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MAPPING OF VERY SHALLOW GEOTHERMAL POTENTIALS IN RURAL AREAS OF BAVARIA

Abstract: Climate change is a rising issue which strongly influences contemporary society. Therefore, the utilization of sustainable non-fossil energy sources is one of the most important goals in order to reduce greenhouse gas emission. Utilization of geothermal energy for heating and cooling buildings or residential units is one of the significant steps in providing sustainable and renewable energy supply. This paper presents very Shallow Geothermal Potentials (vSGP) of German federal state Bavaria, with special focus on rural areas. Main goal of the study was to analyze the potentials for utilization of very shallow geothermal systems in terms of thermal conductivity and heat extraction. High-resolution soil maps containing information of grain size conditions served as an area-wide data basis for the research, while the analysis and visualization of the results were conducted by GIS software. Thermal conductivity as well as system-specific heat extraction were calculated depending on soil texture and climate conditions. Thermal conductivity results are intended to be further used as the basic parameter for planning and installing horizontal geothermal heating and cooling systems.

Key words: very shallow geothermal potentials (vSGP), thermal conductivity, heat extraction, sustainable cooling, rural area, Bavaria

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Introduction

According to the Intergovernmental Panel on Climate Change, human influence on the climate system is unequivocal, with each of the last four decades successively warmer than any preceding decade since 1850. The Fifth Assessment Report (AR5) of the IPCC (IPCC, 2014) highlights the role of anthropogenic emissions in driving climate change, emphasizing the need for immediate and substantial reductions in greenhouse gas emissions to mitigate its impacts. Additionally, studies such as those by Hansen et al. (2017) and Le Quéré et al. (2018) provide further evidence of the reality of climate change and its anthropogenic drivers, underscoring the urgency of collective action to address this global challenge.

Mitigating climate change is one of the main goals of the 2015 Paris Agreement, in which the global community agreed to limit the global temperature rise. This goal and the limitation of greenhouse gas emissions into the atmosphere are to be achieved by substituting fossil fuels with renewable energy sources (RES) (Johnsson et al., 2019).

Although the current global energy mix consists of around 80 % fossil fuels (Jess et al., 2011), the share of renewable energy in global energy production is increasing every year (REN21., 2019). In addition to energy generation and transportation, renewable energies also contribute to heating and cooling systems (Cansino et al., 2011) through various technologies and applications (Soltani et al., 2019).

The use of geothermal energy is beneficial in various fields, such as electrification, space heating and district cooling, greenhouse heating, aquaculture and industry (Dickson & Fanelli, 2005). A distinction can therefore be made between deep and shallow geothermal energy (Stober & Bucher, 2014; Zeh et al., 2021). While shallow geothermal energy is acquired from the depth less than 400 m (Hähnlein et al., 2010), very shallow geothermal energy is extracted from sources that are no deeper than 10 m (Bertermann et al., 2014). Usually, the installation depth of horizontal geothermal applications is around 1.5 m (Rammler et al., 2023; Zeh et al., 2021).

Countries around the world have different strategies for the energy transition. Germany has set ambitious targets for the transition to renewable energy. Some of them are part of general European agreements and laws on climate change and energy stability. The German Climate Action Plan 2050 is a political document adopted by the German government in 2014. According to this plan, Germany should reduce greenhouse gas emissions completely by 2050. This plan provides for a gradual reduction in greenhouse gas emissions and fulfils Germany's international commitments under the Paris Climate Agreement. Key medium-term targets include a 65% share of renewable energy in electricity generation by 2030, as well as continued work on energy efficiency, new solutions for heating and reducing coal consumption (Bundesministerium für Wirtschaft and Energie, 2019).

Bavaria is one of Germany's 16 federal states and is located in the southern part of the country. It covers an area of more than 70,000 km^2 and has more than 13 million inhabitants. In addition to the urban areas, the rural areas of Bavaria are also important, as around 60% of the total Bavarian population live there (Bayerisches Staatdministerium für Ernährung, Landwirtschaft und Forsten, 2020), the rural areas comprise around 85% of the whole of Bavaria, generate around 47% of the Bavarian

GDP and comprise around 80% of all Bavarian villages, municipalities and towns (Oberste Baubehörde im Bayerischen Staatsministerium des Innern, 2010). Their importance is also reflected in the fact that around 77% of urban development funding in Bavaria currently goes to rural areas (Bayerisches Staatsministerium für Wohnen, Bau und Verkehr, 2020). They are also included in the plan for the energy transition and sustainable energy supply. This topic is covered in the 2016/17 report on the restructuring of the energy supply (Bayerisches Staatsministerium für Wirtschaft, Energie und Technologie, 2018). In addition to green electricity and the increasing use of biomass, geothermal energy is another renewable energy source that can significantly change the energy mix in rural areas. Particularly very shallow geothermal systems, which can be installed in gardens and yards as well as in form of agrothermal energy systems in fields near rural settlements coupled with a low temperature district heating and cooling network, can be used. Against this background, detailed geothermal potential maps are essential as a first-step planning and dimensioning tool.

