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Groundwaters of the "Valjevo Karst" Area (Western Serbia)

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Key words:
karst aquifer, groundwater traces, springs, wells, discharge, multipurpose use

Abstract. "Valjevo karst" is an area of about 780 km^2 in a broader sense, while the uncovered karstified limestone makes about 330 km^2. It is a part of the Inner Dinarides (Western Serbia). In the litho-stratigraphic view, the karstified limestones of Middle–Upper Triassic dominate, in which karst aquifers are formed. Analysis and systematization of the available data of hydrogeological and other relevant research is carried out. A branched network of groundwater traces between swallow holes and discharge points is presented as well as main features of sixteen karst springs (or scattered discharge zones) and nine (group of) wells, divided into five sectors. Average karst aquifer discharge of the whole area is calculated on 5.18 m^3/s. Total minimum flow rate of the analysed karst springs and discharge zones is estimated at 1.2 m^3/s, while the total flow rate of the analysed wells is estimated at about 0.3 m^3/s, which makes about 1.5 m^3/s of total (minimum) discharge. All analysed waters are low-mineralized (<1 g/l), while temperatures range from 9–35 °C. Use of the waters is multipurpose: municipal and local water supply, commercial bottling, recreational pools etc.

Кључне речи:
карстна издан, трасе подземних вода, извори, бунари, издашност, вишенаменско коришћење.

Апстракт. "Ваљевски карст" је подручје које заузима површину од око 780 km^2, док откривени кречњак чини око 330 km^2. Припада Унутрашњим Динаридима западне Србије. У литостратиграфском погледу доминирају карстификовани кречњаци средњег и горњег тријаса у којима су формиране карстне издани. Анализирани су и систематизовани доступни подаци хидрогеолошких и других релевантних истраживања. Приказана је разграната мрежа траса подземних вода између понора и дренажних пунктова, као и главне карактеристике шеснаест карстних врела (или „разбијених" дренажних зона) и девет (група) бунара, подељених у пет сектора. Просечна издашност карстних издани целог подручја срачуната је на 5.18 m^3/s. Сумарна минимална издашност анализираних карстних извора и дренажних зона процењена је на 1.2 m^3/s, док је сумарна издашност анализираних бунара процењена на око 0.3 m^3/s, што чини сумарну (минималну) издашност од око 1.5 m^3/s. Све анализиране воде су маломинерализоване (<1 g/l), док се температуре крећу у распону од 9–35 °C. Користе се вишенаменски: комунално и локално водоснабдевање, комерцијално флаширање, рекреативни базени и др.

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Introduction

“Valjevo karst” (VK) covers the area from Valjevo-Mionica Neogene basin (VMB), in the North, to the northern slopes of Valjevo Mountains range: Suvobor Mt., Maljen Mt., Povlen Mt., Jablanik Mt, Medvednik Mt., in western Serbia, with a frame range of altitudes of app. 50–1350 masl (Fig. 1). On the West-East direction, it is stretched from the Jablanica River Basin to the Toplica River Basin. Geographically, it belongs to the Kolubara river basin, and administratively to the Kolubara District and (mostly) to the municipalities of Valjevo and Mionica. The total area, including two (relatively) separated karst oases is about 780 km^2, while the main mass of uncovered karstified limestone makes about 330 km^2. Field hydrogeological research were carried out, on several occasions, at various locations and were partial both in terms of the size of the researched areas and in terms of time continuity: short-term flow-rate monitoring of few karst springs, tracing tests, exploratory drilling, well-drilling for water supply of few settlements and commercial water bottling, thermal water capture. The paper gives the analysis and systematization of available data derived from previous researhes.

Geo(morfo)logical features

VK belongs to the geotectonic region of the Inner Dinarides. The main mass of uncovered karstified limestone has features of holokarst, while the total area represents a merokarst. In the litho-stratigraphic view, the karstified Medium-Upper Triassic limestones are dominant, the thickness of which is estimated to be 300 m (Mojsilović *et al.*, 1975) and, in which, the karst aquifers are formed (Fig. 2, Fig 3). To a much lesser extent, karstified Upper Cretaceous limestones, up to 50 m thick exist in the catch-

