GIS-Supported evaluation and mapping of the physical parameters affecting shallow geothermal systems efficiency at a continental scale

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ABSTRACT

The initial high investment of Ground Source Heat Pump (GSHP) systems is tackled by the GEOCOND project by, among other issues, the improvement of thermal properties of the grouting of the Borehole Heat Exchangers (BHE) as a way to improve the whole system efficiency. In this work a systematization and evaluation of the variability of the ground in the study area (continental scale) has been performed using GIS tools. This GIS-based work has transformed the geological study area context into information on relevant GSHP parameters affecting GSHP efficiency. This paper presents the resulting thematic maps that have been obtained at this stage of the project, such as thermal conductivity and potential for TSE (Thermal Soil Enhancement), and the knowledge of the relative frequency of the underground properties affecting GSHP efficiency, which are considered a great contribution to the GEOCOND project.

Future project steps will result in a GIS-based Multicriteria Decision Making Tool, and the layers obtained in this work and those prepared in future will work as a criterion therein. It will be a powerful instrument to spread knowledge among European policy-makers and promote the use of shallow geothermal energy in European energy policies. The output will support decisions based on the level of accessibility and based on the environmental and economic benefits segmented by geographical zones.

1. INTRODUCTION

Although the heating and cooling sector is moving to a clean low carbon energy, 75% of the fuel it uses still comes from fossil fuels (European Commission 2016). Fossil fuel depletion along with pollutant emissions and global warming have motivated efforts to reduce society´s dependence on fossil fuels, by reducing demand and substituting alternative energy sources (Self et al. 2013). The exploitation of Shallow Geothermal Energy (SGE), as an alternative energy source, using GSHP linked to Borehole Heat Exchangers (BHE) has become popular in Europe for heating and cooling (Rybach and Sanner 2017). However, the current state of technology uptake varies across EU member States due to the market barriers, which could be reduced by moderating investment costs, reducing system complexity as well as enhancing SGE recovery rates (Tinti et al. 2018). In this regard, the European funding project GEOCOND (Sanner and Urchueguia 2018) objectives tackles this issue by removing market barriers with particular focus on capital cost reduction. One of the research lines of the project is focused on the development of new technologies to improve thermal properties of the grouting of the Borehole Heat Exchanger and the soil surrounding (Thermal Soil Enhancement Technologies) with a potentially very high impact in system efficiency and cost downturn.

While thermal properties must be determined among the GEOCOND European countries the geological variability of the ground make this an arduous task. Indeed, identifying geology variability and parameters involving spatial shallow geothermal information is a complex task involving decision-making and is subject to human error (Noorollahi et al. 2008). Besides, processing such a huge amount of geological information cannot be performed manually, so a Geographical Information System (GIS) is required (Ondreka et al. 2007). Using GIS is a great contribution in the evaluation of SGE. GIS thematic maps provide a simple decision support tool and reduces the distance between the physical knowledge of the territory and the accuracy of the evaluation and statistics obtained (Gemelli et al. 2011).

2. METHODOLOGY

The geological variability of the underground conditions in the partner countries and the representative geological contexts were identified. Available geological and hydrogeological data, mainly from the European Geological Data Infrastructure (EGDI), from national geological surveys and from other projects, were collected and analysed. The main lithological groups and the suitability of the underground to different grout types, Phase chance materials addition (PCM) and Thermal Soil Enhancement was defined. The most representative lithological groups and rock-types were roughly characterised, mainly based on origin (sedimentary, magmatic or metamorphic), and sediments were defined on basis of their granulometric composition. The geological context was transformed into information on relevant parameters for shallow geothermal applications, mainly concerning thermal conductivity and suitability for Thermal Soil Enhancement. Doing so, the invariant components of the territory (lithological and groundwater conditions) affecting the shallow geothermal systems efficiency and costs could be localised and quantified. The relative frequency of respective properties within the GEOCOND partner countries and throughout Europe was determined, and statistical approaches could be used to assess the relative importance of certain properties. For thermal conductivity, this included also the relation to population density, as a measure of the market demand for heating and cooling.

2.1 Study area

In order to make statistical findings from geological data for Europe meaningful for the project, a specific delineation of the study area was applied. Since GEOCOND is a project that looks at technology to be implemented in the EU it was decided to exclude the Eastern European landmass, which represents 45% of the European area. On the other hand, the GEOCOND partner countries Turkey and Israel are included, despite of their location partly or fully outside Europe in the geographical understanding. For Israel, the area with data provided by the Geological Survey of Israel is used, thus including the Palestinian areas. Here the work is focused on the countries where the GEOCOND partners are located, i.e. (in alphabetical order) Germany, Israel, Italy, Spain, Sweden, Turkey and the United Kingdom.

2.2. Systematization of geological data.

A main source of geological and hydrogeological data for the GEOCOND project was the European Geological Data Infrastructure (EGDI), provided by EuroGeoSurveys and created by the Federal Institute of Geosciences and natural Resources of Germany. The information is part of the International hydrogeological map of Europe 1:1.500.000 (IHME1500) and is openly available on the internet:
http://www.europe-geology.eu/

EGDI map offers different lithological groups at five aggregation levels from “Litho1” to “Litho 5”. “Litho 1” is the most detailed one with a uniform lithological taxonomy scheme and encompasses 204 classes. “Litho 5” is the most basic group and provides a class division referring to the degree or rock consolidation, thus a distinction of unconsolidated, partly consolidated and consolidated rocks. To be able to work with the huge amount of data available for Europe, it was necessary to reduce the number of classifications and to focus on certain key properties. For the maps represented in this paper, “Litho 4”, “Litho 2” and “Litho 5” have been used.

