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Research of the geological and geothermal conditions for the assessment of the shallow geothermal potential in the area of Ljubljana, Slovenia

Raziskave geoloških in geotermalnih razmer za oceno potenciala plitve geotermalne energije na območju Ljubljane, Slovenija

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Abstract

Shallow geothermal energy is a renewable source of energy. Using it provides benefits for climate, health and economy. A prerequisite for its efficient and sustainable use is the knowledge of its potential as well as the barriers that limit its use. The paper presents the preliminary results of research carried out within the GeoPLASMA-CE project for the assessment of the shallow geothermal potential in the area of the City of Ljubljana. By compiling existing geological data and field work, a detailed geological map of the study area was elaborated. The spatial distribution of thermal conductivity was estimated with measurements of thermal conductivity on 47 representative samples of 18 lithostratigraphic units and field measurements in unconsolidated sediments at 12 localities. The measured values range between 0.63 and 5.18 $Wm^{-1}K^{-1}$. Continuous groundwater temperature measurements in 17 observation wells with depth to 118 m show relatively small temperature changes over time of 5 months. The measured values on the Ljubljansko polje range between 10.6 °C and 14.6 °C, while in the Ljubljansko barje the temperature increases up to 15.6 °C. Multi-level groundwater temperature measurements in 9 observation wells indicate three different conditions: both negative and positive temperature gradients and a constant temperature in different depths of the aquifer, which reflects the deeper geothermal or hydrogeological conditions and the anthropogenic impact.

Izvleček

Plitva geotermalna energija je obnovljiv vir energije. Njena raba omogoča ugodne učinke na podnebje, zdravje in gospodarstvo. Pogoj za učinkovito in trajnostno rabo geotermalne energije je poznavanje potenciala, kakor tudi ovir, ki omejujejo njeno rabo. V članku smo predstavili prve rezultate raziskav za oceno plitvega geotermalnega potenciala na območju mesta Ljubljana, ki se izvajajo v okviru projekta GeoPLASMA-CE. Z usklajevanjem obstoječih geoloških podatkov in terenskimi raziskavami je bila izdelana natančna geološka karta. Prostorska porazdelitev toplotne prevodnosti kamnin (18 litostratigrafskih enot) je ocenjena z meritvami na 47 reprezentativnih vzorcih in s terenskimi meritvami nekonsolidiranih sedimentov na 12 lokacijah. Izmerjene toplotne prevodnosti kamnin so v razponu med 0,63 in 5,18 $Wm^{-1}K^{-1}$. Zvezne meritve temperature podzemne vode v 17 opazovalnih vrtinah do globine 118 m kažejo relativno majhne spremembe v 5 mesečnem obdobju. Izmerjene vrednosti na Ljubljanskem polju so v razponu med 10,6 °C in 14,6 °C, na Ljubljanskem barju pa naraščajo do 15,6 °C. Temperature podzemne vode izmerjene na različnih globinah v 9 vrtinah kažejo tri različne razmere: negativni in pozitivni temperaturni gradient ter konstantno temperaturo v različnih globinah vodonosnika, kar odraža globlje geotermalne ali hidrogeološke razmere ter antropogeni vpliv.

Introduction

Shallow geothermal energy

Geothermal energy is the energy stored in the form of heat beneath the surface of the solid Earth (RES Directive, 2009). It originates internally from the Earth's core and mantle, from where it is transferred to the surface by the heat flow, and externally from solar radiation, which heats the upper ground. The fluctuation of the air temperature causes an annual variation of the ground temperature. Due to a high thermal inertia of the ground material, the amplitude of these variations diminishes with depth until the amplitude reaches a depth where it remains constant (Fig. 1). This temperature is often called the undisturbed ground temperature (Ouzzane et al., 2015). In Central Europe, a constant temperature around 10 °C is expected in a depth of 20 m (Internet 1; Strgar et al., 2017). Down to depths of 300 or 400 m, which are often referred to as the limit of shallow geothermal energy (Prestor et al., 2017), the temperature of the subsurface ranges between 2 and 20 °C in Central Europe and is similar or slightly higher in Slovenia (Rajver et al., 2006).

Due to the low temperature level, the direct use of shallow geothermal energy is limited. Heat pumps enable the extraction of heat energy from the ground and shallow subsurface, concentrating it and using it to supply heat and domestic hot water (Buckley et al., 2015). The same system can be used to cool a building by removing surplus heat energy and storing it under the ground. The most efficient systems carry out both functions. In general, there are two types of geothermal or ground source heat pump (GSHP) installations: closed loop and open loop systems (Internet 1). Closed loop systems use pipes that are either installed vertically down to several hundred meters (borehole heat exchangers – BHE), horizontally in depths of 1 to 2 meters (collectors), or in foundation piles of buildings. Closed loop systems use a fluid (a mixture of water and a refrigerant) that continuously circulates in the pipes, absorbs heat from the ground and transfers it via a heat exchanger to the heat pump, which raises the temperature up to 60 °C (Internet 1). For cooling, the process is reversed. Open loop systems use groundwater directly as a heat source. Groundwater is pumped from an extraction well, used by the heat pump and, afterwards, reinjected into an injection well.

The utilization of shallow geothermal energy has certain advantages compared to other renewables: it allows for the highest savings in comparison to conventional energy sources; it is available everywhere at any time, independent of weather conditions; and its exploitation has the lowest environment impact (Gemelli et al., 2011). Drawbacks are a higher initial cost, and limited availability of trained technicians and contractors (Kumar et al., 2015).

The heating and cooling of buildings account for approximately 40 % of the global energy consumption (Nejat et al., 2015); therefore, geothermal heat pump systems present one of the key technologies for reducing fossil fuel consumption and emissions that are hazardous to climate and air quality.

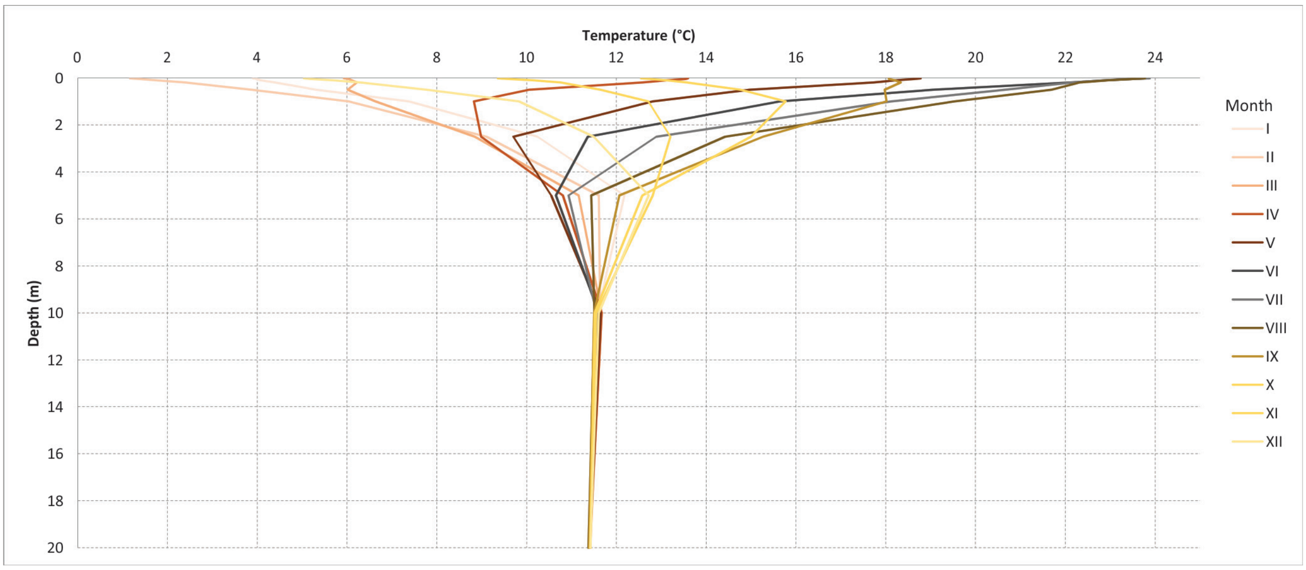

Fig. 1. Seasonal ground temperature distributions (adapted after Strgar et al., 2017).

The current utilization of shallow geothermal energy

The direct utilization of all geothermal energy is applied in at least 82 countries (Lund & Boyd, 2015). The installed thermal power for direct utilization at the end of 2014 equaled 70,329 MW_t, and the thermal energy used was 587,786 TJ/yr (163,287 GWh/yr), which was about a 38 % increase over 2010. GSHPs have the highest share among all the direct use categories, approximately 55 %, and it is assumed their share will continue to rise. Greater progress has been observed in the shallow geothermal energy use also in Slovenia, where, according to the status as of 31 Dec. 2015 (Rajver et al., 2016), the number of all GSHP units was around 9,350 with an installed capacity of 136.64 MW_t and a total energy consumption of 732.1 TJ/yr (203.36 GWh), compared to the status in 2010, when some 4,800 units were in operation. The great majority of units are typically of 11 to 12 kW rated power. About 47 % of them were open loop systems with 322.8 TJ of annual used shallow geothermal energy from groundwater; 46 % were closed loop systems with horizontal collectors with 230.4 TJ of annual used energy; and 7 % were vertical closed loop systems (BHEs) with 47.3 TJ of annual used energy from shallow subsurface.

