GEOLOGIJA 60/2, 267-277, Ljubljana 2017

https://doi.org/10.5474/geologija.2017.019

Application of environmental tracers to study the drainage system of the unsaturated zone of the Ljubljansko polje aquifer

Uporaba naravnih sledil za študij drenažnega sistema nezasičene cone vodonosnika Ljubljanskega polja

Branka TRČEK

University of Maribor, Faculty of civil enginering, Transportation Engineering and Architecture, Smetanova ulica 17, SI-2000 Maribor, Slovenia; e-mail: branka.trcek@um.si

Prejeto / Received 17. 12. 2016; Sprejeto / Accepted 8. 11. 2017; Objavljeno na spletu / Published online 22. 12. 2017

Dedicated to Professor Miran Veselič the occasion of his 70th birthday

Key words: Urban intergranular aquifer, unsaturated zone, drainage system, environmental tracers
Ključne besede: urbani medzrnski vodonosnik, nezasičena cona, drenažni sistem, naravna sledila

Abstract

The groundwater recharge processes were investigated in the unsaturated zone of the Ljubljansko polje intergranular aquifer. The study based on application of environmental tracers. The monitoring of the drainage system was established at an urban lysimeter consisting of artificial and autochthonous sediment layers. Groundwater was sampled with the suction cups instaled at depths of 0.3, 0.6, 1.2, 1.8, 3.0 and 4.0 m. The results pointed out the most important factors that control the hydrodynamic processes and solute transport in the study site where the soil cover and vegetation are missing. The physico–chemical and isotopic properties of sampled groundwater indicated that the clayey layers have an important role in the hydraulic behaviour of the unsaturated zone. As a consequence of a piston effect the event and pre-event water concentrate above these layers causing lateral flow. A vertical breakthrough of this water into lower layers of the unsaturated zone could occur through preferential paths during intensive precipitation events in dependence on pre-accumulated water volumes. Under such conditions groundwater residence time is about 2 months in the unsaturated zone 3 m below the surface.

Izvleček

V nezasičeni coni vodonosnika Ljubljanskega polja z medzrnsko poroznostjo smo proučevali tok podzemne vode v urbanem lizimetru. Monitoring drenažnega sistema zgornjega dela nezasičene cone, ki jo gradijo plasti avtohtonih in nanešenih sedimentov, je slonel na uporabi naravnih sledil. Podzemno vodo smo vzorčevali s keramičnimi sesalnimi svečkami, vgrajenimi v globinah 0,3; 0,6; 1,2; 1,8; 3,0 in 4,0 m. Rezultati so izpostavili najpomembnejše faktorje, ki nadzirajo hidrodinamične procese in prenos snovi na raziskovanem območju, kjer sta horizont tal in vegetacija odsotna. Fizikalno–kemijske in izotopske lastnosti vode so pokazale, da imajo plasti, ki vsebujejo glinen material, pomembno vlogo pri hidravličnih lastnostih raziskovanega območja. Kot posledica batnega efekta se nova padavinska voda in predhodno uskladiščene vode skoncentrirajo nad omenjeno plastjo in pridobijo lateralno komponento toka. Vertikalen preboj vode v nižje plasti nezasičene cone se pojavi po prednostnih poteh le v obdobju intenzivnih padavinskih dogodkov v odvisnosti od volumna predhodno uskladiščene vode. V nezasičeni coni, 3 m pod površjem, je povprečen zadrževalni čas podzemne vode pod takimi pogoji okoli 2 meseca.

Introduction

Groundwater is extensively used worldwide for domestic, industrial, and agricultural purposes. Generally, aquifers contribute at least 25 % to the city drinking water supply (Gleick, 2002), but as much as 75 % in Europe (Sampat, 2000) and 95 % in Slovenia (Uhan & Krajnc, 2003). Groundwater is renewing if the climate does not change dramatically or it is not degraded by inappropriate use. Better understanding of groundwater flow and contaminant transport mechanisms could essentially contribute to protection of this natural resource.

Groundwater from a sandy–gravel aquifer is an invaluable drinking water resource for the Ljubljana city (Slovenia), as well as for the Union Brewery, which is located within an industrial-