A combination between “Litho 2” and “Litho 4” was made for the representation of the lithological map concerning GECOND needs, and was considered well suited to give a proper idea of the lithological composition of the underground in Europe and the individual countries. “Litho 4” encompasses 10 petrographic groups based on the basis of a general description of soil and rocks types, while “Litho 2” contains only primary and secondary consolidated and/or primary and secondary unconsolidated lithological components. For the classification of the lithological maps, the 10 petrographic groups of “Litho 4” were used and 4 more groups from “Litho 2” were added in order to allow for a more precise description of the magmatic rocks. As a result, 14 different groups have been defined and the approximately 200 EGDI lithologies have been distributed into these rock families (Table 1).

Lithological information of Israel and Turkey was extracted from datasets:
https://catalog.data.gov/dataset?tags=lithology
and contrasted with geological information offered in the National Geological Service of their respective countries:
http://www.gsi.gov.il/eng/
http://yerbilimleri.mta.gov.tr/anasayfa.aspx.
Turkey and Israel lithological groups were likewise converted into the 14 lithological groups.

Based on the summarization as in Table 1 lithological maps have been created for the GEOCOND study area and for the GEOCOND partner countries. Figure 6 shows the lithological map of the GEOCOND study area.

2.3. Thermal conductivity and population maps

Thermal conductivity of the underground is the key property when heat transport is considered, and thus controls the possible BHE efficiency. The impact of the GEOCOND materials is active inside the borehole and can only be assessed in relation to the ground thermal conductivity around.

For creating this maps, the thermal conductivity values of VDI 4641-1 were used as a basis for the assignment of thermal conductivity values to the circa 200 individual lithologies provided. VDI 4640-1 was published in 1998 and updated in 2010 with the information amassed of thermal conductivity, both from measurements at samples in the laboratory, and from thermal response test in the field. Experts and authors consider VDI 4640-1 as the most reliable collection of ground thermal conductivity values publicly available in Europe.

For unconsolidated sediments, the thermal conductivity is mainly controlled by the water content. While there is good information on the type of aquifer, hydraulic conductivity etc., the data on the depth of the groundwater level is available only on a local level, e.g. for individual river basins. Hence it was not possible to determine if the respective layers are water saturated, moist or dry, and automatic determination of the thermal conductivity based on water content could not be done. Instead, a thermal conductivity value for every lithology of “Litho 1” classification was determined based on VDI-4640-1.

Table 1: Summarisation of EGDI lithologies into groups for lithological map

Basic classification	GEOCOND Lithologies groups	Litho. Code	Num. EGDI litho.
Sediments, unconsolidated	Fine sediments	Sf	13
	Coarse sediments	Sc	12
Sedimentary rocks and sediments, partly consolidated	Calcareous rocks and fine sediments	CR-Sf	31
	Calcareous rocks and coarse sediments	CR-Sc	10
	Siliciclastics rocks and fine sediments	SR-Sf	30
	Siliciclastics rocks and coarse sediments	SR-Sc	14
	Evaportitic rocks and sediments*	ER-S	2
Sedimentary rocks, consolidated	Calcareous rocks	CR	22
	Siliciclastics rocks	SR	33
Metamorphic rocks	Metamorphic rocks	MR	18
Magmatic rocks	Plutonic rocks (acid)	PRa	3
	Plutonic rocks (basic)	PRb	2
	Volcanic rocks (sensu lato)	VR	10
	Pyroclastic rocks	PcR	4

* Evaporites are only presented in Turkey and thus omitted in the other maps

2.4. Population density maps related to thermal conductivity

Population density of the GECOND countries were used as a measure of the market demand of heating and cooling. Data on distribution of population (population density) in the individual countries are based on the level of the NUTS 3 category of EUROSTAT (https://ec.europa.eu/eurostat/data/database). There are 1452 regions at NUTS 3 level inside EU, with further regions in EEA countries, candidate countries and in Switzerland. For the GEOCOND study area, only Israel is not part of EUROSTAT and thus data from the Central Bureau of Statistics (https://www.cbs.gov.il) CBS (2017) was used. Population density data of Bosnia Herzegovina, Serbia and Albania were not taken into account as they also are not available through EUROSTAT.

A GIS layer for thermal conductivity and population was created following these steps: firstly, population data were assigned to every NUT3 region and then a linkage between this layer and thermal conductivity layer was made.

2.5. Thermal soil enhancement (TSE) maps

Thermal Soil Enhancement (TSE) is a technique based on forced injection of grouting to increase the overall thermal conductivity of soils. This technique consists of the injection of grout with high thermal conductivity into the pore space of the ground (soil) for increasing the overall thermal properties. In many case the ground can be considered as a porous medium, with capacity to be filled with some type of thermally conductive fluid materials. Development also aims at reducing the viscosity of the grouting products, in order to increase the penetration into the pore space with the target to improve the overall thermal conductivity of the system.

For the definition of specific areas where the thermal soil enhancement could be applicable, it is necessary to establish a series of criteria based on the geological setting. Those regions where soil enhancement could be applicable are characterised by:

- A thermal conductivity value lower than 2.2 W/mK
- Unconsolidated material
- Productive porous aquifers

One new layer has been created in GIS for every condition descripted above. The thermal enhancement zones layer is the result of intersecting these three layers.

2.6. Statistics

GIS is a powerful tool that allow, not only to create the thematic maps but, to create some useful statistics of the spatial information of GEOCOND project with lots of relevant information. Additionally, these data will serve as a basis for a Multi-Criteria Decision Tool aimed to assess the accessibility of the Shallow geothermal energy in different European countries.

The statistics were made for the GEOCOND study area and the GEOCOND partner countries separately. They are related to the distribution of the lithology information, thermal conductivity and thermal conductivity associated with population data and Thermal Soil Enhancement zones (TSE).