Most commonly, geothermal potential maps are focused on closed-loop vertical geothermal systems or open-loop systems (Casasso et al., 2017; Casasso & Sethi, 2017; Galgaro et al., 2015; Ondreka et al., 2007) and there are only few with focus on very shallow geothermal systems (Assouline et al., 2019; Bertermann et al., 2014; Schwarz et al., 2022). The focus differs in depth: for vertical borehole heat exchanger the focus is on thermal conductivity of rocks at a depth of several hundred metres, whereas for vSGP the thermal properties of unconsolidated soil are essential. While potential analyses for open-loop and vertical closed-loop systems also focus on urban areas (Bayer et al., 2019), very shallow geothermal installations with larger area requirements can be used particularly effectively in rural areas. For these systems, the very shallow geothermal potential (vSGP) can be defined as a general value by utilising the thermal conductivity of soil (Bertermann et al., 2014) or as a system-specific value by estimating the heat extraction of a distinct geothermal system (Schwarz et al., 2022). The thermal conductivity is mainly influenced by site-specific soil parameters such as water content, pore size distribution and bulk density (Abu-Hamdeh, 2003; Lu et al., 2014; Markert et al., 2017). Furthermore, the organic content has a distinct impact if present (Abu-Hamdeh & Reeder, 2000; Wessolek et al., 2023).

The aim of the study was to estimate and to illustrate vSGP in rural areas of Bavaria based on the high-resolution digital German Soil Survey dataset (https://www.ldbv.bayern.de) and climate data. Therefore, for the calculation of thermal conductivity the influencing soil parameters were considered. For determining the system-specific heat extraction data based on the VDI 4640 (Verein Deutscher Ingenieure., 2019) was used following the approach of Schwarz et al. (2022). The results of the developed algorithm were validated on the basis of three exemplary test sites using soil samples and laboratory tests. The vSGP maps can provide a planning tool for dimensioning very shallow geothermal installations.

Materials and Methods

Data resources for vSGP calculations

The basic high resolved digital soil survey map (1:5000) for the calculation of the vSGP in Bavaria was provided by the respective authorities of the federal state. The German soil survey aimed to evaluate soil resources for agricultural productivity, environmental sustainability, land-use planning purposes and the assessment of property tax across for grassland and agricultural land Germany. This survey integrated field observations, soil sampling, laboratory analyses, and data interpretation to comprehensively characterize soil types, textures, structures, and fertility attributes. The dataset contains area information for all Bavarian districts and consists of more than 2 million polygons.

According to the German Soil Texture Classification System soil can be divided by its sand, silt and clay content into main texture classes (sand, loam, silt and clay) and into more detailed texture sub-sections (Sponagel et al., 2005) (p. 142). The main texture classes can be used for estimating heat extractions from VDI 4640, whereas the thermal conductivity calculations are based on more specific information.

Humus content (organic matter) is another important parameter provided by the soil survey dataset. The humus content of the soil is divided into eight groups according to the German standard DIN 4220 (Deutsches Institut für Normung, 2017) (p. 16) (Table 1). This parameter is relevant for correcting the dry density and the water content of soil.

Tab. 1. Classification of the humus content (organic matter) of soils (Deutsches Institut für Normung, 2017) (p. 16)

Description	**Organic class**	**Humus content in %**
Humus free	h0	0
Very low humus level	h1	0 – 1
Low humus level	h2	1 – 2
Medium humus level	h3	2 – 4
High humus level	h4	4 – 7.5
Very high humus level	h5	7.5 – 15
Extremely high humus level	h6	15 – 30
Peat	h7	More than 30

In addition, information on the climate zones (Figure A1, Table A1) was taken from DIN 4710 (Deutsches Institut für Normung, 2016). The climate data is required for estimating the very shallow geothermal potential in accordance with VDI 4640. Furthermore, climate data from the German Weather Service (DWD), e.g. data based on degree days for characteristic regions were used to calculate the potential. By combining these inputs, an algorithm for the calculation of very shallow geothermal potentials was developed following the study from Schwarz et al. (2022). The digital elevation model (DEM) was used to enable a height-dependent derivation.

Algorithm for determining vSGP in terms of thermal conductivity

As a first step in calculating the thermal conductivity the soil texture information provided by the soil survey map has to be converted into texture classes according to the German Soil Texture Classification System KA5 (Sponagel et al., 2005). In a second step the percentage values for the grain size fractions sand, silt and clay were assigned to the texture classes on the basis of DIN 4220 (Deutsches Institut für Normung, 2017). Based on these two steps, further relevant parameters for determining the thermal conductivity were calculated. The general workflow is Illustrated in Figure 1.

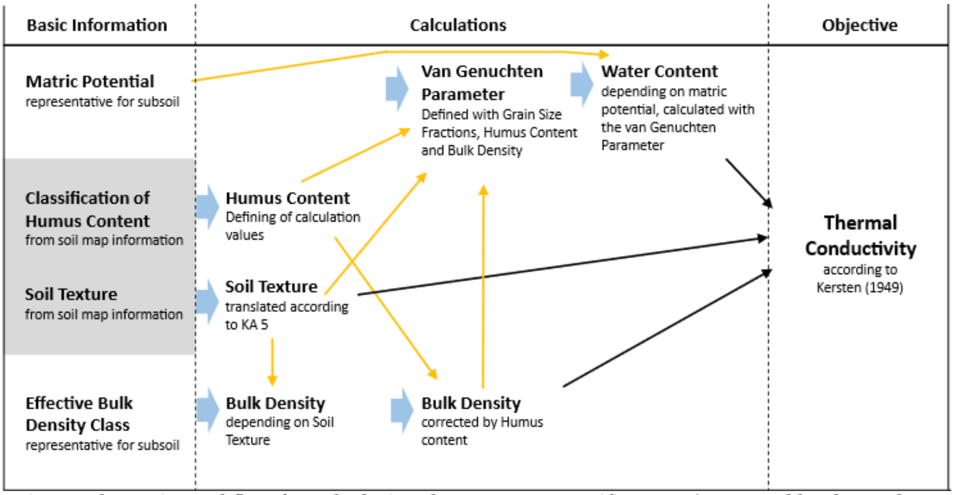


Fig. 1. Schematic workflow for calculation the system-unspecific vSGP (expressed by thermal conductivity)

