Environ Geol (2006) 49: 865–874
DOI 10.1007/s00254-006-0182-8

ORIGINAL ARTICLE

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The vulnerability of karst springs—a case study of the Hubelj spring (SW Slovenia)

Received: 30 August 2004
Accepted: 13 December 2005
Published online: 25 February 2006
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Abstract The hydraulic behaviour of the karst aquifer in the Hubelj spring catchment area (SW Slovenia) was studied by using an indirect research method based on natural tracers. The variations of natural tracers (in precipitation and in groundwater) during the storm event made possible the separation of the Hubelj spring storm hydrograph by the three-component separation technique. The results produced information on the aquifer recharge, storage and discharge processes, as well as on the mechanisms that affected them. They verified the so-called epikarst hypothesis presuming that an important part of a karst aquifer recharge reaches rapidly and intensively from the epikarst zone. It was demonstrated that epikarst water could occupy up to 50% of the spring discharge during precipitation events. This phenomenon could have important consequences on protection and management of the problems of karst aquifers, including engineering problems in karst areas. With this respect the results could give way to new engineering ideas.

Keywords Karst aquifer · Vulnerability · Hydraulic behaviour · Three-component hydrograph separation technique · Slovenia

Introduction

The groundwater of karst aquifers is becoming an increasingly important source of water supply in many countries, including Slovenia. The prevailing opinion is that by 2025 up to 80% of the water supply may originate from karst aquifers. To protect the karst water from pollution and overexploitation, it is necessary to understand the natural factors that control the hydraulic behaviour of karst aquifers. However, the heterogeneity of karst aquifers makes it difficult to quantify and predict the movement of groundwater and contaminants through and/or between different aquifer zones. Most of theoretical and practical problems result from the duality of the aquifer recharge, storage and discharge processes. This duality is reflected in the fast concentrated flow through the karst conduit network and the relatively slow diffuse flow through less permeable rock blocks.

Owing to the specific characteristics of karst aquifers, the study of flow and solute transport mechanisms has become more important (Petrič 2002). This study was also the principal topic of the research work, which was focused on behaviour investigations of a karst aquifer in the catchment area of the Hubelj spring (Fig. 1). The research of the mechanisms that cause the flow and solute transport from an upper unsaturated zone was particularly stressed. Two contrasting hypotheses of the karst aquifer infiltration and recharge processes were tested:

- The first hypothesis presumes that karst aquifers are mainly recharged by a diffuse flow.
- The second hypothesis presumes that an important part of a karst aquifer recharge reaches rapidly and intensively from the epikarst zone.

The indirect research method based on the application of the natural tracer in the field of work was basically used for studies, together with the hydrograph separation techniques.

The natural tracers are important tools for studying the flow and the solute transport from the recharge area through the upper unsaturated zone to the discharge area in a spring. Therefore, the research was centred at the three itemised areas of the study aquifer. The first two were investigated in the experimental field site of Sinji vrh, and the latter in the Hubelj spring (Figs. 1, 2). The upper unsaturated zone was investigated in an artificial tunnel, which represented a natural laboratory for studies of chemical and stable isotopic composition of the seepage water, and with it the drainage system of the tunnel cover.

The research methodology based on the sampling that was performed in two stages: (a) a long-term sampling in monthly intervals, and (b) a short-term sampling during the storm event. The first sampling stage provided an insight into the basic flow characteristics, mostly the age structure and hydrodynamics of the karst aquifer groundwater, while the second one identified the karst aquifer discharge response to the summer storm cycles, subsurface storage zones and mechanisms of groundwater recharge and discharge. The second sampling stage is the theme of this paper. This stage produced data for the hydrograph separation technique. Its results allowed the estimation of

- portions of the event water in a storm hydrograph,
- prevailing types of flow (either fast or diffuse) during the storm hydrograph,
- contributions of karst aquifer zones in a summer storm flow and
- the role of the upper unsaturated zone water during the storm event.

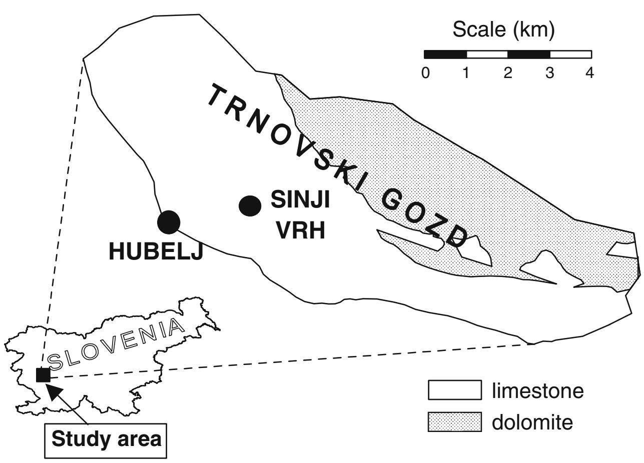

Fig. 1 Study area—the orographically determined catchment area of the Hubelj spring

From the interpretation of data, it follows the substantial importance of the epikarst zone in the aquifer recharge process. The results are in agreement with the above-mentioned second research hypothesis.