The possibility to work with EGDI data directly allowed for statistical evaluation of the distribution of the 14 lithologies in the GEOCOND area and in the different partner countries.

Statistics of thermal conductivity map were based in the different lithology polygons and thermal conductivity by population statistics were based in NUTS3 (https://ec.europa.eu/eurostat/web/nuts/background), so that for every NUTS3 area the thermal conductivity average was calculated and joined with the population data.

3. RESULTS AND DISCUSSIONS

Results are presented in tables, graphs and maps. Maps of the GEOCOND area and partner countries individually are shown. Due to the different size of the countries the maps are shown in different scale with the intention to show as much detail as possible.

Figure 1 presents a histogram of the relative occurrence of the 14 lithological units as in Table 1. The most frequent lithologies are unconsolidated sediments (Sf and Sc), calcareous rocks (CR) and metamorphic rocks (MR) in the GEOCOND study area (Figure 6). But when looking at individual countries, lithology distribution changes significantly (Figure 4 and Figure 5). In Germany, due to the presence of large basin areas together with Upper Rhine Graben, unconsolidated sediments cover up to 50% of total country area. Israel is controlled by Calcareous rocks and unconsolidated material. In Italy unconsolidated material represents almost 40% of the area. In Spain there is a good distribution of all the lithologies whilst Sweden is mainly covered by metamorphic and plutonic rocks. Turkey, as well as Spain, has a good distribution of all lithologies, although Calcareous and volcanic rocks are predominant. And lastly, in the United Kingdom siliciclastic rocks, followed by calcareous and metamorphic rocks are mainly found. It is noteworthy that some detailed lithological information of Israel and Turkey is missed when transforming the classification from the datasets to the EGDI lithologies mentioned above and the use of all the lithological information from a standardized source had provided might have more precise results.

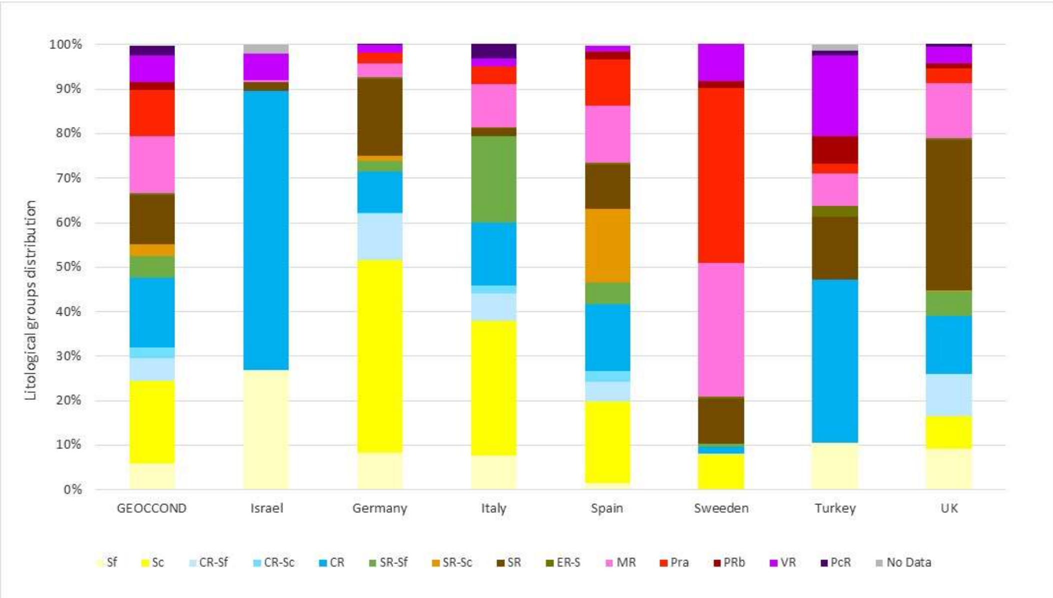

Figure 1: Areal distribution of lithological groups in GEOCOND countries study area and partner countries

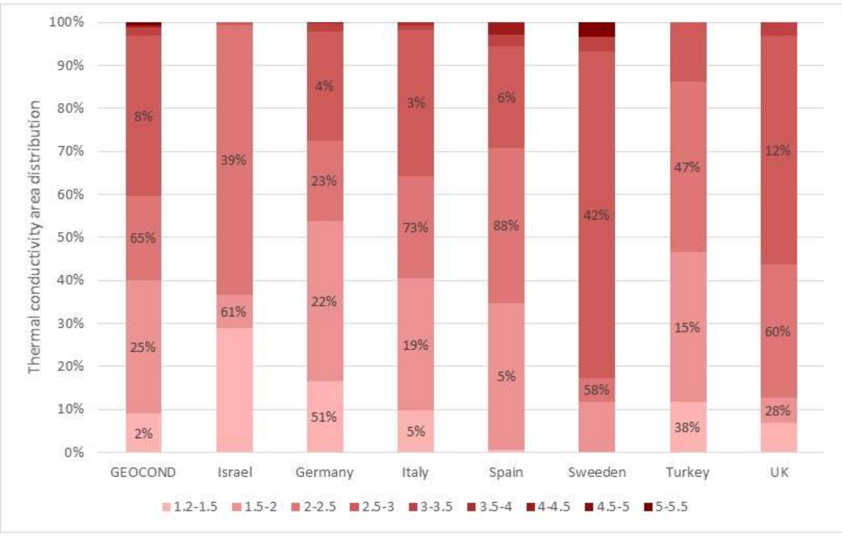

Figure 2: Areal distribution of thermal conductivity in GEOCOND study area and partner countries.

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This assignment of thermal conductivity values to lithologies as done here can be deemed valid on a country scale to see the distribution and provide statistics, but the resulting maps can in no way be used for the actual BHE design on a certain site.

