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INTRODUCTION

Karst aquifers are important sources of water supply, but due to their specific characteristics they are very vulnerable to various human activities. For the efficient planning of protection measures it is essential to understand and consider the characteristics of groundwater flow and the processes of its exchange with surface waters. This is especially difficult for karst springs with a large extent and complex structure of their recharge areas. One of such examples is the Malenscica karst spring in south-western Slovenia, which is captured for the regional water supply. Based on hydrogeological researches, its protection zones were set in 1987, but they have not been properly implemented in praxis. Since then the understanding of the functioning of this karst system has improved and the proposed protection measures should be adjusted adequately. In order to do this the relations between different parts of the recharge area and the changes in the shares of their contribution at different hydrological conditions were studied in more detail. The physical and chemical parameters of water at different locations within the catchment were monitored in the total period of two hydrological years. The elaboration of data is still going on and in this article the first results of the general comparison of data on a time scale of hydrological years are presented.

CHARACTERISTICS OF THE STUDY AREA

Several karst springs are located at the southern border of the Planina karst polje in south-western Slovenia (Fig. 1).

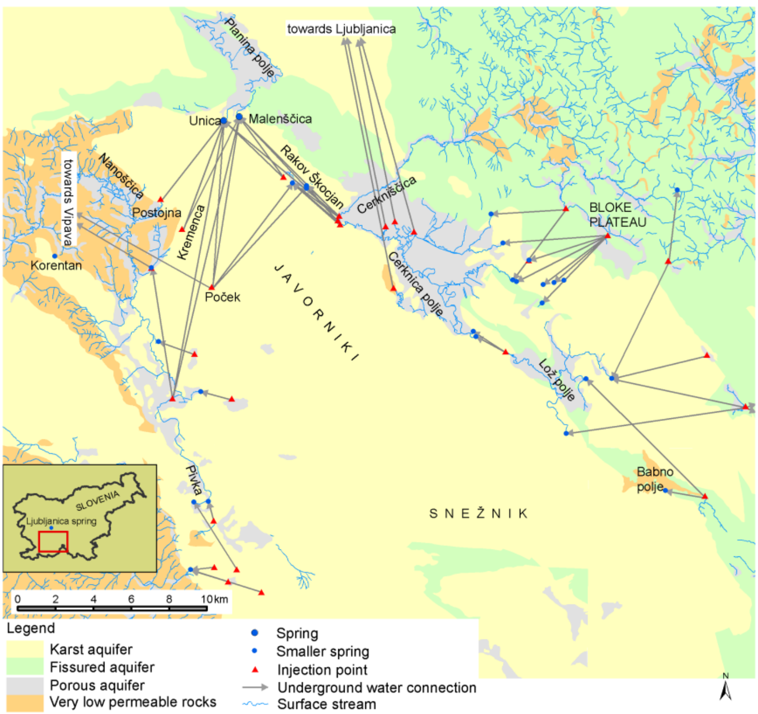

Figure 1. Hydrogeological map of the recharge area of the Unica and Malenscica springs with proved underground water connections.

The most important are the Unica and Malenscica springs. The latter is an important source of water supply for approximately 21,000 inhabitants. Relatively high discharge of the spring at low waters is an important advantage, but due to a large extent of the recharge area it is difficult to plan the protection and control the water quality. Based on the known geological and hydrogeological conditions, and the results of tracer tests, the recharge area of the springs was defined. It can be divided into three separate but hydrologically connected parts (Fig. 1). The central part is the karst massif of Javorniki and Sneznik. It borders at the western side on the valley of the Pivka river and its tributaries, and on the eastern and northern side on a string of karst poljes (the biggest among them is the Cerknica polje), which are distributed gradually in the SE-NW direction. These three areas can be named as Javorniki, Pivka and Cerknica parts of the catchment. In the Javorniki part the underground flow is dominant, and in other two parts surface streams are present also. They are mainly recharged by karst waters, and after a certain distance of surface flow they sink again underground. The underground water connections between various parts of the catchment (Fig. 1) were defined by several tracer tests (Petric, 2010).

The area of Javorniki and Sneznik is composed of Cretaceous carbonate rock, mostly limestone (Fig. 2).

