszyn & Golas, 2014), and the thermal demand of the building (Low, 2015). In this list, the thermal behavior of the ground, and especially the ground thermal conductivity, is the main factor that is not dependent on the GHE installation process or the building itself. The ground thermal conductivity is mainly impacted by the mineralogical composition, dry density and degree of saturation (Farouki, 1981; Clauser & Huenges, 1995; Becker et al., 1992; Dong et al., 2015). There is therefore an interest to propose techniques for the assessment of the ground thermal conductivities in order to design accurately GHE systems.

Many in-situ (e.g. thermal response test (TRT)) or laboratory (on drill cuttings) techniques have been already developed to characterize the ground thermal conductivities. An in-depth and critical literature review can be found in Vieira et al. (2017) and Wilke et al. (2020). Even with these tests, there is still a need for reliable information on the spatial distribution at a regional scale of the ground geothermal properties, especially the thermal conductivity. For small-scale buildings, the costs of investigations are sometimes excessive compared to the total budget of geothermal installations. The design of GHE is thus not necessarily based on ground thermal conductivities obtained from in-situ or laboratory tests, but rather inferred from conservative assumptions on the thermal properties. Spatial estimations of the ground thermal

Abbreviations: BCR, Brussels-Capital Region; ETRT, Enhanced Thermal Response Test; GHE, Ground Heat Exchanger; GSHP, Ground Source Heat Pump; TRT, Thermal Response Test.

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Notations

Symbol	Definition Units
h	Thickness of a stratigraphic unit m
H	Total length of TRT m
$L_{GHE\text{-}final}$	GHE length calculated with the Dutch design method m
n	Porosity -
S_r	Degree of saturation -
w	Water content -
w_{sat}	Saturated water content -
#TRT	Number of TRT penetrating a given stratigraphic unit
%LT	Percent of TRT length penetrating a given stratigraphic unit
Υ_d	Dry unit weight N/m^3
Υ_s	Solid grains unit weight N/m^3
Υ_w	Water unit weight N/m^3
$\delta L_{rel,GHE\text{-}final}$	Relative error on GHE length -
$\delta\lambda_{rel,av}$	Average relative error on thermal conductivity -
$\delta\lambda_{rel,max}$	Maximal relative error on thermal conductivity -
λ	Thermal conductivity of a specific stratigraphic unit W/mK
λ_{air}	Air thermal conductivity W/mK
λ_{dry}	Dry thermal conductivity W/mK
λ_{grout}	Grout thermal conductivity W/mK
λ_s	Solid grains thermal conductivity W/mK
λ_{sat}	Saturated thermal conductivity W/mK
$\lambda_{TRT,meas}$	Average ground thermal conductivity measured in-situ during a TRT W/mK
$\lambda_{TRT,calc}$	Average ground thermal conductivity calculated from the thickness-weighted average of the individual thermal conductivity of each stratigraphic unit W/mK
λ_w	Water thermal conductivity W/mK

conductivity would allow a more precise and efficient design in this case. On the other hand, for large-scale buildings, the lack of pre-existing information on the ground thermal properties prevents a beforehand estimation of the techno-economic benefits, which makes investors risk averse with required, but expensive in-situ investigations. This is why the mapping of the subsurface thermal properties profile at a regional scale has been developed during the last decade (Ondreka et al., 2007; Fujii et al., 2007; Bertermann et al., 2014; Casasso & Setti, 2016; Gemelli et al., 2011; Garcia-Gil et al., 2015; Van Lysebetten et al., 2013; Viesi et al., 2018). Their objective was to have a general knowledge of the spatial distribution of the thermal properties of an area before determining in detail the design parameters for a shallow geothermal energy system. Such mapping can meet the aforementioned needs of stakeholders.

Those GIS-supported mapping of thermal properties combine both a geological model and spatial dependent thermal conductivities. The determination of thermal conductivities can be based on geological material-dependent empirical approximations (Ondreka et al., 2007; Gemelli et al., 2011; Viesi et al., 2018; Dalla Santa et al., 2020), laboratory characterization (Di Sipio et al., 2014), or inverse analysis of in-situ thermal response tests (Van Lysebetten et al., 2013). Consequently, the question of upscaling local thermal conductivity data, whether collected in the field or via laboratory studies, to regional information has become important. However, most of those studies lacked a standard methodology for the determination and the regional upscaling of thermal conductivities, either because the investigated depth is shallower than where the geothermal systems are installed (Bertemann et al., 2015), either because the data points are widely-spaced and the regional upscaling produces large uncertainties (Van Lysebetten et al., 2013) or because empirical relationships are not developed well enough for regional comparisons (Ondreka et al., 2007; Gemelli et al., 2011). Also, few studies estimated the uncertainties for the thermal conductivities, and do not address the consequences of those uncertainties to the GHE design.

This paper aims at developing a consistent and relevant methodology for the determination of lithology-based thermal conductivities at a regional scale from a set of different, but complementary geothermal data, namely (i) an in-depth knowledge of the geological and hydrogeological conditions, (ii) standard and (iii) enhanced thermal response tests, (iv) laboratory experiments on drill cuttings and (v) reference values for geological material-dependent thermal conductivities published in the literature. This unique methodology relies on the interpretation of a large set of TRT measurements well distributed spatially at the scale of the studied area, and assumes that the thermal conductivity determined during a TRT is a thickness-weighted average of the individual thermal conductivity of each stratigraphic unit encountered along a GHE. As the procedure is primarily based on TRT generally conducted for designing GHE, typically installed in the upper 150 m, all the stratigraphic units in the subsurface relevant for GHE are thus characterized. If the piezometric levels in the different aquifers of the region are known, this procedure allows also to differentiate thermal conductivities of saturated and unsaturated materials. Reference geological material-based thermal conductivity values and specific laboratory tests are used to validate the inferred thermal conductivities, especially the values with higher uncertainties. The proposed methodology is intended to be robust, but also flexible since it can be adapted to various geological contexts.

The method is assessed on the Brussels-Capital Region (BCR). The Brussels-Capital Region covers 161 km^2 and the population is increasing (1.18 million inhabitants in 2018). In addition, the dense urban environment leads to a higher potential for implementing green heating and cooling technologies, as it is the case of vertical GHE. After the application of the methodology to BCR subsurface and the subsequent determination of saturated and unsaturated thermal conductivities for each stratigraphic unit encountered in the region, an uncertainty analysis of the ground thermal conductivity is proposed, and its impact on the design of GHE (i.e. drilling length) is quantified and discussed.

2. Geological and hydrogeological context of Brussels-Capital Region (BCR)

The subsurface of the BCR is primarily made up of a succession of sedimentary deposits. Various horizontal strata (from Cretaceous (-70 Ma) to Quaternary (< -1Ma)) unconformably overlie Lower Cambrian basement rocks (-540 Ma). The top of the basement rocks is encountered at depths between 40 and 200 meters. The deposits of the Lower Cambrian are made up of very heterogeneous sedimentary rocks (i.e. interstratified quartzites, shales, phyllites and sandstones layers). The geological structure is rather complex (i.e. nearly vertical and highly fractured strata). More details on the geological context of the BCR can be found in Buffel & Matthijs (2002). The subsurface can be divided into 19 different stratigraphical units that are distinguished mainly by their distinct lithology and age (Devleeschouwer et al., 2017). The data are provided in Table 1.

3. Data

3.1. Geological model

A robust GIS-supported geological model is required to represent the spatial distribution of the different stratigraphic units encountered in the region, with thickness and depth information. The model has to

Table 1
Stratigraphic units in BCR: detailed lithology and maximum thickness

Era	Stratigraphic unit	Detailed lithology	Maximum thickness (m)
Quaternary	Quaternary	Backfill material. Loess and aeolian fine-grained sandy loam on the plateaus and slopes. Deposits of fluvial clay and peat, coarse sand, gravels and silt in alluvial plains.	40
Tertiary	Diest	Fine-grained to coarse sand, highly glauconitic.	2.5
	Bolderberg	Micaceous sand. At the bottom, presence of flint gravels	7.5
	Sint-Huibrechts	Fine-grained micaceous sand, followed by silt and clay to the bottom. At the bottom, presence of quartz and flint gravels	7.5
	Onderdale	Fine-grained sand, silty, glauconitic and micaceous	2.5
	Ursel and Asse	Glauconitic clay. At the bottom, coarse and glauconitic sand	10
	Wemmel	Fine grained and glauconitic sand.	10
	Lede	Fine grained sand, locally calcareous and slightly glauconitic.	22.5
	Brussels	Glauconitic sand.	45
	Vlierzele	Fine grained and glauconitic sand, more argillaceous at the bottom.	7.5
	Merelbeke	Clay.	10
	Tielt	Alternation of fine-grained, micaceous, glauconitic sand and clay	17.5
	Aalbeke	Clay, slightly silty.	10
	Moen	Heterogeneous deposits of silty to clayey sand, with some thin clay layers.	47.5
	Saint-Maur	Clay	52.5
	Grandglise	Fine-grained, glauconitic sand, with thin clay intercalations	15
	Lincent	Clay, slightly sandy	27.5
Mesozoic	Cretaceous	Chalk with some flints	32.5
Paleozoic	Upper Cambrian	Feldspathic sandstone, schist and quartzites. Possible alteration into clay.	-

characterize the subsurface at depths where GHE are generally installed (i.e. up to about 150 m). Such models were developed in different regions across the globe and for various purposes as geological interpretations, quantitative numerical simulations, or resource evaluations (Kaufman & Martin, 2008; Santilano et al., 2016; Xie et al., 2017).

