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Water temperature as a natural tracer – a case study of the Malenščica karst spring (SW Slovenia)

Janja Kogovšek and Metka Petrič

Karst Research Institute SRC SASA, Titov trg 2, 6230 Postojna, Slovenia;
(kogovsek@zrc-sazu.si, petric@zrc-sazu.si)

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ABSTRACT

For the adequate protection of karst springs it is important to understand the functioning of karst systems in their recharge areas. Besides tracer tests with artificial tracers, tracings with natural tracers, such as temperature, are a very useful research tool, especially in complex karst systems with various types and sources of recharge. Detailed monitoring of water levels and temperatures of the Malenščica karst spring, as well as of the intermittent Cerknica Lake and Kotliči spring in its recharge area, indicated that temperature is a good tracer in winter and summer periods, especially when the Cerknica karst polje is flooded. High or low air temperatures influence the temperature of water, which sinks at the Cerknica polje and flows rapidly through karst channels toward the springs. Detailed analysis of selected events enabled calculation of the velocity of groundwater flow toward the Malenščica spring under different hydrological conditions. The estimated values are in accordance with the velocities previously defined in this area, based on several tracer tests with artificial tracers. From the results, it is possible to assess the transport velocities of contaminants under different hydrological conditions. This is important information for the protection of the Malenščica spring, which is captured for the public water supply.

Keywords: karst spring, water temperature, recharge, Malenščica, Slovenia

1. INTRODUCTION

Karst aquifers are very vulnerable to various sources of pollution. To protect them properly, it is important to understand the characteristics of groundwater flow in their recharge areas. Different research methods are used in the studies of karst systems, one of the most often applied methods being tracer tests. Artificial tracers proved to be very useful in research of underground water connections, but in addition, tracings with natural tracers are becoming a very important tool for the study of the functioning of karst springs. A case-study of the Malenščica karst spring in south-western Slovenia is described here, in which water temperature was tested as a possible natural tracer.

Groundwater temperature can be used as a tracer to reveal the regional structure of a groundwater flow system (BONACCI, 1997). It is a parameter that carries information on the hydraulic and thermal conditions in the karst interior (GENTHON et al., 2005). It can be considered as a non-conservative tracer due to the exchanges of temperature between water and rock along the underground flow. When recharge water enters the aquifer system and flows down-gradient through the conduits, the initial temperature difference will decrease due to the heat-exchange at the water-rock interface. The degree of heat exchange is controlled by the thermal characteristics of the rock and the conduit characteristics, such as conduit length, cross-sectional area, and flow velocity (RENNER & SAUTER, 1997). Water tends to establish equilibrium temperature with the surrounding rock and sediments through conductive and advective processes (DOGWILER & WICKS, 2005). Additionally, in complex karst aquifers, significant changes of temperature under a variety of hydrological conditions are a consequence of the inflows of water with different characteristics from various parts of the recharge area.

In several studies, measurements of flow and temperature in karst springs were used to define the physical characteristics of large scale conduits in a karst aquifer (RENNER & SAUTER, 1997; HÜCKINGHAUS et al., 1997; LONG & GILCREASE, 2009). A more detailed study of the heat transport modes occurring in an observed karst aquifer was carried out by BUNDSCHUH (1997). Relationships between air and water temperatures were used to classify stream-groundwater interactions (O'DRISCOLL & DE WALLE, 2006).

The Malenščica spring is an interesting example of a spring fed by primary recharge (autogenic), in the karst massif (deep karst water), and secondary recharge (allogenic), along the karst poljes (surface water in the intermittent lake and sinking streams). Both types of inflows mix within the karst system and their contribution to the spring discharge varies according to the hydrological conditions. The aim of the present study was to compare the water temperatures at various locations within the studied karst system in order to assess the relationship between the main contribution areas within the catchment of the Malenščica spring under different hydrological conditions.

