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Northern Velebit (Croatia) karst hydrological system: results of a preliminary $^2$H and $^{18}$O stable isotope study

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1. INTRODUCTION

Dissolution of soluble rocks such as limestone, dolostone and gypsum, forms a special type of hydrogeological system, which is often reflected at the surface by the distinctive landscape known as karst. Karst aquifers are characterized by extremely heterogeneous hydraulic properties manifested by rapid groundwater flows concentrated in conduits and dissolutionally widened fractures, usually sparsely distributed, while the storage of groundwater is mainly related to surrounding fractured rock matrix and surficial epikarst (or subcutaneous) zone (GOLDSCHEIDER et al., 2007).

Because of its complexity, karst aquifer research necessitates an interdisciplinary approach (DREYBRODT, 1988; COVINGTON et al., 2011). In addition to conventional methods, the use of environmental stable isotope tracers supplemented by statistical analysis, contributes to a better understanding of karst hydrogeology (CRISS et al., 2007; PALMER, 2010; GRIMMEISEN et al., 2017). Stable isotopes of water ($^2$H and $^{18}$O) are analysed for several reasons, e.g. to explore recharge processes and reservoir mixing (LONG & PUTNAM, 2004; MALOSZEWSKI et al., 2002), to explore vadose water mixing, residence times and storage in non-conduit parts of karst systems (PALMER, 2010; MORRERMAN et al., 2014; DOŠA et al., 2011), to estimate mean recharge area elevations (BARBERI et al., 2005; CHARIDHE & RAHMAN, 2007), etc.

Detailed knowledge of the various processes within a karst hydrological system is crucial for the sustainable management of water resources, their allocation, and protection against pollution (MANCE et al., 2018 a, b). The black-box approach is often used in karst hydrogeological research. It is based on rainfall – spring discharge modelling and water quality relationships, which are usually insufficient to reveal all the complexity of the various processes that control groundwater flow through the karst underground. The grey-box approach to karst systems research, besides the input-output relations, employs additional data acquired directly from underground i.e. in caves. Therefore, grey-box models are often more realistic and should be able to determine in more detail the system’s flow paths, linkages, stores, capacities, and throughput volumes than the black-box model (FORD & WILLIAMS, 2007).

The research area of interest, the area of Northern Velebit (Croatia), has been the subject of earlier hydrogeological investigations (PAVIČIĆ, 1997; STROJ, 2010), but a number of parameters required to model the system’s behaviour are still unknown (MALOSZEWSKI, 2000). During the last few decades, many deep caves were discovered in the Northern Velebit karstic massif (BAKŠIĆ et al., 2013), providing an opportunity to gather some new and direct insights into its hydrogeology (STROJ & PAAR, 2019).

The aim of the present preliminary study was to gather new insights into water infiltration and vadose flow properties within the karst massif by determining the $\delta^2$H and $\delta^{18}$O of water in various compartments of the system. Precipitation samples were collected from three locations situated on Mt. Velebit hilltops, while groundwater samples were collected in the caves and at the main discharge outlets of the system. The results presented provide guidelines for establishing a new research project supplemented...
by systematic and more frequent data collection. This could ultimately contribute to the development of a comprehensive conceptual hydrogeological model of the Northern Velebit system.

2. STUDY AREA

The study area is located in the Croatian part of the Dinaric karst, specifically in the northern part of a 145 km long Velebit coastal mountain range (Fig. 1), which is part of the external Dinaric mountains separating the Adriatic Sea coast from the large karst poljes of the Lika, and Gacka rivers that sink in its hinterland. The Northern Velebit area, designated a National Park, covers an area of approximately 109 km$^2$. It has a form of high karst plateau intersected by numerous karst depressions separated by peaks and ridges (the highest peaks are 1600 – 1700 m a.s.l.). The largest part of Northern Velebit is composed of Jurassic carbonate rocks, mainly limestones, and massive calcareous (limestone) breccias of Upper Paleogene to Lower Neogene age (MAMUŽIĆ et al., 1969; VELIĆ et al., 1974; VELIĆ & VELIĆ, 2009). Clastic rock formations of Triassic and Palaeozoic ages form a hydrogeological barrier in the middle-southern parts of the Velebit mountain range. The deeper position of these rocks in the northern part enables deep karstification and underground water flow from the hinterland towards the Adriatic Sea (Fig. 2).

