GEOLOGIJA *62/2*, 237-249, Ljubljana 2019

https://doi.org/10.5474/geologija.2019.011

Risk assessment for open loop geothermal systems, in relation to groundwater chemical composition (Ljubljana pilot area, Slovenia)

Ocena tveganja za odprte geotermalne sisteme, glede na kemično sestavo podzemne vode (pilotno območje Ljubljana, Slovenija)

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Prejeto / Received 16. 10. 2019; Sprejeto / Accepted 5. 12. 2019; Objavljeno na spletu / Published online 24. 12. 2019

Key words: shallow geothermal energy, open loop geothermal system, groundwater, chemical composition, heat pump

Ključne besede: plitva geotermalna energija, odprti geotermalni sistemi, podzemna voda, kemična sestava, toplotna črpalka

Abstract

Shallow geothermal energy is a renewable source of energy that can be used effectively with open loop geothermal systems. Knowledge of hydrogeological conditions is a prerequisite for the successful implementation and operation of such systems. The article describes a risk assessment of open loop geothermal system operation related to the chemical composition of groundwater in the area of the City of Ljubljana. Results of the study show that in the area of the Ljubljansko polje aquifer, the geochemical characteristics of the groundwater do not represent a risk of possible operational problems for an open loop geothermal system. On the contrary, the chemical composition of the groundwater in the Ljubljansko barje aquifer indicates a risk of corrosion and/or the precipitation of minerals, which can lead to diminished efficiency of the geothermal system or even damage that can result in the interruption of operations. In order to avoid operational problems in open loop systems, wells must be a professionally designed and installed, and groundwater geochemical characteristics properly determined. In the latter, it is important to take into account the method of sampling, since the chemical composition of water in the aquifer and in the geothermal system may vary significantly.

Izvleček

Plitva geotermalna energija je obnovljivi vir energije, ki ga lahko učinkovito uporabljamo s pomočjo odprtih geotermalnih sistemov. Pogoj za njihovo uspešno namestitev in delovanje je poznavanje hidrogeoloških pogojev. Članek opisuje oceno tveganja za delovanje odprtih geotermalnih sistemov, povezanih s kemično sestavo podzemne vode na območju Mestne občine Ljubljana. Rezultati raziskav kažejo, da na območju vodonosnika Ljubljanskega polja geokemične značilnosti podzemne vode ne predstavljajo posebnega tveganja za delovanje odprtih geotermalnih sistemov. Nasprotno na območju Ljubljanskega barja kemična sestava podzemne vode nakazuje možnost korozije in obarjanja mineralov, kar lahko povzroči zmanjšanje učinkovitosti odprtega geotermalnega sistema ali celo poškodbe, ki onemogočajo njegovo delovanje. Na tem območju je v izogib težavam pri delovanju tovrstnih sistemov nujno strokovno načrtovanje in izvedba vrtine ter ugotovitev geokemičnih značilnosti podzemne vode. Pri slednjem je pomembno upoštevati način vzorčenja, saj se kemijska sestava vode v vodonosniku in geotermalnem sistemu lahko bistveno razlikuje.

Introduction

Shallow geothermal energy is a renewable source of energy with increasingly important environmental, economic and social impacts. The subsurface temperature at a depth of 10 m is practically constant throughout the year (roughly the annual average ambient temperature). Shallow geothermal systems can take advantage of the stable subsurface conditions and heat stored in the solid rocks or groundwater for heating or cooling, and for seasonal energy storage (Bonte, 2015). There are two kinds of shallow geothermal systems: closed and open loop (Fig. 1). Geothermal open loop systems, which are the focus of this study, use groundwater as a conveyor or carrier of heat. Such systems consist of extraction and injection wells and transfer withdrawn groundwater to a heat exchanger, and after exploitation it is reinjected back into the aquifer. The direct use of groundwater, which is a good carrier of thermal energy due to its high specific heat capacity, makes open loop systems more efficient in general than closed loop systems (Internet 1), which use a mixture of water and antifreeze with lower specific heat capacity and exchange heat with subsurface through a polyethylene pipe. Specific heat capacity of the water and antifreeze mixture decreases as the amount of the volume of antifreeze used in mixture increases (Roslan et al., 2017).

On the other hand, the installation and operation of open loop systems is more challenging. The first condition for the implementation of an open loop system is the availability of groundwater, whereby the hydrogeological conditions can enable the withdrawal and injection of a sufficient quantity of groundwater (or required flow rate). Furthermore, the aquifer may already be used for other priority purposes (e.g. drinking water supply) or may be protected (e.g. nature protection area). The use of shallow geothermal energy with open loop systems affects the local hydraulic regime and temperature of groundwater which can potentially mobilise contaminants and influence physical properties of groundwater, chemical reactions, microbiology and the interaction of these factors with each other (Zuurbier et al., 2013). Due to these risks and risk related to drilling of boreholes, installation of shallow geothermal systems within catchments of drinking water well is often restricted (Zuurbier et al., 2013). Böttcher et al. (2019) outlined the physical, operational and regulatory limits of such, and stressed the fact that detailed knowledge of the local hydrogeological conditions and the resulting technical potential are crucial conditions for the efficient use of open loop systems. Another important factor, which is investigated in this study, is the chemical composition of groundwater, which can introduce problems into open loop systems, namely clogging or corrosion, or both (Rafferty, 1999).

The precipitation of minerals can seriously affect the efficiency of the well and all other installations exposed to groundwater with low dissolved oxygen concentrations (Houben, 2003). When the screen section of the well is clogged with precipitated minerals, the amount of water that can flow into the well decline and thus the well's capacity decreases (Woyessa, 2011). The development of incrustation in wells can be the result of both chemical and biological processes (Park et al., 2015).

Chemical encrustation could be the secondary effect of biofouling oxidation or corrosion (Smith & Tuovinen, 1985). Changes in O_2 and CO_2 con-

