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J. Geogr. Inst. Cvijic. 65(1) (19–32)

Original scientific paper

UDC: 911.2:551.444(497.11)
DOI: 10.2298/IJGI1501019R

KARST GROUNDWATER BUDGET AND DISCHARGE REGIME OF BANJA SPRING NEAR PETNICA

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Received 02 March 2015; reviewed 18 March 2015; accepted 02 April 2015

Abstract: Detailed hydrological and hydrogeological assessments of karst spring discharge require information about the groundwater regime in the study area/watershed. However, groundwater regime monitoring is often organized locally and sporadically, as required for specific studies or projects, and seldom lasts longer than one year. On the other hand, if time series of quantitative parameters are shorter than 15 years, the watershed is considered to be ungauged. As a result, discharge regime and karst aquifer budget assessments of ungauged watersheds can be misleading. To minimize water budget assessment errors, available time series need to be extended as far as possible. Regression models are commonly used to extend, simulate or fill gaps in existing time series. The paper presents an application of multiple linear regression to extend the existing time series of mean monthly discharges of Banja Spring (at Petnica, western Serbia), in order to cover the entire study period (1960-2006).

Key words: karst groundwater, regime, water budget, Banja Spring, Petnica

Introduction

The study area around Banja Spring (source of the Banja River) near Petnica is located in western Serbia and is roughly defined by Mts. Suvobor, Maljen and Povlen to the south, Mts. Jablanik and Medvednik to the west, the Jablanica and Kolubara rivers to the north, and the Ribnica River to the east. The nearest administrative center, the City of Valjevo, is about 7 km away (to the east-southeast, as the crow flies), and Petnica Research Station is in the immediate vicinity (Figure 1).

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The altitude of the drainage area is from 181 m above sea level (at the point of Banja Spring emergence) to more than 600 m (southern parts of the drainage area). The surface morphological features of the Triassic limestones include numerous dolines (12 /km^2 on average), which often occur in clusters (Figure 1). Underground features include caves and fractures, the most important being Petnica Cave, which is also the point of emergence of Banja Spring.

There are two significant surface streams: Zlatar Creek and Bukovik Creek. Zlatar originates in Miocene strata. "Some 300 m after it passes impervious Sarmatian sediments, this creek sinks via Pećurine Ponor (sinkhole), as shown in Figure 1. Petnica Research Station has conducted tracing tests on several occasions and determined that there was a link between Pećurine Ponor and Banja Spring. The other major creek, Bukovik, is formed in Triassic limestones near the Village of Pavlovići, where karstification is less pronounced (there are no dolines) – Figure 1. Bukovik runs in the WE direction and then suddenly changes course and flows to the north/northeast. Its lower course encounters karstified limestones again, where it follows the linear direction of dolines, gradually depletes and ultimately dries out. Tracing tests have confirmed a link between the dolines and Banja Spring (Figure 1)"(Golubović, Ristić – Vakanjac, & Papić, 2014).

In 1990, a weir and staff gauge were installed at Banja Spring (also known as Petnica Spring) for the purposes of monitoring water level and discharge regimes. Monitoring began in 1991 and lasted for a continuous period of ten years. In order to conduct any karst groundwater discharge regime analyses and assess the groundwater budget, it is extremely important to examine the climate conditions in the study area. For that reason, apart from the above-mentioned monitoring, a rain gauge was installed at Petnica Research Station (hereafter: PRS), so that meteorological data (daily precipitation totals and air temperatures) were also available for the monitoring period. In addition to the precipitation data collected by PRS, official data of the National Hydrometeorological Service were available from their nearest meteorological station at Valjevo (period 1960-2006). For comparison purposes, Figure 2 shows monthly distributions of average precipitation totals at the Valjevo station for the study period (1960-2006), as well as the Valjevo station vs. Petnica station for the monitoring period from 1991 to 2000. In general, it is apparent that monthly precipitation totals recorded at PRS are slightly higher than those reported by the Valjevo station, and that the long-term average precipitation totals computed for the study period (783.5 mm) are about 5% higher than those recorded during the period of monitoring (745.9 mm). Further, monthly precipitation levels registered during the first half of the year in the study period are somewhat higher, on average, compared to the monitoring period. However, it is generally vice-versa in the latter half of the year (Figure 2).