The geological structure of the Velebit mountain range is the consequence of two principal periods of tectonic activity (BLAŠKOVICIĆ, 1998; KORBAR, 2009). The first was the main phase of the Dinarides orogenesis (Eocene – Miocene) with compressive movements oriented NE – SW. As a result of the regional tangential stress, deep nappe structures, folds and regional faults of Dinaric strike (NW – SE) have been formed. The second, so-called neotectonic phase, started probably during the late Miocene or early Pliocene, when the main stress changed to NS, resulting in further uplifts and transpressive deformations of older structures. The later phase played a crucial role for the present mountain morphology.

Geological observations in caves revealed complex geological structures expressed by widespread occurrences of compact carbonate breccias down to depths of approx. 1000 m below surface, e.g. in the Lukina jama – Trojama and Velebita cave system (STROJ & VELIĆ, 2015). The breccias in the caves often irregularly intersect a normal succession of Jurassic limestones which points to their tectonic origin. This is commensurate with the assumption that the origin of the breccias observed at the surface is related to strong tectonic movements during the Upper Paleogene and Lower Neogene (BAHUN, 1974). Pronounced resistance to the mechanical erosion of massive carbonate breccia together with its solubility dominates the surface relief forming processes. This enhances the development of distinctive karst corrosion landscapes where the entrances of the most important caves are located. Such landscapes, together with occurrences of extremely deep caves, are instrumental in the National Park designation. Discovery and research of deep caves also revealed a very deep vadose zone of more than 1000 m inside the carbonate massif, as well as some characteristics of epiphreatic zone dynamics at the bottom of the vadose zone (BAKŠIĆ et al., 2013; STROJ & PAAR, 2019).

Sinkholes of the Lika and Gacka rivers are located on the eastern foothills of the Northern Velebit massif (Fig. 2). In the past, the rivers sank completely into the karst massif and reappeared at numerous coastal springs and vruljas (submarine
springs) along the coast on the western side of the massif (Fig. 2) (PAVIČIĆ, 1997; STROJ, 2010). The distance from the sinkholes to the Adriatic Sea is approx. 20 km. Today, the water from the two rivers is used for electricity production and is routed via a tunnel to the power plant on the coast. Only occasional water surpluses sink into sinkholes occurring on average only a few days per year. Taking into account the present conditions, the precipitation in the massif area is assumed to be the main water input for the system.

3. SAMPLING AND DATA

Precipitation samples were collected on a monthly basis from May 2012 to September 2013 on Velebit at three locations - Oltari, Sića, and Crikvena (Fig. 2). Geographical coordinates and altitudes of the precipitation sampling sites are provided in Table 1. Precipitation sampling was performed using samples with anti-evaporation system (GRÖNING et al., 2012). A total of 35 monthly precipitation samples were analysed for their stable isotope content (Table 2). Some of the samples are missing due to

**Table 1. Basic information about sampling locations.**

| Sampling location | Coordinates (latitude; longitude)* | Altitude (m a.s.l.) | Sample Type |
|-------------------|----------------------------------|--------------------|-------------|
| Hilltops          |                                  |                    |             |
| Sića             | 44.83970;14.96629                | 940                | precipitation |
| Oltari            | 44.87348;14.98443                | 1300               | precipitation |
| Crikvena          | 44.75878;14.98957                | 1641               | precipitation |
| Caves             |                                  |                    |             |
| Velebita Cave System** | 44.75755;14.98633 | 1550               | groundwater |
| Sirena Pit**      | 44.76797;14.98763                | 1500               | groundwater |
| Lukina Jama**     | 44.76693;15.02638                | 1450               | groundwater |
| Springs           |                                  |                    |             |
| Jurjevska Žrnovnica (JZ) | 44.90161;14.91036 | 0                | springwater |
| Starigrad Senj (SS) | 44.79790;14.88182             | 0                | springwater |
| Bačvica (BC)      | 44.64268;14.94525                | 1100               | springwater |

