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CHARACTERISTICS AND REASONS FOR THE DISCHARGE INTERRUPTION OF THE ISKRETS KARST SPRING (WESTERN BALKANS, BULGARIA)

ZNAČILNOSTI IN VZROKI ZA PREKINITEV PRETOKA KRAŠKEGA IZVIRA ISKRETS (ZAHODNI BALKAN, BOLGARIJA)

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Abstract UDC 556.35:551.442:551.3.051(497.2)

Aleksey Benderev, Evelina Damyanova, Marin Ivanov, Yordanka Donkova, Peter Gerginov, Doncho Karastanev & Boriana Tchakalova: Characteristics and reasons for the discharge interruption of the Iskrets karst spring (Western Balkans, Bulgaria)

The Iskrets spring is one of the most significant karst springs in Bulgaria. A specific feature of this spring are irregular and abrupt reductions of its discharge after some earthquakes as well as other reasons related to the recharge. This study aims to present a reasonable hypothesis for the reasons of the discharge interruptions. A main feature of the Iskrets karst system is the fact that it is dominated by unconfined water flow in the unsaturated zone with velocities varying in a wide range. This creates conditions for significant erosion, transport and redeposition of the fluvial cave sediments. As a result, in the zones where there is a sharp decrease in the water velocity, a considerable accumulation of sediments occurs which can even fill the entire section of the passage-way and leads to a temporary blocking of the spring discharge. It is supposed that an appropriate section where this happens is located near to the discharge point of the spring. Most likely the main reason for the cave deposit displacement is the soil liquefaction caused by the seismic impact. It has been found that the duration of the discharge interruption period is longer at low water flow rates.

Keywords: karst spring, regime, interruption of the flow, cave sediments.

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Aleksey Benderev, Evelina Damyanova, Marin Ivanov, Yordanka Donkova, Peter Gerginov, Doncho Karastanev & Boriana Tchakalova: Značilnosti in vzroki za prekinitev pretoka kraškega izvira Iskrets (Zahodni Balkan, Bolgarija)

Izvir Iskrets je eden najpomembnejših kraških izvirov v Bolgariji. Posebnost tega izvira so neenakomerna in nenadna zmanjšanja pretoka po nekaterih potresih, lahko pa tudi kot posledica razmer, povezanih z napajanjem. Namen te študije je postaviti razumno hipotezo o vzrokih za prekinitve pretoka. Glavna značilnost kraškega sistema Iskrets je, da v nenasičenem območju prevladuje tok vode s prosto gladino in velikim razponom hitrosti. To ustvarja pogoje za znatno erozijo, transport in ponovno odlaganje fluvialnih jamskih sedimentov. Posledično se na območjih, kjer pride do močnega zmanjšanja hitrosti vode, usedajo večje količine sedimenta, ki lahko zapolnijo celoten presek kraškega kanala in povzročijo začasno prekinitev pretoka izvira. Domnevamo, da se primeren odsek, kjer se to zgodi, nahaja v bližini izvira. Najverjetneje je glavni razlog za premik jamskih sedimentov utekočinjanje tal zaradi potresnega vpliva. Ugotovili smo, da je trajanje prekinitve pretoka daljše pri nizkih pretokih izvira.

Ključne besede: kraški izvir, režim, prekinitev toka, jamski sedimenti.

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1. INTRODUCTION

Karst springs are often characterized by significantly variable flow rates. The nature and amplitude of the changes are related to the conditions of formation, recharging and movement of groundwater in the karst massif (e.g. Bögli, 1980; Fiorillo, 2009; Kresić & Stevanović, 2010; Bonacci, 2012; Malík, 2015). The flow rates decrease considerably during dry periods as well as these with an overall lowering of the groundwater level. Sometimes there is a complete interruption of the spring discharge. Such cases are also found for other springs in Bulgaria (Antonov & Danchev, 1980; Damyanova, 2022). These phenomena are predictable and can be explained by changes in recharging conditions.

The present study aims to elucidate the reasons of the irregular discontinuities in the discharge of the Iskrets Karst Spring, which are not caused by recharge changes nor they have a rhythmic peculiarity typical for the water movement in siphons (Bögli, 1980; Gunn & Bradley, 2023). The Iskrets Spring water is used for urban water supply and these interruptions create serious problems in providing drinking water for about 7,500 inhabitants. The latest interruption of the Iskrets Karst Spring discharge for about 3 days (August 15-18, 2022) also led to the death of tons of fish. Therefore, the main task of this research is to collect and analyze the existing information about the discharge interruptions and on this basis to propose a reasonable hypothesis for the circumstances and reasons of that phenomenon. Some initial results have been presented by Benderev et al. (2022). The performed researches also provide information about the Iskrets Karst Spring included in the MIKAS project (Most Important Karst Aquifer's Springs) (Stevanović 2023; Benderev et al., 2022; Benderev et al., 2023).

2. HYDROGEOLOGICAL CHARACTERIZATION

The Iskrets Spring, known among the local population as Peshta, is one of the largest and most interesting karst springs in Bulgaria. It is located in the Ponor Mountain, part of the Western Stara Planina (Fig. 1). The Iskrets River, a left tributary of the Iskar River, starts from that spring. From hydrogeological view point the Ponor Mountain coincides with the Iskrets karst basin (Antonov & Danchev, 1980).

The first published data for the Iskrets Spring and karst in Ponor Mountain are by Škorpil & Škorpil (1898), Yonchev (1902) and Radev (1915). Subsequently a generalized hydrogeological characteristic of that spring was presented by other authors (Dinev, 1959, Antonov, 1963, Benderev, 1989, Stevanović et al., 2015, etc.). A detailed analysis of the tectonic processes and of the hydrogeological settings of the spring was made by Paskalev et al. (1992). Comprehensive studies of the Iskrets Spring regime were done by Boteva & Raykova (1968), Orehova & Gerginov (2021). Eftimi & Benderev (2007), have demonstrated through a statistical treatment of the chemical analyses of Iskrets Spring that the recharging flow of the mentioned spring is of channel flow. The impact of the anthropogenic diversion of water from the Iskrets Spring recharge zone was assessed by Benderev et al. (2020). Shanov & Benderev (2005) presented a study of natural and man-made seismic impacts on the spring.

The main groundwater collector is the Triassic complex over 600 m thick. It consists of limestones and dolomites, steeping as a monoclinal to the south (Antonov, 1963; Haydutov, 1995) (Figure 1, 2). On the south, the normally bedding Triassic carbonate rocks are bounded by complexly thrust rocks to the north, which include both Triassic carbonate rocks and Paleozoic low-permeability materials. The northern side is defined by the outcrops of Lower Triassic sandstones, which are the deeper aquiclude of the karst complex. From the west the basin is conditionally bounded by the valley of the Ginska River and from the east by the Iskar River Gorge which crosses the entire carbonate complex. The rest part of the carbonate complex area is covered by Jurassic and Lower Cretaceous sediments. The basement consists of sandstones, siltstones and argillites, above which karstified limestones up to 100 m thick are exposed.