Besides the soil texture and the percentage values for the grain size fractions, another basic parameter for calculating thermal conductivity is the bulk density. This parameter can also be derived from parameter soil texture. The corresponding classification is specified in DIN 4220 (Deutsches Institut für Normung, 2017) (p. 19): as very low (Ld1), low (Ld2), medium (Ld3), high (Ld4) and very high (Ld5). Normally the parameter bulk density is increasing with depth. For this study, the effective bulk density class “medium” was assumed due to usual installation depths of very shallow geothermal systems of 1.5 m below ground level (Rammler et al. 2023).

Taking the effective bulk density classes into account, a texture class related bulk density was derived in accordance with DIN 4220 (1) and corrected under consideration of the amount of organic content after (2) when organic matter is > 1%. The procedure (1+2) is described in Renger et al. (2008) and Wessolek et al. (2009).

$$\rho_b\,(Ld_3) = 1.65 - (0.005 \times \%clay) - (0.001 \times \%silt) \qquad (1)$$

$$\rho_{bcorrected} = \rho_b - (0.04 \times \%org) \qquad (2)$$

where:
%clay/silt/sand/org = Volumetric fraction of the named component [%],
ρ_b = bulk density [g/cm^3].

The respective water contents were calculated (3) using the Van Genuchten parameters (Van Genuchten, 1980) and a for subsoil representative matric potential.

$$\theta_{(\Psi)} = \theta_r+((\theta_s-\theta_r) / (1+(\alpha \times |\Psi|)^n)^m) \qquad (3)$$

where:
$\theta_{(\Psi)}$ = Water content as a function of the matric potential [Vol. - %],
Ψ = Matric Potential [hPa]
θ_r = residual water content [Vol. - %]
θ_s = saturated water content [Vol. - %],
α, n, m = van Genuchten Parameter. (m=1)

Various matrix potentials around the field capacity were used to determine the water content (pF=1.8; pF=2.5; pF=3.0). The slightly less moist soil condition (pF=3.0) was used as a conservative value for calculating the geothermal potential. The required Van Genuchten parameters were calculated depending on the soil properties (Van Genuchten, 1980; Vereecken et al., 1989) (4-7):

$$\theta_r = 0.015 + (0.005 \times \%clay) + (0.014 \times \%org) \quad (4)$$

$$\theta_s = 0.81 - (0.283 \times \rho_b) + (0.001 \times \%clay) \quad (5)$$

$$\log(\alpha) = -2.486 + (0.025 \times \%sand) - (0.351 \times \%org) - (2.517 \times \rho_b) - (0.023 \times \%clay) \quad (6)$$

$$\log(n) = -0.053 - (0.009 \times \%sand) - (0.013 \times \%clay) + (0.00015 \times \%sand^2) \quad (7)$$

Based on soil texture, bulk density and water content the thermal conductivity of unfrozen soils was determined according to Kersten (1949) (8+9). For sand contents > 50 %, equation 8 is used and for sand contents ≤ 50 % equation 9.

$$\lambda = 0.1442 \times (0.7 \times \log(\theta_W/\rho_b) + 0.4) \times 10^{\,0.6243\times\rho b} \quad (8)$$

$$\lambda = 0.1442 \times (0.9 \times \log(\theta_W/\rho_b) - 0.2) \times 10^{\,0.6243\times\rho b} \quad (9)$$

where:
λ = thermal conductivity [W/m·K],
θ_W = total volumetric water content [Vol. - %].

Using this workflow, an area-wide calculation of the thermal conductivity based on the soil survey map (1:5000) was realised. GIS software (ESRI ArcGIS) was used to process the data and to visualize the results.

Determining vSCP in terms of the system-specific heat extraction

VDI 4640-2 (2019) specifies area-specific heat extraction, extraction energies, full load hours and pipe spacing for a collection of common horizontal systems on the market depending on the prevailing main soil texture class and climate zone (Table A2, Table A3). These parameters are implemented in the GIS project database following the concept of Schwarz et al., (2022). For the classification of the respective location and the derivation of pumping capacity and pumping energy according to VDI 4640, the climate zones according to DIN 4710 (Deutsches Institut für Normung, 2016) were included in the data set (Fig. A1). For detailed integration of the climatic influence, the data from DIN 4710 (Deutsches Institut für Normung, 2016) and VDI 4640 (Verein Deutscher Ingenieure., 2019) were supplemented with the altitude data of the reference weather stations (m above sea level). In a further step, the freely available digital elevation model (DEM) was used to correlate the extraction rates with the altitudes (Figure 2). Thereby, it was possible to determine location- and altitude-specific extraction rates for the whole of Bavaria.

