# Investigations of flow system and solute transport at an urban lysimeter at Union Brewery, Ljubljana, Slovenia

# Proučevanje tokovnega sistema in prenosa snovi v urbanem lizimetru Pivovarne Union, Ljubljana, Slovenija

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**Abstract:** Investigations of flow system and solute transport have been undertaken at an urban lysimeter at Union Brewery, near the centre of Ljubljana, with the intention of monitoring and controlling the environmental impacts of industry and traffic on groundwater within a Pleistocene alluvial gravel aquifer. The physico-chemical and isotopic properties of sampled groundwater have already produced general information on the hydrodynamic functioning of the study area and on solute transport - the main flow components, the flow hierarchy and the environmental response to the flow system have been indicated. Two important flow types are identified - lateral and vertical flow. The former has an important role in groundwater protection, whilst the latter is the main influence on contaminant transport towards the aquifer saturated zone.

**Izvleček:** V urbanem lizimetru Pivovarne Union, v bližini centra Ljubljane, potekajo raziskave tokovnega sistema in prenosa snovi. Njihov glavni namen je, da se proučijo vplivi industrije in prometa na podzemno vodo pleistocenskega prodnega vodonosnika. Fizikalno-kemične in izotopske lastnosti vzorčene vode so opisale osnovne hidrodinamične lastnosti opazovanega sistema. Opozorile so na hierarhijo toka v nezasičeni coni vodonosnika in odziv okolja nanjo. Identificirani sta bili dve pomembni vrsti tokov - lateralni in hitri vertikalni tok. Lateralni tok ima veliko vlogo pri zaščiti vodnih virov pleistocenskega prodnega vodonosnika. Vloga hitrega vertikalnega toka je povsem nasprotna, saj je le-ta glavni faktor za prenos in širjenje onesnaženja proti zasičeni coni vodonosnika.

**Key words:** urban lysimeter, Pleistocene alluvial gravel aquifer, environmental impacts, flow and solute transport

**Ključne besede:** urbani lizimeter, pleistocenski aluvialni prodni vodonosnik, vplivi okolja, tok in prenos snovi

*Scientific paper*

## INTRODUCTION

Groundwater from a Pleistocene alluvial gravel aquifer is becoming an increasingly important drinking water source for the Ljubljana area. It is also an invaluable water source for Union Brewery, which is located within an urbanised and industrialised area near the centre of Ljubljana and supplies quality groundwater from four production wells (Fig. 1). The managers of the brewery are aware that this water should be protected. Therefore, investigation of the environmental impacts of industry and traffic on groundwater of the Pleistocene alluvial gravel aquifer, have been undertaken. Flow and solute transport monitoring was conducted in numerous piezometers within the brewery and in its vicinity (some of them are illustrated in Figure 1), as well as at the lysimeter, which is a topic of this paper. The main goal of the piezometric monitoring is to investigate groundwater quality, whereas the main goal of the lysimeter monitoring is to study possible contamination in the vicinity of the brewery and with that to evaluate the role of the unsaturated zone in groundwater protection.