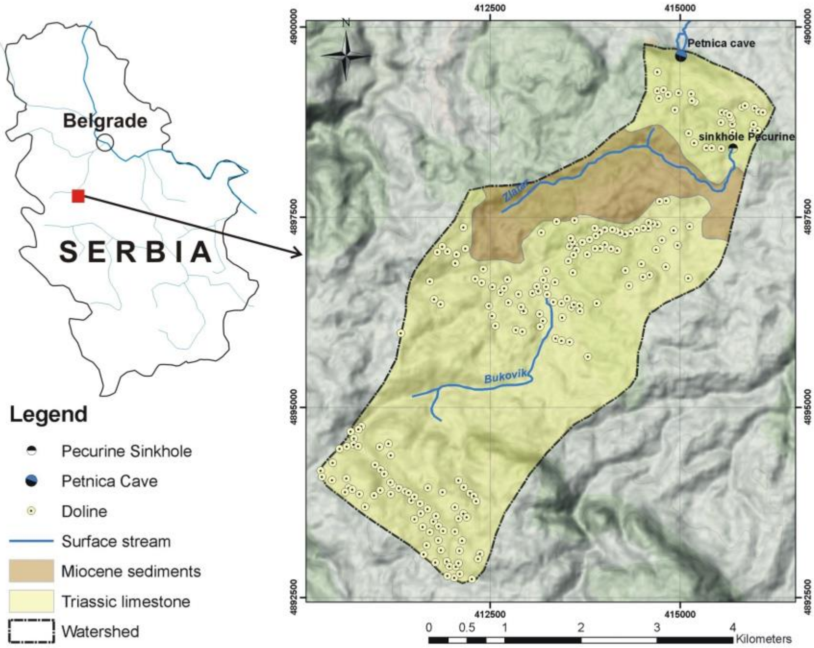

Figure 1. Location and hydrogeological map of Banja Spring watershed

In terms of hydrography, the study area is situated in the Kolubara River Basin. Although Banja Spring, and the Banja River, belong to neither the catchment area of the Gradac River nor that of the Ribnica River, as it is located between them, this paper addresses the hydrology of the Gradac River because that river and Banja Spring drain Lelić karst. A part of the Ribnica River also drains Lelić karst, but water level and discharge monitoring at Mionica (the only station on that river) was established as late as 2003. Given that the monitoring period in the present research is 1991-2000, not a single year of monitoring of the Ribnica River at Mionica falls within the considered monitoring period, such that none of the data reported by that station could be used. In contrast, the station at Degurić on the Gradac River was installed back in 1953 and is still in service. A correlation analysis (or computed coefficients of correlation) of monthly and annual discharges recorded at Banja Spring and the Degurić station is indicative of similar regimes and monthly distributions of Banja Spring and Gradac River discharges. Figure 3 shows their monthly distributions of average discharges.

The coefficient of correlation between annual average discharges is 0.69, and between monthly average discharges 0.74. These coefficients of correlation suggest good and very good correlations, and matching discharges, such that the discharge of the Gradac River at Degurić could be taken as the discharge of an "analog" river.

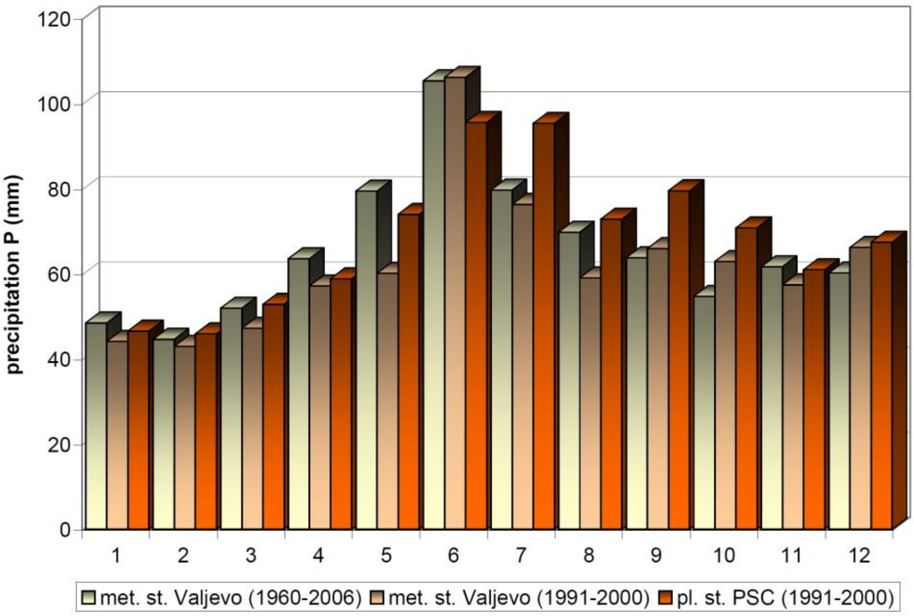

Figure 2. Monthly distributions of average precipitation totals (mm) at Valjevo (1960-2006 and 1991-2000), and at Petnica (1991-2000)

