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Hydrodynamic characteristics of Mt. Biokovo foothill springs in Croatia

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ABSTRACT

Spring hydrographs and thermographs are a direct reflection of all processes that occur within aquifer systems. Therefore, they contain significant information about the hydrogeological characteristics of such systems. This article analyses hydrographs and thermographs from four springs located in the foothills of the Mt. Biokovo massif in southern Croatia. These springs are recharged by carbonate aquifers. Monitoring of yields and groundwater temperatures, as well as analysing hydrograph recessions, daily discharge and rainfall time series and water temperature dynamics, facilitated the identification of the main properties of the aquifer system located in the hinterland of the individual springs. Significant differences in the recharge mechanisms of individual springs were determined to be a consequence of varying geological conditions, degree of karstification and conduit network characteristics. The results suggest that the Cretaceous and Palaeogene basinal carbonate deposits (Kotišina limestones and breccias), the hydrogeology of which has not yet been studied, have the characteristics of permeable karstic rocks.

Keywords: karst hydrogeology, spring hydrograph, time series analysis, Biokovo

1. INTRODUCTION

A spring hydrograph is a direct reflection of all the physical processes that influence groundwater flow within an aquifer. Hydrographs of karst springs are characterised by pronounced, sudden changes of discharge, and a briefly delayed response to rainfall (BONACCI 1987, 1993; GOLDSCHEIDER et al., 2007), which differentiates them from hydrographs of springs that drain other aquifers, i.e. fissured and intergranular aquifers (Fig. 1). Rapid spring responses to rainfall occur mainly as a result of sudden infiltration to conduit systems related to the function of the subcutaneous (epikarst) zone (MANGIN, 1975; WILLIAMS, 1983, 2008; PRONK et al., 2009). When rainfall ceases, a sudden increase in flow is initially followed by a nearly equal sudden decrease, after which the decrease gradually slows, reflecting an alteration in the system dynamics. Hydrographs, therefore, reflect the characteristics of two main types of flow in an aquifer: fast-flow, which is determined by conduit systems and rainfall distribution properties, and base-flow, which is predominantly controlled by slow drainage of low hydraulic conductivity volumes in the aquifer (ATKINSON, 1977; PADILLA et al., 1994). Thus, the shape of a hydrograph is a significant indicator of an aquifer's characteristics and serves as the most important time series in analyses of the hydrogeological characteristics of karstic aquifers.

The Makarska Coast area extends along approximately 53 km of the Central Dalmatian coastline along the foothills and slopes of the Mt. Biokovo massif that stretches from Brela in the north to Gradac in the south (Fig. 2). This area is mostly supplied with water from the Regional Water Supply System, which intakes water from the Cetina River near Zadvarje. This system is important during dry periods, when tourism raises the demand for drinking water. In addition, the water supply system of the Makarska Coast includes six smaller water intakes built on the springs along the base of Mt. Biokovo. These intakes include the springs of Baška Voda, Makarski Vrutak, Orašje, Grebice, Podgorski Vrutak and Izbitac in Drašnice. Although their total yield during the summer is far below the actual consumption rate, the captured springs significantly contribute to the stability of the

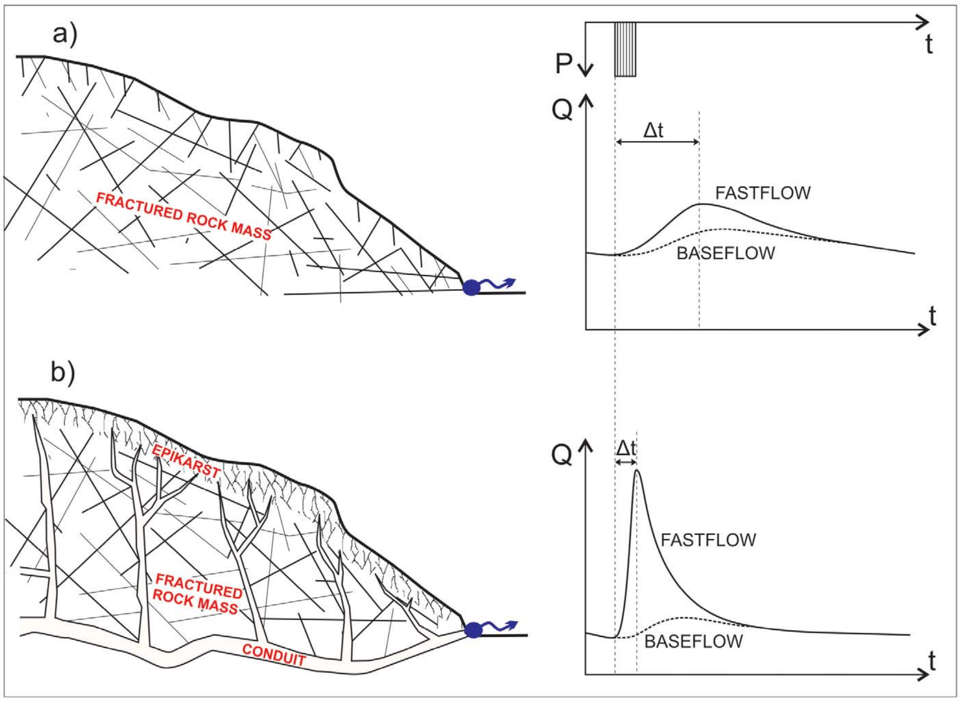

Figure 1: Typical hydrograph characteristics of a spring draining a) a fissured aquifer and b) a karstic (conduit) aquifer (Q – discharge, P – rainfall, t – time, Δt – time difference between rainfall and hydrograph peak; modified from BONACCI, 1993).

public water supply system, especially because the amount of water in the Regional System from the Cetina River is technically limited. During the tourist off-season, and particularly during favourable hydrological periods, the local water intakes alone satisfy the majority of water demands. These springs are especially significant due to their location high above the urban areas, which facilitates gravitational flow.

The majority of the springs on the southern slopes of Mt. Biokovo have not been investigated, and data on their yield and hydrogeological characteristics were based on the empirical insight of the Makarska Water Utility Company. Thus, during investigations to identify sanitary protection zones for springs used in the public water supply system, special attention was paid to the establishment of a system to continuously monitor yields at the technically adequate water intakes, including the springs of Makarski Vrutak, Orašje, Podgorski Vrutak and Izbitac in Drašnice. These data enabled hydrograph analyses to be made.

2. GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

The Dinaric karst is characterized by a succession of more than 8000 m of predominantly carbonate sediments (TIŠLJAR et al., 2002; VELIĆ et al., 2002), that was deposited and exposed to intense tectonic disturbances in several phases from the Triassic period until the present. The main deformation episode began in the Late Cretaceous, when synsedimentary tectonics became stronger, reaching a maximum in the Oligocene/Miocene. This led to tangential movements and uplift of the Dinarides, including the Mt. Biokovo area. Due to the strong NE–SW-oriented regional tectonic stress, the main resulting structures, including folds, faults, thrusts and imbricate structures, are of the NW–SE strike (i.e., the Dinaric strike). Later orogenic movements shifted the regional tectonic stress to the N–S and caused wrench tectonic deformations.

The main part of the Mt. Biokovo massif consists of shallow-water carbonates, mostly limestones with subordinate dolomites, deposited in the period from the Lower Jurassic to the Upper Cretaceous (Fig. 3). The basic structural form defines a large and prominent Biokovo anticline (MARINČIĆ et al., 1977) in the southwest. This anticline is in tectonic contact with highly deformed limestones that contain pelagic elements and carbonate breccias of the Upper Cretaceous-Palaeogene, (i.e., the Kotišina deposits) and/or a narrow belt of tectonically reduced flysch deposits. JELASKA et al. (2003) proposed a name for this basinal domain: the Kotišina-Tilovica trough. Palaeogeographically, this trough represents a NW embayment of the Budva-Cukali basin (CHOROWICZ, 1975). Basinal carbonate deposits, were tectonically emplaced into the Dinaridic segment, which had been previously over thrust on them (KORBAR, 2009; KORBAR et al., 2010).

In the SW, these carbonate units are in reverse contact or are overthrust over intensely deformed, predominantly clastic flysch deposits of the Middle and Upper Eocene, which comprise the foothills of Mt. Biokovo. In several places, gently inclined flysch slopes are covered by tens of metres of deluvial and proluvial Quaternary deposits. Recent debris is frequently found below the steep carbonate slopes.

The carbonate deposits of the Mt. Biokovo massif are intensely tectonically fragmented and karstified, and in hydrogeological terms they form a permeable environment in which a deep karst aquifer has developed (Fig. 3). The high karst plateau is dominated by numerous deep dolines, which often contain karst pits. Several hundred pits have been in-

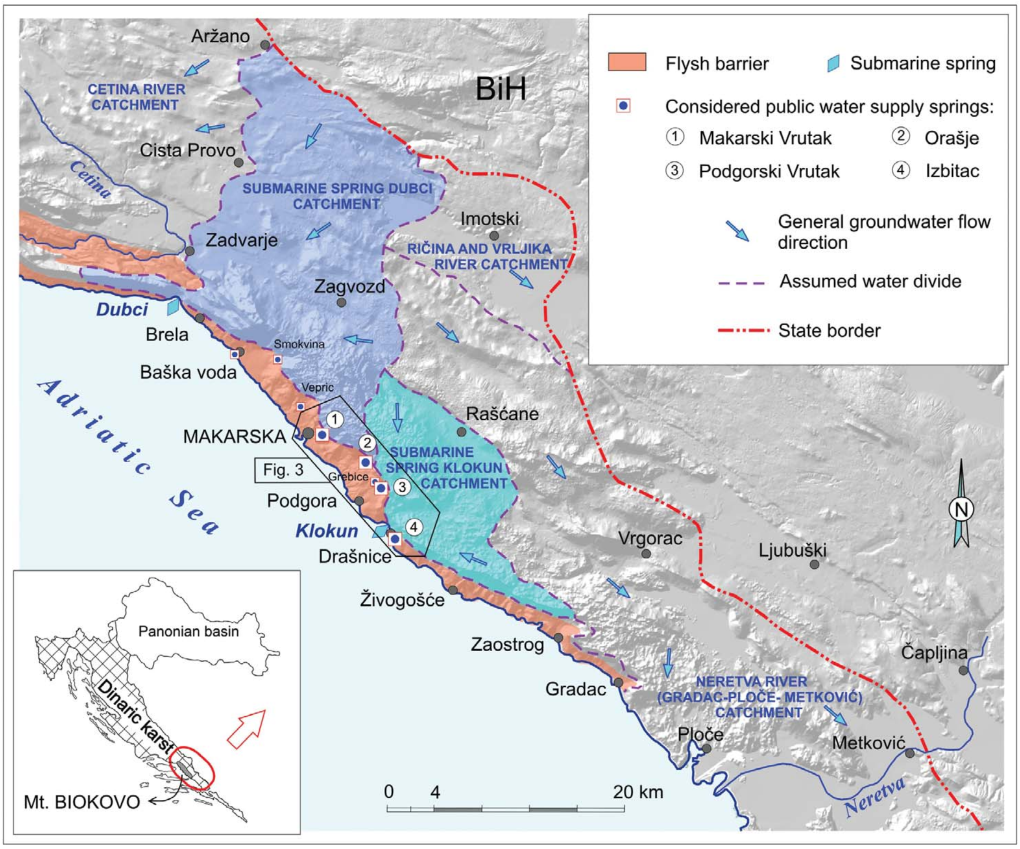

Figure 2: Regional catchments and locations of the investigated springs.