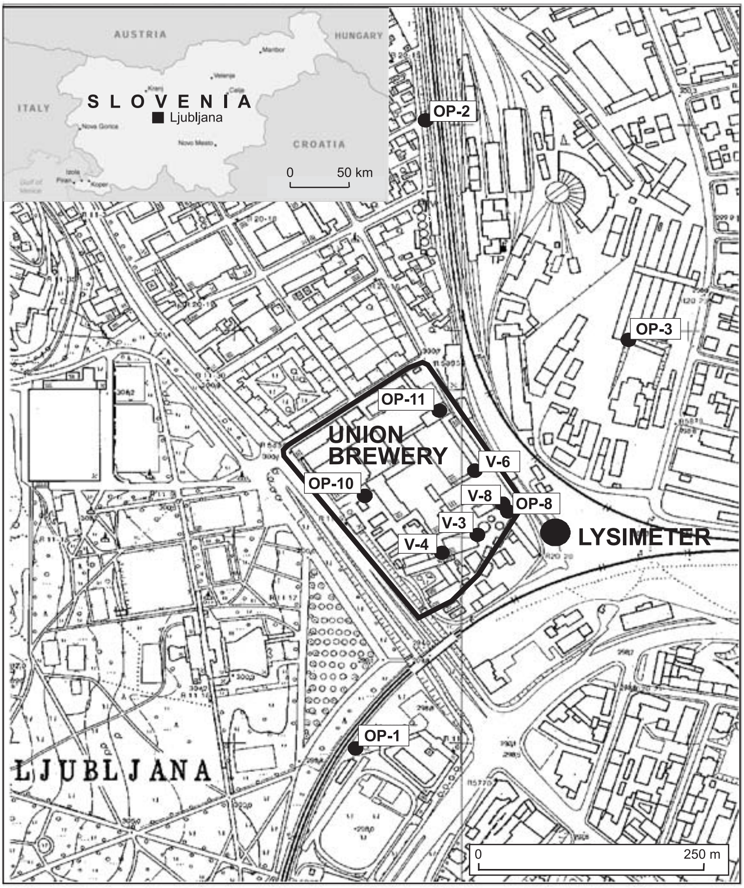


**Figure 1.** Study site (OP-x piezometer, V-x production well)
**Slika 1.** Raziskovalno območje (OP-x piezometer, V-x vodnjak)

## Description of the study area

The urban lysimeter at Union Brewery was constructed (Juren et al., 2003) adjacent to the brewery (Fig. 1). It contains 42 boreholes – 36 on its right side, under industrial railway tracks and 6 on its left side, beneath the asphalt surface (Fig. 2). On the right side of the lysimeter the boreholes are up to 9.5 long and they are distributed in six columns (1-6) and six levels (I-VI) at depths of 0.3-4.0 m (Figs 2 and 3). On the left side of the lysimeter the boreholes are up to 2.5 m long and distributed in six columns (1-6) and three levels (I-III) at depths of 0.60-1.80 m.

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, whereas the fourth layer consists of river deposits. A detailed geological cross-section of the ends of the boreholes on the right wall of the lysimeter is presented in Figure 3.

The lysimeter was equipped with a UMS recording and sampling system (Juren et al., 2003). Tensiometers, TDR probes and suction cups were installed at the ends of boreholes.

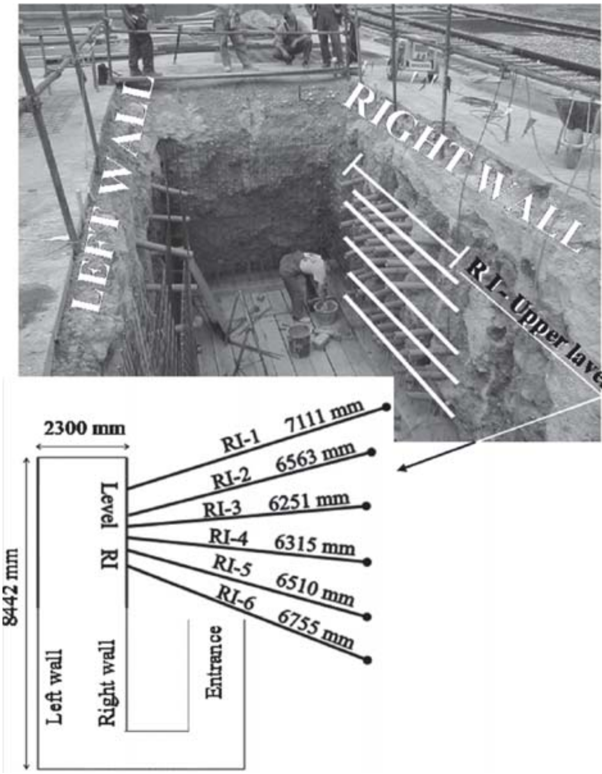


**Figure 2**. Lysimeter construction with the projection of the upper right level boreholes (modified after Juren et al., 2003)
**Slika 2.** Kostrukcija lizimetra z načrtom vrtin na zgornjem desnem nivoju (prirejeno po Juren et al., 2003)

## METHODS AND TECHNIQUES

Monitoring of flow and solute transport processes in the lysimeter commenced in June 2003. During the first year of research, continuous measurement of water balance and of physico-chemical water parameters (pH and electroconductivity) were carried out to obtain basic information on the study area. In addition, monthly water sampling for analysis of the $\delta^{18}O$ and $\delta^{2}H$ isotopic composition was undertaken to obtain additional information about mixing processes and groundwater residence times in the unsaturated zone.

Groundwater was sampled with suction cups. A total of 18 sampling points were established on the right side of the lyimeter: RI-1 to RI-3, RII-1 to RII-3, etc. (Fig. 3), whereas on the left side of the lysimeter only 3 sampling points were established: LI-4, LII-5 and LIII-6. In addition, precipitation was sampled near the entrance to the lysimeter.