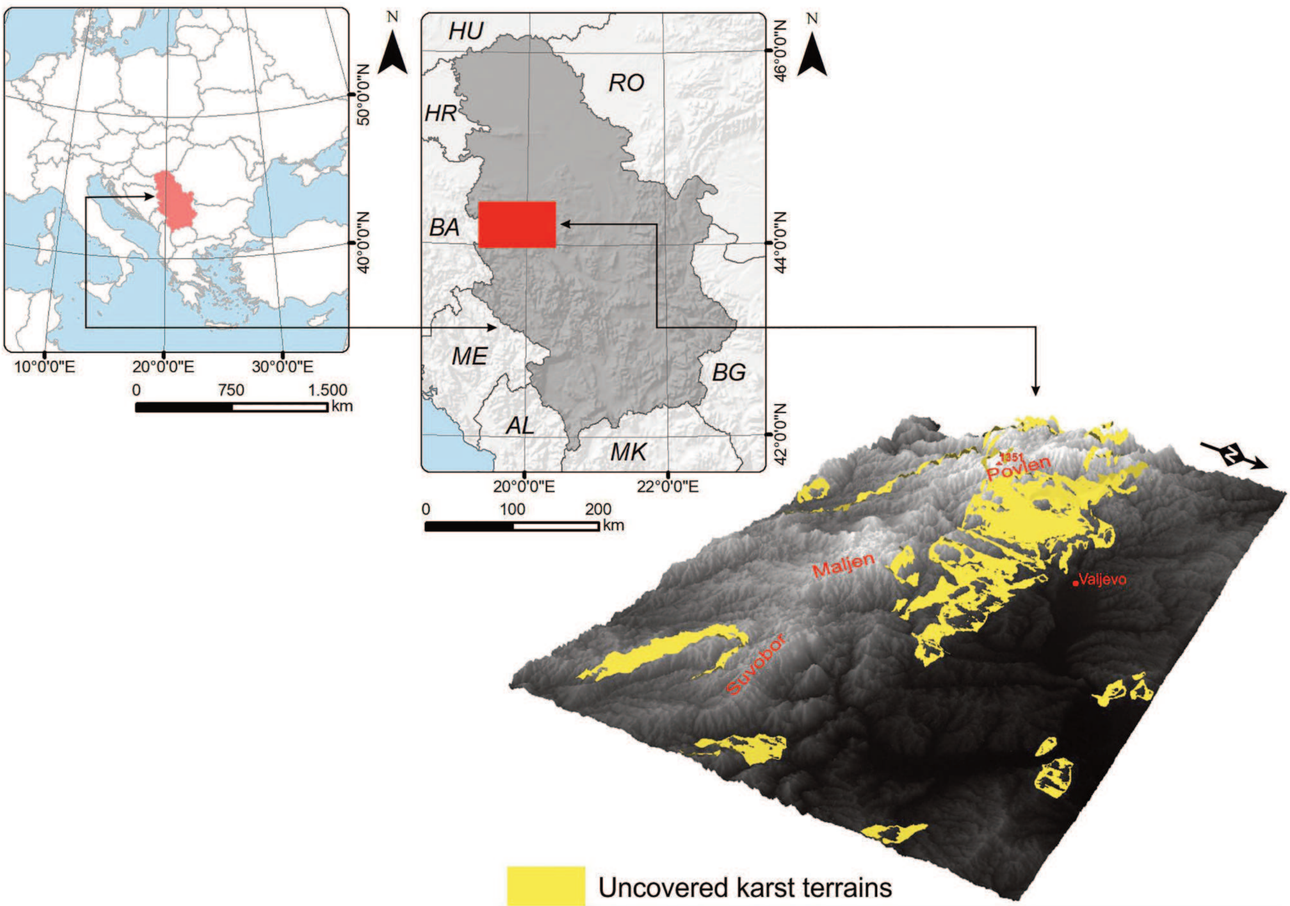

Fig. 1. *Geographical position and digital elevation model of the Valjevo karst area.*

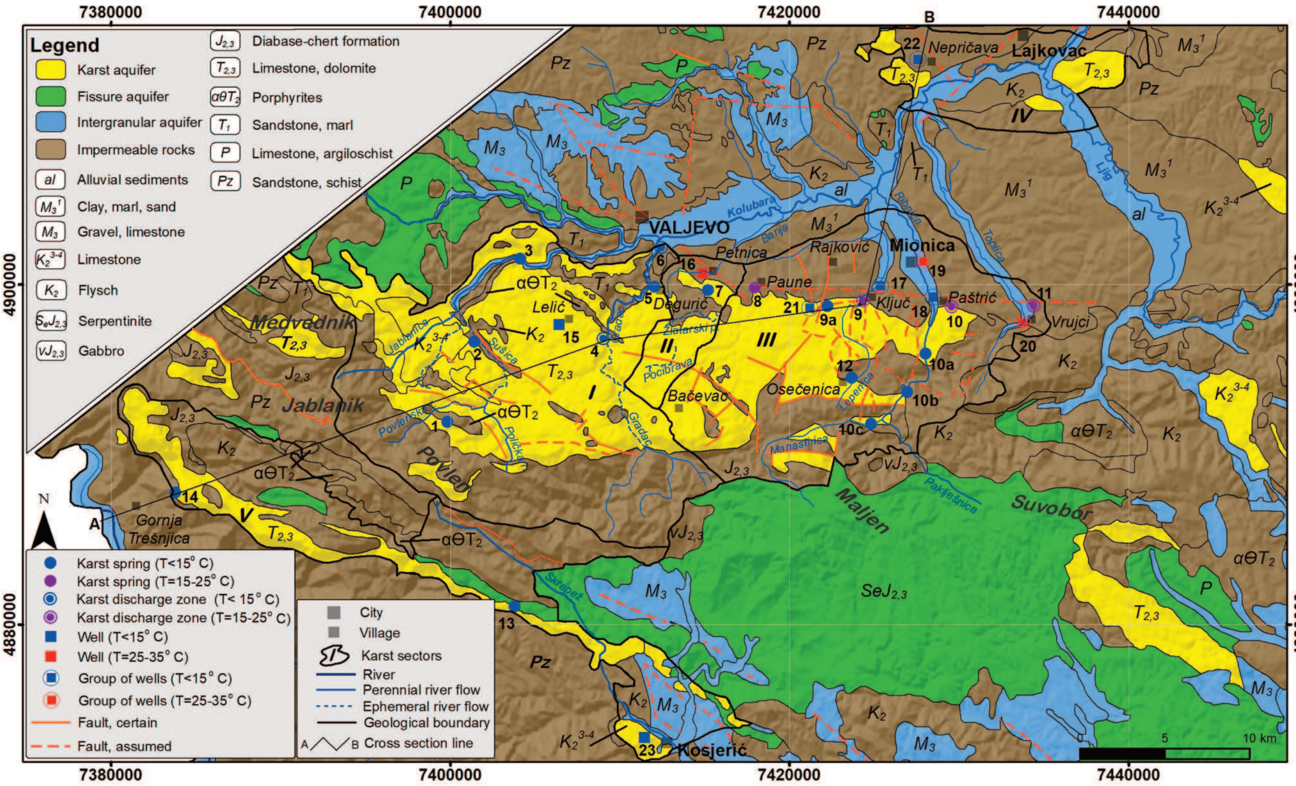

Fig. 2. *Hydrogeological map of the Valjevo karst area (MARINOVIĆ, 2014, adapted).*

