Flow dynamics in a karst aquifer studied by means of natural and artificial tracers: a case study of the Malenščica and Unica karst springs

Študij dinamike toka vode v kraškem vodonosniku z metodami sledenj z naravnimi in umetnimi sledili: primer kraških izvirov Malenščica in Unica

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

Abstract

The Malenščica and Unica karst springs on the southern edge of Planinsko Polje are recharged from a complex karst system that is characterised by interchange between surface and subsurface flow. For periods of two hydrological years from 2007 to 2009 and one hydrological year from 2013 to 2014, selected physical properties of water (precipitation, water level and discharge, temperature, electrical conductivity - EC) were measured at various sites of the system. Time series data were elaborated using various methods. First, the characteristic values of measured parameters were compared, then an alternative method was employed to evaluate the measurement results using the frequency distribution diagram of long-term EC data sets. The temporal variations of EC in various hydrological conditions were analysed and apparent groundwater flow velocities were assessed on the basis of the time lags between the peaks (maximums) or troughs (minimums) of the EC curves of the sinking streams and springs. The aim of the study was to understand the relationships between different parts of the recharge area and their changing contributions to the springs in various hydrological conditions. The results, which were validated by the findings of previous tracer tests using artificial tracers, indicate that the use of selected natural tracers provides a comprehensive understanding of the functioning of karst aquifers.

Izvleček

Kraška izvira Malenščica in Unica, na južnem robu Planinskega polja v jugozahodni Sloveniji, se napajata iz obsežnega kraškega vodonosnika, za katerega je značilno prepletanje površinskih in podzemnih tokov. V obdobju dveh hidroloških let od 2007 do 2009 in v obdobju enega hidrološkega leta od 2013 do 2014 smo na različnih mestih znotraj kraškega sistema merjeni izbrani fizikalni parametri (padavine, nivo vode in pretok, temperatura, specifična električna prevodnost - SEP). Časovne serije podatkov smo analizirali z uporabo različnih metod. Najprej smo primerjali karakteristične vrednosti merjenih parametrov, potem smo privzeli alternativni način obdelave rezultatov merjenja z uporabo diagramov frekvenčne porazdelitve dolgotrajnih časovnih serij vrednosti SEP. Analizirali smo časovno spremenljivost vrednosti SEP v različnih hidroloških razmerah in na osnovi določitve časovnih zamikov med vrhovi in doli krivulj SEP za ponikalnice in izvire ocenili navidezne hitrosti toka podzemne vode. Cilj raziskave je bil razumevanje odnosov med različnimi deli zaledja in spreminjanja njihovih deležev pri napajanju izvirov ob različnih hidroloških razmerah. Rezultati, ki so bili primerjani z izsledki predhodno izvedenih sledenj z umetnimi sledili, potrjujejo primernost uporabe izbranih naravnih sledil za izboljšanje razumevanja delovanja kraških vodonosnikov.

Introduction

Karst aquifers are very complex systems with heterogeneous structure and various types of porosity. They are characterised by concentrated recharge with sinking streams or diffuse infiltration through karstified terrain. Underground, water flows through karst conduits, fissures and pores of different sizes towards karst springs, where it again flows out onto the surface. Together with the water, pollutants – the consequence of various human activities in the sensitive karst environment – can also spread quickly and represent an increasing threat to the quality of karst springs. Karst aquifers as important sources of water supply are therefore highly vulnerable to pollution. For the efficient planning of protection measures it is essential to understand their functioning and to consider the characteristics of groundwater flow and solute transport within karst systems.