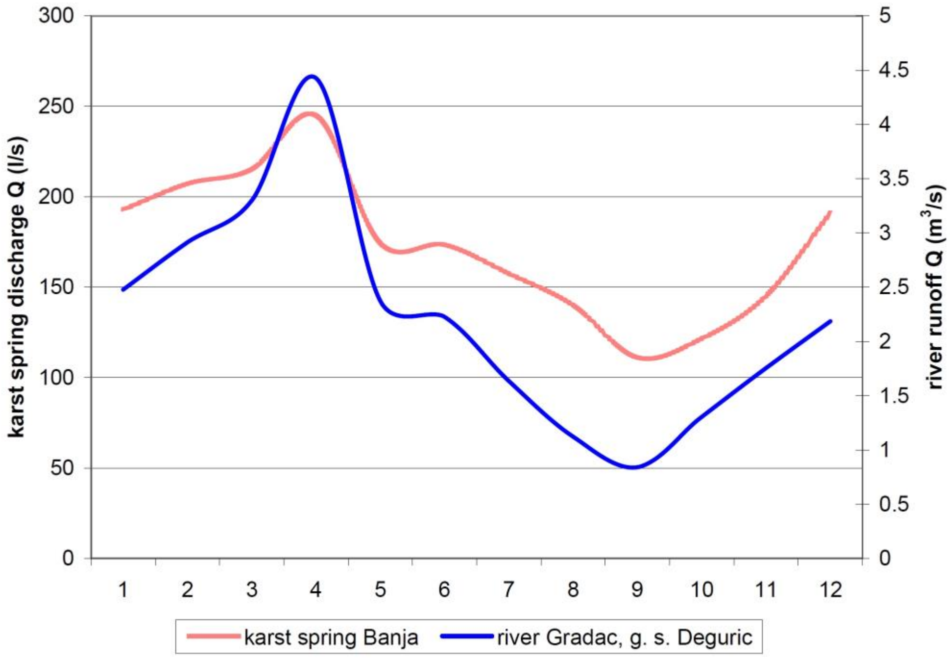

Figure 3. Monthly distributions of average discharges of Banja Spring and the Gradac River at Degurić (1991-2000)

Method

A monitoring time series, as long as possible, is required to determine the water budget equation parameters of a watershed. However, a watershed is deemed gauged if there is a time series of at least 30 years at a given (considered) monitoring point. A watershed is partially gauged if the length of the time series is between 15 and 30 years (Prohaska, 2002). Given that the discharge time series of Banja Spring was only ten years long, it was necessary to extend it to a minimum of 30 years, so that the watershed could be classified as gauged. This was one of the main reasons for filling the gaps and arriving at a study period that would be as long as possible. It was 47 years (1960-2006) in the present case. To extend the time series, a multiple linear regression model, commonly used to fill gaps and simulate/forecast variable quantities (Krešić & Stevanović, 2010), was applied. The model assumes that one phenomenon is a function of two or more independent phenomena. A dependency is established between the dependent variable Y and independent variables X_1, X_2, ... X_k, thus simulating the independent variable, or arriving at a prediction for a certain period of time

(Prohaska, 2006). This dependency is expressed by a regression model of the form:

$$Y_i = \beta_o + \beta_1 \cdot x_{1,i} + \beta_2 \cdot x_{2,i} + ... + \beta_n \cdot x_{n,i} + e_i \tag{1}$$

where:

Y_i - dependent variable of the *i*-th order;

x_i - independent variable of the *i*-th order;

β_i - unknown coefficient of multiple regression;

e_i - random error.

The least squares method is applied to compute the unknown coefficient of multiple linear regression and Equation (1) acquires the form:

$$\tilde{y} = a + b_1 \cdot x_1 + b_2 \cdot x_2 + ... + b_n \cdot x_n$$

where: $\tilde{y}$ - analytical value of the dependent variable; and a, b_1, b_2 ... b_n - computed numerical values of the coefficients of multiple regression.