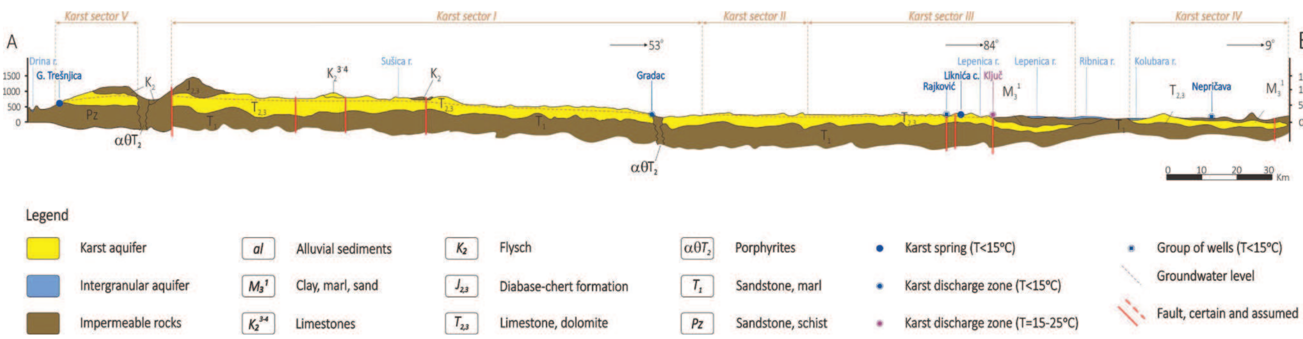

Fig. 3. *Hydrogeological cross-section of the Valjevo karst area.*

ments of the Jablanica and Sušica (the largest tributary of the Jablanica) rivers. Other geological units, starting from the Upper Miocene deposits of VMB, to the Paleozoic formations (Fig. 2, Fig. 3), represent (relatively) impermeable rocks i.e. the barriers for karst groundwater flows. The intense radial tectonics, followed by volcanic activity, formed the block structure of the terrain, which was the main predisposition for an intense karstification (MILOJEVIĆ, 1959; MIJATOVIĆ, 1983).

The karst relief is made up of karst plateaus separated by the valleys (canyons) of the Sušica, Gradac, Lepenica and Ribnica River, oriented in general, in the South-North direction. The dominant surface karst forms are sinkholes, with the average density higher than 10/km^2. A total of 195 underground forms i.e. speleological objects, have been detected: 134 caves and 61 potholes. The total length of the explored caves is 6122 m, and the total depth of the potholes is 1178.5 m (LAZAREVIĆ, 2008).

Tracing tests showed high development of the karst channels and complex underground traces between the swallow holes (ponors) and the springs (Fig. 4) (Lazarević, 1996). Triassic limestone was discovered (by drilling) below the Upper Miocene deposits of VMB in the villages of Petnica, Mionica and Vrujci. It is likely that these limestones continue to extend to the north (under the Upper Miocene deposits), to the zone (karst oasis) of Nepričava village, on the left side of Kolubara valley. It is possible, but unproven that, in the southern part, under the Jurassic and Cretaceous formations, the limestones are partly extended to the karst oasis of Gornja Trešnjica and Taor springs (Fig. 2).

and Bačevac plateau; ***II-Banja River catchment***; ***III-Catchments of the Lepenica, Ribnica and Toplica River***; ***IV-Northern karst oasis** - around Nepričava village;* ***V-Southern karst oasis** - discharge zones of Taor and Gornja Trešnjica springs.*

I-Lelić karst. Within this area an extensive karst aquifer is formed and is mostly drained by Paklje spring and Gradac springs (discharge zone) (Mijatović, 1983; Simić, 1990). On the Lelić and Bačevac plateaus there are no permanent streams because all precipitations infiltrate through the dense network of sinkholes and swallow holes. At the site of the Lelić Monastery (407 m asl), a small diameter borehole of 147 m depth was drilled for local water