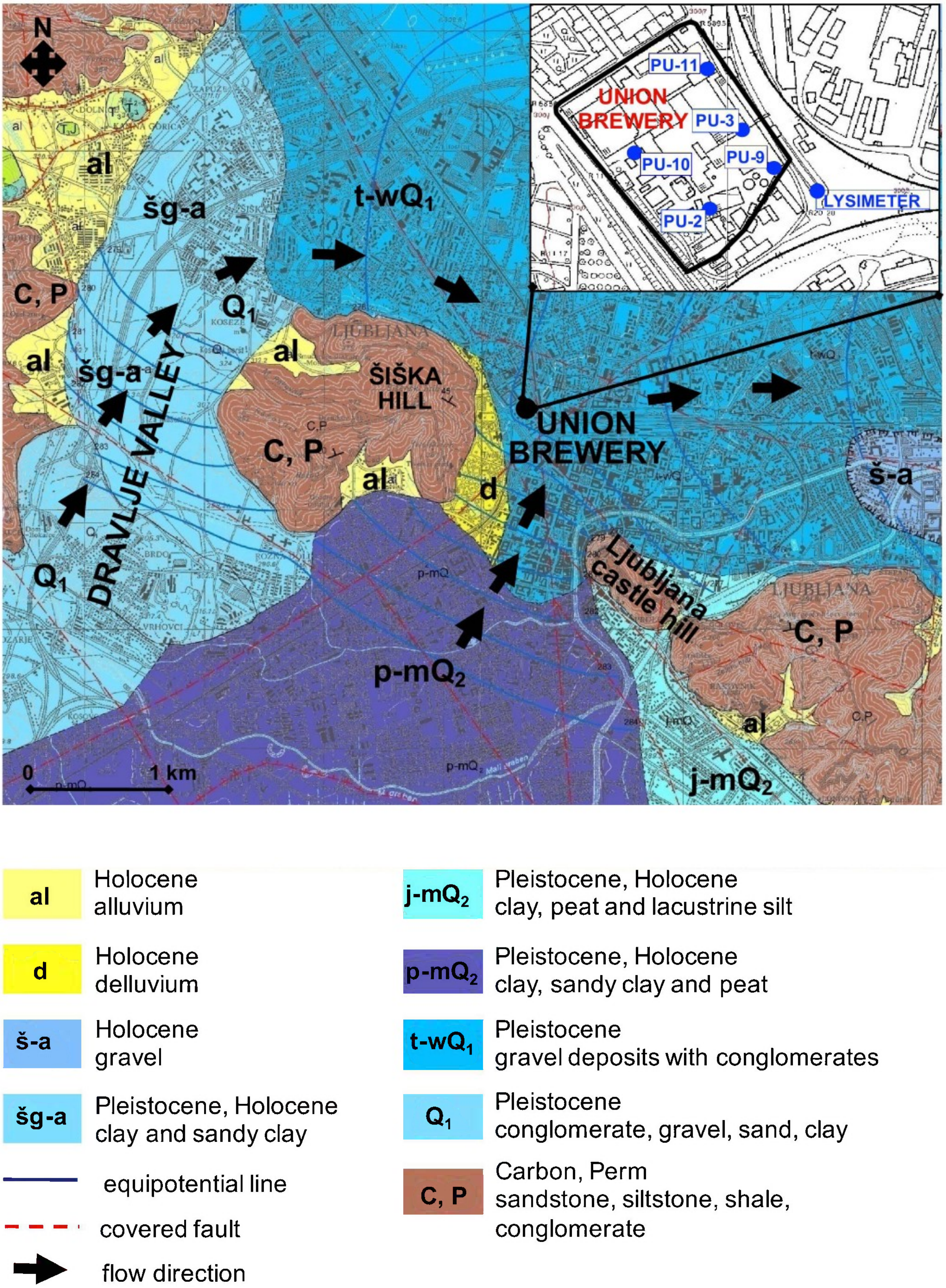

Fig. 1. Study area (PU-X observation well).
Sl. 1. Raziskovalno območje (PU-X opazovalna vrtina).

ized area near the centre of Ljubljana. A large sector of the aquifer recharge area is highly urbanized, which represents a great risk for the groundwater quality. The brewery exploits quality groundwater from the lower part of the aquifer that is bounded by an impermeable barrier from the upper part that is contaminated. Chemical analyses of groundwater samples from the brewery vicinity indicated the local contamination with herbicides, chlorides and some urban contaminants derived from traffic, industry and waste water systems (Trček et al., 2010; Vižintin et al., 2009). In regard with the implementation of the sustainable groundwater management the extensive studies of groundwater flow and solute transport were performed in the period from 2000 to 2014 in the catchment area of the Union Brewery groundwater resources (Juren et al., 2003; Trček, 2005, 2006; Trček & Juren, 2007; Trček et al., 2010, 2013; Vižintin et al., 2009). Their main research goal was the assessment and prediction of groundwater flow and the contaminant directions through the unsaturated and saturated zone of the urban intergranular aquifer. The quality and quantity monitoring was conducted in numerous observation wells within the brewery and in its vicinity (some of them are illustrated in Fig. 1), as well as at the urban lysimeter (Fig. 1), which is a topic of this paper.

To understand groundwater flow and solute transport mechanisms in urban aquifers a comprehensive study of the urban water cycle components and impacts of urbanisation should be integrated (Vižintin et al., 2009). Different land-uses in urban areas significantly affect the infiltration and recharge characteristics. The complex urban groundwater recharge patterns were investigated with a help of lysimeters in the Ljubljansko polje intergranular aquifer. The lysimetry enable accurate measurements of water flow and water balance parameters, and can be used for investigating hydrological and hydrogeochemical processes in the aquifer unsaturated zones (Meissner et al., 2007; von Unold & Fank, 2008).

Since 2000 active researches were performed at the lysimeter station in the Ljubljana Kleče Water Pumping station (Zupanc et al., 2005, 2012). The water balance components were investigated in monolith lysimeters consisted from 2-m deep layers of sandy gravel sediments covered by the autochthon soil and vegetated by grass. In time of high water usage of vegetation only subsequent substantial precipitation events directly result in water flow towards lower layers (Zupanc et al., 2012). At the same time, gravely layers of the deeper parts of the unsaturated zone have little or no capacity for water retention, and in the event that water line leaves top soil, water flow moves downwards fairly quickly. Zupanc et al. (2012) stressed that the low water retention of the aquifer sediments showed susceptibility of the aquifer to groundwater pollution.

The lysimeter of the Union Brewery differs a lot from the one in the Ljubljana Kleče Water Pumping station. It consists from boreholes that penetrate a much larger sector of the aquifer unsaturated zone (Fig. 2). It was constructed in the industrialized area, adjacent to the brewery (Fig. 1) where the soil and the upper sediment layers were removed during construction processes and nowadays some artificial sediments cover the aquifer. Moreover, there is no vegetation in the lysimeter vicinity. Hence, the Union Brewery lysimeter represents a polygon to study the typical urban infiltration conditions. This article presents the study of the lysimeter drainage system that based on environmental tracers. The sampled water $\delta^{18}O$ served as a leading parameter for hydrodynamic investigations of the unsaturated zone in the urban intergranular aquifer.

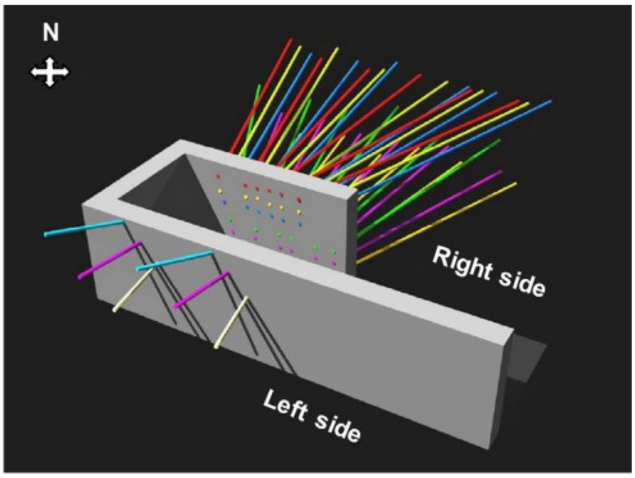

Fig. 2. Scheme of the lysimeter construction.
Sl. 2. Shema kostrukcije lizimetra.

Study area

The Union brewery is located in the Ljubljana city at an altitude of 300.3 m asl. The Ljubljana area is a large tectonic depression, surrounded by hills and mountains. It was formed in Plio–Quaternary by the sequential subsiding. Its northern part is named Ljubljansko polje. It is filled by fluvial deposits that form the so called Ljubljansko polje aquifer. The deep Holocene and Pleistocene sediments are very heterogeneous. The upper layers consist mostly of sands and gravels and the lower ones mostly of conglomerates, which is reflected in the aquifer hydrodynamic parameters (Auersperger et al., 2005; Bračič Železnik et al., 2005; Vižintin et al., 2009). Lenses of the low permeable clay and sandy–clay layers locally divide the aquifer into two parts – the upper and lower aquifer, as it is the case in the Union Brewery area, where the unsaturated zone is 20 m deep on average, while the aquifer depth is approximately 90 m. The effective porosity ranges between 5 % and 12 % in the study area and the groundwater velocity between 5 and 19 m/day (Trček et. al., 2010).