Geological-hydrogeological and physio-geographical conditions predetermine favourable conditions for the formation of surface and underground karst forms. The most widespread areal distribution is the normally lying Triassic limestones and dolomites. Due to their significant thickness (about 500-600 m) and the monoclinal bedding of the carbonate complex to the south, the difference between the recharge and draining zones of karst waters is about 800-900 m. In the northern, highest parts of the mountain, the flattened plateau-like nature of the relief has created conditions for the formation of numerous negative surface forms (karren, dolines, etc.), which are the main reason for the complete absence of

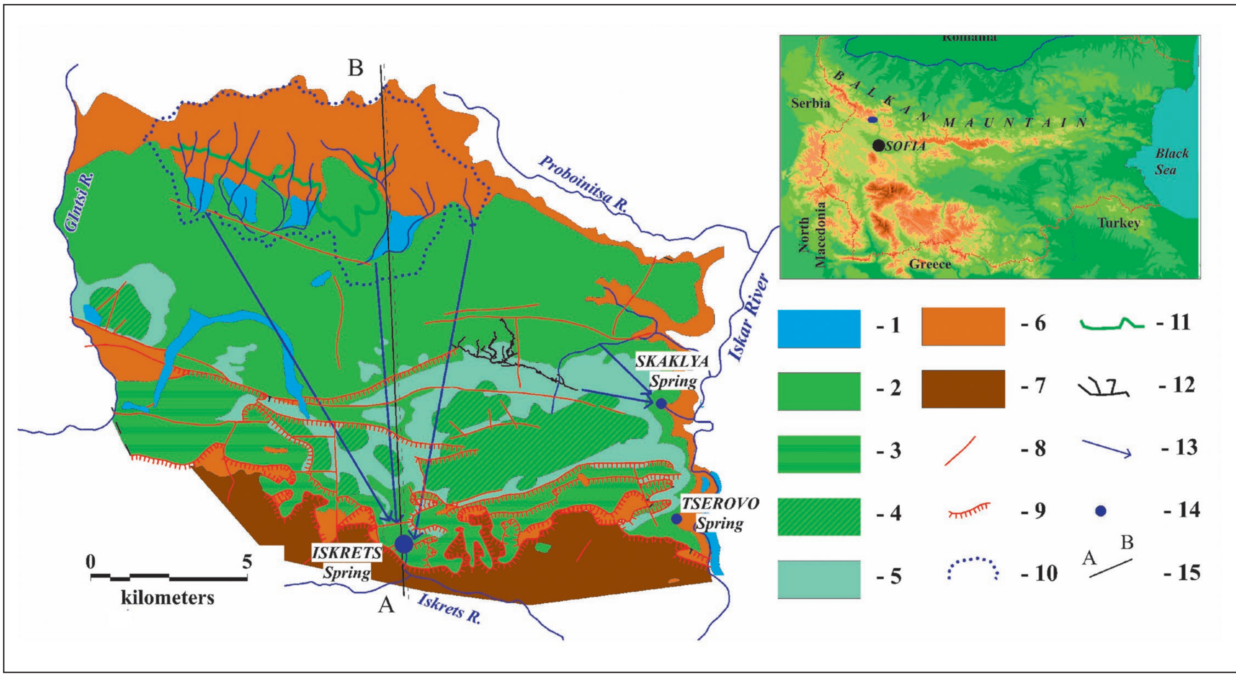

Figure 1: Hydrogeological map of the Iskrets karst basin (after Benderev, 1989): 1 – highly productive porous aquifer (alluvium deposits) ; 2.– highly productive karst aquifer (Triassic limestones and dolomites); 3 – highly productive karst aquifer (allochthonous Triassic limestones and dolomites); 4 - highly productive karst aquifer Upper Jurassic – Low Cretaceous limestones); 5 – moderate productive fissured aquifer (Jurassic sandstones, siltstones, argillites); 6 – local and limited groundwater (Triassic sandstones); 7 – essentially no groundwater (Paleozoic terrigenous rocks); 8 – faults; 9 – nappe; 10 - boundary of watershed of recharge rivers; 11 - diversion channel; 12 – Kolkina Dupka Cave (https://pod-rb.eu/); 13 – connections established with tracers; 14 – main karst springs; 15 – line of cross-section.

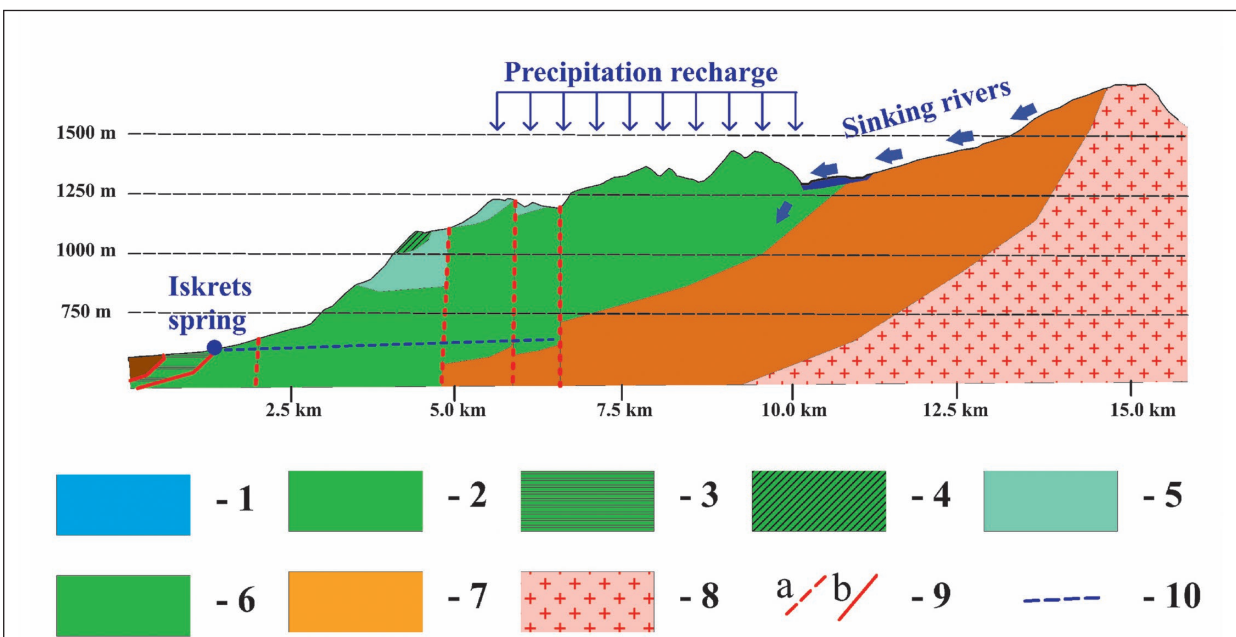

Figure 2: Hydrogeological cross-section of the Iskrets karst basin (after Benderev, 1989): 1 – highly productive porous aquifer (alluvium deposits) ; 2 – highly productive karst aquifer (Triassic limestones and dolomites); 3 – highly productive karst aquifer (allochthonous Triassic limestones and dolomites); 4 - highly productive karst aquifer Upper Jurassic – Low Cretaceous limestones); 5 – moderate productive fissured aquifer (Jurassic sandstones, siltstones, argillites); 6 – local and limited groundwater (Triassic sandstones); 7 – essentially no groundwater (Paleozoic terrigenous rocks); 8 – granite; 9 – fault structure (a – fault, b – nappe); 10 - water level of saturated zone.