Description of the study area

The catchment area of the karst spring Hubelj (Fig. 1) is estimated at 50–80 km^2 (Trišič 1997). This region belongs to the high karstic plateau Trnovski gozd with mean altitude of 900 msl. The plateau consists of carbonate rocks, which are covered by shallow soils (10–50 cm) of low water-holding capacities (22–142 mm) and high infiltration rates (Matičič 1997).

The study area is the first topographic barrier from the seaside to the interior of the mainland. Hence, it represents a divide between the Mediterranean, Continental and Alpine climates. The real Alpine climate with quite large amounts of snow during the rather cold winter is typical for the Trnovski gozd plateau. The average annual precipitation amount is 2,450 mm, while the average annual air temperature is 7–9°C.

The highly karstified carbonate rocks, consisted mainly of the Jurassic limestone, are bounded by the Norian–Rhaetian dolomite in the north and by the Eocene flysch beds in the south and in the east (Figs. 1, 2). The limestone is bedded to thick-bedded. The thickness of strata is usually from 40 cm to 2 m, but it can reach even 10 m in some places.

The tectonic structure of the research region is complicated. The predominant tectonic elements are complex overthrusts cut by a dense system of subvertical faults (Janež et al. 1997). The Avče fault is the most important regional fault crossing the study area (Fig. 2). Near the thrust lines carbonate rocks are finely crushed and ground and, consequently less permeable.

The aquifer hydrogeological conditions depend on the geological structure and lithology. The flysch rocks act as a practically impermeable basement of carbonate beds. Therefore, they represent a complete, partial or hanging hydrogeological barrier (Janež et al. 1997). The shape and the inclination of flysch layers essentially influence the groundwater flow direction.

The research included observations of two aquifers zones: (a) a saturated zone and (b) an upper unsaturated zone. The saturated zone was observed in the Hubelj spring (Fig. 1) which is one of the biggest Slovene karst springs. The Hubelj spring lies at the bottom of a deep structural depression in the thrust plane of the Trnovo

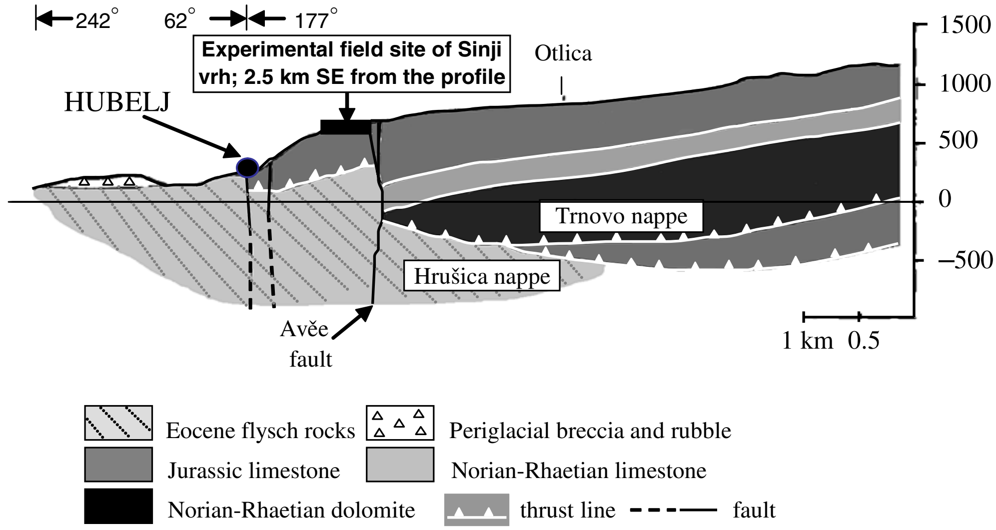

Fig. 2 Geological cross section near the Hubelj spring (after Janež et al. 1997)

nappe (Fig. 2). The permanent outflows are between 219 and 235 msl. However, the outflow level can rise by about 40 m at high waters. At that time the groundwater springs out of the Hubelj cave and falls 50-m deep into the riverbed. The spring mean discharge is 3 m^3/s, and the minimum one is 0.2 m^3/s while the maximal one is 59 m^3/s (Janež et al. 1997).

The unsaturated zone was investigated in the experimental field site of Sinji vrh, which is 600 m above the Hubelj spring (Figs. 1, 2). Most of the studies were performed in the artificial tunnel which lies 5–25 m below the surface at about 800 msl mean altitude (Fig. 3). This area consists of an intrabiopelmicritic, an oolitic and a biopelmicritic limestone of the Jurassic age (Lias-Dogger) (Bole 2000; Čenčur Curk and Veselič 1999; Trček 2002, 2003). Since the experimental field site of Sinji vrh belongs to a region of the Avče fault, the rock is fractured, broken and crushed near the fault lines. The Avče fault zone of Dinaric stricke (NW–SE) is cut by numerous subvertical faults striking NNW–SSE and NNE–SSW (Čar 1997).