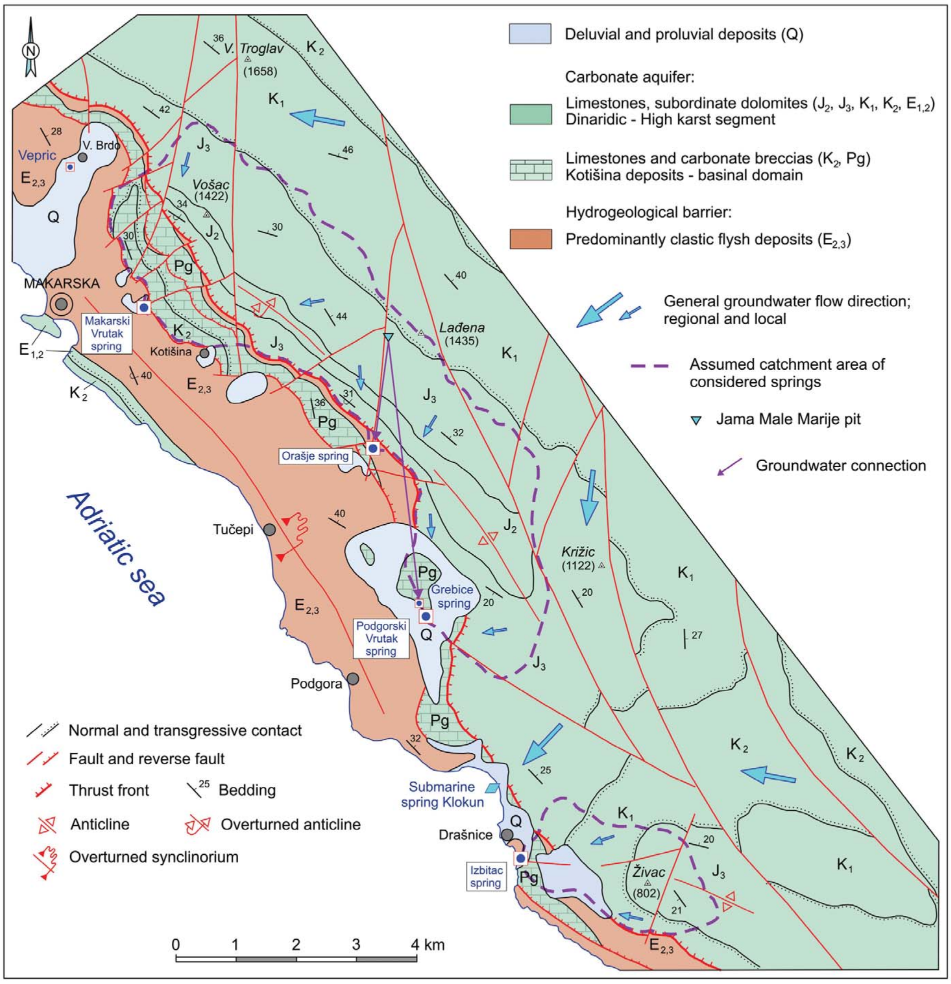

Figure 3: Hydrogeological map of the study area (geological background according to MARINČIĆ et al., 1977, partly modified).

vestigated through speleological activities on Mt. Biokovo. Ten of these pits were deeper than 250 m, and four exceeded a depth of 500 m. The deepest pit of Mt. Biokovo is the Amfora pit, which has been investigated to a depth of 788 m (BAKŠIĆ & JALŽIĆ, 2001; BAKŠIĆ & LACKOVIĆ, 2002). In hydrogeological terms, deep pits are a significant indicator of karstification of the vadose zone and a deep groundwater table. The lowest absolute elevation of approximately 790 m a.s.l. is reached in the Vilimova Jama pit.

The flysch deposits that comprise the SW foothills of the carbonate massif of Mt. Biokovo are lithologically heterogeneous. However, due to the dominance of marls, this sediment series, when considered in its entirety, is impermeable to water. In the study area, the flysch outcrops appear to extend to a distance of 3 km from the coastline (Fig. 3), and in places reach an altitude of 500 m. Considering their structural position and their nearly uninterrupted stretch along the coastline and far beyond the study area, the flysch deposits form a complete hydrogeological barrier to groundwater movement from the carbonate hinterland toward the sea. Thus, they have a significant impact on the regional hydrogeology.

According to previous regional hydrogeological studies (BOJANIĆ, 1980)[1], groundwater from the Mt. Biokovo massif and a portion of its spacious karstic hinterland drains primarily through strong submarine springs: Dupci NW of Brela, and Klokun near Drašnice (Fig. 2). They develop in locations where flysch and carbonate rocks come into contact below sea level. The springs function as the primary groundwater drains for the greater regional area, which explains the discharge values during rainfall periods of up to several dozen m^3/s. The Dupci is considered to be one of the strongest submarine springs of the Adriatic.

In addition to these submarine springs, several permanent springs with lower discharge values, some of which are captured for use in the public water supply system, are located along the area of tectonic contact between permeable carbonate rocks and impermeable flysch. This research focused on the hydrogeological characteristics of four captured springs located at the foot of steep slopes in the central and SE parts of the Mt. Biokovo massif between Makarska and Drašnice. The recharge of these springs is unrelated to inflows from the regional hinterland. They are recharged from the carbonate deposits of the Mt. Biokovo massif, and they have their own recharge areas in the SW, marginal parts of the regional catchments of the Dupci (Makarski Vrutak and Orašje) and Klokun (Podgorski Vrutak and Izbitac) submarine springs. This fact was confirmed by tracing from the Jama Male Marije pit in the Lađene area of Mt. Biokovo, which proved the groundwater connection with the Orašje and Grebice springs (Fig. 3).

The Makarski Vrutak spring is captured by a 10-m long water intake gallery located at 160 m a.s.l. The gallery was built in partly consolidated breccia debris, although it can be assumed that there are flysch deposits ($E_{2,3}$) in the bedrock. The nearest outcrops of carbonate rocks from the Upper Cretaceous (K_2^3) and Palaeogene (Pg) ages form the structural unit of the Kotišina-Tilovica trough, located approximately 100 m north of the water intake. The primary source is probably located in the tectonic contact zone between the carbonate aquifer of Mt. Biokovo and the flysch, which is covered by recent debris, as indicated by a temporary spring in the gully above the water intake.

The Orašje spring is located at the foot of Mt. Biokovo's steep slopes, at an altitude of approximately 465 m a.s.l. Groundwater is extracted by two small intake galleries 35 m apart and then transferred by pipelines to a nearby collection chamber. Although the intake is in an area composed of flysch deposits located approximately 160 m away from its fault contact with the carbonate rocks of Mt. Biokovo, and the groundwater inflow route is unknown, (draining through the debris or the more permeable sequences within the flysch), it is indisputable that the springs derive recharge from a karstic carbonate aquifer in the Mt. Biokovo massif, as confirmed by the aforementioned tracing study.