In the case of the BCR, a 3D GIS-supported geological model of the subsurface exists and is used in this study (Devleeschouwer et al., 2017). This BCR model provides all the information on the extent of the 19 stratigraphical units encountered in Brussels (i.e. up to the top of Upper Cambrian deposits). The lateral resolution of the model is 10 × 10 m. Isopach maps with equidistance of 2 meters have been extracted from the geological model for each stratigraphical unit and allows the characterization of the thicknesses and depths of each unit.

3.2. Piezometric maps

Knowledge about the groundwater table level in each aquifer of the region is necessary. For that purpose, piezometric maps were generally constructed at the scale of the hydrogeological basin (Fasbender et al., 2008; Buchanan & Triantafilis, 2009).

For the BCR, piezometric maps have been built for each aquifer and aquitard by the agency in charge of the water resources management in Brussels (Agniel, 2020). Maps are based on data collected in May 2013, with equidistance of 2 meters and lateral resolution of 10 × 10 m. No piezometric map is available for the Lower Cambrian bedrock.

3.3. Thermal response tests

A TRT is an in-situ test performed in GHE to infer the average thermal conductivity of the ground penetrated by the GHE. The test includes injecting heated water with controlled heating power within a GHE, and to measure the change of the inlet and outlet temperature in the geothermal loop (Gehlin, 2002). From the Infinite Line Source (ILS) model, it is then possible to calculate the average ground thermal conductivity. It is worth mentioning that only an average ground thermal conductivity can be deduced, while the specific thermal conductivities of each stratigraphic unit surrounding the GHE cannot be measured directly.

Twenty-one TRT were performed in the BCR by research centers or companies involved in the field of geothermal energy. Five additional TRT were performed outside the BCR, but in similar geological strata, and at a distance within 15 km from the boundaries of the region. For each test, the exact location (Figure 1), the depth of the GHE and the average ground thermal conductivity were recorded.

3.4. Enhanced Thermal Response Tests

An Enhanced Thermal Response Test (ETRT) is a testing method that allows consideration of measurement variations in the ground thermal conductivity along the entire length of GHE (Heske et al., 2011; Vieira et al., 2017). It relies on the measurement of temperatures at different depths along the borehole, using temperature sensors (e.g. PT100, optic fibers, etc.). In addition to the temperature measurements, heat is injected into the ground by means of a copper heating cable. Generally, the copper cable and the optic fibers are integrated into a single hybrid cable installed on the external surface of the heat exchanger. The use of a copper cable allows to impose a constant heating power all along the GHE. This is not the case in TRT for which the heating power is controlled only at the ground surface. Hence the heating power injected within the ground during TRT is not necessarily constant along the depth of the borehole and depends on the ground thermal properties.

Three ETRT were performed by research centers in BCR. In addition, two ETRT performed in similar geological strata and at distances within 15 km from the boundaries of the region have been added. For each ETRT, the location (Figure 1), depth of GHE, and the evolution of thermal conductivity with depth were collected.

3.5. Laboratory optical scanning technique

The optical scanning technique is a laboratory method that aims at measuring the thermal properties of the geomaterials, such as the thermal conductivity, without contacting the sample, and allows eliminating the contact thermal resistivity (Popov et al., 1999). One sample surface is heated up by an optical focused mobile heat source that moves at a constant speed over the sample. The temperature is measured before and after the passage of the source at the sample surface. Under quasi-steady state conditions, the thermal conductivity is determined based on the heat flux imposed and the temperature variation recorded at sample surface before and after the heat source passage. A thin layer of black paint must be applied on the sample surface being tested to ensure that all the heat radiation is absorbed by the sample and not reflected.

To analyze the samples in similar conditions to in-situ, it is preferable to collect undisturbed core samples. However undisturbed sampling requires specific and generally expensive drilling techniques. In most cases, drill cuttings are collected. Remolded samples have thus to be prepared with the following procedure. After drying and packing, drill cuttings from a same stratigraphic unit and a same borehole are first

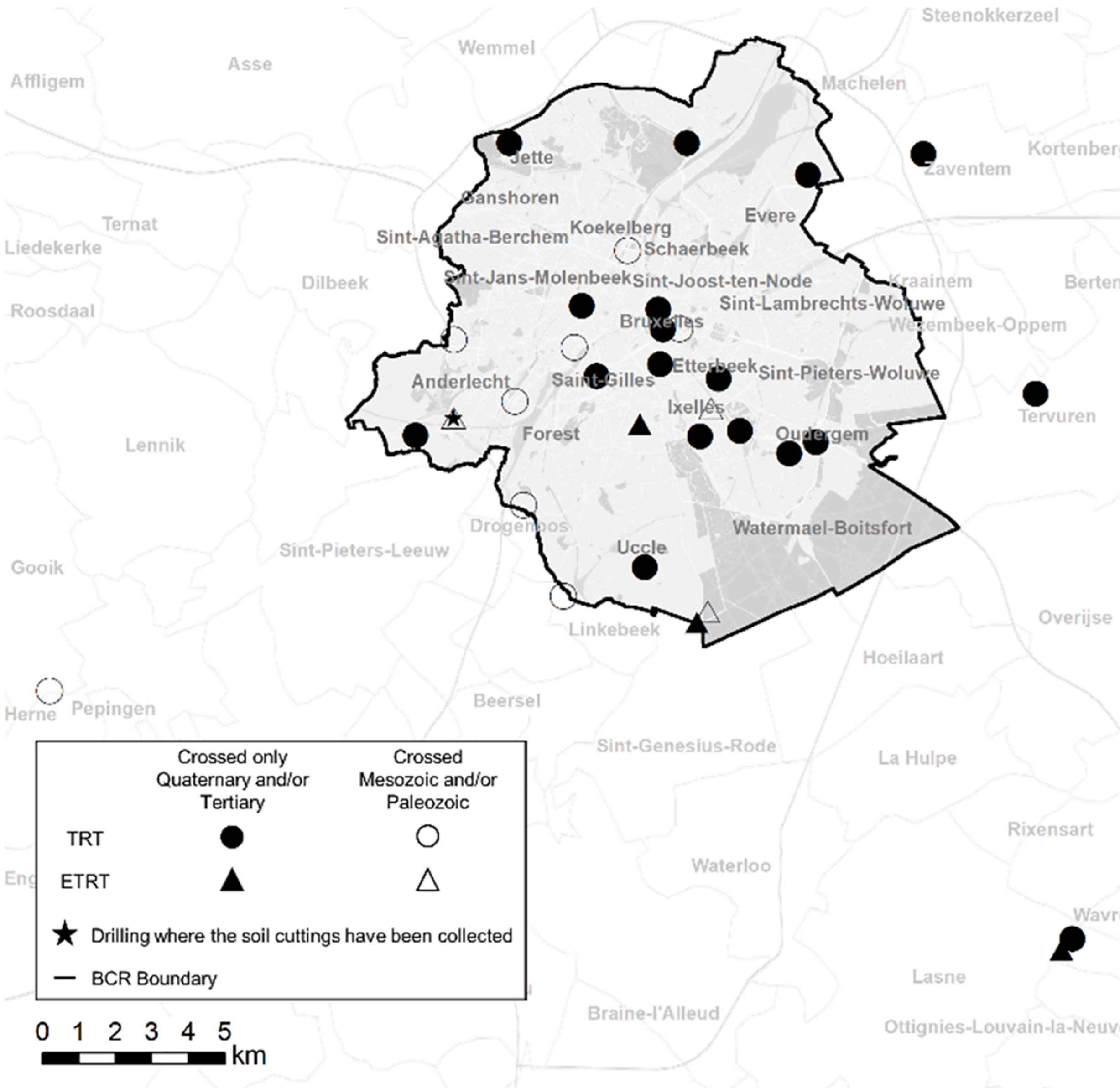

Figure 1. Locations of thermal response tests (TRT) and enhanced response tests (ETRT) collected for the study, as well as the site where drill cuttings were collected for laboratory tests

mixed at a given water content. After homogenization, wet cuttings are compacted dynamically in a cylindrical mold at a given unit weight. The target unit weight aims at replicating the in-situ dry unit weight for each stratigraphic unit. On the other hand, it is unrealizable to replicate the in-situ water content of saturated stratigraphic units. It is indeed complex to manipulate saturated samples. In addition, the exact water content of unsaturated ground is generally not known above the groundwater table, even when advanced in-hole geophysical techniques (e.g. neutron-neutron) can sometimes provide such preliminary information (Bell & McCulloch, 1969). Consequently, samples at different water contents are prepared and tested for each stratigraphic unit. An empirical relationship predicting the evolution of the thermal conductivity λ with the water content is then used to extend the measurements to a wider range of water content (Johansen, 1977).