Various research methods are used to study karst aquifers. Artificial tracers have proven to be very useful in research of groundwater flow, its directions and characteristics, and identification of recharge areas (e.g. KÄSS, 1998; BENISCHKE et al., 2007; KOGOVŠEK & PETRIČ, 2014). Another very important tool for the study of functioning of karst springs is the use of natural tracers (e.g. RYAN & MEIMAN, 1996; GRASSO & JEANNIN, 2002; BIRK et al., 2004; HUNKELER & MUDRY, 2007; RAVBAR et al., 2011). This method involves detailed monitoring of natural properties, such as discharge, temperature, electrical conductivity, and chemical composition of water at different sites within a karst system. Based on the comparison of the data obtained, it is possible to make inferences about the characteristics of groundwater flow, the influence of different types of recharge, exchange between
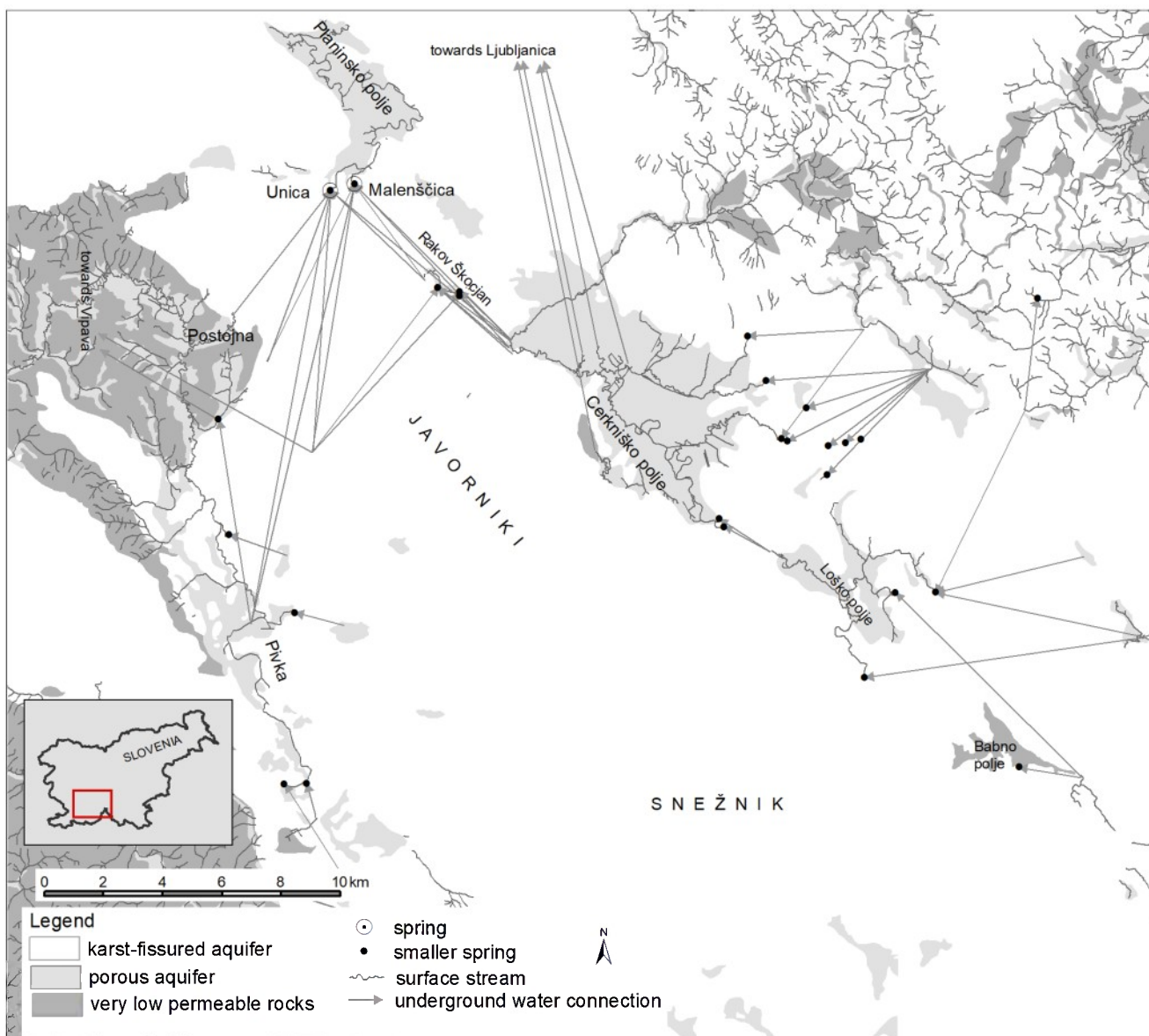

Fig. 1. Hydrogeological context of the study area with proven groundwater flow connections.

surface water and groundwater, and the relationship between inflows from various parts of the catchment and their contributions to the springs. In some cases, natural and artificial tracers were applied in conjunction in order to investigate the hydrogeological functioning of karst aquifers (Kogovšek, 2001; Einsiedl, 2005; Ravbar et al., 2012; Mudarra, et al., 2014; Lauber & Goldscheider, 2014).

In the research presented here, natural tracers were used for an investigation of recharge dynamics in the catchment area of the Malenščica and Unica springs in south-western Slovenia. The former is a regional source of water supply. The relatively high discharge of the spring when water levels are low is an important advantage, but due to the large size and complex structure of the recharge area it is difficult to plan and implement the protection and control of water quality. To understand the relationships between different parts of the recharge area and the changes in their contributions, the physical parameters of water at different locations within the recharge area and at the springs were monitored and analysed. The emphasis was on a detailed analysis and comparison of spatial and temporal variations of natural tracers in various hydrological conditions. The information obtained about the characteristics of groundwater flow and solute transport was compared with the results of tracer tests with artificial tracers previously carried out in the study area.