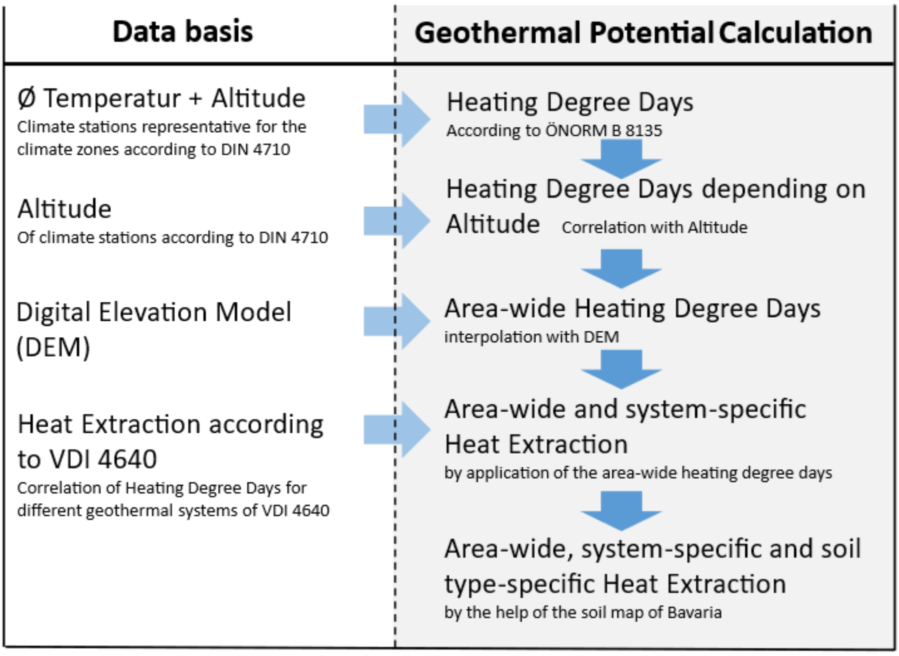


Fig. 2. Calculation workflow for the system- and soil-specific extraction capacity

Slope degree is calculated using the GIS software (ESRI ArcGIS). The calculation was based on the DEM (DEM50) of the Federal Agency for Cartography and Geodesy (Federal Agency for Cartography and Geodesy, 2020). Slope degree > 15% was considered as unsuitable for installing very geothermal systems (Bertermann et al., 2014, 2015).

Categorization of the heat extraction capacities

In order to be able to categorise the heat extraction capacities of the system-specific potential, different demands for heating certain house types were taken into consideration.

The database of the Institut Wohnen und Umwelt contains the heating energy requirements for various types of residential houses in Germany. This information was extracted using the TAB-ULA web tool for 12 different generations of buildings with different energy efficiency standards (Table A4). Using these 12 different generations of buildings it is possible to correlate the building specific heating energy demand with the calculated local geothermal potential. This enables the calculation of the area required for the shallow geothermal systems listed in the VDI 4640.

Validation of the derived soil texture classes and the calculated thermal conductivities (vSGP)

At three exemplary rural test sites in Bavaria, soil samples were taken by drilling or from construction pits at depths ranging from 1.0 to 2.0 m below ground level. The different geographical locations (Table 2, Figure 3, Figure 4) provided variations in geological bedrock and soil configuration.

Grain size analyses were performed on the soil samples to validate the KA5 soil texture classes derived from the soil map information at the specific polygons. The grain size distribution of the soil (sand, silt, clay) was determined by sieving and by using a particle size analyzer (Sedigraph from Micromeritics Instrument Corporation), which uses the sedimentation method and determines particle mass directly by X-ray absorption.

In addition, thermal conductivity measurements were carried out on a laboratory scale to compare the results with the calculated values of the vSGP map. Thermal conductivities were measured using the evaporation method according to Markert et al. (2016) in order to obtain data for a wide range of water contents. A detailed description of the measurement setup and approach can be found in Rammler et al. (2023). The validation was then carried out between the point-measured values and the same positions on the potential map.

The following table gives an overview of the analyses for each test site:

Tab. 2. Test sites and number of laboratory measurements used for validation with the type of measurement interval for the thermal conductivity measurements as described in Rammler et al. (2023).

Test site	Grain size analysis	Thermal conductivity measurements
Kasendorf	4	4 (temporary measurement interval)
Merkendorf	3	3 (continuous measurement interval)
Spiegelau	3	2 (continuous measurement interval)

Results

As a result, the calculated mean thermal conductivities for three different matric potentials for representative moisture conditions at the installation depth of horizontal geothermal systems (usually > 1.5 m) are illustrated in Table 3. The calculations related to the three matric potentials pF 1.8, pF 2.5 and pF 3.0 showed an average thermal conductivity in Bavaria between 1.1 and 1.3 W/(m·K). Related to the heat conductivity classes developed under the umbrella of the ThermoMap MapViewer (Bertermann et al., 2015) the values can be categorised as medium high (1.1-1.2 W/(m·K)) to high (>1.2 W/(m·K)). As a result, the thermal conductivity averages of all grassland und farmland areas in Bavaria are theoretically suitable for shallow geothermal utilisation.

Tab. 3. Calculated thermal conductivities according to Kersten (1949); given as mean value for all areas covered by the digital survey soil map for three selected matric potentials (pF-value)

	pF 1.8	pF 2.5	pF 3.0
Min value	1.03 W/(m·K)	1.02 W/(m·K)	1.02 W/(m·K)
Max value	1.73 W/(m·K)	1.61 W/(m·K)	1.45 W/(m·K)
Mean value	1.29 W/(m·K)	1.23 W/(m·K)	1.13 W/(m·K)

The very shallow geothermal potential of Bavaria in terms of thermal conductivity as a function of soil texture, bulk density and water content is shown in Figure 4. The calculated system-specific heat extractions are shown in Figure 3 for the classical horizontal heat exchangers. This research is focused on four different very shallow geothermal system types: horizontal geothermal collectors, capillary tube mats, geothermal baskets and trench collectors. Thermal conductivity is an important factor for planning and dimensioning process of heating and cooling systems but cannot directly represent the efficiency of a specific geothermal system. However, the heat extraction (in W/m²) expresses the efficiency more clearly, as it actually defines the theoretical output of a specific system.