2. CHARACTERISTICS OF THE STUDY AREA

The Malenščica spring is captured for the water supply of approximately 21,000 inhabitants in the municipalities of Postojna and Pivka. It is situated at the southern border of the Planina karst polje (Fig. 1). According to data for the period 1961–1990, its lowest discharge was 1.1 m^3/s, with mean discharge of 6.7 m^3/s, and maximum discharge at 9.9 m^3/s. The recharge area of the spring was defined on the known geological and hydrogeological conditions, and the results of tracer tests. Its central part is the karst massif of Javorniki and Snežnik, in which underground flow is dominant. The area is composed of Cretaceous carbonate rock, mostly limestone. On the eastern and northern sides of Javorniki there is a string of karst poljes that are distributed in a SE-NW direction, of which the Cerknica polje is the largest. The oldest rocks in this part are Upper Triassic dolomites between the Planina and Cerknica poljes. Jurassic limestone and locally dolomite form the north-eastern boundary of the sequence of karst poljes. Quaternary alluvial sediments were deposited on karst poljes. At high water, these are flooded and intermittent lakes are formed. At the north-western boundary of the Cerknica polje, the Cerkniščica and Stržen surface streams, which flow along the polje, sink and flow underground mostly toward the Rak and Kotliči springs in Rakov Škocjan. Both springs recharge the Rak River, which flows on the surface for 2 km. The Rakov Škocjan area is composed of Cretaceous limestone, which is covered along the stream with Holocene sediments. Rak sinks underground again in the Tkalca Cave and flows toward the Malenščica and Unica springs at Planina polje. Due to the great extent and complex structure of the catchment, the proportions of the different inflows change in time with the different hydrological conditions.

A variety of geological, geomorphological, speleological and hydrogeological research has been carried out in the described study area. The results improved the understand-

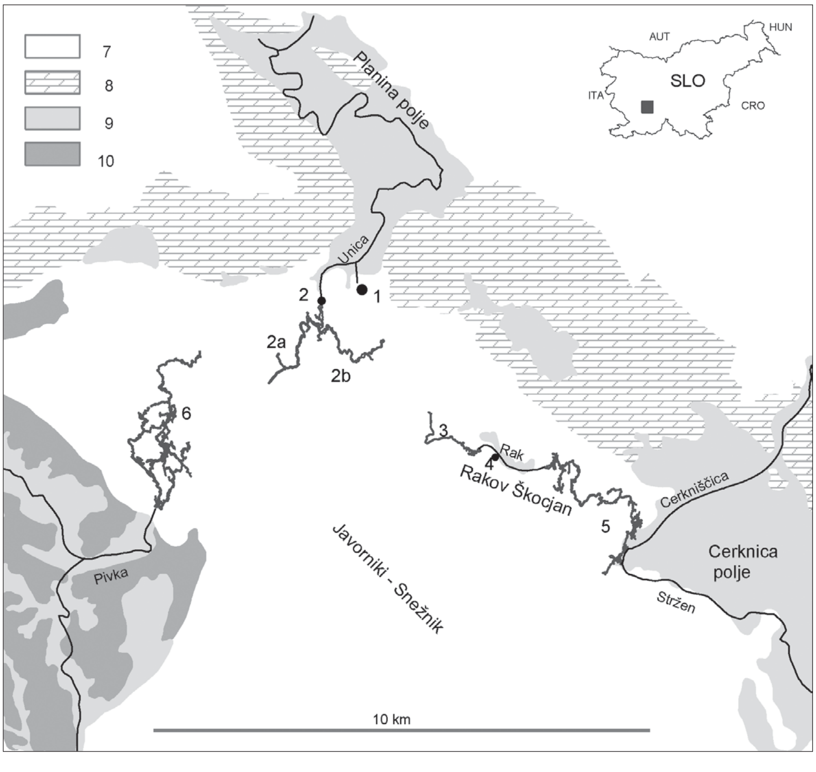

Figure 1: Hydrogeological map of the study area.

Legend: 1. Malenščica spring, 2. Unica spring, 2a. Planina Cave-Pivka branch, 2b. Planina Cave-Rak branch, 3. Tkalca Cave (ponor of the Rak River), 4. Kotliči spring, 5. Cave system Zelše (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.

ing of the functioning of this karst system. An important proportion of recharge with primary infiltration on the Javorniki massif was proved by tracer test on the Poček military training area (KOGOVŠEK, 1999). Underground water connections between the Malenščica spring and the ponors at the north-western border of the Cerknica polje, and ponors in Rakov Škocjan were also confirmed by several tracer tests (HABIČ, 1987b). The inflow from the Cerknica part of the recharge area greatly depends on the hydrological conditions, which were not registered in the above mentioned tracer tests.