Study area

Hydrogeological characteristics

Several karst springs are located on the southern margin of Planinsko Polje in south-western Slovenia. The biggest among them are the Unica and Malenščica springs (Fig. 1). The latter is an important source of water supply for approximately 21,000 inhabitants in the Postojna and Pivka municipalities. The overall daily discharge of the Malenščica spring is regularly measured by the Environmental Agency of the Republic of Slovenia. According to data for the 1961–1990 period, the lowest discharge was 1.1 m³/s, the mean discharge 6.7 m³/s, and the maximum discharge 9.9 m³/s (Kolbezen & Pristov, 1998). Higher discharges were measured in 2002, with a maximum daily value of 11.2 m³/s on 24 October 2002. Long-term data on discharges of the Unica spring before its confluence with the Malenščica spring are

only available for the period from 1954 to 1975 (Internet 1). In this period the lowest discharge was 0.04 m³/s, the mean discharge 16.6 m³/s, and the highest discharge 75.6 m³/s. The obvious difference in discharges at high water levels indicates that the maximum flow rates of the Malenščica spring are limited by the structure of the outflow zone. At low water levels this spring is the main outflow of the karst system (more than 90 %), but when water levels are high only one tenth of the overall discharge on Planinsko Polje comes through it. At medium water levels the discharge of the Malenščica spring exceeds 8 m³/s, but only at very high water levels does it increase above 9 m³/s.

The recharge area of the Malenščica and Unica springs, which is estimated to extend over about 746 km², is a complex karst system that can be divided into three separate but hydrologically connected parts (Petrič, 2010). The central part is the Javorniki–Snežnik karst massif, which is composed of Cretaceous carbonate rocks, mostly limestone. It is bordered on the western side by the valley of the river Pivka, which has a karst catchment in its upstream section and is additionally recharged by surface water through less permeable Quaternary alluvial sediments and Eocene flysch in its downstream section. At the contact with carbonate rocks, the Pivka sinks underground in the cave Postojnska Jama and provides allogenic recharge to the studied karst system (Fig. 2).

On the eastern and northern sides, the karst massif is bordered by a string of karst poljes, which are distributed along a SE–NW trend (Fig. 1). The area between the Planinsko and Cerkniško poljes is composed of Upper Triassic dolomite, which is bordered on the north-eastern side by Jurassic limestone and, locally, dolomite. Quaternary alluvial sediments are deposited on the karst poljes. At high water levels these are flooded and intermittent lakes form. From the ponors on the north-western margin of Cerkniško Polje, water flows underground towards the springs of the Rak river and continues for a distance of 2 km on the surface in the valley of Rakov Škocjan. This area is composed of Cretaceous limestones, which are covered along the stream reach by Holocene sediments. The Rak sinks again in the cave known as Tkalca Jama and flows underground toward the springs on Planinsko Polje (Fig. 2). The Unica spring emerges from the cave Planinska Jama,
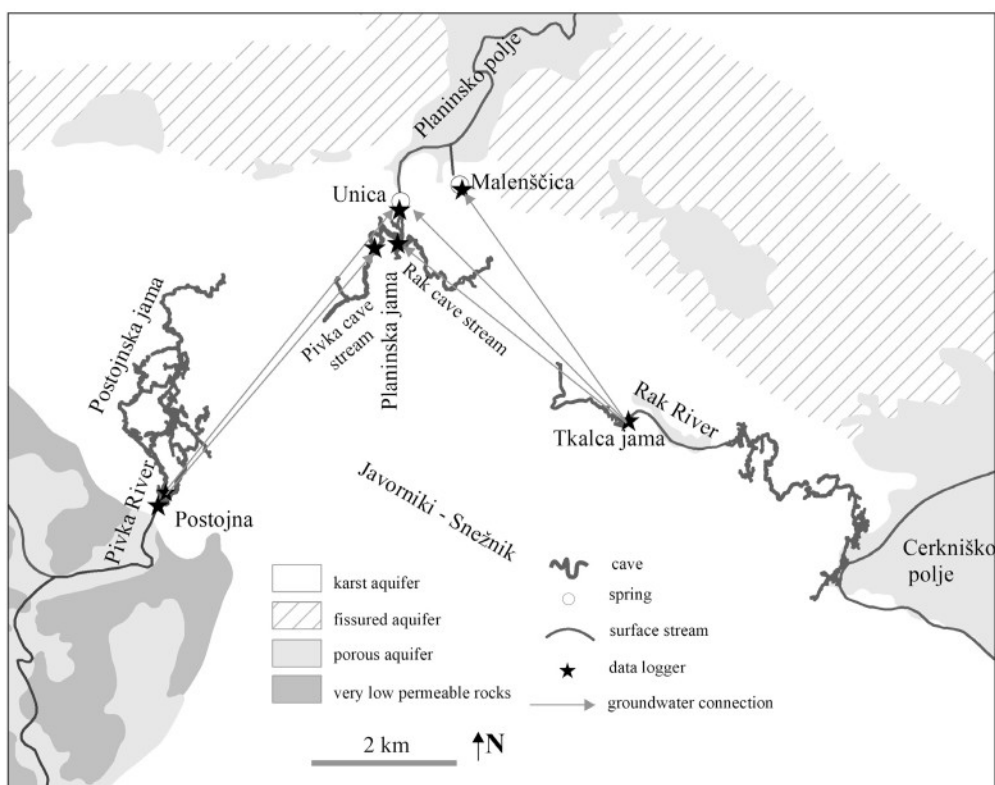
in which the subsurface waters from the Pivka area (along the Pivka cave stream) and from the area of Rakov Škocjan (along the Rak cave stream) flow together and form a unique subsurface confluence.

