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ORIGINAL ARTICLE

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How can the epikarst zone influence the karst aquifer hydraulic behaviour?

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Abstract The role of an epikarst zone in the karst aquifer hydraulic behaviour was brought into focus in our studies referring to the catchment area of the Hubelj spring (SW Slovenia). This study points out the significance of effects of the fast preferential flow—epiflow, which is the main factor controlling solute/contaminant transport towards the aquifer saturated zone. The so-called epikarstic hypothesis is verified on the basis of the most significant research results that are supported by the most important findings from the literature.

Keywords Karst aquifer · Epikarst zone · Hydraulic behaviour · Natural tracers · Slovenia

Introduction

The study of flow and solute transport mechanisms have been undertaken in a karst aquifer in the catchment area of Hubelj spring in southwestern Slovenia (Fig. 1), with the intention to answer several questions connected with problems which result from the duality of the aquifer recharge, storage and discharge processes.

The study area is a high karstic plateau, Trnovski gozd, with a mean altitude of 900 m asl and an average annual precipitation of 2,450 mm. The catchment consists mostly of the Jurassic limestone and occupies 50–80 km^2. The research was centred at three areas of the observed aquifer: the recharge area, the upper unsaturated zone and the discharge area. The latter was investigated in Hubelj spring and the first two at the experimental field site of Sinji vrh, which is 600 m above the spring (Fig. 1). The upper unsaturated zone was investigated in an artificial tunnel 5–25 m below the surface (Fig. 2).

The study was based on natural tracers that are important tools for investigating flow systems, mixing processes, residence times and connected storage properties of groundwater, dilution and transport phenomena.

The results verified the so-called epikarstic hypothesis presuming that an important part of a karst aquifer recharge arrives, rapidly and in concentrated form, from the epikarst zone. Numerous arguments indicate that the karst aquifer flow and solute transport mechanisms depend on the hydraulic behaviour of the epikarst zone. The most significant ones are described here and supported by the most important findings from the literature, with the intention to approach as much as possible the discussed hypothesis.

Results

The study problem is based on a karst aquifer model that consists of three hydrogeological zones (Fig. 3):

1. The upper unsaturated zone, including
   a. Storage zones in soil
   b. Storage zones in the epikarst zone
2. The lower unsaturated zone, including
   a. Storage zones in larger fractures and conduits
   b. Storage zones in less permeable rock blocks

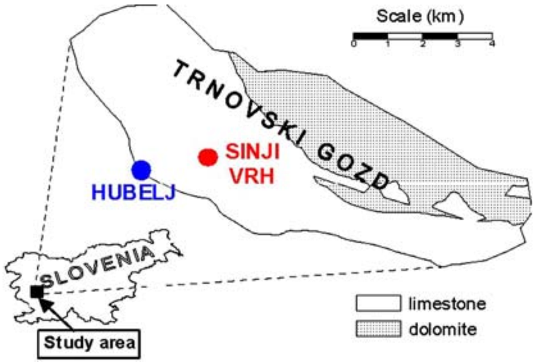

Fig. 1 Study area

3. The saturated zone, including
    a. Storage zones in larger fractures and conduits
    b. Storage zones in less permeable rock blocks (Trček 2001; Trček and Krothe 2002)

Results of the previous research

The following recapitulation of the theory of the epikarst zone is based on works by Mangin (1975), Gunn (1983), Williams (1983), Klimchouk (1995, 2000), Kiraly et al. (1995) and Petrič (2002).

The epikarst zone is defined as a region in the upper unsaturated zone lying below soil horizons. It is structurally different from the lower unsaturated zone owing to a larger and more uniform fracturing, which results in a much higher hydraulic conductivity. The differences in fracturing are observable for 15–30 m in depth, as a rule (Klimchouk 2000), because the fracture width exponentially increases towards the surface.

The described difference between the upper and lower unsaturated zones and a lack of main drainage paths in the former zone allow water concentration at the base of the epikarst zone and thus storage in a perched epikarst aquifer. The epikarst zone plays the role of a Faraday cage with respect to lower aquifer parts, resulting in the water concentration and storage (Kiraly et al. 1995). The flow converges towards enlarged tectonic fractures that are connected with shafts which were formed in the lower unsaturated zone. These fractures have a high permeability and a high hydraulic capacity that assures concentrated recharge of shafts. They are used as the main drainage paths for water conduction from the epikarst zone into the karst conduit network. The aquifer is mainly recharged through this system, as the contributions of diffuse recharge are small.