Results

Assessment of Banja Spring discharge regime

Discharge regime monitoring at Banja Spring began in 1991 and lasted for ten years. The range of annual averages is from 109.7 l/s (2000) to 252.3 l/s (1996). The long-term average discharge of Banja Spring during the monitoring period is 173 l/s. The highest monthly discharge was recorded in April 1996 (376.4 l/s) and the lowest in December 2000 (only 29.5 l/s). The maximum daily discharge on record is 1.690 m^3/s (30 July 1999) (Golubović, Ristić Vakanjac, & Papić, 2014), while the minimum is 0 l/s.

Figure 3 clearly shows that the highest discharges occur in April, followed by March and February. One third of the annual discharge (31.4%) is attributed to this three-month period. At the other extreme, the driest months are August, September and October (together contributing only 18% to the annual discharge).

Figure 4 shows the Banja Spring 1993 discharge hydrograph, which is typical of that karst spring. There is one long spring peak, attributable to snowmelt and/or spring rains (Figure 4). In some cases, when snowmelt and spring rains do not coincide, there are two or even three spring peaks, but of shorter duration. On the other hand, there is a distinct autumn minimum (August, September and October). Additionally, all hydrographs clearly show a rapid propagation of heavy rainfall (Figure 4, beginning of October); there is a sudden increase in spring discharge on the same day or, in some cases, the next day (Figure 5), as a result of heavy rainfall. Although the hydrograph in Figure 5 indicates a one-day lag, it should be kept in mind that rain gauging and water level observations were made once a day, at 7 a.m. Consequently, although rainfall propagation is shown on an hourly basis, if rainfall occurred and was recorded early in the morning, the hydrograph rise was registered on the following day.

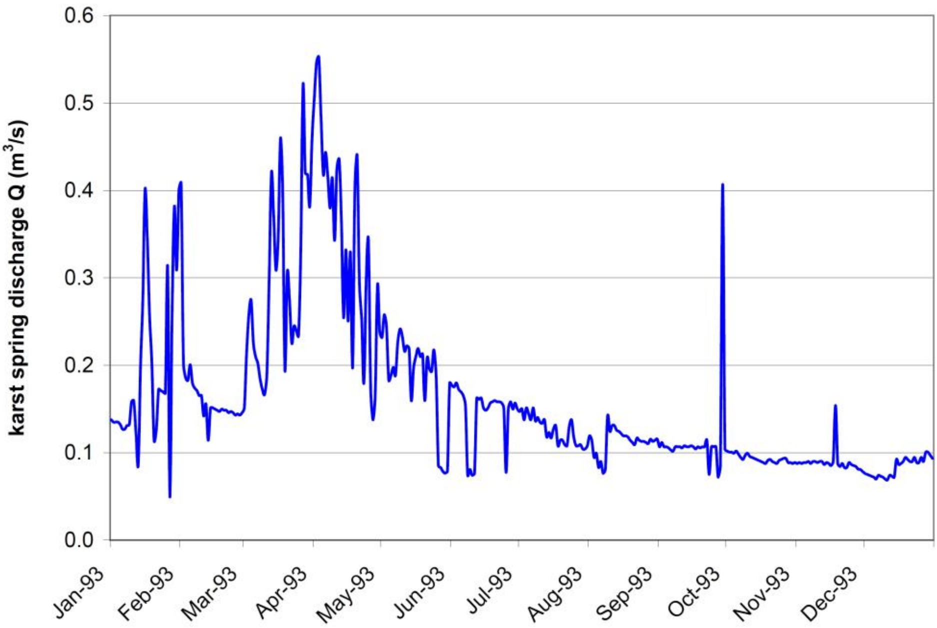

Figure 4. Banja Spring discharge hydrograph (1993)