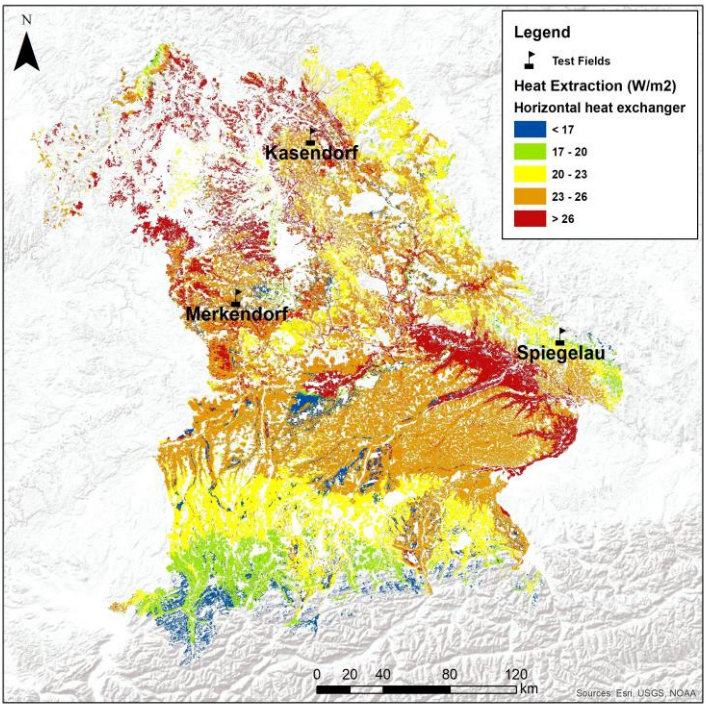


Fig. 3. Map of heat extraction rate for Bavaria regarding the classical horizontal heat exchangers as an example of a system specific vSGP

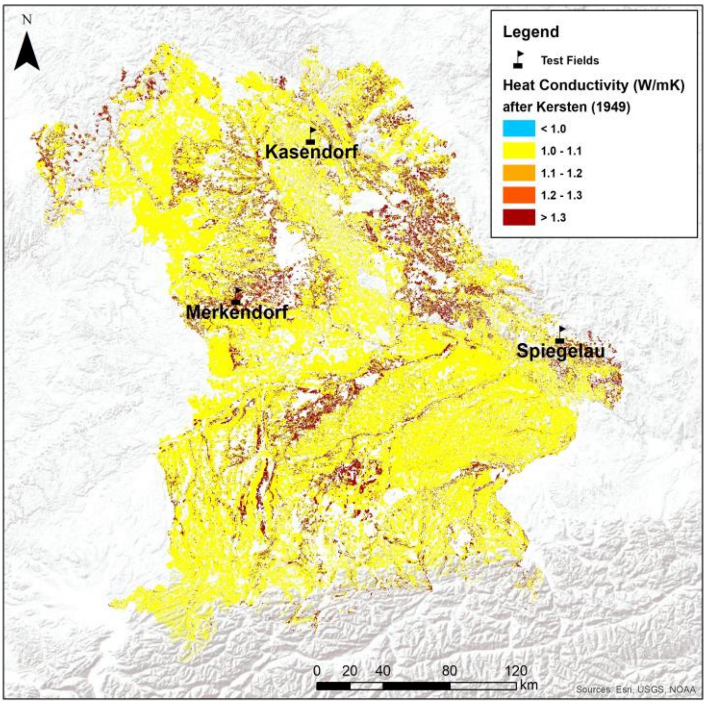


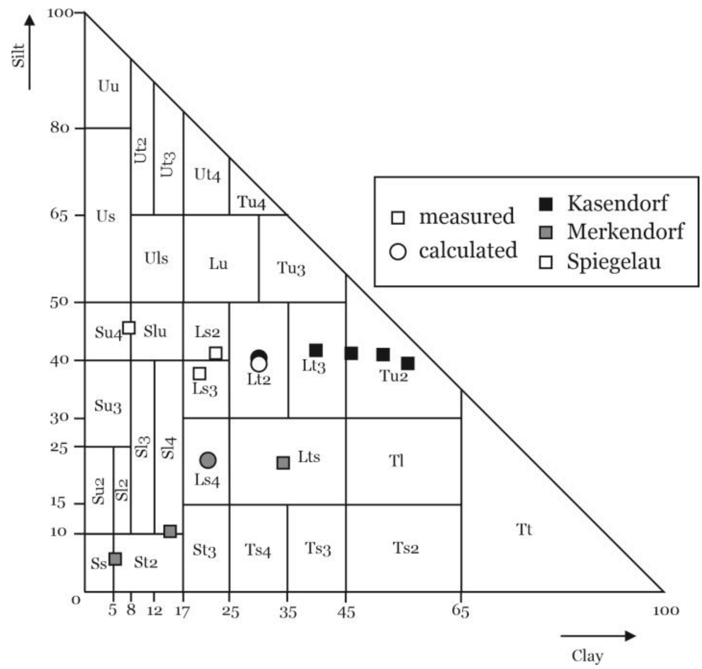
Fig. 4. Thermal Conductivity map of Bavaria representing the general vSGP.