The three areas contributing to the Malenščica and Unica springs are referred to as the Javorniki, Pivka and Cerknica parts of the recharge area. In the Javorniki part, subsurface flow dominates, while in the other two parts surface streams also are present. As a result, surface water and groundwater constitute a single hydrodynamic system.

Groundwater flow velocities defined by tracer tests with artificial tracers

The groundwater connections within the system have been demonstrated by several past tracer tests using artificial tracers. Apparent dominant flow velocities were calculated taking into account the time from injection of tracer to the maximum achieved concentration and the distances between the ponors and springs. The Pivka was traced at the ponor into the cave Postojnska Jama in 1928, 1974, 1977, 2008 and 2009 (ŠERKO, 1946; HABIČ, 1987; GABROVŠEK et al., 2010; RAVBAR et al., 2010). Groundwater flow toward the Pivka cave stream and the Unica spring was proved, whereas no connection with the Malenščica spring was detected. None of these

tracer tests was carried out at high water levels. The highest apparent dominant flow velocity 145 m/h was determined in May 2008 when the discharge of the Unica spring was less than 12 m³/s (GABROVŠEK et al., 2010).

The groundwater connections between the ponors of the Rak in Rakov Škocjan and between the Rak cave stream and the Unica and Malenščica springs were proved by tracer tests in 1928, 1939, 1964, 1967, 2008 and 2009 (ŠERKO, 1946; GAMS, 1970; HABIČ, 1987; GABROVŠEK et al., 2010; RAVBAR et al., 2010). In various hydrological conditions apparent dominant flow velocities of between 7 and 196 m/h were determined. The highest velocity of 196 m/h was defined by a tracer test in November 1967, when the discharge of the Malenščica spring was around 9 m³/s. Other tracer tests were carried out at lower water levels.

In the Javorniki part of the catchment, tracer tests were carried out in 1955, 1988, 1997, 2008 and 2009 (HABIČ, 1987; KOGOVŠEK, 1999; KOGOVŠEK & PETRIČ, 2004; GABROVŠEK et al., 2010; RAVBAR et al., 2010). From various injection sites, groundwater flow towards the Rak and Pivka cave streams and the Unica and Malenščica springs with apparent dominant flow velocities of between 4 and 25 m/h was proved.

Methods

Data for two hydrological years from 4 September 2007 to 15 September 2009 were first gathered by field measurements. Precipitation was measured near Postojna by an Onset RG-M rain gauge. At the Malenščica and Unica springs, the water level, temperature (T) and electrical conductivity (EC) were measured using an ISCO 6700 with a 750 area-velocity flow module and YSI 600 probe, and a Logotronic Gealog S data logger. At the Rak cave stream, water levels, T and EC were measured using an Eikelkamp CTD diver. The second measuring campaign started in 2012, with data for the hydrological year from 9 September 2013 to 29 June 2014 used for comparison. The same type of equipment as in the first period was used for precipitation measurements and at the Malenščica spring. At the Unica karst spring, in the Rak and Pivka cave streams and in the Rak and Pivka rivers, water levels, T and EC were measured using Onset HOBO water level and conductivity data loggers. For both measuring periods all data were collected at 30-minute intervals and the discharges for the Malenščica and Unica springs were calculated on the basis of stage-discharge curves prepared by the Slovenian Environmental Agency.

The minimum, average and maximum values of discharges, T and EC for the two selected periods were calculated and compared.

Additionally, an alternative method was employed to evaluate the measurement results using the frequency distribution diagram of long-term EC data sets (Massei et al., 2007; Mudarra & Andreo, 2011; Caetano Bicalho et al., 2012). The data from the second measuring campaign were used and the range of the classes of EC was 10 µS/cm. For each measurement site the percentage of measured values within each class was defined and EC frequency distribution (ECFD) curves were formed. They reflect the variability of the mineralisation and of the chemical composition of the water. Based on a comparison of the curves, it was possible to identify the existence of different types of water recharging the Malenščica and Unica springs.

In the next step, the temporal variations of EC in various hydrological conditions were analysed. For the selected time interval from 18 December 2013 to 16 February 2014, the change of hydrological conditions from low to high water levels is characteristic. Comparison of the EC curves of the sinking rivers, cave streams and springs with precipitation and discharges within this period enables the assessment of the influence of hydrological conditions on the shares of recharge of the springs from different parts of the catchment.

Based on the assumption that the velocity of the transfer of the EC signal along the groundwater flow is equal to the velocity of water flow, the positions of the peaks (maximums) or troughs (minimums) of the EC curves at ponors and springs are compared and the time lags between them assessed. Considering these time lags and the distance as the crow flies between the ponors and springs, the apparent velocities of flow between them were calculated. The values obtained were compared with the apparent flow velocities defined by the tracer tests with artificial tracers carried out in the study area in the context of previous research.