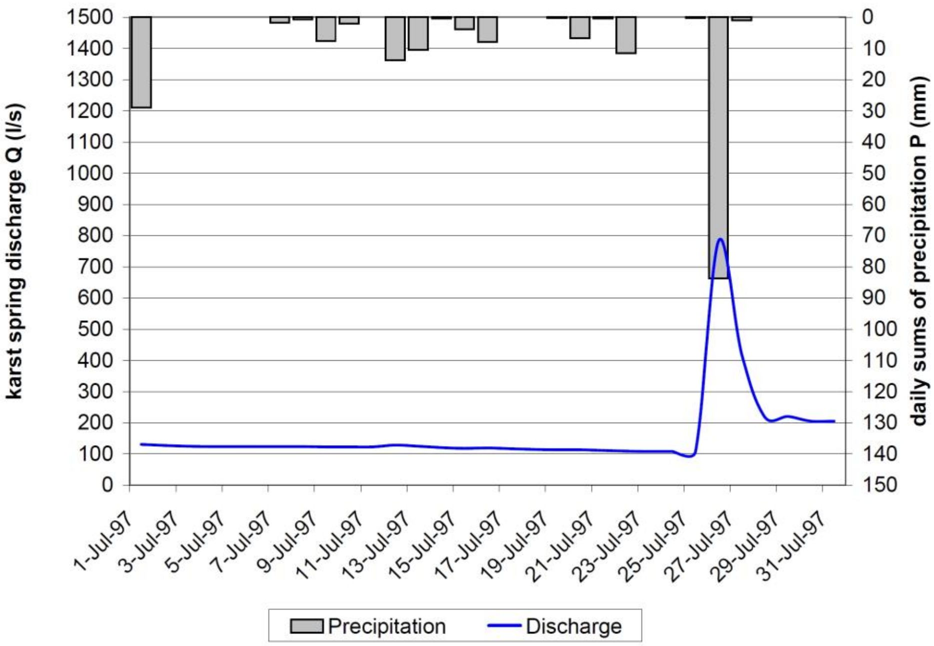

Figure 5. Comparison of daily precipitation totals and discharge hydrograph (July, 1997)

The above shows that the local precipitation regime largely affects the discharge regime of Banja Spring. A rainfall that drops on karst requires a certain time to reach the aquifer and, following privileged pathways of groundwater flow, to emerge at a karst spring (Ristić Vakanjac, 2015). With this in mind, cross-correlation analysis was undertaken to assess time-dependent random variables (in the present case discharge and precipitation). In cross-correlation analyses, the correlation between a time-dependent random variable (daily discharge, water table, ...) and independent random variable (daily precipitation total) can be quantified by computing cross-correlation coefficients at different time steps (Krešić & Stevanović, 2010). The dependency of cross-correlation coefficients at different time steps, as a function of the time steps, constitutes a cross-correlogram.

A cross-correlation analysis of Banja Spring was undertaken with a one-day time step, at the Petnica station, for the monitoring period (Figure 6, black line). The highest coefficient of correlation (r = 0.25) was obtained for a zero-day time step, indicating rapid propagation of precipitation. Cross-correlation analyses were then performed for each year separately. The years that featured extreme events were selected to present the results: the year with the lowest annual average discharge of Banja Spring was 1991, and the highest was 1996. The resulting cross-correlograms are shown in Figure 6.

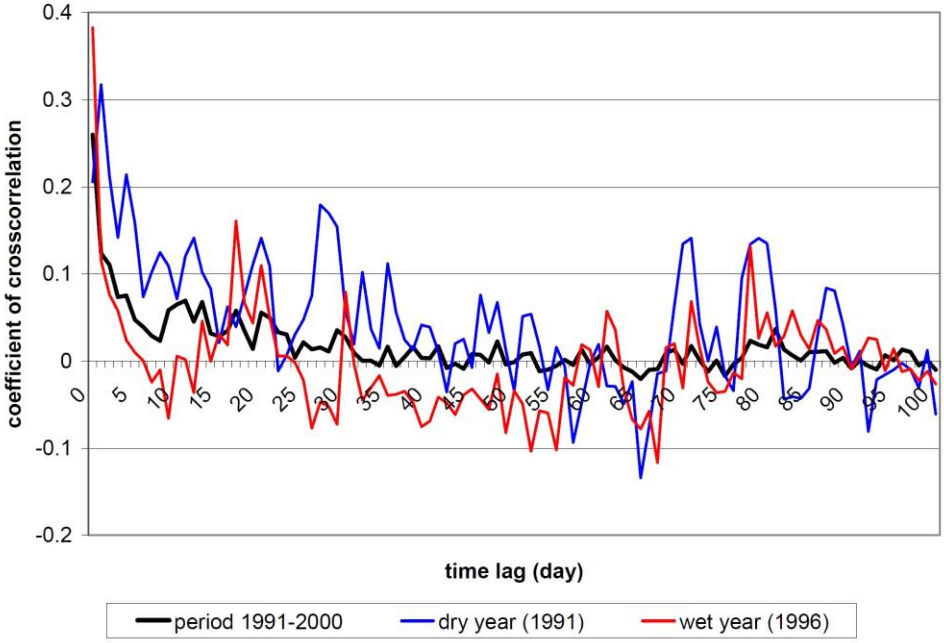

Figure 6. Cross-correlogram of daily discharges of Banja Spring and precipitation at Petnica station, for selected dry (1991) and wet (1996) years and the entire monitoring period