The Podgorski Vrutak spring is captured by a 44-m long water intake gallery at 384 m a.s.l. Although the bedrock is not visible in the water intake area due to the Quaternary cover, it can be assumed that the abstraction site is located where the flysch and Palaeogene carbonate deposits come into contact. A large portion of the hinterland of the abstraction site, which reaches the steep slopes of Jurassic rocks at an approximate altitude of 700 m a.s.l., is also covered with thick Quaternary deposits, and so the geological situation is not fully understood. Based on available data for the area upstream of the abstraction site, there appear to be no flysch deposits or interruptions in the continuity of the karstic aquifer.

The Izbitac spring is captured by a 23-m long water intake gallery located at 20 m a.s.l. The gallery was built along the tectonic contact between the Eocene flysch deposits ($E_{2,3}$) and the Palaeogene carbonate deposits (Pg). Between the Palaeogene carbonate deposits and the carbonate hinterland, (composed of the Jurassic and Cretaceous carbonate deposits), where the majority of the spring recharge area is located, there is an upper layer of flysch deposits. Although tectonically reduced and pinching out to the NW, these layers seem to significantly influence the hydrodynamic characteristics of the Izbitac spring.

3. SPRING MEASUREMENTS AND DATA ANALYSIS

Measurements of water level and temperature were recorded for the Makarski Vrutak, Orašje, Podgorski Vrutak and Izbitac springs (using Hobo Water Level Loggers, Onset Computers, USA). In addition to these springs, in the SW foothills of central Mt. Biokovo, the Grebice spring

[1] BOJANIĆ, L. (1980): Hidrogeološka studija područja Aržano-Brela-Metković [Hydrogeological Study of Aržano-Brela-Metković area]. Unpubl. report, Croatian Geological Survey, Zagreb, 75 p.

(Fig. 3) is captured for use in the public water supply system; however, due to the technical characteristics of the water intake structure, it was not possible to establish continuous water level monitoring at this location.

3.1. Spring measurements

Measurements were taken by installing square or standard triangular weirs in the water collection chamber outlets. Upstream of the weirs, water level and temperature data loggers were installed and programmed to take hourly measurements. Subsequent processing with appropriate mathematical equations, converted the measured level data into spring discharge figures. The monitoring period lasted from 25 November 2007 until 17 December 2008. Direct volumetric measurements were also occasionally made during this period.

Despite the millimetre accuracy of the measurement devices, the data logger results had certain deficiencies due to the inability to fulfil all necessary parameters, including the width and characteristics of the supply canal and the ratio between the weir height and the upstream water depth, at the weir installation sites. These deficiencies were mostly overcome by correcting the parameters in the applied mathematical formulae for square (KINDSVATER & CARTER, 1959), and triangle weirs (RANTZ et al., 1982). For some springs (especially the Orašje spring), it was not possible to fully calm the water surface upstream of the weir, which caused disturbance (noise) in the results.

3.2. Analysis of hydrograph recessions

Methods for analysing the hydrograph recession of individual flood pulses were initially used primarily for discharge forecasts in the case of long dry periods, and to determine available groundwater supplies in aquifers (BOUSSINESQ, 1877, 1904; MAILLET, 1905). Afterwards, karst hydrogeology specific methods for recession analysis were developed (DROGUE, 1972; MANGIN, 1975; ATKINSON, 1977; MILANOVIĆ, 1981; BONACCI, 1987, 1993). These methods are used to determine the characteristics of hydraulically contrasting aquifer volumes, (highly permeable conduit networks and low permeability rock masses with fissure porosity), as well as to characterise and classify karst aquifers based on quantitative values.

In this study, the longest available hydrograph recessions for the monitored springs were analysed. Hydrograph recession in base-flow conditions is described with Maillet's exponential equation (MAILLET, 1905), which is probably the most frequent recession equation used in the literature (DEWANDEL et al., 2003):

$$Q_t = Q_0 e^{-\alpha t} \quad (1)$$

where Q_t is the yield (L/s) in time t, Q_0 is the yield (L/s) at the beginning of a recession segment (in time $t = t_0$), t is the time (day) from the beginning of recession and α is the base-flow recession coefficient (1/day), which depends on an aquifer's characteristics.

The total hydrograph recession can be described by applying an exponential equation with one recession coefficient only when fast-flow spring components are absent. To describe the recession of typical karst springs with marked fast-flow and base-flow components, several different recession coefficients are sometimes used (BONACCI, 1993). The recession coefficient is gradually decreased in several steps. The value of the highest recession coefficient at the beginning of the recession diagram is attributed to the drainage characteristics of the aquifer system's conduit network during fast-flow conditions, whereas the lower recession coefficient, which ends the recession diagram, is attributed to the drainage characteristics of low permeability volumes within a karst aquifer. However, this interpretation is not completely correct due to significant variations in the temporal and spatial distribution of infiltrated rainfall, which impact the hygrograph's shape during fast-flow conditions (GRASSO & JEANNIN, 1994). This phenomenon explains why there are significant differences in the characteristics of hydrograph recession during fast-flow conditions for individual flood pulses and why these hydrographs cannot be used to unambiguously interpret the conduit network characterises of an aquifer. Thus, only the recession components for base-flow conditions were isolated and processed in this study.

By integrating Maillet's equation, the dynamic volume V, which is the groundwater volume at the beginning of the recession period (in time t_0) that is stored in the low permeability medium of an aquifer above spring level, can be determined:

$$V = \int_{t_0}^{\infty} Q_t dt = Q_o \int_{t_0}^{\infty} e^{-\alpha t} dt = c \frac{Q_0}{\alpha} \quad (2)$$

where the constant c depends on the discharge and the recession coefficient units.

3.3. Analysis of the spring hydrograph using autocorrelation and cross-correlation functions

Time series analyses in karst hydrogeology are used to determine karst system characteristics, to investigate the relationships between spring discharge and rainfall and between discharge, to continuously measure physico-chemical parameters and to assess the interdependence of discharge in several springs (MANGIN, 1984; PADILLA & PULIDO-BOSCH, 1995; LAROCQUE et al. 1998; PANAGOPULOUS & LAMBRAKIS, 2006; KOVAČIČ, 2010). Univariate methods are used to analyse the characteristics and structure of individual time series, while bivariate methods are used to analyse the connection between the input and output time series (BOX & JENKINS, 1974). In this study, mean daily discharge series were analysed with the autocorrelation function, while the connection between discharge and rainfall was analysed with the cross-correlation function.

