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ORIGINAL ARTICLE

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Hydrogeological characteristics of some deep siphonal springs in Serbia and Montenegro karst

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Abstract In terms of hydrogeological, engineering-geological, and hydrotechnical tapping in karst in relation to ground waters, karst channels, springs and ponors, speleodiving is the only research method which enables direct observation, studying and exact geological mapping of karst channels and caverns. Data collected during speleodiving research contribute considerably to the analysis of karst evolution process in the given region, which is very important in evaluating the depth of karstification and determining the main direction of the groundwater flow. In the past 30 years in Serbia and Montenegro, speleodivers have investigated over 40 siphonal springs, active cave channels and ponors, of which more than 20 are proof of deep siphonal circulation in karstic aquifers. The karstic springs are the most interesting phenomenon from a hydrogeological view point, and their investigations need particular attention. Most of significant karstic springs are on the rims of erosion basins—perimeters of karst poljes, river valleys, sea coasts and contact areas between karst aquifers and hydrogeological barriers. General characteristics of the spring regime are the direct correlation between precipitation and spring discharge. Moreover, the hydrogeological regime of these springs also depends on the size of the catchment area, karstic aquifer retardation capacity, total porosity, as well as lithological and structural characteristics.

Keywords Karst · Karstic spring · Deep siphonal spring · Cave diving · Montenegro · Serbia

Introduction

Very complex hydrogeological characteristics of karst, particularly directions and zones of groundwater distribution, are not yet adequately explained. Numerous attempts undertaken so far in the course of researching the complex regime of karstic aquifers often did not have satisfying results. Even after detailed and complex research of geological, hydrogeological and geomorphologic characteristics, some rules of karst hydrogeology and groundwater circulation in karst have remained unclear. Explanation of hydrogeological relations, aerial arrangement, correlation and circulation of groundwater in that kind of environment is very hard, and sometimes includes a lot of assumptions but not enough established facts.

Hydrogeological settings of deep karstic springs

The deep siphonal karstic springs generally means karstic springs with large discharge and significant discharge fluctuation. Often it is not assumed that waters flowing through these systems are just an overflow of large underground storages, and that significance of these karstic aquifers is in the tapping technology for water extraction from deeper aquifer levels.

Unfortunately, only a relatively small number of morphological patterns of this type have been thoroughly investigated. These kinds of patterns are mostly found in the siphonal 'vauclusian' springs, which are very difficult in terms of exploration. Channel depth can vary from tens to hundreds of meters, for example:

- Fointaine de Vaucluse, France: surveyed by J. Hasenmayer, 1983 down to −205 m, and by Modexa (automatic diving instruments) down to −315 m.
- Emergence de la Chaudanne, Switzerland: surveyed by C. Brandt, 1988, down to −140 m.
- Fontaine des Chartreux, France: surveyed by C. Touloumdjian, 1989, down to −137 m.
- Wakulla Springs, USA: surveyed down to −111 m, etc.

Karstic siphons (reverse siphon shape) are channels with two or more openings filled with water. By their hydrogeological function, they can be continual or temporary, often directly linked to groundwater levels and fluctuation. By their characteristics such as hydrogeological role, depth, overall dimensions of channels and relation to the groundwater level, they can be divided into siphonal springs, siphonal channels, siphonal passages, siphonal barrier, suspension siphons and siphonal pockets.

Siphonal springs (the most significant hydrogeological pattern) are karstic channels with a role of main drainage channels and are larger in aperture than other siphonal forms. The bottom of a siphonal channel—deepest point of the main base flow channel—is usually covered with gravel and sand deposits. In general, according inclination the siphonal channels can be divided into two types:

- the first type is the springs with sub-vertical and vertical main drainage channels in discharge zone—channels inclined 45–90°, with depths greater than 70 m. These are the springs in which the bottom of siphon is very close to the discharge zone, in the horizontal distance.
- the second type is the springs with lower angle of main drainage channel (less than 45°) but with final depth greater than −70 m or −100 m, in which the deepest point of siphonal channel is far from the discharge zone. In these cases, bottoms of the siphonal channels are hundreds of meters from the spring outlet, often with distances that can be measured in kilometers.