*degree; WGS84 system
**entrance

**Table 2. Basic information about precipitation samples.**

| Sampling location | Sampling period | δD (%) | δD st.dev. (%) | δ18O (%) | δ18O st.dev. (%) | d-excess (%) | d-excess st.dev. (%) | amount (mm) |
|-------------------|-----------------|--------|----------------|----------|-----------------|--------------|----------------------|-------------|
| Sića              | May 2012        | -66.62 | 1.00          | -9.90    | 0.00            | 12.58        | 1.00                 | 123.2       |
|                   | Jun 2012        | -27.21 | 0.27          | -4.79    | 0.02            | 11.11        | 0.28                 | 42.2        |
|                   | Jul 2012        | -30.14 | 1.00          | -4.62    | 0.00            | 6.82         | 1.00                 | 29.6        |
|                   | Sep 2012        | -27.21 | 0.27          | -4.79    | 0.02            | 11.11        | 0.28                 | 42.2        |
|                   | Oct 2012        | -30.14 | 1.00          | -4.62    | 0.00            | 6.82         | 1.00                 | 29.6        |
|                   | Dec 2012        | -57.12 | 0.35          | -9.33    | 0.01            | 17.52        | 0.36                 | 220.5       |
|                   | Jan 2013        | -60.15 | 0.08          | -9.39    | 0.01            | 14.97        | 0.19                 | 212.3       |
|                   | Apr 2013        | -38.77 | 0.43          | -6.94    | 0.04            | 15.15        | 0.44                 | 59.2        |
|                   | May 2013        | -48.25 | 0.10          | -8.00    | 0.01            | 15.75        | 0.10                 | 197.2       |

Oltari

| Sampling period | δD (%) | δD st.dev. (%) | δ18O (%) | δ18O st.dev. (%) | d-excess (%) | d-excess st.dev. (%) | amount (mm) |
|-----------------|--------|----------------|----------|-----------------|--------------|----------------------|-------------|
| May 2012        | -67.96 | 0.57           | -9.84    | 0.01            | 10.76        | 0.57                 | 132.6       |

Crikvena

| Sampling period | δD (%) | δD st.dev. (%) | δ18O (%) | δ18O st.dev. (%) | d-excess (%) | d-excess st.dev. (%) | amount (mm) |
|-----------------|--------|----------------|----------|-----------------|--------------|----------------------|-------------|
| May 2012        | -67.12 | 0.16           | -10.02   | 0.02            | 13.04        | 0.17                 | 132         |
sampling locations inaccessible during severe winter weather conditions. Also, some samples had to be discarded due to an overflow of collectors (November 2012), while others were not suitable for the analysis due to insufficient volume (August 2012, summer 2013).

Water samples in the Velebita cave system (VCS, entrance approx. 1550 m a.s.l., Fig. 2) were collected during Summer 2012 and Summer 2013 spelaeological expeditions. A total of 20 groundwater samples were collected in the caves. Samples were collected during dry summer days as summer storms increase the probability of sudden, increased water flows through cave passages, which is dangerous for cavers. The VCS sampling in 2012 started at a depth of approx. 100 metres, and continued to 1026 metres depth (Table 3). In 2013, two samples were collected in the VCS at a depth of approx. 600 m, and one sample was collected in the Lukina jama cave (entrance at approx. 1450 m a.s.l., Fig. 2) at a depth of 1000 m. The 2013 expedition also included the Sirena Pit (entrance approx. 1500 m a.s.l., Fig. 2) where one sample was collected at 45 m depth. Basic information about groundwater sampling in the caves is provided in Tables 1 & 3.

The main coastal springs along the western foothills of the massif: Bačvica (BC), Jurjevska Žrnovnica (JZ) and Starigrad Senj (SS), were sampled in the summer of 2012 (Fig. 2). Additionally, two samples were collected from Štirovača spring (ST), located in the central part of the Velebit massif at 1100 m a.s.l. (Fig. 2). A total of 9 spring water samples were collected (Table 4).

All collected samples (precipitation, groundwater collected in caves and spring water) were stored in 50 ml, double capped, polyethylene bottles until analysis.

The Meteorological and Hydrological Service provided meteorological data for the Zavižan meteorological station (1600 m a.s.l.), the only permanent meteorological station on Northern Velebit.