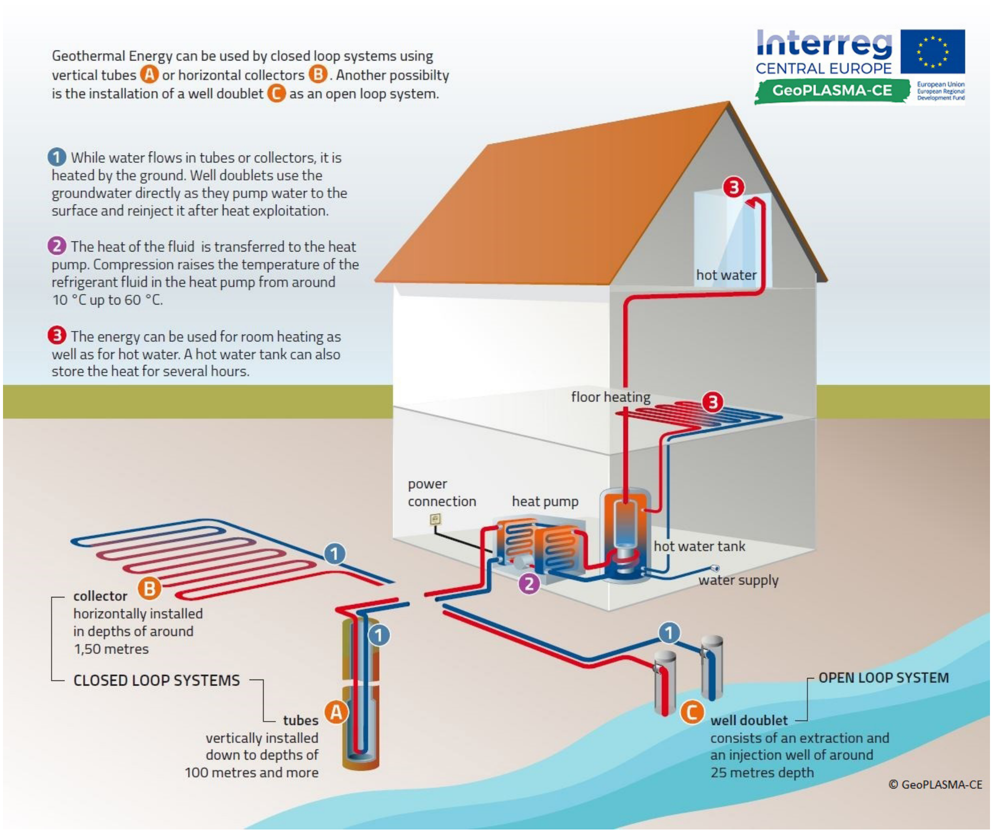

Fig. 1. Scheme of shallow geothermal energy systems, used for heating and cooling of buildings (Internet 1).

tent in groundwater, as well as in pressure and temperature, can lead to the formation of carbonate and silica minerals, as well as iron and manganese containing minerals (Abesser, 2010; Brons et al., 1991; Holm et al., 1987; Rafferty, 1999). Minerals containing iron, such as $Fe(OH)_3$, goethite (FeOOH) and hematite (Fe_2O_3) can be precipitated as scale within the open loop system (Park et al., 2015). The Langelier Saturation Index (LSI) and Ryznar Stability Index (RSI) are often used as an indication of the aggressiveness of the water and the risk of the precipitation of carbonate minerals inside the open loop system (Rafferty, 1999).

If under natural conditions the oxygen concentration in groundwater is low and the pH value ranges from 6.5 to 7.5, iron occurs primarily as dissolved ferrous iron (Fe^{2+}). Fe^{2+} is unstable in contact with oxygen, and in the presence of air it changes to insoluble ferric iron (Fe^{3+}) and precipitates as ferric oxide or oxyhydroxide. The oxidation rate of Fe^{2+} is highly dependent on pH conditions (Woyessa, 2011) and dissolved oxygen concentrations (Donald, 1997). When water is aerated, almost all the iron becomes insoluble. This condition can arise from the mixing of groundwater with low dissolved oxygen concentrations with oxygen rich groundwater during operation of the well (Donald, 1997). Ferric oxides and oxyhydroxides precipitate and coat surrounding surfaces. This process also results in rust on metal surfaces exposed to the atmosphere. If Fe^{2+} is combined with carbonate ions, iron bicarbonate is formed. Manganese resembles iron in its chemical behaviour and occurrence, but in groundwater it is less abundant than iron (Kemmer, 1977). Indicators of incrusting groundwater are high pH value (> 7.5), RSI < 7, iron content > 0.5 mg/L (precipitation of iron), carbonate hardness > 300 mg/L (precipitation of calcium carbonate), manganese content > 0.2 mg/L (precipitation of manganese) and the presence of oxygen (Driscol, 1986; Götzl et al., 2018).

Clogging can also occur due to the presence of iron bacteria, which form biological incrustations (Smith & Tuovinen, 1985). Iron bacteria's natural environment is wetlands (Pringsheim, 1949), where they mainly generate most of their energy for metabolism by oxidising soluble Fe^{2+} into insoluble Fe^{3+}, and in this way gain a small amount of energy by utilising large amounts of Fe^{2+} (Howsam, 1988).

Beside the clogging, another risk for open loop systems is corrosion, which is the result of chemical and electrochemical processes. Chemical corrosion can be expected if the water has a low pH value (< 7), elevated concentrations of dissolved oxygen (> 2 mg/L), hydrogen sulphide presence (even less than 1 mg/L), high TDS concentration (> 1000 mg/L), CO_2 concentrations > 50 mg/L and chloride content > 500 mg/L (Driscoll, 1986). Electrochemical corrosion can occur when two conditions are fulfilled: an electrical potential difference on metal surfaces, and enough dissolved solids in water to constitute a conductive fluid (electrolyte). An electrical potential difference may develop between two different kinds of metals, or between proximate yet separate areas on the surface of the same metal (Driscoll, 1986). Corrosion can cause damages (new openings) in the open loop system: the enlargement of well screen openings and increased entry of finer material into the well are particularly common, and can harm the pump and reduce the efficiency of the well (Driscoll, 1986). Due to corrosion in an ionizing solvent the metal ion initially goes into solution but may then undergo a secondary reaction, combining with other ions present in the environment to form an insoluble molecular species such as rust (Schofield, 2002).

In this study a risk assessment of the efficient operation of open loop geothermal systems, related to the chemical composition of groundwater is presented. The study follows a procedure, developed within the GeoPLASMA-CE project (Götzl et al., 2018) which was implemented in the Ljubljana pilot area. The procedure consists of three main steps. 1) Calculation of LSI and RSI indices using available archive data on chemical composition of groundwater. 2) Additional field measurements and chemical analysis of groundwater in those areas where in the previous step a risk was identified and operational problems in open loop systems were reported. Different sampling procedures (in wells and from the system) were implemented and analysed in this step. 3) Outlining areas with a risk for the efficient operation of open loop geothermal systems.

Hydogeological setting

The study area is part of the area of Municipality of Ljubljana, with aquifers potentially suitable for implementation of open loop systems: the Ljubljansko polje unconfined aquifer and the northern part of the Ljubljansko barje confined aquifer system (Fig. 2). The average annual precipitation in this area is 1383 mm (2001–2010) while the average annual ambient temperature is 11.3 °C (2001–2010) (Internet 2).