When assigning thermal conductivity to the lithologies a quantitative analysis of the availability of suitable ground for BHE becomes possible. In the GEOCOND countries (Figure 7Figure 7) the value of 2.5-3 W/mK is the most extended with up to almost 40% of the total area and higher values (3-5.5 W/mK) are much less frequent (<3%) although covers over 6% in Sweden, 5.5% of Spain, almost the 3% of United Kingdom, around 2% in Germany and Italy and no presence in Turkey and Israel. The highest values (5.5 W/mK) can be found in Scandinavia (Figure 7) and the higher distribution of the poorer values can be found in Israel where almost the whole country presents values lower that 2.5 W/mK followed by Turkey and Spain with a 86% and 70% respectively.

Nevertheless, areas with low thermal conductivity (up to 2.5 W/mK) are by far vaster and more populated than those with higher values (2.5 to 5.5 W/mK). Indeed, looking at the GEOCOND study area, more than 90% of the population lives in territories with lower values than 2.5 W/mK, representing 60% of the total territory (Figure 8). In contrast, areas where thermal conductivity values are higher (2.5-5.5 W/mK) represent about 40% of the territory in the GEOCOND areas but only 8% of the population resides there. The same dynamic is followed by the GEOCOND countries, but some slight differences are found. In Israel, 100% of the population lives in grounds with thermal conductivity values lower than 2.5 W/mK. In Germany, the majority of the population lives in ground with thermal conductivity below 1.5 W/mK and the rest lives in the ground with 1.5-3 W/mK proportionally (the low value for the majority could be explained by the fact that groundwater content in unconsolidated sediments is not considered, cf. 2.3). Both Italy and Spain have its more populated areas where the ground rises to 2.0-2.5 W/mK (73% and 88%, respectively). In Sweden, 58% of the population lives in grounds with thermal conductivity values between 1.5-2 W/mK, but this only represents 6% of the total country area, whilst the rest of population is distributed over grounds with values of 2.0-2.5 W/mK, which cover 42% of the territory. However, Sweden is the country where higher values of thermal conductivity are found, but mainly in areas with very low population density. As for Turkey, thermal conductivity and population density values are more proportionally distributed. The higher values are found in areas where thermal conductivity varies between 2-2.5 W/mK, occupying 34% of the country with almost half of population, followed by 1.5-2.0 W/mK thermal conductivity areas that occupy 40% of aera with 15% of the population, and lastly, 38% of the population is living in areas below 1.5 W/mK and covering 38% of the country. In the United Kingdom, instead, higher conductivity values of up to 3.5 W/mK are found, but 60% of the population are concentrated in areas with 1.5-2.0 W/mK that spread over 60% of the territory.

As mentioned before, statistics with population density and thermal conductivity data were based in NUTS3 as it is the smaller division with population density data available. Arcmap calculated population density average and thermal conductivity average for every NUTS3, so that values obtained can differ from the spatial original information. Thus, basing these calculations on smaller areas would provide more exhaustive results.

TSE potential results are shown both in graphic (Figure 3) and maps (Figure 9, Figure 10, Figure 11). Concerning the GEOCOND study area (except Turkey and Israel), the suitable area is almost 28% of the total area. For the individual countries, values ranged from 7% in Sweden, where solid rock is predominant, and over 50% in Germany, where more than 50% of the underground is classified as unconsolidated sediments.

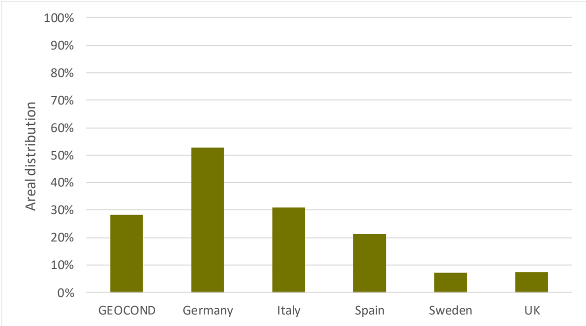

Figure 3: TSE potential in GEOCOND study area (without Israel and Turkey) and GEOCOND countries.

4. CONCLUSIONS

The geological and hydrogeological diversity of the ground in the GEOCOND study area was characterized. Available data from European Geological Data Infrastructure, Official Surveys and other projects were collected and used for this purpose. The geological and hydrogeological context was transformed into information on relevant parameters for shallow geothermal applications, concerning mainly lithological groups and thermal conductivity. The spatial distribution and statistics on the frequency of the individual properties within the GEOCOND study area and among the partner countries was calculated.

The most representative lithological groups were defined based on origin (sedimentary, magmatic and metamorphic) and sediments were characterized on basis of their granulometric composition. According to the results, in the GEOCOND study area, unconsolidated sediments present the largest area, followed by calcareous rocks and metamorphic rocks.

The key interest of the systematization of the geological context was on thermal conductivity as the most important parameter that determines heat transport in the ground. Different thermal conductivity categories were made and the share of the area for each was computed. In addition, spatial distribution of population density for every thermal conductivity category in the study area was determined as an energy demand indicator. It was concluded that the vast majority of the population (65%) lives in areas with 2.0-2.5W/mK as an average, albeit considerable deviations can be found in Germany and Sweden where the majority of the population lives in 1.2-1.5 W/mK and 2.5-3 W/mk areas respectively.

Lastly, the potential in the GEOCOND area for Thermal Soil Enhancement (TSE) as a technique aimed to increase thermal performance of soils was determined. Under some specific conditions, it turned out that more than 30% of the GEOCOND area is likely to offer potential for TSE, with over 50% in Germany. Moreover, a direct relation between coarse sedimentary grounds and TSE spatial distribution was found.