Results and discussion

Comparison of characteristic values

Table 1 compares the characteristic values of discharges, T and EC for the two hydrological years 2007–2009 and one hydrological year 2013–2014. Data for three measurement sites are available for the first period, along with data for six measurement sites for the second period. Similar maximum discharges were measured in the two periods, while significantly higher values of mean discharges and the absence of very low discharges in the second period characterise it as a wet year.

The largest range of values is characteristic for the river Pivka. It is recharged by karst springs with higher EC values, which after precipitation events are significantly lowered by surface streams from flysch areas. The highest values at low water levels are probably also a result of pollution (untreated waste waters, agriculture). The high range of T values is due to the long distance of surface flow and adaptations to changes in air temperature. The Rak also has the characteristics of surface flow but the fluctuations are smaller because it is mostly recharged by karst springs, there is no significant influence of surface tributaries, and the distance of surface flow from karst springs to the measurement site is shorter.

Table 1. Characteristic values of measured parameters in the two hydrological years 2007–2009 and in the hydrological year 2013–2014.

Location/parameter	2007-2009				2013-2014			
	Min	Mean	Max	Max-Min	Min	Mean	Max	Max-Min
Malenščica spring								
Discharge (m³/s)	1.09	5.93	9.91		2.56	7.06	9.89	
Temperature (°C)	1.7	8.9	17.7	16.0	2.5	9.0	14.3	11.8
Conductivity (µS/cm)	278	369	440	162	312	359	402	90
Unica spring								
Discharge (m³/s)	0.04	11.20	69.34		0.68	25.8	69.3	
Temperature (°C)	3.0	9.2	14.6	11.6	2.7	8.6	12.3	9.6
Conductivity (µS/cm)	221	377	479	258	274	364	480	186
Rak cave stream								
Temperature (°C)	2.6	9.4	15.0	12.4	3.6	8.6	12.7	9.1
Conductivity (µS/cm)	267	362	451	184	314	358	429	115
Pivka cave stream								
Temperature (°C)					2.1	9.1	12.3	10.2
Conductivity (µS/cm)					229	371	519	290
Rak River								
Temperature (°C)					2.3	9.9	18.0	15.7
Conductivity (µS/cm)					294	378	477	183
Pivka River								
Temperature (°C)					0.9	10.7	26.9	26.0
Conductivity (µS/cm)					192	371	536	344

Both described rivers are sinking streams which flow underground through highly permeable channels toward cave streams in Planinska Jama and the Unica and Malenščica springs. High fluctuations of measured values in the Pivka river are mostly reflected in the Pivka cave stream. This shows that this stream is mainly recharged by the Pivka river and that the share of recharge from other parts is very low. Noticeable but far less marked is the influence of the river Pivka on the Unica spring, which additionally receives an important share of recharge from the Rak cave stream.

EC Frequency Distribution (ECFD)

Various ranges of EC values in the hydrologically connected system indicate the existence and mixing of different types of water, which contribute in various shares to the recharge of the Unica and Malenščica springs. EC Frequency Distribution (ECFD) was used to identify the existence of and relationships between these groundwater types. In Figure 3A the ECFD for the Malenščica and Unica springs is first compared. The curves for the two springs differ significantly, which indicates the existence of different types of water in the recharge area.

In the next step, the curves for both springs were compared with the curves for the monitoring sites in their recharge area. First the curve for Unica spring was compared with the curves for the Rak and Pivka cave streams, which flow together in Planinska Jama and form the Unica spring. The two cave streams differ significantly in terms of ECFD, and the Unica spring is a mixture of them (Fig. 3B).

The ECFD curves for the Pivka river and the Pivka cave stream are practically identical (Fig.3C), which confirms the direct connection between the sinking stream and the cave stream and fast water flow through well-developed karst channels.

