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RECENT RESULTS OF TRACER TESTS IN THE CATCHMENT OF THE UNICA RIVER (SW SLOVENIA)

NOVEJŠI REZULTATI SLEDILNIH POSKUSOV V ZALEDJU REKE UNICE (JZ SLOVENIJA)

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Franci Gabrovšek, Janja Kogovšek, Gregor Kovačič, Metka Petrič, Nataša Ravbar & Janez Turk: Recent results of tracer tests in the catchment of the Unica River (SN Slovenia)

In the catchment area of the Unica River two combined tracer tests with fluorescent dyes have been performed aiming to characterize the properties of groundwater flow and transport of contaminants through the vadose zone and well developed system of karst channels in the epiphreatic and phreatic zone in different hydrologic conditions. Tracers were injected directly into the ponors and to the oil collector outlet on the karst surface. Prior to tracing monitoring network has been set up, including precipitation, physical and chemical parameters of the springs and cave streams. Field fluorimeters were used to detect tracers in the underground river and conventional sampling techniques and laboratory analyses were used at the springs. Some of the results were quantitatively evaluated by QTRACER2 Program. During the first tracer test, when injection was followed by rain event, flow through the well conductive cave system was characterized by apparent dominant flow velocities of 88–640 m/h. Breakthrough curves were continuous, uniform and single peaked, and almost complete recoveries were observed. During the second tracer test, when water level was in constant recession, the transport velocities through the well developed karst conduits were significantly slower (apparent maximal flow velocities being 2–4 times lower). Results also show lower dispersivity during the second tracer test, which corresponds to lower flow velocities. The tracer injected at the karst surface arrived with the expected delay (v_{dom} around 9 m/h) and showed irregular and elongated breakthrough curves with secondary peaks. In this paper only tracer test results are presented, which are a part of a comprehensive study of groundwater flow through the complex karst aquifers aiming at improving karst water resources understanding, protection and management. The presented assessment will beyond be utilized for further detailed analysis, studies and modelling.

Povzetek UDK 556.34.04(497.4-14)

Franci Gabrovšek, Janja Kogovšek, Gregor Kovačič, Metka Petrič, Nataša Ravbar & Janez Turk: Novejši rezultati sledilnih poskusov v zaledju reke Unice (JZ Slovenija)

Da bi bolje spoznali značilnosti pretakanja voda in prenosa onesnaževal skozi vadozno cono in skozi dobro razvit sistem kraških kanalov v epifreatični in freatični coni v različnih hidroloških pogojih, sta bila v zaledju reke Unice izvedena dva kombinirana sledilna poskusa s fluorescentnimi sledili. Sledila so bila injicirana neposredno v ponore in v iztok lovilca olj v kraško površje. Pred sledenjem je bila vzpostavljena mreža monitoringa, ki je obsegala merjenje količine padavin, fizikalnih in kemičnih parametrov na izvirih in jamskih vodotokih. Za zaznavanje sledil v podzemnih rekah so bili uporabljeni terenski fluorometri. Na izvirih je bila uporabljena običajna vzorčevalna tehnika, vzorci pa analizirani v laboratoriju. Nekateri rezultati so bili kvantitativno ovrednoteni s pomočjo programa QTRACER2. V času prvega sledilnega poskusa, ko je injiciranju sledil padavinski dogodek, je bil tok skozi dobro prevoden jamski sistem hiter, z navideznimi dominantnimi hitrostmi med 88 in 640 m/h. Sledilne krivulje so neprekinjene, enotne in z enim vrhom. Sledila so se skoraj v celoti povrnila. V času drugega sledilnega poskusa, ko je bila gladina podtalnice v nenehnem upadanju, so bile hitrosti pretoka skozi dobro razvite kraške kanale pomembno nižje (navidezne maksimalne hitrosti nižje za 2–4 krat). Rezultati kažejo nižjo disperzivnost v času drugega sledilnega poskusa, kar ustreza nižjim hitrostim toka. Takrat se je tudi sledilo, injicirano na površje, pokazalo na izvirih s pričakovano zamudo (v_{dom} okoli 9 m/h), njegova krivulja preboja pa nepravilna, raztegnjena in z mnogimi sekundarnimi vrhovi. V tem članku so predstavljeni le rezultati sledenj, ki pa so del obsežne raziskave toka podzemne vode skozi kompleksen kraški vodonosnik, katerega cilj je izboljšanje poznavanja kraških vodnih virov, njihove zaščite in upravljanja. Predstavljeni rezultati bodo uporabni za nadaljnje podrobne analize, študije in modeliranje.

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Ključne besede: kraški vodonosnik, sledilni poskus, monitoring v jami in na izviru, Postojnski jamski sistem, Planinska jama, kraški izvir Malenščica.