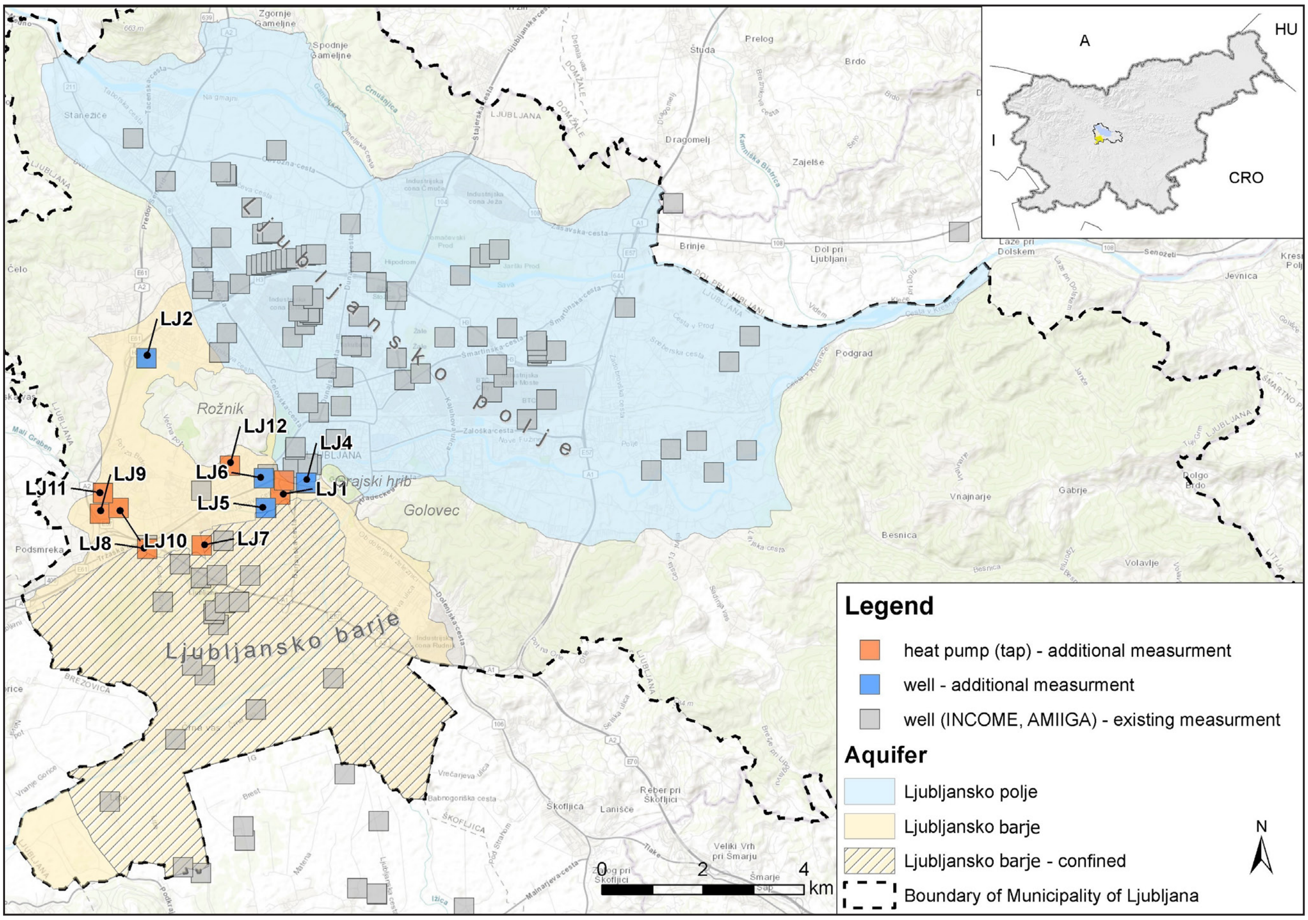

Fig. 2. Study area with locations of measurements.

The Ljubljansko polje aquifer is composed of permeable gravel and sand beds with lenses of conglomerate. Due to its great thickness (which exceeds 100 m in the deepest parts) and high permeability, this Quaternary aquifer contains significant quantities of groundwater, which is the main source of public water supply for the City of Ljubljana (Janža, 2009; Šram et al., 2012). The Ljubljansko barje aquifer is composed of alternating fluvial and lacustrine deposits with a heterogeneous composition (silt, clay, sand, gravel) (Mencej, 1988/89). The top low-permeable layer in the northern part of the Ljubljansko barje is 10–20 meters thick (Fig. 3, A).

Under this layer the heterogeneous and low permeable upper Pleistocene aquifer (Fig. 3, B) is situated. Beneath the upper Pleistocene aquifer, a thick silty and clayey layer (Fig. 3, C) is present and underneath the lower Pleistocene aquifer (Fig. 3, D), which consists of gravel and contains good quality groundwater (Prestor & Janža, 2002). It is a confined or semi-confined aquifer with artesian to sub-artesian conditions.

Research of the Barje landfill influence on groundwater has revealed a reducing environment and presence of iron, manganese, ammonium and arsenic in groundwater (Prestor & Janža, 2002). This influence of the landfill overlaps with the natural reduction environment and the consequences of reducing conditions resulting from the immission of pollution from other sources in the urbanized area (Prestor & Janža, 2002).

The Sava River, which recharges the Ljubljansko polje aquifer in its north-western part, has an electrical conductivity around 300 µS/cm (Jamnik et al., 2014). The low electrical conductivities, between 200 and 300 µS/cm, and fluctuating temperatures at the north-western part of

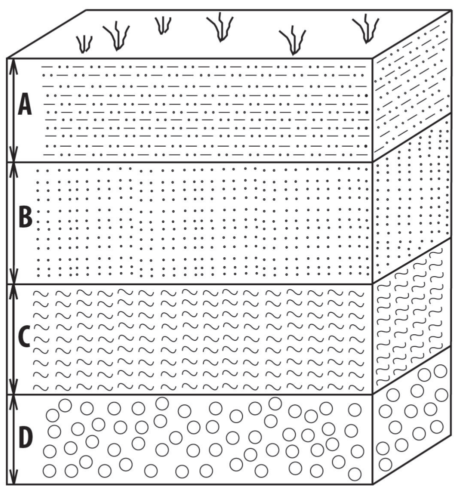

Fig. 3. Schematic representation of Ljubljansko barje aquifer (after Prestor & Janža, 2002)

Fig. 4. Iron mineral deposits on heat pump filter from northern part of Ljubljansko barje.

the Ljubljansko polje aquifer (Kleče and Jarški prod well fields) are therefore the result of a significant recharge of the Sava river (Jamnik et al., 2014). Under highly urbanized parts of the Ljubljana polje aquifer, electrical conductivity ranges between 500 and 700 µS/cm. The temperature of the groundwater at the Ljubljansko polje range between 10.6 and 14.6 °C, while in the Ljubljansko barje the temperature rises up to 15.6 °C (Janža et al., 2017).

According to the archive and publicly accessible data (Internet 3), 93 open loop geothermal systems (December 2018) are installed in the Ljubljana pilot area. Problems in the operation of open loop systems, that could be related to groundwater chemical composition, were reported from the users from northern part of the Ljubljansko barje. The most commonly reported problems consist of deposition of iron minerals on filters which requires frequent cleaning in order to maintain system efficiency (Fig. 4).