Figure 3: Surface karst forms in the Triassic carbonate complex.

surface flow (Figure 3). The rivers descending from the high parts of the Stara Planina, north of the outcrops of the karstifying rocks, reaching the border with the Triassic limestones and dolomites, have led to the formation of a series of typical blind valleys. In the areas of deep incision of the river network, carbonate rocks form steep to sheer slopes.

According to previous speleological research, over 140 caves have been identified in Ponor Mountain. About 30 of them are formed in Upper Jurassic limestones, and all the rest are in the Triassic carbonate complex. Most of them (about 120) are less than 100 m long (https://www.hinko.org/; https://speleo-bg.org/). Only a few caves are of significant size (Table 1), and all of them are in the Triassic limestones and dolomites. In the plateau part of the mountain, where the main recharge of the karst waters takes place, descending caves predominate. Caves are widespread on the slopes of the mountain, which are mainly connected to old or active springs.

Table 1: Significant caves in Ponor Mountain.

Cave name	Length, m	Denivelation, m
Kolkina dupka cave	24,388 m	561,0 m
Vodnata cave	3,264 m	+85,0 m
Katsite	2,560 m	193,0 m
Dushnika	870 m	27,0 m

Kolkina Dupka Cave is not only the longest and deepest cave in Ponor Mountain but also in Bulgaria. It is located in the eastern part of the area under consideration and has been explored for the last eighteen years by the Speleo Club "Pod RB" (https://pod-rb.eu/). Its entrance is located in the highest parts of the mountain. The cave has a dendroid structure, with several underground streams converging into a common river (Figure 4). With the help of a tracer experiment, its connection with a spring located on the slopes of the Iskar River valley has been proven.

The Vodnata Cave is a typical single-gallery spring cave, with an underground river running along its entire length, emerging to the surface in a spring on the slopes of the Iskar River valley. Katsite Cave is a descending cave, with its entrance being an old sinkhole, and it is also located in the high parts of the outcrops of Triassic carbonate rocks. Dushnika Cave is located in the lowest, southern part of the outcrops of normally lying Triassic carbonate rocks. It is characterized by a complex hydrological regime and should be considered as part of the Iskrets spring complex (Nejkovski & Somov, 1970; Benderev, 1989; Stevanoviç et al., 2015; etc.). During the dry seasons, it reaches an underground lake, flowing into a syphon, marking the border of the saturated zone. During high water levels, after a significant rise through the cave, passed considerable water masses.

In hydrogeological terms, two stratified aquifer horizons are distinguished in Ponor Mountain, separated by Lower and Middle Jurassic terrigenous rocks (Antonov & Danchev, 1980; Benderev, 1989). The first consists of Triassic limestones and dolomites and has a wide distribution. It includes both normally lying and allochthonous rocks, although in many places the hydraulic connection between them is not particularly good. The second aquifer is associated with isolated outcrops of Upper Jurassic limestones, exposed high on the local erosional base.

The relatively high degree of karstification plays an important role in the recharge conditions and the nature of groundwater movement. Over 65% of the Triassic carbonate rocks are outcropped and represent the precipitation recharge area of the karst aquifer (Figure 3). Over 65% of the Triassic carbonate rocks are outcropped and represent the recharge area of the karst aquifer (Figure 3). The main part of this zone occupies the higher elevation areas of about 1000-1400 m above sea level. There are no conditions for the formation of surface runoff in it, and the precipitation quickly penetrates into depth. According to Benderev (1989), they form about 60% of the total water quantity of the Triassic aquifer. According to available climatic data, the annual amount of precipitation in Ponor Mountain varies widely depending on the altitude – from 600-700 mm to over 1100-1200 mm. Beside this the rivers lose their flow when entering the Triassic complex. According to correlations (Benderev, 1989), in the area where the precipitation recharge of the karst waters is more intensive, the annual amount of precipitation is about 800-1000 mm. The areas occupied by non-karstified rocks, situated north of the carbonate rock outcrops to the main ridge of the Stara Planina (Balkan) Mountains, should also be referred to as the recharge area. In

Figure 4: Underground river in Kolkina Dupka cave with thick fluvial deposits.

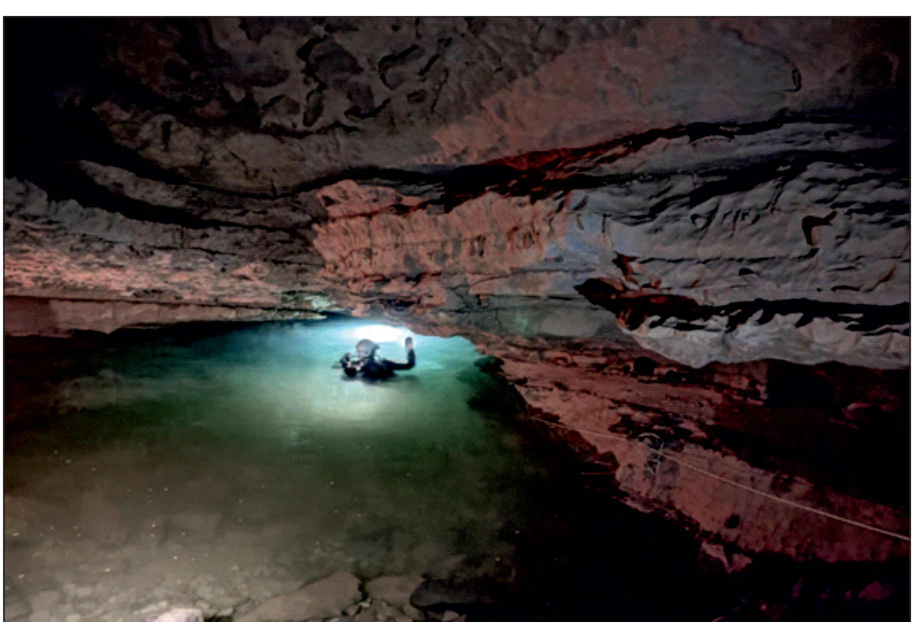

Figure 5: Lake in Dushnika cave.

the higher altitude areas, 1300-1700 m a.s.l., heavier rainfalls are more frequent. The rivers formed at these areas are lost completely in blind valleys with alluvial deposits. Part of the runoff formed in the upper zone of the watershed of these rivers (about 1/3 of its area) is taken away by a diversion channel which takes water to another watershed for energy supply (Benderev et al., 2020). Despite the relatively small area of the catchment area (41 km²) and redirection of part of the runoff, these waters play a significant role (about 20%) for the water quantities of the Triassic aquifer.

The karstified Triassic carbonate rocks, as well as the significant difference in elevation between the recharge and draining zones (at elevations between 600 and 900 m), determine the presence of a thick unsaturated zone in which the movement of groundwater occurs in wide channels with a general direction to the south and east. Conditions for the formation of a thin saturated zone exist only in the southernmost part of the basin, where groundwater is dammed by tectonic contact with non-karst rocks.

