

The Hydrogeological Setting of Križna jama

by

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Zusammenfassung

Aus hydrogeologischer Sicht liegt die Križna jama in einem dreieckigen Aquifer, der aus dem Bloke-Plateau, Cerknica Polje und dem Lož Polje besteht. Während Niedrigwasser-Phasen wird die Križna jama v.a. durch Sickerwasser aus dem naheliegenden hügeligen Karstgebiet versorgt. Bei Hochwasser wird die Križna jama auch mit allogenetischem Wasser des Bloke-Plateaus versorgt. Dieses Wasser erscheint dann wieder flussabwärts in der Križna jama 2 und schließlich in der Štebršćica-Quelle am Rand des Zirknitzer-Sees. Die Verbindungen der unterirdischen Wasserwege wurden durch eine Serie von Tracer-Versuchen nachgewiesen. Aufgrund der überwiegend autogenischen Grundwasseranreicherung ist das Wasser reich an CO₂ und gelöstem Calcit und Dolomit, was Sinterbildung ermöglicht. Die Wassertemperatur ist stabil, genauso wie die Durchflussmenge. Im Sommer kann der Durchfluss beim ersten See versiegen und bei Hochwasserständen bis zu mehreren Kubikmeter pro Sekunde ansteigen. Der mittlere Durchfluss in der Križna jama liegt bei 0,2 m³/s. Während des Pleistozäns war der Wassereintrag aus dem Bloke-Plateau viel größer, was dazu geführt hat, dass es keine Sinterbildung gegeben hat. **Schlüsselwörter:** Križna jama, Hydrogeologie, Karst-Aquifer, Tracer-Versuche, lokale Versorgung, Slowenien

Abstract

From the hydrogeological point of view, Križna jama is located in the aquifer in the triangle formed by the Bloke plateau, Cerknica polje and Lož polje. During periods of low water levels, Križna jama is mainly characterized by

the flow of percolated water from the nearby hilly karst area. When water levels are high, Križna jama also drains allogenic water from the Bloke plateau. The water reappears downstream in Križna jama 2 and, finally, in the Štebršćica spring at the edge of Cerknica polje. Underground water connections have been proved by a series of tracer tests. Owing to the mainly autogenic recharge, the water is rich in CO₂, dissolved calcite and dolomite, and therefore flowstone is deposited from the water. Water temperature is stable, as is general discharge. Water flow can, however, dry up during summer near the first lake and can increase by several cubic metres per second during flood events. Average discharge through the cave is approximately 0.2 m³/s. Water flow from the Bloke Plateau was probably much more intense during the Pleistocene, as a result of which flowstone was not deposited from the water.

Key words: Križna jama, hydrogeology, karst aquifer, water tracing, autogenic recharge, Slovenia

Izvleček

Hidrogeološko gledano leži Križna jama v vodonosniku med Bloško planoto, Loškim in Cerknjskim poljem. Ob nizkem vodostaju se skozi njo pretaka večinoma prenikla voda iz okoliškega kraškega hribovja, ob visokem pa tudi ponorna voda z Bloške planote. Voda iz Križne jame se dolvodno pojavi tudi v Križni jami 2, na površju pa v izviru Štebršćice ob robu Cerknjskega polja. To je bilo potrjeno z nizom sledilnih poskusov. Zaradi pretežno avtogenega napajanja so vode bogate s CO₂ ter raztopljenim kalcitom in dolomitom, zato se iz nje odlaga sga. Voda ima tudi konstantno temperaturo in dokaj konstanten pretok. Kljub temu lahko leta v poletnem času okoli 1. jezera povsem presahne, ob padavinah pa naraste na več m³/s. Povprečen pretok znaša okoli 0,2 m³/s. V pleistocenu je bil dotok z Bloške planote najverjetneje precej intenzivnejši iz vode pa se sga ni odlagala.