Materials and Methods

Archive data processing

The first step of the investigation involved the analysis of existing data on groundwater field parameter measurements and chemical analysis. The main body of said data was collected and organized from previous projects (AMIIGA, INCOME). Additional data from the national monitoring program, accessible through a portal (Internet 4), were used in the analysis. The datum consist of measurements for basic chemical parameters (anions and cations), which were used to determine the type of water and the ion balance (software AquaChem 2014.2.; Waterloo Hydrogeologic, 2018) for each observation point.

The LSI was calculated using readings for alkalinity, hardness, TDS, pH and temperature (Lentech, 2018a). The groundwater electrical conductivity of unpolluted groundwater is usually correlated with the concentration of dissolved carbonates in the water or the carbonate hardness of the water. If LSI < 0 the water is undersaturated with calcium carbonate and has a tendency to remove the existing protective coatings of calcium carbonate in pipelines and equipment (is corrosive); and if LSI > 0 the water is supersaturated with respect to calcium carbonate ($CaCO_3$) and the formation of scale may occur (Gonzalez et al., 2019).

Additional field measurements and groundwater sampling

Additional groundwater sampling and field measurements were focused on the northern part of the Ljubljansko barje, where operational problems of open loop systems related to the chemical composition of groundwater were reported. Since the number of locations, where the sampling could be performed from wells was limited, sampling was performed also on the surface part of the open loop systems, where water samples were taken from the heat pump system taps. A total of four observation wells and eight open loop systems were selected.

In order to assess the material resistance of open loop systems, two sampling campaigns were carried out. First sampling on all 12 sampling locations was performed in March 2018. A second sampling in May 2018 was repeated in three wells (LJ1, LJ2 & LJ6) and on one tap (LJ3) in order to analyse the comparability of results of chemical analysis of samples taken on different object types in different time periods. Groundwater sampling on wells was performed on 27th March and 14th May using a Grundfos M1 submersible pump (Eijkelkamp, 2017). Wells LJ2 (depth: 84 m), LJ4 (depth: 92 m), LJ5 (depth: 92 m) and LJ6 (depth: 72 m) are observation wells, while LJ1 (24 m) is an injection well and is part of an open loop system. In other cases, water samples from open loop systems were taken from taps. Field parameters such as pH, electrical conductivity (Cond.), temperature (T), redox potential (Eh), dissolved oxygen (DO) and oxygen saturation (O_2) were measured with a portable WTW Multimeter pH/Cond (pH value: SenTix 42, Cond. and T: TetraCon 325 (WTW GmbH, 2004) and with WTW Multi 3410/set C (redox potential: Sentix ORP (WTW GmbH, 2008), oxygen content: FDO 925 (WTW GmbH, 2010). Fe^{2+} and Fe (total) content in water was measured with a HACH DR 2800 portable spectrophotometer (Hach Lange, 2012). Analysis of major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}; SIST EN ISO 14911:2000), anions (Cl^-, SO_4^{2-}, NO_3^-; SIST EN ISO 10304-1:2009; and $HCO3^-$; ASTM D 1067-B mod.), and Fe total (SM.3500-Fe-B) (if the value in the field was above 3 mg/L) were performed by the accredited Vodovod-Kanalizacija d.o.o. laboratory. Additional samples for analysis of Mn (ISO 17294-2:2016(E), NM) and dissolved sulphide (as H_2S – SIST ISO 10530: 1996, NM) content were also taken and analysed in Vodovod-Kanalizacija d.o.o. laboratory. Uncertainties of measured contents are in following ranges: for HCO_3^- ±0.02 mg/L, Fe total (measured in laboratory) ±0.14 mg/L, Mn ±0.016 mg/L and for dissolved sulphide ±0.014 mg/L (Auersperger & Železnik Bračič, 2018).

Results and discussion

Archive data processing

Data from 126 locations, 91 from the area of the Ljubljansko polje aquifer and 35 from the area of the Ljubljansko barje aquifer, were analysed. The data consist of total 2227 analysis of chemical parameters, performed between the years 2008 and 2017. 28.7 % of the data included in the data processing procedure contain no data on NO_3^- content; therefore, a calculation for ion balance could not be performed. On the rest of the data, accuracy check was made using an AquaChem 2014.2, which indicated that 15.5 % of the data showed poor ion balance, 11.6 % fair and 44.2 % good ion balance. The most common water type in both aquifers is Ca-Mg-HCO_3.

Based on the calculated LSI in the study area, the risk of the formation of lime scale (where median LSI is > 0) and/or corrosion is present (where median LSI value is < 0) (Fig. 5). According to the distribution of electrical conductivity in the Ljubljansko polje and Ljubljansko barje aquifer, figure 5 shows the risk of corrosion or limescale formation, but since the expected changes in groundwater temperature in shallow, low-temperature open loop geothermal system is less than 5°C, such risk is low (VDI-Richtlinien, 2001).

The RSI is influenced by pH value, electrical conductivity, Ca^{2+}, HCO_3^- and water temperature (Lentech, 2018b). Based on calculations of RSI, very aggressive groundwater was identified in