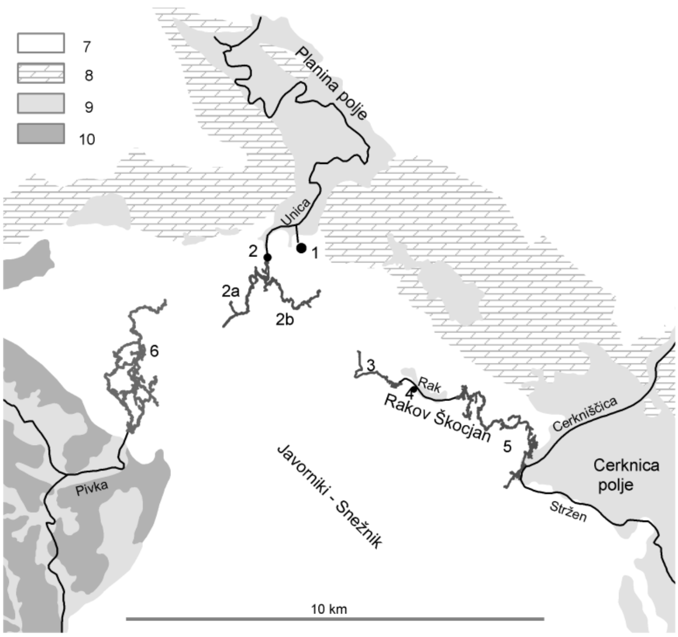

Figure 2. Hydrogeological map of the study area (Legend: 1. Malenscica spring, 2. Unica spring, 2a. Planina Cave-Pivka branch, 2b. Planina Cave-Rak branch, 3. Tkalca Cave (ponor of the Rak River), 4. Kotlici spring, 5. Cave system Zelse (spring of the Rak river)–Karlovica (ponor on the Cerknica polje), 6. Postojna Cave, 7. Karst aquifer, 8. Fissured aquifer, 9. Porous aquifer, 10. Very low permeable rocks).

On very low permeable Eocene flysch in the Pivka valley a surface drainage net is developed. Quaternary alluvial sediments are deposited along the surface streams. The oldest rock in the Cerknica part is Upper Triassic dolomite between the Planina and Cerknica poljes. Jurassic limestone and locally dolomite build the north-eastern border of the sequence of karst poljes.

Quaternary alluvial sediments are deposited on karst poljes. At high waters these are flooded and the intermittent lakes are formed. At the north-western border of the Cerknica polje, the Cerkniscica and Strzen surface streams, which flow along the polje, sink and flow underground mostly toward the Rak and Kotlici springs in Rakov Skocjan. Both springs recharge the Rak River, which flows on the surface for 2 km. The Rakov Skocjan area is composed of Cretaceous limestone, which is covered along the stream with Holocene sediments. Rak sinks again underground in the Tkalca Cave and flows toward the Malenscica and Unica springs at Planina polje. The Unica spring emerges from the Planina Cave, in which the underground waters from the Pivka area (along the Pivka branch) and from the area of Rakov Skocjan and Cerknica polje (along the Rak branch) flow together and form a unique underground confluence.

METHODS

The monitoring net was installed within the catchment of the Malenscica and Unica springs in 2007. Three rain-gauges were set in the three contribution areas (Onset RG-M at Postojna and Javorniki, and Eijkelkamp e+ diver at Bloke plateau). The sondes for measuring of discharge, temperature and electrical conductivity were installed at 2 karst springs (ISCO 6700-Sonde YSI 600 and 750 Area-Velocity Module at Malenscica spring, and Gealog S Logotronic at Unica spring) and 5 water streams within their catchment (Eijkelkamp CTD divers at Kotlici spring, Rak branch, and Pivka sinking stream, and Eijkelkamp TD diver at the Cerknica polje and in the Rak spring). In this way we gathered data on precipitation, water levels, discharges, electrical conductivity and temperature in 30-minute intervals from the autumn 2007 to the autumn 2009 (at some locations only data for one hydrological year are available due to later instalment or technical troubles).

RESULTS

Days with detected precipitation are distributed similarly at all three precipitation stations, and the differences are mainly in recorded daily amounts. Therefore for further comparison only the data for the Postojna station were used. To assess the daily values of effective infiltration (assessment based upon the soil water balance, methods used described in Petric, 2002), meteorological data were obtained at the Environmental Agency (Tab. 1).