Methods and techniques

The study area was investigated by the natural tracer research method that was based on the sampling performed in two stages:

(a) The long-term sampling in monthly intervals for establishing the base flow characteristics.
(b) The short-term sampling during the storm event for identifying the karst aquifer discharge response to the summer storm event.

The short-term monitoring of the precipitation and karst system water (the upper unsaturated zone and spring water) during the storm event in July 2000 (presented in Fig. 4) is stressed in this paper. The monitoring of ^{18}O and DOC content

- in precipitation from Sinji vrh and
- in karst system water (in seepage water from the artificial tunnel and in the aquifer outflow) was carried out.

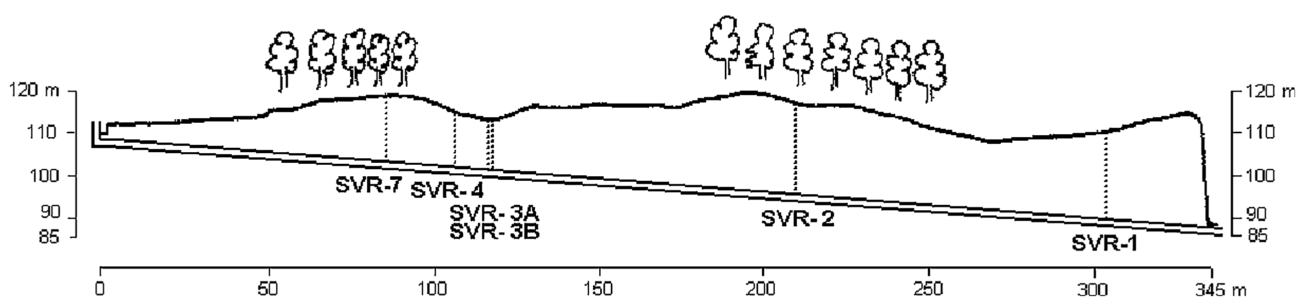

Fig. 3 Longitudinal profile of the Sinji vrh artificial tunnel with sampling points for the groundwater isotopic and chemical analyses

The saturated zone outflow was monitored in the Hubelj spring. The water was sampled from one fracture in the old water capture. All other observations were performed at the experimental field site of Sinji vrh. The precipitation and upper unsaturated zone seepage water was monitored near the tunnel entrance and at six tunnel sampling points—SVR-1, SVR-2, SVR-3A, SVR-3B, SVR-4 and SVR-7 (Fig. 3). The water was sampled and preserved depending upon the method that was in accordance with the instructions of Clark and Fritz (1997). The sampling frequency was keyed to the discharge of sampling points. The Hubelj spring was sampled hourly during the first 3 days and once a day later on. The precipitation and tunnel seepage water was sampled in the shortest possible intervals.

The Hubelj discharge was registered at a gauging station about 1 km away from the spring site. Besides at Sinji vrh, the precipitation was registered also at rain gauging stations Vojsko (1,070 m asl), Slap (130 m asl), Črni Vrh (683 m asl), Otlica (near Sinji vrh, 820 m asl) and Podkraj (799 m asl). Previous investigations demonstrated that there is a general pattern of $\delta^{18}O$ variation at all listed precipitation stations (Stichler et al. 1997; Trček et al. 2001), and therefore the precipitation data from Sinji Vrh were used as a regional input.

The data of the described monitoring were used for the analyses of the Hubelj spring storm hydrograph. The variations of two conservative natural tracers, the oxygen stable isotopic ($\delta^{18}O$) and dissolved organic carbon (DOC) composition, provided the application of the three-component hydrograph separation technique (Ogunkoya and Jenkins 1993; Clark and Fritz 1997; Kendall and McDonnell 1998).

The hydrograph separation into (n) components requires the use of ($n-1$) tracers. A combination of conservative and also the nonconservative natural isotopes or chemical substances is convenient for that purpose (Kendall and McDonnell 1998). It should be stressed that the rational and objective selection of the representative end members is a key problem of this technique, which is also closely linked with the planning of a suitable sampling strategy.

The following assumptions were considered in the three-component separation of the Hubelj spring storm hydrograph:

- the spring hydrograph could be separated into the following end members:
  - the event water,
  - the upper unsaturated zone water (soil + epikarstic water), and
  - the base flow water (phreatic + lower unsaturated zone water) component;
- waters stored in the lower unsaturated and saturated zones of the aquifer, insignificantly differ in the isotopic and chemical composition, and thus represent the base flow water component;
- the base flow has a constant oxygen isotopic and dissolved organic carbon composition, −8.6‰ and 0.33 mg/l, respectively;
- the isotopic and chemical composition of the tunnel upper unsaturated zone water is representative for the catchment area of the Hubelj spring;
- the upper unsaturated zone water preserves the uniform isotopic and chemical composition throughout the event;
- the precipitation preserves the uniform isotopic and chemical composition throughout the event;
- the temporal variability of the precipitation $\delta^{18}O$ at Sinji vrh is the representative also for one of the Hubelj spring catchment areas (Stichler et al. 1997).