Assessment of the shallow geothermal potential

Efficient use of shallow geothermal energy requires solid knowledge of natural conditions. The design of GSHP systems has to adapt to them, thus geological and geothermal data (rock type and hardness, ground thermal characteristics, groundwater occurrence) is of essential importance (Sanner, 2010). It is acquired by field investigation (geological mapping, rock sampling, investigations of hydrogeological, geochemical and geothermal conditions in the subsurface, etc.) and by laboratory measurements (thermal parameters of rock samples, etc.). The visualization of data in the form of geological/geothermal maps and their upgrade into geothermal potential maps can be very supportive in the planning of geothermal installations and can contribute to the fostering of their implementation. Methods for the estimation of the shallow geothermal potential and its integration into local energy plans and strategies are currently being developed within the projects GeoPLASMA-CE (Internet 1) and GRETA (Internet 2).

In the City of Ljubljana, a coal and biomass powered district heating system covers most of the densely populated area and distributes heat to 74 % of all households (COL, 2012). Natural gas is the complementary source of heating. The share of geothermal energy use for heating and cooling is very low. To achieve the environmental goals related to an increased share of renewable energy in the final energy consumption and reduction of the greenhouse gas emissions as set forth in the Sustainable Energy Action Plan of the City of Ljubljana (COL, 2012), the improvement of the energy efficiency and intensification of research and introduction of new technologies for the utilization of renewable energy sources are planned. The local heat and cold production is a sector in which the largest share (65 %) of the greenhouse gas emissions reduction can be achieved. In this respect, shallow geothermal energy will have an important role. The objective of the planned activities, part of which is presented in this study, is to quantify the shallow geothermal potential and provide geoscientific information that could be integrated into development strategies and help to foster the use of shallow geothermal energy.

In this paper, the research results of the geological and geothermal conditions for the assessment of the shallow geothermal potential in the area of the City of Ljubljana are presented. The harmonization of existing geological data/maps was performed to create a basis for spatial distributions of geological units (3D model) and thermal properties of the shallow subsurface in the study area. Using the harmonized geological map, 47 representative samples of lithological units were taken, their thermal parameters (thermal conductivity and diffusivity) measured, and a map of thermal conductivities elaborated. For assessing the geothermal potential of the groundwater, a monitoring network with temperature loggers in 17 observation wells was established and 5 months of measurements obtained. The presented investigations and results are part of the workflow for mapping the shallow geothermal potential developed within the GeoPLASMA-CE project (Hofmann et al., 2017), which will be implemented in six pilot areas (including the presented study area) across central Europe.

The study area

The study area covers 275 km² (Fig. 2) and corresponds to the administrative area of the City of Ljubljana (COL). The central flat urbanised area is surrounded by a hilly hinterland and divided by hills (Golovec, Grajski hrib and Rožnik) in the middle on the Ljubljansko polje (Ljubljana Field) and the Ljubljansko barje (Ljubljana Marsh).

Geologic setting

The geological structure of the study area is extremely diverse regarding both the lithology and age of the geological units. This is due to the tectonic collage of several paleogeographic units represented today in three geotectonic units. The largest part of the area belongs to the External Dinarides with the transition into the Internal Dinarides to the east and north. In the north-western corner, the Dinarides border the Southern Alps. Characteristic for the External Dinarides is the thrust and nappe structure that became accomplished in the Upper Eocene to the post-Eocene times. In the study area territory, only the Hrušica and Trnovo nappes can be recognized with certainty in the area's western rim (Placer, 2008). There, the Trnovo nappe is the highest structural unit of the External Dinarides. The Carboniferous-Permian siliciclastic rocks in the north-eastern part of the nappe west of the Ljubljana basin undoubtedly lie on the Mesozoic mostly carbonate beds of the lower Hrušica nappe unit. On the contrary, the Carboniferous-Permian clastic rocks of the Litija anticline in the Sava folds east of the Ljubljana basin lie consistently below the Mesozoic beds. The Carboniferous-Permian clastites of the Trnovo nappe and Litija anticline then come into contact in the area of the Ljubljana basin, although they belong to different structural units. In the Sava folds nappe structure, units occur that lie structurally above the Trnovo nappe. The contact of the two tectonic settings is the Želimlje fault, which passes over the central part of the External Dinarides along the eastern rim of the Ljubljansko barje and the western rim of Ljubljana basin (Placer, 1998a, b, 2008).

Along the north-western rim of the study area, deep-marine rocks belonging to the Slovenian basin paleogeographic unit are overthrust on the Trnovo nappe (Placer, 2008).

In the wider territory of the study area, the recent continuing tectonic activity with deformations is evidenced in geodetic and geomorphologic data (e.g. Rižnar et al., 2005; Jamšek Rupnik, 2013; Jamšek Rupnik et al., 2013; Moulin et al., 2016).

Pre-Quaternary basement

The most widespread lithological unit of the pre-Quaternary basement is represented by the Carboniferous-Permian siliciclastic rocks which build the predominant part of the rim of the Ljubljana basin with the largest extent to the east

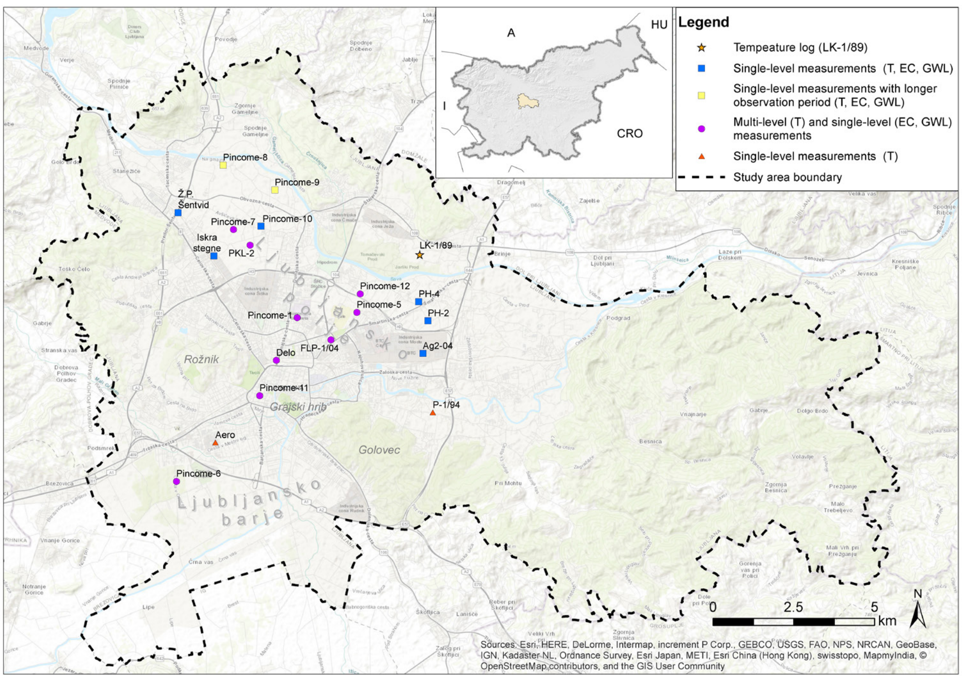

Fig. 2. Study area and monitoring network (T, EC, GWL denote temperature, electric conductivity and groundwater level measurements).

in the Sava folds. These rocks are also the oldest in the study area. Quartz sandstone and lithic quartz sandstone strongly prevail over quartz conglomerate, siltstone and shale. In the lithostratigraphic succession of these rocks, three superpositional units were distinguished (Mlakar, 1987; Mlakar et al., 1993). Due to the absence of fossils, up till now only the rocks of the middle sandstone subunit have been dated and attributed to the Late Carboniferous (Namurian-Westphalian A and Westphalian A) based on fossil plant remains found between Ljubljana (Grajski hrib, Golovec) and Polšnik near Litija (Kolar-Jurkovšek & Jurkovšek, 1985, 2002, 2007).

The only other unit that also occurs to a larger extent is the Middle to Upper Triassic (Ladinian to Carnian) dolomite of the Schlern formation. This whitish, coarse grained late diagenetic dolomite, usually non-bedded (massive) and heavily tectonized, builds the south-eastern rim of the study area.