INTRODUCTION

The springs at the rim of the Planinsko Polje belong to the karst catchment of the Ljubljanica springs (Fig. 1), which are listed as one of the biggest karst springs in the world (Ford & Williams 2007). The springs of the Planinsko Polje are especially interesting as natural phenomena and drinking water resources. The catchment of these springs, which flow together into the Unica River, can be divided in separate, but hydrologically connected parts. Various researches have been carried out already in the past to study the relations between these contribution areas. In several tracer tests, sinking streams, shafts or dolines were used as injection points. But still many questions regarding the characteristics of recharge from various contribution areas at different hydrological conditions and transport of contaminants remained unanswered, especially because the majority was single tracer tests, performed several decades ago. Further development of the tracing techniques, a necessity for a more holistic approach to the research of karst systems, and a need for more efficient protection measures in the catchment of the important source of drinking water stimulated us to start with new studies in this area. A monitoring net with measurements of precipitation at three stations, and discharge, temperature and electrical conductivity at the eight observation points within the catchment was set. Additionally, during the flood events samples for chemical analysis were taken at these points. To supplement the information obtained by these methods, two combined tests with artificial tracers were carried out. In the first, two fluorescent dyes were injected simultaneously into the sinking streams, which represent the two main sources of allogenic recharge to the studied karst system. In the second test, we compared the characteristics of allogenic and autogenic recharges with a simultaneous injection of two tracers into a sinking stream and the oil collector outlet at the karst surface.

Detailed underground flow pathways in most of the investigated system are not known. On the other hand, the underground flow of the Pivka River between Postojnska Jama and Pivka Jama is a continuous and almost completely accessible water passage with various flow characteristics in various channel geometries. Whether it can serve as a representative channel system for the whole area is of course disputable. Study of transport properties in part of the system with well defined flow characteristics can add important piece of information to the results obtained on a larger scale where only input and output points are known. Therefore, a detailed study of tracer transport along the Pivka River was part of both campaigns.

Detailed analysis and models, which additionally include the data obtained by the above described monitoring, are still under development; here we will mainly present the basic results of the tracer tests.

CHARACTERISTICS OF THE AREA

The study focuses on the catchment of the Planinsko Polje karst springs in southwestern Slovenia (Fig. 1). On the southern suburbs of the Polje two permanent karst springs emerge: Unica and Malenščica that join together into the Unica River. Unica crosses the Polje and sinks on its northern and western suburbs and finally re-emerges at the edge of the Ljubljana basin as the Ljubljanica River.

Malenščica is an important drinking water source that supplies more than 20,000 inhabitants of two municipalities. Its discharge ranges between 1.1 m^3/s and 9.9 m^3/s; mean discharge is 6.7 m^3/s. Unica springs from the Planinska Jama, where two subsurface river channels (Rak and Pivka branches) confluence. The phenomenon is exceptional in the world's scale. The joint discharge of all springs varies between 1.1 and 100 m^3/s, whereas the mean discharge is 21 m^3/s (Frantar 2008).

The Unica River is recharged both by autogenic and allogenic recharge from sinking rivers in its catchment, that embraces area of the Ljubljanica catchment and extends over a series of karst poljes (the biggest among them is the Cerkniško Polje), which are distributed in the SE-NW direction. During the low-water level significant amount of water comes directly from the primary infiltrated precipitation water of the Javorniki karst plateau that holds important groundwater quantities. The springs of the Planinsko Polje are fed also by the water from the Pivka valley. Total size of the catchment is estimated to 746 km^2 (Petrič 2010).

In the Unica River catchment (Fig. 1) rocks with karst porosity prevail (Cretaceous and Jurassic limestones), covering over 73% of the area, 13% of the area is characterized by predominating fissured porosity (Triassic dolomites). In some parts of the catchment area also surface runoff from the Eocene flysch rocks and Triassic dolomite is present. Alluvial deposits from the Quaternary period are found along the surface streams and at the bottom of the poljes.