Groundwater was sampled and preserved based upon the method described by CLARK & FRITZ (1997). The characteristics of the isotopic composition of natural substances are described in numerous publications (e.g. CLARK & FRITZ, 1997; KENDALL & MCDONNELL, 1998; PEZDIČ, 1999).
The $\delta^{18}O$ composition is expressed relative to the standard SMOW (Standard Mean Ocean Water), conventionally reported in terms of a relative value δ, expressed with equation

$$\delta_x\,(‰) = (R_x/R_{st} - 1)1000 \qquad (1)$$

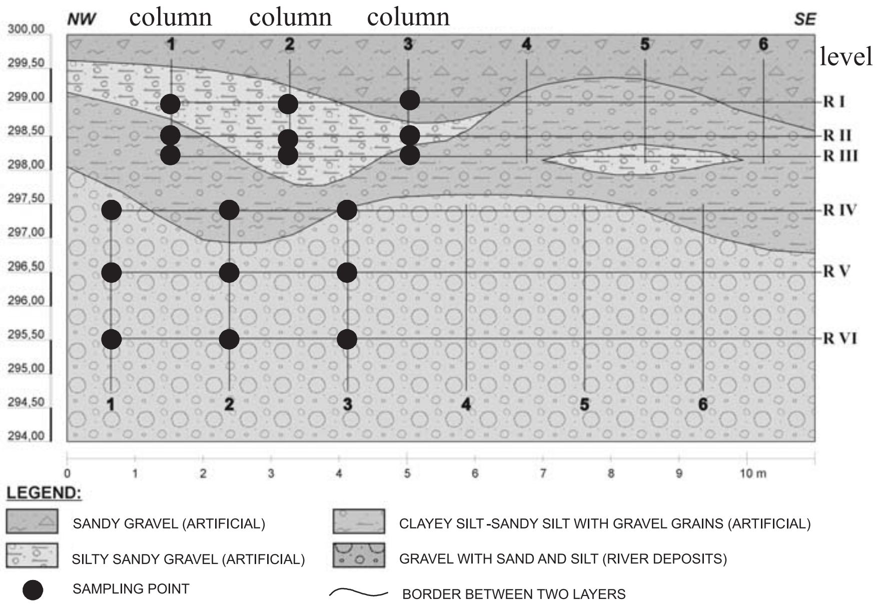


**Figure 3.** Geological cross-section of the right side of the lysimeter at the end of boreholes, with sampling points indicated (modified after JUREN ET AL., 2003)
**Slika 3.** Geološki prerez s konca vrtin na desni strani lizimetra z označenimi vzorčnimi mesti (prirejeno po JUREN IN SOD., 2003)

where $R_x$ is the isotope ratio (e.g. $^{18}O/^{16}O$) in the substance X, $R_{st}$ is the isotope ratio in the corresponding international standard substance, and δ is expressed in parts per thousand.

Water samples were analysed for $\delta^{18}O$ in the isotope laboratory at the GSF-Institute of Groundwater Ecology in Neuherberg (Germany), with a standard analytical error of ± 0.05 ‰.

## Results

The water balance for the lysimeter sampling points during the first phase of the research is presented in Table 1. There is an absence of data for sampling points RIII-2 and RIII-3 for the first part of the monitoring period, because a proper measuring system was only established in April 2004. Nevertheless, it can be observed in Table 1 that these two sampling points discharged the highest volumes, and that on both, the right and left side of the lysimeter, the bulk of the water is discharged to sampling points on level III. It is important to note that a low discharge occurs under the asphalt surface (LIII-6, since none of the other sampling points did yield any drainage water at that period).

Figure 3 illustrates that the sampling points on level III are located near the contact between two structurally different layers: silty-sandy gravel and underlying clayey silty-sandy silt with gravel grains. The hydraulic conductivity of the upper layer is higher than that of the lower layer. Therefore it is presumed that the greater volumes discharged from level III result from the development of a lateral flow component. Figures 4 and 5 demonstrate that the discharges of level III are strongly dependent on precipitation levels and intensity. Figure 5 also indicates the occurrence of vertical flow from level III, which results in increased volume of discharge from sampling points