Water could be retained in the epikarst zone some days to several months (Gunn 1983; Williams 1983; Klimchouk 1995). The storage volume depends on (1) the age of the epikarst zone, and (2) the hydraulic

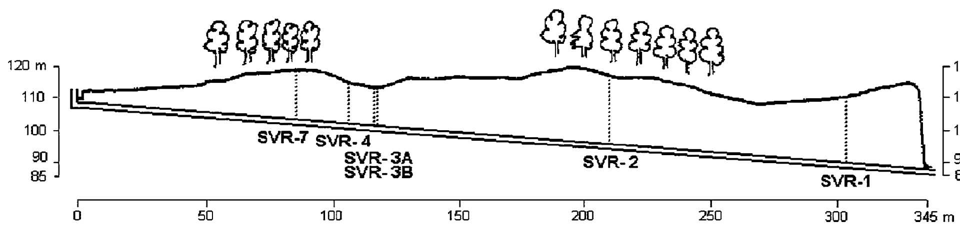

Fig. 2 Longitudinal profile of the Sinji vrh tunnel, with sampling points for the groundwater isotopic and chemical analyses

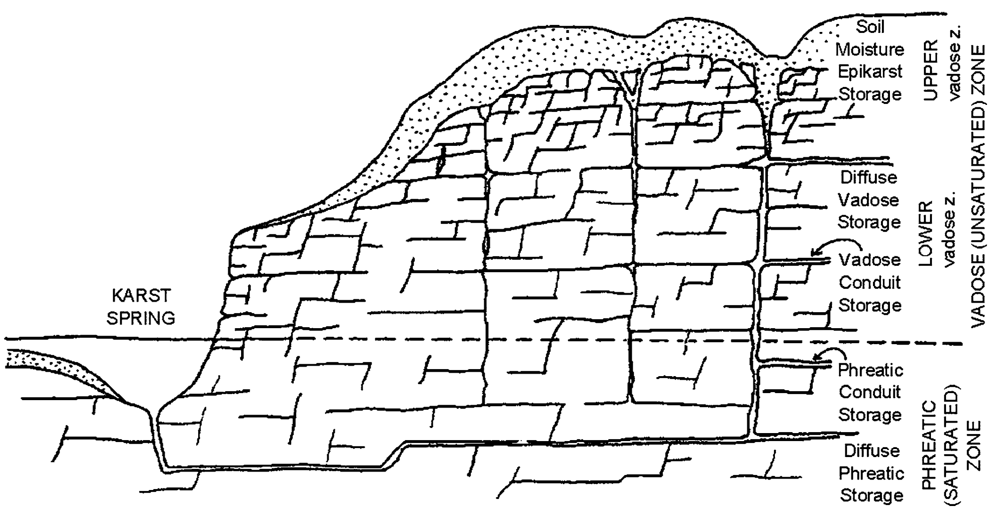

Fig. 3 Conceptual model of the karst aqufer (modified after Lakey and Krothe 1996; Trček and Krothe 2002)

conductivity differences between the epikarst and lower unsaturated zones. In addition, it also depends on the local conductivity and the development of the karst conduit network.

Like the karst aquifers, the epikarst zone is also very heterogeneous. It may develop 10 cm to 30 m deep (Klimchouk 2000). The distribution and hydraulic capacity of vertical flow paths in the lower unsaturated zone (i.e., shafts) influence the continuance of the epikarst zone.

Results of the research in the catchment area of the Hubelj Spring

The methodological concept of the natural tracer research was designed on a multi-parametric approach—the oxygen isotopic composition (δ^{18}O) and the dissolved organic carbon concentration (DOC) of the precipitation, tunnel seepage water (Fig. 2) and Hubelj spring samples were leader parameters. Sampling was performed in two stages, the long-term sampling during the period from 1999 to 2000, and the short-term sampling during the storm event in July 2000.

Among the results of the long-term sampling stage, the most important ones are the age estimations of sampled groundwater based on the δ^{18}O monitoring (Trček 2001). Differences between the seasonal variation of δ^{18}O in precipitation and in groundwater were taken into consideration. Because there is just a 2-year series of data for the study area precipitation, the data of the nearest compatible precipitation station (Ljubljana) were used. Polynomial trends (amplitudes and their phase shifts), linear trends and annual averages of sampled water δ^{18}O were compared (Fig. 4). Because of the typical δ^{18}O seasonal variation and its positive linear trend, the average residence time of the SVR-7, SVR-4, Hubelj and SVR-3A groundwater should be less than 5 years. On the other hand, the average residence time of the SVR-3B, SVR-1 and SVR-2 groundwater should be longer, owing to the untypical δ^{18}O seasonal variation and its negative linear trend. The estimations of the groundwater average residence time for single sampling points are 3 months for the SVR-7 groundwater, 9 months for the SVR-4 groundwater, 2–3 years for the Hubelj spring, 4–5 years for the SVR-3A groundwater, 5–6 years for the SVR-3B groundwater and at least 10 years for the SVR-1 and SVR-2 groundwater (it can be one or more decades longer).

According to the relevant information from the literature, the presented data indicate that the tunnel should penetrate the epikarst zone as well as the lower unsaturated zone.

The short-term sampling stage refers to the study of the karst aquifer hydraulic reaction to the storm event. The hydrograph separation techniques were applied to determine the contributions of different end members to the discharges of sampling points (Trček 2003).

By the two-component separation technique, hydrographs of the tunnel sampling points were separated into (1) event, and (2) pre-event water components (Trček 2003). The results indicated that the old pre-event water mostly recharged the sampling points, which reflects the piston effect—the event water displaced the pre-event water in the unsaturated zone of the aquifer.