### 4. MEASUREMENT AND ANALYSIS

Stable isotope measurements were performed using the water equilibration technique (HORITA & KENDALL, 2004) on a Delta plusXP (Thermo Finnigan) isotope ratio mass spectrometer. An HDO eq48/24 (IsoCal) equilibration unit and a Dual Inlet

| Sampling location | Altitude (m a.s.l.) | Cave depth (m) | Sampling date | δ²H (‰) | δ¹⁸O (‰) | d-excess (‰) |
|-------------------|---------------------|----------------|---------------|----------|----------|--------------|
| VCS 1462          | -95                 | 31-Jul-12      | -63.05        | 0.73     | -9.3     | 0.01         | 11.35       | 0.73       |
| VCS 977           | -580                | 31-Jul-12      | -61.49        | 0.72     | -9.66    | 0.00         | 15.79       | 0.72       |
| VCS 977           | -580                | 31-Jul-12      | -60.66        | 0.28     | -9.6     | 0.00         | 16.14       | 0.28       |
| VCS 772           | -785                | 1-Aug-12       | -60.92        | 0.03     | -9.47    | 0.01         | 14.84       | 0.04       |
| VCS 707           | -850                | 1-Aug-12       | -62.17        | 0.11     | -9.57    | 0.01         | 14.39       | 0.11       |
| VCS 687           | -870                | 1-Aug-12       | -62.17        | 0.09     | -9.59    | 0.01         | 14.55       | 0.09       |
| VCS 582           | -975                | 1-Aug-12       | -62.39        | 0.02     | -9.72    | 0.01         | 15.37       | 0.04       |
| VCS 531           | -1026               | 2-Aug-12       | -62.98        | 0.49     | -9.78    | 0.00         | 15.26       | 0.49       |
| VCS 777           | -780                | 2-Aug-12       | -60.69        | 0.85     | -9.47    | 0.00         | 15.07       | 0.85       |
| VCS 597           | -960                | 2-Aug-12       | -61.47        | 0.96     | -9.7     | 0.01         | 16.13       | 0.96       |
| VCS 531           | -1026               | 2-Aug-12       | -62.17        | 0.68     | -9.72    | 0.00         | 15.59       | 0.68       |
| VCS 531           | -1026               | 2-Aug-12       | -62.4         | 0.65     | -9.56    | 0.01         | 14.24       | 0.65       |
| VCS 531           | -1026               | 2-Aug-12       | -61.84        | 0.83     | -9.69    | 0.00         | 15.68       | 0.83       |
| VCS 1457          | -100                | 3-Aug-12       | -62.13        | 0.42     | -9.39    | 0.02         | 12.99       | 0.42       |
| VCS 707           | -850                | 4-Aug-12       | -62.02        | 0.8      | -9.6     | 0.01         | 14.78       | 0.8        |
| VCS 531           | -1026               | 4-Aug-12       | -61.34        | 0.11     | -9.68    | 0.00         | 16.1        | 0.11       |
| VCS 977           | -580                | 1-Aug-13       | -66.29        | 0.11     | -10.23   | 0.01         | 15.55       | 0.12       |
| VCS 977           | -580                | 1-Aug-13       | -65.86        | 0.2      | -10.19   | 0.02         | 15.66       | 0.2        |
| Lukina jama       | 475                 | 2-Aug-13       | -68.11        | 0.14     | -10.44   | 0.03         | 15.41       | 0.16       |
| Sirena Pit        | 1453                | 5-Aug-13       | -70.19        | 0.15     | -10.85   | 0.04         | 16.61       | 0.18       |

VCS – Velebita Cave System

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system (Thermo Finnigan) were peripheral units. $\delta^2$H and $\delta^{18}$O values are expressed relative to the Vienna Standard Mean Ocean Water (VSMOW) standard. The measurement precision was better than 0.1 ‰ in case of $\delta^{18}$O, and better than 1 ‰ for $\delta^2$H. Accordingly, the measurement error for d-excess is calculated to be 1.04 ‰ (CRIS, 2007). Normalization and analyses of measurements were performed by the US Geological Survey Laboratory Information Management System.