The drainage of the Iskrets karst basin is realized mainly by 3 karst springs (Table 2, Figure 1) which are localized in two zones. So far there is no information about boundaries between their watersheds. The one of these zones is in the eastern part of the basin, in the Iskar River valley, and is defined by a lithological contact between carbonate rocks and the underlying sandstones. The waters of two karst systems are directed towards it. The first is discharged by the spring near the village of Tserovo. That spring is coming out of a cave with a length of 3264 m. The second karst system is discharged by the Skaklya Spring. A significant part of the passages along which underground water moves to the Skaklya Spring is revealed by the longest and deepest (561 m) cave in Bulgaria – Kolkina Dupka. It has a typical dendritic structure with smaller streams flowing into a general underground river. Another drainage zone is located in the lowest part of the outcrop of autochthonous Triassic carbonate rocks in the valley of the Iskrets River (a tributary of the Iskar River). The tectonic contact, associated with a thrust fault from the south, creates conditions for the confinement of karst water and occurance of the Iskrets Spring.

Table 2: Main karst springs in the Iskrets karst basin (Benderev, 1989).

Spring	Drainage zone	Elevation, m a.s.l.	Discharge, l/s	
			Minimum	Maximum
Tserovo	Iskar River	525	6	299
Skaklya	Iskar River	575	12	1256
Iskrets	Iskrets River	550	~ 150	54900

Considering the actual hydraulic conditions, the Iskrets Spring is characterized as a barrier spring (Figure 1, 2, 8) – It is located on the border of autochthonous and allochthonous Triassic limestones and dolomites. Its approximate catchment area is about 140 km². About 40 km² of it comprises rivers losing their flow when entering

Figure 6: Entrance of the cave Dushnika in different times.

Figure 7: Monitoring hydrometric station (Iskrets karst spring).

the carbonate rocks. The cave Dushnika plays a role of a temporary overflow of karst waters (Figure 6). A lake is revealed in the cave marking the groundwater level at low waters. Large water volumes (sometimes over 10-15 m^3/s) flow out at the cave entrance at high waters. The spring has been included in the National Groundwater Monitoring Network since 1959 (Figure 7). Significant fluctuations of the spring discharge and a very rapid increase after intense rainfall are found. Based on the tracer tests the connection between the rivers flowing down from the main ridge of the Balkans and the Iskrets spring has been proven (Dinev, 1959; Benderev, 1989). About 20% of the total discharge of the spring is recharged by the rivers. The chemical composition of the spring water changes depending on the flow rate of the spring (Eftimi & Benderev, 2007). This is important for the total mineralization, hydrogen carbonates, calcium and magnesium, whose values decrease with increasing water quantities. At maximum flow rates the spring water has often high turbidity.

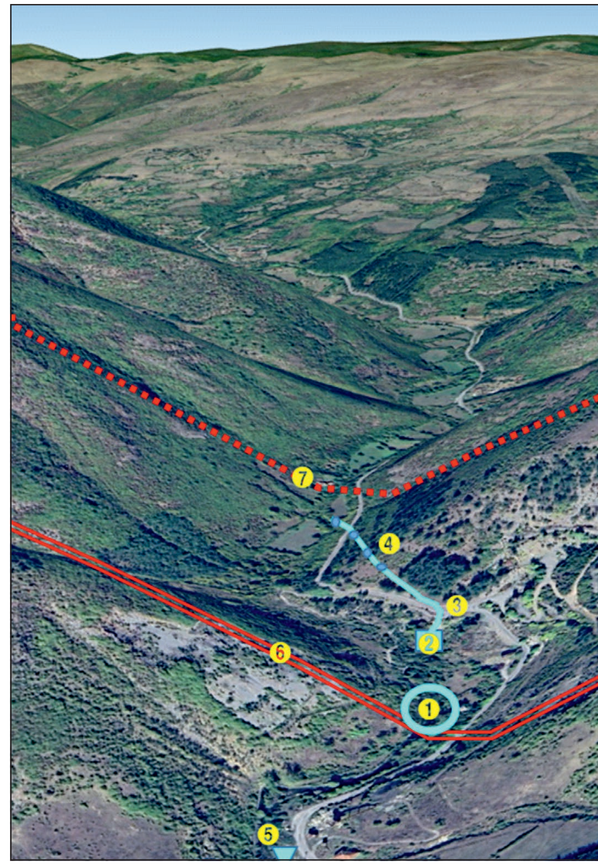

Figure 8: Area of the Iskrets Spring: 1 – Iskrets Spring; 2 – Dushnika Cave entrance; 3 – cave gallery where high water flow passes; 4 – permanent lake in the cave which marks the limit of the saturated zone; 5 – monitoring station; 6 – front of the nappe; 7 - Chernovodtsy fault.

A part of the Iskrets Spring discharge is used for drinking water supply of the town of Svoge and the surrounding villages. Free-flowing water is used also for fishponds.

3. DISCHARGE INTERRUPTIONS OF THE SPRING

An interesting phenomenon are the sudden interruptions or significant reductions in the discharge of the spring in a period from several hours to 2-3 days after some earthquakes or without evident reason. After that a significant increase of the discharge occurs. So far information on seven such cases has been published. The first four spring interruptions happened in the 19th century and are mentioned by Škorpil & Škorpil (1898). Petrov (1983) described a decrease in spring discharge on 4 March 1977 for 7.5 hours after an earthquake with magnitude M=7 at the Vranchea seismic zone situated 430 km northeast in Romania. The discharge of the spring before the earthquake was 5500 l/s and decreased to 500 l/s after it. This case and two other sudden discharge interruptions were described by Benderev (1989), Paskalev et al. (1992) and Stevanoviç et al. (2015). The first of them happened on 3 Sept 1980 and was associated again with a seismic event - an earthquake with M=4.4 with epicentre near to the spring. The discharge of the spring was 1060 l/s before the earthquake and the period without outflow lasted 19 hours. On 11 April 1982, the discharge of 7880 l/s without any reason begun to decrease and after a few hours the spring dried up. A few days before this event, a very high discharge was registered. On 5 April 1982 a water quantity of 10260 l/s was measured at the spring, slowly decreasing until the discharge was interrupted.

The last interruption of the spring discharge was in August 2022 (Benderev et al., 2022). The monitoring devices installed several years ago to continuously measure the flow rate and temperature of the spring allowed to follow the changes before, during and after the interruption of the discharge (Figure 9). About a week before the Iskrets Spring ceasing, its discharge was 140-160 l/s. On 14 August 2022, after a rainfall on 13 August 2022 in the higher parts of the catchment (3.4 mm - precipitation station Gintsi), the discharge increased to 240 l/s for a while, and then decreased to the initial values. Around noon on the next day, 15 August 2022, after a rainfall of 6.9 mm, a sharp decrease of the spring discharge began and it almost completely dried up. During this discharge interruption, only 8 l/s were collected into the spring capture, which is less than the total water quantity entering the karst massif from the rivers. This flow rate did not increase even after the second day of the outflow of water from the diversion channel was stopped and the flow rate of the recharge rivers increased significantly. A trend of increasing water temperature was also observed.

On 18 August 2022 in the afternoon, a gradual increase of the discharge began. Over 50,000 m^3 of water has been retained in the karst massif. At the automatic measuring station, after 8 p.m. on the same date, a sharp increase of the outflow up to 10000 l/s was recorded. The water temperature drops sharply to around 12°C, which is close to the average annual air temperature in the area and in the local caves. Immediately after this, the spring flow rate initially decline relatively quickly, and after some time more slowly, reaching approximately the values before August 16, 2022 after about 15-16 hours. The time for restoring the water quantity that was before the interruption, despite the very high value of the piston flow outflow, is too short compared to the recession of water quantities flowing from the spring after peak values due to intensive precipitation recharge (Figure 10). As an example, again in November 2022, the spring flow rate increases from 130 L/s after heavy precipitation in the high parts of Ponor Mountain to about 10000 L/s. For about 2 days and then gradually decreases to 790 L/s for 13 days, after which there is an increase in the flow rate again through the karst system due to new precipitation. This, together with the fact that in August 2022 there was not enough intense rainfall in the recharge area, one could believe that the reason for this is not related to the increased recharge.

