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Shallow Geothermal Energy Potential in Transboundary Region Between Austria and Slovakia (Results from the GeoPLASMA-CE Project)

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ABSTRACT

The increasing demand for sustainable energy use and growing measures to improve environmental quality along with rising awareness toward the benefits of renewable technologies impact the ground source heat pump market. Interreg project GeoPLASMA-CE was focused on the estimation of the shallow geothermal energy potential. The research was applied to the pilot areas that were focused on urban and/or transboundary regions. One of the investigated areas was the region between Austria and Slovakia, including the towns of Bratislava – Hainburg – Kittsee located in both countries with a total area covering 603 km^2. Bratislava city is representing the urban area with a higher density of population and higher demand for heat and cold. The second part represents the rural area on the side of the settlements on the Austrian side. The geological and hydrogeological setup (up to investigated depth 400 m) is characterised by various types and regimes of groundwater flow. The complex attitude for shallow geothermal energy potential included joint approach, harmonisation of the necessary information, data and following compilation of geological, hydraulic and geothermal models. The high potential for shallow geothermal energy provides the opportunity to overcome certain challenges in cities. However, if geothermal energy is used extensively in a city and thermal effects of heating outweigh the effects of cooling and lead to the development of "urban-heat-islands". The integrative approach was implemented and included not only outcomes of the geoscientific modelling but as well the comparison of the different standards, methods of evaluation of the legislative approach in both countries. Common strategies were outlined to deliver the proper information for the stakeholder. The article gives a basic insight into the resource management maps elaborated for open-loop systems with possible installations in the Quaternary aquifer. Though this is just one set of the delivered outputs within the project.

1. INTRODUCTION

The growing need for renewable energy sources has led to the increased interest in shallow geothermal applications for the heating and/or cooling of buildings. By providing an alternative to fossil fuels and reducing peak demand from the grid, they also provide an attractive tool towards energy independence and distributed generation with no adverse impact on the environment.

Shallow geothermal resources are generally considered up to 400 m depth by governmental definition in several countries; however, an exact definition replacing that of arbitrary character has not been found yet. Generally, below 15 - 25 m depth the temperature field is governed by terrestrial heat flow and local ground thermal conductivity structure (± groundwater flow). In the wide range of the literature, different systems are used for heat extraction from underground.

Part of the successful installation of a ground source heating/cooling system is knowledge of the subsurface and how much of that energy we can extract and deliver to the end-user. To choose the right system for a specific installation, several factors have to be considered: Geology and hydrogeology of the underground (sufficient permeability and chemical properties of groundwater, thermal properties of the rock environment), area and current utilisation on the surface and subsurface, existence of potential heat sources and the heating and cooling demands of the end-user (or buildings).

Interreg project GeoPLASMA-CE (CE 177) was established as a complex project focused on comparing legal schemes, management attitudes, description of underground environment and calculation of the geological environment thermal properties for fostering the share of shallow geothermal use in heating and cooling strategies in central Europe. To achieve this goal, a set of complex works were carried out that include measurements performing and construction of integrated maps and models describing energetic potential in the pilot area. As an outcome, the project created a web-based interface between geoscientific experts and public as well as private stakeholders to enable the transfer of the existing know-how about resources and risks associated to geothermal use accessible for territorial energy planning and management strategies. Within the project, one of the investigated areas is the region between Austria and Slovakia, including towns Bratislava – Hainburg located in both countries.

2. INVESTIGATED AREA SETUP - BRATISLAVA-HAINBURG–KITTSEE

2.1 Natural Conditions

The pilot area Bratislava-Hainburg–Kittsee covers 603 km² between Slovakia and Austria in the vicinity of Hungary (Figure 1). This area is delimited by natural borders (river Leitha on the south, river Morava and Danube on the west) and by administrative borders of the Bratislava city on the north and east. Rivers Danube, Leitha and Morava confine the area towards the west, whereas the eastern border is delineated by the Bratislava city administrative outline. The Austrian/Slovakian border dissects the pilot area into the rural (Austrian part in the southwest) and the urban part in the northeast with Bratislava city as a capital of Slovakia. The total population in the entire pilot area of ca. 450,000 is also concentrated in the Slovak part. Topographic Elevation ranges from

480 m a.s.l. in the Male Karpaty Mountains in the northern section to 125 m a.s.l. in the east, where the Danube exits the pilot area towards the Hungarian Plain. At the northern part, the Danube crosses the NE-SW-striking Male Karpaty and Hainburg Mountain Range, draining the Vienna Basin located northwest of the Pilot area and entering the Danube/Pannonian Basin towards the southeast.