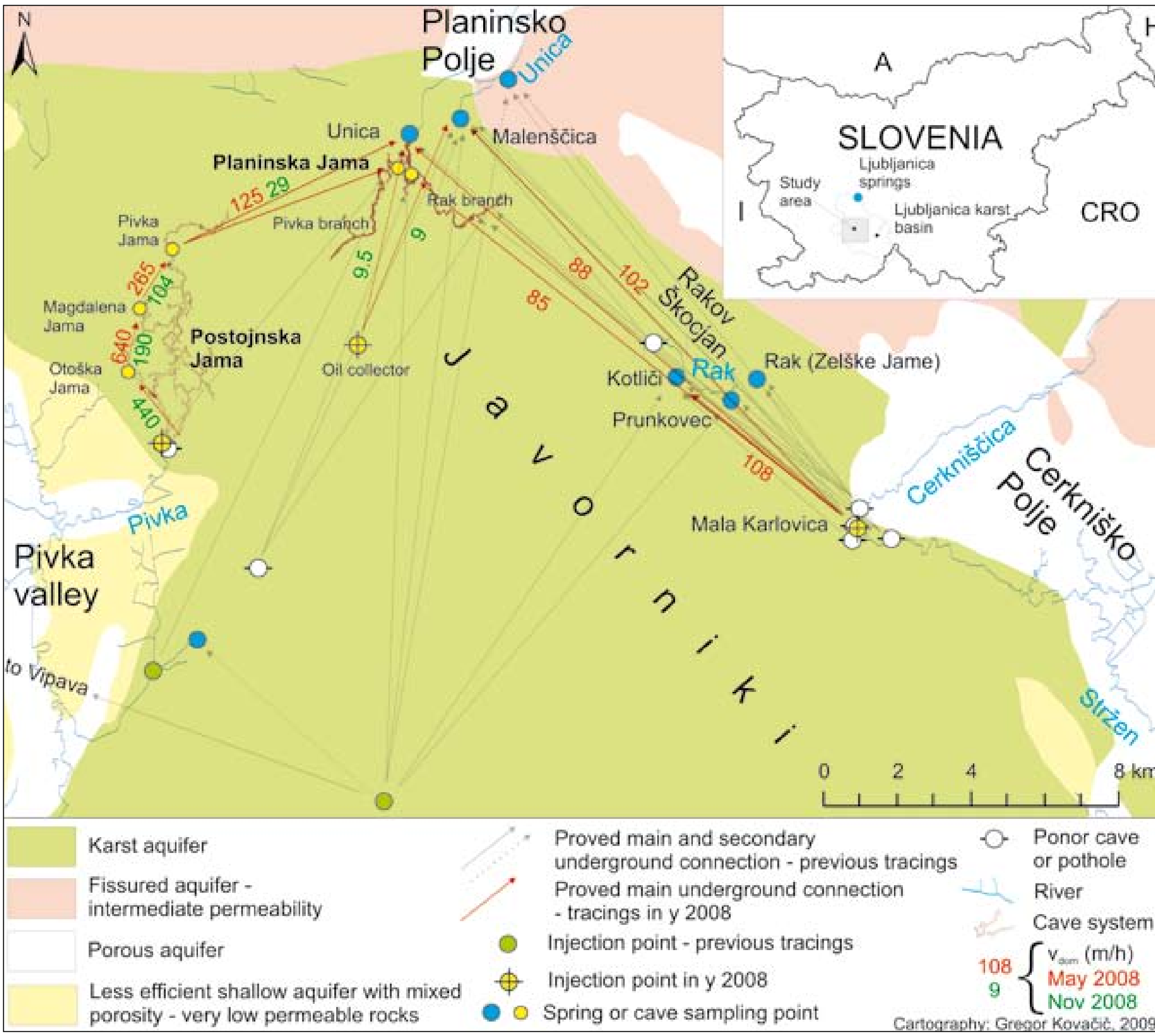


Fig. 1: Hydrogeological map of the studied area including results of the previous and recent tracer tests.

Different geological, geomorphological, speleological and hydrological studies have been carried out so far, including several tracer tests (e.g., Jenko 1959; Gams 1965; Habič 1989 and others). Their main purposes have been the acquisition of groundwater flow directions and velocities, as well as the catchment area and protection zones delineation. In 1976, 3rd Symposium of Underground Water Tracing has been organized in the Ljubljanica catchment area in order to better characterize hydrogeological conditions of the area and to improve groundwater tracing techniques (Gospodarič & Habič 1976). Recently, artificial tracers were applied in the studied area for various puposes, e.g., to study the impact of different land use patterns on the quality of water sources (e.g., Kogovšek 1999; Kogovšek *et al.* 1999; Petrič & Šebela 2005; Kogovšek *et al.* 2008), to study the dynamics of water percolation through the vadose zone

(Kogovšek & Šebela 2004) and to study the vulnerability of karst (Ravbar & Goldscheider 2007).

CHARACTERISTICS OF UNDERGROUND FLOW BETWEEN POSTOJNSKA JAMA AND PLANINSKA JAMA

The Pivka River is the main allogenic recharge to the Postojna Cave System that comprises of several caves (Postojnska Jama, Otoška Jama, Magdalena Jama, Pivka Jama; Fig. 1). Altitude of the ponor is approximately 520 m asl. The known underground course of the river is about 3.5 km long. We estimate that another 3.5 km of the underground course is not yet explored. The average discharge of Pivka in Postojnska Jama is about 4 m^3/s.

The general flow path of Pivka along the known part of Postojna Cave System is well surveyed and documented. Average channel slope (gradient) between ponor and Magdalena Jama is 0.005. First part of the flow between the ponor and Otoška Jama is relatively uniform with significant gradient 0.006. Between Otoška Jama and Pivka Jama, the flow is obstructed by several collapses. The water partially flows through the collapses and partially through the bypass conduits. The collapses cause significant ponding of water, so that the flow cascades along a series of lakes formed in front of the collapse zones. The flow between Magdalena Jama and Pivka Jama is only partly known. It is evidently more braided and the actual flow paths depend on the flow rates. The channel slope in this part is about 0.01, i.e., about double compared to the slope in the first part of the cave system. At low and mean discharge, a free surface flow in channels prevails and only small segments of channels are fully flooded. Several channel segments experience transition to pressurized flow at high waters. The discharge estimation is based on our own stage-discharge curve and stage record in the entrance part of the Postojnska Jama.

METHODS

During the tracer tests precipitation was measured in 30-minute intervals at the surface above Postojnska Jama with an Onset RG-M. At the Malenščica spring the water levels were measured in 30-minute intervals with an ISCO 6700-750 Area-velocity flow module, and at the Unica spring with a Gealog-S data-logger. For both springs the discharges were calculated based on the stage-discharge curves, which were obtained by the Environmental Agency of the Republic of Slovenia. In the Planinska Jama, the electrical conductivity (EC) was measured at the Pivka and Rak branches and at the Unica spring manually with a WTW conductometer parallel with the sampling. Based on the assumption that the discharge of Unica spring is the sum of the discharges of Pivka and Rak branches, and measured EC values at all three points, the mixing equation was used to assess the discharges of the two branches in the time of tracing. The values obtained were corrected in relation to water levels in both branches, which were measured with Schlumberger TD Divers.