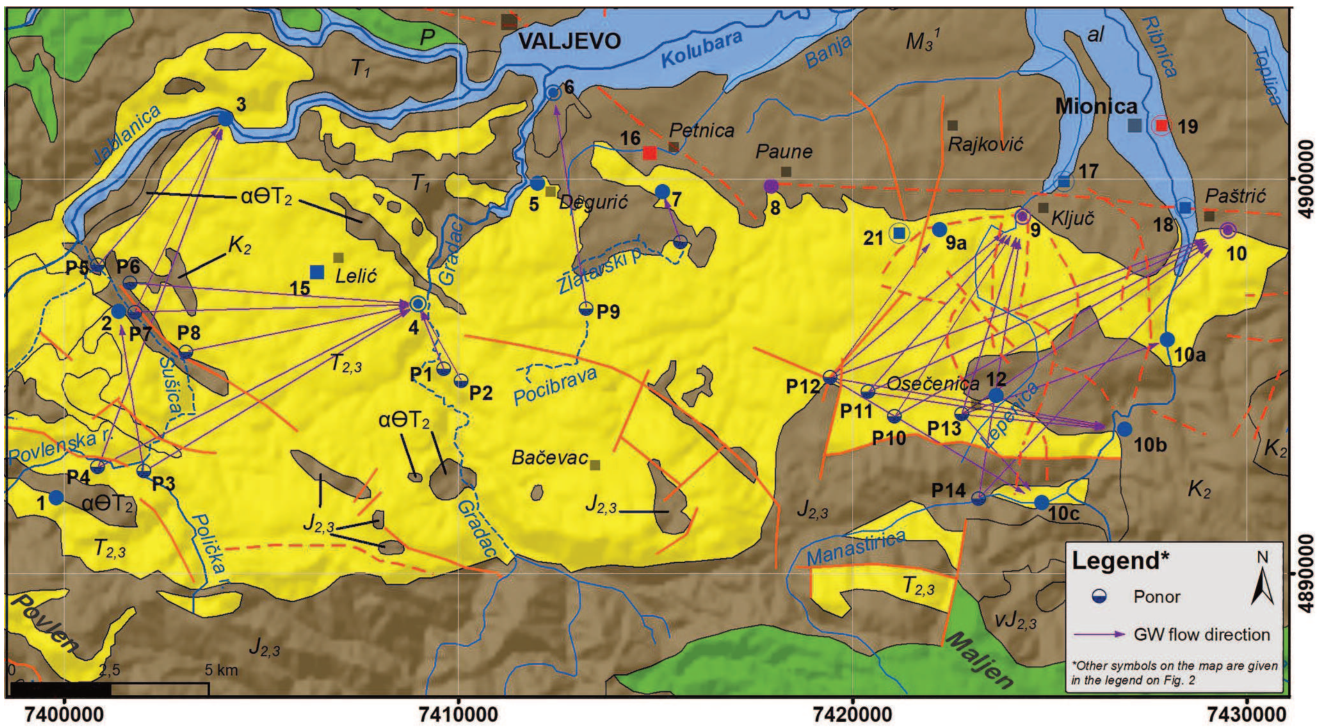

Fig. 4. Proven karst groundwater traces in the Valjevo karst area.

Hydrogeology

According to the spatial distribution of the most important discharge points and zones of the karst aquifers (Fig. 2, Tab. 1) as well as available data on proven groundwater traces (Fig. 4, Tab. 2), the following division into five sectors (Tab. 3) is adopted for further exposure: ***I-Lelić karst***, that includes: Sušica River catchment, Lelić plateau, Gradac valley

supply. The depth to the groundwater was 60 m and about 1 l/s of water is pumped out (Petrović, 2013).

The Sušica River is formed by merging of the Povlenska and Polička River. The most remarkable spring in the upper Sušica catchment is Povlen spring (app. 930 m asl) with minimum flow rate estimated at around 20 l/s (Petrović, 2013). In its upper stream, but only in high water periods, the Sušica River (Fig. 5) flows through a 4 km canyon, along which there

Table 1. *Significant hydrogeological occurrences and objects of the Valjevo karst area.*

No (on Fig. 2)	Name	Altit (masl)	Flow rate	TDS (g/l)	T (°C)	Use
Springs / Discharge zones						
I-Lelić karst						
1	Povlen spring	930	Q_{min}=20 l/s	low min.(1)	cold (2)	no*
2	Savinac spring	338	Q_{min}=3 l/s	low min.	cold	no*
3	Paklje spring	258	$Q_{min/max}$= 0.2–1.04 m^3/s	0.24–0.31	10–13	MWS
4	Gradac spring	261–265	$Q_{min/max}$=0.4–10 m^3/s	0.18–0.23	cold	MWS**
5	Degurić cave spr.	216	Q_{min}=12 l/s	low min.	cold	no*
6	Novaković dis. Zone	195	Q_{min}=15 l/s	low min.	cold	no*
II-Banja river catchment						
7	Petnica spring	184	$Q_{min/max}$=0.1–1 m^3/s Q_{av}=0.11–0.25 m^3/s	low min.	cold	no*
III-Lepenica, Ribnica and Toplica catchments						
8	Paune spring	210	Q_{min}=2 l/s	0.5	21	no*
9	Ključ dis. zone	165–205	$Q_{min/max}$=0.12–4 m^3/s	0.5	9–21	no*
9a	Liknića cave	296	Tempor. spring	low min.	cold	no*
10	Paštrić dis. zone	192–234	Q_{min}=30 l/s Q_{av}=0.6 m^3/s	low min.	cold, subth.(3)	no*
10a–c	Springs in the upper catch. of Ribnica	232–295	Tempor. springs	low min.	cold, subth.	no*
11	Vrujci dis. zone	180–185	$Q_{min/max}$= 0.2–0.5 m^3/s	0.5	Thermal(4): 26–27	SP
12	Orlovac spring	345	Q_{min}=20 l/s; Q_{av}=40 l/s	low min.	cold	MWS
V-Southern karst oasis						
13	Taor springs	703	$Q_{min/max}$= 17–250 l/s	low min.	cold	MWS
14	G.Trešnjica spring	754	Q_{av}=80 l/s	low min.	cold	no*
Wells						
I-Lelić karst						
15	Lelić well	260(5)	Q=1 l/s	low min.	cold	LWS
16	Petnica deep well	from –300 to –50	Q=15 l/s	0,5 g/l	29	SP
III-Lepenica, Ribnica and Toplica catchments						
17	Ključ group	50–100	20–30 l/s	low min.	cold, subth.	LWS, SP, WB
18	Paštrić group	70–120	Q=40 l/s	low min.	cold, subth.	MWS
19	Mionica deep well	from –310 to –230	Q=15 l/s	low min.	35	Unknown
20	Vrujci group	70–120	30–40 l/s	0.5	26–27	SP, WB
21	Rajkoviæ group	100–150	20–30 l/s	low min.	cold, subth.	WB, SP, LWS
IV-Northern karst oasis						
22	Nepričava group	from –230 to –10	Q=100–120 l/s	low min.	cold	MWS
V-Southern karst oasis						
23	Kosjerić well	300–350	–	low min.	cold	MWS

(1) Low min(eralised): TDS<1g/l; (2) Cold: <15 °C; (3) Subth(ermal): 15-25°C; (4) Thermal: >25 °C; (5) App. altitude of the intake part(s) - for all displayed (groups of) wells; *Probably in use for local water supply and agriculture needs, but no data; *Capture is not (directly) on the springs, but app. 2.5 km downstream the Gradac river flow; **Abbreviations**: **MWS**-Municipal (centralized) water supply, **LWS**- local water supply, **SP**-swimming pools, **WB**-water bottling;