The urban lysimeter of the Union Brewery was designed in the upper unsaturated zone of the sandy–gravel aquifer (Fig. 1). 36 boreholes were drilled into the right and left walls of the construction, which is 8.5 m deep in NE and SW directions, respectively (Fig. 2). The boreholes are up to 8 m long. They are located under the industrial railway tracks on right side of the lysimeter and beneath the asphalt surface on the left lysimeter side. By the beginning of January 2003, the lysimeter was completely equipped with the UMS recording and sampling system (Juren et al., 2003). Tensiometers, TDR probes and suction cups were installed into the ends of boreholes.

The boreholes of the right lysimeter side were included into discussed study. They are distributed in six columns (1–6) and six levels (I–VI) at depths of 0.3, 0.6, 1.2, 1.8, 3.0 and 4.0 m (Figs. 2 and 3). The boreholes are named by their distribution: RI-1, RI-2, RVI-5 and RVI-6.

A detailed geological cross-section of the ends of the boreholes is illustrated in Figure 3. The boreholes penetrate four layers: sandy gravel, silt–sandy gravel, clayey silt–sandy silt with gravel grains and gravel with sand and silt. The upper three layers are artificial. The fourth layer is autochthon and consists of fluvial deposits. The boreholes of levels I, II, and III end in artificial layers, the boreholes of the level IV end close to the contact with the autochthon layer, while the boreholes of levels V and VI end in the autochthon layer.

Methods

The monitoring of the drainage system of the aquifer unsaturated zone was performed in 18 observation points on right side of the Union Brewery lysimeter: RI-1 to RIII-6 (Fig. 3). Groundwater was sampled with suction cups that are distributed at depths of 0.3, 0.6, 1.2, 1.8, 3.0 and 4.0 m. In addition, precipitation was monitored and sampled near the entrance to the lysimeter.

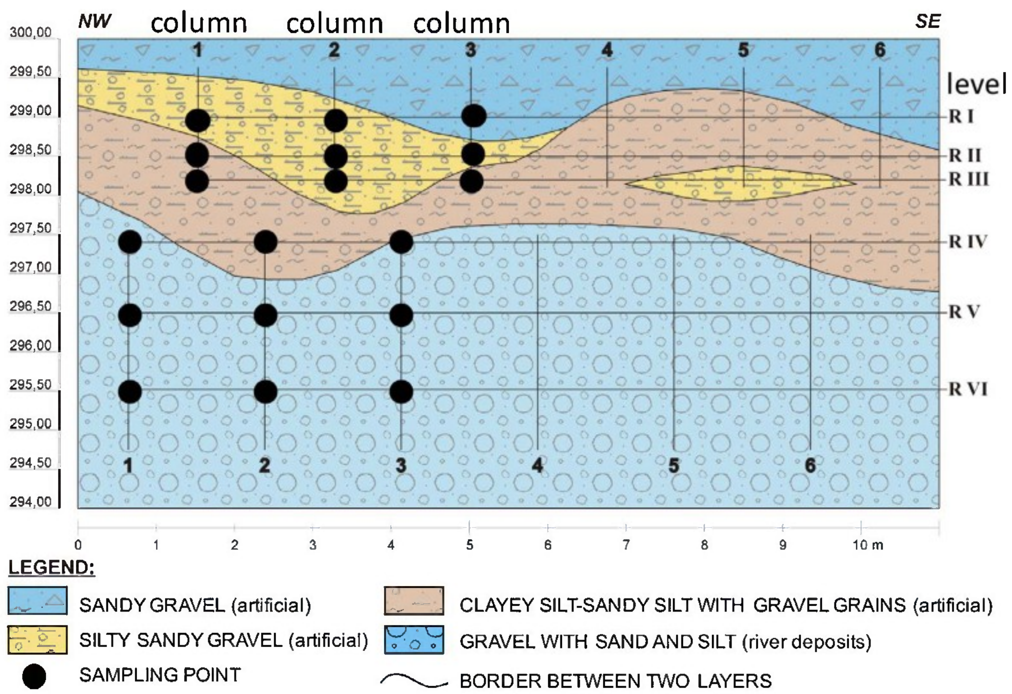

Fig. 3. Geological cross-section of the right side of the lysimeter at the end of boreholes, with sampling points indicated (modified after Juren et al., 2003)

Sl. 3. Geološki prerez s konca vrtin na desni strani lizimetra z označenimi vzorčnimi mesti (prirejeno po Juren et al., 2003).

In the period from 2004 to 2014 continuous measurements of water balance and physico–chemical water parameters (T, pH and specific electroconductivity - SEC) have been performed and water has been sampled temporarily for chemical and isotopic investigations. Water was sampled and preserved based upon the method described by Clark & Fritz (1997). Isotopic analyses of stable isotopes of H and O were made in Laboratory Centre for Isotope Hydrology and Environmental Analytics, Joanneum Research, Graz, Austria. The oxygen isotopic composition ($\delta^{18}O$) of water was measured by the classic CO_2 – H_2O equilibrium technique (Epstein & Mayeda, 1953) with a fully automated device adapted from Horita et al. (1989) coupled to a Finnigan DELTAplus Mass Spectrometer. Deuterium (δ^2H) was measured in a continuous flow mode by chromium reduction using a ceramic reactor slightly modified from Morrison et al. (2001). Stable oxygen isotopic ratios are reported relative to the VSMOW (Vienna–SMOW) standard with an overall precision of 0.1 and 1 ‰, respectively.

The stable isotope ^{18}O was applied to investigate the urban recharge process. The study based on isotopic variations in precipitation as the predominant groundwater source. After infiltration of precipitation into the unsaturated zone the physical processes of diffusion, dispersion, mixing and evaporation alter the groundwater isotopic composition (Clark & Fritz, 1997; Hoefs, 1997). The stable isotope content of water was considered conservative, because the processes took place under low–temperature and low–circulation conditions and the relative amount of water involved in chemical reactions remained limited (Clark & Fritz, 1997; Hoefs, 1997).

The sampled water $\delta^{18}O$ together with hydrometric data provided information on the movement and mixing of water masses. Precipitation infiltrates and recharges the aquifer, where it is mixed with pre–stored groundwater, which results in the input signal attenuation indicated in a lowering of the isotopic variation amplitude. Owing to different mixing and homogenisation stages, groundwater has different $\delta^{18}O$ throughout the unsaturated zone and with that different amplitude of the isotopic seasonal variation. These differences were applied for the determination of groundwater residence time seeing that the longer residence time, the lower is the amplitude of groundwater isotopic seasonal variation.