First tracer test was carried out on May 20, 2008 at 12:00, when we injected a solution of Amidorhodamine G into Pivka River just in front of the ponor to Postojna Cave System (Fig. 2, Tab. 1) and solution of Uranine in the ponor cave of Mala Karlovica on the Cerkniško Polje (Fig. 3, Tab. 1). Hence tracers were injected directly into sinking rivers, which flow through conduit systems in the underground.

Fig. 2: Injection of Amidorhodamine G into the Pivka River at the ponor to Postojna Cave System (Photo: M. Perne).

On November 18, 2008 at 10:00 we repeated injection of the same tracer at the ponor of the Pivka River. This tracer test was combined with injection of Uranine solution into an oil collector at Ravbarkomanda (Fig. 4,

Fig. 3: Injection of Uranine in the ponor at Mala Karlovica on the Cerkniško Polje (Photo: M. Petrič).

Fig. 4: Injection of Uranine into the oil collector at Ravbarkomanda (Photo: M. Petrič).

Tab. 1), which collects and retains more or less polluted drainage water from the highway. From the oil collector water drains into vadose zone of the studied karst aquifer. Solution was washed off with approximately 11 m^3 of water.

The selection of sampling points was based on the previous tracer tests and hydrogeological studies (Gospodarič & Habič 1976; Kogovšek 1999). In the area of Rakov Škocjan water samples were collected manually at the spring of the Rak River in Zelške Jame, and at Prunkovec and Kotliči springs during the first tracer test. The frequency of sampling was changing in time, the shortest interval was 1 hour at Rak in Zelške Jame, and 2 hours at other springs. Samples from these springs were tested to Uranine.

During both tracer tests the samples were taken manually in the Planinska Jama, at the Pivka and Rak branches and at the Unica spring. Samples from all three sampling points were tested to Amidorhodamine G and Uranine. The frequency of manual sampling was 2 hours at the beginning of the tests, and less frequent in the following period.

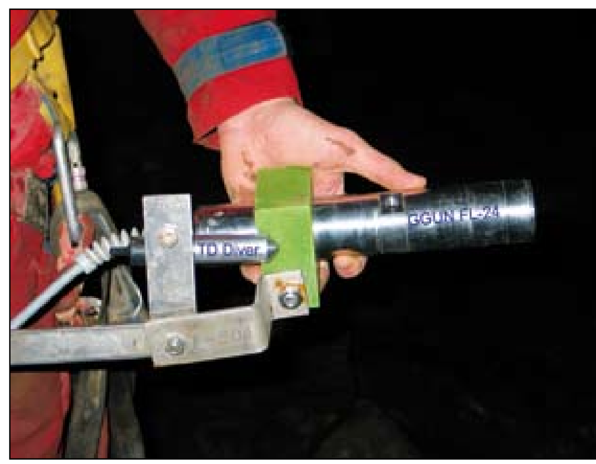


Fig. 5: Set-up of GGUN-FL24 and Schlumberger TD Diver fixed to a frame before the instalation to the river bank in Magdalena Jama (Photo: J. Turk).

At the Malenščica spring the samples were taken automatically with a frequency of 2 hours or more, and were tested to Uranine and Amidorhodamine G. Additionally, the fluorescence of the Malenščica spring was measured *in situ* by Fibrooptic Fluorometer LLF-M in 30-minute intervals.

Fluorescence of manually or automatically (ISCO 6700) sampled waters was measured in laboratory by a luminescence spectrometer LS 30, Perkin Elmer: Uranine at E_{ex}=491 nm and E_{em}=512 nm with detection limit of 0.005 mg/m^3 and Amidorhodamine G at E_{ex}=531 nm and

Tab. 1: Details of tracer tests injection.

May 20, 2008 at 12:00		
Location	**Applied tracer**	**Mass (kg)**
Ponor of Pivka River at Postojnska Jama	Amidorhodamine G	2.82
Ponor at Mala Karlovica	Uranine	2.85
November 18, 2008 at 10:00		
Location	**Applied tracer**	**Mass (kg)**
Ponor of Pivka River at Postojnska Jama	Amidorhodamine G	1
Oil collector at Ravbarkomanda	Uranine	1

E_{em}=552 nm with detection limit of 0.04 mg/m^3. First measurements were carried out immediately after sampling and then also later when possible suspended particles in the samples were decanted. Low, uncertain concentrations were additionally tested several times.

Sampling points in Postojna Cave System were in Otoška Jama, Magdalena Jama and Pivka Jama (Figs. 1 and 5). The field fluorometers GGUN-FL24 were fixed into the river bank. They have quadruple excitation and detection axes, allowing simultaneous use of three tracers and independent turbidity measurement. The fluorometers were preliminary calibrated for the Amidorhodamine G and turbidity. For more data on the properties and use of the fluorometers refer to Schnegg & Bossy (2001).