Results of validation based on three exemplary test sites

The comparisons of the measured and derived grain size distributions and thermal conductivities are shown in Figure 5 and Table 4.

As can be seen in Figure 5a, the laboratory results for the Kasendorf and Spiegelau test sites differ from algorithmic grain size distributions, particularly in terms of clay and sand content. The silt contents of approximately 40% for Kasendorf and between 38 and 45% for Spiegelau are almost identical in each case. In the case of the soil samples from Merkendorf, the laboratory results also indicated a natural variation in clay, silt and sand content on a small scale in the study area, which is not resolved by the soil base map.

One average, the thermal conductivities of the Kasendorf samples did not differ from the calculated values of the vSGP map. At the Merkendorf test site, only one soil sample showed a significant higher thermal conductivity of 2.1 W/(m·K) compared to the calculated value. This is mainly due to the significantly higher sand content of the soil sample compared to the value defined by the algorithm, which has a positive effect on the thermal thermal conductivity. The two laboratory measurements for the Spiegelau test site also both showed significantly higher thermal conductivities compared to the values given by the vSGP map. It is assumed, that the weathering of the meta-sedimentary bedrocks (dGK25) (Bayerisches Landesamt für Umwelt, 2024) leads to a specific mineralogical composition of the resulting fine-grained soil with corresponding thermal properties. Mineralogical peculiarities are not taken into account in the algorithm by using the thermal conductivity model by Kersten (1949).



(a)

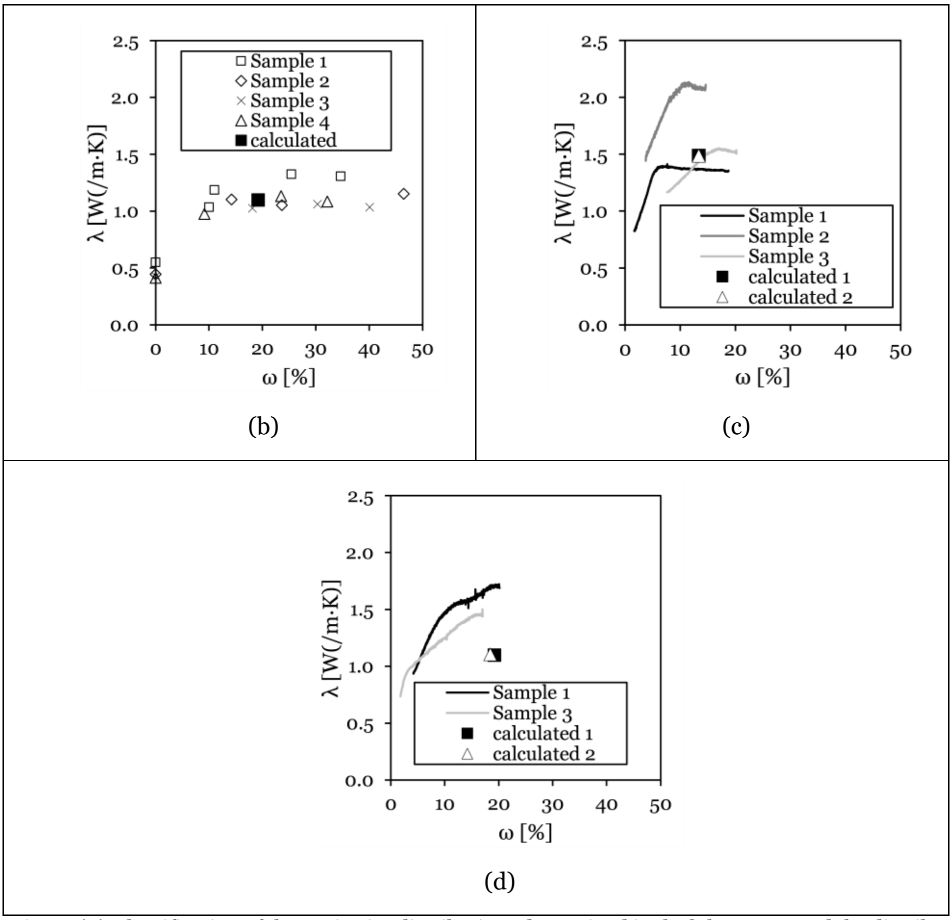


*Fig. 5. **(a)** Classification of the grain size distributions determined in the laboratory and the distributions derived by the algorithm according to KA 5;**(b-d)** Comparison of the measured thermal conductivities (λ) with the calculated values of the vSGP map at specific gravimetric water contents (ω) for **(b)** Kasendorf, (**c**) Merkendorf and (**d**) Spiegelau. The soil samples from Merkendorf and Spiegelau were taken from two different polygons. However, this does not result in any significant differences in the derived grain size distribution and calculated thermal conductivity.*

Tab. 4. Differences (Δλ) between measured thermal conductivities (λ) and calculated values for the corresponding polygons at the specific gravimetric water contents (ω) based on matric potential pF = 3.0.