The isotopic sampling was performed in the long–term (monthly/seasonally) and short–term protocol during significant precipitation events. In the period 2004–2007 the water was sampled in daily, weekly or monthly intervals, while only the seasonal sampling followed by 2010. The detailed sampling focused on the investigation of preferential flow on right side of the lysimeter. The snow $\delta^{18}O$ with significant low values was applied as a signal to trace the distribution of snowmelt water through heterogeneous sediment layers of the unsaturated zone (Fig. 3).

Isotopic data were statistically processed with a help of the classical method of weighted averages (McDonnell et al., 1990):

$$\delta^{18}O = (\Sigma^{n}_{i=1} P_i \delta_i {}^{18}O) / (\Sigma^{n}_{i=1} P_i) \qquad (1)$$

$\delta^{18}O$ – weighted average of the oxygen isotopic composition of precipitation/sampled water,
P_i – precipitation amount/water volume of the sample (i),
$\delta_i{}^{18}O$ – oxygen isotopic composition of the sample (i).

Results and discussion

Data of sampled water $\delta^{18}O$ and SEC measurements during snowmelt events in the period 2004–2010 indicated that this relatively slow but concentrated infiltration generated a recharge process with a prevailing vertical flow component in the lysimeter levels, I, II and III. The result is in accordance with findings at the lysimeter station in the Ljubljana Kleče Water Pumping station (Zupanc et al., 2012) considering the absence of retention due to the soil and vegetation activities. However, $\delta^{18}O$ and SEC data evidenced the so-called piston effect at the lysimeter level III – the following precipitation events displaced the pre-stored snowmelt water, which resulted in the attenuation of the isotopic response at the lysimeter lower layers. The analysis of $\delta^{18}O$ and SEC measurements during storm events indicate that the intensive rain infiltration could lead to a breakthrough of water that was pre-stored in the lysimeter upper levels (I, II and III) into the lysimeter lower levels through preferential paths. The responses were dependant on the pre-accumulated water volumes.

The discussed characteristics of recharge and discharge processes in the urban unsaturated zone are presented through isotopic analyses from 2005 when the sampling frequency was the highest (Fig. 4). The lysimeter responses to the snowmelt event in March and to the storm events at the beginning of April, at the end of August and at the beginning of September were studied. 25 cm of snow was melted in the middle of March, while the maximal daily precipitation amounts during investigated storm events were 46, 42 and 71 mm, respectively (Fig. 4).

The isotopic response to the snowmelt was fast and intensive in the level I. Nevertheless, the maximal response was observed almost two weeks after the event beginning (Fig. 4). The similar situation was evidenced in the level III, but with a greater delay. The peak isotopic response of this level was registered after high precipitation at the beginning of April that displaced the pre-event water, which reflects the piston effect. The mentioned rain event pushed water of low $\delta^{18}O$ from the lysimeter upper levels also to levels IV, V and VI (Fig. 4). However, their impact on the parameter oscillation was much lower. The process was not intensive, but resulted in a characteristic $\delta^{18}O$ decrease. In the beginning of June the lowest $\delta^{18}O$ was indicated in the sampling point RV-2. It most probably reflects the snowmelt influence that has an approximately two months' shift. In September the highest $\delta^{18}O$ value was monitored at the sampling point RV-3, after the intensive rainy period. It is presumed that the August precipitation temporally saturated the lysimeter upper part above the clayey silt–sandy silt and gravel layer (Fig. 3), while the September rain generated a water breakthrough into the lysimeter lower level RV-3 through the preferential paths.

The statistical characteristics of water $\delta^{18}O$ sampled in the period 2004–2010 are graphically illustrated with boxplots in Figure 5. The distributions of data sets significantly distinguish among themselves. Precipitation values range between -3 and -18 ‰, whilst the groundwater values vary between -6 and -16 ‰. The means that as well as the spread of $\delta^{18}O$ data for various lysimeter sampling points differ significantly, which most probably reflect different residence times of the seepage water. A comparison with precipitation indicates that $\delta^{18}O$ ranges of groundwater for the upper three levels are the highest, reflecting the intensive groundwater dynamics and short residence times. The similarity between the precipitation and level I boxplots is