Table 2. *Basic parameters of the performed tracing tests in the Valjevo karst area (adapted from: Lazarević, 1996).*

INLET POINT (PONOR) **No** *(on Fig. 4)*	*Alt. (masl)*	*OUTLET POINT (SPRING)* **No** *(on Fig. 2)*	**Alt.** *(m.a.s.l)*	*GW flow* **velocity** *(m/hour)*	*Date*
Lelić karst					
P1	475	4	261–265	86	may 1972
P2	496	4	261–265	18	sep. 1984
P3	473	2	338	83	sep.1972
		4	261–265	28	july 1973
P4	602	4	261–265	62	sep. 1984
		3	258	21	
P5	338	3	258	23	nov. 1984
P6	355	4	261–265	86	
P7	356	3	258	58	sep.1985
P8	376	4	261–265	43	
		4	261–265	inaccur. data	aug. 1987
Banja river					
P9	247	6	195	144	aug. 1987
Lepenica-Ribnica catchement					
P10	355	9	160–180	91	sep.1985
		10	200–210	167	
P11	371	10b–10c	270–295	127	nov.1985
		10	200–210	175	
		9	160–180	130	
		10b-10c	270–295	41	apr. 1987
		9	160–180	42	
P12	362	10c	295	29	jan.1986
		10b	270	47	
		10	200–210	122	
		9a	296	68	
		9	160–180	94	
P13	353	10c	295	40	feb.1986
		10b	270	173	
		10a	232	inaccur. data	
		10	200–210	287	
		9	160–180	360	
P14	347	10a	232	15	sep.1987
		9	160–180	inaccur. data	

Table 3. *Spatial features of the marked sectors.*

Sector	**Alt. range (masl)**	**Average alt. (masl)**	**Area size (km^2)**	**Uncovered karst (km^2)**
I	188–1351	645	285	163
II	160–694	375	29	18
III	109–030	369	232	88
IV	47–384	139	74	15
V	297–1230	795	159	45
Total area	47–1351	488	779	330

are several ponor zones. The ponor zones that are downstream from 400 m asl act as temporary springs (estavelle), but only during the rainy periods. Further downstream, in the range of 335–360 m asl, there is another zone of some 15 ponors and temporary springs, as well as the only permanent spring Savinac with a minimum flow rate of about 3 l/s (Simić, 1990). Downstream, surface flow to the Jablanica River exists only in high water periods.

The appearances of the Paklje spring and Gradac springs is caused by the position of the Triassic porphyrite and Lower-Triassic sediments (Fig. 2) that represent hydrogeological barriers. Depending on the data source (Mijatović, 1983; Simić, 1990; Lazarević, 1996), the Paklje spring altitude is app. 258 m asl, and is partially captured (up to 300 l/s) for the municipal water supply of Valjevo (Fig. 6). There is no continuous flow rate monitoring and the only longer observation periods were 1972–76 and 2015–16. During 1972–76, the flow rates were in the range of 0.2–2 m^3/s, and the average value was 0.3 m^3/s (Mijatović, 1983). During 2015–16, the flow rates were in the range of 0.2–1.04 m^3/s, and the average value was 0.43 m^3/s (Dokmanović & Vukićević, 2019).

The Gradac discharge zone consists of several springs in the Gradac canyon, on both valley sides, in the altitude range of 261–265 masl, from where the permanent river flow begins. Upstream, the surface flow exists only after abundant rains or snow melting. The dry river valley has a lot of ponor zones and the tracing tests showed groundwater traces to the Gradac springs (Lazarević, 1996) (Fig. 2). For the 1972–76 period, the total flow rate of Gradac springs was in the range of 0.4–10 m^3/s, and the av-

Fig. 5. *Dry valley of the Sušica River (Dokmanović et al., 2012).*

Fig. 6. *Uncaptured overflow of the Paklje spring (Petrović, 2013).*

erage value was 1.1 m^3/s (Mijatović, 1983). Downstream, the karst aquifer is drained through several minor springs and discharge zones along the Gradac River: Degurić cave (216 m asl, Q_{min}=12 l/s), Novaković spring (195 m asl) etc. The average flow for the Gradac River on the hydrometric profile Degurić (201 m asl) (Fig. 2), for the 1972–76 period, was 3.22 m^3/s, and the average annual flows vary from 2.59 to 4.63 m^3/s. For the 2000–2015 period, the average flow was 2.58 m^3/s, and the average annual flows vary from 1.49 to 3.81 m^3/s. In the same period, the average monthly flows range from 1.2 m^3/s (Sept.) to 5.28 m^3/s (March) (database of the Republic Hydro-meteorological Survey of Serbia). A little downstream of the Degurić profile, a part of the Gradac River flow is captured for the municipal water supply of Valjevo, as a supplement to the Paklje spring in recession periods. Basic chemical features of Gradac springs water are typical for karst aquifers: TDS=180–230 mg/l and belong to the carbonate class and the calcium group (Marinović, 2014). Paklje spring water is similar, with TDS of 240–310 mg/l, but several analysed water samples (during the period 2015–2016) were bacteriologically polluted (Dokmanović & Vukićević, 2019).

Total average discharge of the Lelić karst aquifers was estimated at 2.5-3 m^3/s (Mijatović, 1983; Simić, 1990).