Town	Parameter	Calculated	S 1	S 2	S 3	S 4	Average
Kasendorf ω = 19 %	ρ_b [g/cm³]	1.46	1.42	1.42	1.40	1.41	1.41
	λ [W/(m·K)]	1.1	1.3	1.1	1.0	1.1	1.1
	Δλ [W/(m·K)]	-	-0.2	0.0	0.1	0.0	0.0
Merkendorf ω = 13 %	ρ_b [g/cm³]	1.52	1.60	1.58	1.39	-	1.52
	λ [W/(m·K)]	1.5	1.4	2.1	1.4	-	1.6
	Δλ [W/(m·K)]	-	0.1	-0.6	0.0	-	-0.1
Spiegelau ω = 18-19 %	ρ_b [g/cm³]	1.46	1.47	-	1.57	-	1.52
	λ [W/(m·K)]	1.1	1.7	-	1.4	-	1.6
	Δλ [W/(m·K)]	-	-0.6	-	-0.3	-	-0.5

In the case of Merkendorf and Spiegelau, the soil samples were taken from two different polygons. However, this does not result in any significant differences with regard to the calculated thermal conductivities, which are therefore given as one value. Also shown are the bulk densities (ρb) of the measured soil samples (S1-S4) and the values obtained by the algorithm. The thermal conductivity values have been linearly interpolated due to the temporary measurement intervals of the Kasendorf samples.

Comparison of the area requirements of different collector systems

The comparison between the heating energy demand and the calculated very shallow geothermal potential is shown in Table 5. It is clear that the different heat extraction capacities of the individual geothermal systems also result in very different space requirements. Furthermore, it is also clear that older houses have higher energy requirements and therefore also require more space to cover the heating demand.

Tab. 5. The area requirements of the five mentioned systems corresponding to the extraction capacities outlined in VDI 4640 at the same location (see Figure 7) and specific house type or consumption are determined to be 97.87 m²

Type	Year of construction	System	**Area required** [m²]
single-family house	1969 - 1978	horizontal collector	197
		capillary tube mats	192
		heat basket 1.3x1.3	154
		heat basket 2.0x0.5	266
		slinky/trench collector	91
	1995 - 2001	horizontal collector	212
		capillary tube mat	208
		heat basket 1.3x1.3	168
		heat basket 2.0x0.5	280
		trench collector	98
	2010 - 2015	horizontal collector	104
		capillary tube mat	102
		heat basket 1.3x1.3	84
		heat basket 2.0x0.5	140
		trench collector	48

Discussion

Parameters for generating the vSGP maps

Parameters such as thermal conductivity of the soil as well as climate and topographical parameters are the key factors for describing the specific vSGP.

Thermal conductivity is one of the key physical soil parameters for dimensioning a very shallow geothermal system. It provides a planning basis for designing very shallow or horizontal geothermal installations. As the thermal conductivity has a direct effect on the heat extraction potential (Schwarz et al., 2022), regions with low thermal conductivity need more installation space for very shallow geothermal systems.

Besides the geological or pedological characteristics and geographical features some other important factors are the current technical solutions as well as the current socio-economic and political framework conditions. Therefore, there are three levels of potential barriers and constraints – technical, economic and social/political (Jocić et al., 2020).

Significance of the validation results for use of the vSGP maps

Validation of the derived grain size distributions and calculated thermal conductivities was carried out using soil samples from three test sites. Grain size analysis revealed a natural variation in sand, silt and clay content that is not represented in the soil survey map and therefore not in the derived soil texture classes of the algorithm.

Based on the laboratory measurements of thermal conductivity, no or only minor deviations from the calculated values of the vSGP map were found. On the other hand, a significant underestimation of the vSGP was observed compared to the measured values. In these cases, observed in this study, this is due to the underestimation of high sand contents or the lack of consideration of mineralogical peculiarities by the algorithm.

In addition, the empirical model by Kersten (1949) is known to underestimate thermal conductivities (Bertermann et al., 2024). However, this underestimation of the geothermal potential ensures a certain degree of certainty, particularly for the planning and design of geothermal installations.

Requirements of the very shallow geothermal technology

The installation of horizontal geothermal systems requires a system-specific installation area. In urban environments where potential installation areas are less available. This can be a limiting factor. Due to less dense urbanisation and surface sealing, rural areas are particularly appropriate for the use of very shallow geothermal systems. In addition, many rural settlements are surrounded by agricultural fields or grassland. Horizontal geothermal systems do not interfere with agricultural activities and can be installed cost- and time efficient via a plough or an excavator. By using these agrothermal energy systems a parallel use of the agricultural land is practicable (Rammler et al., 2023; Zeh et al., 2021).

A decisive prerequisite for an efficient geothermal heating (and cooling) system is a contemporary insulation of the buildings or residential units. Nevertheless, historical buildings can also be tempered by very shallow geothermal systems (Cadelano et al., 2019).

Situation of rural areas in Bavaria

The Bavarian state supports increasing the attractiveness of rural areas by investing in hard and soft infrastructure. In contrast to most rural areas in Europe, the population in Bavaria's rural areas has generally grown over the last decade (Bayerisches Staatsministerium der Finanzen und für Heimat, 2019). As a result, the use and the extension of very shallow geothermal systems especially in rural areas in Bavaria is an important component within the sustainable heating and cooling transition and a green transformation. The provided vSGP maps support to establish these cheap and easy to install sustainable energy source in rural areas of Bavaria.

Conclusion

Climate change is one of the most important challenges facing our generation. More and more progressive movements and politicians are calling for the issue to be taken seriously. One of the most effective means of combating climate change should be to switch the energy supply to renewable and sustainable energy sources.