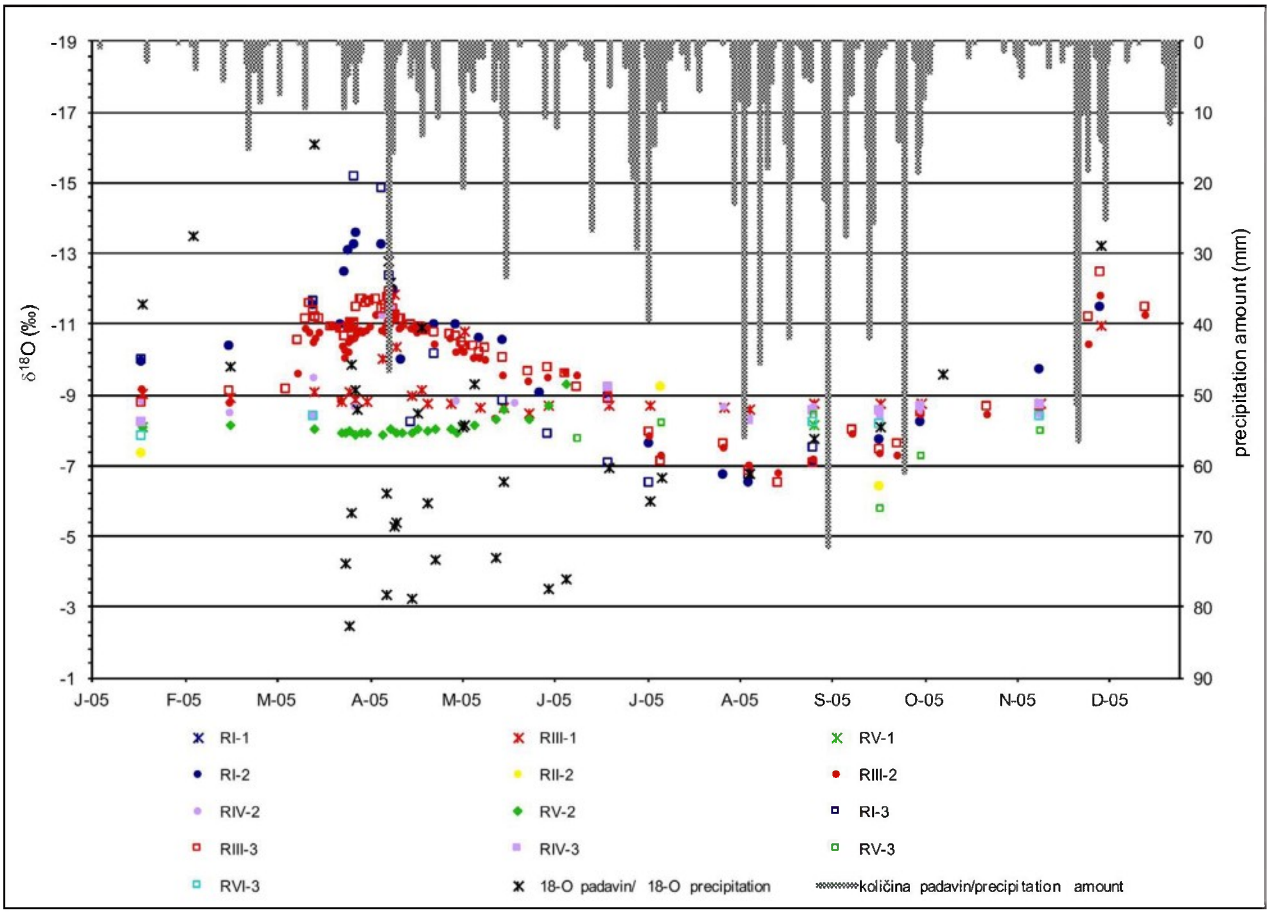

Fig. 4. Time-trend plot of water oxygen isotopic composition sampled at the lysimeter in 2005.
Sl. 4. Časovno nihanje izotopske sestave kisika v vodi, vzorčeni v lizimetru leta 2005.

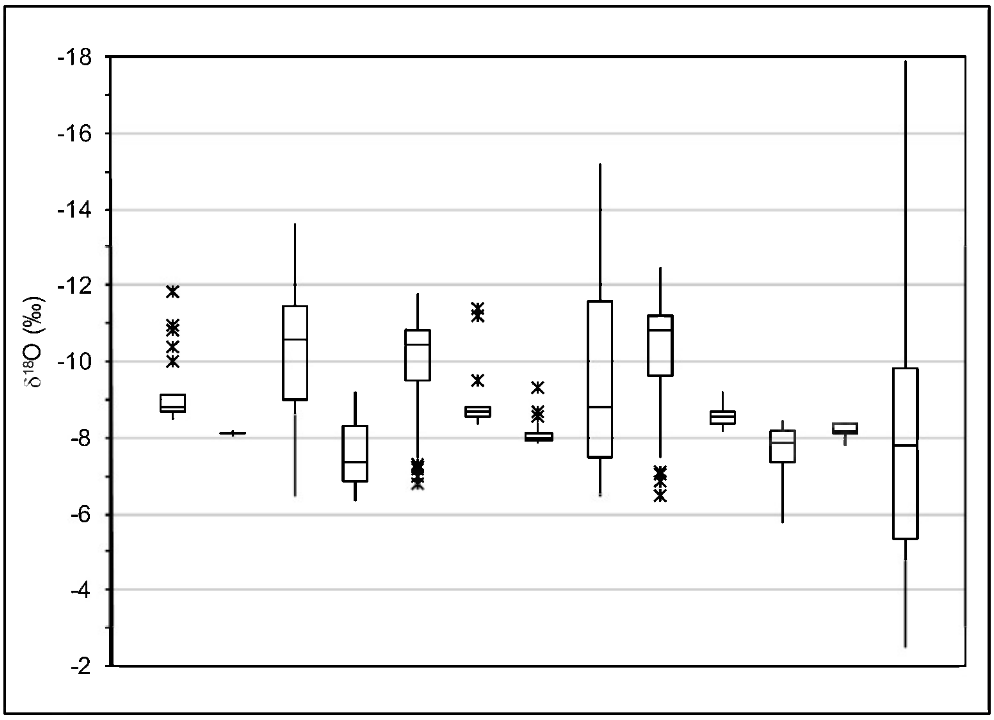

Fig. 5. Boxplots of water oxygen isotopic composition sampled at the lysimeter in the period 2004–2010.

Sl. 5. Škatlasti diagrami izotopske sestave kisika v vodi, vzorčeni v lizimetru v obdobju 2004–2010.

expected, because this level lies only 0.3 m below the surface. On the other hand, the parameter variation is much more attenuated at the lysimeter lower levels (IV, V and VI), which reflects less intensive dynamics and longer groundwater residence times.

The outside values that are marked with asterisks in Figure 5 point out the unusual isotopic composition of sampled water. Considering findings related to Figure 4 and the fact that the outside values are not characteristic for levels I and II it is presumed that the discussed values reflect vertical recharge processes in the intergranular aquifer that occur through preferential paths during important hydrological events. The outside values in the negative direction refer to winter precipitation with the lowest $\delta^{18}O$ and vice versa, the values in the positive direction refer to summer precipitation with the enriched isotopic composition.

To get better insight into the lysimeter drainage system the weighted averages of $\delta^{18}O$ data were calculated (eq. 1) for the period 2005–2009. They are listed in Table 1 together with average annual discharge volumes of lysimeter sampling points. The bulk of water was discharged at the level III as sampling points RIII-2 and RIII-3 discharged the highest volumes. The two sampling points are located near the contact between two structurally different layers: silt–sandy gravel and underlying clayey silt–sandy silt with gravel grains. The hydraulic conductivity of the upper layer is higher than that of the lower layer, which indicates that greater volumes discharged from the level III result from the development of a lateral flow component near this level and that only important hydrological events generate a vertical breakthrough of water from the level III into the lysimeter lower layers.

Table 1. Weighted averages of lysimeter water oxygen isotopic composition, average annual discharge volumes of lysimeter sampling points and precipitation amount in the study site in the period 2005–2009.

Tabela 1. Tehtana povprečja izotopske sestave kisika v vzorčevanih vodah lizimetra, povprečni letni dotok vode vzorčnih mest v lizimetru in letna količina padavin na raziskovalnem območju v obdobju 2005–2009.

	$\delta^{18}O$ weighted averages / Tehtano povprečje $\delta^{18}O$ (‰)	Annual discharge volume / Letni dotok vode (l)	Annual precipitation amount / Letna količina padavin (mm)
RIII-1	-9.30	2.8	
RV-1	-8.17	0.1	
RI-2	-9.46	2.0	
RII-2	-7.75	0.1	
RIII-2	-9.61	1047	
RIV-2	-9.82	1.8	
RV-2	-8.15	3.6	
RI-3	-8.01	1.0	
RIII-3	-9.61	1605	
RIV-3	-8.59	0.4	
RV-3	-7.62	0.4	
RVI-3	-8.22	0.3	
Precipitation / Padavine	-8.79		1353

Weighted averages of the sampled water $\delta^{18}O$ could be interpreted with a help of Tables 2 and 3 that present seasonal weighted averages of sampled water $\delta^{18}O$ and seasonal portions of the sampling point discharged volumes respectively. The sampling points with lower $\delta^{18}O$ averages from the one of precipitation were mostly recharged in winter when the precipitation $\delta^{18}O$ was the lowest, while the sampling points with higher $\delta^{18}O$ averages from the one of precipitation were mostly recharged in summer or autumn when the precipitation $\delta^{18}O$ was high. In addition, the discharge regime of sampling points (Tab. 3) reflects dependence between the preferential and laminar flow regime.