$$\lambda = K_e\left(\lambda_{sat} - \lambda_{dry}\right) + \lambda_{dry} \tag{1}$$

$$K_e = \log S_r + 1 \tag{2}$$

$$\lambda_{sat} = \lambda_w^n \lambda_s^{1-n} \tag{3}$$

$$\lambda_{dry} = \lambda_{air}^n \lambda_s^{1-n} \tag{4}$$

with λ_{sat} and λ_{dry} the thermal conductivities of the saturated and dry material respectively, λ_s the thermal conductivity of the mineral grains (that depend on the mineralogy), λ_w and λ_{air} the thermal conductivities of the water (=0.6 W/mK) and the air (=0.024 W/mK) respectively, n the porosity and S_r the degree of saturation (that is water content w dependent according to the following relationship

$$w = S_r \gamma_w \left(\frac{1}{(1-n)\gamma_s} - \frac{1}{\gamma_w}\right) \tag{5}$$

where Υ_s and Υ_w are the solid grains (=27 kN/m^3) and the water (=10 kN/m^3) unit weights respectively.

The suitability of the optical scanning technique to characterize the thermal conductivity of remolded samples has been demonstrated on similar Belgian materials (Gerard et al., 2019).

For this study, drill cuttings were collected during the installation of a piezometer in the BCR, in Anderlecht (see location on Figure 1). Remolded samples are thus prepared according to the aforementioned procedure. The dimensions of the samples are a thickness of 1.5 cm and diameter of 5 cm. The samples are compacted at the in-situ dry unit weight, whose the values are provided for each stratigraphic unit by the geotechnical maps of Brussels (Dam et al., 1984).

3.6. Reference geological material-based thermal conductivities

Ranges of geological material-based thermal conductivities have been published (Schön, 2015) and provide a first estimation if the lithological composition of a stratigraphic unit is known, but returns a high level of uncertainty. In this study, it is suggested to adopt the geological material-dependent thermal conductivities recommended by the Swiss recommendations for the design of GHE (SIA, 2010), first because the geological material-based thermal conductivities are proposed for GHE applications. Moreover a distinction between saturated and dry thermal conductivities is considered.

Alternatively, lithology or geological material-dependent thermal conductivities may have been proposed for specific regional purposes, based on in-situ or laboratory measurements. When they characterize similar lithologies as encountered in the studied area, such data can be considered as valuable. In this study, geological material-based thermal conductivities exist for the different stratigraphic units from the Tertiary encountered in Flanders, which is a Belgian region located in the North of the BCR that covers 13 625 km^2 (i.e. 85 times larger than the BCR) (Van Lysebetten et al., 2013; Vieira et al., 2017). The stratigraphic units and the geological context of Flanders is similar to the BCR, and those values can provide estimations for our study. The determination of the thermal conductivity in Van Lysebetten et al. (2013) relies on the inverse analysis of fourteen TRT collected in Flanders. The main limitations of this contribution are (i) the low spatial density of data considered (1 TRT/970 km^2), (ii) thermal conductivities determined first based on their geological materials (sand, clayey sand, silt, sandy clay or clay) and then attributed to the different stratigraphic units (i.e. 2 stratigraphic units with the similar geological materials, but having different ages and mineralogy, will have necessary the same thermal conductivity) and (iii) the non-distinction between unsaturated and saturated thermal conductivities in unconfined aquifers.

Table 2 summarizes the reference geological material-based thermal conductivities used in this study.

4. Methodology

4.1. TRT-based inverse analysis procedure

The objective of the study is to develop a methodology allowing the determination of both the saturated and unsaturated thermal conductivities of stratigraphic units encountered in a region. The methodology is primarily based on the interpretation of TRT measurements collected in the studied area. The TRT must have a high spatial density and be well distributed in the studied region. Adopting a TRT-based methodology is motivated by (i) the availability of geological models and piezometric maps in the studied area that allows a reliable reconstruction of the stratigraphic units encountered along each TRT, as well as their total and saturated thicknesses, (ii) the reliability of TRT to characterize in-situ geothermal properties, on the contrary of laboratory tests for which the samples preparation in similar conditions to in-situ is questionable and (iii) the significance of TRT results since TRT is achieved with heat powers close to the ones used in GHE systems.

Table 2
Reference geological material-based thermal conductivity (from SIA, 2010; Van Lysebetten et al., 2013)

Geological material	Saturated state	Thermal conductivity λ (W/mK)			
		Swiss norm (SIA, 2010)		Van Lysebetten et al. (2013)	
		Range	Reference	Minimum	Average
Sand	Dry	0.3 – 0.8	0.5	1.9	2.3
	Saturated	1.5 – 4.0	2.3		
Loam	Dry	-	-	1.6	1.9
	Saturated	-	-		
Clay	Dry	0.4 – 1.0	0.6	1.2	1.5
	Saturated	0.9 – 2.3	1.4		

In case of heterogeneous ground conditions, TRT measurements characterize the average ground thermal conductivity along a GHE. Assuming that the thermal flux between the GHE and the ground is radial (i.e. sufficiently long GHE and horizontal geological layers in the thermal radius of influence), the average ground thermal conductivity $\lambda_{TRT,calc}$ can be calculated by the weighted mean of the thermal conductivity of each stratigraphic unit crossed along the GHE:

$$\lambda_{TRT,calc} = \frac{\sum_{i=1}^{n} \lambda_i h_i}{\sum_{i=1}^{n} h_i} \quad (6)$$

with λ_i and h_i the thermal conductivity and the thickness of the stratigraphic unit i, and n the number of stratigraphic units crossed along the GHE.

Assuming now that the thermal conductivity of a stratigraphic unit is homogeneous at the scale of the studied region, it is possible to determine the thermal conductivity of each stratigraphic unit by inverse analysis and least square method, using the set of TRT results available at the scale of the region. The least square method leads to minimize the following function:

$$min \sum_{j=1}^{m} \left(\lambda_{TRT,meas,j} - \lambda_{TRT,calc,j} \right)^2 \quad (7)$$

where $\lambda_{TRT,meas}$ is the average ground thermal conductivity measured in-situ during a TRT, and m is the number of TRT results available.

4.2. Implementation of the procedure

The methodology consists primarily in the TRT-based inverse analysis procedure described in section 4.1. In this inverse analysis problem, the unknowns are thus the thermal conductivities λ (i.e. saturated and unsaturated) of each stratigraphic unit encountered in the region, while the data are the in-situ TRT measurements $\lambda_{TRT,meas}$. Two points deserve special attention during the implementation of the procedure. First, the use of the TRT-based inverse analysis methodology can lead to undersized problems, because the number of unknowns can be larger than the number of data. In this situation, a reduction of the number of unknowns is necessary, and can be motivated by the in-depth knowledge of the geological and hydrogeological regional context. First the thermal conductivities of stratigraphic units that are in contact and with similar geological materials and mineral compositions can be reasonably considered as similar. Also, some stratigraphic units can be fully saturated in all the studied area (e.g. confined aquifer). The unsaturated thermal conductivities of those stratigraphic units do not have thus to be included as unknowns in the inverse analysis problem, because they are not encountered in the studied region.

Secondly, in an inverse analysis problem, some unknowns are determined based on a much more restricted number of data, and present thus higher uncertainties. In addition, some unknowns are less relevant for the final use of the results (e.g. thin stratigraphic units, or stratigraphic units with low spatial extent do not impact strongly the overall efficiency of GHE). The risk is that the values inferred for those unknowns impact negatively the determination of the other unknowns. In this contribution, the term "non-significant" stratigraphic units will be used to characterize the unknowns that are less relevant for the application, or whose the determination leads to high uncertainties. The TRT-based procedure has to avoid to attribute a too important weight to non-significant stratigraphic units. Indicators are thus defined to assess the significance and the relevance of a stratigraphic unit in the TRT-based methodology. First indicators based on the regional geological context are adopted to assess the relevance of a stratigraphic unit for shallow geothermal energy applications, namely:

5- the relative extent of each stratigraphic unit in the studied region;
5- the maximal thickness of each stratigraphic unit in the studied region;
5- the depth at which the top of each stratigraphic unit is encountered in the studied region.