All other lithostratigraphic units of the pre-Quaternary basement cover only smaller areas. The Middle Permian Gröden formation is composed of alternating quartz sandstone, conglomerate, siltstone and shale, all of them of characteristic reddish or greyish colour. Only in the area of Podmolnik, interbeds of dolomite occur. The Lower Triassic Werfen formation is lithologicaly very heterogenous with alternation of marly limestone and dolomite, marlstone, sandstone and shale. The lower part of the Middle Triassic (Anisian) comprises thickly bedded dolomite, while Ladinian is again heterogeneous. Thin-bedded limestone, with chert laminae and nodules intercalated with marlstone, dominates over shale, marlstone, green tuff and tuffite. Lithologically very similar is the Upper Carnian (Julian-Tuvalian) unit, but with lesser marlstone and volcaniclastic beds and more sandstone. The upper part of the Upper Triassic (Norian-Rhaetian) is represented with two thick-bedded carbonate units, the Main dolomite and the Dachstein limestone, respectively. Similar to the latter, but with oolithic layers and breccia horizons, is the Lower Jurassic (Liassic) limestone, occurring only in Podutik. On the slopes of Šmarna gora and Rašica occur Lower Cretaceous (Aptian-Cenomanian) deeper marine flysch rocks, namely shale, marlstone, sandstone, reddish limestone and limestone breccia with intercalations of conglomerate.

Quaternary sedimentary fill

The central and the most densely populated territory of the study area lies in the neotectonic basin with extensive and thick accumulations of Pleistocene and Holocene fluvial sediments. The foundations for the up-to-date subdivision of Quaternary sedimentary fill in the Ljubljana basin were laid by Kuščer (1955) who subsequently studied the influence of tectonics on sedimentation (Kuščer, 1991). Žlebnik (1971, 1993) considered the Quaternary fill of the Ljubljansko polje (the Ljubljana Field), the northern and central parts of the Ljubljana basin, as glaciofluvial and divided it into four units, namely the Older, Middle and Younger conglomeratic fill, and the latest gravel fill. The chronology of their origin relies mostly on the results of pollen analyses from finer sediments, indicating that most of the sediments are of Würmian age or younger (Šercelj, 1965, 1966). Absolute datings (Vidic & Lobnik, 1997; Vidic, 1998) later upgraded the chronology in the broader area of the Ljubljana basin, which resulted in the division of sedimentary fill into three chronostratigraphic units dating ≤ 62 ka, 450–980 ka, and 1.8 Ma, respectively. The two samples of sandy silt with gravel that covers the wider surroundings of Podutik were dated by employing the OSL method as Late Rissian or Rissian - Würmian interglacial age (Bavec & Pohar, 2009).

The extensive area of the Ljubljansko barje in the south-western part of the Ljubljana basin is filled with lacustrine and paludal sediments. The tectonic model of the Ljubljansko barje is not satisfactorily understood, but a rapid subsidence in Quaternary is an established fact. The sedimentary succession in general thickens from the west and in the north-east of the Ljubljansko barje. According to borehole data, the maximum thickness is around 170 m (Mencej, 1990), although the results of geoelectric surveys also indicate depths surpassing 200 m (Ravnik, 1965). In the bottom part there are gravels, sandy gravels and silty gravels of varying thicknesses, followed upward by a sequence of fluvial, lacustrine and paludal sediments exceeding 100 m in places. The variability of sediments indicates tectonically and climatically affected changes of the sedimentation regime, well-documented and dated for a large part of the Quaternary. Palynologic analyses of sediment indicate an almost continuous sedimentation during the interval from the start of the Mindelian glacial (approx. 650 ka) into the Holocene, when it was terminated by the deposition of organogenic lake clay and, in places, with the formation of peat bog (Šercelj, 1965, 1966; Bavec & Pohar, 2009).

Hydrogeology

The thick accumulation of Pleistocene and Holocene fluvial sediments in the Ljubljansko polje area is highly permeable and contains significant quantities of groundwater, which is the main resource exploited for the public water supply of the City of Ljubljana. The Ljubljansko polje aquifer is unconfined, recharged mainly from the Sava River and partly from rainfall (Janža, 2015). The recharge from the Sava River is intensive in the north-western part of the Ljubljansko polje; in the eastern part, groundwater is drained into the river. Groundwater flow in the western part is directed from the river towards the south and south-east, and in the eastern plain towards the east and north-east. Groundwater flow velocity is high, estimated up to 20 m/day (Janža et al., 2005). The unsaturated zone is on average 25 m and the saturated zone up to 70 m thick. The fluctuation of the groundwater table in observation wells is the highest in the north-eastern part (up to almost 10 m) and decreases towards the central and eastern part, where the difference between high and low groundwater table is around 2 m.

The Ljubljansko barje is composed of alternating fluvial and lacustrine deposits with a heterogeneous composition. The top clay layer in the northern part of the Ljubljansko barje is 4 m thick. A heterogeneous and low permeable upper Pleistocene aquifer, about 2 meters thick, is situated below. It is separated by another thick clay layer from the lower Pleistocene aquifer that consists of gravel and contains groundwater of good quality. The latter is a confined or semi-confined aquifer with artesian to subartesian conditions (Janža et al., 2017).

Deep geothermal conditions

In the study area, the geothermal gradient down to 1000 m depth is between 15 and 28 mK/m. In the 1801 m deep LK-1/89 borehole, drilled almost completely through clastic rocks (claystone to mudstone, siltstone and sandstone) of Car-

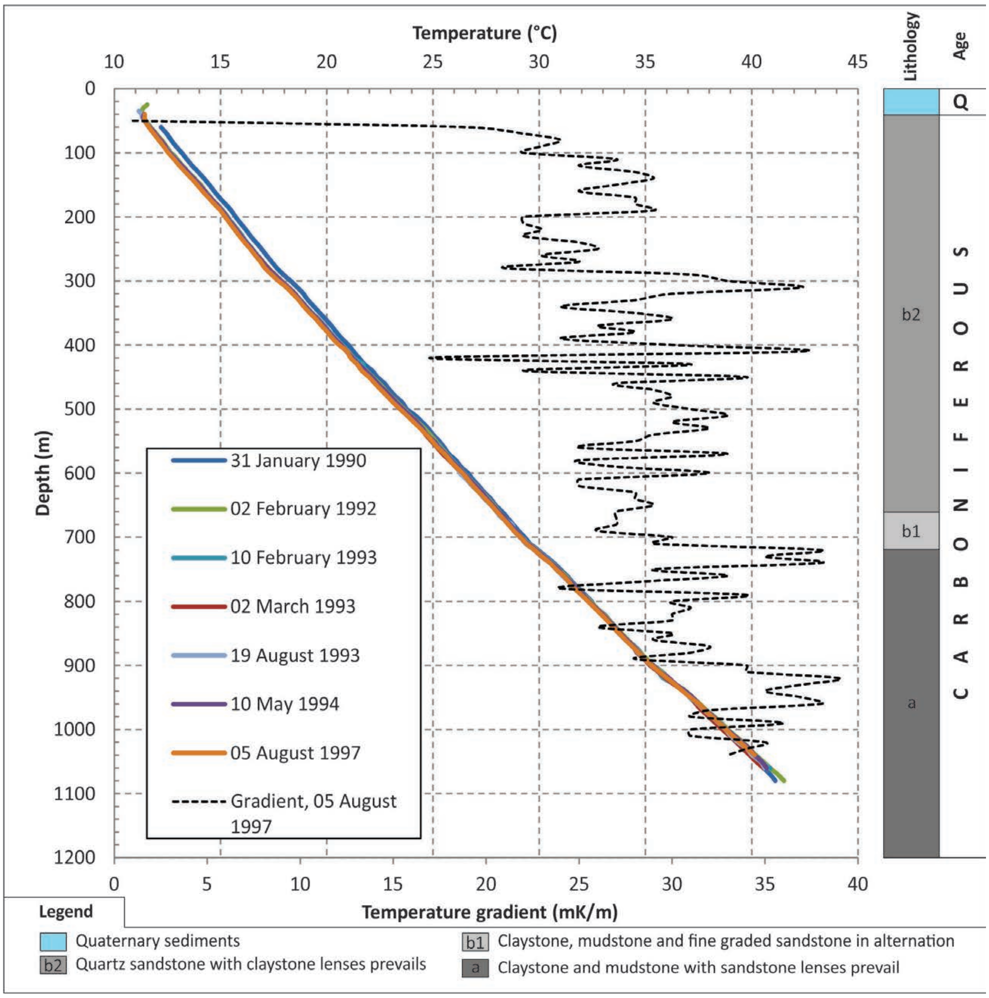

Fig. 3. Temperature logs and geothermal gradient determined in LK-1/89 borehole. Geological column is simplified after Kranjc et al. (1989).

boniferous-Permian age near Nadgorica (Fig. 2), temperature logging was performed eight times in a period 1990 to 1997 (Fig. 3). With the last logging in 1997, 38.8 °C was measured at 1000 m depth. Slightly higher geothermal gradients are in lowlands of the study area, especially south and southwest of Ljubljana in the Ljubljansko barje, where temperature logging was carried out in 21 shallow boreholes. In this southern part of the study area, none of the examined boreholes was deeper than 370 m. But geophysical research there in the period 1988–1993 indicated the existence of local positive geothermal anomaly in the Quaternary low permeable sediments, which is probably a consequence of a thermal convection zone in the carbonate rocks, mostly dolomite of Triassic age, just below the Quaternary sediments (Živanović & Rajver, 2004).