The autocorrelation function defines the linear dependence of successive data values within a time series, depending on their time lag. A time series is compared with itself, with a discrete increase of time lag, and the autocorrelation coefficient *r(k)* is calculated for individual time lags *k* with the following equation:

$$r(k) = \frac{C(k)}{C(0)} \tag{3}$$

$$C(k) = \frac{1}{N}\sum_{i=1}^{N\pm k}(x_i - \overline{x})(x_{i+k} - \overline{x}) \tag{4}$$

where $x_i = (x_1, \ldots x_i, \ldots x_N)$ is a time series of N data points for which m autocorrelation coefficients $r_k = (r_0, \ldots r_k, \ldots r_m)$ are calculated. The value of m should not exceed $N/2$ (BOX & JENKINS, 1974) or $N/3$ (MANGIN, 1984). A graphical presentation of r_k values for individual time lags reflects the character, karstification intensity and retention capacities of an aquifer. MANGIN (1984) terms the time necessary for r_k to fall below 0.2 the „memory effect" which expresses the duration of the system's response to an input impulse. A longer memory effect indicates a less developed karst conduit network and a higher retention capability of the karst system, while a short-term effect reflects the system's low retention capability, with a dense, connected conduit network.

The cross-correlation function defines the linear dependence of output y_t and input x_t time series, depending on their time lags. The output y_t and input x_t time series are mutually compared, with a discrete increase of the time lag, and the cross-correlation coefficient $r_{xy}(k)$ is calculated for individual time lags k with the following equation:

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \ , \tag{5}$$

where:

$$C_{xy}(k) = \frac{1}{N}\sum_{i=1}^{N\pm k}(x_i - \overline{x})(y_{i+k} - \overline{y}) \ , \tag{6}$$

and σ_x and σ_y are the standard deviations of the input and output series, respectively. If the input series is random, then the cross-correlation function $r_{xy}(k)$ presents the system response to the input impulse. Because rainfall can mostly be considered as a random signal, the cross-correlation function of the rainfall and discharge presents a unit hydrograph.

In this study, daily rainfall data from a gauge in Makarska were used. These data represent rainfall at the foot of Mt. Biokovo. Although events in the higher parts of the massif are more relevant for aquifer recharge, no daily rainfall gauges have been installed in the higher parts of the massif.

4. RESULTS AND DISCUSSION

Spring yield and water temperature data were used to determine the hydrodynamic characteristics of the Makarski Vrutak, Orašje, Podgorski Vrutak and Izbitac springs. As late summer and early autumn during the monitoring period were dry, exceptionally low water levels and representative values of minimum yield were observed. Conversely, a wet period at the end of 2008 resulted in exceptionally high water levels, so relevant maximum yields were also recorded. The spring hydrographs and thermographs (Fig. 4) were created using mean daily values of yield and water temperature during the monitoring period. The basic statistical data on discharge for the investigated springs are shown in Table 1.

Due to technical conditions at the water intake of the Makarski Vrutak spring, the installed weir could not reliably measure discharges greater than 200 L/s, which was probably reflected in the slightly higher occurrence of errors in the maximum yield calculations and the shape of the hydrograph peaks. The more pronounced yield fluctuations in the hydrograph for the Orašje spring were caused by an unsettled water surface in the collection basin.

The hydrographs (Fig. 4) exhibit the different hydrodynamic characteristics of the investigated springs. Considering the minimum to maximum yield ratios (Table 1), the Makarski Vrutak spring has a very high ratio, typical of karstic aquifers. The ratios are significantly lower for the Podgorski Vrutak and the Orašje springs and very low for the Izbitac spring.

The hydrograph of the Makarski Vrutak spring shows abrupt flow variations, with a pronounced transition from the fast-flow to the base-flow regime (Figs. 4a and 5a). Recession analysis was conducted for the longest recession period in the monitoring period, which lasted from the middle of June to the end of October 2008, a total of 142 days. After the first 40 days of the recession period, the flow recession assumed an exponential form with a constant recession coefficient (Fig. 5a). The transition to slow exponential recession (i.e., to base-flow recession) occurred at a low discharge rate (12 L/s), which was considerably lower than the spring's median and mean discharges (Table 1). This result indicates that the discharge of the Makarski Vrutak spring is in the fast-flow regime for most of the year. The pronounced discharge fluctuations in the fast-flow regime result from both the rapid infiltration of precipitation in the epikarst and a well developed system of drainage conduits, which effectively convey infiltrated water to the spring. A fast throughput, with an accompanying low residence time in the system, results in the spring's high vulnerability to contamination. A relatively low recession coefficient during the base-flow regime reflects the high retention capability of low permeability volumes in the aquifer, although their contribution to the total spring discharge is minor. Consequently, the spring's dynamic volume is lower than those of the Podgorski Vrutak and Izbitac springs (Table 2), despite its higher mean and median discharges (Table 1).

The Orašje spring hydrograph is characterised by a clear distinction between the fast-flow and base-flow regimes and a less dominant fast-flow component in the total spring discharge, compared to the Makarski Vrutak spring (Figs. 4b and 5b). The analysed recession period lasted for 140 days, of which the first 23 were in the fast-flow regime. The base-flow recession coefficient was the lowest of all investigated springs, but was similar to that of the Izbitac spring. Despite a low recession coefficient, the spring system's dynamic vol-