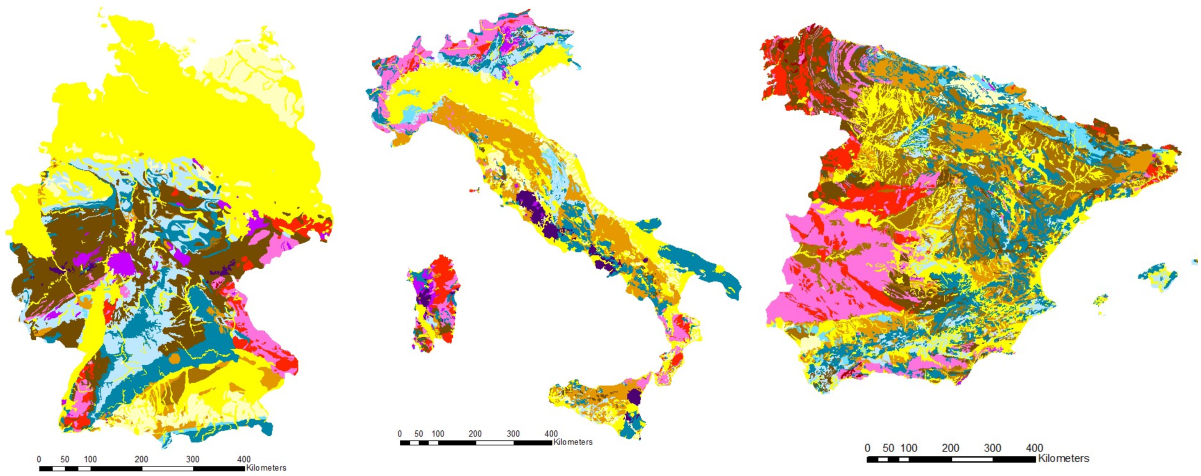

Figure 4: Lithological maps of Germany, Italy and Spain.

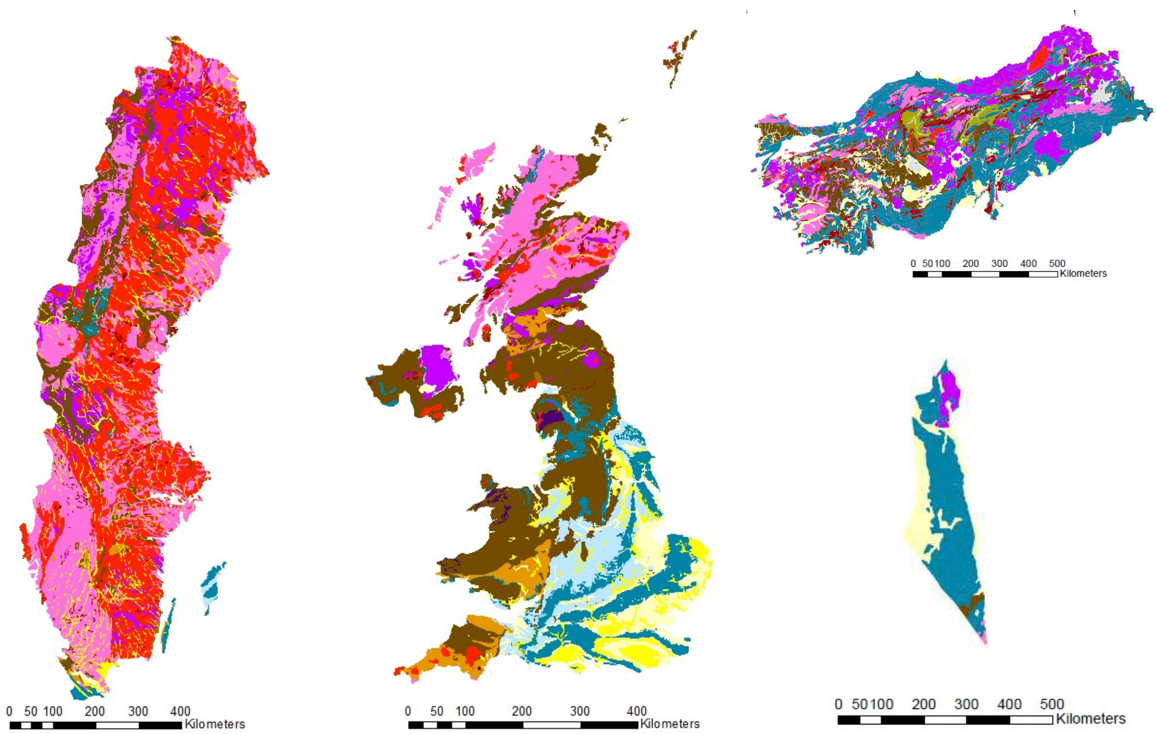

Figure 5: Lithological maps of Sweden, United Kingdom, Turkey and Israel.