Then indicators based on the available data are considered to detect stratigraphic units poorly characterized by the TRT, which could lead to results with large uncertainties. These indicators are:

5- the number of TRT penetrating each stratigraphic unit in the studied region (# TRT);
5- the average percentage of TRT length crossing each stratigraphic unit (%LT), defined for a stratigraphic unit i by:

$$\%LT_i = \frac{\sum_{j=1}^{m} h_{ij}}{\sum_{j=1}^{m} H_j} \quad (8)$$

with h_{ij} the thickness of stratigraphic unit i along TRT j, H_j the total length of TRT j and m the number of TRT collected.

In order to reduce the weight of the stratigraphic units that are considered as less significant for the TRT-based methodology according to the aforementioned indicators, these non-significant unknowns are determined beforehand from an adapted methodology. The adapted methodology consists to assign a geological material (Quaternary, sand, silt, clay) to each stratigraphic unit based on the detailed lithology. The determination of the thermal conductivity of each geological material (differentiating between unsaturated and saturated thermal conductivities) is then done using the TRT-based procedure eqs. 6 and (7). The high heterogeneity of Quaternary deposits (i.e. mixture of fill - disturbed ground, loess, alluvium, etc.) and the subsequent weak reliability of 3D geological models to differentiate the lithology of such deposits require to consider it explicitly as a distinct geological material (e.g. Quaternary). Reference geological material-based thermal conductivities from the literature will be used to validate the thermal conductivities of each geological material obtained with this procedure.

The thermal conductivities of the significant stratigraphic units can be then determined based on the TRT-based procedure eqs. 6 and (7), imposing to the non-significant stratigraphic units the thermal conductivities of the corresponding geological materials. ETRT and published data will be consulted to validate these results.

In case of thermal conductivities with high uncertainties or unrealistic values (i.e. not consistent with the ranges of geological material-based thermal conductivities proposed in the literature) in some stratigraphic units, laboratory optical scanning tests will be achieved on remolded samples from drill cuttings to confirm or adapt slightly the results.

In summary, this TRT-based inverse analysis procedure consists of five steps represented in Fig. 2.

4.3. Applicability of the methodology

The aforementioned methodology is applicable for regions for which (i) a thorough knowledge of the area geology is available (i.e. the exact lithology of each stratigraphic unit encountered in the subsurface has to be known) and (ii) the lithology of each stratigraphic unit can be reasonably considered as homogeneous at the scale of the studied region. Both conditions have to be met for all the stratigraphic units encountered at depths where GHE are generally installed (i.e. up to about 150 m).

In addition to geological models and piezometric maps of the different aquifers, TRT measurements spatially well distributed have to be collected. As a general rule, ideally, the number of stratigraphic units should be fewer than the number of TRT measurements. However, in practice, if it is not the case, the problem is undersized. Both additional geothermal data (such as ETRT, laboratory tests on undisturbed or remolded samples, or reference geological material-based thermal conductivities) and additional assumptions based on the knowledge of the geological context can be used to reduce the number of unknowns, and consequently improve the robustness and the reliability of the methodology. However, if the problem is initially well-posed (more data than unknowns), those additional data or assumptions are not compulsory.

5. Results

5.1. Application to the BCR

The methodology described in Figure 2 is now applied to the BCR. The aim is to determine the thermal conductivities of saturated and unsaturated materials of the 19 stratigraphic units encountered in the BCR (Table 1), namely 38 unknowns/stratigraphic units thermal conductivities, using the set of geological, hydrogeological and geothermal data presented in section 3. In the case of BCR, 26 TRT are available, which corresponds to a spatial density of 1 TRT/6 km^2. The TRT are also well spatially distributed (Figure 1). The problem is thus undersized (38

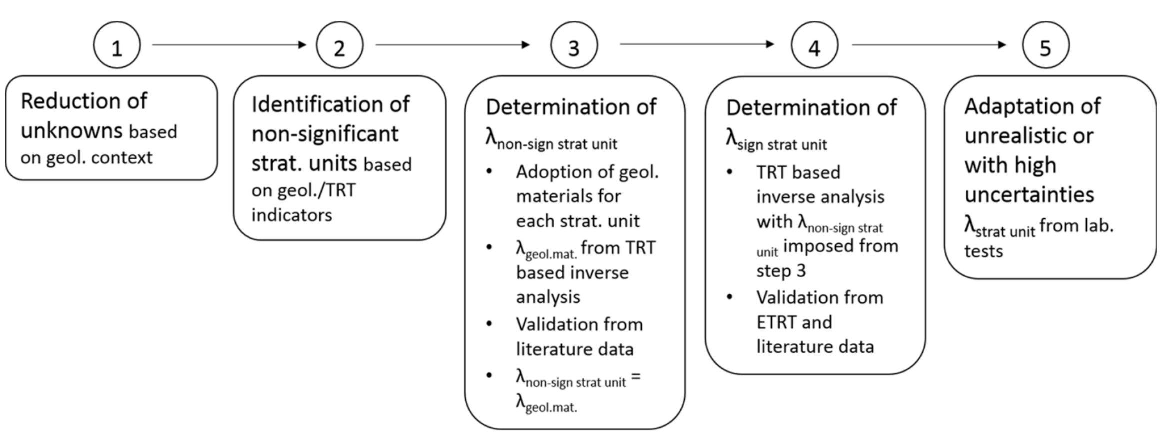

Figure 2. Flowchart of the proposed methodology focused on a TRT-based inverse analysis procedure

unknowns vs 26 data).

Furthermore the determination of the thermal conductivities of Mesozoic and Paleozoic bedrock with the aforementioned TRT-based procedure is not really significant and relevant, since these layers are less explored for GHE systems in BCR because they are encountered at greater depths (i.e. the top of Mesozoic and Paleozoic units are encountered at depths > 80 m over more than two thirds of the BCR; Devleeschouwer et al., 2017) and require different drilling techniques than penetrating the softer Tertiary stratigraphic units. Also, the Mesozoic and Paleozoic units are characterized by highly heterogeneous and poorly characterized geological conditions, which impacts the reliability of the TRT-based inverse analysis procedure. A 2-phase methodology that gives the priority to Quaternary and Tertiary stratigraphic units is thus adopted. In a first phase, the thermal conductivities of Quaternary and Tertiary stratigraphic units are determined with the aforementioned methodology Fig. 2), considering the 18 TRT in those layers. The lithology of each Quaternary and Tertiary stratigraphic unit is well homogeneous at the scale of BCR (Dam et al., 1984), which provides reliability in the TRT-based procedure (eq. 6 and (7) in this first phase. In the second phase, the thermal conductivities of Mesozoic and Paleozoic stratigraphic units are determined using the same general procedure, but instead using only the 8 TRT conducted in those layers, and adopting the thermal conductivities of Quaternary and Tertiary stratigraphic units determined in the first phase. In conclusion, this 2-phase procedure limits the impact of the high uncertainties on the thermal conductivity of Mesozoic and Paleozoic units (due to their heterogeneities) on the determination of Quaternary and Tertiary thermal conductivities.

For each phase, the results are detailed and analyzed hereafter in order to demonstrate the relevance of the method.

5.2. Phase 1 – Thermal conductivities of Quaternary and Tertiary stratigraphic units

The determination of the thermal conductivities of Quaternary and Tertiary stratigraphic units is based on 34 unknowns (17 stratigraphic units, dissociating saturated and unsaturated thermal conductivities) and 18 data (TRT results). The inverse analysis problem is thus undersized.

Step 1 – Reduction of number of unknowns

The knowledge of the geological conditions in the BCR, and the comparison between the associated geological model and piezometric maps lead to the following conclusions or assumptions:

- The stratigraphic units of Saint-Maur, Grandglise and Lincent are fully saturated everywhere. The stratigraphic units of Aalbeke and Moen are considered fully saturated (more than 95 % or their surfaces are saturated).
- A similar thermal conductivity is attributed to Brussels, Wemmel and Lede stratigraphic units because of similar lithologies and mineralogical compositions (Dam et al., 1984) .

Step 2 – Identification of non-significant stratigraphic units

Using the aforementioned indicators, the non-significant stratigraphic units can be identified. It is worth noting that the indicator related to the depth at with a stratigraphic unit is encountered has been already used to motivate the 2-phase approach. For that reason, this indicator is not considered anymore in Step 2.