However, some temporal variability of the precipitation and upper unsaturated zone water $\delta^{18}O$ and DOC composition was observed. This was accounted for by the application of the method of incremental weighted

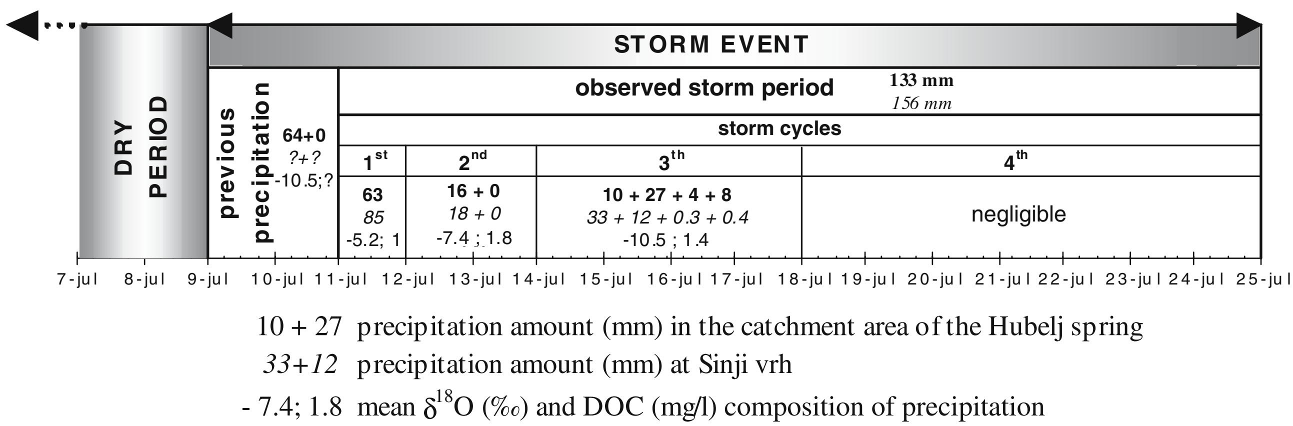

Fig. 4 Presentation of the storm event in July 2000

mean values (McDonnell et al. 1990). This method refers to the same equation as the classical method of weighted averages, except that in the calculations of each point of the hydrograph, only data of this precipitation should be considered, which fell in the catchment by the time defined separately by each point.

The relative contributions of end members to the Hubelj storm discharge were calculated for each stream sample by solving a system of three linear equations with three unknowns (Ogunkoya and Jenkins 1993):

$$Q_t = Q_e + Q_u + Q_b \quad (1)$$

$$Q_t C_t = Q_e C_e + Q_u C_u + Q_b C_b \quad (2)$$

$$Q_t \delta_t = Q_e \delta_e + Q_u \delta_u + Q_b \delta_b \quad (3)$$

where
Q is discharge,
C is DOC composition,
δ is ^{18}O composition, while
the subscripts t, e, u and b represent

- the total stream flow,
- the event water component,
- the upper unsaturated zone water component and
- the base flow water component, respectively.

Results

The karst system response to the summer storm event was studied from 11 to 25 July 2000 in the so-called observed storm period that consisted of four separated storm cycles (Fig. 4). The precipitation amounts and the discharge measurements of the Hubelj spring are illustrated in Figs. 4, 5.

The first storm cycle was the dominat, as the precipitation amount was 85 mm at Sinji vrh and 63 mm in the catchment area of the Hubelj spring (Figs. 4, 5). This cycle resulted in an increase of the Hubelj spring discharge from 0.6 to 24 m^3/s (Fig. 5). Time-to-peak discharge was 7 h after the beginning of the first storm cycle (Fig. 5).

The following storm cycles did not influence the Hubelj spring discharge so much, as well as the previous precipitation. It follows from data illustrated in Fig. 5 that the previous precipitation amount was even greater than the one of the first storm cycles. Nevertheless, this precipitation resulted in just a slight increase of the Hubelj spring discharge, namely from 0.4 to 1.8 m^3/s. Later the discharge decreased to only 0.6 m^3/s before the observed storm period.

The collected information indicates that the previous precipitation mainly resulted in the recharge and storage processes, while, in contrast to the observed storm period, the discharge process was not typical. The previous precipitation had an insignificant impact on the phreatic zone, because the δ^{18}O and DOC composition of the Hubelj spring reached again base flow values before the observed storm period (Trček 2001).

The Hubelj δ^{18}O and DOC composition of the observed storm period is presented in Fig. 6. Oxygen isotopic composition increased from the base flow value (−8.6‰) to the maximum one, −7.64‰. Its peak occurred 16 h after the peak discharge, while the DOC peak (1.53 mg/l) occurred immediately after the first spring reaction to the first storm cycle. Afterwards, both parameters had similar time trends. The δ^{18}O peak coincided with the second peak of DOC (1.26 mg/l).

The statistical characteristics of δ^{18}O and DOC composition of upper unsaturated zone water are presented in Table 1. The values of parameters varied from −9.8 to −6.7‰ and from 0.22 to 4.62 mg/l, respectively.