The passage of peak values after other established

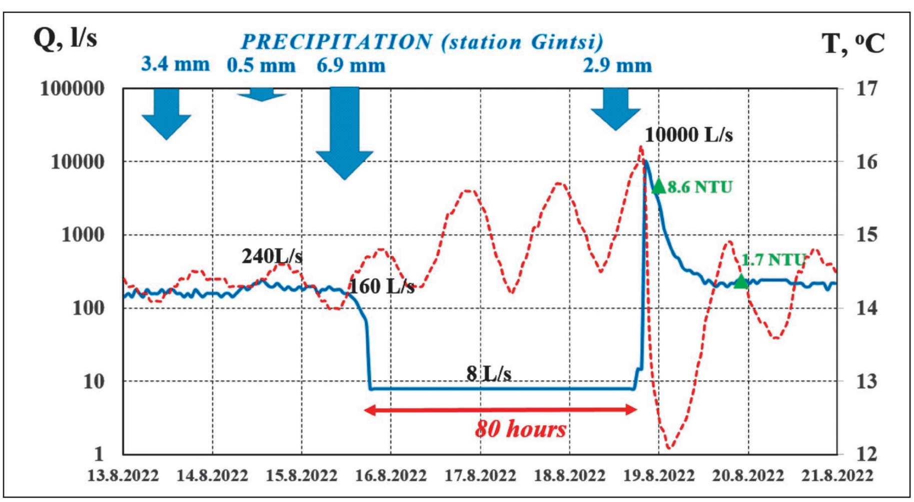

Figure 9: Diagram of the Iskrets Spring fluctuations of discharge (blue line) and temperature (red dashed line) for the period 13 Aug – 21 Aug 2022.

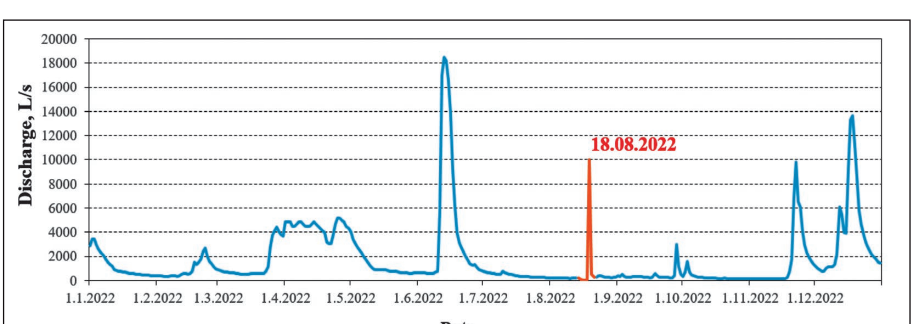

Figure 10: The fluctuations in spring discharge in 2022.

anomalous interruptions and discharge declines also have a similarly short character. When comparing the diagram of the discharge fluctuations (Figure 9) with the diagram of the water level in the spring limnigraph during the interruption associated with the Vranchea earthquake in 1977 (Figure 11) (Petrov, 1983), it can be seen that both diagrams have a similar pattern. Unfortunately, there is no data to draw similar diagrams characterizing other spring interruptions.

At the beginning of the discharge recovery the water was turbid. Approximately half a day after the start of recovery, the turbidity value of 10 NTU was determined. The transport of solid particles continued for almost 10 days as long as the turbidity values were below 1 NTU. It was evaluated that more than 900 kg of undissolved sediments were carried out by the spring water during this period.

During the period of the discharge interruption a tendency for the temperature of the water in the spring capture to rise was observed. After the peak discharge recovery, the temperature decreased by 2°C for a short period. With the recovery of the regular discharge, the water temperature changed gradually assuming its usual limited diurnal fluctuations.

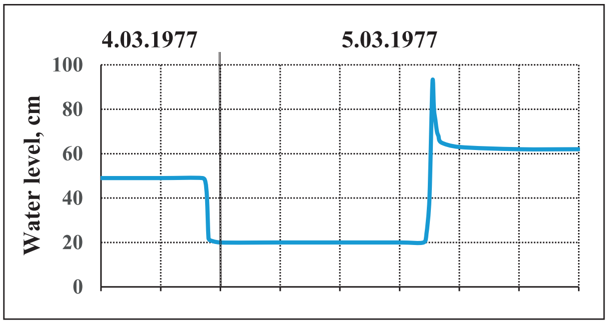

Figure 11: Diagram of the water level in the Izkrets Spring limnigraph during the interruption associated with the Vranchea earthquake in 1977 (after Petrov, 1983).

4. DISCUSSION

All the circumstances related to the interruption of the spring discharge prove that these are irregular events in time with no relation to changes in the recharge conditions. Typically, the reduction of the discharge occurs in a very short time, and its recovery is sharp, with some time higher water quantity. The subsequent normalization of outflow is relatively rapid but gradual. The water is quite turbid and carries out significant amounts of undissolved solid particles.

The leading hypothesis for the described interruption of the Iskrets Spring discharge is that it is due to the blocking of the karst passages, temporary ponding and unclogging after a certain increase of the hydraulic head behind of the plugged sectors (Benderev, 1989; Paskalev et al., 1992; Stevanović et al., 2015). Initially it was assumed that the plugging was a result of underground subsidence along fault zones but no evidence of that assumption was found. In similar situations, poorly graded and coarse-grained materials would have to prevail in the range of the fault zones, but it is not the case, as this type of sediments will allow amounts of water to pass through such materials.

In order to identify the reasons and the mechanism of the blocking of the karst passages, it is necessary to clarify the peculiarities of the karst environment and the conditions for the karst groundwater movement as well as the genesis and characteristics of the plugging material. An important issue is how to predict these events and their duration as well.

The Triassic limestone and dolomite rocks are characterized by a significant karstification throughout their whole thickness. The complete absence of surface runoff, the concentrated loss of the rivers descending from the main ridge of Stara Planina Mountain and the rapid arrival of their waters to the spring suggest the existence of a karst system with wide passages and high transmissivity. The elevation difference between the recharge area and the spring, which in some places reaches up to 900 m, suggests that most of the galleries are in the aeration zone and the waters move like free-flowing underground rivers. Considering the fact that so far, no caves have been discovered in the watershed area of the Iskrets Spring, the conditions for groundwater movement can be assumed by analogy with the Kolkina Dupka Cave in the catchment area of the Skaklya Spring (https:// pod-rb.eu/). Most likely the slope of the cave passages changes in large range. This predetermines the existence of cave waterfalls as well as considerable alteration of the local velocity of the cave rivers along the galleries. It is assumed that there are lakes and siphons in which a delay of the underground currents happens. The saturated zone around the nearby Dushnika Cave Spring is not large and it has almost no buffering effect. In addition to the change of velocity of the karst water movement, there is also a significant variation of the average velocity of the recharge water from the river sinkholes to the karst springs. According to the results of the tracer tests (Benderev, 1989), the travel time of the waters from one of the sinkholes to the spring situated 9.5 km away was about 200 hours (average velocity of 47 m/h in a straight line) at low groundwater levels (spring discharge of 600 l/s). At high groundwater levels (spring discharge of 6500 l/s) the travel time of the tracer to the spring was 20 hours. The tracer concentration gained maximum values 30 hours after its injection (average velocity of 32 m/h). This means that at the same point of the karst system, the water moves with different velocities, sometimes differing by an order of magnitude. Depending on that, both erosion and sedimentation conditions may exist at this point.

