VERIFICATION OF CATCHMENT SIZE USING THE WATER BALANCE EQUATION

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Abstract
To determine water balance equation parameters, sufficiently long time-series of monitoring data, such as river discharges at a river cross-section of interest or discharges of a spring/river source, are required along with isohyet maps of the extended area of the catchment. If isohyet maps are not available, then rain gauge or meteorological stations are needed in the considered catchment, which are rare in small and medium catchments, especially in mountainous regions. It is also extremely important to accurately define the size of the catchment but that is not an easy task in karst and arid areas. In such cases, especially karst, it is wrong to calculate water balance equation parameters using a topographic or surface water divide. Instead, the active, subsurface catchment area needs to be defined and used in subsequent calculations. One of the objectives of the paper is to take the Dojkinacka River, which drains the southern slopes of Mt. Stara Planina, as an example to demonstrate the types of errors that can occur if mean annual precipitation is not used as a reference, and the ultimate goal is to show how the water balance equation can be applied to verify whether the size of the catchment has been defined properly or not.

Key words: hydrogeologic catchment size, water balance, precipitation, karst, Dojkinacka River catchment, Serbia

INTRODUCTION

The total surface area of a catchment is a horizontal projection of the part of Earth from which water is drained into a river network or a particular river up to its mouth or a gauging station. There are surface and subsurface catchments. The surface catchment of a river is separated from the catchment of a neighboring river by a surface water divide, which passes over the hypsometrically highest points between the two neighboring rivers. The boundary between neighboring subsurface catchments is called a subsurface water divide. Almost as a rule, surface and subsurface water divides do not coincide. Since it is difficult to define subsurface water divides, surface catchments are generally used in hydrological practice and not enough attention is paid to the subsurface/hydrogeologic or active catchment area. If the hydrologic (or topographic) catchment area is used, the errors that can occur as a result of a poorly defined catchment size can be significant only in the case of small catchments and where catchments are situated in specific geologic settings, such as karst (Prohaska, 2004).

Knowledge of the hydrogeologic divide in karst, or knowledge of the real catchment size of a karst spring or river formed in karst, is essential not only because it is a significant water balancing parameter, but also for purposes of protection because karst waters are much more vulnerable than waters in other settings (Bonacci and Andić, 2015).

One example of a poorly sized catchment is the karst spring of Žrnovica near Split, Croatia. The size of the hydrologic (or surface) catchment of this spring, defined using topographic maps, is only 8.4 km^2. It is important to note that the spring was monitored from 1990 to 2013 and that the perennial average discharge of the Žrnovica Spring, during that time, was 1.81 m^3/s (Bonacci and Andić, 2015). Analyses determined that the reference rain-gauge station for this spring was Bisko, which reported a perennial precipitation total during the period of monitoring of 1487.4 mm (Bonacci and Andić, 2015). Given that water levels and discharges were monitored for 24 years, it is safe to say that the perennial average discharge of the Žrnovica Spring is a reliable quantity. As such, it is also safe to say that the annual average discharge was about $57*10^6$ m^3, which is also an acceptable quantity. Based on the calculated discharged volume and the defined catchment size, it is possible to estimate the average runoff layer on an annual basis, which in this specific case, for the defined topographic catchment size, amounts to 6795 mm but cannot be accepted as a realistic quantity. In other words, based on data reported by the Bisko rain-gauge station, it would seem that the catchment of the spring receives about 1500 mm of rainfall on average, and that nearly 6800 mm is drained, which is impossible. Based on this example, but also in general in the case of karst, the hydrogeologic divide should be used to define the real catchment size.

One of the objectives of the research reported in this paper was to use the Dojkinacka River, which drains the southern slopes of Mt. Stara Planina, as an example to demonstrate the types of errors that can occur if mean annual precipitation is not used as a reference, and the ultimate goal was to show how the water balance equation can be applied to verify whether the catchment was sized properly or not.