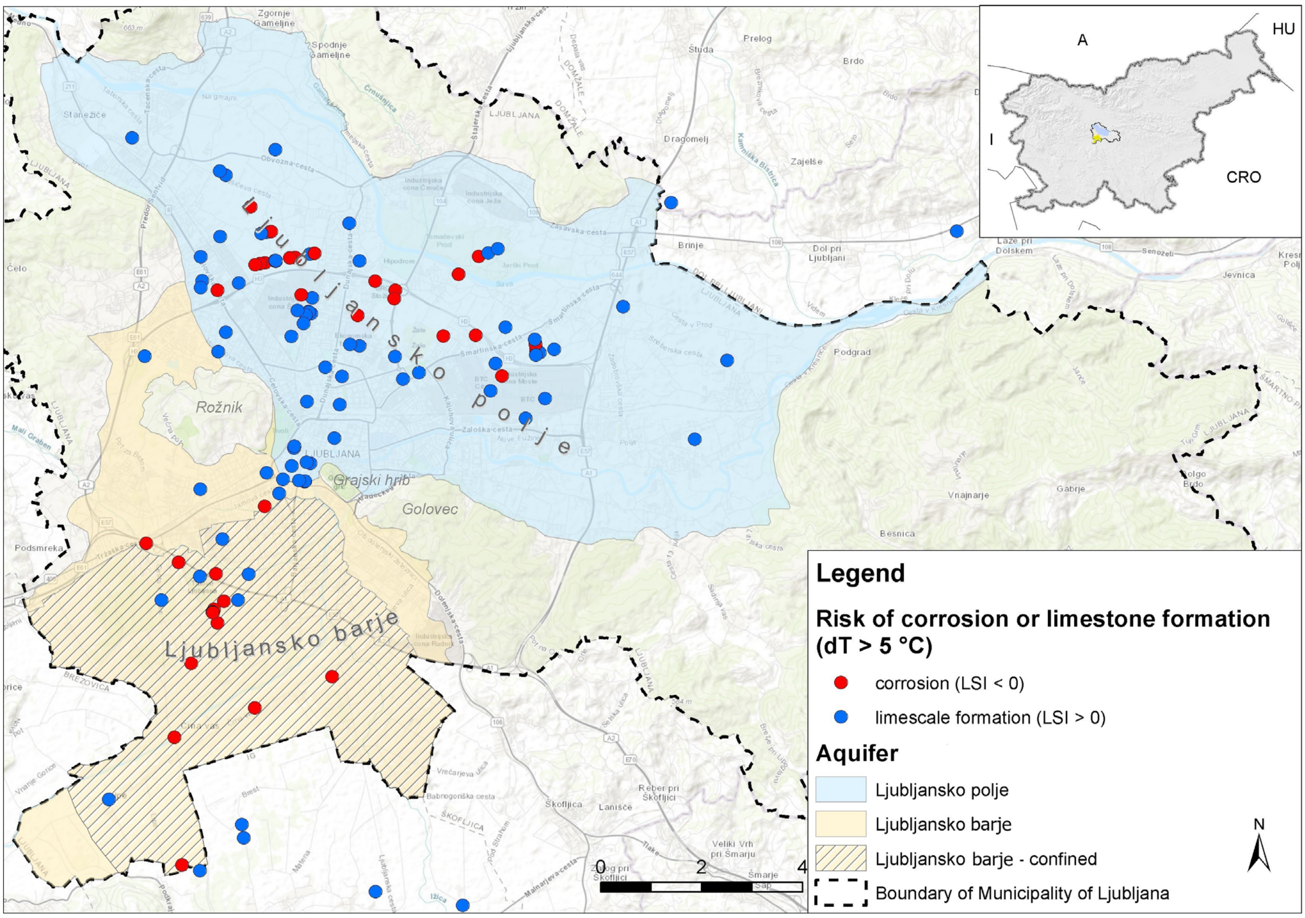

Fig. 5. Risk of corrosion or formation of limescale in the case of $_{\Delta}T$ of groundwater > 5 °C.

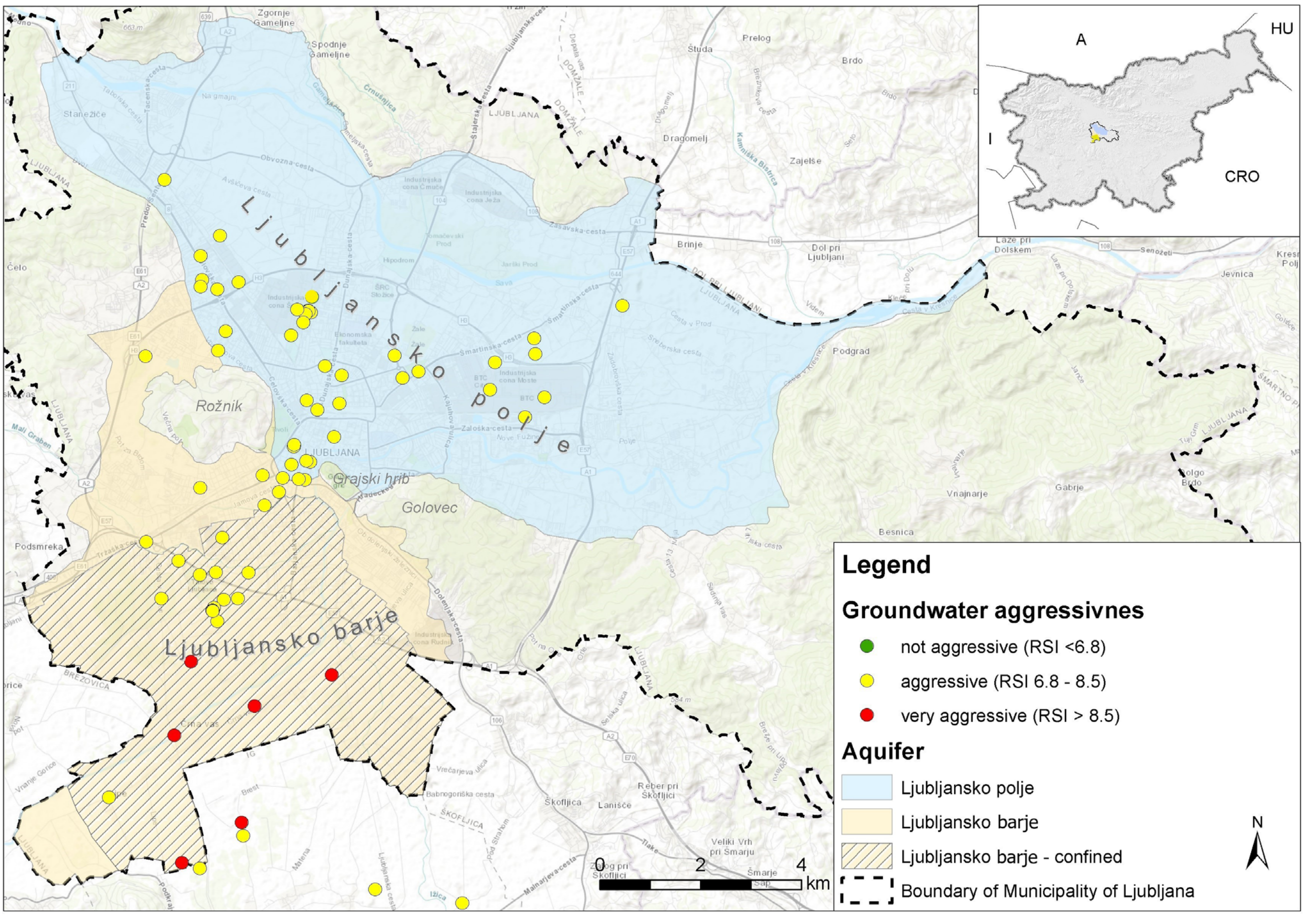

Fig. 6. Groundwater aggressiveness based on RSI.