**Table 1.** Water balance of lysimeter sampling points
**Tabela 1.** Vodna bilanca vzorčnih mest v lizimetru

| | Volume (ml) | | | | | | | | | | | | | Vol.(mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RII 1 | RV 1 | RI 2 | RII 2 | RIII 2 | RIV 2 | RVI 2 | RI 3 | RIII 3 | RIV 3 | RV 3 | RVI 3 | LIII 6 | Precipitation |
| 10.7.03 | 280 | 340 | 86 | 41 | | 70 | 19 | 455 | | 110 | 45 | 160 | 5 | 57.7 |
| 27.8.03 | 385 | 490 | 38 | 45 | | 95 | 38 | 370 | | 45 | 65 | 38 | | 71.6 |
| 17.9.03 | 175 | 175 | 21 | 20 | | 50 | | 220 | | | 40 | | 38 | 44.5 |
| 16.10.03 | 380 | 200 | 110 | 24 | | 890 | 29 | 190 | | 100 | 24 | 40 | 37 | 110.7 |
| 12.11.03 | 190 | 180 | 100 | 20 | | 60 | 55 | 180 | | | 20 | 30 | | 121.4 |
| 9.12.03 | 190 | | 60 | 20 | | 60 | | 120 | | | | | 20 | 73.8 |
| 20.1.04 | 280 | | 20 | | | 80 | | 90 | | | | | | 150.3 |
| 17.2.04 | 180 | 10 | 35 | 20 | | 48 | | 25 | | 27 | 7 | 7 | 10 | 12.7 |
| 25.3.04 | 230 | 30 | 190 | | | 50 | | 40 | | | | 35 | 20 | 122.5 |
| 15.4.04 | 420 | | 110 | | 49936 | 620 | | | 75580 | 40 | | | 25 | 94.3 |
| 12.5.04 | 190 | 23 | 25 | 27 | 79590 | 40 | | 20 | 92550 | | 20 | 35 | 5 | 64.8 |
| 15.6.04 | 520 | 10 | 30 | 20 | 76880 | 510 | | 110 | 136210 | 50 | 20 | 30 | 25 | 83.1 |
| 13.7.04 | 210 | 40 | 100 | 20 | 81140 | 50 | | 150 | 125330 | | 30 | 30 | 15 | 133.0 |
| 11.8.04 | 220 | 25 | 80 | 22 | 89320 | 70 | | | 132530 | | 70 | 50 | 20 | 89.2 |
| total volume | 3420 | 1485 | 825 | 237 | | 2573 | 141 | 1820 | | 372 | 241 | 375 | 185 | 1007.4 |

at the lower levels, particularly from RIV-2 (Oct. 2003, Apr. and Jun. 2004).

Statistical characteristics of the electroconductivity of sampled water are presented in the form of boxplots range from 180 to 615 μS/cm (Fig. 6).

Significantly higher values were recorded on the left side of the lysimeter - up to 4000 μS/cm. These most probably result from winter contamination.

Lowest electroconductivity values in the lysimeter are connected with levels I and II (Fig. 6 and 7), whereas highest values are connected with level III (Fig. 6 and 7), not with lower levels, which reflects the important role of the lateral flow component near this level. On the other hand, Figure 7 also illustrates when and where the vertical flow component dominated. Vertical breakthrough of water from level III into level IV is particularly highlighted for April 04.

Boxplots of the $\delta^{18}O$ isotopic composition of sampled water (precipitation and groundwater) are presented in Figure 8. Precipitation values range between -4.1 and -15.2 ‰ with a mean value of -8.9 ‰. Groundwater values vary between -4.5 and -14.7 ‰, whilst the means of single sampling points are between -8 and -10.7 ‰. The means that as well as the spread of $\delta^{18}O$ for the various lysimeter sampling points differ significantly. These differences most probably reflect different residence times of the seepage water. Comparison with precipitation indicates that the ranges of groundwater for the upper two levels (I, II and III) are highest, reflecting the intensive groundwater dynamics and short residence times. On the other hand, the range of groundwater values for the lower levels (IV, V and VI) are relatively small, which reflects less intensive dynamics and longer residence times.

The $\delta^{18}O$ characteristics of the sampled water are also illustrated in Figures 9 and 10, which