From the geological point of view, the area is created by core mountains (with crystalline core and sedimentary envelope) Malé Karpaty Mts. and Hainburger Berge. Lowland belongs to the Vienna basin and the Danube basin with the sedimentary fill of Neogene and Quaternary sediments. From the lithological point of view, the area has great variety in rock types and sediments that creates a different condition for water recharge and groundwater circulation, as well as geothermic conditions important for shallow geothermal heat pumps installation. The Quaternary sediments have sufficient thickness and effective porosity and create the background for water sources with high yield and good quality of the water. At the Austrian side, the groundwater body has a yearly average value of 12.8°C, an average thickness of 7 m (range of the aquifer thickness is 3 to 20 m) (Austrian side, Umweltbundesamt, 2016) and it has a lower amount of the groundwater resources in comparison to Danube River alluvial deposits. The Danube river deposits (gravels and sands – alluvium in the area between Devín and Bratislava) show thicknesses between 2 and 18 m. The direction of groundwater flows, as well as of groundwater levels, are connected to the Danube river and its deviation channel. The aquifer has a yearly average temperature of 12.4°C and an average thickness of 11 m (Austrian side, Umweltbundesamt, 2016). The fluvial sediments at the eastern part of the investigated area have the highest mean values of the transmissivity coefficient, with values of hydraulic conductivity of up to $4x10^{-2}$ m/s. The maximum thickness of the groundwater body is 100m and the mean permeability coefficient of $4x10^{-3}$ m/s (Malík et al., 2000).

2.2 Input Data

At first, geological and hydrogeological data sources in Bratislava - Hainburg area were compared for and checked for frequency and data quality by geological surveys of Slovakia (SGIDS) and Austria (GBA). The accessible data were organised into the databases, were processed and accommodated for project needs, borehole data were re-evaluated and simplified. Both partners had sufficient relevant data in archives and databases to create 3D geological, hydrogeological and geothermal modelling.

For the compilation of output maps indicating geothermal potential, input maps were generated and included aquifer parameter maps (aquifer outline maps, map of aquifer thickness, hydraulic conductivity maps) and thermal boundary conditions – temperature maps (maximum and minimum groundwater temperature maps). The methods of the data assessment and processing and resulting map compilation were evaluated in workflows for all the investigated areas in the project and were applied in investigated area Bratislava – Hainburg – Kittsee (Fuchluger et al., 2019, Goetzl, 2017, Goerz, 2017).

2.2.1 Aquifer Outline Map

Aquifer outline maps deliver information about the overall groundwater availability. To delineate the aquifer, distribution of the Quaternary sediments was derived from geological maps and used as an input for further processing towards the 3D geological model. This created a basis for background Quaternary basin geometry and boundary conditions. (Figure 1).

2.2.2 Aquifer Thickness Map

Net aquifer thickness delivers information about the fully saturated zone, calculated by subtraction of two grids: mean groundwater level and pre-Quaternary basement. Input values that were used in calculations had different sources. For the pre-Quaternary basement, a 3D geological model was compiled based on published maps, known geological borehole profiles and published (or for the purpose of the project generated) cross-sections. The grids of the mean groundwater level were obtained from numerical steady-state models of the groundwater flow calibrated on observation wells. The aquifer thickness grid was used as the main input parameter for energy potential calculation. The map of the aquifer thickness is investigated area is shown in Figure 2.

2.2.3 Hydraulic Conductivity Map

The hydraulic conductivity map of the Quaternary aquifer was compiled from different sources. Quaternary deposits at the proluvial sediments were used as general data from other sources by methods of analogy. The main body of the Holocene sediments in the vicinity to the Danube and Leitha river comprise of gravels and sandy gravels. In the further distance, the terrace sediments are present. Hydraulic tests have often verified both lithological units. This "local" information about the hydraulic properties was interpolated by kriging method, and a grid showing the areal distribution of the hydraulic conductivity was compiled (Figure 3).