GENERAL CHARACTERISTICS OF THE DOJKINACKA RIVER CATCHMENT

The catchment of the Dojkiancka River is located in eastern Serbia, on the southern fringes of Mt. Stara Planina, in an area called Visok. The river course is formed by waters discharged by springs cluster known as Tri Kladenca. The river generally flows to the southeast and forms a series of cascading waterfalls. Together with its main tributary, the Jelovica, it empties into the Visočica River at Visočka Ržana, which belongs to the drainage area of the Temštica River and in turn to the Nišava River Basin and ultimately to the Black Sea Basin.

In geotectonic terms, the study area is situated in the Carpatho-Balkanides. The highest elevations of the catchment are on Mt. Stara Planina – the peaks of Vražja Glava (alt. 1934 m) and Tri Čuke (alt. 1933 m). The lowest part of the terrain is in the area of the mouth of the Dojkinacka River, at about 690 m above sea level. It is a torrential stream, with large gradients. Figure 1 shows a longitudinal section through the Dojkinacka River and its main tributary, the Jelovica. The slope of the Dojkinacka River is 44.1‰ and that of the Jelovica 68.8‰. The average slope of the river bed gradients are 24.5‰ of the Dojkinacka River and 35.8‰ of the Jelovica River.

The channel of the Dojkinacka River is determined by and follows a fault of the same name. After leaving Lower Triassic sediments, the river flows over Middle Triassic carbonate rocks. There is a ponor zone (Fig. 2a) at the very contact between Lower and Middle Triassic rocks, which, apart from the contact, is governed by a fault structure perpendicular to the Dojkinci Fault (Fig. 2b). In the summer months, the channel of the Dojkinacka River often dries up downstream from the ponor zone, and features many decimeter-size stones. Farther downstream, near the village of Brnjica, the Dojkinacka River receives back a part of the water lost to the ponors. The presence of large stones through to the mouth of the Dojkinacka River attests to the fact that at high flows the river is torrential in nature and exhibits enormous kinetic energy (Nikić, Radošević and Ristić, 2003).

One of the noteworthy morphological features of the karst is a cave near the Jelovica Spring. The cave is located on the left side of the Jelovica River, at an elevation of 752 m (8m above the river channel). Its total length is 132 m. The cave is comprised of a network of short, inter-connected conduits. It has no hydrogeologic function. The cave was formed by subsurface erosion, where subsurface flow later descended to the level of hypsometrically lower fractures and today emerges at the Jelovica Spring below the cave (Fig. 3).

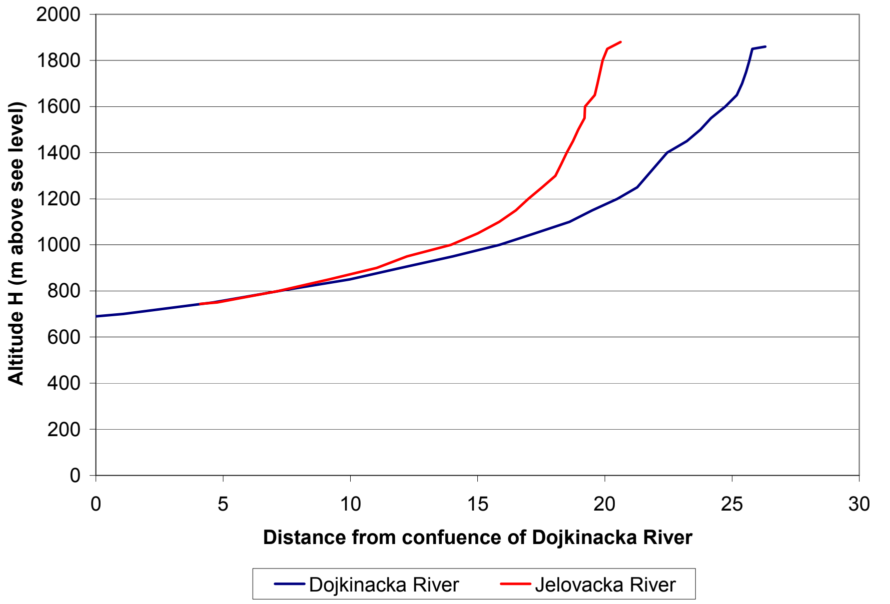

Fig. 1 *Longitudinal section through the Dojkinacka River and its main tributary, the Jelovica.*