In May 2008 a tracer test was carried out with the injection of uranine in a ponor at the north-western border of the Cerknica polje (GABROVŠEK et al., 2010). Under the conditions of a relatively stable discharge of the Malenščica spring of 6.4 m^3/s, the main direction of groundwater flow towards the Kotliči spring and further toward the Malenščica spring was proven. Lower concentrations were later detected in the Rak branch of the Planina Cave. The dominant apparent flow velocity, (regarding the first peak of the breakthrough curve) toward the Kotliči spring was assessed at 109 m/h, and from there to the Malenščica spring as 99 m/h. Analyses of calcium and magnesium concentrations were carried out simultaneously with the tracer test. Comparison of Ca/Mg ratios of the Rak (2.5), Kotliči (4.5) and Malenščica (6.5) springs indicates an important part of the recharge of the Malenščica spring is from the Javorniki karst aquifer, which is mainly composed of Cretaceous limestone. Detailed monitoring of the Ca/Mg ratios between 1999–2001 (KOGOVŠEK, 2004) proved comparable values of Ca/Mg ratios: 1.6 for Rak, 4.8 for Kotliči, and 6.5 for Malenščica springs for similar hydrological conditions.

3. METHODS

The study is based on the fact that the waters that recharge the spring have different water temperature characteristics. Surface flows are much more influenced by the air temperature and the changes of water temperatures are significantly higher than in the infiltrated water in the karst massif, which reaches equilibrium with the rock temperature at a depth of approximately 100 m. This was proven by long-term continuous measurements of water temperature in the vadose zone of the Postojna Cave (KOGOVŠEK, 2009). In the underground system, these two types of recharge interact, and the temperature at the spring may reflect the relationship between them. This important influence of hydrological conditions should be considered in the interpretation of the data obtained, but we should be aware that some other impacts, which are very difficult to detect and explain, also influence the characteristics of temperature at the spring.

The first systematic observations of water temperature of the Malenščica spring were carried out from June 1999 to the end of 2000 using a Gealog S Logotronic data-logger, and in 2001 with an ISCO 6700-Sonde YSI 600. Analysis of the data obtained indicated the important influence of the intermittent Cerknica Lake on the spring, but the lake temperatures were not regularly measured. In order to improve understanding of the functioning of the studied karst aquifer, instruments were installed in 2007 to measure data on the watercourses in the catchment of the spring and its water capture. Data was collected on water levels, discharges, electrical conductivity and temperature in 30-minute intervals from autumn 2007 to spring 2009. These parameters were measured with an ISCO 6700 with the YSI 600 sonde and 750 Area-Velocity Module at the Malenščica spring, and with TD divers (Van Essen, a Schlumberger company) at other locations. Analysis of the temperature and water level data (or discharge) of the Malenščica and Kotliči springs, were compared with the Cerknica Lake. Data for the latter was provided by our colleague Janez Turk. Air temperature data at the Postojna meteorological stations was obtained from the Environmental Agency of the Republic of Slovenia.

4. RESULTS

The comparison between air temperatures and temperatures of the Cerknica Lake indicated that water temperature reacts