2.2.4 Minimum and Maximum Groundwater Temperature Maps

The information of the groundwater temperature was calculated based on groundwater temperature monitoring stations, the temperature fluctuation in monitoring points and depth temperature profiles in the monitored wells. Based on the data described above two grids have been generated - a minimum of the mean groundwater temperature $T_{OBS\text{-}LOW}$ (related to the winter minimum) and a maximum of the mean groundwater temperature $T_{OBS\text{-}HIGH}$ (related to the summer maximum). The minimum and maximum temperatures in the uppermost saturated zone are shown in Figure 4.

3. RESULTING MAPS

The open-loop potential calculation was performed for Quaternary aquifers with porous media (e.g. gravel or coarse sand). Only the upper groundwater body was considered for assessment of the potential.

Available geothermal potential of open-loop systems depends mainly on the availability of groundwater and geothermal resources that can be reported in terms of the thermal capacity of a well doublet (installed thermal capacity), or energy content of a defined area (thermal work or energy available per year).

Two basic output maps were produced to help to manage the groundwater resources for open-loop systems in the quaternary aquifer. The maps delivered aimed to provide potential values that would be related to the areal units independent from the calculation grid. Therefore, the values for energy potential and peak load and hydraulic productivity were calculated in units for flow rate per square meter (l/d/m²) or power per square meter (W/m²).

3.1 Map of the Hydraulic Productivity at the Peak Load

The maximum yield available for the peak load Q [m³/s] in an unconfined aquifer was calculated with Equation 1 (after Thiem, 1906) and Equation 2 (after Sichardt, 1928) for each calculation area. It depends on the hydraulic conductivity kf [m/s], the effective thickness of the saturated zone SZ_{eff} [m] in the area and the hydraulic radius R [m] that was generally set to 50 m value. The default value of well radius r was set to 1 m.

$$Q_{PEAK} = \frac{\pi \cdot kf \cdot s \cdot \left(2 \cdot SZ_{eff} - s\right)}{\ln\left(\frac{R}{r}\right)} \tag{1}$$

$$s = \frac{R}{3000 \cdot \sqrt{kf}} \tag{2}$$

By fixing the hydraulic influence radius (R) for one well, the needed area for one well-doublet can be calculated. The closest surrounding square-shaped area defines the influence area of one well, see Equation 3.

$$A_{PEAK} = 2 \cdot (2 \cdot R)^2 = 2 \cdot (2 \cdot 50m)^2 = 20{,}000\, m^2 \tag{3}$$

The effective aquifer thickness $SZeff$ was limited to 20 m to avoid unrealistic high discharge values. This includes the assumption that not more than 20 m of the aquifer can be used efficiently with a standard well.

During the process of the workflow, the peak load calculation was improved. The maximum hydraulic yield was limited by fixing the hydraulic radius and not by limiting the maximum drawdown of the groundwater table to 1/3 of the net aquifer thickness. By setting a constant hydraulic radius of one well, also the area needed for one well doublet was estimated, and therefore the peak load values were calculated per square meter (Figure 4).

The highest values of the peak load pumping rates are correlated to the higher rates of hydraulic conductivity of the well-sorted gravels and sandy gravels at both banks of the Danube river at the central part of the studied area. With descending basement of the Quaternary aquifer towards the east, the thickness of the aquifer increases. Though higher values of hydraulic productivity (available pumping rates at the peak load) are delimited by the arbitrary maximum effective thickness of the aquifer. Other parts of the higher values can be found in the south part with Quaternary deposits of the Leitha river. By the distribution of the values part of the uncertainty has a source in input data distribution and subsequent interpolation method related to the hydraulic conductivity data.

3.2 Map of the Peak Load Thermal Power

The thermal capacity (P) refers to a single well-doublet and can be described using the following equation (Equation 4).

$$P_{PEAK} = Q_{PEAK} \cdot c_{vw} \cdot minimum(\Delta T, \Delta T_{BAL}) \tag{4}$$