Due to different duration of the hydrological years, the average daily values are compared. In the second hydrological year the average daily precipitation was slightly higher, but the difference is more significant for the effective infiltration. The main reason is in the distribution of precipitation, which is in the first year more uneven, with shorter precipitation events and larger amount during the summer when the share of effective infiltration is lower. More intensive precipitation events in the second hydrological year, when several days of consecutive rain were often recorded, are reflected in hydrographs with intervals of very high discharges.

The lowest oscillations of discharges were observed in the Malenscica spring with the ratio $Q_{min} : Q_{max} = 1 : 9.1$. Also the difference in average discharges between the two hydrological years is not significant for this spring. Its discharge is mostly closer to Q_{max} than to Q_{min}, which indicates that during the high waters the discharges of this spring are limited with the permeability of the inflow channels and the surplus water flows toward the nearby Unica spring. At other monitoring points the differences between the minimum and maximum discharges are much larger, and their average discharges are significantly higher in wetter hydrological year 2008-2009.

Table 1. Characteristic values of measured parameters for two hydrological years.

	Precipitation P and effective infiltration I_{ef} (mm)								
	2007–2008 (413 days)			**2008–2009 (334 days)**			**2 hydrological years (747 days)**		
	Max	**Sum**	**Avg**	**Max**	**Sum**	**Avg**	**Max**	**Sum**	**Avg**
P (mm)	49.8	1,410	3.4	113.4	1,279	3.8	113.4	2,689	3.6
I_{ef} (mm)	39.1	598	1.4	100.6	758	2.3	100.6	1,255	1.7
I_{ef}/P (%)		42			59			47	
	Discharge (m³/s)								
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Malenscica	1.45	5.92	9.50	1.09	5.94	9.91	1.09	5.93	9.91
Unica	0.05	5.58	56.89	0.04	14.43	69.34	0.04	11.20	69.34
Rak branch	0	9.00	26.46			36.10	0		36.10
Pivka	0.05	3.20	31.83			91.42	0.05		91.42
	Water level (in cm above the minimal measured value)								
Kotlici	15	174	696	0	472	1308	0	219	1308
Cerknica L.	0	743	924						
	Temperature (ºC)								
Malenscica	5.0	9.8	17.7	1.7	7.9	13.8	1.7	8.9	17.7
Unica	4.0	9.6	14.6	3.0	8.7	12.6	3.0	9.2	14.6
Rak branch	5.5	10.8	15.0	2.6	7.6	12.8	2.6	9.4	15.0
Kotlici	2.6	10.7	22.7	2.0	9.4	15.3	2.0	10.1	22.7
Cerknica L.	2.0	12.2	25.1						
Pivka	0.1	8.3	21.9						
	Electrical conductivity (μS/cm)								
Malenscica	338	378	428	278	359	440	278	369	440
Unica	288	381	479	221	373	479	221	377	479
Rak branch	290	362	398	267	362	451	267	362	451
Kotlici	205	378	452	162	392	460	162	384	460
Pivka	204	394	574						

Interesting results were obtained by the comparison of hydrological conditions and temperature of water (Figs. 3 and 4). The Cerknica Lake and the Pivka sinking stream are surface water bodies which represent the sources of recharge of the Malenscica and Unica springs from two different parts of the catchment. In both the oscillations of temperature are high due to the adaptation to the changes of air temperature. In the underground path of water from the ponors to the springs, its temperature changes according to the residence time, discharge and geometry of the karst system (Dogwiler, Wicks 2005). But also the mixing of waters due to the inflows from different parts of the recharge area should be considered.

The comparison of characteristic values of water temperature at all observed springs shows high oscillations. This confirms a significant share of secondary recharge from the surface water bodies. This is the most evident in the Kotlici spring, which is the closest to the ponors of the Cerknica Lake. In the Malenscica spring the oscillations are lower as the residence time of the water in the underground is longer. The reactions of temperature of the Unica spring are often very similar, but a more detail comparison shows an important influence of the recharge from the Pivka sinking stream, which is not characteristic for the Malenscica spring. This difference between the two springs is additionally confirmed by the comparison of measured values of electrical conductivities. Namely, a significant influence of the Pivka stream on the Unica spring can be detected.