Figure 1 illustrates the most common type of siphonal spring.

Research results of the most significant karstic springs

There are a lot of karstic springs in Serbia and Montenegro (investigated by speleodiving) with deep karstic channels. Generally, they can be divided according geological macro units into Carpathian–Balkanic and Dinaric karstic springs.

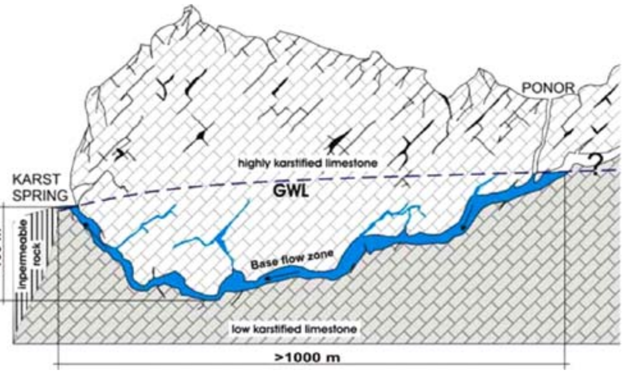

Fig. 1 Deep siphonal spring channel

In Serbia, the largest number of investigated deep siphonal karstic springs belongs to the Carpathian–Balkan mountain range, where more than 35 cave springs have been investigated so far by speleological and speleodiving methods. Main characteristics of five of the most significant springs are shown in Table 1.

After investigation of these hydrogeological active caves, conclusions have been made that there are very promising deep karstic channels with regard to possibilities of their use for water supply. Carbonate rocks in which the most significant channels are found and were formed during the Mesozoic time. Processes of terrain uplifting and forming occurred at the end of Cretaceous time, when conditions for the initial karstic process were established (Stevanović 1991; Milanović 2004, 2005).

Table 1 Investigated (or partially investigated) karstic springs with deep siphonal circulation in Serbia and Montenegro

	Locality	Length (m)	Depth (m)	No. of Siphons	Continues
Spring in Serbia					
Vrelo Mlave	Žagubica	120	−73	1	Continues
Vrelo Krupaje	Beljanica	150	−72	2	Continues
Vrelo Krupac	Niš	170	−86	1	Continues/ tight
Vrelo	Pirot	65	−30	1	Continues
Topilo	Niš	50	−22	1	Continues
Montenegro					
Opačica	Herceg N.	58	−22	1	Continues
Sopot	Risan	350	−42	2	Continues
Spila	Risan	270	−72	3	Continues
Ljuta	Orahovac	150	−133	1	Continues
Gurdić	Kotor	460	−52	2	Continues
Krvenica	Tuzi	250	−50	1	Continues
Gornopoljski vir	Nikšić	80	−63	1	Continues
Obošničko oko	Nikšić	130	−37	1	Continues
Vilina pećina	Petrovac	100	−42	1	Continues

A part of the Dinaric karst which belongs to Montenegro (8,050 km^2) represents a special, well-expressed karst entirety on a world scale. It consists of carbonate rocks of Mesozoic age (Triassic, Jurassic, Cretaceous) in which are formed, at the same time, the main aquifers with the largest discharge zones along the coastal area.

Case studies

During the investigative work for tapping of Krupac spring near the Nis city, speleodiving investigations of the deep siphonal channels—provided the key contribution. Speleodivers have investigated and mapped the main channel of karst spring at a distance of 170 m and a depth of −86 m (in relation to the spring overflow level). Based on this investigation, location of the temporary tapping structure was determined; i.e., the testing wells were drilled directly into the karstic channel.

By installation of two pumps of 2 × 200 l/s capacity at 30 m of depth it was made possible to organize pumping tests in the period of several years (periods of minimum discharge), and to provide data about available quantity of water. This enabled extraction of static reserves during the drought period; in other words, to increase considerably minimum discharge capacity and at the same time, define the real water balance of the Krupac aquifer.