The thermal capacity is derived as a result of the hydraulic productivity, reflecting the available pumping rate (Q) of a groundwater well doublet, and the thermal productivity reflecting the temperature difference (ΔT) between the production and injection well and of the volumetric heat capacity of the energetically used groundwater (for calculations value 4100 kJ/m³/K was used). It describes the thermal power (for heating and cooling) of a well doublet for a certain moment or period. Usually, it delineates the maximum capacity with respect to the hydrogeological and thermal settings of the aquifer. In that context, the operational period at a certain capacity level (peak load, baseload or on a daily or annual basis) has to be taken into consideration to derive the energy from the thermal capacity. For calculating the maximum peak load, the smaller value (minimum) of the temperature difference between extraction and injection (ΔT) and the temperature difference for balanced use (ΔT_{BAL}) is used. For the case study at the investigated area, Austrian values of ΔT was used with maximum of 5 K. The main reason set in national guidelines (OEWAV; 2009; OEWAV Regelblatt 207 Thermische Nutzung des Grundwassers und des Untergrunds – Heizen und Kühlen; Vienna) is the thermal protection of groundwater and respect to the equal access to the shallow geothermal energy source and avoiding the principle of first come - first served.

Hydraulic productivity and thermal capacity are important parameters to describe resources related to the use of open-loop systems. As resources are related to a range of different input parameters, productivities may give important information on the resources available. The thermal capacity only describes the potential of use (in the unit of thermal power) without taking into account the energy available, which depends on the operational hours of the open-loop application. In Figure 6, the thermal capacity was set equal to the maximum value at peak load.

The maximum values of the thermal capacities at the peak load can be observed at the vicinity to the Danube river in the middle of the investigated area. The magnitude of the peak values is primarily sensitive to the hydraulic conductivity and secondarily to the effective aquifer thickness. Therefore, the quality of the peak load result depends strongly on the quality of this input data. The specific power (thermal capacity) P_{PEAK} is additionally influenced by the allowed temperature change to the groundwater between extraction and injection. The default value is 5 K.

The calculated values of Q_{PEAK} and P_{PEAK} are as well strongly dependant on the fixed value of the hydraulic influence radius R. A high number of small open loop systems with small R lead to a high area-specific pumping rate, while a large R reduces it.

3.3 Calculation of the Energy Potential

The evaluation of the energy content was performed for three different operational modes of open-loop systems:

- Balanced annual heating and cooling demand
- Heating purposes only (groundwater is cooled down)
- Cooling purposes only (groundwater is heated up)

In general, the calculation was based on the energy stored in the aquifer. At a balanced use, the energy content can be provided yearly, not compromising the mean annual aquifer temperature. For unbalanced use, the stored energy content can be used over the lifetime of the open-loop system (e.g. 20 years) while the temperature of the aquifer will change. Therefore, a recharging effect from the layer above and below the aquifer is considered as well. Thermal recharge from natural groundwater flow was not considered in the calculations, as just the first user can use this energy. The results give the user a magnitude of the available groundwater potential for open-loop systems divided per area (in this case per square meter). By multiplying it with the size of the area of interest, the total amount can be calculated easily. In urban developing areas city planners may give priority to properties with a public building.

Energy content (energy stored) in the saturated aquifer ($E_{storage}$) that is available for balanced heating and cooling can be derived using Equation 5. Results are instantly sensitive to aquifer thickness *(SZ)* and particularly to allowed temperature change (ΔT_{BAL}).

$$E_{BAL}\left[\frac{kWh}{yr\cdot m^2}\right] = E_{storage} = \frac{C_{VA}\cdot SZ\cdot \Delta T_{BAL}}{3.6}\cdot rf \qquad (5)$$

Energy content available for unbalanced use (unbalanced use the stored energy) is divided by the lifetime (LT). Additionally, the calculation considers heat flows from the surface ($E_{surface}$, Equation 6) and the underground ($E_{underground}$, Equation 7).

$$E_{surface}\left[\frac{kWh}{yr\cdot m^2\cdot K}\right] = Maximum\left(E_{underground};\ \frac{\lambda_{OB}}{GWD + SZ/4}\cdot\frac{4380h/yr}{1000W/kW}\right) \qquad (6)$$

$$E_{underground}\left[\frac{kWh}{yr\cdot m^2\cdot K}\right] = q_{10}\cdot\frac{8760\,h}{1000} \qquad (7)$$

where

$$q_{10} = \frac{\lambda Bott\cdot\left[1-erfc\left(\frac{x}{2\sqrt{a\cdot t}}\right)\right]}{x} \qquad (8)$$

The recharge from the surface is based on the estimated mean thermal conductivity of the top layer (everything above groundwater level up to the surface). First, the heat flow from the surface is calculated, when the aquifer changes the temperature in depth of the upper quarter of the aquifer. Second, the recharge happens only half a year or 4380 h/yr (summer), see Equation 6. The energy recharge from the underground is estimated by using the formula for sudden temperature change on a half-space and its dynamic heat flow (Equation 8). The calculation uses the Gaussian error function and depends on the thermal diffusivity of the aquitard and the distance to the aquifer (x) and time (t). For calculation used in maps compilation values x = 10 m and t = 10 years were used.