Table 2. Seasonal weighted averages of lysimeter water oxygen isotopic composition (‰) in the period 2005–2009.

Tabela 2. Sezonska tehtana povprečja izotopske sestave kisika v vzorčevanih vodah lizimetra (‰) v obdobju 2005–2009.

	Winter / Zima	Spring / Pomlad	Summer / Poletje	Autumn / Jesen
RIII-1	-9.76	-9.28	-8.70	-8.75
RV-1	-8.17	-9.02	-8.16	-8.21
RI-2	-10.79	-11.03	-7.04	-8.39
RII-2	-7.35	-8.97	-9.21	-6.38
RIII-2	-10.62	-10.55	-7.41	-8.80
RIV-2	-9.34	-11.04	-8.69	-8.44
RV-2	-8.11	-8.19	-7.32	-8.20
RI-3	-10.45	-10.09	-6.98	-8.91
RIII-3	-10.71	-10.91	-7.72	-9.38
RIV-3	-8.34	-8.11	-8.61	-8.64
RV-3	-8.24	-7.74	-8.36	-7.13
RVI-3	-8.11	-7.82	-8.20	-8.26
Precipitation / Padavine	-13.67	-7.04	-6.95	-8.65

Table 3. Seasonal discharge volumes of the lysimeter sampling points (%) in the period 2005–2009.

Tabela 3. Sezonski dotok vode vzorčnih mest v lizimetru (%) v obdobju 2005–2009.

	Winter / Zima	Spring / Pomlad	Summer / Poletje	Autumn / Jesen
RIII-1	45	20	20	15
RV-1	48	0.1	53	0.1
RI-2	35	21	23	22
RII-2	9	0.2	45	45
RIII-2	37	26	23	14
RIV-2	46	36	9	9
RV-2	51	49	0.1	0.1
RI-3	7	26	68	0.1
RIII-3	44	8	29	19
RIV-3	12	0.1	54	34
RV-3	0.2	11	34	54
RVI-3	17	0.1	20	63
Precipitation / Padavine	21	34	20	26

The presented results indicate the existence of a perched aquifer near the lysimeter above the clayey silt–sandy silt with gravel grains (Fig. 3). The comparison analysis between isotopic and hydrometric data demonstrated that the extension of the perched accumulation and of a subsequent discharge to the lysimeter lower levels depends on the water saturation and are not correlated with precipitation amounts.

It is well known that low permeability clayey layers give rise to perched aquifer conditions to the north and to the east of the Permo–Carboniferous outcrop of the Šiška hill (Auersperger et al., 2005; Bračič Železnik et al., 2005; Trček et. al., 2010, 2013; Vižintin et al., 2009). In the brewery area the clayey lances are distributed in the unsaturated and saturated zone of the aquifer (Trček et. al., 2010, 2013; Vižintin et al., 2009). The observation well PU-9 that is 50 m distant from the lysimeter (Fig. 1) includes layers of clayey sediments at depths of 3, 19 and 28 m. To verify the lysimeter results the isotopic interpretation of the unsaturated zone hydraulic behaviour was transferred to SEC data that are available on a much greater extend for the lysimeter and for the wider study area. Figure 6 presents the hourly oscillation of groundwater SEC data in the observation well PU-9 approximately 10 m below the groundwater table (at a depth of 30 m) in the period 2005–2014. SEC data are not correlated with groundwater table (R^2 = 0.58). Nevertheless, the increase of SEC values is most often connected with the rise of groundwater table, which reflects the displacement of pre-stored water in the aquifer. It is presumed that groundwater with higher SEC values is stored above the upper clayey lances and it is discharged to the aquifer lower parts during hydrological events. The reverse process connected with the inflow of event water is rare (Fig. 6).

The described recharge mechanism is important for understanding transport of contaminant loads in the investigated aquifer in a vertical direction. It is in agreement with estimates of groundwater residence time. The average age of PU-9 groundwater determined with the $^{3}H/^{3}He$ dating technique is estimated to 4 years (Trček et. al., 2013), which supports the presented results. Based on $\delta^{18}O$ data groundwater residence time is about 2 months below the first clayey lance at depth of 3 m.

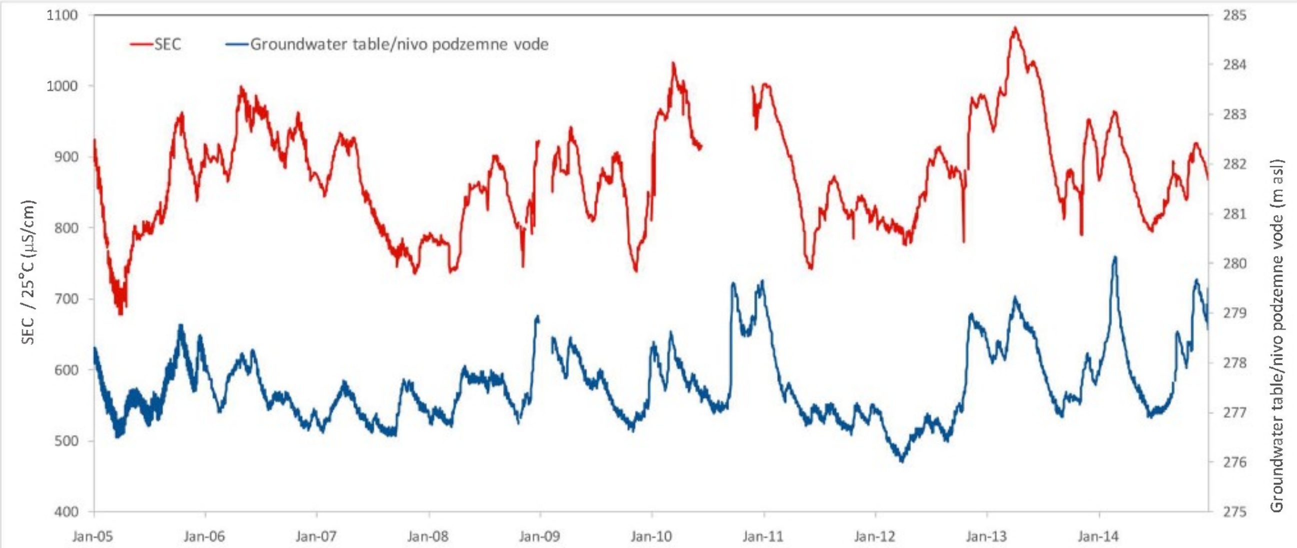

Fig. 6. Hourly oscillation of groundwater electroconductivity in the piezometer PU-9 in the period 2005–2014.
Sl. 6. Urno nihanje elektroprevodnosti podzemne vode v piezometru PU-9 v obdobju 2005–2014.