The actual recharge and discharge conditions of the Iskrets Spring karst system suggest that it has a dendritic structure like the Skaklya Spring system. The galleries starting from the river's swallow holes gradually merge towards the spring to concentrate in a common passage. Numerous streams formed by rainwater are included in the Iskrets Spring karst system as well.

The clastic fluvial deposits in the karst passages are characterized by the highest transport dynamics deposition and re-washing away capacity (Bögli, 1980; Gillieson, 1986; Springer, 2005; Ford & Williams, 2007). For example, in the Kolkina Dupka Cave, allochthonous alluvial sediments are found. These sediments are poorly graded with different grain size composition according to the local morphological conditions and the velocity of underground stream (Figure 12). This is a consequence of the morphological conditions in the cave galleries, determining the actual and the past groundwater character. Analogically with this cave, it is assumed that there is also a similar diversity of cave sediments in the karst passages of the Iskrets Spring system. The changing velocity of the karst conduit flow is the reason for the dynamics of the processes of moving and depositing of the cave alluvial deposits. An important factor is the amount of the lost karst water, which varies depending on the climatic conditions, from a few L/s to over 1 m^3/s for the particular rivers. Naturally at high groundwater velocity the previously deposited sediments are washed away and transported. A new accumulation begins at subsequent reduction of water quantities as well as in the zones with slow underground stream.

The main filling materials are those in the blind valleys, where the rivers flowing along the slopes of the Stara Planina Mountain, are lost. They consist of gravels mainly of granite and sandstone nature as well as sands and clays. Sometimes dolines are formed in them as a result of suffusion or collapse. Another source of these deposits are the weathering products of the karstified carbonate rocks and the Jurassic rocks partially covering them. This was elucidated from Benderev & Sultanov (1991) by the analysis of the mineralogical composition of the deposits in the Dushnika Cave which actually plays a role of overflow of the Iskrets Spring at high groundwater stream. The conditions for the deposition of sediments differ comparing with the main part of the considered karst system. Two types of deposits are found in the Dushnika Cave.

The first type of sediments refers to the so-called "renewable" sands. They are flushed away at each high conduit flow and during the gradual decreasing of the water flow, new quantities of sands are deposited (Figure 13A). This takes place only in particular sections of the cave, where there are conditions for swirling and slowing of the velocity of the water flow. Most likely, this type of sediment, due to its proven mobility in the karst sys-

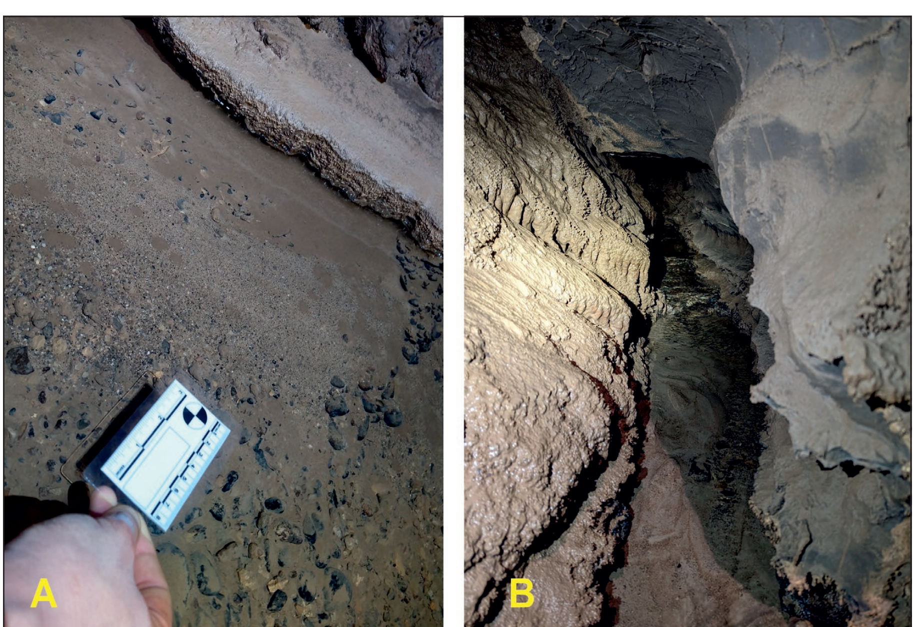

Figure 12: Fluvial deposits in the Kolkina Dupka Cave: A - poorly graded deposits; B - clayey deposits.

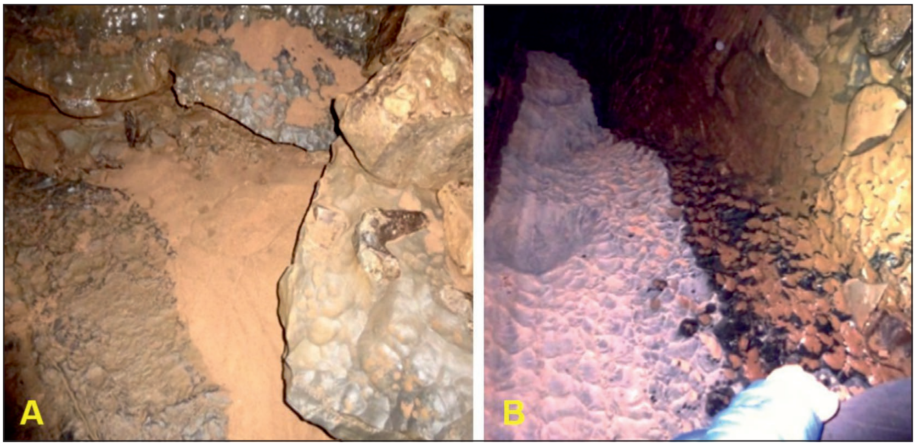

Figure 13: Deposits in the Dushnika Cave: A - "renewable" sand; B– lacustrine clay.