The energy content available for heating and cooling were calculated based on the following equations (Equation 9, Equation 10).

$$E_{HEAT}\left[\frac{kWh}{yr\cdot m^2}\right] = \left(\frac{E_{storage}}{LT} + E_{surface} + E_{underground}\right)\cdot\Delta T_{HEAT}\cdot rf \qquad (9)$$

$$E_{COOL}\left[\frac{kWh}{yr\cdot m^2}\right] = \left(\frac{E_{storage}}{LT} + E_{surface} + E_{underground}\right)\cdot\Delta T_{COOL}\cdot rf \qquad (10)$$

4. SUMMARY

Bratislava – Hainburg pilot area has significant groundwater resources in the lowland area. The main aquifer is connected to the Danube river quaternary deposits giving the investigated area a high potential for open-loop systems. Part of the urban area (on SVK side) and on the rural area (on AT side) is placed above the aquifer. For sustainable use of this great shallow geothermal energy potential its quantification as well as awareness of constraints for its utilisation is needed. In the investigated area, users are more prone to use shallow geothermal energy by closed-loop systems due to easier maintenance and complicated and lengthy legislative permission processes for open-loop systems and protection regulation of direct use of groundwater. On the other hand, open-loop systems are popular in cooling of administrative buildings in Bratislava city without balanced use (heating and cooling regime). In terms of groundwater thermal regime protection, we can treat this regime not to be sustainable.

In the investigated area (Bratislava – Hainburg – Kittsee) management strategies for shallow geothermal use are missing. That was the reason for and one of the aims of the GeoPLASMA-CE project, to develop the background for management strategies at a regional scale. The project outputs were based on standardised databases, joint attitudes in the compilation of the background maps and models. Detailed workflows were applied in the investigated area leading to the uniform outputs published on a web-based platform, including the geothermal potential as well as factors of risk and land-use conflicts. Data used at the potential calculation comprised geological and structural data, petrophysical and technical parameters as well as the model data produced during different stages of the project.

Available geothermal potential of open-loop systems depends mainly on the availability of groundwater and geothermal resources. Among other outputs, hydraulic productivity and thermal capacity at the peak load were calculated representing the important parameters to describe resources related to the use of open-loop systems.

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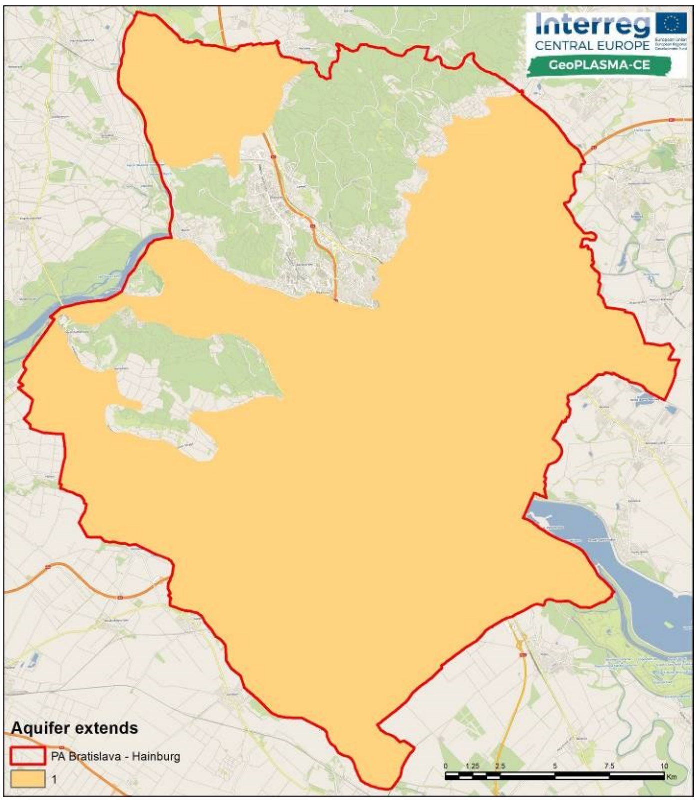