Conclusions

The vertical seepage of measured parameters in groundwater of the Ljubljansko polje aquifer was observed in numerus investigations (Auersperger et al., 2005; Bračič Železnik et al., 2005; Vižintin et al., 2009). The presented results pointed out the most important factors that control the hydrodynamic processes and solute transport in the aquifer unsaturated zone without the soil cover, which is a typical phenomenon in urban areas. Hence, the vegetation has no impact on infiltration and recharge processes and water/solutes are not affected with the soil attenuation factors. The results indicated that layers of clayey sediments have an important role in the hydraulic behaviour of the study site due to the lower hydraulic conductivity that allows the formation of perched aquifers. It is presumed that the recharge process above these layers is a consequence of the piston effect. The recharged pre-event and event water concentrate above them, which results in a development of a lateral flow component. A vertical breakthrough of this water into lower layers of the unsaturated zone and into the saturated zone could occur through preferential paths during intensive precipitation events in dependence on pre-accumulated water volumes. Under such conditions groundwater residence time is about 2 months in the unsaturated zone 3 m below the surface and about 4 years 10 m below the water table at a depth of 30 m (Trček et. al., 2013).

The lateral flow component has an important role in the protection of groundwater of the Ljubljansko polje aquifer. However, the role of vertical flow is quite the opposite, because it is the main factor controlling contaminant transport towards the drinking water resources. Hence, the main goal of future investigations is directed to transport studies of contaminant loads in the investigated aquifer in a vertical direction.

Uporaba naravnih sledil za študij drenažnega sistema nezasičene cone v urbanem okolju

(Povzetek)

Pivovarna Union izkorišča kvalitetno podzemno vodo pleistocenskega medzrnskega vodonosnika. Precejšen del napajalnega območja vodonosnika je urbaniziran, kar predstavlja veliko tveganje za onesnaženje vodnega vira pitne vode. Da bi se vzpostavilo sonaravno gospodarjenje s podzemnim vodnim virom, se je izvajala obsežna študija toka podzemne vode in prenosa snovi na območju vodnega telesa pivovarne v obdobju 2000-2014 (Juren et al., 2003; Trček, 2005, 2006; Trček & Juren, 2007; Trček et al., 2010, 2013; Vižintin et al., 2009).

Hidravlični procesi nezasičene cone so se proučevali v urbanem lizimetru, v neposredni bližini pivovarne (sl. 1 in 2). Monitoring drenažnega sistema zgornjega dela nezasičene cone, ki ga gradijo plasti avtohtonih in nanešenih sedimentov (sl. 3), je slonel na uporabi naravnih sledil. Podzemna voda se je vzorčila na 18 opazovalnih točkah (RI-1 do RIII-6), s keramičnimi sesalnimi svečkami, vgrajenimi v globinah 0,3; 0,6; 1,2; 1,8; 3,0 in 4,0 m (sl. 2 in 3). Od leta 2004 naprej so se izvajale zvezne meritve vodne bilance vzorčnih mest in fizikalno-kemijskih parametrov vode (T, pH in specifična elektroprevodnost), medtem ko se je vzorčila voda za kemijske in izotopske raziskave v posameznih fazah.

$\delta^{18}O$ vzorčenih vod predstavlja vodilni parameter hidrogeološke študije. Med pomembnimi padavinskimi dogodki so se proučevali procesi polnjenja in praznjenja nezasičene cone. Posebno pozornost je treba nameniti podatkom detajlnega vzorčenja topljenja snega, ki je nastopilo sredi marca (sl. 4). Le to je povzročilo, da so bile izmerjene dva tedna kasneje najnižje vrednosti $\delta^{18}O$ v vodah zgornjega nivoja lizimetra, 0,3 m pod površjem. Podobno situacijo opazimo tudi na nivoju III, le da je bil tam maksimalem odziv kasnejši. Povzročile so ga intenzivne padavinah na začetku aprila, ki so izpodrinile predhodno uskladiščeno vodo iz višjih nivojev, kar odseva batni efekt. Te padavine so potisnile vodo z nižjo $\delta^{18}O$ iz višjih nivojev lizimetra tudi v nivoje IV, V in VI, vendar je bil njihov vpliv na nihanje parametra precej nižji. Na začetku junija je bila izmerjena najnižja vrednost $\delta^{8}O$ v vzorčnem mestu RV- 2, ki najverjetneje odseva vpliv topljenja snega z dvomesečnim zamikom. Septembra, po obilnem deževnem obdobju, ki se je pričelo konec avgusta, pa je bila zabeležena najvišja vrednost $\delta^{18}O$ v vzorčnem mestu RV-3. Predpostavljamo, do so te padavine po prednostnih poteh povzročile preboj vode z višjo $\delta^{18}O$, ki je bila predhodno uskladiščena v višjih nivojih lizimetra.

Statistične lastnosti $\delta^{18}O$ vzorčenih vod so prikazane grafično s škatlastimi diagrami na sliki 5. Glede na padavine imajo vode zgornjih nivojev lizimetra (I, II in III) največje razpone vrednosti, kar odseva intenzivno dinamiko in s tem kratek zadrževalni čas. Nihanje parametra je veliko bolj dušeno v spodnjem delu lizimetra (nivoji IV, V in VI), kar odseva manj intenzivno dinamiko in daljši zadrževalni čas.

Letne in sezonske tehtane vrednosti $\delta^{18}O$ vzorčnih mest so razvidne iz tabel 1 in 2. Dodatno tabeli 1 in 3 prikazujeta še deleže letnega oziroma sezonskega dotoka vode v vzorčna mesta. Iz tabel je mogoče razbrati, da največja količina vode priteka v vzorčna mesta na nivoju III. Predvideva se, da je to posledica razvoja lateralne komponente toka podzemne vode v bližini kontakta s plastjo sedimentov, ki ima različno strukturo in vključuje tudi glinen material (sl. 3). Posledično se spremeni tudi hidravlična prevodnost, zato le pomembnejši hidrološki dogodki povzročijo vertikalni preboj vode iz nivoja III v nižje nivoje lizimetra.