The connection between the Rak river, Rak cave stream and Malenščica spring is more complex and some additional source of recharge with lower EC values exists (Fig. 3D). Based on the known characteristics of the area, it can be concluded that this source is autogenic recharge from the Javorniki–Snežnik karst aquifer. Differences in the shape of the ECFD curves for the Rak cave stream and Malenščica spring point to some differences in the characteristics of distribution and shares of this autogenic recharge.
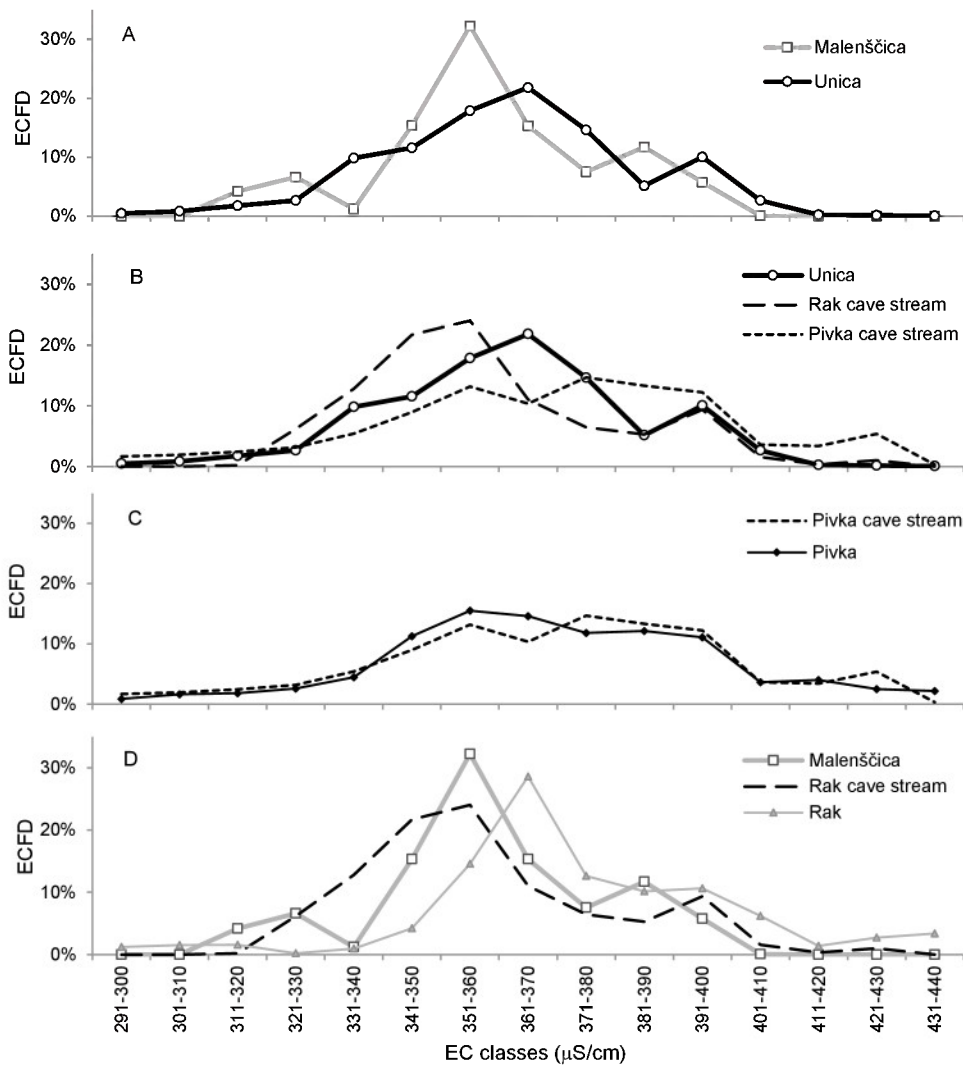
Fig. 3. Comparison of electrical conductivity frequency distribution (ECFD) curves. EC data measured in the period from 9 September 2013 to 29 June 2014 at 30-minute intervals were used.

Temporal evolution of EC values

The analysis described above enables a general characterisation of different types of recharge waters based on the whole set of measured parameters in the period of a hydrological year. A more detailed review of data shows that the shares of recharge from different contribution areas change with hydrological conditions. The data presented in Figure 4 enable an assessment of the temporal evolution of measured EC values. The selected interval begins in December 2013 with low water conditions. In the subsequent period the discharges react to each precipitation event with a typical peak, gradually increasing to high water conditions in February 2014.

As in the case of ECFD, the two main springs, the Unica and the Malenščica, were compared first. Significant differences indicate different sources of recharge. The EC curves of the Unica spring show an important influence of the recharge from the sinking Pivka river that is not characteristic for the Malenščica spring. Comparison of the EC values of the Unica with the EC values of the two cave streams shows that the Unica is a mixture of both cave streams. These two differ significantly in EC values, and the EC value of the Unica is somewhere in between, depending on the share of water from the individual streams. The highest EC values in the Unica were measured at low water levels, when the spring was mainly recharged from the Rak cave stream. After each precipitation event, inflow from the Pivka cave stream, with characteristic lowering of EC values, prevails for the first few hours, after which the share of inflow from the Rak cave stream gradually increases.