Very precise topography of the submerged karstic channel, combined correctly with surface geodetic measurements, and construction of good quality investigative wells have made it possible to precisely define the position of an exploitation well. The well reaches the main vertical channel and enabled installation of the pump at a depth of −65 m (Fig. 2). By placing the pump at this depth and by pumping aquifer static reserves in the periods of drought, a significant increase of the minimum spring capacity will be possible, as well as better water supply for Nis in periods of low groundwater levels.

Krupaja Spring is at the northwest rim of mountain Beljanica, in the zone of red Permian sandstone laying on the top of the Urgonian limestone layer, at about 340 m above the sea level. The water discharges through a well-connected system of submerged channels. Channels are divided into shallow, up to 20 m of depth, which at 70 m come out into a dry siphonal hall; and deeper, which go down vertically, to the maximum investigated depth of −72 m. The entrance is located at the fault zone trended in a northeast–southwest direction. The spring is not tapped, and part of its water is used for a nearby fish farm and mill. Discharging capacity of this spring varies from 380 to 2,800 l/s (Fig. 3).

Mlava Spring is at the north rim of Beljanica Mountain, at 314 m above sea level. The spring is typically ascending, with deep karstic channels. At the discharge outlet there is a lake greater than 30 m deep. From this lake the channel continues almost vertically. At a depth of −73 m, the channel shape enlarges into a funnel shape and then continues even deeper (Fig. 4). Mlava Spring is on the contact line between the Urgonian limestone and the base of the Tertiary formation. Position of this spring is directed by a fault with an east–west direction, along which was found evidence of

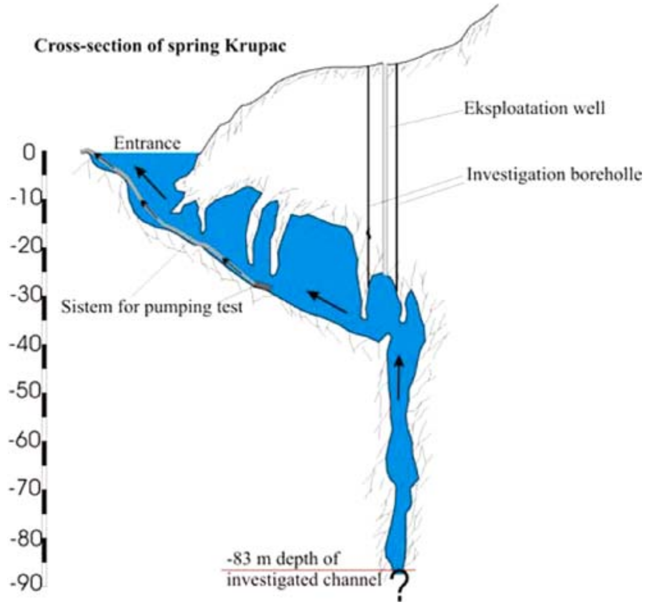

Fig. 2 Profile of Krupac spring—with positions of investigation boreholes and tapping wells

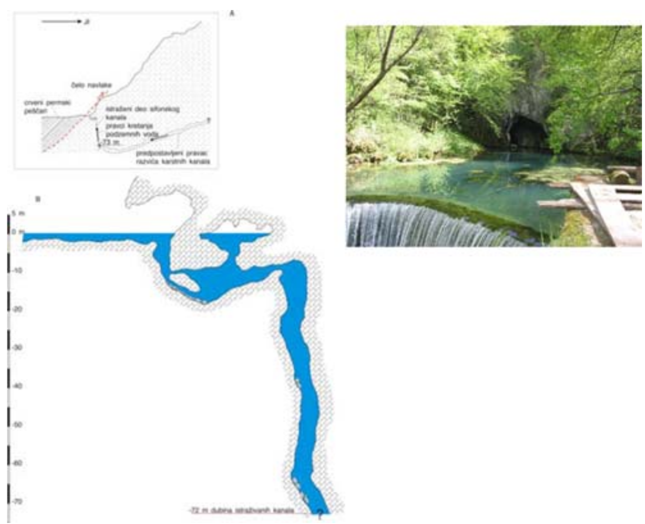

Fig. 3 Krupaja spring in Eastern Serbia (−72 m depth of investigated channel)

