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Groundwater flow mechanism in the well-developed karst aquifer system in the western Croatia: Insights from spring discharge and water isotopes

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A B S T R A C T

Karst aquifers have a fundamental importance to water supply in many countries. Due to their specific hydrogeologic properties, these aquifers are sometimes difficult to use because of the high discharge variations of the karst springs and are almost always sensitive to pollution. With an aim to better understand karst aquifers, different research methods are used to study the karst groundwater system in Croatia.

The spring hydrograph and the stable isotope ($\delta^{18}O$, $\delta^{2}H$) compositions in the water samples collected from the Rječina and Zvir springs and precipitation were analysed and used to characterize the karst aquifer. The recession coefficient obtained from the hydrograph analysis indicates only a fast-flow spring component at the Rječina spring. The lack of the base-flow spring component is the primary reason for the spring drying out during the dry periods. The low recession coefficient of the Zvir spring indicates a base-flow and discharge from well-drained fissures and fractures in the spring catchment area during the low water stage. A mean residence time (MRT) of groundwater was calculated for stable isotope $\delta^{18}O$ using lumped parameter approach by applying the exponential model, combined exponential-piston and dispersion models to isotopic input (rainfall) and output (spring) data sets during 2011–2013. The MRT of 3.24 and 3.6 months for the Rječina spring and 7.2 months for the Zvir spring suggests recent groundwater recharge from precipitation.

1. Introduction

Spring discharge data are used to describe the hydraulic behaviour of aquifers, and the spring hydrograph shape is controlled by the hydrogeological characteristics of the catchment area and the climate conditions (Fig. 1). Identification of the karst aquifer characteristics from which an outflow occurs using the spring hydrograph analysis has been considered by various authors (Drougue, 1972; Newson, 1973; Mangin, 1975; Atkinson, 1977; Brutsaert and Nieber, 1977; Milanović, 1981; Bonacci, 1987, 1993; Bonacci and Jelin, 1988; Hess and White, 1988; Ford and Williams, 1989; Mudry, 1990).

Due to the different karst characteristics, there are two principal flow types (Atkinson, 1977; Gunn, 1986). Slow-flow (or base-flow) occurs through small karst fissures generally in the laminar regime. Turbulent fast-flow (or conduit flow) occurs in large fissures and karst conduits. There are many possible intermediate cases between these end-member flow systems where springs are fed from feeders of both types simultaneously (Dreybrodt, 1988). The base-flow spring component has been investigated since the end of the 19th century (Boussinesq, 1877, 1904; Maillet, 1905). In groundwater hydrology, it is important for the analysis of groundwater storage and exploitation.

In addition to the recession curve, auto- and cross-correlation analyses can be used to analyse spring hydrographs. The autocorrelation of the spring discharge is generally used to assess the interdependence of the spring discharge and the "memory effect" (Krešić and Stevanović, 2010). The cross-correlation method is used to analyse the connection between the input and output time series (Box and Jenkins, 1974; Mangin, 1984; Padilla and Pulido-Bosch, 1995; Larocque et al., 1998; Panagopoulos and Lambrakis, 2006; Kovačič, 2010).

Groundwater and precipitation isotope data can determine the mean residence time, which is an important aspect of the karst aquifer retention capability (Maloszewski and Zuber, 1982, 2002; Maloszewski et al., 1983, 1992, 2002; Rozanski and Dulinski, 1988; McGuire et al., 2002; Bakalowicz, 2005; Ozyurt and Bayari, 2005; Viville et al., 2005; Ogrinc et al., 2008; Wothington, 2007; Müller et al., 2013; Lauber and Goldscheider, 2014; Torkar et al., 2016).

Spring hydrograph analysis, environmental tracer measurements ($\delta^{18}O$, $\delta^{2}H$) and the interpretation of hydrodynamic and isotopic data is conducted for the catchment area of the Rječina and Zvir springs in western Croatia. A major objective of this study was to better

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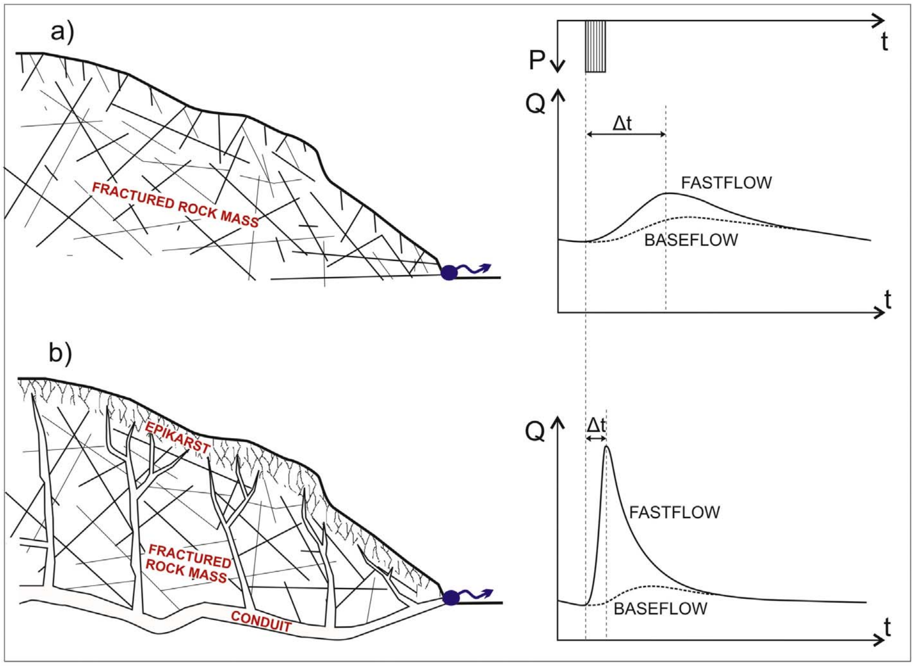