Comparison of the EC curves for the Pivka river and Pivka cave stream confirms a direct connection between the two water flows. The shapes of the curves are very similar, only the one of the Pivka cave stream is slightly attenuated and has a certain time delay.
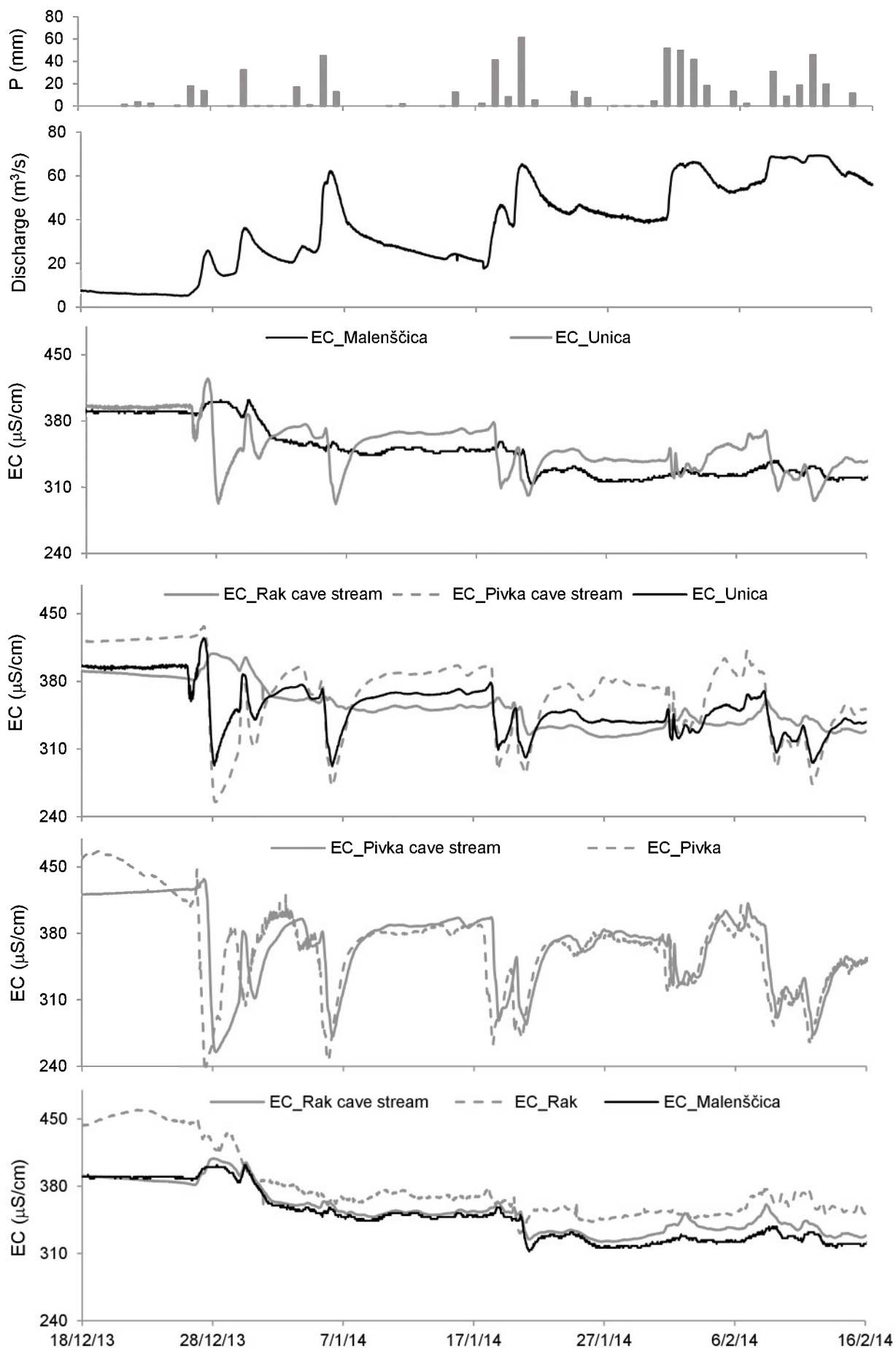
Fig. 4. Temporal evolution of precipitation in Postojna, discharge of the Unica spring and electrical conductivity (EC) of water at various locations within the studied karst system in the selected time interval from 18 December 2013 to 16 February 2014.

The EC curves for the Rak cave stream and the Malenščica spring are significantly different from the EC curves of the Pivka and very similar to those of the Rak river. This excludes their connection with the Pivka river and confirms their recharge from the Rak river. Significantly lower EC values in the cave stream and spring (by 20 to 30 μS/cm) are due to an important share of autogenic recharge from the Javorniki–Snežnik karst aquifer. The EC values of the Rak cave stream and Malenščica spring are practically the same, only differing significantly when water levels are high. The shift of the EC values of the Rak cave stream toward the EC values of the Rak river could be explained by limited maximum discharges of the Malenščica spring at high water levels and an increased share of recharge of the Rak cave stream from the Rak river.

Finally, for the assessment of the flow velocities between the ponors and the springs, the positions of the peaks (maximums) or troughs (minimums) of the EC curves at these monitoring sites were compared. Using the graphs, the time lags of peaks and troughs were defined for groundwater flow between the Pivka river, Pivka cave stream and Unica spring, and between the Rak river, Rak cave stream and Malenščica spring in various hydrological conditions. On the basis of these time lags and the distance as the crow flies between the monitoring sites, the apparent flow velocities were calculated. The circles and squares in Figure 5 represent the relationships

between assessed flow velocities and the discharges of the springs. For the Unica spring (left graph in Fig. 5) it is evident that the velocities increase with increasing discharges, while for the Malenščica spring (right graph in Fig. 5) such a relationship does not exist. The apparent flow velocities in the Pivka river–Unica spring system range from 263 to 769 m/h for discharges of the Unica spring between 18 and 69 m³/s. For the Rak river–Malenščica spring system, apparent flow velocities from 129 to 258 m/h were defined for discharges of the Malenščica spring ranging from 8 to 8.5 m³/s. A further increase of discharge is not followed by an increase of velocity, and for the discharge of 9.5 m³/s the apparent flow velocity was only 166 m/h. This indicates that when water levels in the Rak river–Malenščica spring system are very high, water flow is retained and slower due to the limited outflow from the Malenščica spring. On the other hand, the karst channels in the Pivka river–Unica spring system are large and permeable enough to allow the unimpeded transfer of water.