Fig. 2 *Point of sinking of the Dojkinacka River: (a) ponor zone, and (b) fault structure above the ponor zone, normal to the Dojkinacka River and the Dojkinci Fault.*

Fig. 3 *Jelovica Spring, source of the Jelovica River*

There is one rain-gauge station in the catchment, located in the village of Dojkinci. The precipitation regime was analyzed based on a 50-year time series (1961-2010) of this station. The annual average precipitation total of the time period is 793 mm. The highest value, 1196.9 mm, was recorded in 1962 and the lowest (393.2 mm) in 1993. Mean monthly precipitation levels during the sad period vary from 0.3 mm (July 2007) to as much as 232.9 mm, also recorded in July but of 1976. On average, the highest precipitation levels are registered in May and June, and the lowest in October. About 55% (449.1 mm) of the annual precipitation occurs during the plant growing season, and 45% (344.5 mm) during the rest of the year. This pattern favors crop farming and livestock breeding, which are widespread in the region (Ristić Vakanjac et al., 2015). It should be noted that part of the 344.5 mm average during the non-growing season includes snow, which remains on the ground during the winter months and melts in March and April, increasing the amount of water in the growing season water balance (Ristić Vakanjac et al., 2015).

Data obtained from the National Hydrometeorological Service (from their hydrologic station on the Dojkinacka River at Visočka Ržana, about 0.3 km upstream from its mouth) were used to study the hydrologic characteristics of the Dojkinacka River. The location of this station is deemed representative of the entire Dojkinacka River catchment. Given that the station was installed back in 1981 and that it has been operating continuously since then, the catchment of the Dojkinacka River is deemed to be a gauged catchment. A detailed analysis of the Dojkinacka River regime is provided in Ristić Vakanjac et al., 2015, so the present paper will only mention typical annual values. The perennial average discharge of the Dojkinacka River at Visočka Ržana is 3.498 m^3/s. The highest runoff was registered in 2010, when the average annual discharge was 6.393 m^3/s. The driest year, or the year with the lowest discharge, was 1966 (1.566 m^3/s). The driest month was December of 2002, with an average discharge of 0.212 m^3/s. The highest discharge was recorded in April 2000 and amounted to 17 m^3/s. The monthly distribution shows that the highest discharges are generally observed in April (Fig. 4). It corroborates the intra-annual distribution of precipitation. As previously mentioned, the highest monthly precipitation levels are registered in May and June, so it is to be expected that the discharges would also be the highest during these two months. However, precipitation in the form of snow, a snow cover in the winter months and snowmelt as temperatures increase (March, April and May) affect the monthly distribution to the extent that the highest discharges of the Dojkinacka River are recorded in April and May (Fig. 4).

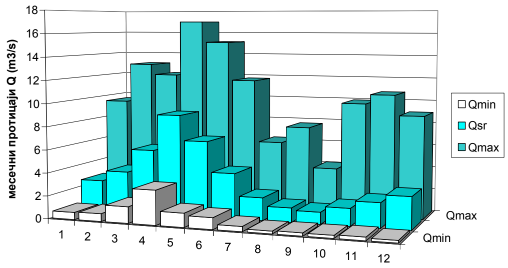

Fig. 4 *Monthly distribution of minimum, maximum and average discharges of the Dojkinacka River at Visočka Ržana (after Ristic Vakanjac et al., 2015).*

WATER BALANCE OF THE DOJKINACKA RIVER

The water balance of the Dojkinacka River was assessed for the entire catchment area. The following components were calculated:

Perennial average volume of water available in the catchment

$$W = \overline{Q} \cdot 31.536 \quad (10^6\ \mathrm{m}^3)$$

Perennial average runoff layer

$$h = \frac{1000 \cdot W}{F} \quad (\mathrm{mm})$$

Evaporation

$$E = P - h \quad (\mathrm{mm})$$

Runoff modulus

$$q = \frac{Q}{F} \quad (\mathrm{l/s/km^2})$$

Perennial average runoff coefficient

$$\varphi = \frac{h}{P}$$

As previously stated, the perennial average discharge of the Dojkinacka River is 3.498 m^3/s and the perennial average precipitation total at the rain-gauge station in Dojkinci 793 mm. Now the size of the catchment of this river needs to be determined in order to arrive at the above parameters. If the topographic or hydrologic catchment size is used (138 km^2, see Fig. 5), the water balance parameters are (Table 1):

Table 1. Summary of water balance of the Dojkinacka River catchment based on topographic size: Option 1

Size of catchment area F (km^2)	138
Average annual precipitation P (mm)	793.6
Average annual evapotranspiration E (mm)	-5.8
Average annual discharge Q (m^3/s)	3.498
Runoff modulus q ($l/s/km^2$)	25.35
Discharged volume W (10^6 m^3)	110.31
Runoff layer h (mm)	799.4
Runoff coefficient φ	1.01

Based on the results, it follows that it is not possible to reliably calculate the main components of the water balance equation using the topographic catchment size since the resulting values are unreasonable: (1) the annual runoff layer is greater than the annual amount of precipitation, (2) evaporation is negative, and (3) the runoff coefficient is greater than 1 (or greater than 100%).

The reason for the unrealistic values shown in Table 1 is certainly attributable to a poorly sized catchment. Based on hydrogeologic research, the hydrogeologic divide was assumed to be as shown in Fig. 5. Hydrogeologic reconnaissance revealed that part of the water during rainy years and all of the water of the Rosomac and Vodenica rivers during dry years sinks as it passed from Lower Triassic rocks to Middle Triassic limestones. These waters are presumed to emerge at the Jelovica Spring. Given that no tracing tests have been undertaken to date, the catchment size can only be assumed. It should also be noted that the topographic water divide was taken as the western boundary of the catchment because no hydrogeologic exploration had been conducted in that part of the area. Based on the assumed hydrogeologic divide, the catchment size of the Dojkinacka River is 187.1 km^2 (Fig. 5). The water balance equation parameters were recalculated based on this figure and the results are shown in Table 2.

Unfortunately, the results based on the assumed catchment size are still not satisfactory. The runoff coefficient remains high, compared to those previously determined for other karst catchments in Serbia, which are in the interval from 0.4 to 0.6. The reason for this is the fact that annual precipitation totals recorded at the village of Dojkinci are not representative for calculations of the other water balance equation parameters. The rain-gauge station is at an altitude of 880 m. Even though the elevation of this station the highest on Mt. Stara Planina, the elevations of the upper catchment of the Dojkinacka River are as high as 2000 m, or much higher than that of the station. To arrive at the most realistic annual precipitation totals, representative of the entire catchment, the isohyet method needs to be used to calculate perennial average amounts of precipitation. Figure 6 shows an isohyet map of perennial average amounts of precipitation based on the period 1949-2006. It was used to zone precipitation levels (Table 3).

Table 2. Summary of water balance of the Dojkinacka River catchment based on realistic catchment size: Option 2

Size of catchment area F (km^2)	190.0
Average annual precipitation P (mm)	793.6
Average annual evapotranspiration E (mm)	213.0
Average annual discharge Q (m^3/s)	3.498
Runoff modulus q ($l/s/km^2$)	18.41
Discharged volume W (10^6 m^3)	110.31
Runoff layer h (mm)	580.6
Runoff coefficient φ	0.73

Table 3. Perennial average amounts of precipitation in the Dojkinacka River catchment based on the isohyet method