Table 3 presents (amongst the 18 TRT considered for Phase 1) the number of TRT penetrating each stratigraphic unit and the average percentage of TRT length in each stratigraphic unit. The maximal thickness and the relative extent (compared to the surface area of BCR) of each stratigraphic unit in BCR is also provided. It highlights that the stratigraphic units of Diest, Bolderberg, Sint-Huibrechts-Hern, Onderdale, Ursel and Asse, Vlierzele, Merelbeke, Tielt and Aalbeke are crossed by no TRT or with %LT lower than 5%. Besides those stratigraphic units have generally limited thicknesses compared to the standard length of GHE and their relative spatial extent is very small (≤ 25%). Hence the incorporation of those unknowns in a TRT-based procedure would lead to results with high uncertainties owing to their low weightings in the inverse analysis. Those stratigraphic units are therefore considered as non-significant. Furthermore the saturated part of the Quaternary deposits is added to the list of non-significant stratigraphic units. Even if this unit presents a higher relative extent (45%), the low number of TRT penetrating this unit and the lower %LT, associated to the high lithological heterogeneity of such fluvial deposits, can lead to thermal conductivities with high uncertainties using the TRT-based procedure. In the 25 stratigraphic units given in Table 3, 18 are thus considered as non-significant and 7 as significant (i.e. unsaturated Quaternary, unsaturated and saturated Wemmel/Lede/bruxelles, saturated Moen,

Table 3
Number of TRT available (# TRT) and average percentage of TRT length (% LT) crossing the stratigraphic units from Tertiary and Quaternary periods

Era	Stratigraphic unit	Saturated state	# TRT	%LT (%)	Maximum thickness (m)	Relative extent (%)	Geological material
Quaternary	Quaternary	Unsaturated	17	8.3	40	100	Quaternary
		Saturated	2	0.2		45	
Tertiary	Diest	Unsaturated	0	-	2.5	0.1	Sand
		Saturated	0	-			
	Bolderberg	Unsaturated	0	-	7.5	0.1	Sand
		Saturated	0	-			
	Sint-Huibrecht	Unsaturated	0	-	7.5	6.0	Silt
		Saturated	0	-			
	Onderdale	Unsaturated	0	-	2.5	0.1	Sand
		Saturated	0	-			
	Ursel and Asse	Unsaturated	2	0.7	10	8.9	Clay
		Saturated	0	-			
	Wemmel, Lede and Brussels	Unsaturated	13	13.1	40	61.8	Sand
		Saturated	11	10.8			
	Vlierzele	Unsaturated	0	-	7.5	4.6	Sand
		Saturated	1	0.4			
	Merelbeke	Unsaturated	0	-	10	5.9	Clay
		Saturated	1	0.5			
	Tielt	Unsaturated	1	0.03	17.5	21.3	Silt
		Saturated	3	1.6			
	Aalbeke	Saturated	3	0.5	10	19.8	Clay
	Moen	Saturated	17	29.3	47.5	93.9	Silt
	Saint-Maur	Saturated	17	23.3	52.5	100	Clay
	Grandglise	Saturated	10	5.3	15	99.7	Sand
	Lincent	Saturated	9	5.9	27.5	96.4	Clay

saturated Saint-Maur, saturated Grandglise and saturated Lincent).

To complete the analyses, different alternative criteria on the indicators (# TRT ≤ 3; (# TRT = 0 or %LT < 5%) and Quaternary; # TRT ≤ 3 and Quaternary) allowing to isolate the non-significant stratigraphic units have been tested, without affecting significantly the thermal conductivities of the 7 significant stratigraphic units obtained during Step 4.

Step 3 – Determination of thermal conductivities of non-significant stratigraphic units

In order to determine the thermal conductivities of the stratigraphic units classified as non-significant, a geological material (i.e. Quaternary, sand, silt, clay) is assigned to each stratigraphic unit (Table 3). Table 4 summarizes the number of TRT, as well as the average percentage of total length of TRT, crossing each geological material on the basis of 18 TRT penetrating only Tertiary and Quaternary deposits. It appears that 3 units (saturated Quaternary, unsaturated silt and unsaturated clay) would have a low weighting in the inverse analysis procedure, because both the number of TRT and the average percentage of total length of TRT crossing those units are low. It is proposed to focus first only on the 5 other geological materials and the 13 TRT penetrating them (excluding thus 5 TRT for this modified configuration). The results of this modified configuration are provided in Table 4.

The analysis of the calculated values in the modified configuration highlights the relevance of the results ($\lambda_{sand} > \lambda_{silt} > \lambda_{clay}$; $\lambda_{sand\text{-}sat} > \lambda_{sand\text{-}unsat}$). In addition, the comparison of those values with the reference geological material-based thermal conductivities presented in Table 2 shows good consistency, especially for the saturated clay that is in agreement with the Swiss norm and the values proposed by Van Lysebetten et al. (2013) for similar geological conditions. For the saturated silt, the calculated thermal conductivity is higher than the value proposed by Van Lysebetten et al. (2013). However it is worth to note that the unsaturated and saturated thermal conductivities are not differentiated in Van Lysebetten et al. (2013). It is thus consistent to obtain a saturated thermal conductivity of the silt higher than the value proposed by those authors. For the dry sand, the calculated thermal conductivity is close to the minimal value proposed by Van Lysebetten et al. (2013). Considering again the methodology adopted in Van Lysebetten et al. (2013), it is consistent to consider that the minimal value corresponds to the one of the dry sand. No comparison is possible for the Quaternary. However, the obtained value seems realistic, even if the high heterogeneity of the Quaternary deposits necessitates to use this value with care. Due to the lack of in-situ data, the thermal conductivity of the 3 remaining units (i.e. saturated Quaternary, unsaturated silt and unsaturated clay) is then determined using reference values suggested in Table 2 and adopted in Table 4 (column “final recommendation”).

Finally, the geological material-based thermal conductivities obtained in Table 4 are attributed to stratigraphic units classified as non-significant (i.e. # TRT = 0 or %LT < 5%).

Step 4 – Determination of thermal conductivities of significant stratigraphic units

In order to determine the thermal conductivities of the 7 stratigraphic units (i.e. classified as significant), the TRT-based procedure eq. 6 and (7) is then applied, using the 18 TRT crossing only Quaternary and Tertiary deposits. The results are provided in Table 5. The obtained thermal conductivities (except for Grandglise and Lincent for which a thorough analysis is given later) seem realistic for several reasons. First, they are in good agreement with the geological material-based thermal conductivities determined in Table 4 when the geological material of the 7 stratigraphic units is considered. Then they are also consistent with the reference values of Table 3. Finally, the results are compared with the range of local thermal conductivities measured in front of each stratigraphic unit by the 5 ETRT collected in or near BCR and that are provided in Table 5. A good agreement is observed between the in-situ thermal conductivities obtained from ETRT and the TRT-based procedure respectively.

Those results demonstrate first the consistency of the TRT-based procedure and the indicators adopted. Also the good agreement between in-situ measurements and the calculated lithology-based thermal conductivities highlight the reliability of the methodology. However, the results seem less convincing for Grandglise and Lincent stratigraphic units. The obtained thermal conductivities are not in agreement with any of the sources of data that can be used for validation, despite the large number of TRT penetrating both stratigraphic units. For Lincent, the thermal conductivity is too low for a saturated clay, while the thermal conductivity of Grandglise is too high for a saturated sand. The depth of those two stratigraphic units and the subsequent higher uncertainties in the 3D geological model can probably explain the inconsistencies.

Step 5 – Adaptation of unrealistic thermal conductivities or with high uncertainties from laboratory tests

Laboratory thermal scanning technique has then been used to provide deeper insights and address the uncertainties associated with the thermal conductivities of Grandglise and Lincent stratigraphic units. Drill cuttings from those stratigraphic units have been compacted at a dry unit weight (Υ_d) provided by Brussels geotechnical maps (i.e. Υ_d = 15.2 kN/m^3 for both Grandglise and Lincent units, which corresponds to a porosity of 0.43). Different water contents have been tested for the Lincent unit, as illustrated in Figure 3(a). The thermal conductivity of the solid grains λ_s is then fitted (λ_s = 5.3 W/mK) in order to obtain a good agreement between the experimental data and the Johansen empirical model (equation 1). The Johansen model can be then used to predict the saturated thermal conductivity of the Lincent stratigraphic unit from the saturated water content w_{sat} given by eq. 5 considering S_r = 1.