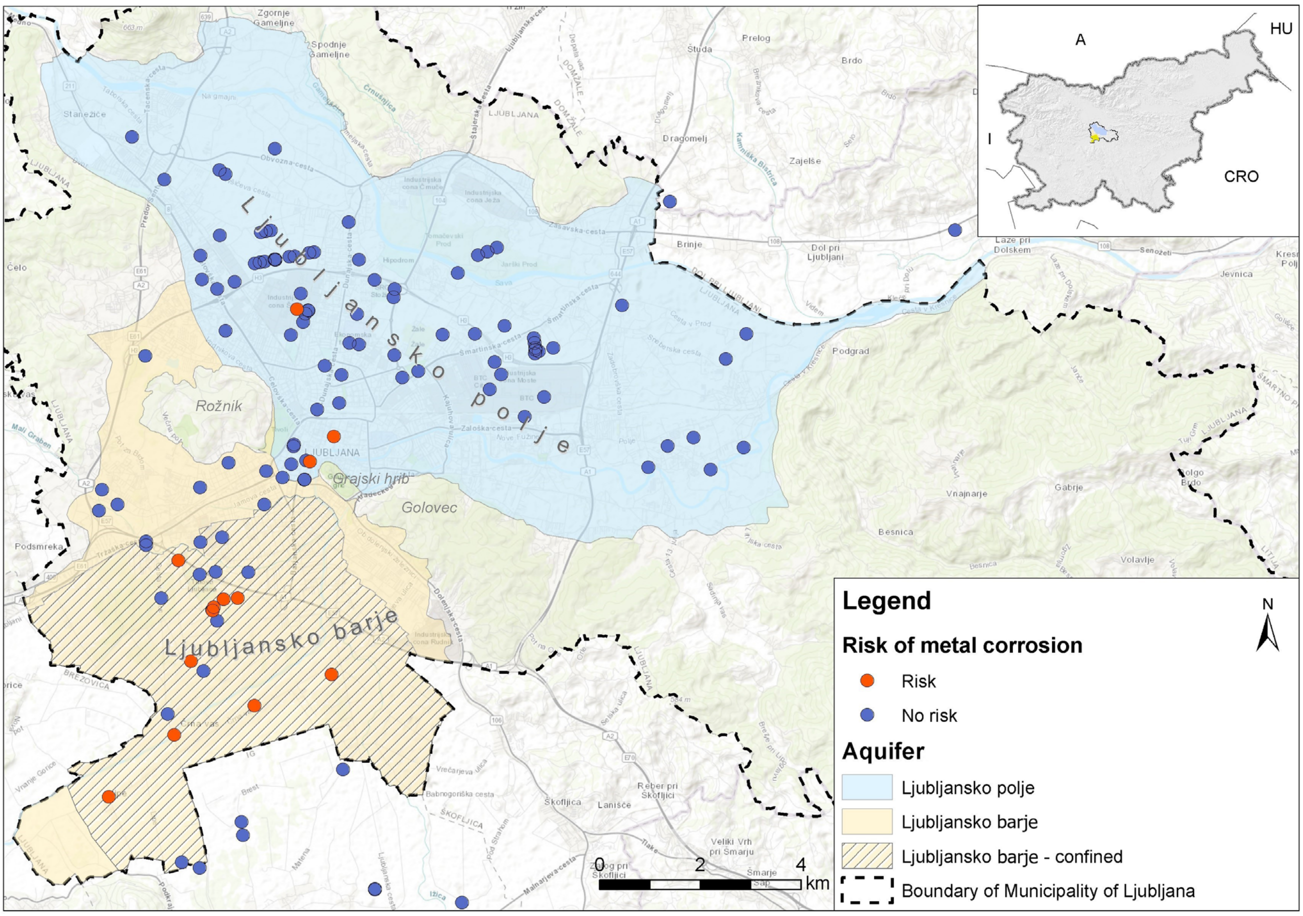

Fig. 7. Risk of metal corrosion, due to high SO_4^{2-} and DO content.

the Ljubljansko barje aquifer (Fig. 6), where the minimum pH value (6.8) is noticeable lower than in Ljubljansko polje aquifer (7.3).

RSI value higher than 7.5, pH value < 7.5 and presence of dissolved oxygen (> 2 mg/L) in groundwater indicate the risk of metal corrosion mainly in the Ljubljansko barje aquifer (Fig. 7).

Since archive data on iron and manganese content are scarce it was not possible to assess the risk of iron and manganese precipitation: therefore, additional sampling was carried out.

Additional field measurements and groundwater sampling

Results of the field measurements and chemical analyses of samples taken from wells and from taps (open loop systems) are presented in (Table 1). In order to determine the risk in relation to the chemical composition of groundwater for the operation of open loop systems, the results of field measurements and chemical analyses were compared with parameter limits. They are recommended by heat pump manufacturers Ochsner Wärmepumpen GmbH, Viessmann Ltd. and Dimplex Ltd (Kmiecik et al., 2017) and represent conditions required for the undisturbed and efficient operation of open loop systems. A conservative approach was used, and most restrictive limits of the mentioned manufacturers were considered (Table 1).

Results of the analysis (Table 1) show that manufacturers' requirements could not be met in all cases. There is no risk of corrosion at four locations (Table 1; LJ3, LJ7, LJ8 and LJ9), which can occur at eight locations (Table 1; LJ1, LJ2, LJ4, LJ5, LJ6, LJ10, LJ11 and LJ12). Due to the high iron and dissolved oxygen content at five locations a risk of iron or manganese scaling is indicated (Table 1; LJ1, LJ4, LJ5, LJ6 and LJ-12). To mitigate this kind of risk filtration after oxidation (Appelo & Postma, 2005) was reported as most cost-effective method for removal of iron or manganese scaling from the system (Power & Prasad, 2010).

The central part of the Ljubljansko barje confined aquifer is covered with a thick layer of clay, which causes lower oxygen content in groundwater. Oxygen deficiency creates hydrochemical conditions in which iron and manganese, usually present in poorly soluble chemical forms, become mobile (Jamnik et al., 2014). Based on the analyses of archive data and the results of additional measurements, including knowledge of natural hydrogeological conditions we identified metal corrosion and iron or manganese scaling as the highest risk to the efficient operation of open loop systems (Table 1) and outlined the area with the highest risk (Fig. 8).

Comparison of different sampling approaches

A comparison of the results of different sampling approaches (Table 2) shows that the values of parameters measured on different dates do not differ noticeable for the samples on locations LJ2, LJ3 and LJ6, when the samples taken from the same object type (well or heat pump tap). At location LJ-1, samples were taken one time from the well and one time from the tap, but at different times. Due to the different sampling periods, direct comparison is questionable; however, taking into account the results of measurements taken at other locations, it seems that sampling from different types of object produces the highest differences in measured parameters and reflects the different conditions in the geothermal system and in the well, or before and after heat extraction. The most noticeable differences are observed in the values of parameters dissolved oxygen (3.38 and 0.71 mg/L), electrical conductivity (676 and 483 µS/cm), and concentration of HCO_3^- (289 and 355 mg/L). Heat extraction results in lower water temperatures in the injection well (10.1 °C) than at the tap (13.0 °C). However, for more detailed comparison of two sampling approaches, more data would have to be collected. Since no data on the iron content of groundwater sampled from well are available (only at tap), no interpretation of the processes that occur during heat extraction within the system is possible.