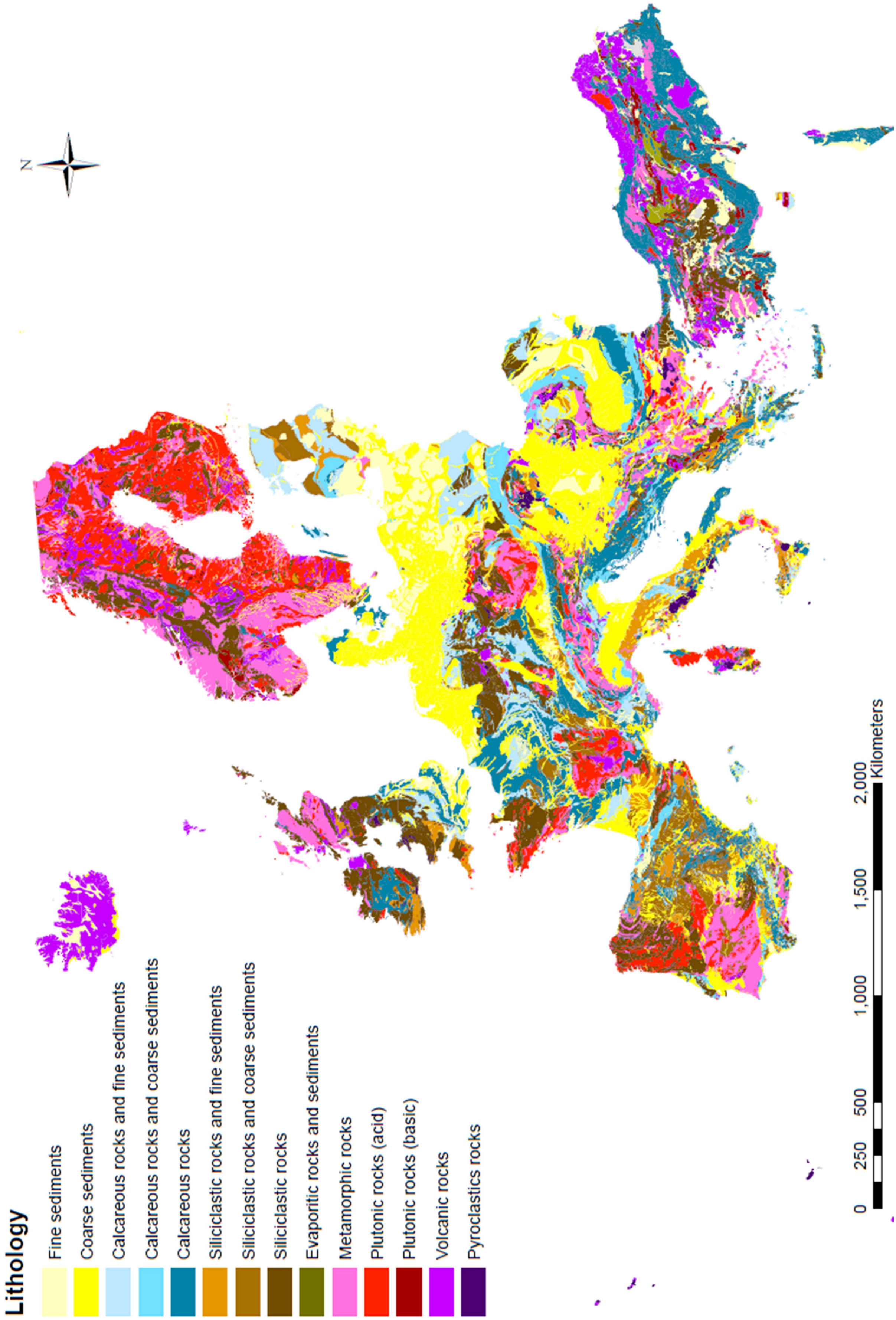

Figure 6 Lithological map of Europe (GEOCOND definition for area and lithological groups).