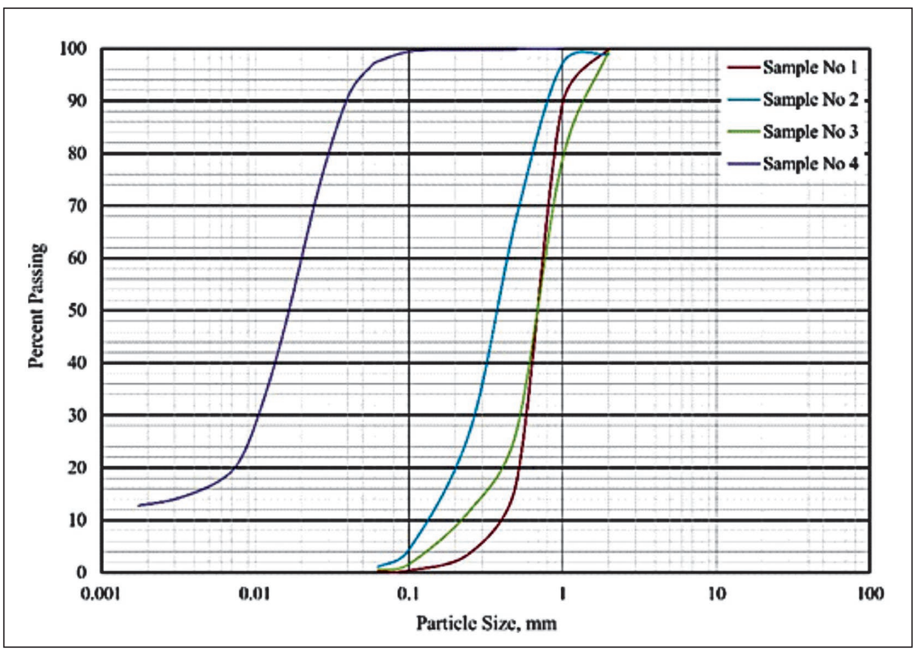

Figure 14: Grain size distribution of the samples from the fluvial deposits in the Dushnika Cave.

tem, is a cause of the temporary and irregular blocks of the groundwater flow. The samples taken from the fluvial deposits in the cave are classified according to EN ISO 14688-2:2018 as uniformly to poorly graded sand (samples 1, 2 and 3 in the Figure 14 and the Table 3) with coefficient of uniformity Cu<6 and coefficient of curvature Cc<1. These cave deposits are cohesionless, loose to very loose which have been newly placed. In saturated conditions they can be assessed as highly susceptible to liquefaction. According to the nomogram proposed by Sundborg (1956), the range of water flow velocities in the Dushnika cave, leading to repeated erosion/deposition processes, after the temporary flow of significant amounts of groundwater, was determined (Figure 15). For this purpose, the minimum value of d_{10} from the three samples taken from these sands and the maximum for d_{90} were used (Table 3).

Table 3: Grain size distribution parameters.

Parameter		Sample No 1	2	3	4
Particle fractions percentage	>2.0 mm	-	1	-	-
	2.0 - 0.063 mm	100	98	100	3
	0.063 - 0.002 mm	-	1	-	84
	<0.002 mm	-	-	-	13
Coefficient of uniformity Cu		1.88	3.07	3.59	-
Coefficient of curvature Cc		0.65	0.22	0.97	-
d_{10}, mm		0.41	0.14	0.22	-
d_{60}, mm		0.69	0.38	0.69	0.016
d_{90}, mm		1.02	0.80	1.40	0.039

The second type of sediment (Figure 13B) is deposited in the permanent lake in the cave which marks

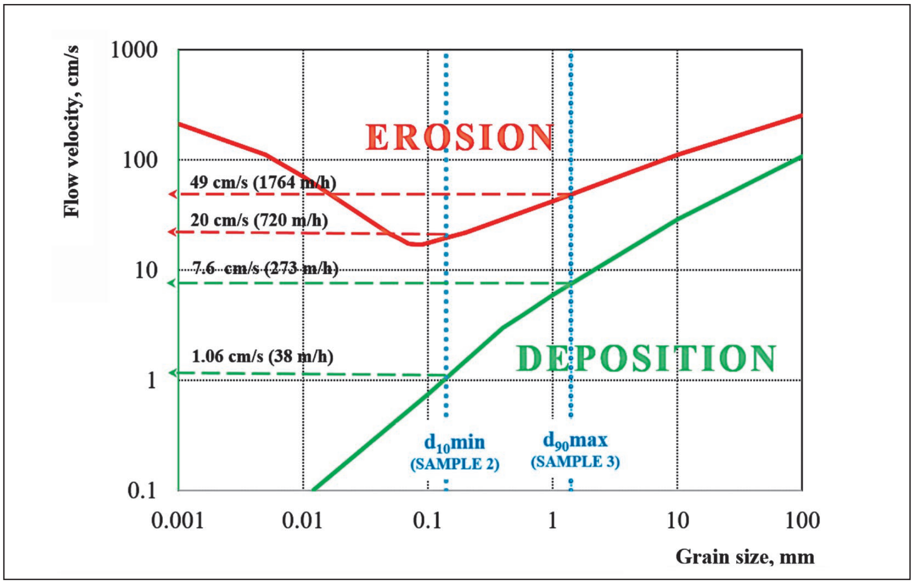

Figure 15: The range of critical water flow velocities in Dushnika Cave causing erosion/deposition processes.

the upper limit of the phreatic zone. This deposit is classified as silty clay (sample 4 in the Figure 14 and the Table 3) and it is probably the reason for the rising of the turbidity in the spring when the water quantity increases sharply.

The considerable changes in the velocity of karst water flow cause continuous alterations in the conditions and dynamics of the erosion, transportation and redeposition of fluvial cave sediments. It is a prerequisite for the significant accumulation of deposits which leads to a temporarily blocking of the karst groundwater conduit flow. Such cases are mentioned by Gunn & Bradley (2023) in Castleton Karst, Derbyshire (UK), where as a result of such processes there is a temporary redirection of the karst groundwater along other passages which extend its underground pathway. The same authors pointed out another similar case concerning the Big Spring in Kings Canyon National Park, California, USA. Therefore, the hypothesis of karst passage blocking as a result of transport and deposition of huge quantities of sediments is more reasonable. The most favourable zones for the redeposition of transported sediments are with a sharp slowdown of the groundwater velocity. Normally these are the sections with alteration of the slope of karst passages: in the zones of inflow into an underground lake, at the border between the unsaturated and saturated zones in the karst massif as well as at the crossing of a karst passage by a fault. In these cases, the water flow is laminar through the crushed rocks (Figure 16). In case of a larger amount of temporarily deposited sediments, in areas where there are conditions for slowing the velocity of underground water, it is possible for narrower karst passages to be completely blocked. It is assumed, that after the 6.9 mm rainfall on August 15, 2022, conditions arose in the karst system for erosion of fluvial sediments and their transport to a section where, due to specific morphological features, the movement of the underground river and their deposition slowed down. The reduced water temperature to that in the massif after it starts flowing again is also evidence of the water being retained inside the rocks for a longer period of time.

As a result, the water stream to the karst cavities stops. This is also confirmed by the fact that the discharge interruptions (excluding seismic events) are usually in a period when the flow rate of the spring decreases, which is also associated with a decrease of the velocity of karst water flow and more favorable conditions for sedimentation. The caverns and the fissures in the unsaturated zone of the karst massif behind the blocked section gradually saturate and the groundwater level steadily rise. Upon reaching a critical hydraulic head, the water breaks through the barrier and quickly destroys it. The outflow is in burst toward the springs, transporting the deposits from the temporary barrier.