Statistical calculations were conducted in Statistica 13.0 (Statsoft Inc., Tulsa, OK, USA). The descriptive statistics for data that are normally distributed are presented with arithmetic mean and standard deviation, while data that do not follow a normal distribution are presented with the median and minimum and maximum values. To test whether a sample distribution matches the characteristics of a normal distribution we used the Kolmogorov-Smirnov test. A measure of the linear correlation between two variables is expressed with the Pearson correlation coefficient ($R$). The relationship between two variables was determined by linear regression analysis. Testing the differences between the continuous variables was accomplished by $t$-test (for normally distributed data) or Mann-Whitney test (for data that do not follow a normal distribution), and regarding the categorical variables by $\chi^2$-test. The level of statistical significance was chosen at $p < 0.05$.

5. RESULTS AND DISCUSSION

5.1. Meteorological conditions in the hydrological years 2012 and 2013

Daily air temperatures of the hydrological year 2012 (Oct 2011 – Sep 2012) and the hydrological year 2013 (Oct 2012 – Sep 2013) do not differ significantly (Mann-Whitney test, $p = 0.43$). The average monthly air temperatures for the period showed typical seasonal behaviour with the highest temperatures in summer and the lowest temperatures in the winter months (Fig. 3A).

Monthly precipitation during the hydrological year 2012 (median 218.6 mm; minimum 45.1 mm; maximum 462.9 mm) was significantly higher compared to the hydrological year 2012 (median 86.2; minimum 0.8 mm; maximum 278.3 mm) (Mann-Whitney test, $p = 0.001$). The thickest snow layer of 2011–2012 was 120 cm (Feb 2012), while in the winter season 2012–2013 the maximum snow thickness was 322 cm (March 2013, Fig. 3B).

5.2. Precipitation

Due to the small number of precipitation samples, we weren’t able to set up a Local Meteoric Water Line (LMWL) that would be relevant for a longer period. Nevertheless, there is a statistically significant correlation between $\delta^2$H and $\delta^{18}$O precipitation values ($R = 0.99; p < 0.001$). A corresponding precipitation regression line: $\delta^2$H = 7.15$ \times \delta^{18}$O + 6.14 ‰ ($R^2 = 0.98$) plots close to the Global Meteoric Water Line (GMWL) that expresses the worldwide average (CRAIG, 1961) (Fig. 4).

Given the strong correlation between $\delta^2$H and $\delta^{18}$O precipitation values, only $\delta^{18}$O values are mentioned below. The time series of precipitation $\delta^{18}$O shows higher values in the summer months than during the rest of the year (Fig. 5A). This is typical for low latitudes where ‘the amount effect’ accounts for $\delta$ variations: low isotopic signals in months with significant precipitation, and more positive isotopic signals in months with scarce rainfall (DANSGAARD, 1964).

The average d-excess value of precipitation samples is $(13.16 \pm 2.72)$ ‰. Fig. 5B shows that precipitation d-excess values are lower during summer than during the rest of the year. This is comparable to previously reported results from the bordering region with similar climatic conditions (MANCE et al., 2014). Therefore, we can conclude that the sources of the precipitation are comparable, i.e. that the dominant summer precipitation in the area of Northern Velebit originates in the Atlantic Ocean, while in winter there is the predominance of Mediterranean-origi-
5.3. Groundwater

The isotope measurements for samples collected in 2012 across the VCS profile (depths >1000 m) show a very small variation of δ18O values (Figure 6, Table 3). The average δ18O value of these samples is (-9.59 ± 0.13) ‰. The values are within a narrow range (< 0.5 ‰) and without the presence of a uniform vertical gradient. Stable isotope composition of the samples collected in caves corresponds to the lower part of the precipitation cluster (Fig. 4), indicating that the groundwater flowing through the cave during low water conditions is dominantly fed by the September – May precipitation (Fig. 5).

The relatively constant isotopic composition of the samples suggests that groundwater homogenization already occurs within the epikarst zone. The epikarst zone comprises a relatively shallow, but most intensely fractured and karstified subsurface zone where precipitation quickly infiltrates and could be temporarily stored (MANGIN, 1974; WILLIAMS, 1983). Water stored in such epikarst storages during the wet season slowly drains into the underlying vadose zone during the dry summer season. Therefore, we can conclude that consistent water characteristics across the VCS profile suggest that the cave streams are dominantly fed from the epikarst storages. The substantial inflow of water with different characteristics from deeper storages, i.e. from fractures in rock walls along the cave profile, would probably be reflected by more pronounced variations in the stable isotope composition with cave depth. It should be mentioned once again that all samples were taken during low water conditions. If samples were collected during summer storms, when fast infiltration can bypass epikarst storages through fractures widened by dissolution, δ18O would probably show different values, i.e. the isotopic composition would be more influenced by recent (summer) precipitation.