Due to several problems only results from Magdalena Jama were obtained from automatic measurements in May while in November the results from all three observation points were gathered. The sampling rate was 10 min in May and 2 min in November. Some of the results of field fluorometers were regularly checked by manual sampling and analysis in the laboratory. The results were quantitatively analysed by QTRACER2 Program (Field 2002).

RESULTS

From the middle of March to the end of April, 2008, the discharges of the springs were high (Malenščica around 9 m^3/s, Unica above 40 m^3/s). After a period of recession until May 19 (Malenščica 5.4 m^3/s, Unica 4.2 m^3/s), some more intensive precipitation events (42 mm from May 18 to 21) resulted in increased discharges (up to 7.2 m^3/s of Malenščica, and 12.6 m^3/s of Unica on May 21, 2008) and accelerated the transfer of tracers which were injected on May 20, 2008. The injected Uranine at the mala Karlovica ponor was first detected in the Kotliči spring and reached the maximum concentration of 13.6 mg/m^3 on May 21 at 5:30 p.m. (Fig. 6). In the Malenščica spring the maximum concentration of 4.1 mg/m^3 was measured on May 23 at 3 p.m., and in the Rak branch of 2.4 mg/m^3 on May 24 at 7 a.m. A half hour later the maximum concentration of 1.2 mg/m^3 was detected in the Unica spring. The calculated apparent flow velocities to individual springs are presented in Tab. 2. At all observed springs continuous and uniformly shaped breakthrough curves were formed, which indicates transfer of tracers through well permeable karst channels. Already in the first wave until May 27, 2008, almost 95% of injected uranine was recovered at Malenščica (66%) and Unica (29%) springs.

The next more intensive reaction of discharges was observed in the middle of June, 2008 (Malenščica 8.9 m^3/s, Unica 30.6 m^3/s on June 18), accompanied with small peaks in the tracer breakthrough curves (up to 0.12 mg/m^3 in Unica, and up to 0.1 mg/m^3 in Malenščica). Then the discharges were mostly decreasing until November and in the Malenščica spring the concentrations of Uranine were oscillating around the detection limit. Only 3 smaller peaks were observed after more intensive precipitation events, the highest of 0.1 mg/m^3 on November 4, 2008 following the increase of discharge to 8.7 m^3/s. After that, the concentration decreased to 0.01 mg/m^3, four days before the injection of tracer in the second test. We can infer that at that time the majority of Uranine injected in May was washed out of the system. Still it is possible that some residual amount of this tracer was

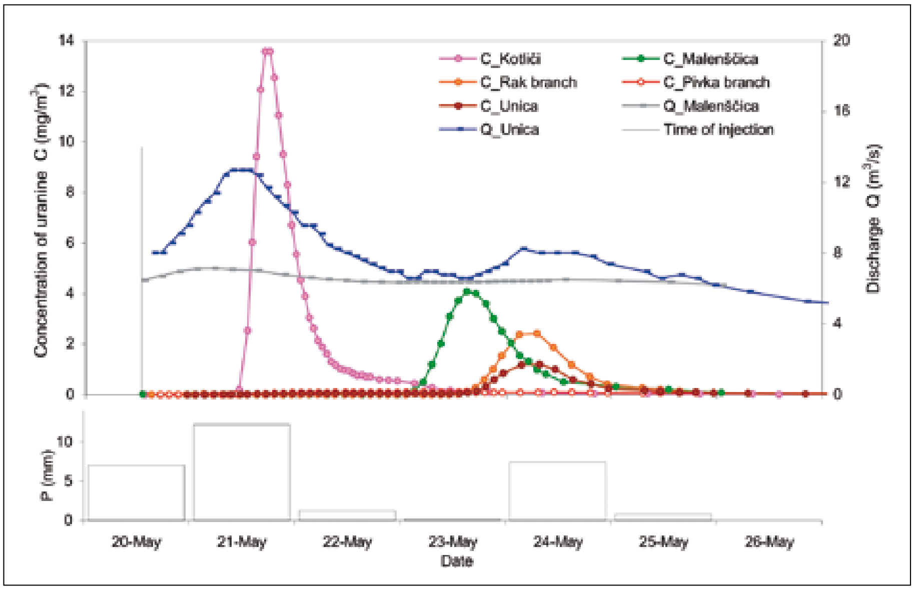


Fig. 6: Uranine breakthrough curves, discharges of springs and precipitation measured above Postojnska Jama in May, 2008.