Ključne besede: Križna jama, hidrogeologija, kraški vodonosnik, sledenje, avtogeno napajanje, Slovenija

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1. Introduction

Križna jama belongs to the aquifer between Bloke plateau, Cerknica polje and Lož polje. Due to underground hydraulic gradient from NE (Bloke plateau) toward SW (Cerknica and Lož polje) general water flow is oriented in this direction. This is also a direction of water flow in Križna jama. From this point of view, the general hydrological situation seems to be clear – waters that flow superficially on Bloke plateau sink there, reappear in Križna jama and Križna jama 2 and appear at the surface again at Cerknica polje. Such thinking prevailed from the earliest explorations but recently done studies (KOGOVŠEK et al., 2008; PRELOVŠEK, unpublished) raised a big question on validity of such thinking. Probably the biggest mistake done in the past was neglecting of autogenic recharge of aquifer which can contribute about 66% of water to the aquifer. Where does this water flow? Can we neglect many tributaries in Križna jama and their variable hydrological function during low and high water levels? What is the function of dolomite in the upstream parts of aquifer and in Križna jama? Now we know that basic hydrogeological situation is in general very simple but in details quite complex and therefore complicated. Simple structure of two brooks

that disappear at Bloke plateau, reappear in Pisani rov and Blata passage, join at Kalvarijska and appear at Cerknica polje is much more complicated. Some basic hydrological functions of Križna jama are already known now, but some detailed work is still needed to confirm elementary ideas.

2. Hydrological Settings of Križna jama's Surrounding

From the hydrogeological point of view Križna jama lies between fluvio-karstic Bloke plateau on the NE and mainly karstic Cerknica basin on the SW (Fig. 1). Between Bloke plateau and Cerknica polje spreads out completely karstified surface without superficial streams. Consequently, due to combined underground water flow of originally superficial water and waters, which percolate through vadose zone, aquifer around Križna jama is composed of allogenic and autogenic recharge (Fig. 3). Only two major brooks on Bloke plateau contribute allogenic water to the aquifer between Bloke plateau, Cerknica and Lož polje: Bloščica and Farovščica. Both are fed by minor karst springs and partially by surface runoff. Catchment area of Bloščica brook extends on