The surface heat-flow density (HFD) was determined in the past 30 years at localities of ten boreholes in a wider study area. In nine boreholes, the rock samples were cored, and thermal conductivity was measured using mostly the devices with transient hot wire method (Prelovšek & Uran, 1984; Prelovšek et al., 1982). The HFD values, corrected for topographic effect, range from 60 to 135 mW/m^2. However, the highest values (100 to 135 mW/m^2) are influenced by the mentioned thermal convection zone (between Vnanje Gorice and Trnovo), while outside of this zone, the values range between 86 and 96 mW/m^2, which are 40 to 57 % higher than the rest of Slovenia (Rajver & Ravnik, 2002) and 33 to 49 % higher than the continental (European) average (Čermák, 1979; Hurtig et al., 1992; Majorowicz & Wybraniec, 2011).

Methods

The harmonization of the geological map and an update of the pre-Quaternary bedrock

The basis for 3D geological modeling and for the determination of the sampling localities for the measurement of thermal parameters was the Basic Geological Map of SFR Yugoslavia 1:100,000 which cover the study area with four sheets, namely: Kranj (Grad & Ferjančič, 1974), Ljubljana (Premru, 1983), Postojna (Buser et al., 1967), and Ribnica (Buser, 1969). The newer and revised Geological Map of Slovenia 1:250,000 (Buser, 2009) was used for emendations and harmonization, while several maps of larger scales were used for fine tuning and adjusting the model to the data from the boreholes (e.g. Novak, 2000).

The pre-Quaternary very low permeability base of the Ljubljansko polje aquifer and the northern part of the Ljubljansko barje aquifer (Mencej, 1990; Kristensen et al., 2000) was updated using new data from the boreholes (Janža et al., 2017).

Measurements of thermal parameters

The evaluation of the conduction and absorption of heat in the Earth's upper crust requires knowledge of the thermal properties of the ground material. Heat transmission in the Earth occurs principally by conduction and secondarily by convection and radiation (Robertson, 1988; Kappelmeyer & Haenel, 1974; Beck, 1988).

Measurements of the thermal parameters of rocks and hard soil

For the evaluation of the thermal parameters of the rocks, it was necessary to sample many different types of rock in the field. In the field, the main lithostratigraphic units which cover larger areas and their most common lithological varieties were sampled in several localities. Altogether, 47 samples from 18 solid rock units were collected. The measurements of thermal conductivity (TC) and thermal diffusivity (TD) on compact rocks and also on hard soil (e.g. clays and similar soils that are not too soft) were performed in the laboratory using Thermal Conductivity Scanner (TCS), produced by TCS Lippmann and Rauen GbR (Popov et al., 2017, Fig. 8). The TC and TD measurements were carried out on 47 rock samples with 86 rock pieces. All these rock pieces were measured to obtain better representative mean values of the thermal properties of rocks for each lithological unit. The samples were wrapped in plastic bags, and those assigned in Table 1 as "saturated" were put in water over night, others were put in water for one or two hours, but their surface was left to dry out just before the scanning.

The optical scanning technology is based on the scanning of the plane or cylindrical surface (along the cylinder axis) of a studied sample with a focused, mobile and continuously operated heat source in combination with infrared temperature sensors (Popov et al. 1999; 2012). The determination of thermal conductivity values is based on the comparison of excessive temperatures of standard samples (having a known thermal conductivity λ_R) with excessive temperatures of one or more unknown samples being under heating by the movable concentrated heat source. The thermal conductivity of unknown samples is calculated as a result of a comparison of the excessive temperatures using the standard thermal conductivity values. For the TCS method, a low tolerance is prescribed for the flatness of the sample surface (+/- 0.5 mm), and hence, almost all the samples were first cut with a circular saw to cope with this requirement. The simultaneous measurements of TC and TD use a 2-channel type of temperature sensor measuring two temperatures after heating at spots located some mm apart.

Measurements of the thermal parameters of soft soil

Field measurements of the thermal parameters, the TC and thermal resistivity, of the softer or unconsolidated and porous sediments were carried out at 12 localities (3 lithological units). They were performed with the use of the KD2 Pro thermal properties analyzer (Decagon Devices, 2016), which is especially dedicated for soft and loose sediments (Fig. 4). Typically, the probe for measuring TC and thermal resistivity consists of a 6 cm (optionally 10 cm) long needle with a heater and temperature sensor inside. More recently, the heater and temperature sensors have been placed in separate needles, both 3 cm long and 6 mm apart. Within such a dual probe, the analysis of the temperature versus time relationship for the separated probes yields information on TD and volumetric specific heat capacity along with TC and thermal resistivity. All four thermal parameters were measured at 7 of the mentioned 12 localities.

Groundwater temperature measurements

Groundwater temperature has been continuously measured on 17 locations (Fig. 2). Single-level (8 locations) and multi-level measurements (9 locations) (Fig. 5) have been performed with GSR 120 NTG loggers (15 pcs) (Internet 3) and HOBO temperature loggers (44 pcs) (Internet 4). Along with the temperature measurements, GSR 120 NTG loggers also enable measurements of the water level and the electrical conductivity of the groundwater. Loggers were installed in May 2017 and set up to record measurements at one hour intervals. The spatial distribution of measurement locations was designed in a way to capture the influence of the factors which presumably affect the groundwater temperature in the study area (e.g. recharge from the Sava River and the urban area heat island).

Results and discussion

The harmonized geological map and the updated pre-Quaternary bedrock

The harmonized geological map of the study area (Fig. 6) and an updated interpretation of the pre-Quaternary bedrock (Fig. 7) are presented in the following text.

Fig. 4. Field measurement of the thermal parameters with the KD2 Pro meter.

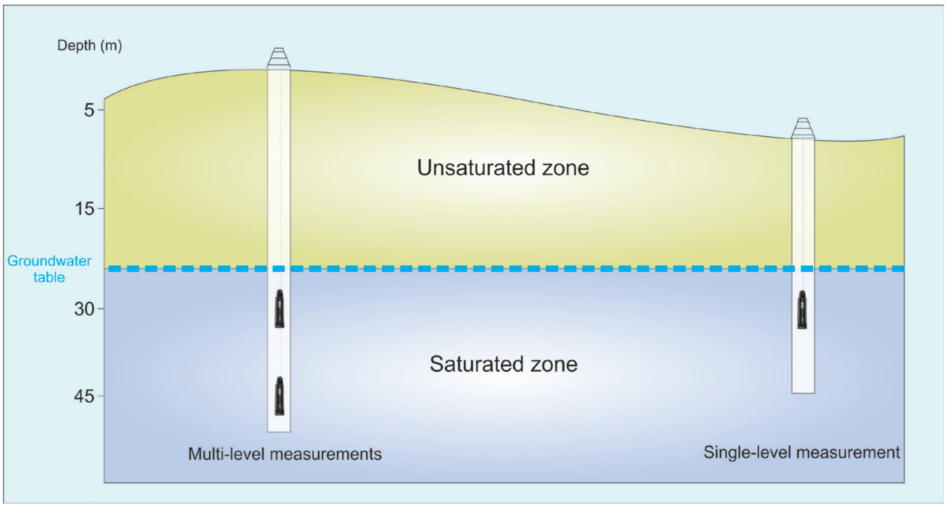

Fig. 5. Scheme of multi-level and single-level measurements in observation wells.