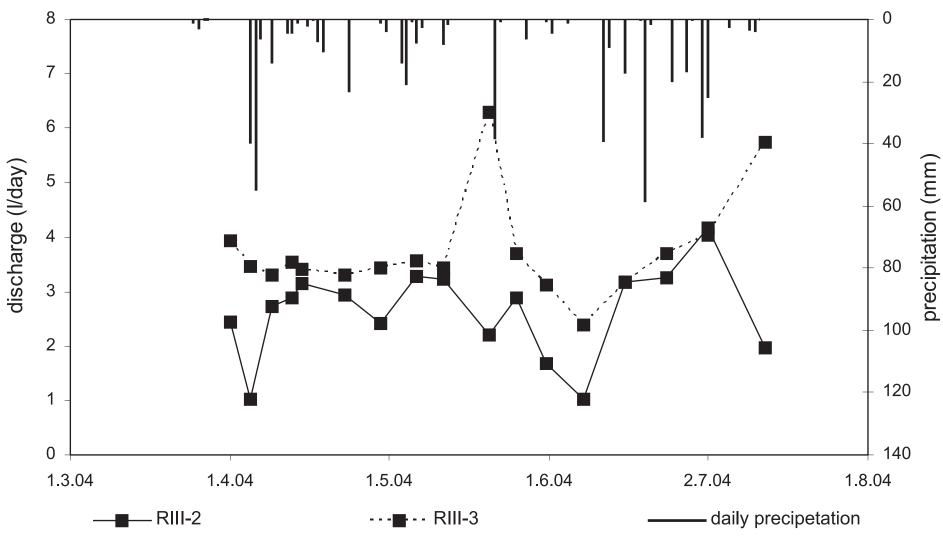


**Figure 4.** Daily discharge collected at lysimeter sampling points RIII-2 and RIII-3
**Slika 4.** Dnevni pritoki, zbrani v vzorčnih mestih RIII-2 in RIII-3

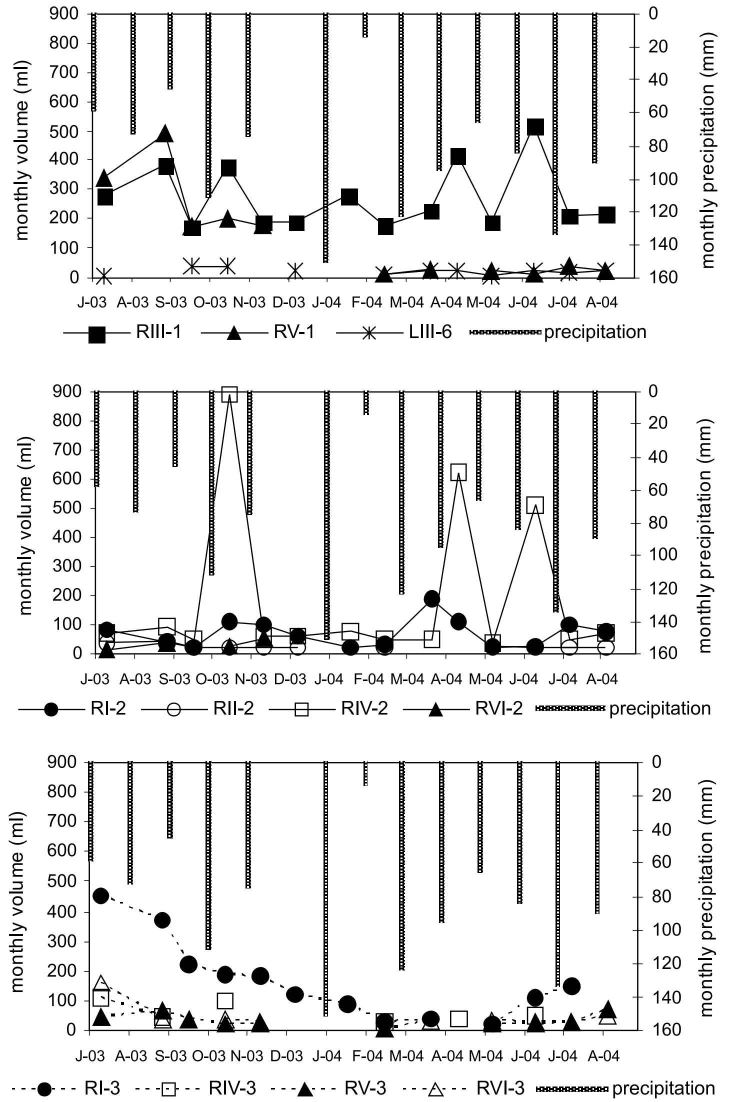


**Figure 5.** Monthly water volumes collected at lysimeter sampling points.
**Slika 5.** Mesečna količina vode, zbrana v vzorčnih mestih lizimetra

present the parameter time-trends for groundwater of the upper and lower lysimeter levels, respectively.