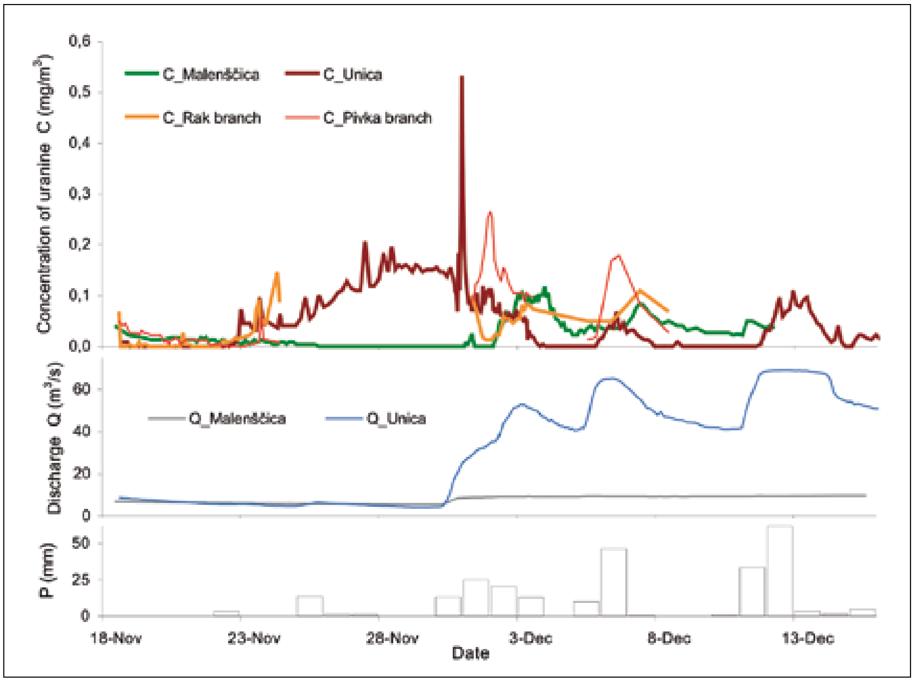


Fig. 7: Uranine breakthrough curves, discharges of springs and precipitation measured above Postojnska Jama in November, 2008.

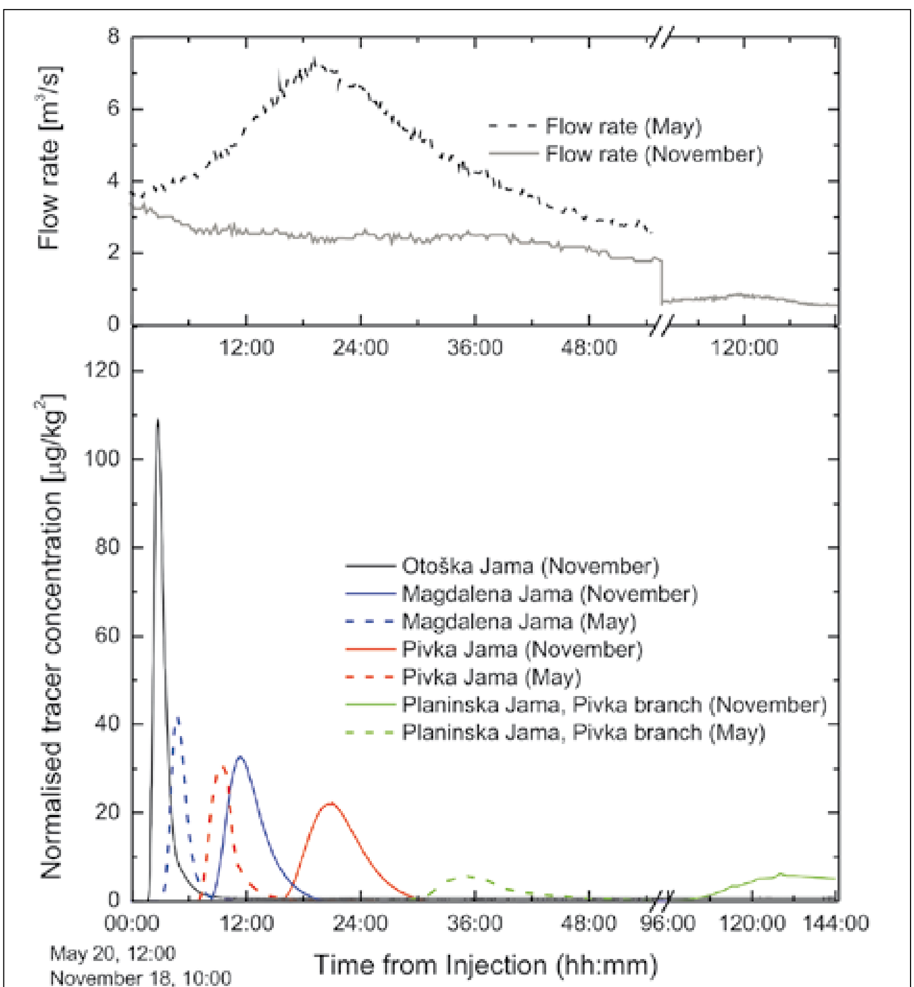
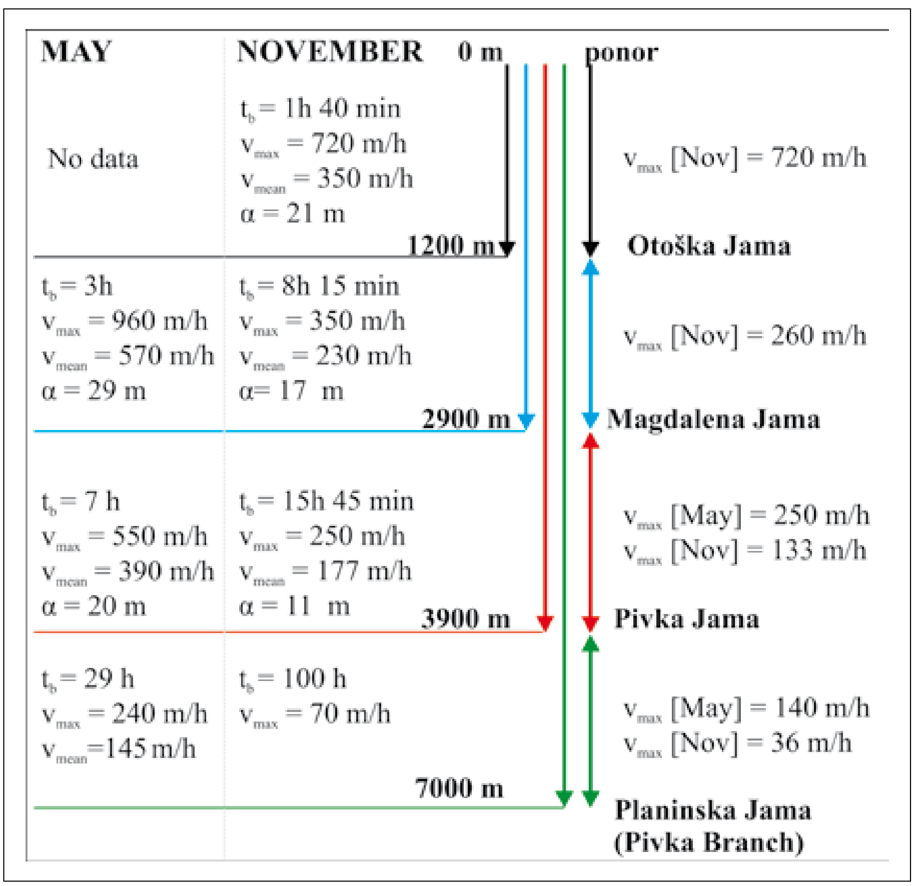