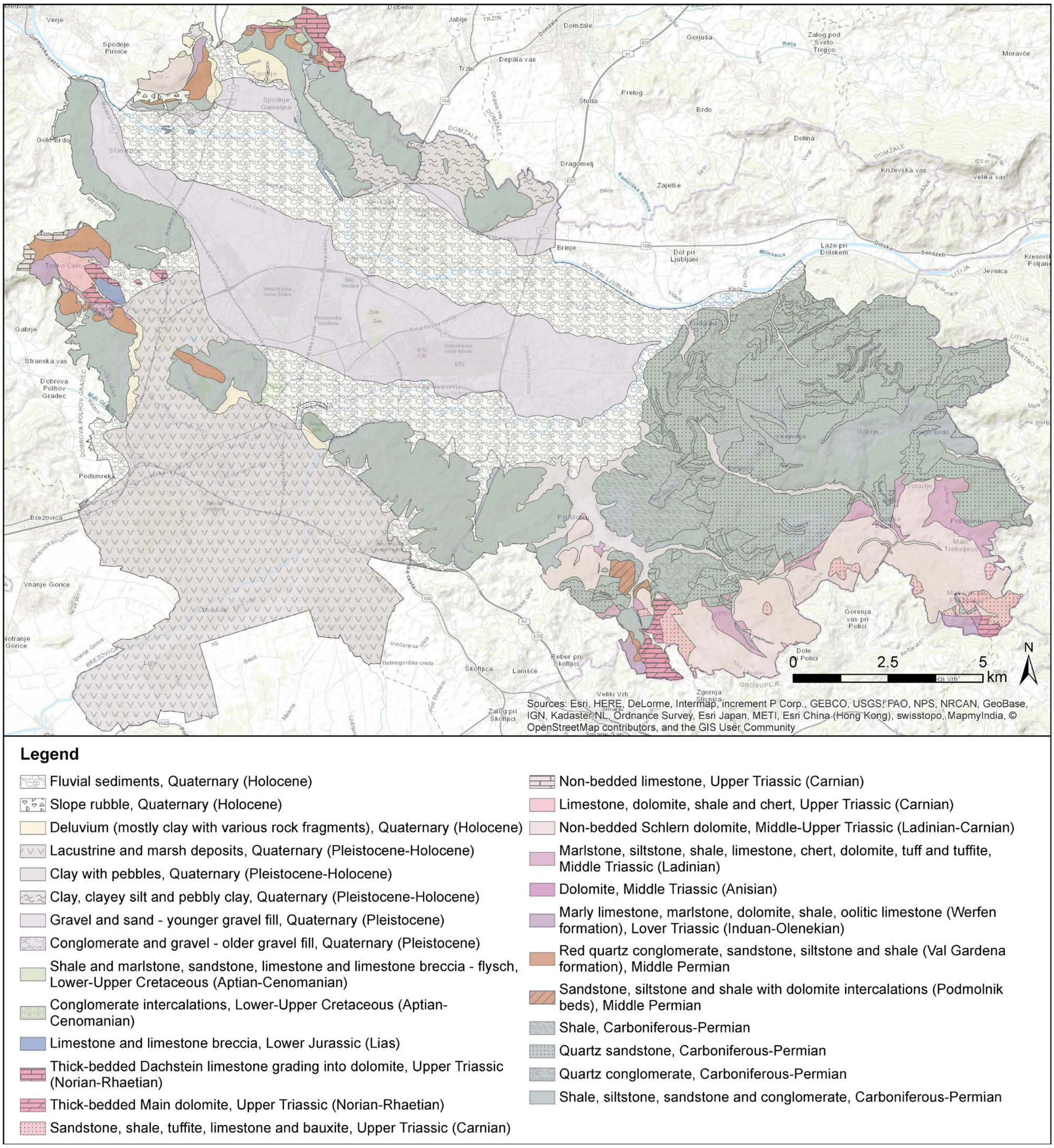

Fig. 6. The harmonized geological map of the study area.

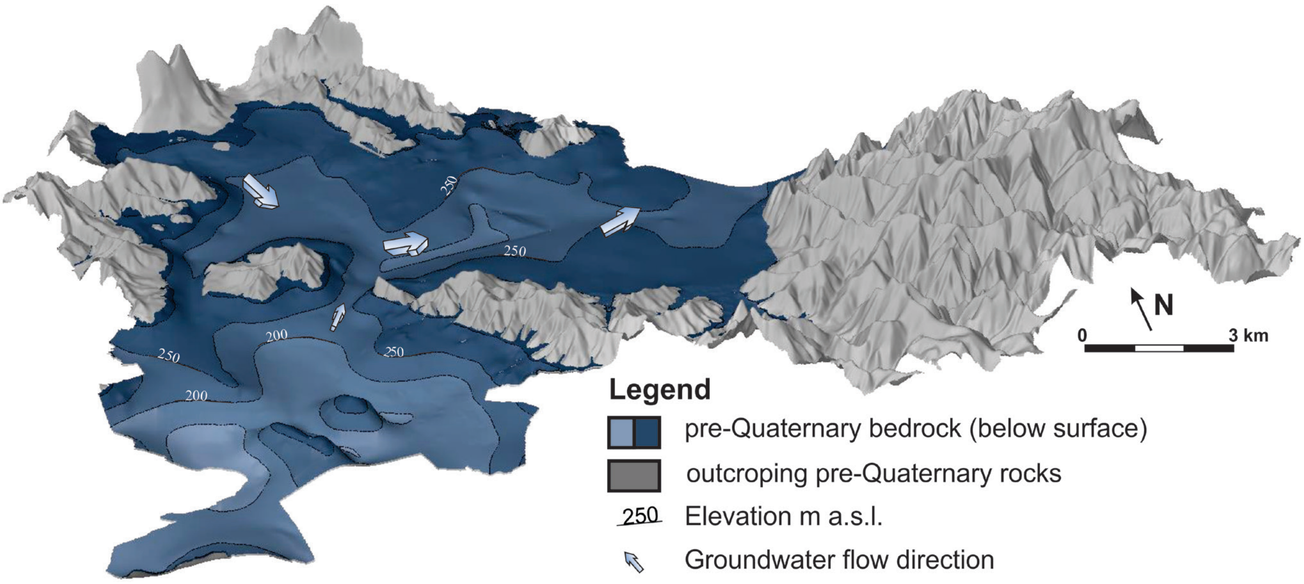

Fig. 7. 3D model of pre-Quaternary bedrock (5 × vertical exaggeration).

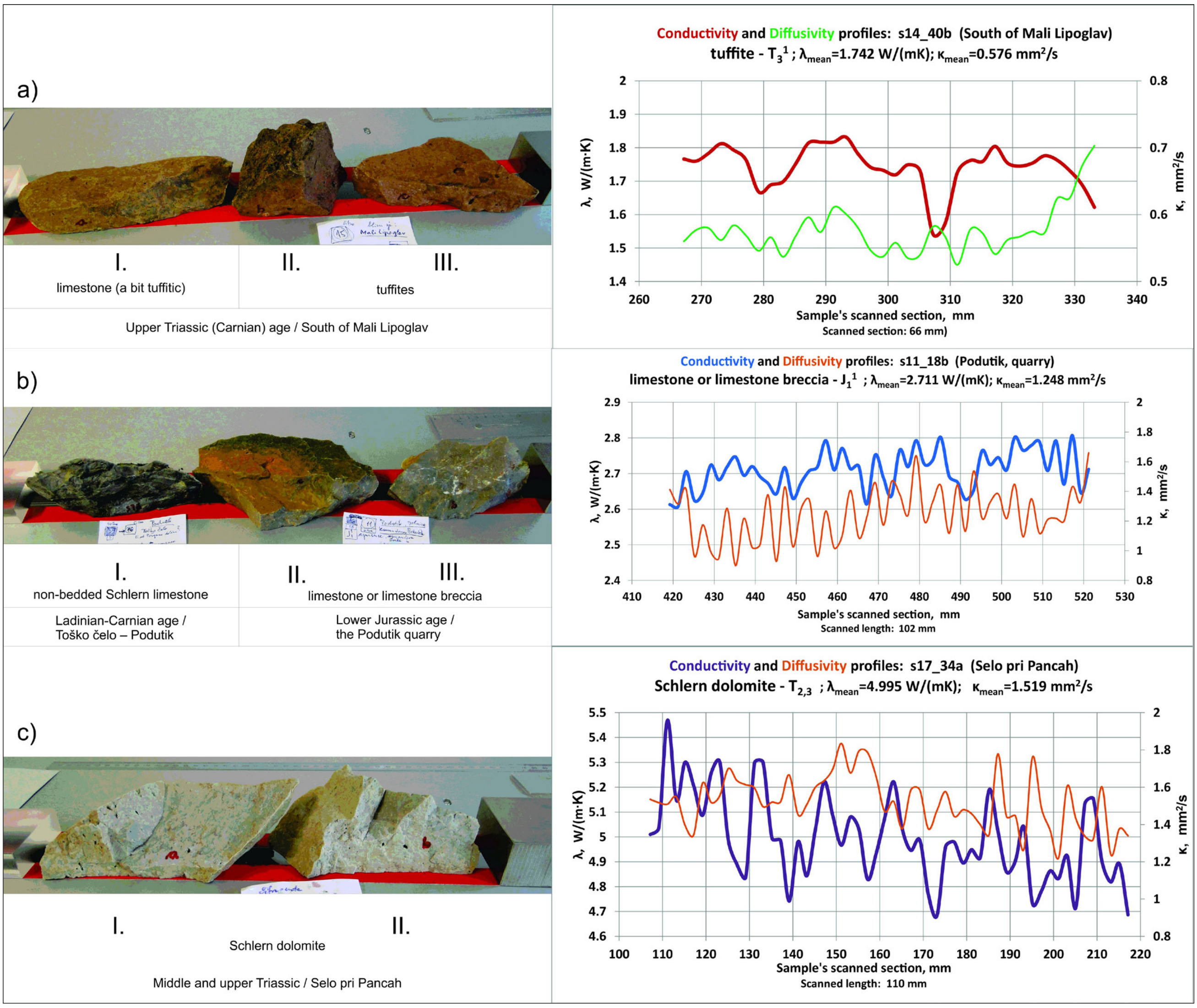

Fig. 8. Set of rock samples along the scanning line of TCS meter (left); the TC and TD profiles from the scanning of rock samples (right).