Conclusion

Based on archive data, the calculated values of LSI and RSI indicate potential risk of lime scale formation and/or corrosion in both aquifers. But since for shallow geothermal open loop systems expected changes in groundwater temperature are smaller than 5 °C, this kind of risk is low.

Archive data on groundwater composition in the Ljubljansko polje aquifer show a high concentration of dissolved oxygen (on average 7.67 mg/L) and low iron content (on average 0.09 mg/L of Fe^{2+}), thus the risk of iron precipitation is low. In contrast, in the confined aquifer of the Ljubljansko barje the concentrations of iron are elevated (> 0.2 mg/L) and risk of iron precipitation was

Table 1. Comparison of additional field measurements and chemical analyses (different sampling dates) with limitations of the installation, as indicated by heat pump manufacturers (Kmiecik et al., 2017)

			LJ1				LJ2				LJ3				LJ4		LJ5		LJ6				LJ7		LJ8		LJ9		LJ10		LJ11		LJ12	
			Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK	Value	RISK
Parameter	Risk*	Limit value	HP tap		Well (depth: 24 m)		Well (depth: 84 m)				HP tap				Well (depth: 92 m)		Well (depth: 92 m)		Well (depth: 72 m)				HP tap		HP tap		HP tap		HP tap		HP tap		HP tap	
Sampling date			28th March 2018		14th May 2018		27th March 2018		14th May 2018		28th March 2018		14th May 2018		27th March 2018		27th March 2018		27th March 2018		14th May 2018		28th March 2018		28th March 2018		28th March 2018		28th March 2018		28th March 2018		28th March 2018	
Cond. [mg/L]	0	<10																																
	+	10 - 500	676	–	483	+	491	+	463	+	438	+	345	+	1024	–	502	–	375	+	417	+	340	+	463	+	461	+	380	+	389	+	703	–
	–	>500																																
pH value	0	<7.5																																
	+	7.5 - 8	7.28	0	7.33	0	7.1	0	7.5	0	7.68	+	7.57	+	7.12	0	7.81	+	7.51	+	7.6	+	7.65	+	7.56	+	7.68	+	7.58	+	7.77	+	7.23	0
	–	>8																																
DO [mg/L]	+	<0.2																																
	0	0.2 - 8	3.38	0	0.71	0	5.7	0	5.51	0	6.81	0	6.21	0	2.51	0	0.08	+	1.64	0	3.79	0	4.87	0	7.47	0	5.88	0	5.52	0	9.91	-	7.28	0
	–	>8																																
Fe [mg/L]	+	<0.2	2.2	-	/	/	<0.03	+	/	/	<0.03	+	/	/	2.28	-	3.11	–	0.855	–	/	/	0.13	+	<0.03	+	<0.03	+	0.025	–	0.01	+	2.14	–
	–	>0.2																																
HCO_3^- [mg/L]	0	<70																																
	+	70 - 300	289	+	355	0	231	+	253	+	260	+	286	+	466	0	265	+	253	+	261	+	221	+	268	+	270	+	243	+	229	+	415	0
	0	>300																																
SO_4^{2-} [mg/L]	+	<50																																
	0	50 - 100	15.5	+	16.1	+	18.5	+	18.1	+	21.9	+	22.4	+	75.4	0	<1.5	+	10	+	11.9	+	5.98	+	10.5	+	8.49	+	9.03	+	7.05	+	22.1	+
	–	>100																																
Cl^- [mg/L]	+	<100																																
	0	100 – 200	53.8	+	53.4	+	28.9	+	27	+	4.59	+	4.16	+	79.3	+	50.2	+	13.5	+	12.6	+	4.95	+	21.5	+	19.6	+	8.26	+	14.3	+	30.3	+
	–	>200																																
NO_3^- [mg/L]	+	<100	<2.2	+	2.26	+	7.17	+	7.17	+	<2.2	+	<2.2	+	<2.2	+	<2.2	+	5.09	+	5.98	+	<2.2	+	5.18	+	4.87	+	4.92	+	4.12	+	<2.2	+
	0	>100																																
Mn [mg/L]	+	<0.05	0.06	-	/	/	<0.0001	+	/	/	0.029	+	/	/	0.06	-	0.13	-	0.012	+	/	/	0.0006	+	0.0003	+	0.0001	+	<0.0001	+	<0.0001	+	0.23	-
	-	>0.05																																
Risk	Corrosion		May lead to corrosion and installation isn't recommended		May lead to corrosion		May lead to corrosion		May lead to corrosion		No problems expected		No problems expected		May lead to corrosion and installation isn't recommended		May lead to corrosion and installation isn't recommended		May lead to corrosion and installation isn't recommended		No problems expected		No problems expected		No problems expected		No problems expected		May lead to corrosion and installation isn't recommended		Installation isn't recommended		May lead to corrosion and installation isn't recommended	
	Scaling – iron/ manganese		Possible – high Fe, DO		/		Low risk - low Fe, Mn concentrations		/		Low risk - low Fe, Mn concentrations		/		Possible – high Fe, DO		Possible – Fe, pH – if aerated		Possible – pH, DO, Fe		/		Low risk - low Fe, Mn concentrations		Low risk - low Fe, Mn concentrations		Low risk - low Fe, Mn concentrations		Low risk - low Fe, Mn concentrations		Low risk - low Fe, Mn concentrations		Possible – Fe, Mn, DO	

- (0) may lead to corrosion, when two or more parameters are exceeded
- (-) installation isn't recommended, if one of the parameter's limit is exceeded
- (+) material is usually resistant