P interval (mm)		P_{av} of the interval	Associated surface area f_i (km^2)	Product of P_{av} x f_i
from	to			
750	800	775	4.94	3,828.5
800	850	825	22.35	20,913.75
850	900	875	46.28	40,495.00
900	950	925	59.63	55,157.75
950	1000	975	26.29	25,632.75
1000	1050	1025	27.59	28,279.75
sum			190.08	174,307.5

The above values were used to calculate the representative perennial average amounts of precipitation in the Dojkinacka River catchment, based on the equation:

$$\overline{P} = \frac{\sum_{i=1}^{n} f_i \cdot P_i}{F} = \frac{174307.5}{190} = 917.0 \text{ mm}$$

If these perennial average amounts of precipitation and the assumed active catchment size are used, the water balance equation parameters will be as shown in Table 4.

Table 4. Summary of water balance of the Dojkinacka River catchment based on realistic catchment size and annual average amounts of precipitation typical of the entire catchment: Option 3

Size of catchment area F (km^2)	190.0
Average annual precipitation P (mm)	917.0
Average annual evapotranspiration E (mm)	336.4
Average annual discharge Q (m^3/s)	3.498
Runoff modulus q ($l/s/km^2$)	18.41
Discharged volume W (10^6 m^3)	110.31
Runoff layer h (mm)	580.6
Runoff coefficient φ	0.63