Thermal parameters

The results of TC and TD measurements show a great variety in the thermal properties of different lithological units (Table 1). The heterogeneous nature of the rock samples is noticeable, especially TC, which is a consequence of the mineral composition, rock density, their structure and texture and the pores' filling (water saturation) (Kappelmeyer & Haenel, 1974; Beck, 1988). It must be stressed that despite the efforts to simulate the natural conditions as much as possible, no rock sample could be completely water saturated, due to the lack of appropriate pressure devices. On the other hand, particularly compact solid rock samples are less susceptible to water saturation, therefore their rock status (Table 1) has been assigned as slightly or partly saturated or just wet during the TC and TD scanning. Some examples are presented herein in regard to the rock samples with typical low (Fig. 8a), average (Fig. 8b) or high (Fig. 8c) values of TC.

Table 1. The mean TC and TD values of the 47 rock samples (86 rock pieces altogether), measured with the TCS method.

Locality	Type of Rock	Rock state: saturated, slightly sat., wet or dry	Chrono-stratigraphic unit	Thermal Conductivity	Thermal Diffusivity
				λ, W/(m·K)	**κ**, mm²/s
Rašica hill, NW slope	red calcareous sandstone grading into siltstone	slightly sat	K1,2	**3,13**	**1,25**
Rašica hill, NW slope	red to pink limestone		K1,2	**3,24**	**1,26**
Rašica hill, NW slope	conglomerate (Cenomanian)	saturated	K1,2	**3,11**	**1,24**
Podutik, quarry Podutik	limestone & limestone breccia	slightly sat	J1/1	**2,79**	**1,23**
Rašica hill, NW slope, more to west	Dachstein limestone (thick bedded) grading into dolomite	wet	T3/2+3	**2,98**	**1,21**
Podutik, Dolnice, along road to Kamna Gorica	Dachstein limestone grading into dolomite (thick bedded)	saturated	T3/2+3	**3,66**	**1,40**
Podutik, Bike park	Main dolomite (thick bedded)	slightly sat	T3/2+3	**5,18**	**2,10**
N of Repče, near quarry along road	Main dolomite (thick bedded)	dry	T3/2+3	**4,21**	**1,43**
ESE of Mali Vrh at Prežganje, S of Veliko Trebeljevo	limestone & marly limestone	slightly sat	T3/1	**2,84**	**1,17**
S of Mali Lipoglav, between M. Lipoglav and Zg.Slivnica	limestone (a bit tuffitic)	slightly sat	T3/1	**2,73**	**0,98**
S of Mali Lipoglav, between M. Lipoglav and Zg.Slivnica	tuffite	slightly sat	T3/1	**1,73**	**0,56**
S of Mali Lipoglav, between M. Lipoglav and Zg.Slivnica	limestone (tuffitic?)	slightly sat	T3/1	**2,92**	**1,05**
Podutik, Toško Čelo, E of Požgane doline	non bedded limestone	slightly sat	T2,3	**3,01**	**1,49**
Podutik, Prevalnik, Toško Čelo	marly limestone with chert	slightly sat	T3/1	**3,46**	**1,53**
between Selo at Pance and Pance	Schlern dolomite	slightly sat	T2,3	**4,79**	**1,74**
Podutik, S of Bike park	tuff (pieces & weathered matrix)	wet	T2/2	**2,72**	**1,21**
Podutik, S of Bike park	tuff	slightly sat	T2/2	**3,50**	**1,45**
Toško čelo	limestone with cherts & marly limestone	wet	T2/2	**3,14**	**1,37**
Malo Trebeljevo, beyond right bend, on open meadow	dolomitic marlstone & marly dolomite	slightly sat	T2/2	**3,19**	**1,42**
Malo Trebeljevo (N part of village), roadside S of long right bend	dolomite	wet	T2/2	**4,44**	**1,25**
W of Podutik, SE of Toško Čelo	dolomite	slightly sat	T2/1	**4,44**	**1,83**
Toško Čelo, S of restaurant „Pri Bitencu"	oolite limestone (marlstone?)	slightly sat	T1	**2,39**	**0,82**
road to Toško Čelo	dolomite	partly sat	T1	**3,74**	**1,83**
road to top of hill on Toško Čelo	oolite limestone	dry	T1	**2,92**	**1,03**
road to top of hill on Toško Čelo	sandstone & siltstone	slightly sat	T1	**2,81**	**1,02**
road to top of hill on Toško Čelo	dolomitic marlstone & marly dolomite	slightly sat	T1	**3,48**	**1,37**
along road Repče - Pleše	marlstone, marly limestone	slightly sat	T1	**1,64**	**1,02**
along road Repče - Pleše	limestone	wet	T1	**2,80**	**1,01**
along road Repče - Pleše	dolomite	wet	T1	**4,05**	**1,50**
Rašica hill, SW slope, along road to Srednje Gameljne	red sandstone & shale	slightly sat	P2/2	**3,14**	**1,76**
W of Podutik, Stražni vrh, N slope	siltstone (aleurolith)	slightly sat	P2/2	**2,19**	**0,80**
W of Podutik, Stražni vrh, N slope	tuffite (light brown)	slightly sat	T2	**3,60**	**1,88**
Rašica hill, SW slope, along road to Srednje Gameljne	quartz sandstone	slightly sat	P2/2	**3,18**	**1,44**
SE of Šentpavel	quartz-dolomitic sandstone (Podmolnik beds)	slightly sat	P2	**3,24**	**1,38**
SE of Šentpavel	mudstone (Podmolnik beds)	slightly sat	P2	**2,38**	**0,90**
SE of Šentpavel, along road to south	red siltstone (Podmolnik beds)	slightly sat	P2	**2,40**	**0,72**
SE of Šentpavel, along road to south	red quartz sandstone (Podmolnik beds)	slightly sat	P2	**3,63**	**0,96**
Brezje at Podlipoglav	shale (Podmolnik beds)	slightly sat	P2	**1,86**	**0,84**
NW of Češnjica, SE of Sostro	shale	wet	C3	**1,44**	**1,09**
Javor above Besnica, NW of Javor	sandstone	partly sat	C3	**2,55**	**0,99**
NE of Malo Trebeljevo	quartz conglomerate	saturated	C3	**4,84**	**3,62**
NE of Veliki Lipoglav, W of Selo at Pance	quartz conglomerate	slightly sat	C3	**4,51**	**2,32**
along road Javor-Zagradišče, WNW of Radioamateurs' Mt. hut	quartz conglomerate	saturated	C3	**4,01**	**2,19**
Ljubljana Castle, W part of circular path	shale, partly siltstone (aleurolith) (=mudstone)	wet	C3	**2,49**	**0,93**
Ljubljana Castle, SE part of circular path at bridge	shale	wet	C3	**2,10**	**0,76**
Ljubljana Castle, SE part of circular path at bridge	shale	wet	C3	**1,70**	**0,61**
Ljubljana Castle, at NE corner of castle vineyard	siltstone (claystone?)	wet	C3	**1,68**	**0,80**
for TD: *T.D. of sample out of calibration range; Error in T.D. correction of sample. It could be mostly due to water saturated sample, even if only slightly sat.					

The results of thermal conductivity measurements (Table 1; Fig. 8) show that the rocks with high TC are especially dolomites and quartz conglomerates (3.6 to 5.4 $Wm^{-1}K^{-1}$). Those with average to high TC are marly dolomites, Dachstein limestones grading into dolomite, quartz sandstones, quartz-dolomitic sandstones, conglomerates, limestones with cherts, red limestones, tuffites and some sandstones (2.8 to 4.2 $Wm^{-1}K^{-1}$). Rocks with average TC parameter are limestones, marly limestones, (carbonate) sandstones, tuffs, most siltstones and mudstones (2.3 to 3.6 $Wm^{-1}K^{-1}$), while those showing low TC values are notably shales and some tuffites, and less remarkably some marlstones and siltstones or claystones (1.4 to 2.5 $Wm^{-1}K^{-1}$).

Table 2. The mean values of TC, thermal resistivity, volumetric heat capacity and TD from the measurements of the loose sediments.