In the case of the wet year (Figure 6, red line), the cross-correlogram is almost identical to that produced for the entire study period. The difference is that in this case the correlation values are slightly higher, or the correlations are stronger. More precisely, for a 0-day time lag, the coefficient of cross-correlation was found to be nearly 0.4 for wet years, and to suddenly drop to 0.1 at a one-day time lag. This can be explained by the fact that in wet years fissures and medium-scale fractures tend to be filled with water, and heavy rainfall propagates rapidly along fissure systems, most often exhibiting turbulent flow characteristics.

On the other hand, during dry years (Figure 6, blue line), the highest coefficient of cross-correlation was obtained for a one-day time lag. This is attributable to the fact that in dry years dynamic reserves of karst groundwater in the watershed become depleted, such that some of the precipitation infiltrated into the aquifer recharges the dynamic volume. Additionally, this water flows along small-scale fractures, where the flow is slower than along fissures in wet years.

Extension of monitoring time series

For the purposes of determining the water budget components of Banja Spring, it was first necessary to fill the gaps, or extend the existing discharge time series by means of multiple linear regression. Since the period 1960-2006 was selected as the study period, it was necessary to seek out the proper equations to extend the time series to include the years 1960-1990 and 2001-2006.

Equation (1) was used for 2001-2006, where the dependent variable was Banja Spring discharge, averaged on a monthly basis, and the independent random variables were:

$Q_{i\text{-}1,Banja}$ – discharge of Banja Spring in the *i*-1-th month;

$Q_{i,Gradac}$ – discharge of the Gradac River recorded at Degurić (analog watershed) in the *i*-th month;

$P_{i,Valjevo}$ – monthly precipitation totals at Valjevo in the *i*-th month;

$T_{i,Valjevo}$ – monthly average temperatures at Valjevo in the *i*-th month;

In other words, Equation (1) yielded the following dependency:

$$Q_{i,Banje} = a + b_1 \cdot Q_{i-1,Banje} + b_2 \cdot Q_{i,Gradac} + b_3 \cdot P_{i,ISPetnica} + b_4 \cdot T_{i,Valjevo} \quad (2)$$

The parameters a, b_1, b_2, b_3 and b_4 were obtained by the least squares method, such that Equation (2) acquired the form:

$$Q_{i,Banja} = 0.02355 + 0.4504 \cdot Q_{i-1,Banje} + 0.0274 \cdot Q_{i,Gradac} + \\ + 0.0009414 \cdot P_{i,ISPetnica} + 0.000606 \cdot T_{i,Valjevo} \quad (3)$$

The coefficient of correlation between the registered monthly average discharges of Banja Spring and those computed using Equation (3) was 0.83 (Figure 7).