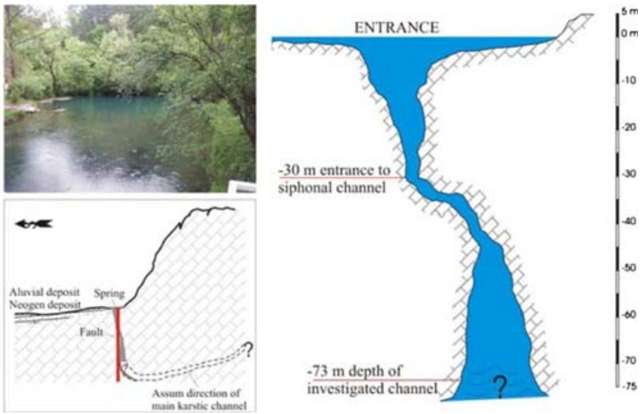

Fig. 4 Cross-section of Mlava spring

sinking of the northern block. Discharge from this spring varies from 300 to 15,000 l/s.

The most distinctive examples of deep siphonal circulation can be found in the coastal karst zones. In coastal karst, the sea level represents the main erosion base level. In the coastal part of the aquifer, due to its depth, sea water intrusion and dynamic fluctuation of salt/fresh water ratio occurs.

Cave diving explorations have been applied successfully in deep siphonal channels, as in springs. Examples are Gurdić, Škurda, Orahovačka Ljuta, Sopot and Spila Risanska in Bokakotorska Bay, to depths sometimes greater than −130 m. Data collected during these explorations indicate that further investigations are necessary to collect reliable data about salt water intrusion into the karst aquifers. New data related to possibilities of groundwater tapping from karstic channels in the deep background of these springs are expected. These explorations can contribute significantly to successfully solving water supply problems in this part of Montenegro coast. Figures 5, 6 and 7 show springs outlets of Sopot, Spila Risanska and Orahovačka Ljuta.

Detailed investigations, much deeper into the karstic background of springs Sopot and Spila Risanska, with continual monitoring of NaCl concentration, at depth and along the investigated channels are needed. After determination of distance of sea water intrusion, a detailed analysis of possible methods of groundwater tapping from those karstic aquifers could be provided, including construction of necessary geotechnical structures (tapping galleries, tapping wells and grout curtains, if necessary).

Only this approach can determine the direction of future investigations. Any uncontrolled pumping of ground water can induce further development and deepening of sea water intrusion into the karstic aquifer in dry periods.

Together with spring Škurda and submarine spring Gurdić, Orahovačka Ljuta composes the larger discharge area of the karst aquifer in eastern and north-eastern background of Bokakotorska Bay. Maximum discharge of these springs varies from tens to hundreds of cubic meters per second. For example, the discharge of Orahovačka Ljuta at its maximum has been estimated to more than 200 m^3/s.

Conclusion

The above-presented examples are the only part of experiences that point out the importance of investigations of deep karstic channels in the karst areas of Serbia and Montenegro. Great possibilities of speleodiving in