Comparison of $\delta^{18}O$ trends in precipitation and groundwater in Figures 9 and 10 demonstrates that variations in this parameter are much more attenuated in the lysimeter lower levels, which probably reflects longer groundwater average residence time. Peak values in both figures indicate vertical flow and solute transport in the aquifer during the main hydrological events, i.e. October 2003 and April 2004. For example, in April 2004, precipitation pushed low $\delta^{18}O$ water into the lower lysimeter levels (Fig. 10). It is presumed that these values may have resulted from snowmelt. The influences of snowmelt may be observed in the lysimeter upper levels one month earlier (Fig. 9).

## DISCUSSION AND CONCLUSIONS

Results of the first phase of the research at the Union Brewery lysimeter has produced general information on the hydrodynamic functioning of the study area and on solute transport. Synthesis of one-year of monitoring data has revealed the basic characteristics of flow and solute/ contaminant transport, since the main flow components, the flow hierarchy and the environmental response to the flow system are all indicated. Two important flow types were identified - lateral and vertical flow. Lateral flow has an important role in the protection of groundwater of the Pleistocene

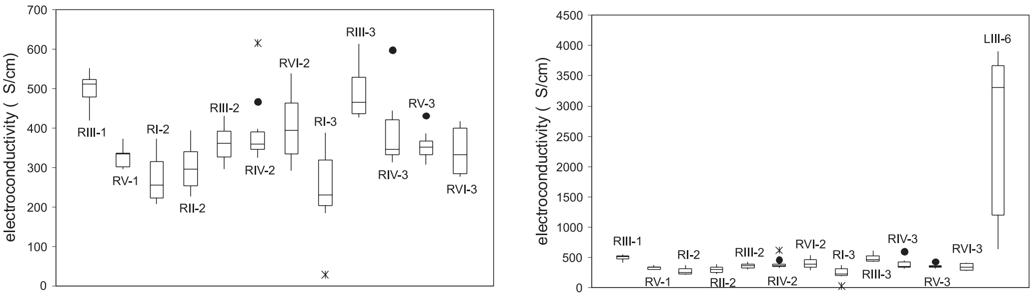


**Figure 6.** Boxplots of electroconductivity values for water sampled on the right and left side of the lysimeter beneath the industrial railway tracks and the asphalt surface respectively
**Slika 6.** Škatlasti diagrami električne prevodnosti v vodi, vzorčeni na levi in desni strani lizimetra

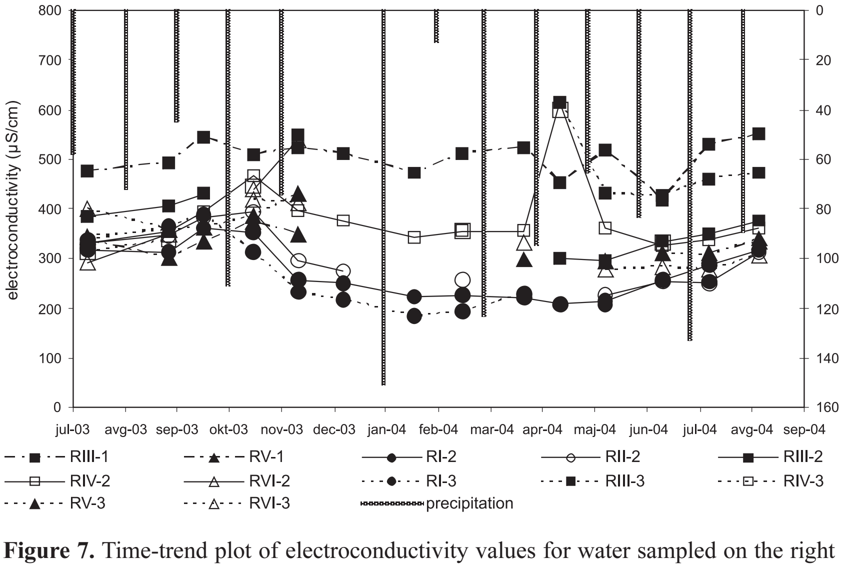


**Figure 7.** Time-trend plot of electroconductivity values for water sampled on the right side of the lysimeter beneath the industrial railway tracks
**Slika 7.** Časovno nihanje električne prevodnosti v vodi, vzorčeni na desni strani lizimetra

alluvial gravel aquifer. However, the role of vertical flow is quite the opposite, because it is the main factor controlling contaminant transport towards the aquifer saturated zone. Hence, investigation of the occurrence and frequency of rapid recharge events represents one of the main themes of the next research phase. With this regard, the monitoring of chlorides, of heavy metals and of herbicides has been established at the beginning of 2005 and the first tracing test was undertaken at the end of March 2005.