The calculated apparent flow velocities were compared with the apparent flow velocities defined by the tracer tests using artificial tracers. For these values, the ratios to discharges are presented as triangles in Figure 5. The established good correlation between the two sets of defined apparent flow velocities supports the applicability of the method of apparent flow velocity assessment based on a comparison of EC curves.
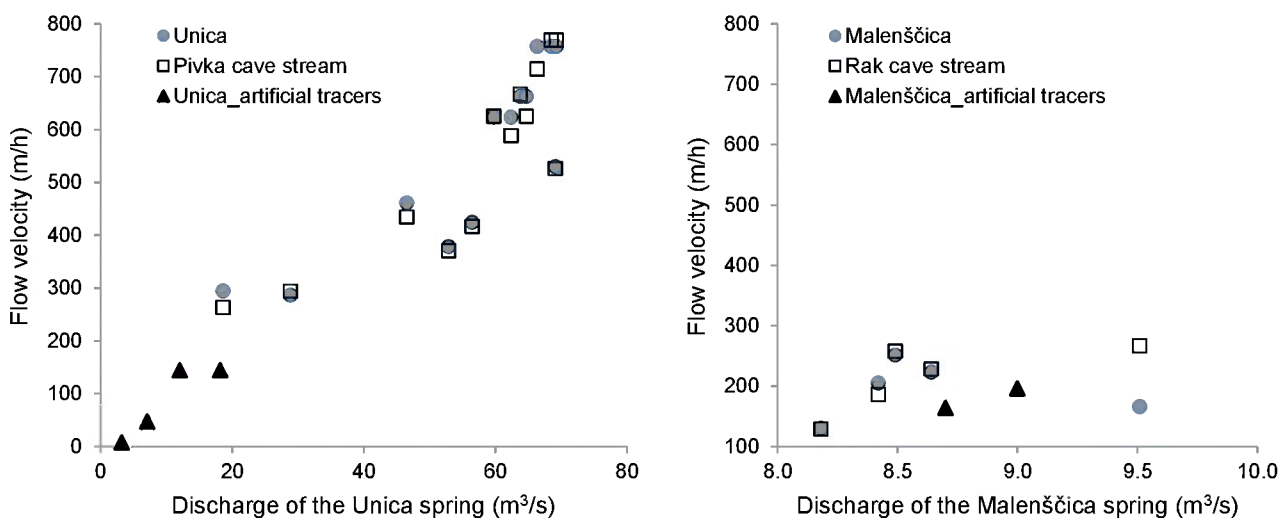

Fig. 5. Dependence between hydrological conditions and estimated flow velocities (based on the comparison of electrical conductivity (EC) curves and tracer tests with artificial tracers).

Conclusions

The Malenščica and Unica springs on the southern edge of Planinsko Polje are recharged from a large and complex karst aquifer in which different sources of allogenic and autogenic recharge are combined. Several tracer tests using artificial tracers have been carried out in this area in past years, so the directions and characteristics of subsurface flow are relatively well defined. This study, however, tested the potential of the use of natural tracers for the investigation of recharge dynamics and understanding of hydrological relations between different parts of the recharge area. Some general properties of the groundwater connections and relations between various recharge sources and the springs were already indicated on the basis of a comparison of the characteristic values of the measured parameters, while a more detailed analysis was enabled by the use of ECFD curves. In the next step, a temporal evolution of the EC values for different monitoring sites was compared and the influence of changes in hydrological conditions on the relationships between different types of recharge and the springs were evaluated. The important influence of hydrological conditions was confirmed. However, a more detailed analysis of the EC curves and the use of adequate statistical tools would be needed for a better understanding of these relationships.

The defined connections and the similar shapes of the EC curves also enabled an estimate of flow velocities between the ponors and the springs based on the comparison of the positions of the peaks (maximum) or troughs (minimums) of the EC curves at these monitoring sites. The estimated values of apparent flow velocities are in good agreement with the velocities defined by the tracer tests using artificial tracers. This supports the applicability of the method tested, particularly for periods of high water levels, where data from the tracer tests using artificial tracers are lacking. Information about the velocity of flow and solute transport in high water conditions is essential for testing various scenarios of pollution spread and the planning of protection of drinking water sources. The method described for processing the EC time series is straightforward, while the equipment for field measurements of EC is relatively cheap and simple to use.

The results presented in the paper were obtained through some basic, mostly qualitative analysis of data. However, the research project continues with new activities, including a more detailed, quantitatively based analysis of the time series data. The monitoring net has been expanded with new measuring sites, most notably the data loggers installed in caves within the Javorniki–Snežnik karst aquifer, which will provide some additional information about the characteristics of autogenic recharge.

Acknowledgement

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