The same experimental procedure is applied with remolded samples of the Grandglise unit. However, the low quantity of cuttings collected

Table 4

Thermal conductivities of geological materials encountered in the BCR obtained from TRT-based procedure (initial configuration = 8 geological materials and 18 TRT; modified configuration = 5 geological materials, excluding geological materials with low weight in the inverse analysis (indicated with grey cells) and 13 TRT)

Geological material	Saturated state	Initial configuration		Modified configuration			Final recommendation
		# TRT	%LT (%)	# TRT	%LT (%)	λ (W/mK)	λ (W/mK)
Quaternary	Unsaturated	17	8.3	12	7.1	1.6	1.6
	Saturated	2	0.2				2.2
Sand	Unsaturated	13	13.1	11	14.7	1.8	1.8
	Saturated	17	16.5	13	18.5	2.6	2.6
Silt	Unsaturated	1	0.03				1.6
	Saturated	17	30.9	12	27.9	2.2	2.2
Clay	Unsaturated	2	0.7				1.2
	Saturated	17	30.3	12	31.8	1.4	1.4

Table 5
Thermal conductivities of Tertiary and Quaternary stratigraphic units from BCR obtained with TRT-based procedure (grey cells correspond to thermal conductivities imposed during the procedure). (*) The obtained thermal conductivities for Grandglise and Lincent stratigraphic units present unrealistic values, corrected in Step 5.

Era	Stratigraphic unit	Saturated state	λ (W/mK)		
			TRT-based procedure	Optical scanning technique	ETRT
Quaternary	Quaternary	Unsaturated	1.9		1.4 -2.2
		Saturated	2.2		
Tertiary	Diest	Unsaturated	1.8		
		Saturated	2.6		
	Bolderberg	Unsaturated	1.8		
		Saturated	2.6		
	Sint-Huibrechts	Unsaturated	1.6		
		Saturated	2.2		
	Onderdale	Unsaturated	1.8		
		Saturated	2.6		
	Ursel and Asse	Unsaturated	1.2		
		Saturated	1.4		
	Wemmel, Lede and Bruxelles	Unsaturated	1.6		0.9 – 1.9
		Saturated	2.6		1.8 – 2.9
	Vlierzele	Unsaturated	1.8		
		Saturated	2.6		
	Merelbeke	Unsaturated	1.2		
		Saturated	1.4		
	Tielt	Unsaturated	1.6		1.4 – 2.2
		Saturated	2.2		
	Aalbeke	Saturated	1.4		
	Moen	Saturated	2.1		1.6 – 2.4
	Saint-Maur	Saturated	1.4		1.4 – 2.2
	Grandglise	Saturated	4.2 (*)	2.2	1.9 – 2.6
	Lincent	Saturated	1.0 (*)	2.0	1.4 – 2.3

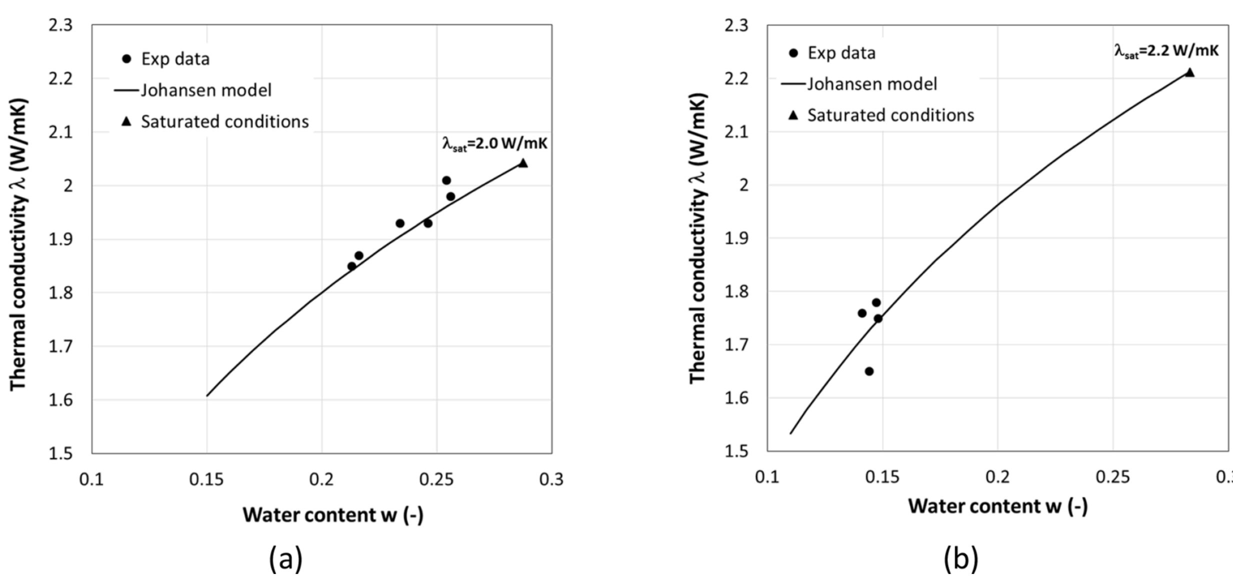

Figure 3. Prediction of saturated thermal conductivity of (a) Lincent and (b) Grandglise stratigraphic units from optical scanning experimental technique data and Johansen (1977) empirical model.

did not allow testing of a large range of water contents. In addition, the sandy texture of the Grandglise unit leads to compact samples at water contents noticeably lower than the saturated water content in order to provide to the specimen a sufficiently high capillary cohesion to be handled during the testing. Despite these limitations, a solid grains thermal conductivity $\lambda_s = 6$ W/mK was fitted on the experimental data (Figure 3(b)), which allows the determination of the saturated thermal conductivity of the Grandglise unit.

The saturated thermal conductivities obtained by means of the optical scanning technique are given in Table 6. The comparison with the lithology-based thermal conductivities (Table 4), with the reference thermal conductivities (Table 2) and the ETRT results show relatively good agreement for the Grandglise stratigraphic unit. The value obtained for the Lincent unit is high for a saturated clay, but it is worth mentioning that this stratigraphic unit is composed of a high sand content, as indicated in Table 1 and confirmed by the high thermal conductivities determined through ETRT. Those thermal conductivities are thus considered for Phase 2.

5.3. Phase 2 – Thermal conductivities of Mesozoic and Paleozoic stratigraphic units

In a second phase, the thermal conductivities of Mesozoic and Paleozoic stratigraphic units are determined, by assigning to the Quaternary and Tertiary units the thermal conductivities determined in Phase 1.

Step 1 – Reduction of number of unknowns

The geological heterogeneities of the Mesozoic and Paleozoic deposits, associated with the lack of information concerning the piezometry of those stratigraphic units, prevents dissociating unsaturated and saturated thermal conductivities and to consider a unique thermal conductivity per stratigraphic unit. The problem is thus composed of 2 unknowns (i.e. thermal conductivities of Mesozoic and Paleozoic stratigraphic units) for 8 data (TRT results crossing those layers). Additional assumptions are thus not needed, and it is possible to directly apply the TRT-based procedure (i.e. Steps 2 and 3 are not necessary).

Step 4 – Determination of thermal conductivities of significant stratigraphic units

The thermal conductivities of Mesozoic and Paleozoic stratigraphic units are determined through the TRT-based procedure eq. 6 and (7), using the 8 TRT crossing those layers and by imposing to the Quaternary and Tertiary units the thermal conductivities determined in Phase 1 (Table 6). The number of TRT, as well as the average percentage of TRT length, crossing each stratigraphic unit is given also in this table. It highlights the high weight of the Cambrian unit in the TRT-based inverse analysis procedure. The thermal conductivities determined by this procedure are given in Table 6. A high thermal conductivity is obtained for the Cambrian bedrock, which is consistent in light of the rocky lithology and the presence of some highly conductive (quartzite) layers. The thermal conductivities are also in good agreement with the results obtained with ETRT. However, it is worth mentioning the limitation of the approach, attributing a single thermal conductivity for the highly heterogeneous Cambrian bedrock. The lack of geological knowledge (i.e. exact lithology, geological structure), but also the limited number of geothermal data do not allow a more precise upscaling of the Paleozoic geothermal properties measured in-situ. On the other hand, the Cretaceous unit is more geologically homogeneous. Upscaling that thermal conductivity obtained with TRT-based procedure is thus relevant. Even if the number of TRT and the average percentage of TRT length crossing this unit are low, the thermal conductivity obtained is consistent and is therefore adopted. Hence there is no need to achieve laboratory tests to adapt or confirm those thermal conductivities and Step 5 is not considered.