Underground flow traces to the Paklje spring and to the Gradac springs have been detected by marking the ponors with sodium-fluorescein (uranine), in the Sušica valley and in upper part (upstream of the Gradac springs) of Gradac river valley (Lazarević, 1996) (Tab.2, Fig. 4). The tracer from 2 ponors (P1 and P2), in the valley of river Gradac, appeared only on Gradac springs, and the velocities of groundwater flows were 18-86 m/hour. Tracing from 6 ponors (P3-P8), in the Sušica valley, showed the (expected) groundwater traces to the Savinac spring and the Paklje spring, but groundwater bifurcation was also determined, considering that the tracer appeared also on the Gradac springs. The velocities of groundwater flows were 21–86 m/hour.

II-Banja river catchment. Banja river originates from the Petnica spring, near Petnica village. There are two streams in the topographic catchment of Banja: Zlatar and Pocibrava, and both of them lose water on the karst terrain. A tracing test showed bifurcation i.e. the connection of the ponor (P9) in Pocibrava stream and Novaković discharge zone in the Gradac river catchment (Lazarević, 1996) (Fig. 4).

Petnica spring (184 masl) appears in Petnica cave (Fig. 5), and the drainage is conditioned by the barrier of the Miocene sediments of VMB. The spring is featured by an intermittent character with visible daily flow rate fluctuations (Simić, 1990; Lazarević, 1996). For the period 1972–1976, the flow rate of the Petnica spring varies from 0.1–1 m^3/s (Mijatović, 1983). For the period 1991–2000 the average annual flow rates were 0.11–0.25 m^3/s (Golubović *et al.* 2014). Downstream (app. 181 m asl), a thermal (23 °C) low mineralized (0,5 g/l) spring occurs in the Banja riverbank (Protić, 1996). This phenomenon initiated drilling of a deep well which captures about 15 l/s of low mineralized water of 29 °C, from the deeper parts (232–500 m) of the karst aquifer (Petrović, 2013; Marinović, 2014). The water is used for swimming pools.

Fig. 7. *Petnica cave and spring (Petrović, 2013).*

III-Lepenica-Ribnica-Toplica catchments. Several discharge zones are detected in this sector and are featured by the occurrences of thermal waters (Fig. 2). Thermal (21 °C) low mineralized (0.5 g/l) spring in the village Paune (210 m asl) appears in the contact zone with the barrier of Miocene sediments of VMB (Protić, 1995). The Ključ discharge zone also appear in the contact zone with the barrier of Miocene sediments of VMB, along the Lepenica riverbed (165–205 m asl). Cold (9–11 °C) and (sub)thermal (up to 20,5 °C) low mineralized (0,5 g/l) springs are detected. The estimated total flow rate is in the range of 0.12–4 m^3/s (Simić, 1990). Several wells have been drilled in this zone for local water supply, commercial water bottling, swimming pools, etc. (Petrović, 2013).

The Paštrić discharge zone appears in the contact zone with the Miocene sediments, as well, along the Ribnica river bed, in the length of about 3 km (192–234 m asl). The zone of temporary springs appears about 2 km upstream. The estimated total minimum flow rate is about 30 l/s and the average one is about 0.6 m^3/s (Simić, 1990). In this zone, the Mionica municipal water supply source is located. Several deep wells capture about 40 l/s of groundwater, below the 20–100 m thick Miocene sediments (Petrović, 2013). Orlovac spring, in the village of Osečenica, is also captured for the water supply of Mionica. The minimum flow rate is about 20 l/s and the average is about 40 l/s (Petrović, 2013). In the village of Rajković, there are several wells that capture karst groundwater, among other purposes, for commercial water bottling (Petrović, 2013).

In Mionica, a well captures about 15 l/s of thermal (35 °C), from the deep parts (405–485 m) of the karst aquifer (Protić, 1995).

The Vrujci discharge zone is formed by an upward mechanism of outflow of thermal (26–27 °C) low mineralised (0.5 g/l) water with the appearance of gases. The outflow is ostensibly from the alluvial deposits of the Toplica River in the range of 180–185 masl. Total outflow rate is difficult to determine due to the outspread and the secondary character of the discharge zone and mixing with river water. Estimated range is 0.2–0.5 m^3/s (Simić, 1990). In this zone, several drilling wells capture thermal water for swimming pools and commercial bottling (Petrović, 2013).

The karst groundwaters of this zone are low mineralized and belong to the carbonate class and the calcium or calcium-magnesium group. Estimated total average discharge (including Banja river catchment) is about 3.0 m^3/s (Simić, 1990).

Tracing tests (all made with sodium-fluoresceine) in the Ribnica and Lepenica (without Toplica) catchments (Tab. 2, Fig. 4) showed the “crossings” and bifurcations of underground streams (Lazarević, 1996) (Fig. 4). The velocities of groundwater flows were 15–175 m/hour.

IV- Northern karst oasis. The source for municipal water supply of Lazarevac and Lajkovac (loc. Nepričava) (Fig. 2) is based on the six deep (120–350 m) drilled wells that capture app. 120 l/s of karst groundwaters (Dokmanović *et al.*, 2012). Total thickness of overlaying Miocene and alluvial deposit is 20–100 m.

V- Southern karst oasis. Two springs are noteworthy in the southern oasis, in the contact zone with the Paleozoic formation (Fig. 2, Fig 3): Gornja Trešnjica (Q_{av}=80 l/s) and the Taor springs (discharge zone), that is partially captured for municipal water supply of the Kosjerić village. The flow rate of non-captured part of the Taor springs varies in the range 17–250 l/s (Petrović, 2013). Supplement water supply of Kosjerić is based on the capture of karst water by a drilled well (Fig. 2), during the recession of Taor springs.

Groundwater quantity

There is no continuous (systematic) outflow monitoring at significant drainage points of the karst aquifer, which would significantly facilitate the precise water balancing and the assessment of available groundwater quantity in the area. Based on the available meteorological data, for the period 2000–2015, an approximate water balance is made for the area covered by sectors I, II and III.