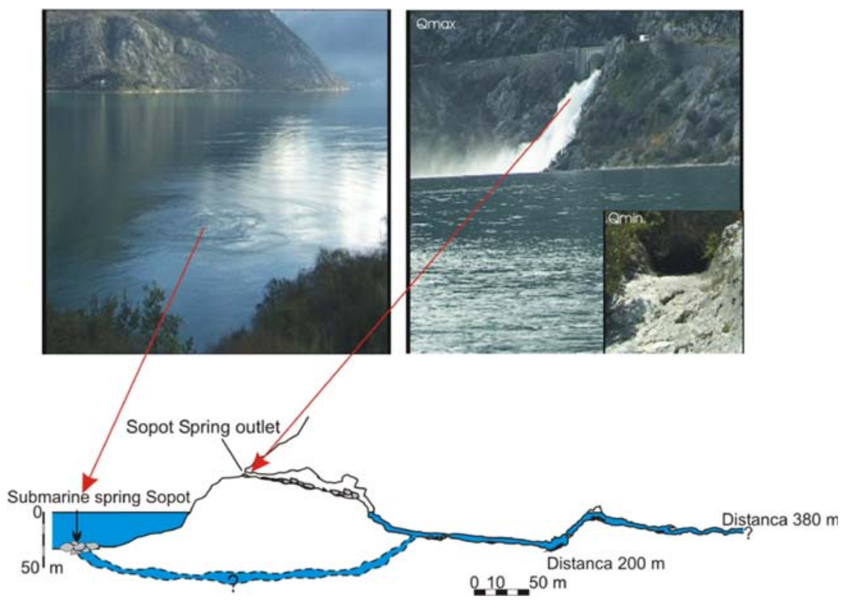

Fig. 5 Spring and submarine spring Sopot with draining levels in maximum and minimum flow periods

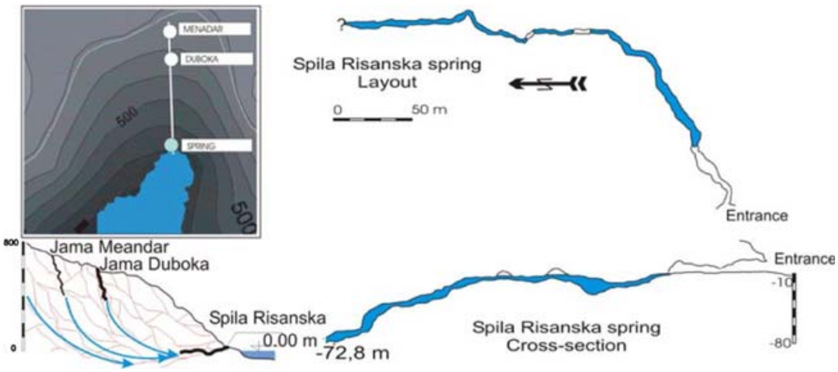

Fig. 6 Karstic spring Spila Risanska with detail—map of Risan Bay background—and position of deep karst shafts with their connection to Spila Risanska

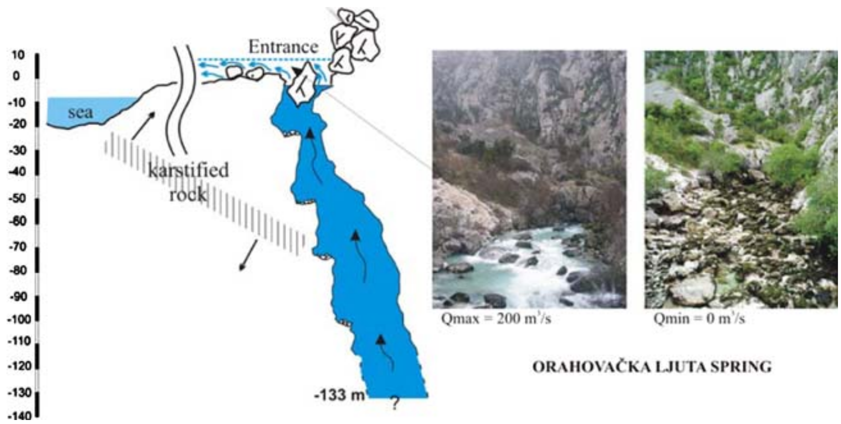

Fig. 7 Profile of karst spring Orahovačka Ljuta with photos made in the period of maximum and minimum discharge

investigations of large karstic aquifers are obvious. The contributions of speleodiving in solving the water supply problems and specific problems during construction of hydrotechnical structures in karst are already confirmed. Together with other geological, hydrogeological and geophysical methods, speleodiving appears to be a very powerful tool in karst investigations.

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