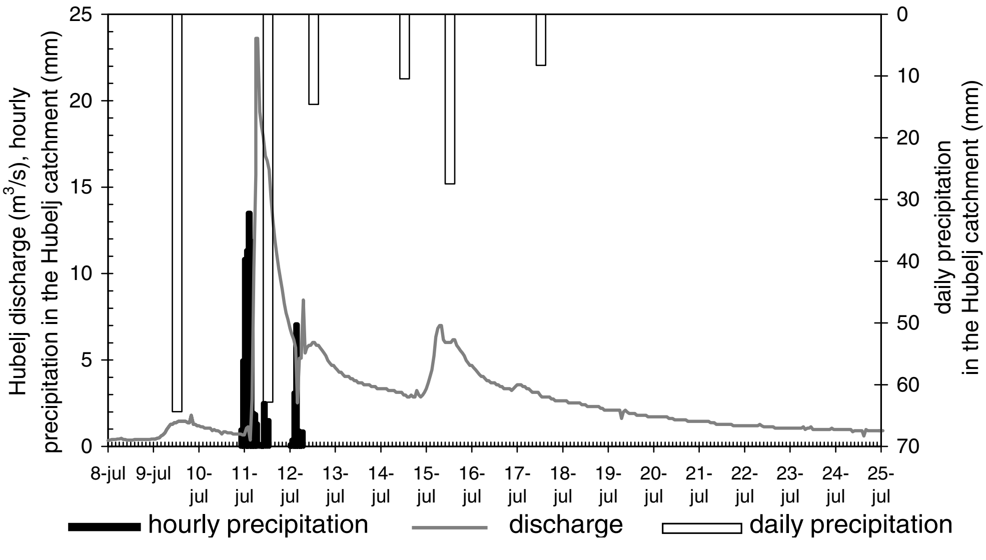

Fig. 5 Daily precipitation, hourly precipitation and discharge of the Hubelj spring

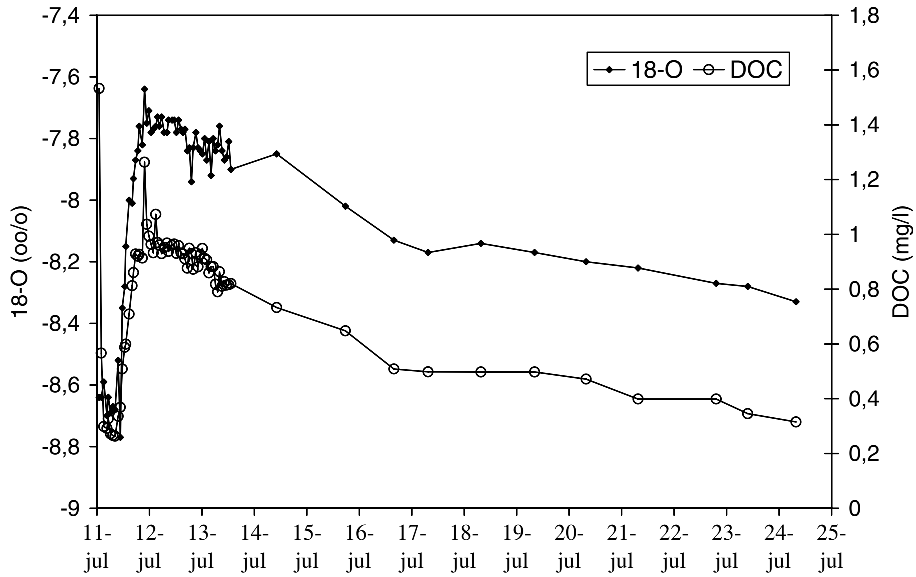

Fig. 6 δ^{18}O and DOC composition of the Hubelj spring

The presented data were used for the three-component separation of the Hubelj spring storm hydrograph. The applied sampling design allowed the Hubelj spring storm hydrograph separation into the (a) base flow, (b) upper unsaturated zone and (c) event water components. The validity of the end members was tested by the examination of Fig. 7. The figure demonstrates that the bulk of spring data plots in the triangle with average values of end members at its corners. It should be stressed that the triangle fixed point refers to the spring base flow only, while the others are the so-called moving points, owing to the use of the method of incremental weighted mean values. Hence, it follows that the triangles of the selected end members practically include the entire data set of the spring. Therefore, it was assumed that the selected end members adequately describe the studied system.

The three-component separation of the Hubelj spring storm hydrograph is presented in Fig. 8. They indicate that the portions of the event and upper unsaturated zone water components from 15 to 25 July should be illogical. On one hand, the high portions of the event water component point out the fast flow through the karst conduits even if the precipitation amount was low after 17 July (Fig. 4). On the other hand, the negative portions of the upper unsaturated zone water component reflect the inversion of the hydraulic gradient—the pressure of the less permeable rock blocks became higher than the one of the karst conduit networks, and with that the diffuse recharge process. This process could be inferred also from the water balance of the tunnel sampling points during the period from 14 to 25 July, as the volume of SVR-1 and SVR-3B, which were recharged by a laminar flow, represented 79% of the total (Trček 2001, 2003).