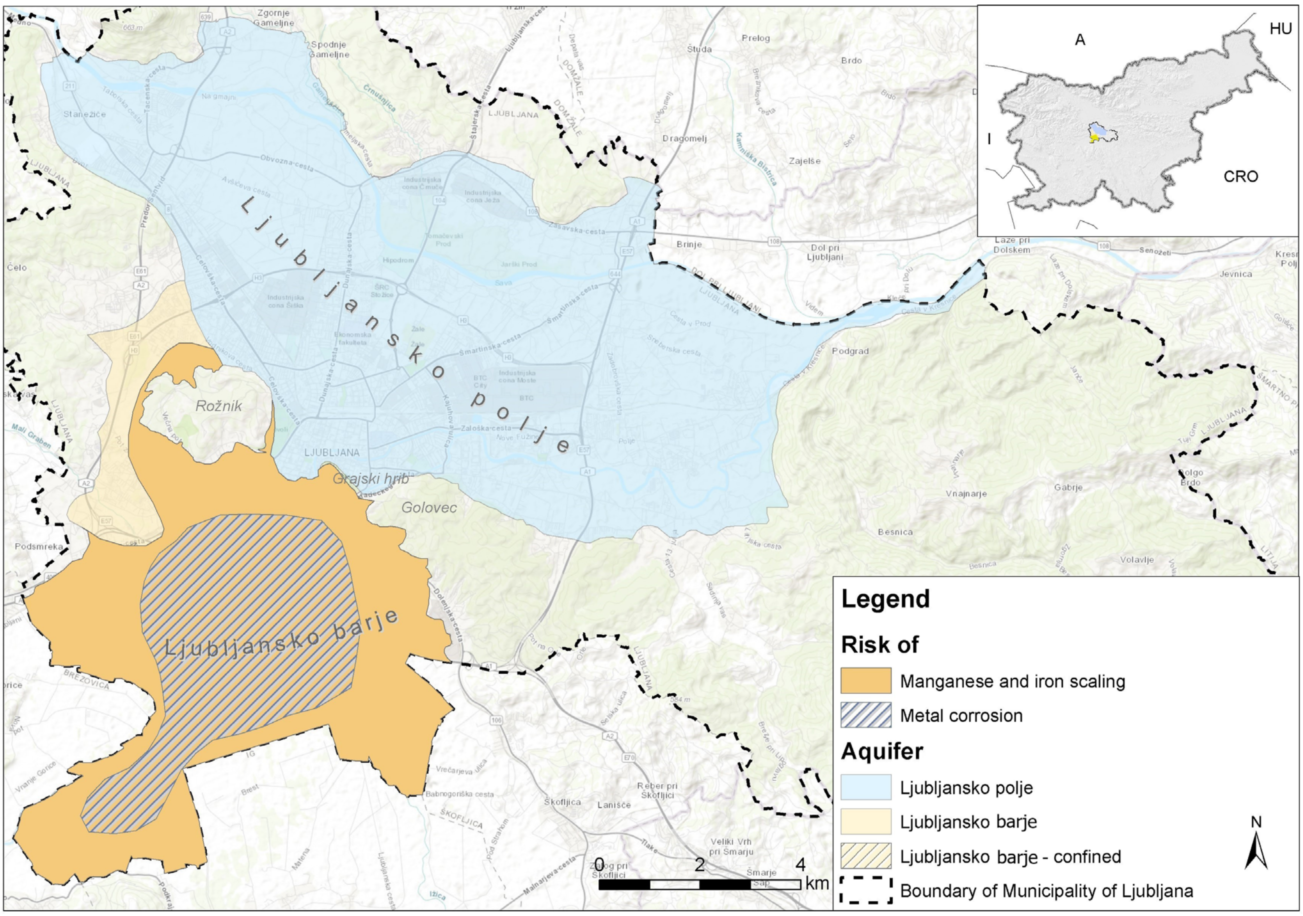

Fig. 8. Outline of area with risk of metal corrosion or iron and/or manganese scaling.

Table 2. Comparison of results of field parameter and chemical parameter measurements at tap or in well (March 27th, March 28th and May 14th, 2018).

Location	LJ1		LJ2		LJ3		LJ6	
Object type	tap	well	well	well	tap	tap	well	well
Sampling date	28th March	14th May	27th March	14th May	28th March	14th May	27th March	14th May
T [°C]	**13.0**	**10.1**	12.2	11.5	13.3	13.1	13.1	12.5
Cond [µS/cm]	**676**	**483**	491	463	438	345	375	417
pH value	*7.28*	*7.33*	7.10	7.50	*7.68*	*7.57*	7.51	7.6
Eh [mV]	*229*	*216*	*363*	*353*	400	332	96	175
DO [mg/L]	**3.38**	**0.71**	*5.7*	*5.51*	*6.81*	*6.21*	1.64	3.79
O_2 [%]	33.4		*55.0*	*52.2*	*67.5*	*60.8*	17	36.6
Fe^{2+} [mg/L]	0.27	/	<0.03	/	<0.03	/	0.186	/
Fe tot [mg/L]	2.2#	/	<0.03	/	<0.03	/	0.855	/
HCO_3^- [mg/L]	**289**	**355**	*231*	*253*	*260*	*286*	253	261
K^+ [mg/L]	*1.1*	*0.83*	*0.48*	*0.51*	*0.79*	*0.66*	1	0.97
Ca^{2+}[mg/L]	*81*	*83*	*88*	*88*	*56*	*58*	54	60
Mg^{2+}[mg/L]	*34*	*34*	*12*	*12*	*25*	*25*	22	23
SO_4^{2-}[mg/L]	*15.5*	*16.1*	*18.5*	*18.1*	*21.9*	*22.4*	10	11.9
Cl^- [mg/L]	*53.8*	*53.4*	*28.9*	*27.0*	*4.59*	*4.16*	13.5	12.6
$NO3^-$[mg/L]	*<2.2*	*2.26*	*7.17*	*7.17*	*<2.2*	*<2.2*	5.09	5.98
Suspended solids [mg/L]	44	/	<10	/	<10	/	26	/
Mn [mg/L]	0.06	/	<0.0001	/	0.029	/	0.012	/
S diss. [mg/L]	<0.05	/	<0.05	/	<0.05	/	<0.05	/

- measured in laboratory (in-situ > 3 mg/L)
Italic – Comparable data (<10 % difference between measurements)
Bold –Noticeable difference between measurements (>40 % difference)

identified in the area of Ljubljansko barje aquifer. Taking into consideration these results and the hydrogeological conditions, the area with a high risk of threat to the efficient operation of open loop systems in the study area was outlined.

Additional measurements at the Ljubljansko barje indicate that the known operational problems of open loop systems are the consequence of manganese or/and iron precipitation. Higher sulphate and dissolved oxygen content also indicate corrosive groundwater. When compiling information on the chemical composition of groundwater in the aquifer, it must be taken into consideration that samples of water taken from the open loop system (from a tap) do not always represent the content of dissolved oxygen in groundwater of the aquifer. Due to the lack of data on the iron content of groundwater sampled from well, no interpretation of the processes that occur during heat extraction within the system was possible. This important issue should be addressed in following investigations.

Operational problems of open loop geothermal systems related to scaling or corrosion are most often the consequence of the fact that geothermal systems are installed without consideration of the chemical composition of the groundwater and hydrogeological conditions in general. In such cases mitigation measures are required in order to ensure the efficient operation of open loop systems.

The findings of this study underpin the importance of knowledge of the hydrogeological conditions and the composition of groundwater before the installation of an open loop system. Only a combination of said knowledge and proper consideration of the parameter limits recommended by heat pump manufactures can ensure the optimised, site specific selection, installation and efficient operation of geothermal systems.

Acknowledgments

The authors acknowledge the project GeoPLASMA-CE co-financed by Interreg CENTRAL EUROPE Programme, project MUSE (GeoERA) which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166, and the financial support from the Slovenian Research Agency (research core funding No. P1-0020). The authors wish to thank Dejan Šram and Simona Adrinek for graphical work and help in cartography.

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