Cave samples collected during the 2013 expedition have lower δ18O values than those from the 2012 expedition (Fig. 6, Table 3). These observed differences are tentatively explained by the characteristics of the rainfall period that preceded the second expedition. Namely, lower isotopic values could be associated with higher levels of snow and rainfall during the hydrological year 2013 in comparison with hydrological year 2012 (Fig. 3).

Unfortunately, sampling along the complete VCS profile was not performed in 2013, and only samples at approx. 600 m depth were available. It is interesting that the sample taken in the Lukina jama in the same year has a very similar isotopic value. This suggests similar recharge mechanisms for different caves in the area.

It is generally considered that the preserved seasonal amplitude of the spring water isotopic signal indicates a mean residence time of ≤ 1 year (TRČEK & ZOJER, 2009, LAUBER & GOLDSCHREIDER, 2014). If lower isotopic values of the sampled groundwater in 2013 (Fig. 6) are a consequence of the characteristics of the preceding wet season, this points to a relatively short mean residence time of groundwater in storages before draining to the cave conduits. Nevertheless, this should be confirmed by longer and more extensive sampling of the precipitation, and groundwater in the caves.

The sample collected at a depth of 45 m from the Sirena pit in 2013 was depleted in comparison to other samples collected...
that year (Fig. 6). We may attribute the depletion of the sample to the probable origin of the water sampled from the snowmelt, as for snow lower isotopic values are expected (MANCE, 2014). Also, perennial snow accumulation was reported by the cavers in a deep dolina where the cave entrance is located.

For d-excess values of the samples collected in caves, we may also see that most of the data plots within the range of the measurement error (Fig. 7). The average d-excess value of cave collected samples is $(14.89 \pm 1.26)$ ‰. Approximately constant d-excess values of cave water samples indicate the absence of significant evaporation before infiltration, i.e. fast infiltration of precipitation to the epikarst storage. Similar d-excess values of cave samples collected in 2013 and 2012 indicate similar geographic origins of the precipitation recharging the system. The average d-excess value of samples collected in caves corresponds to the d-excess of precipitation collected in the period Sep 2012 – May 2013 $(14.61 \pm 1.57)$ ‰ (t-test, p = 0.28). This is an additional indicator of predominant groundwater recharge by the winter precipitation. The extreme d-excess values have samples collected at the highest altitudes i.e. the lowest cave depths. This may be explained by some contribution of newly infiltrated precipitation in the sampled water.

Fig. 4 shows that the samples from springs plot above the samples collected in caves. Water from coastal springs was slightly brackish due to seawater intrusion into the karst aquifer, which was manifested by the elevated conductivity of the spring water. Specific conductivity measured during sampling at the BC, JZ and SS springs was 6.7-7.0 mS/cm, 7.9 mS/cm and 13.8-14.7 mS/cm, respectively. Specific conductivity of the spring water during high flow conditions (when seawater intrusion doesn’t affect it) was approx. 0.3-0.4 mS/cm (STROJ, 2010). We estimated the seawater proportion in the spring water samples by applying two-component mixing analysis (PETERLLA & CELICO, 2013) based on the sample conductivities, unaffected groundwater conductivity and seawater conductivity (55 mS/cm, measured during sampling). The calculated proportion of seawater in the spring water was approx. 12 % at BC, 14 % at JZ and 25 % at SS springs. We further applied two-component mixing analysis for corrections of coastal springs’ isotopic compositions. Corrections were based on the estimated proportion of seawater and presumed seawater isotopic composition of $\delta^{18}O = +1$‰ (GAT et al., 2003). After the correction, groundwater samples from the springs have similar values to water from the caves in the same year (Tables 3 & 4), confirming the coastal springs are predominantly fed by the recharge from the massif.

Stable isotope compositions of groundwater collected in both, caves and springs, coincide with the precipitation regression line (Fig. 4). This indicates the meteoric origin of the groundwater without significant influence of additional post-precipitation fractionation.