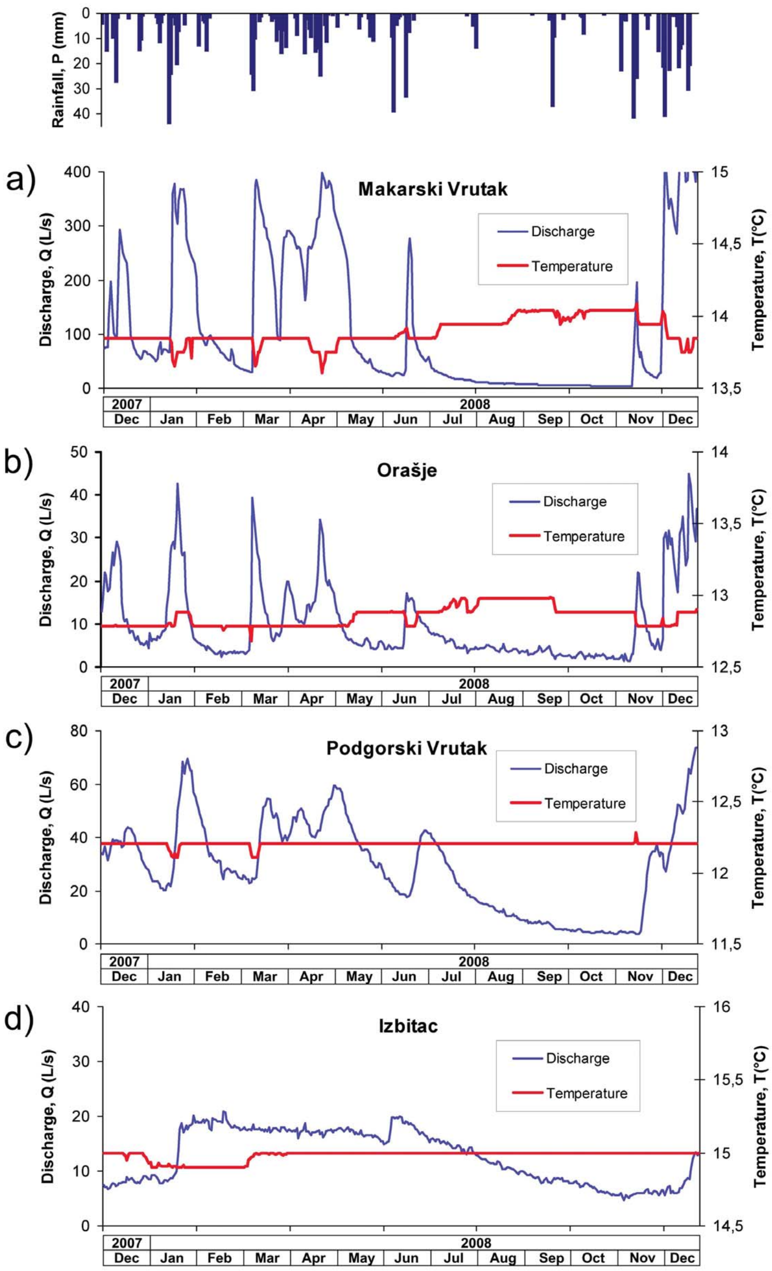

Figure 4: Daily rainfall in Makarska and temperature and discharge values of a) the Makarski Vrutak spring, b) the Orašje spring, c) the Podgorski Vrutak spring and d) the Izbitac spring.

Table 1: Basic statistics for daily discharge of the springs during the monitoring period (25 November 2007 – 17 December 2008).

Parameter	Location			
	Makarski Vrutak	Orašje	Podgorski Vrutak	Izbitac
Q_{min} (L/s)	3.7	1.3	3.7	4.8
Q_{max} (L/s)	448.2	44.9	73.7	20.9
Q_{mean} (L/s)	112.6	9.9	28.9	12.6
Q_{stdev} (L/s)	129.2	9.0	17.2	4.9
Q_{med} (L/s)	54.4	6.0	28.9	12.9
$Q_{min} : Q_{mean} : Q_{max}$	0.03 : 1.00 : 3.98	0.13 : 1.00 : 4.54	0.13 : 1.00 : 2.55	0.38 : 1.00 : 1.66

ume was also the smallest (Table 2) as a consequence of its lowest mean and median discharges (Table 1).

The difference between the fast-flow and base-flow components of the Podgorski Vrutak spring hydrograph was much less pronounced than those of the Makarski Vrutak and Orašje springs (Figs. 4c and 5c). The base-flow was a dominant component of the spring's total discharge. The hydrograph's less pronounced changes in the fast-flow regime