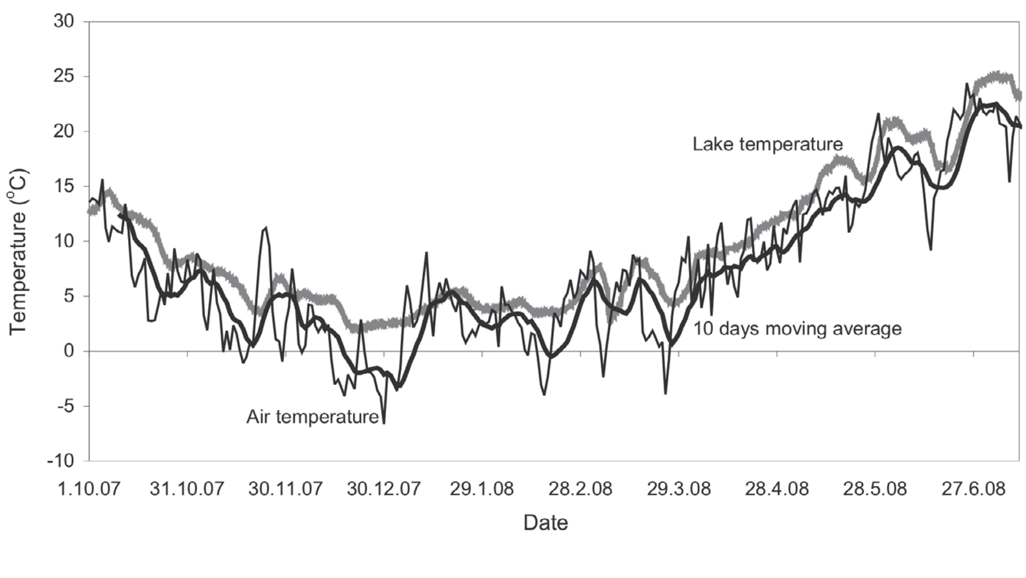

Figure 2: Comparison between air temperature and the temperature of the Cerknica Lake.

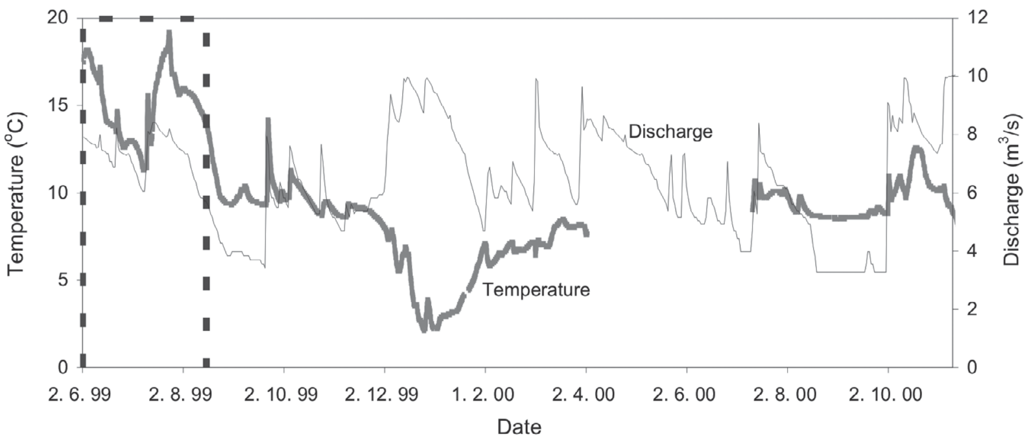

Figure 3: Recorded temperatures and discharges of the Malenščica spring from June 1999 to December 2000. Dotted line borders a selected interval presented in Fig. 4.

to the changes of air temperature with a particular time lag. The best fit in the comparison of the periods of increase and decrease of temperature was obtained by the calculation of the 10 day moving average of air temperatures, which means that the lake temperature is conditioned by the average temperature of the 10 preceding days (Fig. 2).

High oscillations of water temperature of the Malenščica spring were detected by measurements in the period from June 1999 to December 2001. The highest recorded temperature was 19.2ºC on July 24, 1999, and the lowest 1.7 on January 21, 2001. These extremes were reached in periods when the Cerknica polje was flooded and with contemporaneous high or low air temperatures (Table 1).

Between 1999–2001, the minimum discharges of the Malenščica spring were recorded at the end of August and September (Fig. 3). The lowest discharge of 1.97 m^3/s was recorded on September 2, 2001, when the water temperature was 8.4 ºC. Under such hydrological conditions in the ponors at the north-western edge of the Cerknica polje, only a small amount of the Cerkniščica River sinks, and the Stržen River does not reach the ponors, so the inflow from the Cerknica area has only a minor influence on the Malenščica spring. Therefore the temperature of the spring reflects primary recharge from the Javorniki karst aquifer. At low waters in August 2003 (the spring of the Rak River was dry), the Ca/Mg ratio of the Malenščica and Kotliči springs was practically the same (approximately 4.5) (KOGOVŠEK, 2004). This indicates that under such conditions both springs are mainly recharged from the Javorniki area, where more permeable fissures and conduits are activated, and their contribution dominates over that from the less permeable parts of the karst system. In August and September 2000, the discharge of Malenščica did not fall below 3.28 m^3/s, but its low temperature of 8.6 ºC indicates that inflow from the Cerknica area was very low.