Table 1 Mean values and ranges of δ^{18}O and DOC composition of sampling points in the upper unsaturated zone during the observed storm period (from Trček 2001)

Sampling points	δ^{18}O (‰)		DOC (mg/l)	
	Mean	Range	Mean	Range
SVR-1	−8.98	−9.02 −8.78	0.32	0.27 0.37
SVR−3A	−8.91	−9.12 −8.39	1.12	0.57 4.62
SVR-3B	−9.78	−9.82 −9.55	0.33	0.22 1.04
SVR-4	−7.70	−7.92 −7.55	0.60	0.52 0.94
SVR-7	−6.98	−7.34 −6.69		

It could be summarised that only portions of the base flow water component should be logical (Fig. 8). Thus, the validity of the epikarst hypothesis (Mangin 1975; Gunn 1981, 1983; Williams 1983; Dodge 1983; Smart and Friderich 1986; Bonacci 1987; Klimchouk 1995, 2000; Klimchouk et al. 1996; Kiraly et al. 1995) was tested to get to the heart of the problem. According to this hypothesis, it was examined whether it is possible to combine the event and upper unsaturated zone water components into one component representing the fast flow that arrives from the epikarst zone. This flow is called the epiflow (after Kiraly et al. 1995). The epiflow is defined as the fast flow of (a) the water that was prestored in the epikarst zone and (b) the event water, which was concentrated at the base of the epikarst zone and later drained into the karst conduit network, where they could mix with the water of the sinkholes. In this respect the portions of the event and upper unsaturated zone water components were summed into the portion

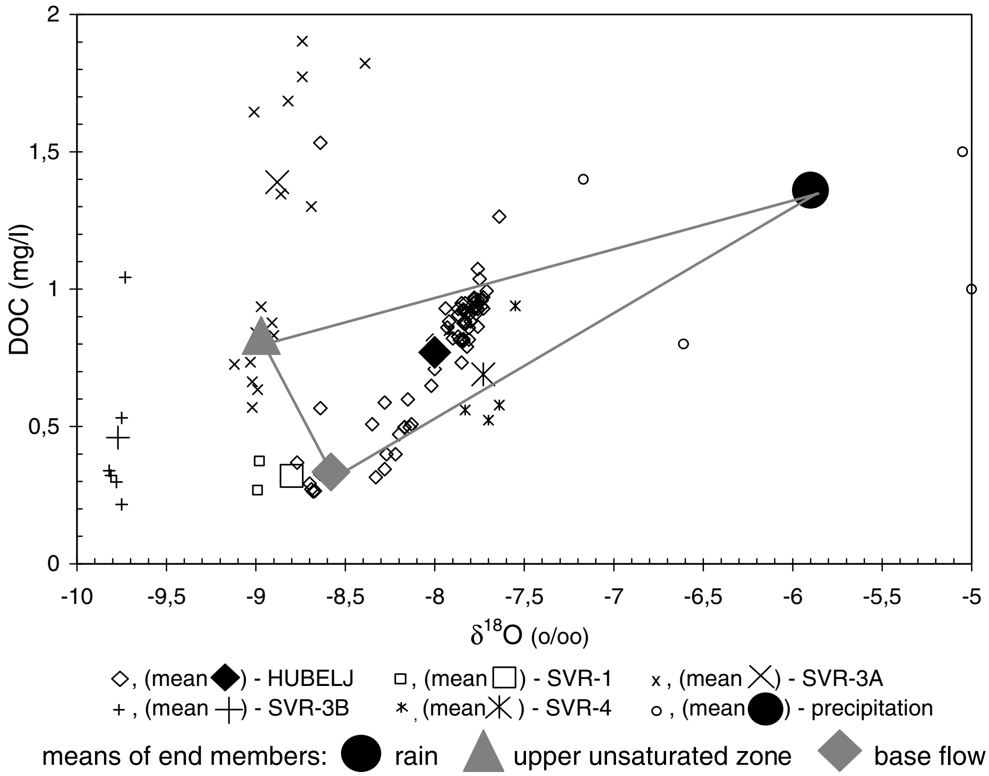

Fig. 7 Relationship between the sampled water $\delta^{18}O$ and DOC composition during the observed storm period in July 2000