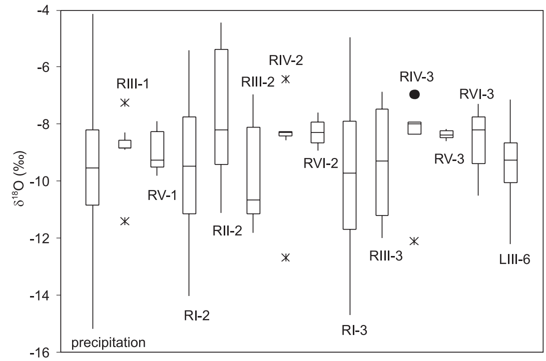


**Figure 8.** Box plots of $\delta^{18}O$ values in sampled water
**Slika 8.** Škatlasti diagram $\delta^{18}O$ vzorčene vode

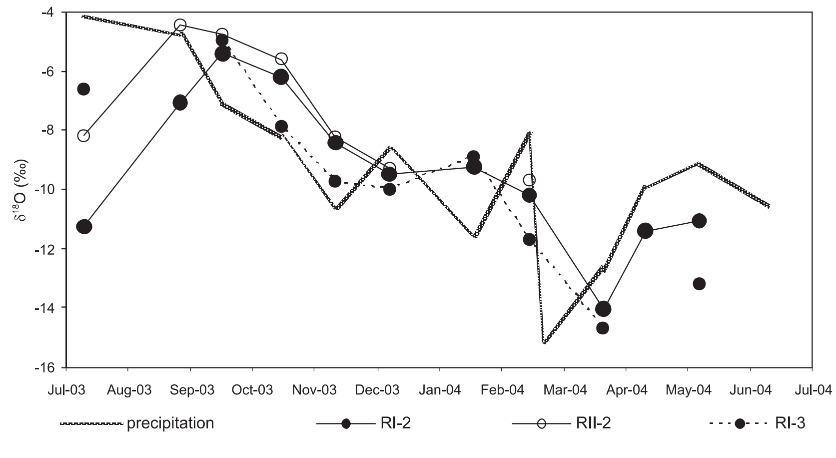


**Figure 9.** Time-trend plot of $\delta^{18}O$ values in water sampled from the lysimeter upper levels
**Slika 9.** Časovno nihanje $\delta^{18}O$ v vodi, vzorčeni v zgornjih nivojih lizimetra

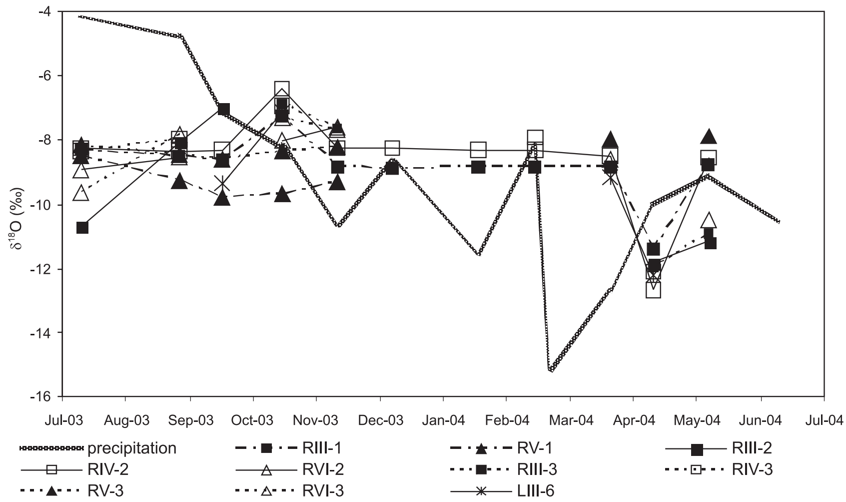


**Figure 10.** Time-trend plot of $\delta^{18}O$ values in water sampled from the lysimeter lower levels
**Slika 10.** Časovno nihanje $\delta^{18}O$ v vodi, vzorčeni v spodnjih nivojih lizimetra

## POVZETEK

### Proučevanje tokovnega sistema in prenosa snovi v urbanem lizimetru Pivovarne Union, Ljubljana, Slovenija

V urbanem lizimetru Pivovarne Union (sl. 1 in 2) potekajo raziskave toka in prenosa snovi v nezasičeni coni pleistocenskega prodnega vodonosnika (sl. 3), ki je vse pomembnejši vir pitne vode, ne le za Pivovarno Union, ampak tudi za mesto Ljubljana. Glavni cilj raziskav je študij vplivov industrije in prometa na omenjen vodonosnik, ki omogoča, da se prouči možnost onesnaženja virov podzemne vode na območju Pivovarne Union ter oceni vlogo nezasičene cone pri njihovi zaščiti.