Water balance equation can be expressed as (Mijatović, 1997):

$$D = P - E_r = R + I_e \quad (1)$$

where: D– runoff ; P– precipitation; E_r–evapotranspiration; R– surface runoff; I_e- infiltration (in karst aquifer)

Evapotranspiration was calculated according to the Turc formula:

$$E_r = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \quad (2)$$

"L" parameter is calculated as:

$$L = 300 + 25T + 0.05T^3 \quad (3)$$

where „T" is the average annual air temperature.

Table 4 shows calculated average annual evapotranspiration values for the period 2000–2015, based on annual sum of precipitation and average air temperature in Valjevo meteorological station (10.7 °C).

Table 4. *Annual sums of precipitation and calculated evapotranspiration for MS Valjevo (167 masl) for 2000–2015 period.*

Year	P (mm)	Er (mm)
2000	470,3	403,3
2001	992,6	526,8
2002	657,3	476,8
2003	580,4	434,5
2004	697,4	471,0
2005	770,9	474,4
2006	797,3	498,8
2007	756,0	503,8
2008	694,9	495,6
2009	868,0	534,4
2010	1030,4	551,9
2011	581,8	431,4
2012	611,1	460,2
2013	702,3	513,8
2014	1332,4	645,0
2015	767,6	542,3
Aver.	769,4	**497,8**
%	100	**64,69**

Calculated from Tab. 4, (average) annual runoff (D) is 271,6 mm. According to Mijatović (1997), in karst terrains of western Serbia, infiltration makes 70–85% of the runoff. Adopted value for our calculation is 70%, given that app. 50% of calculated area is (un)covered karst (Tab. 5). It makes effective annual infiltration of 190,12 mm and that means average ground water quantity i.e. average karst aquifer discharge of 4.37 m^3/s (Tab. 5).

When it comes to (peripheral) sectors IV and V (233 km^2), the applied calculation parameters should be changed, given that the presence of outcrop karst is significantly lesser (Table 3). A rough estimation is that the infiltration here accounts for about 40% (109 mm/year) of the total runoff, giving a total (for both sectors) discharge of 0.81 m^3/s.

Total average karst aquifer discharge rate for whole VK area is 5.18 m^3/s.

__Table 5.__ Groundwater quantity calculation for the sectors I, II and III (2000–2015).

Total area	Uncovered Karst	Effective infiltration (GW quantity/discharge)		
km^2	km^2	mm/year	m^3/year	m^3/s
546	270	190,12	$137{,}8 \times 10^6$	4,37

Discussion

The area is featured by complex underground hydrography and discordance of topographic and hydrogeological (sub)catchments, that makes difficulties for precise water balancing.

Tracing tests were conducted on several occasions, in the period 1972–1987. The obtained results, and above all the calculated velocities of underground flows, should be accepted with a certain reserve. Observations at outlet points were not continuous, so the first occurrences of tracers were most likely registered with a delay. This means that all calculated groundwater velocities (Tab. 2) are less than the real ones. In addition, observations were made at (only) a few (expected) points, so the number of traces is probably higher than shown in Fig. 4 and Tab. 2.

Calculated average aquifer discharge is 5.18 m^3/s and is lower than the mentioned estimates of some mentioned researchers (about 6–6.5 m^3/s). It is important to point out that both values represent the results of relatively rough calculations/estimations, as well as that the discharge rate depends on the annual quantity and seasonal distribution of precipitation. In addition, our calculation is based on precipitation registered at the altitude of 167 m asl (Tab. 4), while the real average altitude (Tab. 3) is much higher, especially in sectors I, III and V (which make the largest part (about 86%) of the total space). Therefore, the real average values of precipitation and, consequently, infiltration are higher than the calculated ones.

Total minimum flow rate of the analysed karst springs and discharge zones is 1.2 m^3/s, where the elevations of the discharge points (zones) vary in range 180–930 m asl. Total flow rate of the analyzed wells is about 0.3 m^3/s, which makes about 1.5 m^3/s, totally. Altitudes of the well intake intervals are from –300 to (+)350 m asl. All analysed waters are low-mineralized (<1 g/l), while temperatures range from 9–35 °C. Cold water (<15 °C) makes about 1.2 m^3/s (80%), subthermal (15–25 °C), about 80 l/s (2%) and thermal (>25 °C), about 200 l/s (18%). Captured groundwater is used for multiple purposes: municipal water supply, commercial bottling, recreational pools etc.

The Q_{min}/Q_{max} spring discharge regimes vary from 1:10 (Paklje and Petnica spring) to 1:25 (Gradac springs), which makes these resources, under natural conditions, relatively unreliable in dry periods. Higher altitude of Gradac springs is probably the reason for more (than Paklje and Petnica spring) variable discharge regime.

Bacteriological pollution of groundwater drained by Paklje spring is a direct consequence of the aquifer openness (exposure) and unfavourable conditions of its natural vulnerability. The pollution hazard is reflected in the fact that agricultural activities are present in the catchment, and rural settlements do not have sewerage. A similar situation is typical for most of the area in in sectors I, II and III.

Conclusion

An analysis and systematization of available data derived from previous researches is given in the paper.

VK is an area of about 780 km^2, while the uncovered karstified limestone makes about 330 km^2. According to the spatial distribution of the most important discharge points and zones of the karst aquifers as well as available data of proven groundwater traces, the area is divided into five sectors. A branched network of groundwater traces between swallow holes and discharge points is presented as well as main features of sixteen karst springs (discharge zones) and nine (group of) wells. Average karst aquifer discharge of the whole area is calculated on 5.18 m^3/s. Total minimum flow rate of the analyzed karst springs and discharge zones is estimated at 1.2 m^3/s, while the total flow rate of the analyzed wells is estimated at about 0.3 m^3/s, which makes about 1.5 m^3/s of total (minimum) discharge. All analysed waters are low-mineralized (<1 g/l), while temperatures range from 9–35 °C. Use of the waters is multipurpose: municipal and local water supply, commercial bottling, recreational pools etc.