Table 6

Thermal conductivities of stratigraphic units from BCR obtained with TRT-based procedure (grey cells correspond to thermal conductivities imposed during the Phase 2, following from Phase 1)

Era	Stratigraphic unit	Saturated state	# TRT	%LT (%)	λ (W/mK)	
					TRT-based procedure	ETRT
Quaternary	Quaternary	Unsaturated	8	8.7	1.9	1.4 -2.2
		Saturated	5	0.6	2.2	
Tertiary	Diest	Unsaturated	0	-	1.8	
		Saturated	0	-	2.6	
	Bolderberg	Unsaturated	0	-	1.8	
		Saturated	0	-	2.6	
	Sint-Huibrechts	Unsaturated	0	-	1.6	
		Saturated	0	-	2.2	
	Onderdale	Unsaturated	0	-	1.8	
		Saturated	0	-	2.6	
	Ursel and Asse	Unsaturated	0	-	1.2	
		Saturated	0	-	1.4	
	Wemmel, Lede and Bruxelles	Unsaturated	1	0.1	1.6	0.9 – 1.9
		Saturated	1	0.3	2.6	1.8 – 2.9
	Vlierzele	Unsaturated	0	-	1.8	
		Saturated	0	-	2.6	
	Merelbeke	Unsaturated	0	-	1.2	
		Saturated	0	-	1.4	
	Tielt	Unsaturated	0	-	1.6	1.4 – 2.2
		Saturated	0	-	2.2	
	Aalbeke	Saturated	1	0.2	1.4	
	Moen	Saturated	6	6.7	2.1	1.6 – 2.4
	Saint-Maur	Saturated	8	19.1	1.4	1.4 – 2.2
	Grandglise	Saturated	8	6.5	2.2	1.9 – 2.6
	Lincent	Saturated	7	8.7	2.0	1.4 – 2.3
Mesozoic	Cretaceous	Saturated	3	3.2	2.2	
Paleozoic	Cambrian	Saturated	7	45.9	3.0	2.0 – 6.0

6. Discussion

6.1. Analysis of the error on the ground thermal conductivity

The relevance and reliability of the thermal conductivities determined through the TRT-based inverse analysis have to be analyzed carefully. Complementary analyses were conducted on the 18 TRT crossing only Quaternary and Tertiary stratigraphic units. The choice of approach is motivated by the aforementioned limitations of the methodology for the determination of the Cambrian bedrock thermal conductivity. Including the TRT crossing this unit in an error analysis could alter significantly the conclusions drawn for the Quaternary and Tertiary units.

First the measured average thermal conductivities $\lambda_{TRT,meas}$ of each of the 18 TRT are compared with the average thermal conductivities $\lambda_{TRT,calc}$ calculated using Equation 6 and the specific thermal conductivities of each stratigraphic units obtained with the TRT-based procedure and provided in Table 5. Figure 4(a) highlights a small bias in the methodology. The procedure overestimates slightly the materials with low thermal conductivities ($\lambda_{TRT,meas}$ < 1.9 W/mK), while it underestimates the materials with higher thermal conductivities ($\lambda_{TRT,meas}$ > 1.9 W/mK). From those data, a relative average and maximum error on the thermal conductivity ($\delta\lambda_{rel,av}$ and $\delta\lambda_{rel,max}$ respectively) can be calculated as a function of ground average thermal conductivity (Table 7). Average relative errors lower than 10 % are calculated for the thermal conductivities measured during TRT.

In addition, the relative error was mapped for each of the 18 TRT. Figure 4(b) illustrates the absence of spatial bias associated with the methodology. There is indeed no area in BCR where the ground thermal conductivity is systematically under- or over-estimated. It confirms the relevance of the initial assumption on the homogeneity of the thermal properties of each stratigraphic unit at the scale of BCR.

Table 7
Average and maximal relative error on the thermal conductivity calculated from the TRT-based procedure

	$\delta\lambda_{rel,av}$ (%)	$\delta\lambda_{rel,max}$ (%)
$\lambda_{TRT,meas}$ < 1.9 W/mK	7.5	16.9
$\lambda_{TRT,meas}$ > 1.9 W/mK	-9.7	-22.8

6.2. Impact of thermal conductivities uncertainties on the design of closed-loop GHE

The relative error analysis on the thermal conductivity has to be contextualized to assess the reliability of the methodology and the subsequent results. For that purpose, the impact of the relative error on the ground thermal conductivity for the design of GHE (i.e. total GHE length necessary for the heating/cooling of a given building) was assessed. The normal Dutch design method of GHE is considered (cf. ISSO73, 2005). For this design method, the preliminary total GHE length L_{GHE} is calculated first based on the thermal load that has to be supplied to/from the ground, as well as the heat transfer rate per unit length between the ground and GHE and additional parameters as the heat pump coefficient of performance (COP), the heat pump operation time per year and the ratio between heating and cooling energy demand. The preliminary total GHE length is thus not spatially dependent, because does not depend on the ground conditions. Furthermore, several correction factors are applied to L_{GHE} to consider the ground geothermal properties C_{ground}, the grout composition C_{grout}, the minimum temperature allowed on the heat carrying water C_{temp}, the type of GHE C_{GHE} or the geometrical configuration of the probes in case of GHE field C_{field} in order to obtain the final total GHE length $L_{GHE\text{-}final}$.

$$L_{GHE-final} = L_{GHE} C_{ground} C_{grout} C_{temp} C_{GHE} C_{field} \quad (9)$$

Amongst those correction factors, C_{ground} varies with the ground

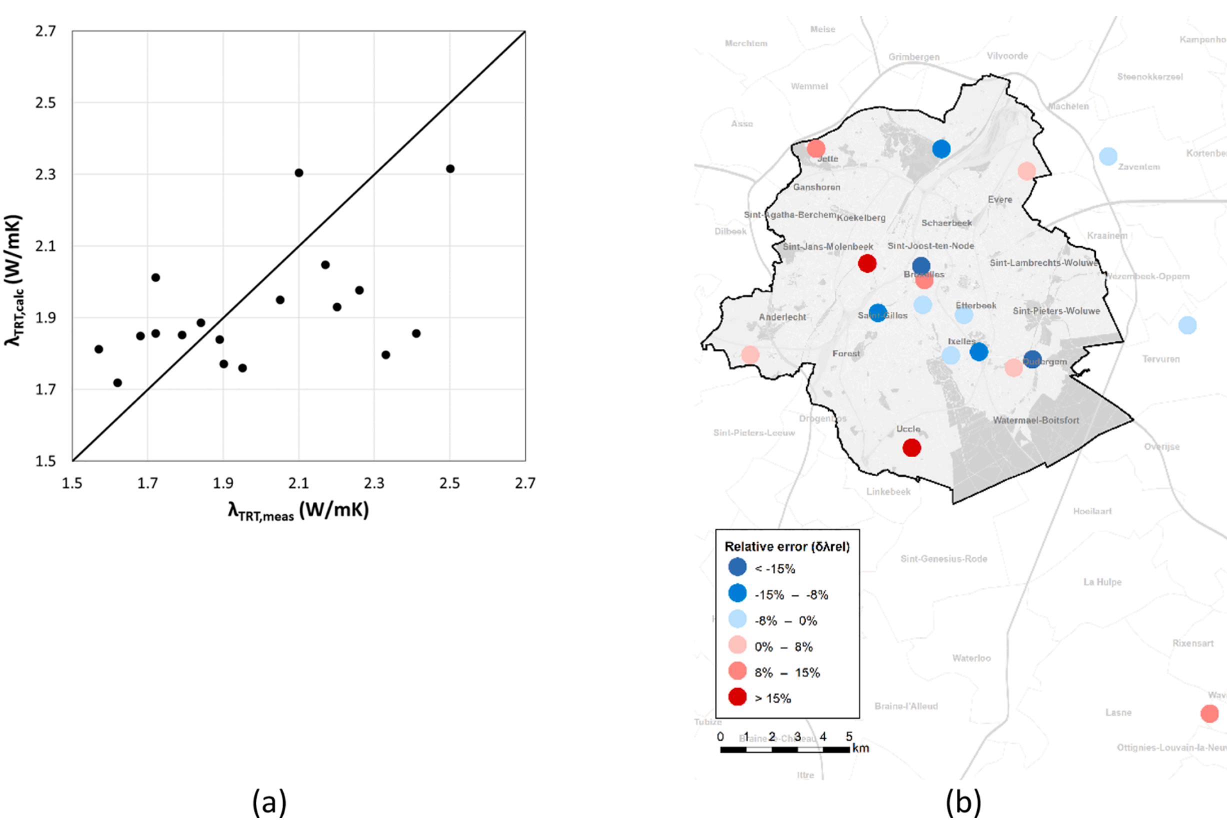

Figure 4. Analysis of the error on the ground thermal conductivity: (a) Measured thermal conductivity $\lambda_{TRT,meas}$ vs. Calculated thermal conductivity $\lambda_{TRT,calc}$– (b) Mapping of the relative error on the thermal conductivity $\delta\lambda_{rel}$ for the 18 TRT crossing only Quaternary/Tertiary stratigraphic units

thermal conductivity. It is also the case of C_{grout} that depends on the ratio between ground and grout thermal conductivities.