Rezultati raziskav v urbanem lizimetru Pivovarne Union so izpostavili najpomembnejše faktorje, ki nadzirajo hidrodinamične procese na raziskovanem območju, kjer sta prst in vegetacija odsotna. Fizikalno-kemijske in izotopske lastnosti vode so pokazale, da imajo zaglinjene plasti pomembno vlogo pri hidravličnem obnašanju raziskovanega območja (sl. 4 in 6). Kot posledica batnega efekta se nova padavinska voda in predhodno uskladiščene vode skoncentrirajo nad omenjeno plastjo in pridobijo lateralno komponento toka. Vertikalen preboj vode v nižje plasti nezasičene cone se pojavi po prednostnih poteh le v obdobju intenzivnih padavinskih dogodkov v odvisnosti od volumna predhodno uskladiščene vode. V nezasičeni coni, 3 m pod površjem, je povprečen zadrževalni čas podzemne vode pod takimi pogoji okoli 2 meseca, medtem ko je v zasičeni coni, v globini 30 m, okoli 4 leta.

Urbani lizimeter Pivovarne Union predstavlja odličen poligon za proučevanje specifičnih infiltracijskih in napajalnih procesov v urbanem okolju. Vertikalna komponenta toka podzemne vode ima poglavitno vlogo pri nadzoru prenosa onesnaženja proti virom pitne vode, zato je glavni cilj nadaljnih raziskav proučevanje vertikalne obremenitve podzemne vode z onesnaževali.

Acknowledgement

The author would like to acknowledge the Union Brewery, the European Commission under the Fifth Framework Program and Knet Water, for the financial support of the studies.

References

Auersperger, P., Čenčur Curk, B., Jamnik, B., Janža, M., Kus, J., Prestor, J. & Urbanc, J. 2005: Dinamika podzemne vode. In: Rejec Brancelj, I., Smrekar, A. & Kladnik, D. (eds.): Podtalnica Ljubljanskega polja. Geografija Slovenije, 10: 39–61.

Bračič Železnik, B., Pintar, M. & Urbanc, J. 2005: Naravne razmere vodonosnika. In: Rejec Brancelj, I., Smrekar, A. & Kladnik, D. (eds.): Podtalnica Ljubljanskega polja. Geografija Slovenije, 10: 17–26.

Clark, I. & Fritz, P. 1997: Environmental Isotopes in Hydrogeology, Lewis Publishers: 342 p.

Epstein, S. & Mayeda, T. 1953: Variation of O^{18} content of waters from natural sources. Geochimica et Cosmochimica Acta, 4/5: 213–224, doi:10.1016/0016-7037(53)90051-9.

Gleick, P. 2002: The biennial report on freshwater resources. The World's Water 2002–2003, Washington DC, Island Press: 97-148.

Hoefs, J. 1997: Stable isotope geochemistry. 4th edition. Springer-Verlag, Berlin-Heidelberg: 168 p.

Horita, J., Ueda, A., Mizukami, K. & Takatori, I. 1989: Automatic δD and $\delta^{18}O$ analyses of multi-water samples using H_2 and CO_2-water equilibration methods with a common equilibration set-up. Applied Radiation and Isotopes, 40/9: 801–805, doi:10.1016/0883-2889(89)90100-7.

Juren, A., Pregl, M. & Veselič, M. 2003: Project of an urban lysimeter at the Union brewery, Ljubljana, Slovenia. RMZ - Materials and Geoenvironment, 50/3: 153–156.

McDonnell, J.J., Bonell, M., Stewart, M.K. & Pearce, A.J. 1990: Deuterium variations in storm rainfall: Implications for stream hydrograph separation. Water Resources Research, 26/3: 455–458, doi:10.1029/WR026i003p00455.

Meissner, R., Seeger J., Rupp H., Seyfarth M. & Borg H. 2007: Measurement of dew, fog, and rime with a high precision gravitation Lysimeter. Journal of Plant Nutrition and Soil Science, 170: 335–344, doi:10.1002/jpln.200625002.

Morrison, J., Brockwell, T., Merren, T., Fourel, F. & Philips, A.M. 2001. On-line high-precision stable hydrogen isotopic analyses on nanoliter water samples. Analytical Chemistry, 73/15: 3570–3575, doi:10.1021/ac001447t.

Sampat, P. 2000: Groundwater shock: the polluting of the world's major freshwater stores. World Watch, 10–22.

Trček, B. 2005: Investigations of flow system and solute transport at an urban lysimeter at Union Brewery, Ljubljana, Slovenia. RMZ – Meterials and Geoenvironment, 52/4: 685–696.

Trček, B. 2006: Isotopic investigations in the area of the Union brewery water body. Geologija, 49/1: 103–112, doi:10.5474/geologija.2006.008

Trček, B. & Juren, A. 2007: Flow and solute transport monitoring at an urban lysimeter of Union brewery, Ljubljana, Slovenia. In: Howard, K.W.F. (ed.): Urban groundwater - meeting the challenge: selected papers from the 32nd International Geological Congress (IGC), Florence, Italy. Taylor & Francis, London: 19–28.

Trček, B., Petauer, D., Leis, A., Harum, T. & Juren, A. 2010: Sustainable management of the Union Brewery groundwater resources, Ljubljana (Slovenia). Steirische Beiträge zur Hydrogeologie, 57: 71–85.

Trček, B, Auersperger, P., Leis, A. & Sültenfuss, J. 2013: Risk assesment of an urban aquifer based on environmental tracers. Geologija, 56/1: 97–106, doi:10.5474/geologija.2013.008.

Uhan, J. & Krajnc, M. 2003: Podzemna voda. In: Uhan, J. & Bat, M. (eds.): Vodno bogastvo Slovenije. ARSO, Ljubljana: 55-66.

Vižintin, G., Souvent, P., Veselič, M. & Čenčur Curk, B. 2009: Determination of urban groundwater pollution in alluvial aquifer using linked process models considering urban water cycle. Journal of Hydrology, 377/3–4: 261–273, doi:10.1016/j.jhydrol.2009.08.025.

Von Unold, G. & Fank, J. 2008: Modular design of field lysimeters for specific application needs. Water, Air & Soil Pollution, 8/2: 233–242, doi:10.1007/s11267-007-9172-4.

Zupanc, V., Bračič-Železnik, B. & Pintar, M. 2005: Water balance assessment for lysimeter station based on Water Pumping Station Kleče in Ljubljana. Acta Agriculturae Slovenica, 85/1: 83–90.

Zupanc, V., Nolz, R., Cepuder, P., Bračič-Železnik, B. & Pintar, M. 2012: Determination of water balance components with high precision weighing lysimeter in Kleče. Acta Agriculturae Slovenica, 99/2: 165–173, doi:10.2478/v10014-012-0016.