The applied sampling design allowed the Hubelj spring storm hydrograph separation into three end-members: (1) base flow, (2) upper unsaturated zone and (3) event water components (Trček 2003). However, the results indicated that according to the epikartic hypothesis, the event and upper unsaturated zone water components should be combined into one component

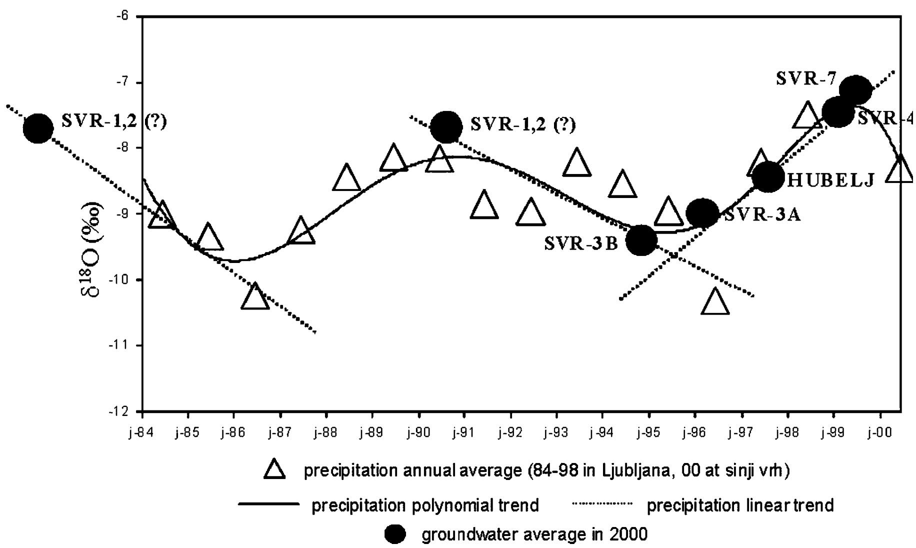

Fig. 4 Trends of the average annual δ^{18}O of the Ljubljana precipitation compared with the average annual δ^{18}O of groundwater samples

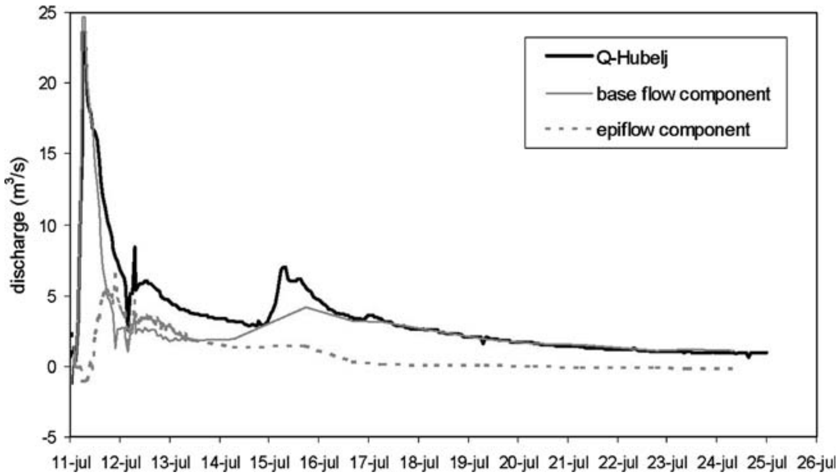

Fig. 5 Hubelj spring hydrograph separation into the (1) base flow and (2) epiflow component

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 (1) water that was pre-stored in the epikarst zone, and (2) the event water. Both were 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. The separation of the Hubelj spring hydrograph into the epiflow and base flow components is presented in Fig. 5. During the observed storm period their average contributions were 41 and 59%, respectively. Epiflow contained 54% of the event water and 46% of the upper unsaturated zone water component on average. These data reflect an important role of the epikarst zone in the karst aquifer recharge processes.

Discussion and conclusions

The results of both sampling stages and of previous researches were synthesized and interpreted in the conceptual model of the karst aquifer in the catchment area of the Hubelj spring (Fig. 3). On the basis of numerous arguments, the model presumes that the aquifer flow and solute transport mechanisms, and hence the contaminant movement depend on the hydraulic behaviour of the epikarst zone. As a consequence of the piston effect, which results from a hydrological event, the epikarst zone pre-stored water and the event water are concentrated in the base of the epikarst zone. The epikarst zone discharges this water to aquifer lower parts dependent on the water storage volume:

1. In the case of a small volume most of the water is retained and stored in the base of the epikarst zone—this water slowly seeps through tiny fractured rock blocks and diffusely recharges aquifer lower parts.
2. In the case of a large volume (1) part of the water could be rapidly drained through large fractures into the karst conduit network, where the epiflow is formed; the epiflow recharges the aquifer lower parts and the spring as long as the hydraulic pressure of the karst conduit network is higher than the pressure of the water in the rock blocks; (2) after the inversion of the hydraulic gradient, the remaining water is stored in the epikarst base and a diffuse recharge process is restored.

It was demonstrated that epiflow could occupy up to 50% of the spring discharge during the precipitation events. This phenomenon could have important consequences on protection and management problems of karst aquifers.

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