By combining climate- and soil datasets very shallow geothermal potential maps were derived. The potential was specified by thermal conductivity by using the thermal conductivity model of Kersten (1949) and system-specific heat extraction. The heat extraction information based on the shallow geothermal systems according to the VDI 4640. With developed spatial approach the vSGP was illustrated via a GIS. The derived vSGP maps serve as a high-resolution planning basis for very shallow geothermal applications. As the validation of three exemplary test sites showed, a certain degree of certainty is given by the underestimation of the thermal conductivity by the vSGP map. An area requirement calculation was carried out using exemplary building data. This area requirement could be calculated for the specific very shallow geothermal systems mentioned in the VDI 4640.

Very shallow geothermal energy is a renewable sustainable source for heating and cooling buildings and could cover a significant part of the increasing energy demand. In rural areas, especially very shallow geothermal systems are easy and fast to install due to the availability of the required space.

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Appendix

Tab. A1. Climate zones in Bavaria – percentual share of area

Climate Zone	**6**	**10**	**11**	**12**	**13**	**14**	**15**
%	2.28	11.50	2.09	1.08	72.05	0.47	10.54

Tab. A2. Heat extractions and extraction energy for horizontal ground heat collectors. The table shows parameters for different main soil types and for all climate zones spreading in Bavaria (abstracted from VDI 4640-2).

Climate Zone 6	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	16	26	28	30
extraction energy [kWh/(m²a)]	31	50	54	58
full-load hours [h/a]	1950	1950	1950	1950
Climate Zone 10	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	13	23	26	28
extraction energy [kWh/(m²a)]	23	41	46	50
full-load hours [h/a]	1800	1800	1800	1800
Climate Zone 11	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	5	9	12	13
extraction energy [kWh/(m²a)]	12	21	28	31
full-load hours [h/a]	2400	2400	2400	2400
Climate Zone 12	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	30	37	39	42
extraction energy [kWh/(m²a)]	40	49	52	56
full-load hours [h/a]	1350	1350	1350	1350
Climate Zone 13	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	16	25	27	29
extraction energy [kWh/(m²a)]	28	45	48	52
full-load hours [h/a]	1800	1800	1800	1800
Climate Zone 14	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	14	25	27	28
extraction energy [kWh/(m²a)]	25	46	49	51
full-load hours [h/a]	1850	1850	1850	1850
Climate Zone 15	**Sand**	**Loam**	**Silt**	**Sandy clay**
heat extraction [W/m²]	14	25	26	29
extraction energy [kWh/(m²a)]	24	43	45	50
full-load hours [h/a]	1950	1950	1950	1950

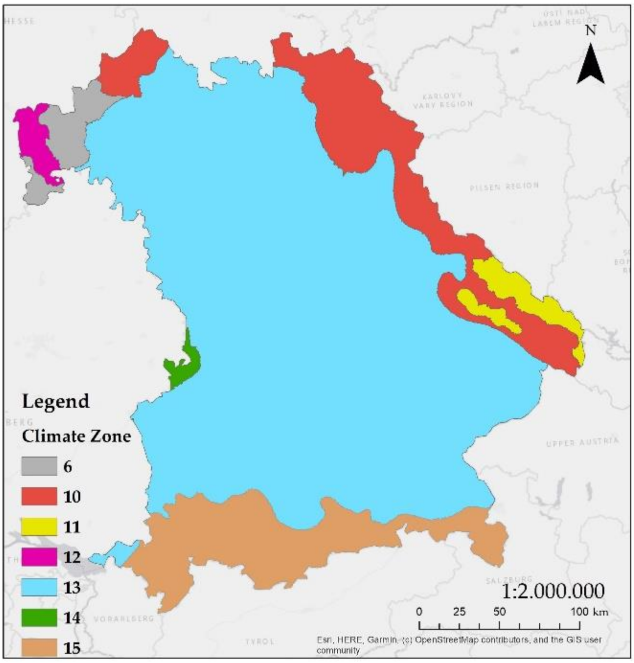

Fig. A1. Climate zones in Bavaria for heating, ventilation and air conditioning according to DIN 4710 (Deutsches Institut für Normung, 2016, p. 4)

Tab. A3. Main soil types in Bavaria – percentual share of area

Main soil type	**Sand**	**Loam**	**Silt**
%	3.33	96.10	0.57

Tab. A4. Different types of houses built in different years and the corresponding energy requirement

	Type	**Year of construction**	**Heating Energy Demand** [kWh/(m2*a)]
1	single-family house	bis 1859	93.0
2	multi-family-house	bis 1859	98.3
3	single-family house	1860 - 1918	95.9
4	multi-family-house	1860 - 1918	80.5
5	single-family house	1919 - 1948	83.7
6	multi-family-house	1919 - 1948	82.5
7	single-family house	1949 - 1957	111.5
8	multi-family-house	1949 - 1957	79.3
9	single-family house	1958 - 1968	117.4
10	multi-family-house	1958 - 1968	67.2
11	single-family house	1969 - 1978	90.4
12	multi-family-house	1969 - 1978	74.0
13	single-family house	1979 - 1983	74.9
14	multi-family-house	1979 - 1983	68.6
15	single-family house	1984 - 1994	94.4
16	multi-family-house	1984 - 1994	72.6
17	single-family house	1995 - 2001	97.6
18	multi-family-house	1995 - 2001	68.8
19	single-family house	2002 - 2009	72.9
20	multi-family-house	2002 - 2009	54.0
21	single-family house	2010 - 2015	47.8
22	multi-family-house	2010 - 2015	46.5
23	single-family house	von 2016	40.8
24	multi-family-house	von 2016	27.6

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