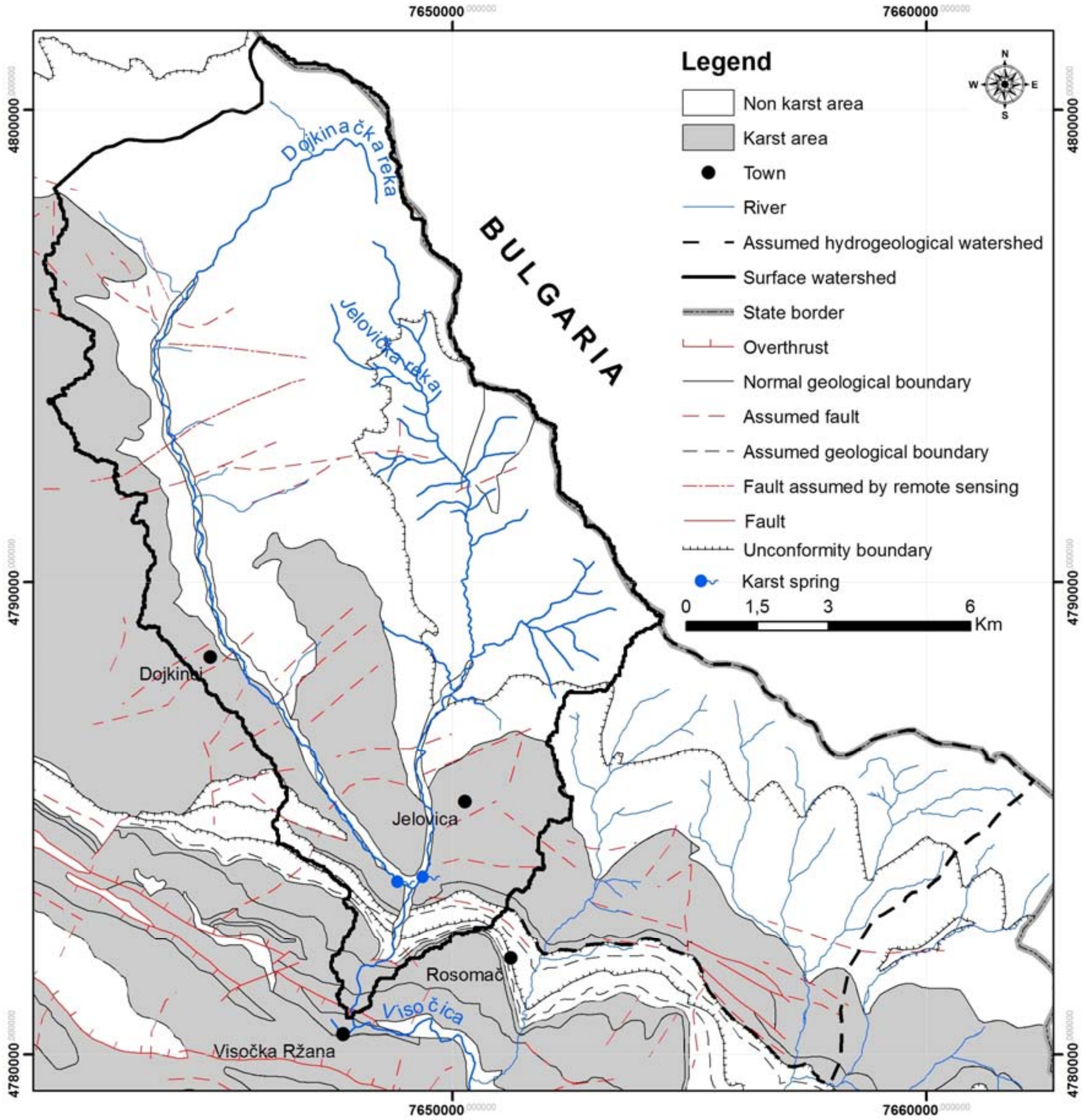

Fig. 5 Shematic hidrogeological map of the Dojkinacka river catchment

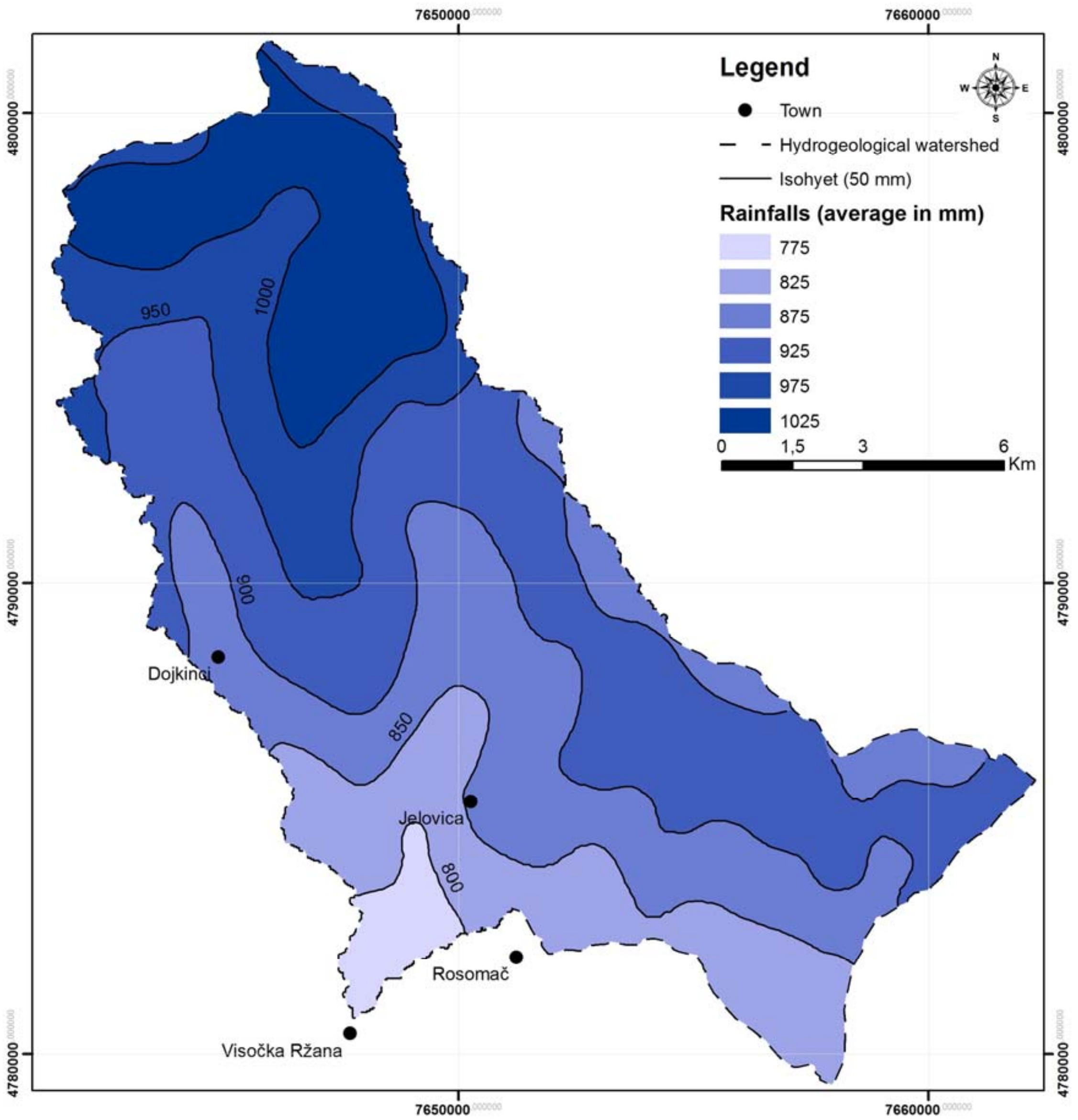

Fig. 6 *Isohyet map of the Dojkinacka River catchment (1949-2006).*

CONCLUSION

A lack of data on certain meteorological parameters (or unreliable data) is a major challenge associated with the determination of water balance parameters of small catchments. In addition, if the considered catchment is that of a karst spring or a river that is fully developed or in part passes through karst, another problem is defining the catchment size because in such cases only the real/active catchment size must be used.

In this regard, water balancing of the Dojkinacka River catchment using the topographic catchment size yielded totally unreasonable results. However, defining the real/hydrogeologic catchment size of the Dojkinacka River was not an easy task. The definition of the hydrogeologic divide was hindered by the presence of a large number of ponors and ponor zones detected in the channel of the Dojkinacka River, as well as those of the Rosomac, the Vodenica and the Visočica, which are situated at the points of contact between non-karst and karst rocks, as well as along the river channels in carbonate rocks, and the presence of karst springs that emerge within the river channels several kilometers downstream from the ponor zones. The previously mentioned Jelovica Spring, which features the highest discharge in the Visočica River Basin and whose hydrogeologic divide is much larger than the topographic divide, belongs to the catchment of the Dojkinacka River. In view of all the above and based on hydrogeologic research of the Dojkinacka River