Table 1: Minimum and maximum temperatures of the Malenščica and Kotliči springs occuring during floods in the Cerknica polje.

	Malenščica spring		Kotliči spring	
Hydrological year	T_{max} (°C)	T_{min} (°C)	T_{max} (°C)	T_{min} (°C)
until 19.9.1999	19.2 (24.7.99)			
20.9.1999–30.9.2000		2.3 (26.12.99)		
31.9.2000–1.9.2001	14.4 (7.5.01)	1.7 (21.1.01)		
4.9.2007–17.10.2008	17.7 (17.8.08)	5.0 (16.2.08)	22.7 (3.7.08)	2.6 (22.2.07)
from 17.10.2008		1.7 (2.1.09)	15.3 (17.5.09)	2.0 (5.1.09)
Total period	19.2	1.7	22.7	2.0

During low waters in September 1999, when the minimum yearly discharge of 3.41 m^3/s was reached, a somewhat higher temperature of 9.4 ºC indicated a more significant inflow of warmer water from the Cerknica area. This was the end of a long, very hot summer period of high waters, which did not occur in the following two years.

At the beginning of June 1999 the temperature of the Malenščica spring had already reached 18ºC. From June 6 to July 1, 1999, the temperature decreased to 13ºC in conditions of minor oscillations of discharge around 7 m^3/s, that indicates the gradual decrease of inflow from the Cerknica area. On July 10, 1999, the discharge started to increase, reached the maximum value above 8 m^3/s, remained at that level for 12 days, and then started to decrease (Fig. 4). The temperature of the Malenščica spring increased rapidly, and even daily oscillations of temperature were registered. The highest temperature of 19.2ºC lasted for 7 hours on July 24, 1999. With a further decrease in discharge, the temperature was also decreasing as a consequence of a reduction of the recharge from the Cerknica area and an increased proportion of the contribution from the Javorniki karst aquifer. Evidently the temperature of the sinking water in the Cerknica polje was very high, and further flow through well developed karst channels was rapid, so that no significant cooling of a relatively large amount of flowing water occurred along the underground path.

The discoveries described above were additionally confirmed by observations between 2007–2009. At very low water when the discharge of the Malenščica spring decreased toward 2.9 m^3/s on March 9 in 2008 (Figs. 5 and 6), the temperature of the spring slowly increased, (even though the air temperature and consequently the lake temperature were very

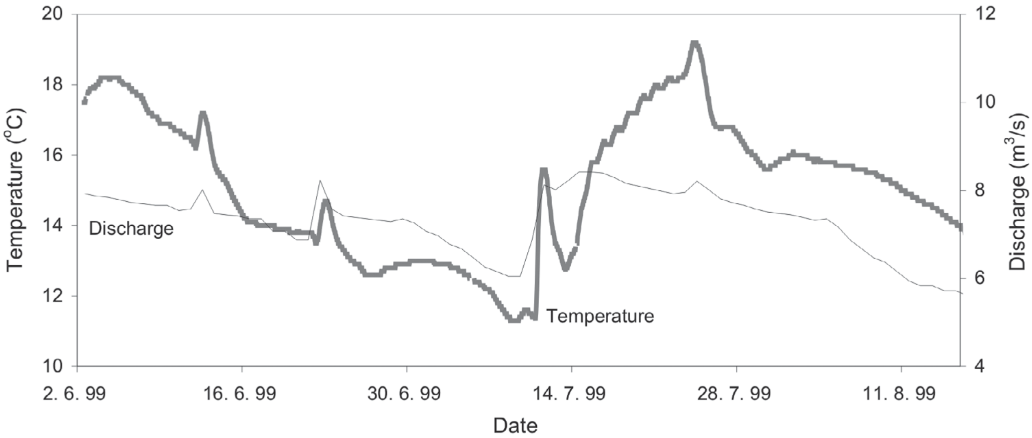

Figure 4: Temperatures and discharges of Malenščica spring for a selected interval in the summer of 1999.

low), reaching 8.1ºC. This indicates that the amount of inflow from a very cold Cerknica Lake was very low. A slightly larger influence of the lake was observed in the Kotliči spring.