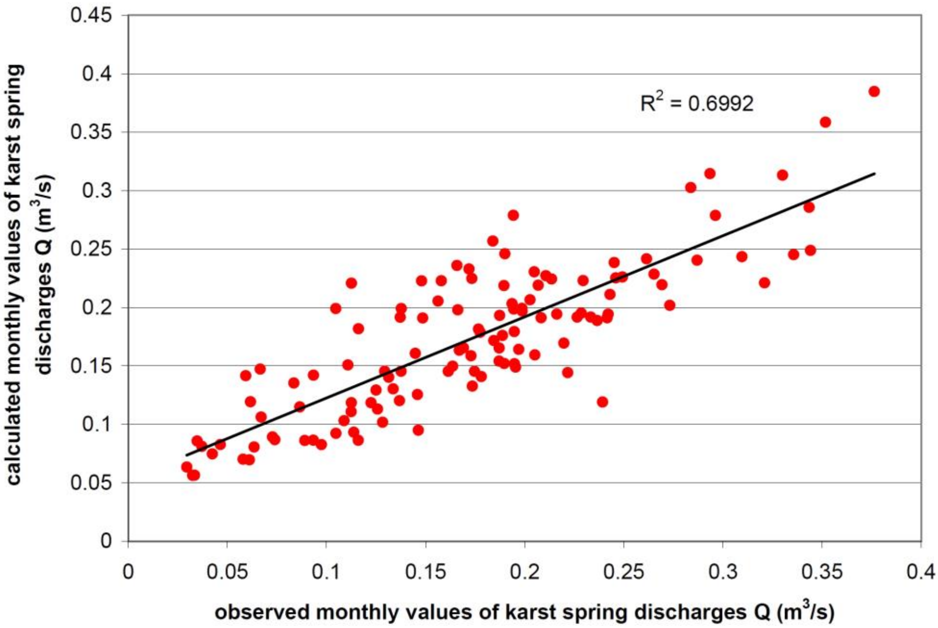

Figure 7. Recorded vs. computed (Equation 3) monthly average discharges of Banja Spring

The same principle was followed for the period 1960-1991, only the following equation was used:

$$Q_{i,Banje} = a + b_1 \cdot Q_{i+1,Banje} + b_2 \cdot Q_{i,Gradac} + b_3 \cdot P_{i,Valjevo} + b_4 \cdot T_{i,Valjevo} \quad (4)$$

where all the parameters were the same as in Equation (2), except $Q_{i+1,\ Banje}$, which is the monthly average discharge of Banja Spring in the i+1-th month. After the parameters a, b_1, b_2, b_3 and b_4 were computed, Equation (4) acquired its final form:

$$Q_{i,Banje} = -0.0312 + 0.5256 \cdot Q_{i-1,Banje} + 0.0521 \cdot Q_{i,Gradac} + \\ + 0.00035 \cdot P_{i,ISPetnica} - 0.00124 \cdot T_{i,Valjevo} \quad (5)$$

The coefficient of correlation between recorded monthly average discharges of Banja Spring and those computed using Equation (5) is 0.89 (Figure 8).

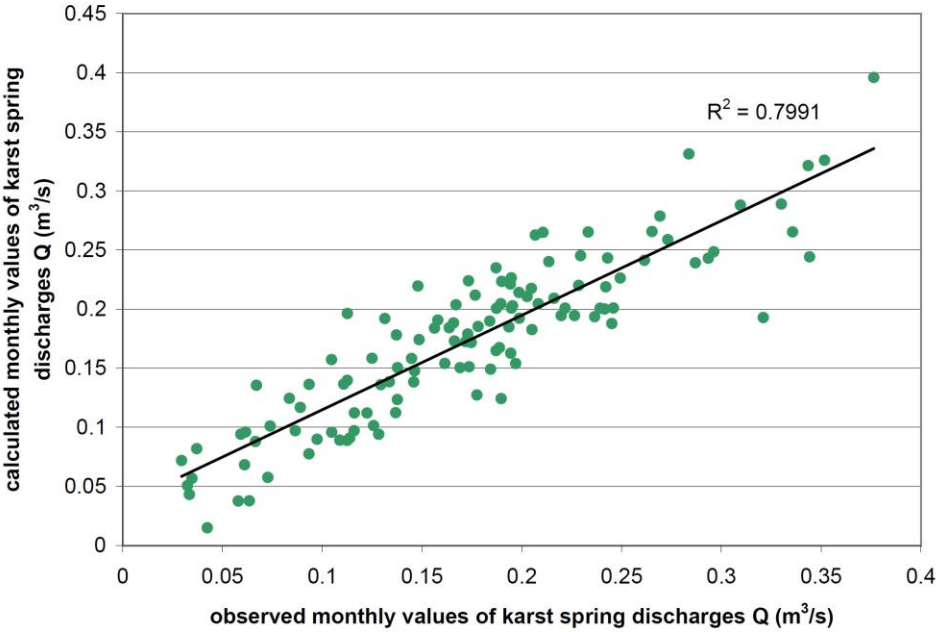

Figure 8. Recorded vs. computed (Equation 5) monthly average discharges of Banja Spring

Equations (3) and (5) were used to extend the time series of monthly average discharges of Banja Spring, in order to cover the period 1960-2006. Then the average monthly and annual discharges of the spring were computed. The monthly distribution for the study period is shown in Figure 9. The results suggest that the long-term average discharge of Banja Spring, for the study period 1960-2006, is 0.203 m^3/s. The maximum computed annual average discharge was 0.324 m^3/s, recorded in 1975. The minimum was recorded in 1990 and its computed value is 0.098 m^3/s. The maximum monthly discharge was 0.495 m^3/s in May 1975, and the minimum of only 30 l/s in December 2000. The monthly distribution shows that the end of winter and spring months are the wettest, especially March. Conversely, August and September are the driest months (Figure 9).