Figure 1: The Quaternary aquifer outline map of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia

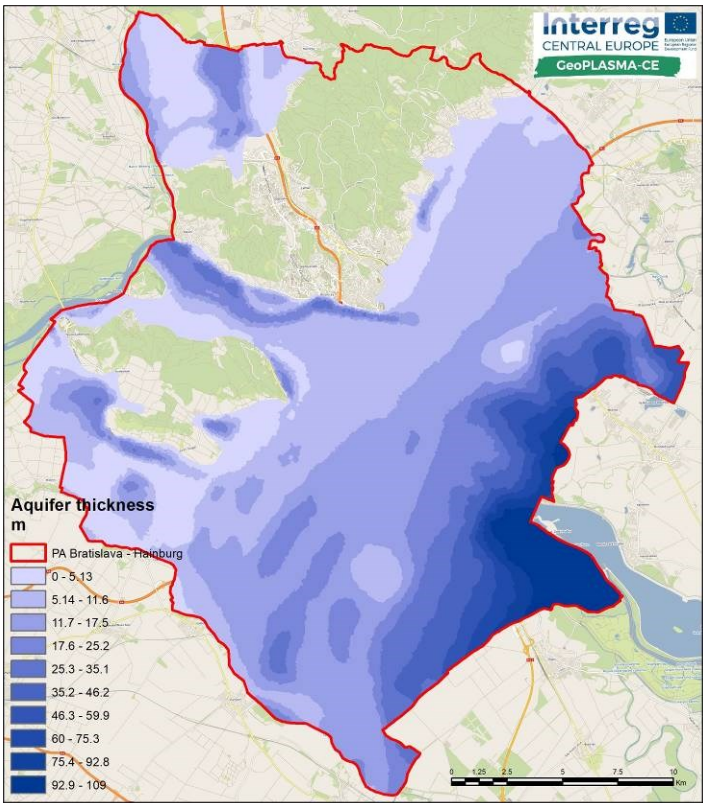


Figure 2: Map of the Quaternary aquifer thickness (in meters) of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia

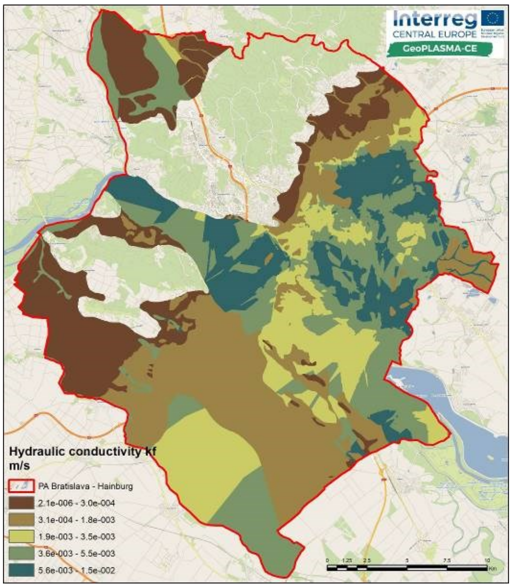
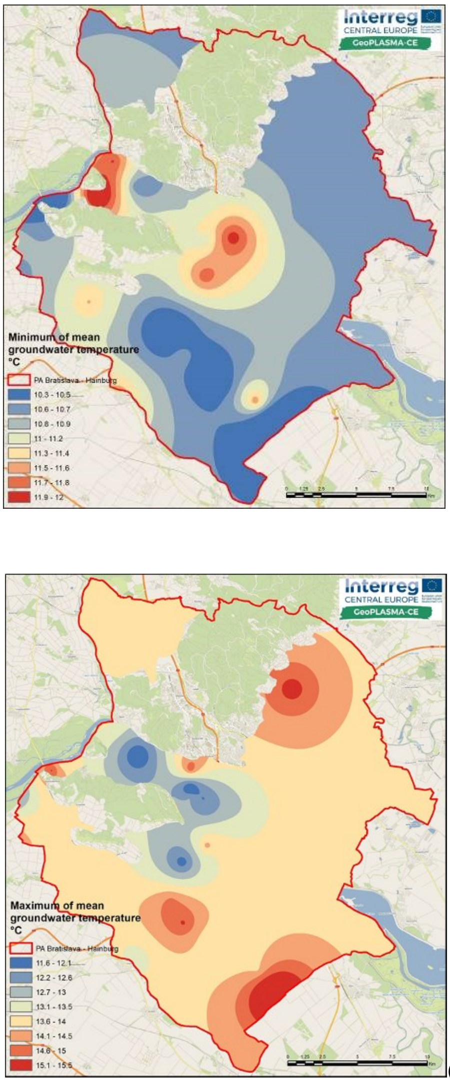