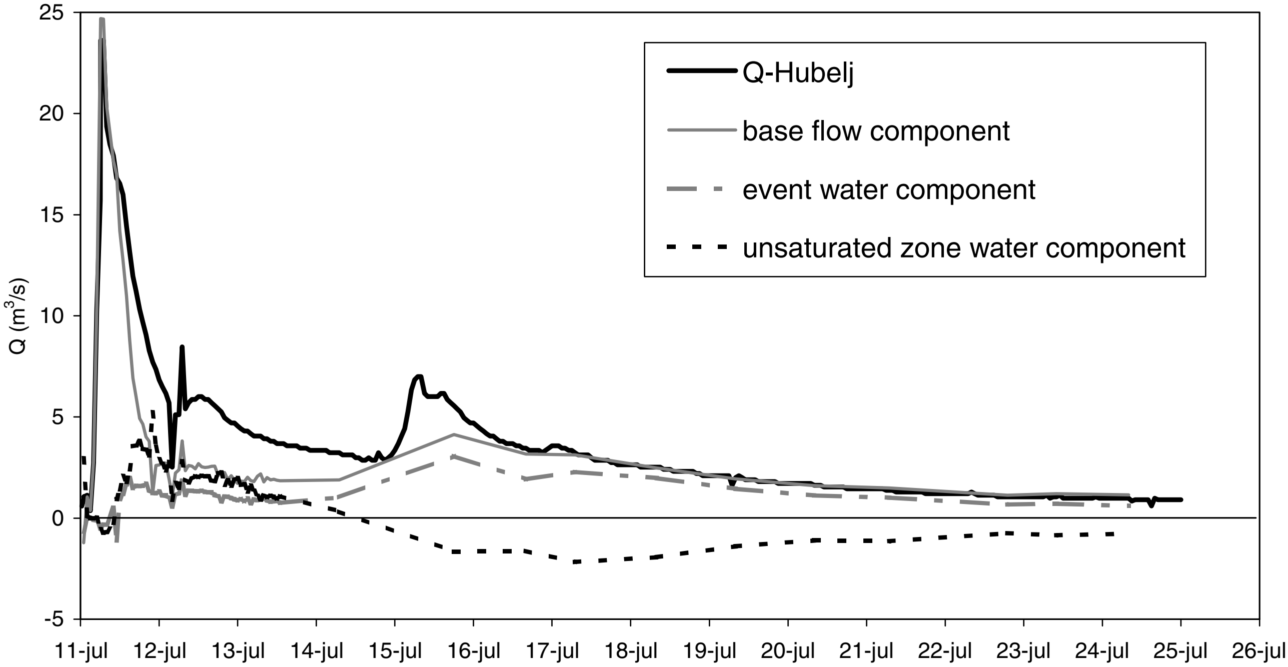

Fig. 8 Hubelj spring hydrograph separation into the (**a**) base flow, (**b**) upper unsaturated zone and (**c**) event water components

of the epiflow water component for each point of the Hubelj spring hydrograph, which is graphically illustrated in Fig. 9.

The hydrograph separation into the base- and epiflow components seemed to be much more realistic, especially at the end of the observed storm period (Fig. 9). It could

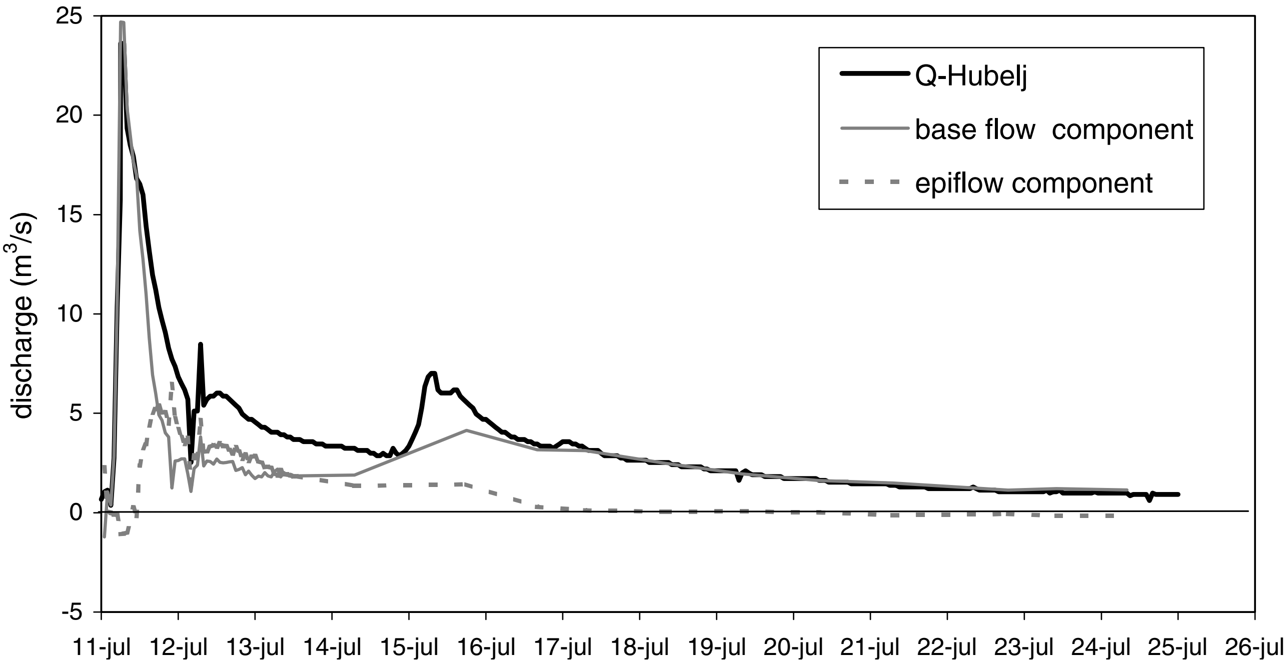

Fig. 9 Hubelj spring hydrograph separation into the (**a**) base flow and (**b**) epiflow components

be noticed that there was the epiflow breakthrough at the very beginning of the hydrograph rise, which did not contain any event water. This breakthrough resulted in the inversion of the hydraulic gradient—the pressure of the karst conduit network became higher than the one of the rock blocks. Hence, the recharge process had been tied to the karst conduit network during the hydrograph rise, and only waters that were prestored in the most permeable parts of the saturated and lower unsaturated zones have been discharged in the spring.