A reverse situation was observed in autumn 2008. The temperature of the Cerknica Lake increased during the summer to 25ºC, and the Malenščica spring reached 17.7ºC. In September and in the beginning of October the lake temperature was still above 20ºC, while in the Malenščica spring, the temperature decreased to 9ºC, parallel with the decrease of discharge to 1.6 m^3/s on October 17, 2008. Again this can be explained by an increased amount of recharge from the Javorniki karst aquifer.

During lengthy flood conditions (from March to the beginning of May 2008, and December 2008 to March 2009) the water temperature was very uniform within the observed system (Cerknica Lake–Rakov Škocjan–Malenščica).

Water temperatures of the Malenščica and Kotliči springs were compared in more detail over the short interval from March to April 2008 (Fig. 6). In the beginning, the discharges were low and recharge from the Javorniki area prevailed in both springs. After precipitation a greater influence of the inflow from the Cerknica area was indicated by rapid changes of temperature. The reaction of the two springs is similar, but due to a larger distance and longer path of underground flow the changes at the Malenščica spring are delayed and reduced. Based on the assumption that the velocity of the transfer of temperature along the underground flow is considered to be equal to the velocity of water flow, the positions of the peaks (maximum) or saddles (minimum) of the temperature curves of the Kotliči and Malenščica springs were compared. In this way the flow velocity in the karst system between the two springs was estimated at 145 to 215 m/h (at discharges of Malenščica from 5 to 9 m^3/s). These values are comparable with flow velocities from 140 to 256 m/h, which were calculated as a result of 5 tracer tests performed in the area between Rakov Škocjan and Malenščica (HABIČ, 1987a). A lower flow velocity of 99 m/h was defined by the tracer test in May 2008 (discharge 6.4 m^3/s, slowly decreasing). Unfortunately, only small changes of hydrological conditions and water temperatures were recorded during this tracer test, and it was not possible to accurately define the peaks and saddles of the curves. Nevertheless, an approximate comparison of both temperature curves indicates a similar range of velocity as was calculated based on the results of tracing with uranine in the same period.

Daily oscillations of temperatures, recorded during high waters in the beginning of April 2008 (Fig. 6) are interesting. They were very regular at the Kotliči spring and slightly less distinctive at the Malenščica spring. The comparison of

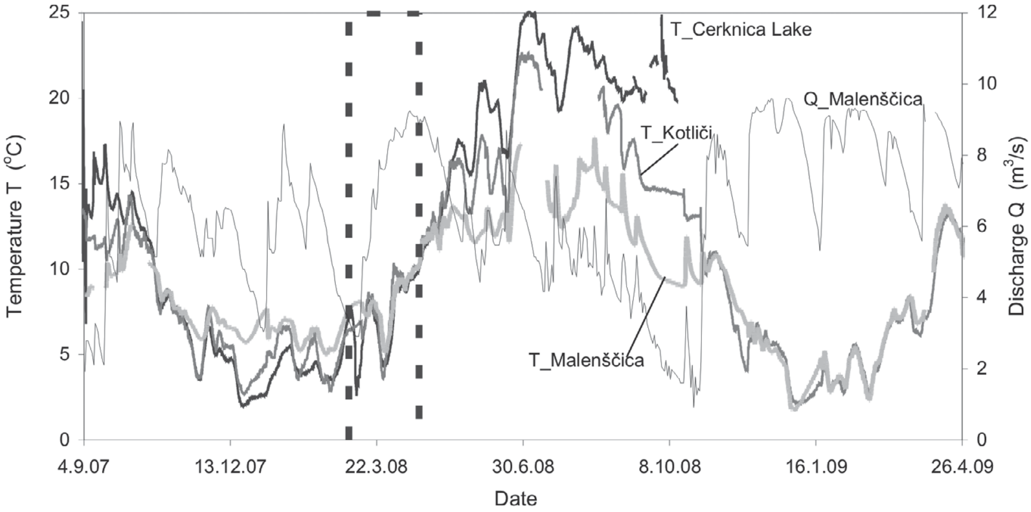

Figure 5: Recorded temperatures and discharges from September 2007 to April 2009. Dotted line borders a selected interval presented in Fig. 6.