The only sampled inland spring, located in the central, but somewhat lower part of the massif (1100-1300 m a.s.l.) is the Štirovača (ST) spring (Fig. 2). Both ST samples have $\delta^{18}O$ values which are comparable to, but slightly less depleted than those collected in caves (Tables 3 & 4) suggesting it is fed from its immediate surroundings. This is consistent with the geological situation: the spring is located close to the geological boundary with the impermeable clastic rocks situated on the southern margin of the Northern Velebit.

The $\delta^{18}O$ values of samples collected in the caves and the ST spring are comparable to values for some of the Gacka river springs sampled during summer months of 2005 – 2011 (MANDIĆ et al., 2008; OZYURT et al., 2014). This indicates similar mechanisms of winter (wet) season recharge of water storages, which are slowly drained during the dry season. The ST d-excess values are comparable to d-excess values of samples from the caves (Tables 3 & 4). This is another indication of similar water feeding into the caves and the ST spring. Lower d-excess values of coastal springs are probably a consequence of mixing with seawater or/and a small contribution from recent summer precipitation.

5.4. Preliminary conceptual model of the Northern Velebit hydrogeological system

Taking groundwater samples directly from the deep caves within the massif permitted the use of the grey-box model instead of the black-box model that takes into account only system’s input and output data. Fig. 8 shows a conceptual model of the Northern
Veleviš hydrological system developed on the basis of the results presented here, including the results of previous speleological and hydrogeological research (PAAR et al., 2008; STROJ, 2010; BAKŠIĆ et al., 2013; STROJ & PAAR, 2019).

The proposed conceptual model includes provision of significant storage capacities within the epikarst zone, situated immediately below the surface, down to the depth of a few metres (or few tens of metres in case of massive and well lithified carbonate breccias). During the dry season, the flow in cave conduits is mostly fed by the water stored in the epikarst during the previous winter / wet season. Across the vadose zone, the flow is fast and predominantly concentrated in conduits, which is expressed by constant isotope characteristics. The preliminary findings presented earlier suggest that the mean residence time of water stored in the system is relatively short, possibly less than a year. This is indicated by the cave water stable isotope composition influenced by characteristics of the preceding winter / wet season. Coastal karst springs, that are the main discharge points of the system, are predominantly fed by the water of similar characteristics as that observed in the caves. The infrequent nature and short duration of concentrated inflows from sinkholes on the Lika and Gacka rivers under present conditions limits their significance. Therefore, it may be concluded that epikarst storages on the massif are probably the main source of spring water during dry season.

6. CONCLUSIONS
The paper presents the results of a preliminary stable isotope study of the waters of the Northern Velebit karst hydrological system. The aim of the study was the application of a grey-box modelling approach to karst hydrogeological research. The approach combined the results from classical hydrogeological methods with the findings from the sampling of the water in the caves. The study used stable isotope analysis of water samples as a tool to investigate the functioning of the karst hydrogeological system.

The results of this study, together with the results from previous research enabled us to develop a preliminary conceptual recharge and storage model of the Northern Velebit karst system. The main features incorporated in the model are:

• groundwater storage is mainly related to the function of the epikarst zone;
• recharge of the epikarst occurs mainly during the wet / winter season;
• the mean residence time of epikarst storage is relatively short, probably within one year;
• the deeper vadose zone has a low storage capacity and water flows within are concentrated in conduits;
• system outflow via coastal springs and vruljas (submarine springs) in the base flow conditions is dominantly fed by epikarst storage of the massif.

Based on the obtained results, we conclude that the grey-box modelling approach is an improvement in the investigation of complex karst systems. In addition to classical hydrological methods, speleological investigations play an important role in this type of approach and give researchers the opportunity to study different hydrological processes in situ.

Although the number of analysed water samples is relatively low, limiting their interpretation, this study provides preliminary results, enabling the establishment of a recharge and storage model for the system that will serve as a basis for future research.

Establishing a future longer term monitoring programme for the Northern Veleviš hydrogeological system would provide data required to further test and upgrade the presented model. This would provide a better and more detailed understanding of the functioning of the Northern Veleviš karst system and enable efficient water management and nature conservation to be undertaken.

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