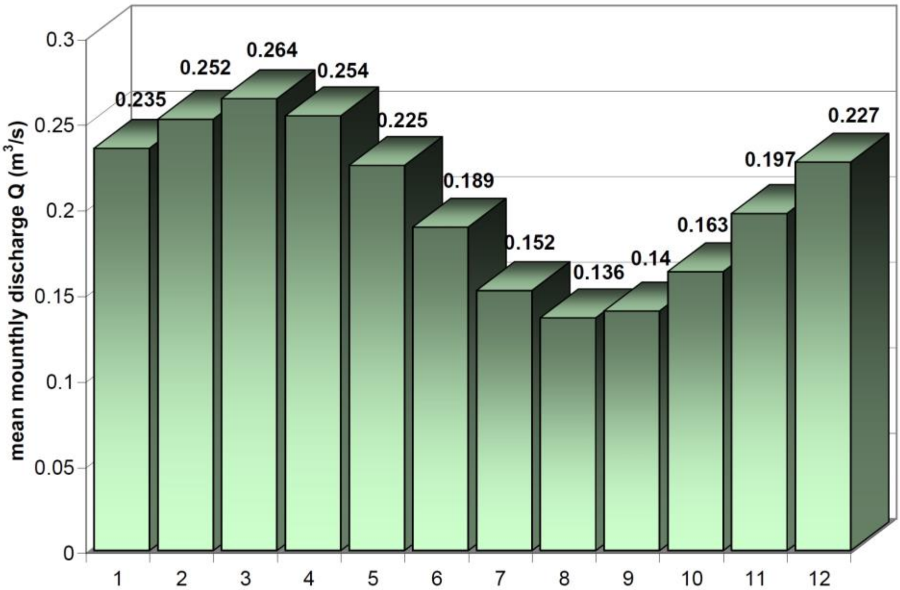

Figure 9. Monthly distribution of Banja Spring discharges (1960-2006)

Discussion

The results shown above were used to compute water budget equation parameters, as shown in Table 1 which contains long-term averages for the monitoring period (1991-2000) and the study period (1960-2006). The parameters shown in Table 1 are: watershed area F (km^2), long-term average capacity/discharge Q (m^3/s), volume of discharged water W (10^6 m^3), long-term average runoff modulus q ($l/s/km^2$), runoff layer h (mm), annual average precipitation P (mm), annual average evapotranspiration E (mm), and long-term average runoff coefficient φ.

Table 1 Summary of Banja Spring karst aquifer water budget (monitoring period and study period)

Period	F*	P	E	h	Qav	q	W	φ
	km^2	mm	mm	mm	m^3/s	$l/s/km^2$	10^6 m^3	
1960-2006	17.72	852	490.7	361.3	0.203	11.46	6.40	0.42
1991-2000	17.72	820	512.1	307.9	0.173	9.76	5.46	0.38

*Note: Size of Banja Spring watershed taken from Golubović et al., 2014.

According to Table 1, the annual average discharge of Banja Spring is about 0.203 m^3/s, or some 17% more than during the monitoring period.

From a water abundance perspective, the specific yield of Banja Spring was found to be 11.46 $l/s/km^2$, while the computed runoff coefficient suggested that 42% of precipitation was infiltrated and later emerged at the spring. Given that this spring drains a karst aquifer, the values obtained for the study period were much more realistic than those computed for the monitoring period.

Conclusion

The results presented above lead to the conclusion that the long-term average discharge of the studied karst spring is more than 203 l/s ($6.4 \cdot 10^6$ m^3 of water during the year). In the first six months, Banja Spring discharged 58.3% and in the latter half of the year 41.7% of the annual amount. The discharge rates were the highest in February, March and April, totaling 31.6% of the annual amount. In the driest period (July, August and September), only 17.6% of the annual amount was discharged, generally coinciding with minimum spring capacity. It should be noted that, at present, all the water is carried away by the Banja River and not used for any specific purpose.

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