Fig. 8: The results of both tracer tests in Postojna Cave System and Planinska Jama. Note the break between 55 h and 96 h in x-axis. Because different mass of tracer was utilised in tests, the concentrations are normalised to the tracer mass (i.e., the units are given in µg of tracer per kilogram of solution per kilogram of injected tracer). Upper graph shows the discharge of the Pivka River calculated from the stage measurements close to the ponor in Postojnska Jama.

Tab. 2: Times of the first appearance of tracer (t_{min}) and its maximum concentration (t_{dom}), and calculated apparent maximal (v_{max}) and dominant (v_{dom}) flow velocities. Values in brackets denote velocities in the segment from Kotliči to the sampling point.

Injection and sampling points	Distance (m)	t_{min} (h)	v_{max} (m/h)	t_{dom} (h)	v_{dom} (m/h)
1st test_May, 2008, Mala Karlovica					
Kotliči spring	3108	23	135	29	108
Malenščica spring	7597	61	125 (119)	74	102 (101)
Rak branch	7703	73	106 (92)	90	85 (75)
Unica spring	7993	75	107 (94)	91	88 (79)
2nd test_November, 2008, Oil collector					
Unica spring	2865	106	27	302	9.5
Malenščica spring	3358	330	10	373	9.0



Tab. 3: Left column: tracer breakthrough times t_b, maximal and mean velocities v_{max} and v_{mean} longitudinal dispersivities α_l and dispersion coefficients D_l for both tests. Values are valid for the entire flow path, from the injection point to the corresponding sampling point. Right column: maximal velocities in the section between the two consecutive sampling points.

pushed out through the springs during very high waters in December, 2008.

In the Pivka branch an increased signal (conversion to concentrations would give up to 0.1 mg/m^3) was detected in the time of the flood wave of the Pivka River. This augmentation could also be influenced by pollution, therefore the appearance of Uranine in the Pivka branch is uncertain.

Following the interval of higher discharges in the first part of November, 2008 (Malenščica up to 8.6 m^3/s, Unica up to 29.0 m^3/s), the injection of tracers in the second tracer test was carried out during a recession period. On November 18, the discharge of Malenščica was approximately 7 m^3/s, and of Unica less than 9 m^3/s. The first traces of Uranine were detected at the Rak branch and Unica spring on November 24 (Fig. 7). Less intensive precipitation on November 25 resulted in a slight increase of the discharges and a slow, continuous increase of the Uranine concentration up to 0.16 mg/m^3. Very intensive rain on November 30 and in the beginning of December resulted in floods with extremely high discharges, which persisted through the whole month. The Unica spring reacted rapidly with higher discharges, and after 10 hours the Uranine concentrations started to increase quickly. The maximum concentration 0.6 mg/m^3

was reached after additional 3 hours on November 30 at 12 p.m., when the discharge was 24 m^3/s. In 8 hours the concentration returned to the starting value and decreased below the detection limit in 5 days. In the following period several smaller peaks were observed.

The discharge of Malenščica increased simultaneously with the discharge of Unica, but the Uranine was first detected only on December 2 in the morning and reached the maximum concentration of 0.11 mg/m^3 after 24 hours at discharge of 9.2 m^3/s. Increased Uranine concentrations were also measured in the Rak and Pivka branches.