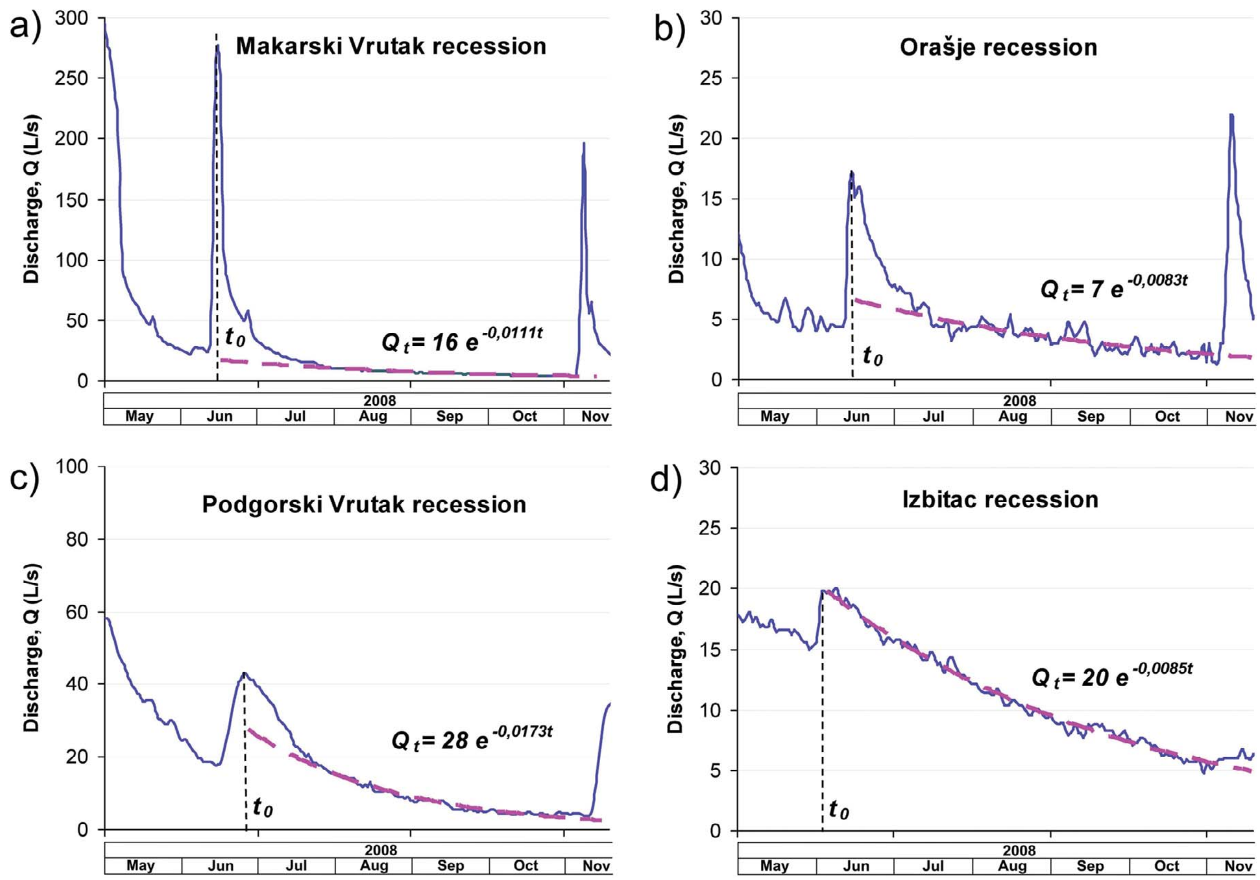

Figure 5: Hydrograph recession characteristics for a) the Makarski Vrutak spring, a) the Orašje spring, c) the Podgorski Vrutak spring and d) the Izbitac spring.

could be a result of the lower maximum draining capacity of the system's conduit network or the significant sediment layer that covers the karst and retards infiltration. However, the highest base-flow recession coefficient suggests the existence of a dense conduit network. Because of the fast-flow to base-flow transition at a relatively high discharge (approximately the magnitude of the mean and median annual discharges, Table 1, Fig. 5c), the system has a proportionally high dynamic volume (Table 2).

The characteristics of the Izbitac spring hydrograph are different from those of the other springs. The fast-flow discharge component is completely absent, and the hydrograph recession can be described with the same exponential relationship from the beginning of the recession period (Figs. 4d and 5d). This, in combination with a low recession coefficient, results in the system's highest dynamic volume (Table 2). The lack of a fast-flow component suggests the absence of a developed karstic conduit network in the spring catchment. Given the lithological composition of the spring's surrounding area (Fig. 3), the appearance of flysch rocks in the nearby hinterland could also retard the discharge dynamics. Occasional, slight increases in the chloride contents recorded for this spring indicate bathyphreatic recharge conditions, possibly through non-karstified carbonate rocks below the flysch deposits. A good retention capability and longer groundwater residence times make the Izbitac spring the most valuable for purposes of water supply.

The time series analysis utilises daily discharge values of the springs and daily rainfall values measured in Makarska. The uniform decline of autocorrelation function values for the Izbitac spring discharge series confirms the presence of only one base-flow component, while the presence of both fast-flow and base-flow components is clearly marked by a transition from the steep to the gentle slope in the shape of

Table 2: Base-flow recession parameters (α – recession coefficient; Q_0 – base-flow discharge at the beginning of recession; V – dynamic aquifer volume).

Parameter	Location			
	Makarski Vrutak	Orašje	Podgorski Vrutak	Izbitac
α (day^{-1})	0.0111	0.0083	0.0173	0.0085
Q_0 (L/s)	16	7	28	20
V (m^3)	12.5·10^4	7.3·10^4	14.0·10^4	20.3·10^4

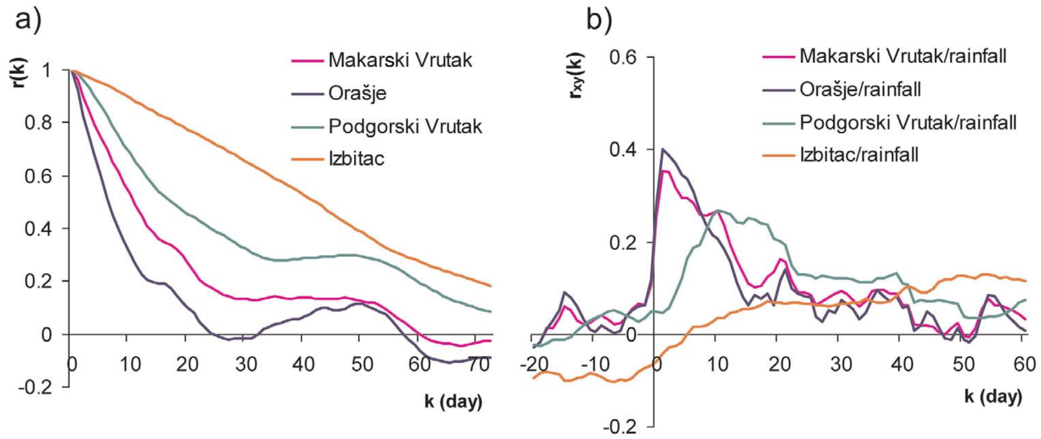

Figure 6: a) Autocorrelation functions of the springs' daily discharge series and b) cross-correlation functions of the springs' daily discharge series and daily rainfall series.

the other springs' functions (Fig. 6a). Consequently, the Izbitac spring hydrograph shows the longest memory effect (Fig. 6a, Table 3). The Makarski Vrutak spring's autocorrelation function has typically, a two component shape, with a steep slope for the first 25 days and an almost horizontal slope for the next 55 days. Because of fast-flow dominance in the Makarski Vrutak discharge dynamics, the transition to an almost horizontal function shape occurs at low autocorrelation values below 0.2 (Fig 6a), resulting in a short memory effect. The Orašje spring's autocorrelation function shows similar characteristics to that of the Makarski Vrutak spring, with an even lower memory effect (Fig 6a, Table 3). Low memory effect and zero autocorrelation values for the time lags of 24 to 33 days on these springs are largely caused by irregularities in the Orašje discharge measurement data, which is especially pronounced in the low flow (i.e., baseflow) regime (Fig. 4). The Podgorski Vrutak function presents an intermediate case between the Izbitac and Makarski Vrutak functions, with two distinct flow components and a less dominant and more inert fast-flow component, compared to the Makarski Vrutak function (Fig 6a).