V prvi raziskovalni fazi so se izvajale tedenske meritve vodne bilance in osnovnih fizikalno-kemičnih parametrov vode, poleg tega pa je potekalo tudi mesečno vzorčenje vode za analizo izotopske sestave kisika ($\delta^{18}O$).

V lizimetru se je vzorčila voda s pomočjo keramičnih svečk. 18 svečk je vgrajenih na koncu vrtin, na desni strani lizimetra (RI-1 do RI-6, RII-1 do RII-6 itd.), ki leži pod industrijskimi železniškimi tiri, 3 pa so vgrajene v vrtine na levi strani lizimetra (LI-4, LII-5 in LIII-6), ki leži pod asfaltnim območjem (sl. 2 in 3). Geološki prerez na sliki 3 kaže, da vrtine predirajo štiri različne plasti, vzorčna mesta pa so razporejena v 3 kolone in 6 nivojev na globinah 0,3-4 m.

Za prvo raziskovalno leto je prikazana vodna bilanca vzorčnih mest lizimetra v tabeli 1 ter na slikah 4 in 5. Pretoki vzorčnih mest so močno odvisni od količine in intenzivnosti padavin (sl. 4 in 5), iz tabele pa je mogoče razbrati, da največja količina vode priteka v vzorčna mesta na nivoju III. Predvideva se, da je to posledica razvoja lateralne komponente toka v bližini kontakta med dvema plastema z različno strukturo ter, posledično, različno hidravlično prevod-nostjo (sl. 3). Na sliki 5 je mogoče opaziti tudi pojavljanje vertikalnega toka iz nivoja III v nižja območja – povečana količina vode v vzorčnih mestih nižjih nivojev, zlasti na nivoju IV (oktober 2003, april in junij 2004).

Lastnosti električne prevodnosti vzorčenih vod so prikazene na slikah 6 in 7. V lizimetru so najnižje vrednosti parametra vezane na nivoja I in II, medtem ko so najvišje vrednosti vezane na nivo III in ne na nižje nivoje, kar odseva pomembno vlogo lateralne komponente toka v bližini nivoja III. Po drugi strani pa slika 7, ki prikazuje časovno nihanje električne prevodnosti v vzorčenih vodah, kaže, kdaj in kje je bilo izrazito vertikalno napajanja spodnjih nivojih lizimetra (oktobra 2003 in aprila 2004).

Lastnosti $\delta^{18}O$ so ilustrirane na slikah 8, 9 in 10. 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 ( IV, V in VI), kar odseva manj intenzivno dinamiko in daljši zadrževalni čas. Na slikah 9 in 10 je treba pozornost nameniti odstopanjem od običajnih trendov. Le-ta opozarjajo na vertikalni tok in prenos snovi v vodonosniku med glavnimi hidrološki dogodki - oktobra 2003 in aprila 2004. Aprila 2004 so npr. padavine izpodrinile v spodnji del lizimetra vodo, ki je bila izotopsko osiromašena (sl. 10), kar je mogoče pripisati topljenju snega. Primerjava slik 9 in 10 kaže, da je vpliv topljenja snega opazen v zgornjem delu lizimetra že mesec prej.

Rezultati prve faze raziskav v urbanem lizimetru Pivovarne Union so opisali osnovne lastnosti toka in prenosa snovi v opazovanem okolju. Opozorili so na hierarhijo toka v nezasičeni coni vodonosnika in odziv okolja nanjo. Identificirani sta bili dve pomembni vrsti tokov - lateralni in hitri vertikalni tok. Lateralni tok ima pomebno vlogo pri zaščiti podzemnih vodnih virov pleistocenskega prodnega vodonosnika. Vloga vertikalnega toka je povsem nasprotna, saj je le-ta glavni faktor za prenos in širjenje onesnaženja proti zasičeni coni vodonosnika. Glede na to, je glavna tema druge raziskovalne faze proučevanje hitrega vertikalnega napajanja. V ta namen se je vzpostavil na začetku leta 2005 monitoring kloridov, težkih kovin in herbicidov, konec marca 2005 pa se je izvedel prvi sledilni poskus.

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