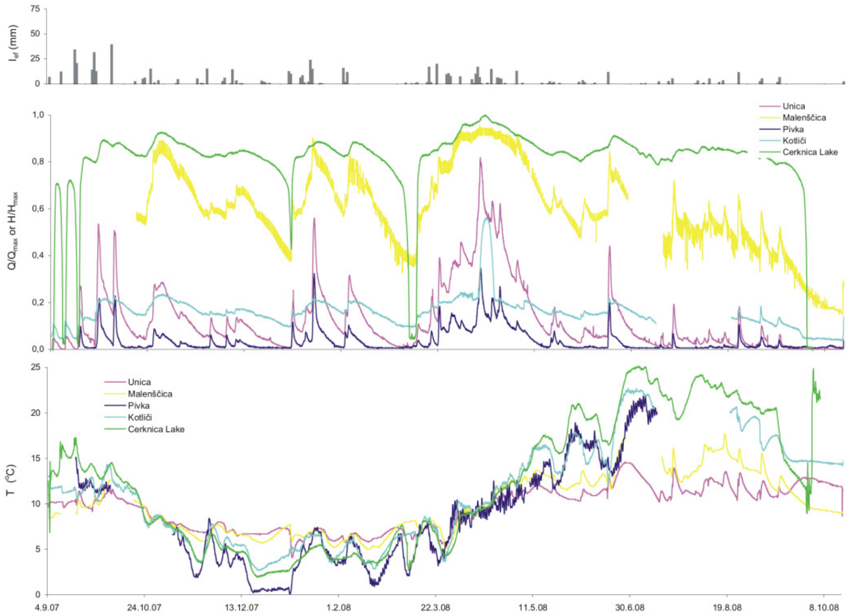

Figure 3. Effective infiltration and discharges or water levels (presented relatively to the maximum value for the two hydrological years) at selected monitoring points in the first hydrological year 2007-2008.

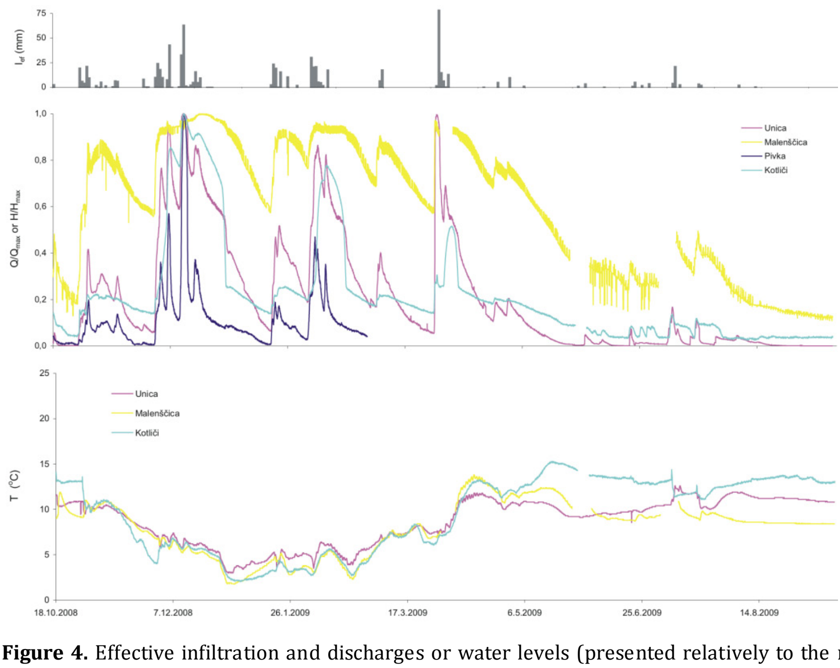

Figure 4. Effective infiltration and discharges or water levels (presented relatively to the maximum value for the two hydrological years) at selected monitoring points in the second hydrological year 2008-2009.

During high waters the temperatures of the springs approaches to the temperatures of the surface waters in the recharge area. The reason is very fast groundwater flow from the ponors to the springs, but it also indicates an important share of secondary recharge of the springs. Only at such conditions the lowest and highest temperatures of springs are detected. On the other hand, during low waters the extreme temperatures of the surface water bodies in the recharge area are not significantly reflected on the temperatures of the springs. In these periods the recharge is slower and the retention time of water in the karst underground longer, but the comparison also indicates larger share of primary recharge from the Javorniki-Sneznik karst aquifer.

CONCLUSIONS

The characteristics of groundwater flow in the catchment of the two observed springs are strongly dependent on meteorological and hydrological conditions and are changing very fast. Different shares of recharge from various parts of the catchment were indicated by the described analysis, but for a more detailed assessment we continue with the study in which we will compare all measured parameters in selected flood events at different hydrological conditions.

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