As mentioned previously two of the discharge interruptions have followed seismic events. It is not possible that the interruption of the flow in August 2922 was due to seismic causes, because the last recorded earthquake in the area was in September 2019, without affecting the discharge of the spring. Most likely the reason for that phenomenon is that during an earthquake, the ground shaking causes the loose sand to collapse, resulting in an increase in pore water pressure. The development of high pore water pressure due to ground shaking turns the cave cohesionless deposits into liquefaction condition. Liquefaction causes lateral movement and create flow slides with very large movements. In general, flow liquefaction

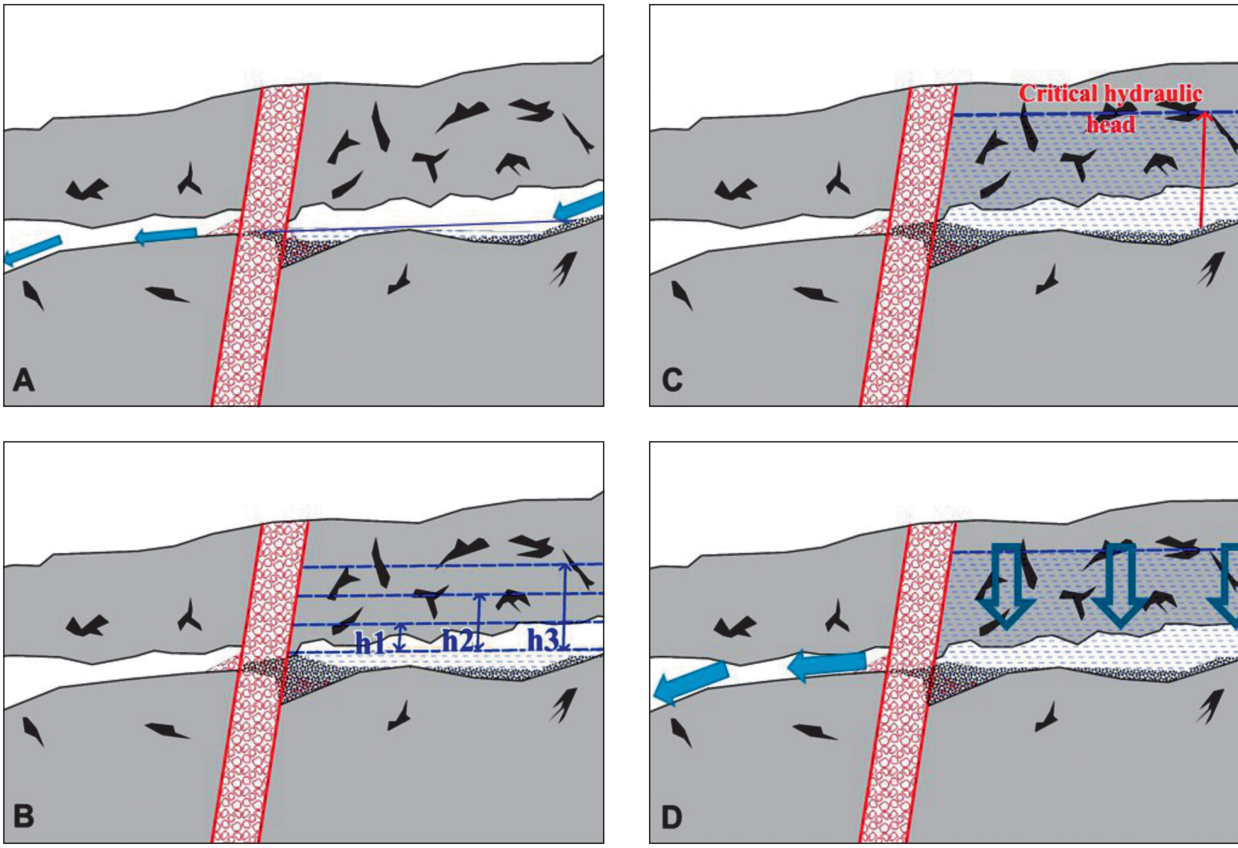

Figure 16. Schematic chart of a karst passage blocked at fault crossing and subsequent interruption of flow: A–presumed situation before the outflow interruption; B – sedimentation of fluvial deposits in the section of slowing water velocity and gradual rising of groundwater level upstream of the blocked zone; C - reaching of a critical hydraulic head; D – burst outflow of the collected water.

failures are characterized by the sudden nature of their origin and can occur only in loose soils (Kramer, 1996) which is the case.

The mostly complete interruption of the spring discharge as well as the dendritic groundwater system with a general stream passage, give grounds to conclude that the conduit flow blocking takes place relatively close to the discharge spring. Paskalev et al. (1992) supposed that the presumable location of that provisionally flow blocking is at the Chernovodtsy Fault zone. The fault is normal with an east-west orientation and a northern hanging wall block located to a distance of less than 1000 m from the spring (Figure 8). As a result of this, the thickness of the karstified rocks in the block towards the spring is significantly less.

Unfortunately, it is not possible to predict when such an extraordinary event may occur. It largely depends on the current spatial distribution of fluvial deposits throughout the whole karst system and the dynamics of the groundwater velocity in it. What can be roughly predicted is the duration of the discharge interruption. It is observed that when the spring discharge is lower, then the interruption period is much longer (Figure 17). It is understandable because the critical hydraulic head capable to destroy the barrier, will be reached much more slowly with small amounts of water.

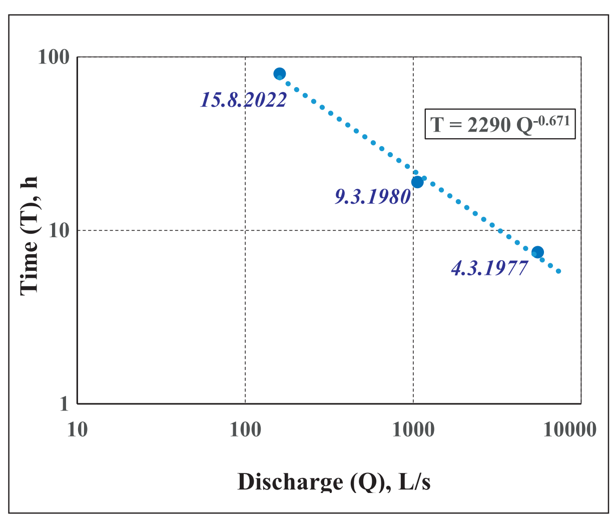

Figure 17: Relationship between the Iskerts Spring discharge and the duration of the interruption period – the blue spots indicate the dates of the interruption cases.

5. CONCLUSIONS

The unpredictable, even rare, interruptions of the Iskrets Spring discharge cause difficult water supply problems for the nearby settlements. The analysis of the hydrogeological situation in the area and the available hydrometric data before, during and after the interruptions, especially the last and longest one in the period 15-18 Aug 2022, allow a hypothesis explaining the circumstances and reasons for these discharge interruptions to be proposed. The Iskrets Spring drains a large karst system of a conduit type, developed mainly in the unsaturated zone of the karst massif. It provides conditions for very dynamic changes in groundwater velocities in different parts of the system as well as temporal changes depending on the current conditions of rainfall and river recharge. This is the reason for the continuous processes of erosion, transport and deposition of fluvial materials, which lead to complete blockage of karst water passages. In such cases, a saturated zone is formed behind the blocked sector with a constantly rising groundwater level. When the hydrostatic pressure becomes high enough, the barrier is destroyed and the collected water flows out in a burst. It is supposed that this occurs relatively close to the spring. One of the most important conclusions is that there is a correlation between the spring discharge and the duration of the interruption period. The anomalous and unpredictable interruptions of the Iskrets Spring are one of the reasons why it has been included in the Global List of Most Important Karst Aquifer's Springs (https://mikasproject.org/mikas-list/).

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https://speleo-bg.org/ - Bulgaria Federation of Speleology