The results obtained along the Pivka flow between the Postojna Cave System and Planinska Jama are shown on Fig. 8 and summarised in Tab. 3. Retrieved data exhibit almost a text-book breakthrough curves, that enabled quantitative analyses of the tests. QTRACER-2 Program was used to calculate the parameters given in Tab. 3. The results are based on the time series analysis of the breakthrough curves. The breakthrough time and maximal velocity are calculated from the leading edge of the curve. Mean velocity corresponds to the flow of the centroid of the tracer mass (Field 2002). Dispersion coefficients are determined by a Chatwin method in QTRACER2, which is an appropriate choice for impulse releases and non-Fickian dispersion. Note that dispersivity is a dispersion coefficient divided by a mean velocity.

The flow lengths used for calculations of velocities were estimated from the cave survey. The flow length of non surveyed part between Pivka Jama and Pivka branch of the Planinska Jama was estimated by assuming similar sinousoidity of conduits of the surveyed part.

DISCUSSION AND CONCLUSIONS

During the first tracer test the discharges of Malenščica were between 7 and 6 m^3/s and of Unica between 9 and 5 m^3/s. A precipitation event that followed the injection induced the increase of discharge which pushed also the tracer rapidly through the karst system. Uranine injected at the Mala Karlovica ponor was flowing toward the Kotliči spring with a apparent dominant flow velocity of 108 m/h (Tab. 2). In the nearby spring of the Rak River in Zelške Jame the tracer was detected with a certain delay and in very low concentrations. This gives a new insight into the characteristics of groundwater flow between Cerkniško Polje and Rakov Škocjan at given hydrological conditions, as it indicates a dominant underground water connection between the Mala Karlovica ponor and Kotliči spring. From there on, the main groundwater flow toward the Malenščica spring was proved by high apparent flow velocity (v_{dom} = 102 m/h) and prevalent share of recovered tracer (66% of the injected amount in the period until May 27). In contrast, the flow toward the Unica spring was slower (v_{dom} = 88 m/h), and the share of recovered tracer lower (29%). This indicates that the Malenščica spring, which is a regionally important source of water supply, is highly endangered by pollution from the Cerkniško Polje, and that more strict protection measures should be defined and respected in this relatively densely populated area.

At the same time injected Amidorhodamine G in the Pivka River proved significantly quicker flow through the well developed system of karst channels between Postojna Cave System and Planinska Jama.

The discharges of springs were similar during the second tracer test in November, but they were in a constant recession (Malenščica from 7 to 5.5 m^3/s, Unica from 8.6 to 4.1 m^3/s). At such conditions the flow along the underground Pivka stream was slower than during the first test. In the period without rainfall, the flow through the vadose zone was slow and Uranine was appearing at the springs in very low concentrations. Only the intensive rain at the end of November pushed it more efficiently out of the system. High concentrations were afterwards diluted due to a rapid increase of discharges.

At given hydrological conditions, the main direction of flow from the oil collector toward the Unica spring and only a weak connection with the Malenščica spring were proved. As the oil collector is a possible source of pollution, these are advantageous circumstances for this source of water supply.

The results in the segment between Postojna Cave System and Pivka branch of Planinska Jama showed considerable variations of tracer velocities due to different hydrological conditions at the time of both campaigns. The injection in May was followed by flood event (Fig. 8), while the test in November was done during the discharge recession period. This is also reflected in the tracer velocities, which are between two and three times higher in May. Both tests revealed different flow properties along the course of the underground Pivka River. The flow is fastest between the ponor and Otoška Jama, where it is not obstructed by breakdowns. Considering the similar flow length from the ponor to Pivka Jama and from Pivka Jama to Planinska Jama, the tests showed that the flow is 4–7 times slower in the second part of the system.

Dispersion coefficients exhibit some of the flow properties along the course of the river. Our results show higher dispersivity in May, when the flow rates and flow velocities were higher. The same is valid spatially, highest dispersivities are observed in the first part of the system, where the velocities are the highest. Such behaviour fits to the predictions of empirical equations, which relate dispersion coefficients to the flow velocity, shear velocity, hydraulic dept and width of flow (Fischer *et al.* 1979). On the other hand, one would also expect additional dispersion due to increasingly braided flow in the downstream direction, which is not supported by the data. Further research will be focused on analyses of dispersivities, particularly in relation to heat transport along the Pivka River in Postojna Cave System.

Due to transient flow conditions in May, the tracer recovery along the flow path cannot be correctly determined as the discharge was measured only close to the ponor. In November, when the situation was more stable, we observed an apparent progressive loss of tracer downstream. If a constant flow rate of 1.7 m^3/s is taken as an input to QTRACER2, we obtain 99% recovery in Otoška Jama and 87% in Magdalena Jama and Pivka Jama. There could be several reasons for that; some tributaries entering from the adjacent flysch basin can cause the tracer dilution. Such is Črni Potok from the Lekinka Cave, which enters the stream of Pivka in Otoška Jama. Other tributaries may be expected, which progressively dilute the water.

About 33.8% of the tracer in Pivka Jama were determined also by tracer test in 1974, when 1,500 kg of NaCl, diluted in 8,000 litres of water, was injected to the Pivka River in front of the ponor (Avdagić *et al.* 1976). This tracer test was performed at similar hydrological conditions as ours, discharge of the Pivka River was similar, but more variable (in range 0.7–3 m^3/s) in year 1974.

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