catchment, the catchment size was assumed to be 190.0 km^2. Further, it was determined that the rain-gauge station in the village of Dojkinci, although situated in the catchment area of the Dojkinacka River, is not representative of the entire catchment. Consequently, the isohyet method was used to calculate perennial average amounts of precipitation and the resulting representative annual average for the entire catchment was 917.0 mm. However, the water balance parameters indicated that there were still errors. For example, the runoff coefficient was 0.63, which was too high taking into account the entire catchment, including both karst and non-karst areas.

According to some researchers, the assumed size of the Dojkinacka River catchment is as large as 201.5 km^2 (Nikić, 2003). If this catchment size and the annual average amount of precipitation of 918.5 mm are taken as representative, the runoff modulus is 17.36 l/s/km^2, the annual average runoff from the catchment 547.5 mm of water column, and evaporation 371 mm. Consequently, the runoff coefficient is 0.60.

The final conclusion is that in order to determine the water balance parameters of the Dojkinacka River as accurately as possible, a denser meteorological network of monitoring stations and the installation of a lysimeter will be required. Also, due to the highly complex geologic framework and the hydrogeologic conditions in the catchment, the hydrogeologic, not topographic, catchment needs to be defined. This can be achieved by detailed hydrogeologic reconnaissance, which should definitely include tracing tests to determine the privileged pathways of karst groundwater flow.

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