Locality	Type of Soil or Rock	Sample Soil (Rock) state: saturated (wet), slightly wet or dry	Chrono-stratigraphic unit	Thermal Conductivity λ W/(m·K)	Thermal Resistivity r (rho) m·K / W	Volumetric Specific Heat Capacity c_v MJ/(m³·K)	Thermal Diffusivity κ (kappa) mm²/s
Moste, Zalog, at GLS building	clay, sand, silt	partly wet	šQ2	**1,81**	0,55		
Moste, Spodnji Kašelj, S of St. Andrej church	gravel, sand - younger backfillings	mostly dry	4/ Q1; šQ2 below	**0,76**	1,32		
Center, Tabor, S of Health Center	gravel, sand, silt, soil	wet	šQ2	**1,38**	0,73	2,78	0,46
Bežigrad, Jarški prod, S of Črnuče industr. zone	sand, plant residues	dry, slightly wet	šQ2	**1,18**	0,85	1,85	0,53
Bežigrad, Jarški prod, S of Črnuče industr. zone	sand (river)	wet	šQ2	**1,41**	0,71	3,33	0,42
Bežigrad, Šmartno, ca 300 m E of football field	gravel, sand, silt	mostly dry	šQ2	**1,21**	0,82	3,22	0,38
Vič, Ljubljana Moor, Iška Loka, Ložca creek	organogenic moor sediments	wet	jQ2, bQ2	**1,01**	1,00	3,55	0,26
Vič, Ljubljana Moor, Podkraj - Strahomer	organogenic moor sediments	mostly dry	jQ2, bQ2	**0,75**	1,34		
Šentvid, Dvor-Stanežiče_sand separation	gravel, sand - younger backfillings	slightly wet	fglQ1	**1,34**	0,75		
Bežigrad, Kleče	silty clay (measured): gravel, sand, clay - younger gravel backfillings	slightly wet	4/ Q1 or fglQ1	**1,79**	0,56	2,78	0,60
Bežigrad, Torkarjeva street, new blocks of flats	gravel, sand - younger gravel backfillings	dry	4/ Q1	**0,63**	1,58		
Bežigrad, Jarše, Orehov Gaj	gravel, sand - younger backfillings	mostly dry, slightly wet	4/ Q1; šQ2 below	**1,28**	0,78	2,35	0,46

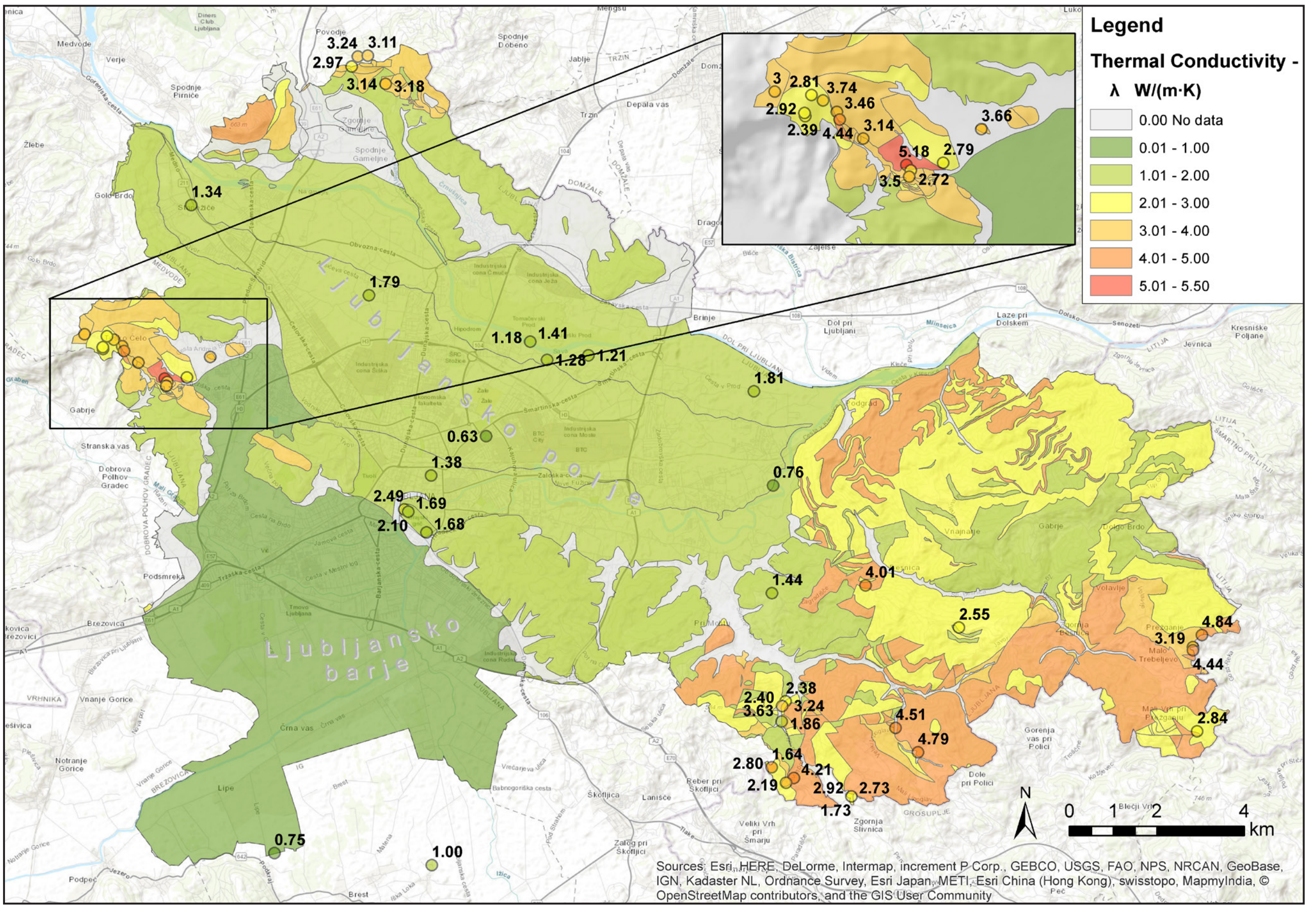

Fig. 9. The thermal conductivity map with the locations of the rock samples (circles with measured mean TC values in Table 1).

The results of the field measurements with the KD2 Pro needle probes (Table 2) show that water saturation plays a very important role. Also the manner of measurements is of great importance, as the method requires a very precise and delicate setting of the needle probes into the measured material. For 7 localities, the values of the volumetric heat capacity and thermal diffusivity are also presented. They are mostly within the expected range of these parameters. TC is obviously higher (1.2 to 1.81 $Wm^{-1}K^{-1}$) at those localities where the needle probe was inserted in a softer sediment very close to gravel pieces, and also where it was inserted in water saturated sandy clay, sand and silt. Measurements with the needle inserted in dry loose sediments gave quite low TC (0.6 to 0.8 $Wm^{-1}K^{-1}$). The spatial distribution of TC based on the harmonized geological map and measurements of TC is presented on the thermal conductivity map (Fig. 9).

Groundwater temperature

The measured groundwater temperatures (GWTs) range between 10.6 °C and 14.6 °C at the Ljubljansko polje and increase up to 15.6 °C in the deepest part of the well Pincome-6 at the Ljubljansko barje (Fig. 10; Appendix A). Measurements were performed over a period of 5 months. Despite the relatively short measurement period, some characteristics of the groundwater temperature distribution can be observed.

Measurements show relatively stable conditions and no significant changes of temperature over time. Exceptions are the measurements in the wells Delo and FLP-1/04, where fluctuations of temperature at some deeper levels are observed. These fluctuations show no trend, thus it can be assumed that they have been caused by anthropogenic influence (e.g. leaking sewage or heating systems, nearby installed heat pumps) or damaged loggers, but at the moment, the causes cannot be determined and further investigations are needed.

Stable temperature conditions indicate an absence of intensive groundwater recharge or inflow of fresh water. On the contrary, the previous GWT measurements in the well Pincome-9 (Fig. 11) located closer to the Sava River (Fig. 2), where an intensive groundwater recharge from the river has been interpreted (Janža, 2015), show annual fluctuations which follow the air or surface water temperature changes with a lag time of about 6 months.

Based on multi-level GWT measurements (Fig. 12), the observation wells can be classified into three groups. In the wells PKL-2, Pincome-1, Pincome-5, Pincome-7, and Pincome-12, there are very small changes or practically no noticeable vertical temperature gradient. In wells Pincome-11, FLP-1/04, and Delo, noticeable are temperature decreases with depth and negative