After the breakthrough, the epiflow component (as well as the combining components) has been negative throughout the hydrograph rise, which reflects the water concentration in the epikarst zone. The epiflow component portion began to increase in the initial hydrograph recession, when the hydraulic pressure of the karst conduit network decreased. The maximum value, 84%, was registered at the end of the first storm cycle. The epiflow component contribution had mostly decreased later on (only the second storm cycle slightly interrupted the trend) and reached a negative value on 21 July, when the inversion of the hydraulic gradient occurred again. Hence, there was only the diffuse recharge process in the aquifer from then, and only the base flow recharged the Hubelj spring. Negative values of the epiflow component indicate that the epikarst zone had to be internally recharged during this period.

The average contribution of the epiflow component to the Hubelj spring storm discharge was 48% during the first two storm cycles (containing 31% of the event water and 69% of the upper unsaturated zone water on average), while it was 41% during the observed storm period, respectively, (containing 54% of the event water and 46% of the upper unsaturated zone water on average).

Discussion

The presented results

- describe the flow and solute transport tracing during the summer storm event,
- indicate the shifts between the peak discharge and the peak water isotopic or chemical composition
- provide an insight into the recharge, storage and discharge processes.

The latter processes reflected

- the duality of recharge and discharge processes—demonstrated by the epiflow and the diffuse flow, as well as
- the flow and solute transport mechanisms—the piston effect and the breakthrough of the preferential flow.

During the observed storm period, 99% of water resulting from the storm cycles was discharged in the Hubelj spring. The average epiflow contribution to discharge was 41%. This flow contained 54% of the event water component on average, which represented 18% of the effective precipitation. Hence, it follows that 82% of the effective precipitation had to be stored in the aquifer and in the soil, but which part of the aquifer? What portion of the effective precipitation was stored or could be stored in the epikarst zone? What is the effective porosity of the epikarst zone in the catchment area of the Hubelj spring?

The answers to these questions and to relating ones are beyond the scope of this research, but they are a very important topic for further investigations. Besides, the results of the applied research method should be verified not only in the catchment area of the Hubelj spring but also in other study areas.

However, the presented information has already demonstrated that most of the effective precipitation should be stored at least temporarily at the base of the epikarst zone. In this regard the epikarst zone acts as a temporal distributor of the karst aquifer recharge. On the basis of numerous arguments, it is presumed that the aquifer flow and solute transport mechanisms, and hence the contaminant movement depend on the hydraulic behaviour of the epikarst zone that should completely depend on momentary conditions and essential change with time, which should be mostly regulated by the storage volume.

Conclusions

The presented data are in agreement with the proposed epikarst hypothesis which presumes that an important part of the karst aquifer recharge rapidly reaches into the karst aquifer conduit network from the epikarst zone.

A piston effect and the duality of karst aquifer hydraulic processes were established. The latter was verified by the storm hydrograph separation techniques, which demonstrated that a karst spring should be separated into

- the base flow component—a relatively slow diffuse flow from low permeability rock blocks of the lower unsaturated and saturated zones, and
- the epiflow component—a fast flow of (a) water that was prestored in the epikarst zone and (b) event water, which was concentrated at the base of the epikarst zone and later drained into the karst conduit network, where it could mix with the water of sinkholes.

It was demonstrated that during the hydrological event an epiflow breakthrough could cause an inversion of the hydraulic gradient that results in the concentrated recharge process through the karst conduit network, which could contribute up to 50% of the epiflow component to the spring storm discharge. However, it was indicated that the hydraulic behaviour of the epikarst zone should completely depend on momentary conditions and essential change with time. The storage volume of the epikarst zone should mostly control it—the extension of the epikarst zone accumulation and of a subsequent discharge to the aquifer lower parts depend on the soil and epikarst zone water saturation.

The results could contribute not only to the scientific understanding of the phenomenon but also to its application. If the hydraulic behaviour of the karst aquifer is clearly understood, then also efficacious characterisation and monitoring strategies for sustainable water management could be recommended.

Although the results may seem more theoretical than practical with respect to the engineering issues, the authors consider them also of great practical values. It was demonstrated that the vertical recharge over the tunnel area is much slower than in the most conductive areas. Further, it was evidenced that also over the tunnel some restricted areas provide a quicker vertical transfer as most of the area. The generally accepted fact of spatial variability of karst vulnerability was clearly pointed out. It is linked to the structural and topographic forms, which may be further implemented in the setting of engineering works with respect to these features.

Acknowledgements The authors would like to acknowledge the Slovene Ministry of Education, Science and Sport for the financial support of these researches.

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