Figure 3: Map of the hydraulic conductivity (in m/s) of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia



(a)

(b)

Figure 4: Minimum (a) and maximum (b) groundwater temperature maps of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia (in °C)

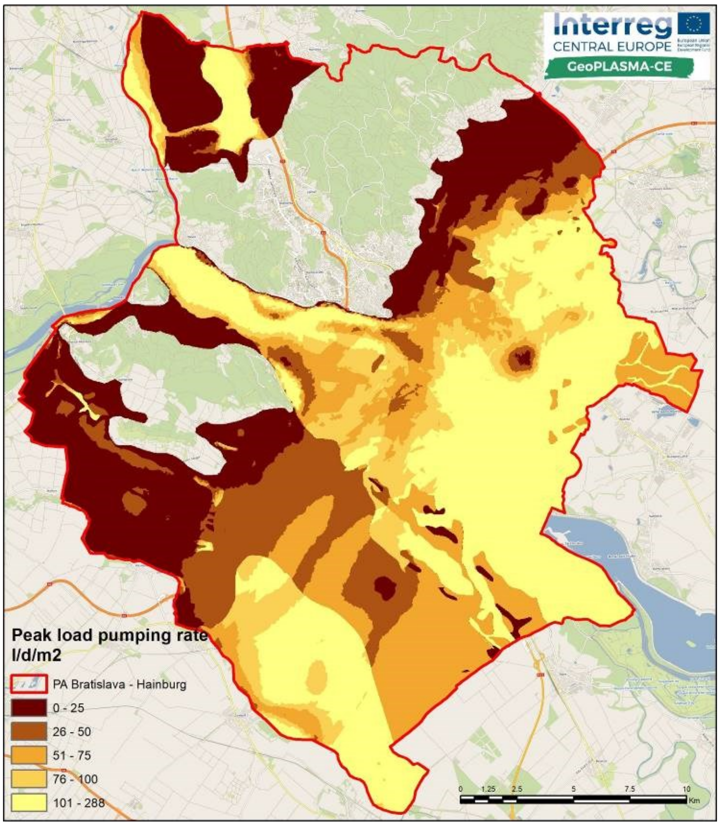


Figure 5: Map of the peak load pumping rate (L/day/m^2) of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia