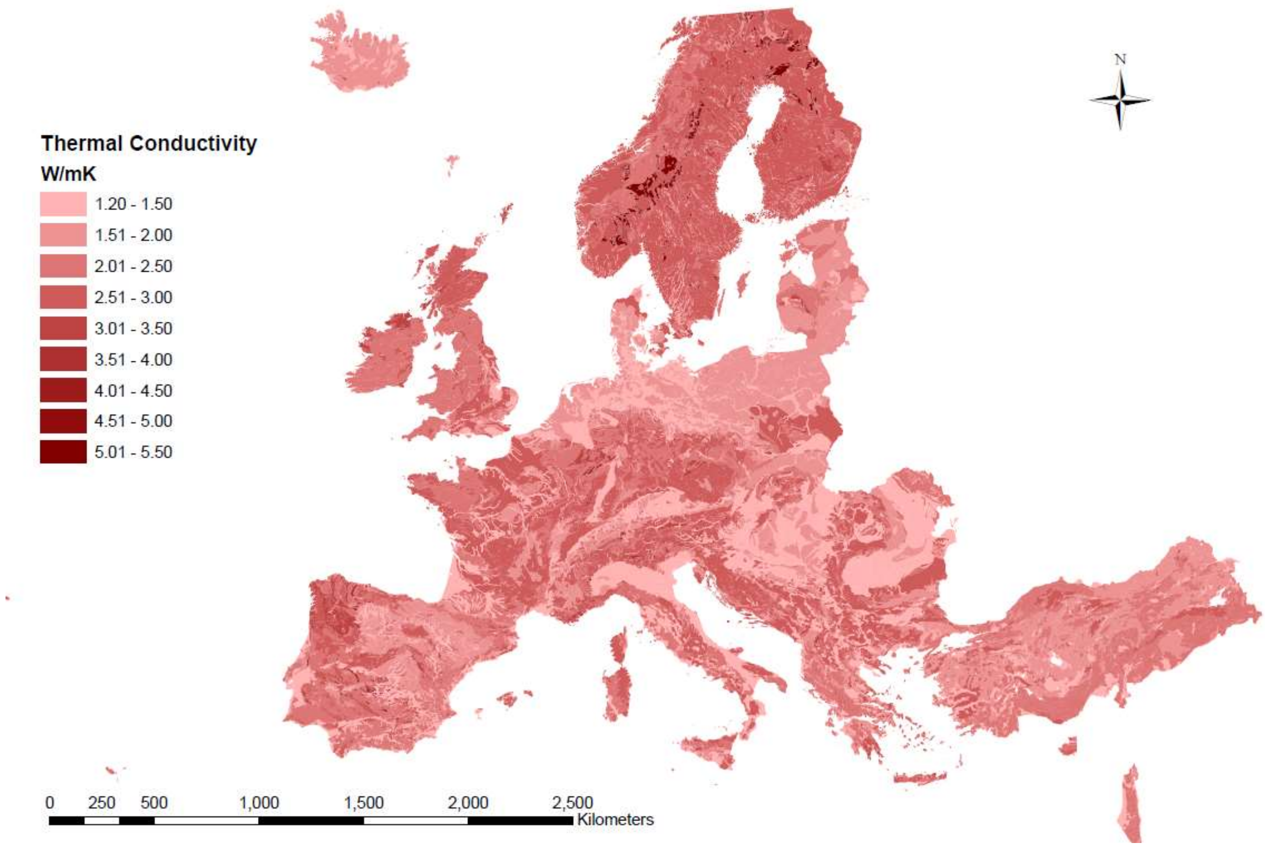

Figure 7: Underground thermal conductivity map of GEOCOND study area

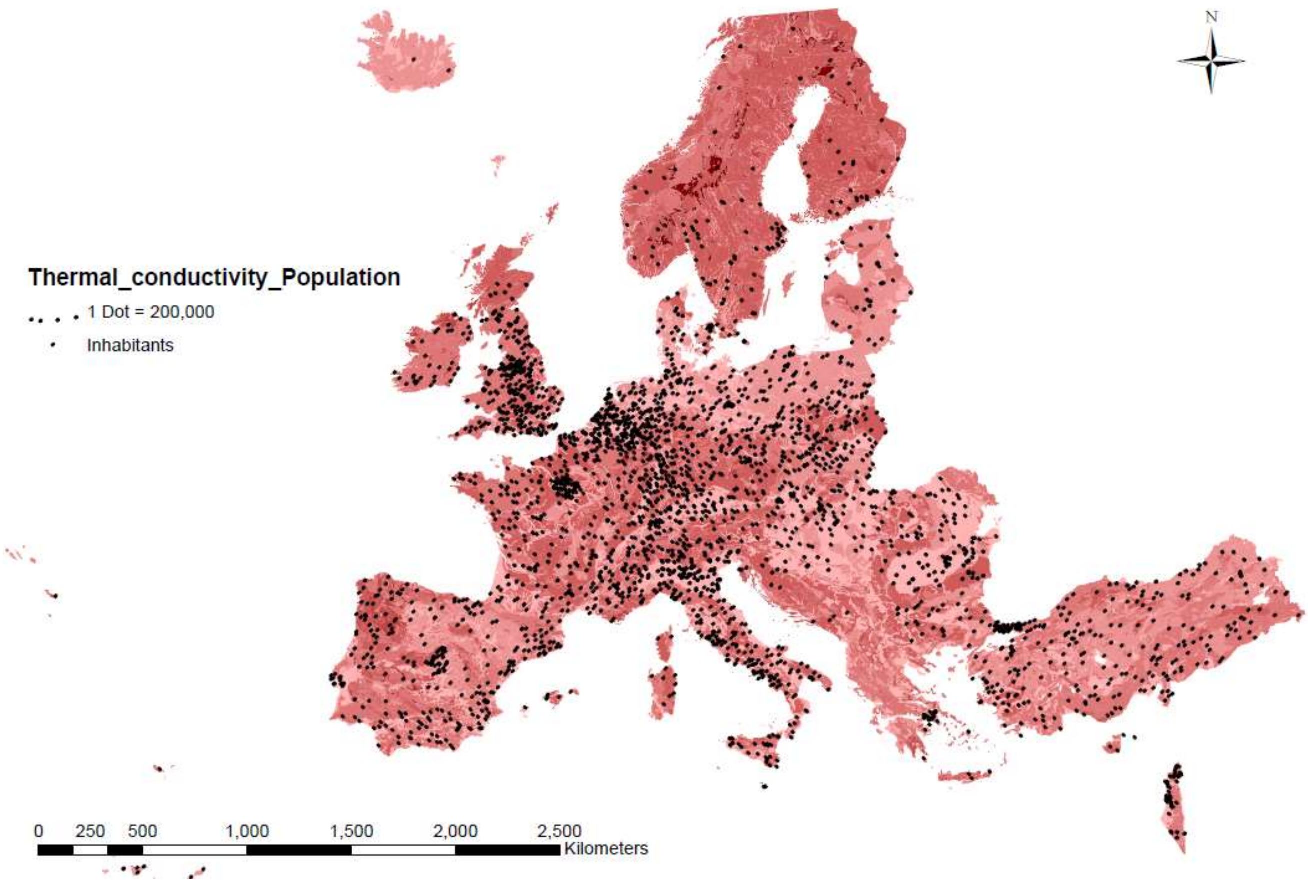

Figure 8: Distribution of underground thermal conductivity with indication of population density in the GEOCOND countries

Table 2 Distribution of thermal conductivity by population in GEOCOND partner countries and in overall GEOCOND study area.

		GEOCOND	Germany	Israel	Italy	Spain	Sweden	Turkey	UK
Inhabitants (x1000)		*509,606.60*	*82,521.60*	*8,628.60*	*60,589.40*	*46,528.00*	*9,995.20*	*80,845.20*	*65,648.10*
Thermal conductivity (W/mK)	1.2-1.5	2.39%	51.04%	0	4.97%	0.00%	0.00%	38.00%	0.00%
	1.5-2	24.93%	22.32%	61.09%	18.85%	5.25%	0.00%	15.00%	27.83%
	2-2.5	64.95%	22.66%	38.91%	72.69%	87.96%	58.47%	47.00%	60.48%
	2.5-3	7.88%	3.99%	0	3.49%	6.42%	41.53%	0.00%	11.69%
	3-3.5	0	0	0	0	0	0	0	0
	3.5-4	0	0	0	0	0	0	0	0
	4-4.5	0	0	0	0	0	0	0	0
	4.5-5	0	0	0	0	0	0	0	0
	5-5.5	0	0	0	0	0	0	0	0