The cross-correlation functions show the most rapid response and the strongest dependence on rainfall for the Orašje spring's discharge series (Fig. 6b, Table 3). The Makarski Vrutak spring's discharge series had a slightly lower value and a longer time lag of maximum cross-correlation coefficient (Table 3). The general shapes of the functions for both springs are similar, with a rapid fall of values for the first 15 or 16 days, reflecting the spring's fast-flow response. The low function values then slowly and irregularly approach zero until a time lag of approximately 45 days is reached. The low values following the initial rapid fall of the functions indicate the dominance of the fast-flow response, whereas the approach to zero marks the total duration of the system response. The cross-correlation function of the Podgorski Vrutak spring discharge and rainfall shows a longer duration of the fast-flow regime (23 days), a lower maximum correlation coefficient and a significantly longer time lag (Fig. 6b, Table 3). A long time lag of the system response implies a delay of rainfall infiltration and slower transport through the system, which could be caused by the presence of a sediment karst cover or a less developed conduit network. Again, the function shows a more regular shape and higher coefficients after the end of the fast-flow regime, which is representative of the Podgorski Vrutak system with its less pronounced difference between the fast-flow and base-flow responses. The Izbitac spring cross-correlation function shows no fast-flow response and a generally low dependence on daily rainfall, with maximum correlation values for time lags of more than 50 days (Fig. 6b).

Groundwater temperature data indicate the varying thermodynamic characteristics of the springs' aquifer systems (Fig. 4). The Makarski Vrutak spring had the most pronounced temperature fluctuations in relation to discharge dynamics. The total range of the measured temperatures fell within the range 13.6 to 14.1 °C. Flood pulses were followed by temperature drops (Fig. 4a). During November, water waves first occurred after a long recession period, and temperature drops were preceded by small increases of short duration. Delayed temperature drops in relation to the start of yield increases during water waves were heterogeneous and lasted, on average, 1 to 2 days. The delays were longer

Table 3: Time series analysis parameters: system memory effect, maximum discharge/rainfall cross-correlation coefficient and time lag for maximum cross-correlation coefficient.

Parameter	Location			
	Makarski Vrutak	Orašje	Podgorski Vrutak	Izbitac
Memory effect	23	17	60	70
Crosscorrelation coefficient	0.35	0.4	0.27	0.13
Time lag	1.5	1	10	50

following longer hydrograph recession periods and shorter during wet periods. Along with sudden temperature changes related to changes in discharge, seasonal fluctuations are also evident in the spring, with a maximum temperature recorded at the time of low yields in September and the beginning of November. Such thermodynamic characteristics indicate the fast transport of water through the system by well-developed conduits. Temperature increases that precede drops are probably related to the mobilisation of the water contained in low permeability fissures due to rapid pressure increases caused by rainfall infiltration. An alternative explanation of antecedent temperature increases is the activation of deep conduit flow as the result of an increase in the hydraulic gradient within the system.

The temperature of the Orašje spring occasionally changed, mostly by dropping, in relation to yield changes, although these changes were small and near the resolution limit of the data loggers (Fig. 4b). As with the Makarski Vrutak spring, seasonal fluctuations were evident, with maximum temperatures observed during the summer recession, in the period from July to the end of September. The total range of measured temperatures in this spring was between 12.7 to 13.0 °C, with an average of 12.85 °C.

The Podgorski Vrutak and Izbitac springs are characterised by different, although relatively homogenous water temperatures during the entire year (Figs. 4c and 4d). The temperature fluctuations in the Podgorski Vrutak spring ranged from 12.1 to 12.3 °C, while those in the Izbitac spring ranged from 14.9 to 15.0 °C. Such small changes are within the resolution limits of the instruments and reveal the thermal stability of the recharge system. The stability of the Podgorski Vrutak system could be a consequence of better heat exchange between rocks and water in conduits with smaller radii, while for the Izbitac spring, the stability is probably the result of the absence of karst conduits in the nearby hinterland. The minimum water temperature values in the Podgorski Vrutak spring were obtained during two short temperature drops in January and March. These drops were not temporally coordinated with yield increases; rather, they occurred during shorter winter recession periods.

The mean annual groundwater temperatures in the observed springs ranged from 12.2 to 15.0°C, whereas the mean annual temperatures in the Mt. Biokovo high karst plateau were 6–7 °C. Such temperature differences indicate that the majority of the investigated springs' local catchments are located in the marginal SW parts of the massif, near the steep slopes along contact between the flysch and carbonate deposits. Water from the major part of the plateau area predominantly drains toward the main discharge areas of submarine springs Dupci and Klokun.

The Cretaceous and Palaeogene deep basinal deposits (limestones and breccias) on the NW slopes of the Mt. Biokovo massif, which according to recent geological investigations are considered to be a separate tectono-stratigraphic unit (Kotišina-Tilovica trough), comprise significant hinterland sections of the Makarski Vrutak and Podgorski Vrutak springs. These deposits haven't been previously hydrogeologically investigated in detail. According to the results of this study, it is significant that in terms of the hydrodynamic characteristics of the springs, they have characteristics of permeable karstic rocks, similar to the platform carbonates of the remaining parts of Mt. Biokovo (High karst, Dinaridic segment).

5. CONCLUSIONS

Hydrograph analyses for the Makarski Vrutak, Orašje, Podgorski Vrutak and Izbitac springs in the Makarska Coast area indicate the different hydrogeological characteristics of the aquifers in the catchment areas of the springs. The Makarski Vrutak and Orašje springs are typical karst springs. The Podgorski Vrutak recession analysis indicates a dense conduit network in the hinterland, but also its lower maximum draining capacity or the significant sediment layer that covers the karst and retards infiltration. The Kotišina deposits in the hinterland of Makarski Vrutak and Podgorski Vrutak springs have not been previously hydrogeologically analysed, and are assessed to have characteristics of permeable karstic rocks, similar to the platform carbonates of the remaining parts of Mt. Biokovo. The analysis results for Izbitac indicate that it is not a typical karst spring. The geological settings of the spring's hinterland (flysch deposits) could be the cause of the spring's dynamics. The results of temperature data analyses additionally confirm the determined differences in hydrogeological conditions in the recharge areas of the investigated springs.

All investigated springs, with the exception of the Izbitac spring, are extremely sensitive to surface pollution. However, due to unfavourable topographic conditions that have prevented urbanisation and the fact that the catchment areas of these springs are located within the „Biokovo“ Nature Park, there are virtually no anthropogenic impacts on the majority of the sanitary protection zones. Thus, the risk of groundwater pollution can be considered to be low.

The specific hydrodynamic characteristics of the Izbitac spring indicate a lower sensitivity to pollution in the context of groundwater flow velocity and residence time. However, the atypical hydrodynamic behaviour is probably a result of the delaying effect of flysch deposits in the spring's immediate hinterland, while the aquifer is karstic and is susceptible to pollution.

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