The relative error on the GHE length of a specific GHE installation $\delta L_{rel,GHE\text{-}final}$ caused by an error in the determination of the ground thermal conductivity can be calculated by

$$\delta L_{rel,GHE-final} = \frac{(L_{GHE-final})_{\lambda_{meas}} - (L_{GHE-final})_{\lambda_{TRT}}}{(L_{GHE-final})_{\lambda_{meas}}} = \frac{(C_{ground}C_{grout})_{\lambda_{meas}} - (C_{ground}C_{grout})_{\lambda_{calc}}}{(C_{ground}C_{grout})_{\lambda_{meas}}} \quad (10)$$

where $(C_{ground}C_{grout})_{\lambda meas}$ and $(C_{ground}C_{grout})_{\lambda calc}$ are the product of the correction factors depending on the ground thermal conductivities, obtained from the thermal conductivities respectively measured with a TRT or calculated with the thermal conductivities of each stratigraphic unit determined by the TRT-based inverse analysis procedure (Table 5).

In the normal Dutch design method, empirical relationships are proposed to determine the values of both correction factors. In addition to the unit lithology and grout composition, those correction factors depend also on the ratio between heating and cooling energy demand from the building (% of regeneration) and the heat pump operation time per year. It is proposed to analyze the relative error on the GHE length $\delta L_{rel,GHE\text{-}final}$ for 3 specific study cases:

- A favorable situation for shallow geothermal energy, i.e. where the heat extraction from the ground is the lowest (100% of regeneration, low heat pump operation time - 1500 h/year and highly conductive grout – $\lambda_{grout} = 2.2$ W/mK)
- A maximum usage for shallow geothermal energy, i.e. where the heat extraction from the ground is the highest (no regeneration (i.e. only heating), high heat pump operation time - 3000 h/year and weakly conductive grout – $\lambda_{grout} = 0.7$ W/mK)
- A standard situation for a single family-house (no regeneration (i.e. only heating), low heat pump operation time - 1500 h/year and moderately conductive grout – $\lambda_{grout} = 1.2$ W/mK)

Figure 5 presents the relative error on the GHE length as a function of the relative error on the ground thermal conductivity for 3 different ground thermal conductivities (i.e. $\lambda_{TRT,meas} = 1.6 – 2.0 – 2.4$ W/mK).

It illustrates first that the relative error on the GHE length increases with the ground thermal conductivity, and when the grout is poorly conductive and heat extraction is maximum (i.e. critical scenario). No significant differences on the relative error on the GHE length are observed when the ground thermal conductivity varies between 2.0 and 2.4 W/mK. Except in the critical scenario and for high ground thermal conductivity, the relative error on the GHE length is lower than the relative error on the ground thermal conductivity. It means that the error on the ground thermal conductivity is not amplified by the design procedure of GHE. Finally, Figure 5 has to be analyzed in light of the relative errors on the ground thermal conductivity provided in Table 7. In the case of a single-family house and for average relative errors on the ground thermal conductivity, the relative error on the GHE length varies between 3.7 and 8.4 % according to the ground thermal conductivity. Such relative errors are acceptable in view of the assumptions considered in the design procedure for GHE.

Such an error analysis allows designers of GHE systems to choose with all the necessary information to design their installation either from the thermal conductivities determined with the TRT-based procedure (with risk based on the relative error analysis) or from a local thermal response test that can represent an additional cost for the project, but that characterizes accurately the ground geothermal properties of the site.

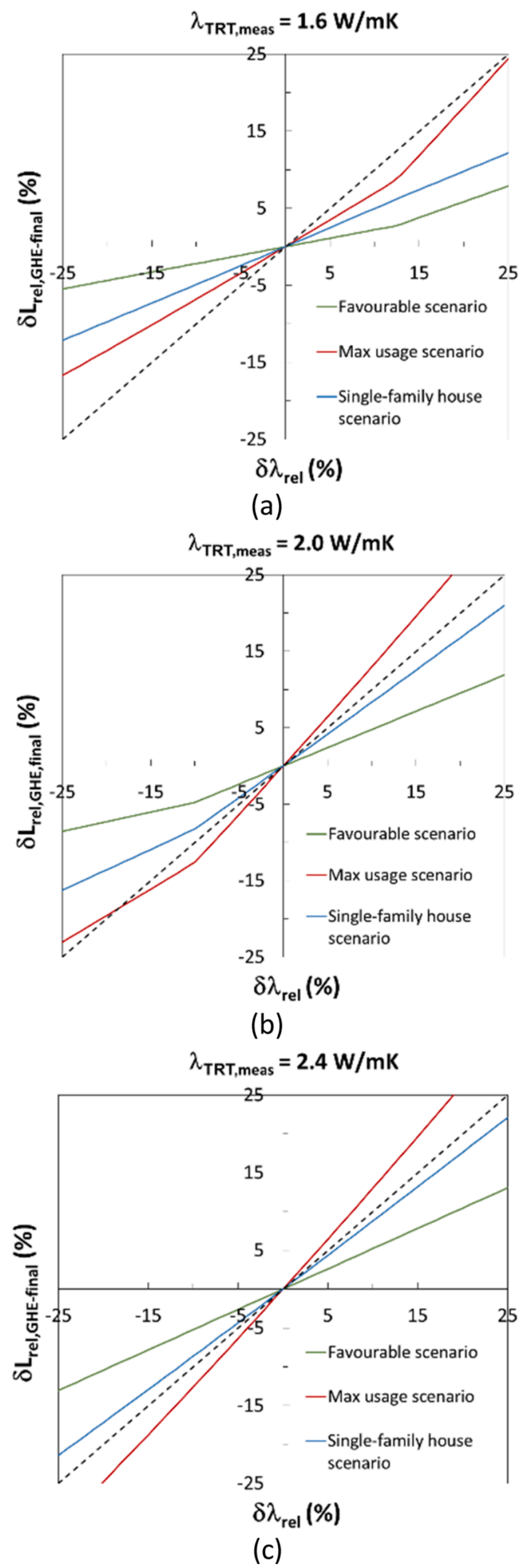

Figure 5. Impact of the relative error on the thermal conductivity $\delta\lambda_{rel}$ on the relative error on the GHE length $\delta L_{rel,GHE\text{-}final}$ for different scenarios (i.e. type of buildings) and ground thermal conductivities (a) $\lambda_{TRT,meas}$=1.6 W/mK; (b) $\lambda_{TRT,meas}$=2.0 W/mK; (c) $\lambda_{TRT,meas}$=2.4 W/mK

7. Conclusions

In this paper, a consistent and reliable methodology is proposed for the determination of lithology-based thermal conductivities at a regional scale, based on complementary ground geothermal data (i.e. essentially in-situ data – TRT and ETRT – completed by laboratory and published data). The methodology includes the inverse analysis of TRT results to determine both saturated and unsaturated thermal conductivities of each stratigraphic unit. The priority is given to in-situ data because TRT tests are reliable, not influenced by remolding samples taken during drilling. Upscaling thermal conductivity from a TRT-based procedure is relevant only if the data present a high spatial density and are well spatially distributed across the studied region. In addition, the proposed methodology gives a higher weight in the inverse analysis to stratigraphic units encountered on a large part of the region, with sufficient thicknesses and at depths where GHE are installed. Different indicators, such as the number of TRT in each stratigraphic unit, the relative extent of each stratigraphic unit or the average percentage of TRT length in each stratigraphic unit, has allowed to establish the most appropriate detailed methodology. The development of such a methodology also requires an extensive knowledge of the geology (both lithology and structural context) and hydrogeological conditions of the region in order to propose relevant assumptions allowing to reduce the number of unknowns of the inverse analysis problem. The methodology is based on a systematic validation of the thermal conductivities obtained at each step through the comparison with reference values of geological material-based thermal conductivities available in the literature, laboratory tests, or in-situ data (ETRT).

The methodology is here tested and analyzed at the scale of the Brussels-Capital Region (BCR) and aims at attributing a thermal conductivity to each stratigraphic unit. Consistent saturated and unsaturated thermal conductivities are obtained according to the geological materials observed and specific in-situ and laboratory measurements conducted in each stratigraphic unit. The relative error on the ground thermal conductivity is lower than 10% in most cases (and 23% in the worst case). Also, the impact of the thermal conductivity uncertainties on the design of GHE is discussed. The relative error on the GHE length is generally lower than the relative error on the thermal conductivity, which means that the error is diminished during the design procedure of GHE. In most scenarios, the relative error on the GHE length due to a relative error on the ground thermal conductivity remains thus acceptable.

CRediT authorship contribution statement

Pierre Gerard: Conceptualization, Methodology, Investigation, Supervision, Writing – original draft, Visualization. **Mathilde Vincent:** Investigation, Methodology, Formal analysis, Visualization. **Bertrand François:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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