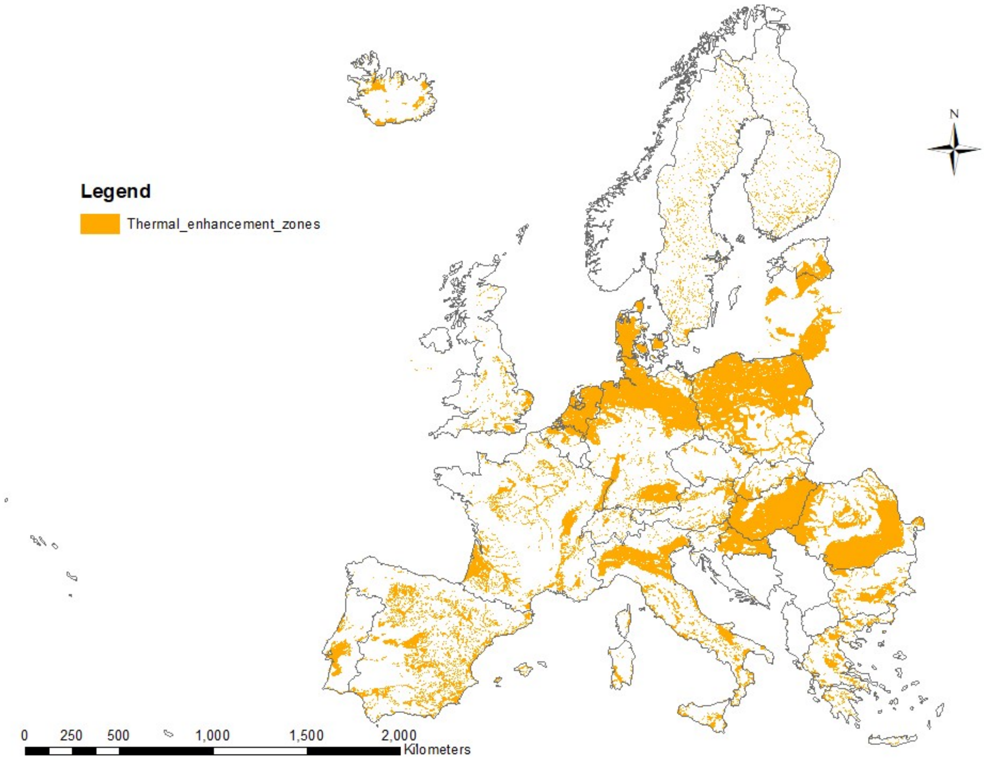

Figure 9: Map of potential for TSE in the GEOCOND countries without Turkey and Israel

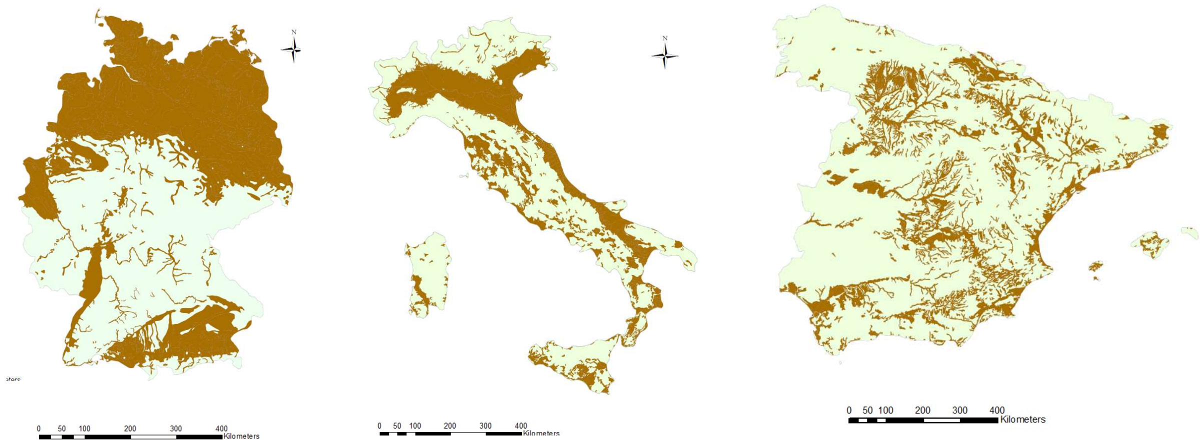

Figure 10: Potential for TSE in Germany, Italy and Spain

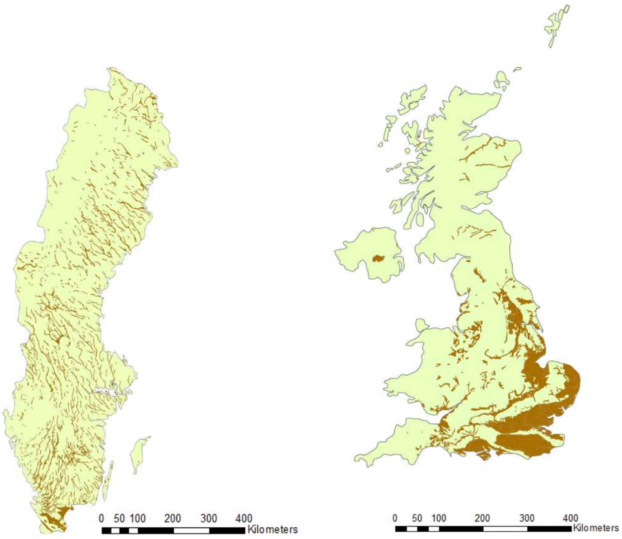

Figure 11: Potential for TSE for Sweden and United Kingdom

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