Fig. 1. Hydrograph characteristics of a spring draining a) a fissured aquifer and b) a karstic aquifer (Q – discharge, P – precipitation, t – time, Δt – time difference between precipitation and hydrograph peak).
(Kuhta et al., 2012, modified from Bonacci, 1993)

understand the hydrodynamics of the complex and well-developed karst aquifer system. By combining results of hydrograph analysis and water isotopes analysis, this study gives insights into groundwater flow mechanism and mean residence time which is needed to groundwater management and protection.

2. Study area

The study area is located in western Croatia and stretches from the Adriatic coast to the mountainous area to the north that encompasses parts of eastern Ćićarija, the peaks of the V. Snežnik (1796 m) in Slovenia and the mountainous area of west Gorski Kotar, including parts of Risnjak (1528 m) and Snježnik (1505 m) (Fig. 2). Between the mountain peaks and ridges, there are several fluvial valleys of glacial origin at altitudes between 900 and 1000 m. The total area of the basin that feeds the karst springs located along the coast of Rijeka is approximately 480 km^2. This is the most productive catchment area in the north Adriatic region and the primary potable water supply for the Kvarner Bay area (approximately 3 m^3/s during the dry summer seasons).

Considering the relief size and variety, the catchment area of the Rječina and Zvir springs is characterized by diverse climatic conditions. In the mountainous area, a continental climate with cold winters is dominant, while a mild Mediterranean climate prevails in the coastal area. The amount of rainfall increases from an average of 1500 mm per year in the coastal area to over 3500 mm in mountainous areas of Snježnik and Risnjak. Precipitation is fairly evenly distributed, with slightly larger amounts in the colder period of the year. In the mountainous areas, there is often abundant snowfall. At the peak areas of Gorski Kotar, snow cover can last > 100 days (Zaninović et al., 2008). The average annual temperature in the city of Rijeka is 13–14 °C, and in the Rječina spring area it ranges from 9 to 11 °C. In the mountainous region of Gorski Kotar and V. Snežnik in Slovenia, the annual mean temperature decreases to 3 °C (Zaninović et al., 2008).

The very short-term heavy rainfall has a dominant influence on the runoff regime, causing the surface water in the study area to flood and causing the rapid infiltration of rainwater and surface water in the karst aquifer. The most significant watercourse is the Rječina river, however, it has a periodic nature.

The geological structure of the study area is presented most completely in the Basic Geological Map at a scale of 1:100.000 for the sheet Ilirska Bistrica and in the accompanying guidebook (Šikić et al., 1972; Šikić and Pleničar, 1975), as well as in the Geological Map of the Republic of Croatia at a scale of 1:300.000 (Croatian Geological Survey, 2009a,b).

The study area belongs to the Dinaric karst that is characterized by an over 8000 m succession of predominantly carbonate sediments (Vlahović et al., 2005) that were deposited and exposed to intense tectonic disturbances in several phases from the Triassic period to the present. The primary deformation episode began in the Late Cretaceous, when synsedimentary tectonics increased and reached a maximum in the Oligocene/Miocene. This led to tangential movements and uplift of the Dinarides, including the expanded area of the Rječina and Zvir springs. Due to the strong NE-SW-oriented regional tectonic stress, the primary resulting structures, including folds, faults, thrusts and imbricate structures, have a NW–SE strike (i.e., the Dinaric strike). Later, orogenic movements shifted the regional tectonic stress to the N–S direction and caused wrenched tectonic deformations.

Research on the hydrogeological characteristics of the wider area have been described by Biondić et al. (1979, 1997), as well as in many professional reports. The study area has dominant karst features (Kuhta, 2001). The primary part of the catchment consists of shallow-water carbonates, mostly limestones and dolomites with subordinate carbonate breccias, deposited from the Lower Jurassic to the Eocene. Within the carbonate complex, three rock groups with different hydrogeological characteristics may be distinguished (Fig. 2). The lithostratigraphic units that primarily consist of limestones represent highly permeable medium and generally the main groundwater collectors. The units characterized by approximately equal dolomite and limestone compositions are considered medium permeable carbonate rocks. The units that primarily consist of dolomites and dolomite breccia represent a low permeable medium, and very often form local barriers to groundwater flow or they direct these flows along the bounding structures.

Although Eocene flysch deposits have limited distribution due to the narrow belt striking from Slovenia to the coastline (Bakar), their hydrogeological role is very significant. The flysch deposits are lithologically heterogeneous; however, due to the dominance of marls, when considering this sediment series in its entirety, it is impermeable to water. Considering their thickness and structural position in the Klana