There is no adequate (systemic) quantitative monitoring of karst groundwater, neither in terms of spatial schedule of points, nor in terms of continuity. None of the springs or discharge zones is observed, and there is only one observed hydrometric profile (Degurić, on the Gradac river).

Regulation of (unfavourable) natural discharge of Paklje and Gradac springs (sector I) have been considered by some researchers, but the realization did not happen given that the construction of the "Stubo-Rovni" dam and reservoir (on the Jablanica and Sušica rivers) was planned several decades ago, for the water supply purpose of the entire Kolubara district. In other sectors regulations have been successfully carried out at several sites by drilled deep wells, for municipal water supply, thermal water use and commercial bottling.

Regardless of the national and district water management plans, the VK aquifers should be kept under continuous quantitative (discharge rates of springs/wells and GWL) and qualitative (because of high vulnerability and pollution hazard) monitoring, in order to preserve and keep this exceptional natural water reservoir in good status.

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Резиме

Подземне воде Ваљевског карста (западна Србија)

Подручје Ваљевског карста припада унутрашњим Динаридима западне Србије и простире се од Ваљевско–мионичког басена на северу, до северних падина Ваљевских планина (Слика 1), са распоном надморских висина 50–1350 mnm. Главна маса кречњака откривена је на површини терена од око 330 km^2, док, у ширем смислу, цело подручје има површину од око 780 km^2. У литостратиграфском погледу, доминантна је форма-

ција кречњака и доломита средњетријаске старости, дебљине око 300 m (Mojsilović et al., 1975), у којој су формиране карстне издани (Слике 2 и 3, Табела 1). Рељеф терена чине карстни платои, који су одвојени долинама (кањонима) река Сушице, Градца, Лепенице и Рибнице. Доминантни површински карстни облици су вртаче (>10/km²), а подземни пећине и јаме. На основу просторних позиција значајнијих карстних врела или дренажних зона (Слика 2), као и на основу резултата опита трасирања (Слика 4, Табела 2), који показују разгранату и комплексну мрежу подземних токова, подручје Ваљевског карста је подељено у 5 сектора (Табела 3): *I – Лелићки карст; II – Слив реке Бање; III – Сливови река Лепенице, Рибнице и Топлице; IV – Северна карстна оаза (Зона Непричаве) и V – Јужна карстна оаза (зоне истицања Таорских врела и врела Горње Трешњице).*

Лелићка карстна издан се, у највећој мери, дренира преко врела Пакље и Градац, чије издашности варирају у опсегу 0,2–1,04 m³/s (Пакље), са просечних 0,43 m³/s (Dokmanović & Vukićević, 2019), односно, 0,4–10 m³/s (Градац), са просечних 1,1 m³/s (Mijatović, 1983). Петничко врело, са опсегом издашности 0,11–0,25 m³/s (Golubović et al., 2014), најзначајнији је дренажни пункт у *сливу реке Бање*, док је најзначајнији водни објекат, дубоки бунар са захватом око 15 l/s термалне (29 °C) воде. (Petrović, 2013; Marinović, 2014). За *сливове Лепенице, Рибнице и Топлице* својствене су дренажне зоне са хладним и (суб)термалним маломинерализованим водама и већи број бунара са захватима вода за вишенаменско коришћење (комунално водоснабдевање, флаширање, рекреативни базени). Најзначајније дренажне зоне хладних и субтермалних вода овог сектора су у зони Кључа и Паштрића, у оквиру којих постоји и највећи број активних бунара. Најзначајнија појава термалних вода (26–27 °C) је у бањи Врујци, док је најтоплија вода (35 °C) захваћена дубоким бунаром у Мионици. Извориште за комунално водоснабдевање Лајковца, у Непричави, са 6 бушених бунара, сумарне издашности 120 l/s, представља најзначајнији захват вода у *северној оази.* У *јужној*, најзначајније појаве су врело Горње Трешњице, са просечном издашношћу од 80 l/s и Таорска врела, са опсегом 17–250 l/s некаптираног дела протицаја (Petrović, 2013).

Укупна минимална издашност свих анализираних врела и дренажних зона Ваљевског карста износи око 1.2 m³/s, док укупна издашност бунара износи око 0.3 m³/s, што укупно чини око 1.5 m³/s маломинерализованих вода, чије су температуре у опсегу 9–35 °C. Просечна издашност карстних издани целог подручја срачуната је на 5.18 m³/s. Природни режим дренирања карстне издани Лелића, са израженим разликама између минималних и максималних протицаја (1:10–1:25), чини ове ресурсе релативно непоузданим за експлоатацију у сушним периодима. Предлагани концепти регулације нису озбиљније разматрани због градње бране и акумулације „Стубо-Ровни“, која би требало да представља окосницу комуналног водоснабдевања целог Колубарског региона. У осталим секторима, регулација истицања је успешно спроведена на већем броју локалитета, за потребе вишенаменског коришћења вода (комунално водоснабдевање, флаширање, рекреативни базени.

На већем делу истражног подручја, услови природне рањивости карстне издани су релативно неповољни, због њене значајне „отворености“ (откривености) према површини терена, док се хазард од загађивања издани огледа у чињеници да је у сливу заступљена пољопривредна делатност, те да сеоска насеља углавном немају канализацију.

Без обзира на националне и регионалне водопривредне планове, издани у оквиру Ваљевског карста треба да буду под континуалним квантитативним (издашности врела/бунара и нивои подземних вода) и квалитативним (због високе природне рањивости и хазарда од загађивања) мониторингом, како би се овај изузетни природни резервоар вода одржавао у добром статусу.

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