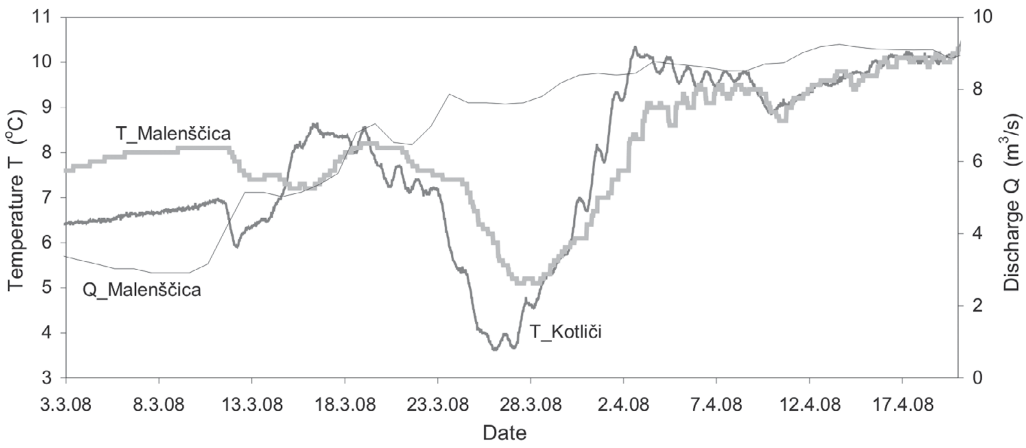

Figure 6: Recorded temperatures and discharges for a selected interval in the spring 1999.

their position confirms the characteristics of groundwater flow in the Rakov Škocjan-Malenščica karst system as described above.

On July 21, 1999, the temperature of the Malenščica spring (discharge 8 m^3/s) was 17.8ºC, 21.5ºC at Kotliči, and 23ºC at the Cerknica Lake. Supposing that the temperature of the inflow from the Javorniki karst aquifer is 8.5ºC (based on the measured temperatures at Malenščica at very low discharges), we assessed the amount of recharge from the Cerknica area in the Malenščica spring to be up to 70%. Similar assessment for the end of December 1999 (discharge of Malenščica approximately 10 m^3/s) resulted in calculation of an even higher amount. In March 2008, the temperature of the Cerknica Lake was 5.4ºC, and the Malenščica spring was at 8.1 ºC (discharge 3 m^3/s). This indicates recharge from the Cerknica area at approximately 15%. Such calculations can give us a general idea about the different contributions to the recharge of the Malenščica spring, but as they do not take into account the changes of water temperature along the underground path due to the exchange with surrounding rock, they are only rough estimations.

5. CONCLUSION

Propagation of temperature signals through the underground system in the catchment of the Malenščica spring was analysed under different hydrological conditions. The results obtained indicate that temperature is a very good natural tracer of water flow in the study area of a very complex karst system, with well developed karst channels, especially in winter and summer periods when the Cerknica polje is flooded. Minimum and maximum temperatures of the spring were recorded in the periods of high water (dominated by recharge from the Cerknica area) and very low or high air temperatures. During low waters the recharge from the Javorniki karst aquifer prevails.

A detailed analysis of selected water waves enabled calculation of the velocities of groundwater flow toward the Malenščica spring for different hydrological conditions. Velocities obtained are comparable with those calculated on the results of tracings with artificial tracers. Information about the flow velocities at different hydrological conditions is important for the protection of the springs captured for the water supply, because it enables assessment of the characteristics of the transfer of contaminants which differ significantly according to the hydrological conditions. One of the main sources of pollution in karst areas is waste water from urban areas. In the settlements on the Cerknica polje, sewage water is only partly cleaned in an old water treatment plant with insufficient capacity, and it endangers the quality of the Malenščica spring.

Although some interesting results were obtained by the research described here, the limitations of the research tool should not be disregarded. In order to verify and improve the findings we applied other research methods in the Malenščica study area, and the data obtained will be used in further studies.

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