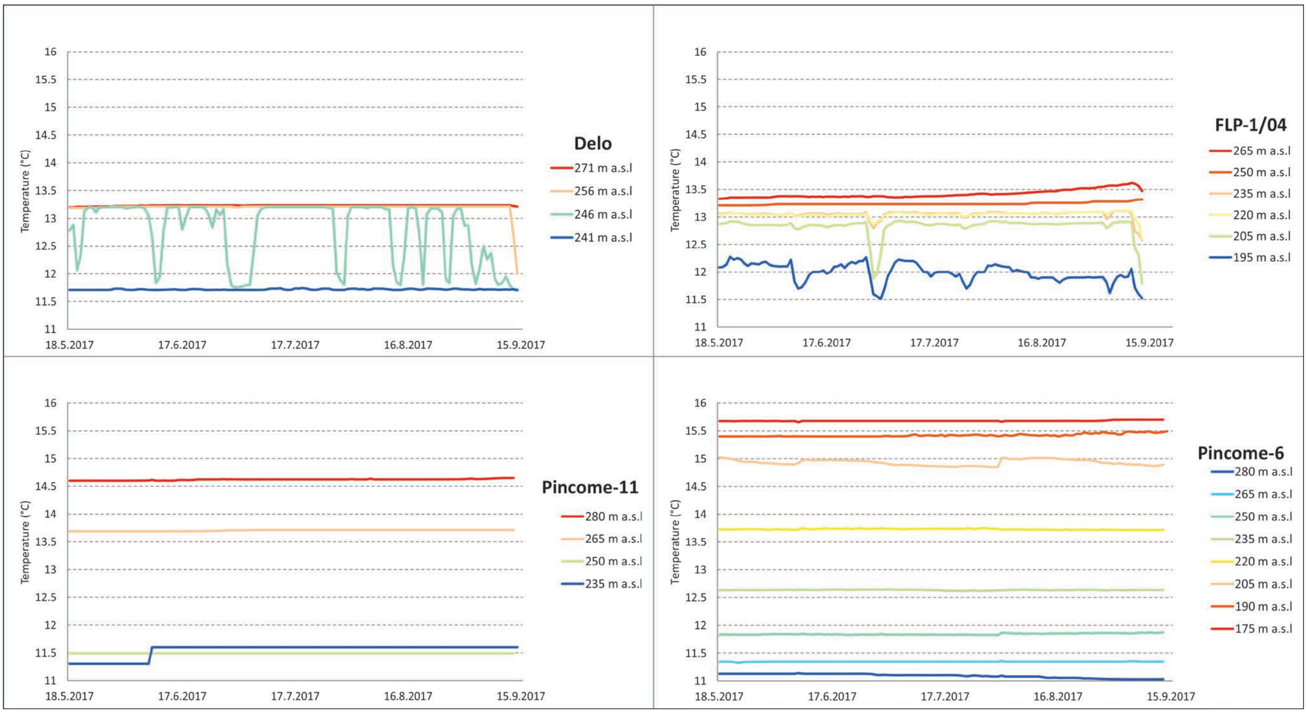

Fig. 10. Multi-level groundwater temperature time series (observation wells Delo, Pincome-11, FLP-1/04 and Pincome-6).

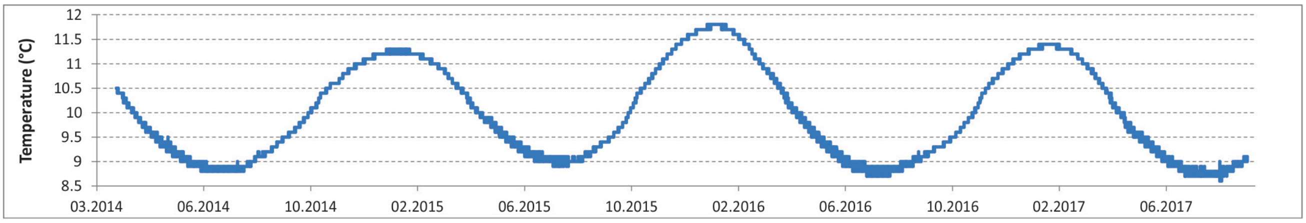

Fig. 11. Single-level groundwater temperature time series measured in observation well Pincome-9.

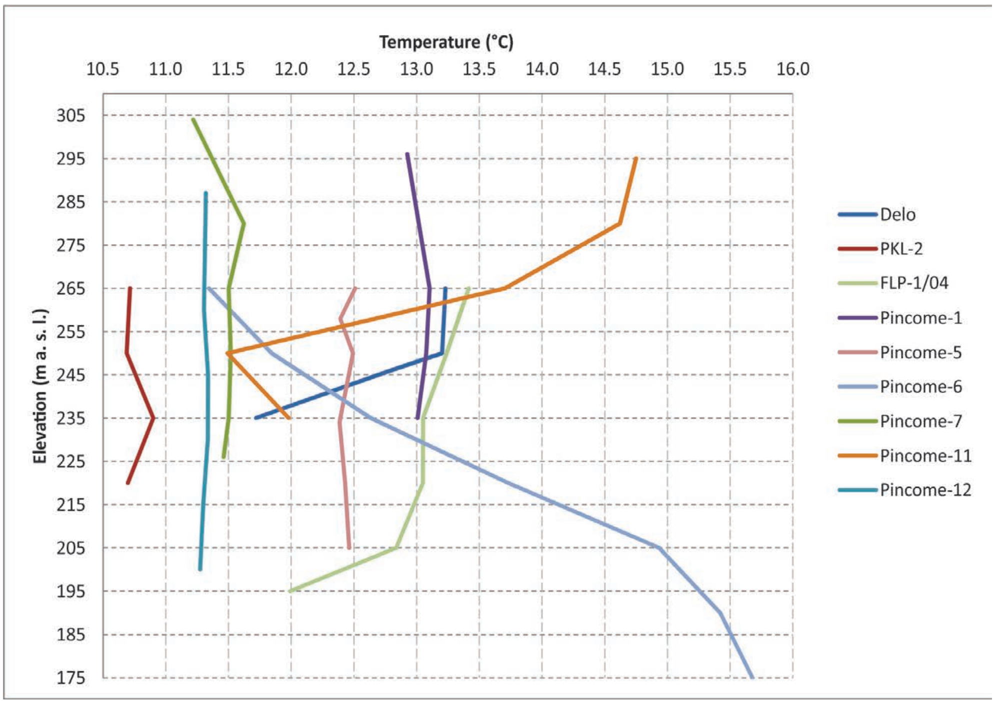

Fig. 12. Multi-level groundwater temperatures in observation wells.

gradients which slightly differ among the wells. In contrast to this, in well Pincome-6 in the Ljubljansko barje, a clear positive temperature gradient is visible and an increase of temperature with depth up to 15.6 °C, measured at 118 m depth.

The observed characteristics could be related to different factors. The first group of wells, except the well Pincome-1, is located outside or at the edge of the urban area, where the anthropogenic impact on GWT is minimal and the measured GWTs reflect undisturbed natural background conditions.

The second group of wells is located within the urban area, where increased temperatures in the upper part of the aquifer could arise from anthropogenic heat sources. Positive temperature anomalies or subsurface urban heat islands are often observed phenomena beneath cities. Measurements of groundwater temperature beneath the German cities showed subsurface urban heat islands (temperature is elevated for 1.9 to 2.4 °C), and revealed hotspots of up to + 20 °C (Menberg et al., 2013). In the city of Basel (Switzerland) an elevation of groundwater temperatures of up to 9 °C above the natural state is reported (Epting & Huggenberger, 2013).

The positive temperature gradient in well Pincome-6 probably originates from an increased heat-flow density and geothermal anomaly related to the thermal convection zone in the Triassic carbonate rocks below the Quaternary sediments (Živanović & Rajver, 2004).

Conclusions

In this paper, new research results for the assessment of the shallow geothermal potential in the area of the City of Ljubljana are presented. The distribution of ground thermal conductivity was derived with the help of a detailed geological map, representative rock sampling and measurements of the samples' thermal parameters. The results show that dolomites and quartz conglomerates have the highest thermal conductivity and, on the contrary, shales and tuffites, and some marlstones and siltstones (or claystones), have the lowest value of thermal conductivity among the geological units in the study area. This is important for the use of the shallow geothermal potential, as the higher thermal conductivity of the subsurface allows for a better heat extraction rate and higher efficiency of geothermal installations. The groundwater temperature measurements indicate relatively stable temporal conditions and a GWT range between 10.6 °C and 14.6 °C at the Ljubljansko polje and up to 15.6 °C in the deepest part of the Ljubljansko barje. Multi-level GWT measurements in observation wells show three different trends: negative, positive and no geothermal gradient in the aquifer, which in general depend on the location of the well and the related anthropogenic impact or the deeper geothermal and hydrogeological conditions.

The results obtained in this study provide a basis for the development of a 3D numerical geothermal model that will be used for the quantification of the shallow geothermal potential and for planning the efficient and sustainable use of shallow geothermal energy in the City of Ljubljana.

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Appendix A. Supplementary material

Data on observation wells and measurements of temprerature (T), electric conductivity (EC) and level of groundwater table (GWL).

Observation well	Ground elevation (m a.s.l.)	GWL (m a.s.l.)	Depth of screening intervals (m)	Number of levels of T, EC, GWL measurements	Number of levels of T measurements	Depth intervals of measurement levels (m)
Ž.P.Šentvid	316	292	no data	1	0	26
Iskra stegne	310	279	no data	1	0	35
Pincome-7	309	279	27-36;42-54;60-81	1	6	2-83
PKL 2-2	308	279	55-84	1	3	43-88
Pincome-1	301	279	24-36; 40-51; 57-69	1	4	5-74
Pincome-11	300	283	54-80	1	4	5-65
Lj-Delo	299	277	no data	1	3	28-58
FIP-1/04	297	276	24-45;57-75; 87-105	1	5	32-102
Pincome-5	294	274	24-48; 54-63;72-90	1	5	5-90
Aero	294	285	no data	0	1	14
Pincome-6	293	284	89-116	1	7	13-118
Pincome-12	292	276	34-55; 58-84	1	5	5-88
PH-4	289	274	11-21	1	0	19
Ag2-04	287	273	8-20	1	0	20
PH-2	287	273	9-20	1	0	18
P-1/94	285	273	15-18	0	1	20
Pincome-10	306	280	25-39; 45-76	1	0	30

Appendix B. Supplementary material

Appendix A. Groundwater temperature time series (observation wells PKL-2, Pincome-7, Pincome-1, Pincome-12; P-1/94, Pincome-5 and AERO)