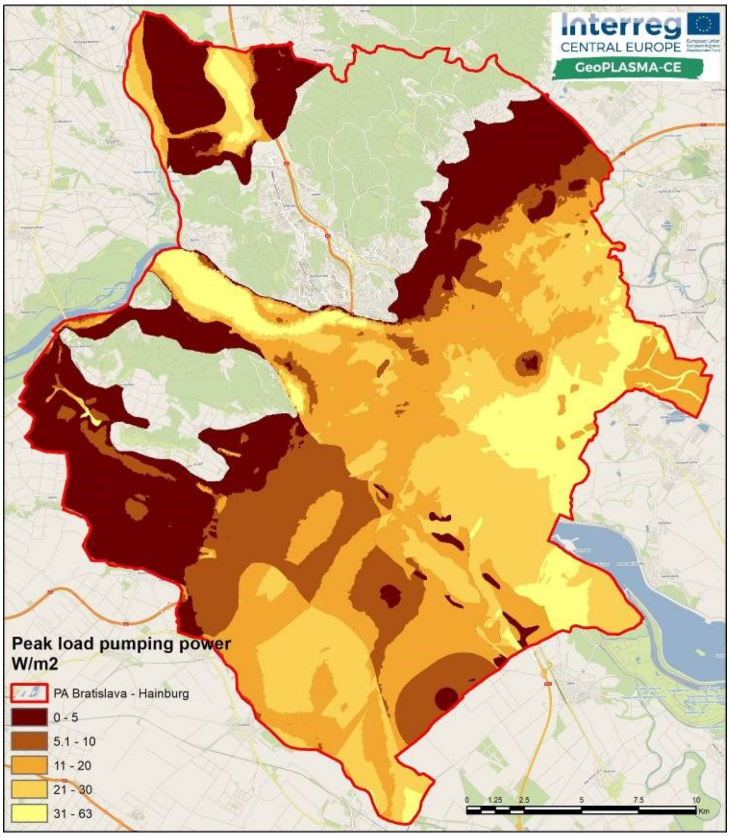
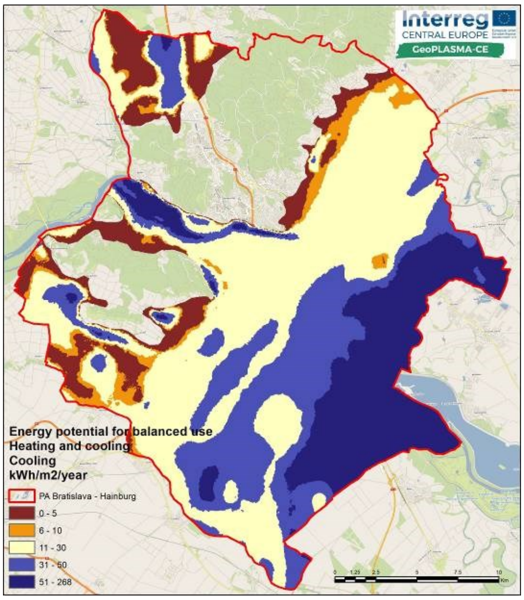
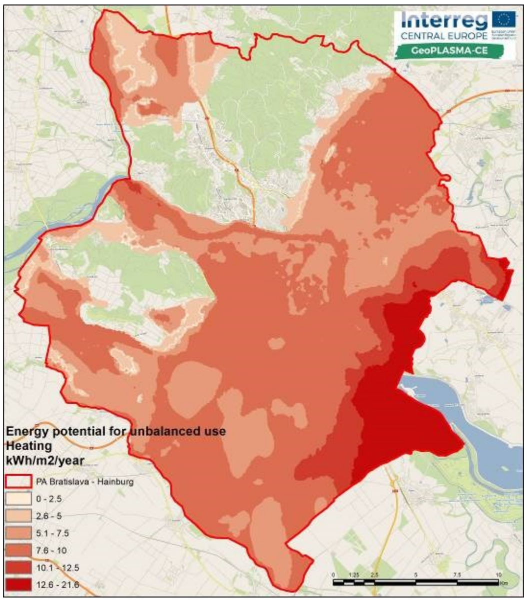


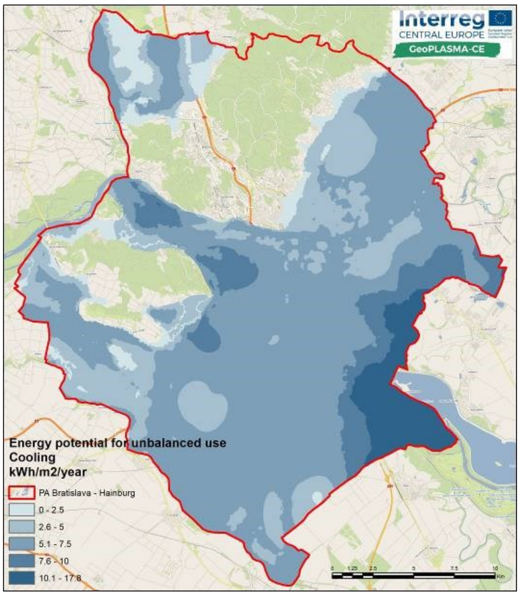
Figure 6: Map of the peak load thermal power (in W/m^2) of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia



(a)



(b)



(c)

Figure 7: Energy potential (in kW_{th}/m^2/year) for balanced use (a) and unbalanced use – heating (b) and cooling (c) of the investigated area Bratislava – Hainburg - Kittsee at the transboundary zone between the Austria and Slovakia