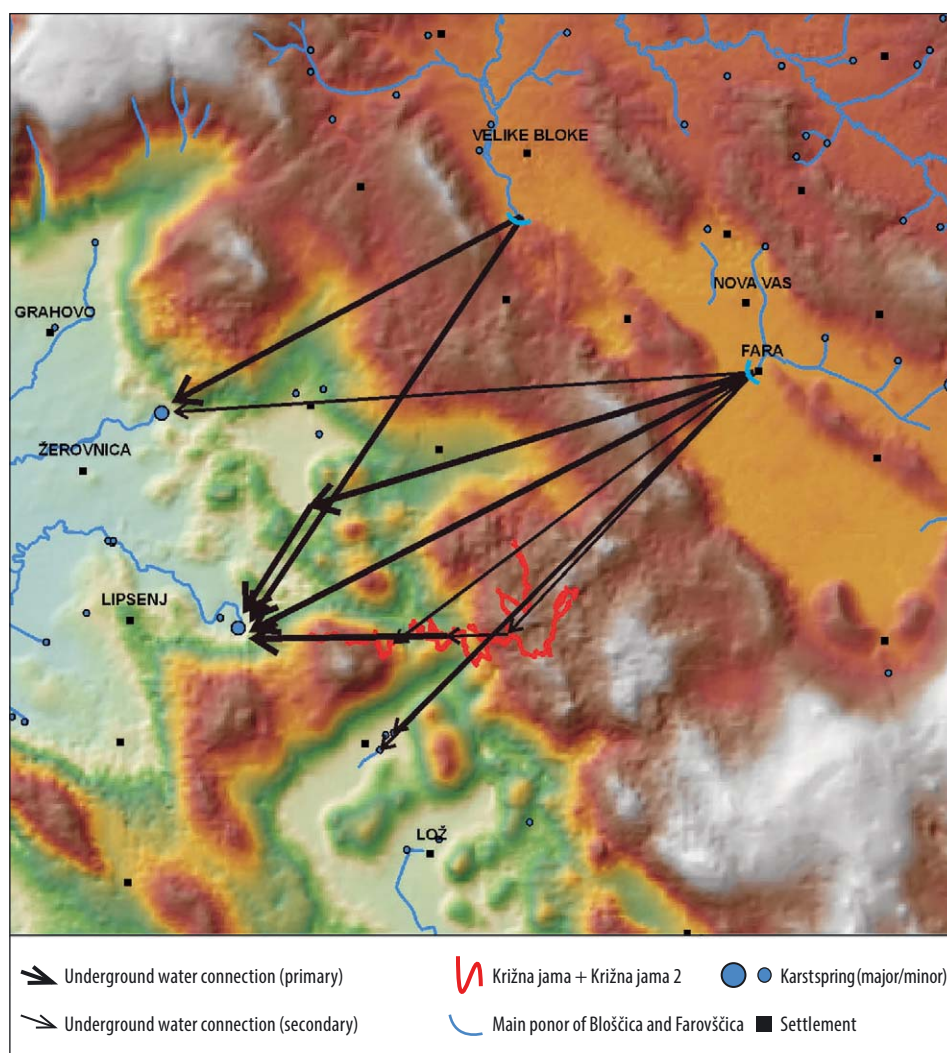


Figure 1: Proved ground-water connections between Bloke plateau, Cerknica and Lož polje (water connections after NOVAK, 1990; KOGOVŠEK et al., 2008; DEM after IAPŠ ZRC SAZU, 2005).

19.5 km² and Farovščica on only 4 km². Between 1972 and 1975 mean discharge of Bloščica was 0.42 m³/s, maximum discharge was 15.9 m³/s and minimum discharge 0.02 m³/s (GOSPODARIČ & HABIČ, 1976:49). Discharge of Farovščica is much smaller; according to Bloščica drainage area characteristics, mean discharge of Farovščica should be 0.085 m³/s. This fits quite well with field observation. According to dye tracing experiments (NOVAK, 1966, 1969, 1990; KOGOVŠEK et al., 2007) Bloščica and Farovščica appear once again on the surface at the springs Štebrščica and Žerovniščica (western part of Cerknica polje). Between 1972 and 1975 mean discharge of Štebrščica was 1.3 m³/s, maximum discharge 16.0 m³/s and minimum discharge 0.01 m³/s. In the same years, mean discharge of Žerovniščica was 0.21 m³/s, maximum discharge 7.59 m³/s and minimum discharge 0.01 m³/s. Comparison between superficial inputs of the aquifer (Bloščica and Farovščica) and outputs of the aquifer (Štebrščica and Žerovniščica) indicates that 34% of water derives from superficial input. The rest (66% of water) originates in the vadose zone and feed the aquifer as autogenic water (Fig. 1).

Ancient belief connected with hydrology of Križna jama was that the brooks in Križna jama are the continuation of Bloščica and Farovščica stream in the underground. Water in the Pirani rov passage should be “underground Farovščica” and water in the Blata should be at least partly from the “underground Bloščica”. This anticipation was not built on dye tracing experiments but on discharge observation (especially when the floods on Bloke plateau

appears), polystyrene findings in Pisani rov and Glavni/Jezerski rov (the polystyrene was deposited in the high-water Farovščica's ponors) and allogenic sediments in Križna cave (the provenance of this sediments lies in the northern Bloke plateau). It is interesting that the idea of a continuation of Bloščica's and Farovščica's underground flow in Križna jama was easily accepted by early cavers, that explored the Križna jama (PUC, 1986), and also by karstologists (for example GOSPODARIČ, 1974). If we do not take into account high degree of autogenic recharge and physical characteristics of water in Križna jama, the idea of continued superficial and underground flow seems to be quite persuasive.

Contrary to the ideas of Farovščica and Bloščica underground flow in Križna jama are physical and chemical observations of water in Križna jama. Mean water temperature in Križna jama (1st lake) is usually about 8.1° C and the annual fluctuation in water temperature rarely exceed 1° C. At 1st lake positive deviation from the mean temperature was observed in the beginning of flood pulse in summer, which is connected with flow through vadose zone. Lower water temperature is characteristic for winter time, when the cold air that is entering the cave cool down the water in the 1st lake. In any case variations in water temperatures are very small and can not be related to Bloščica and Farovščica where the annual fluctuations over 20° C can be observed. It is practically impossible that even at high water level surface waters would adapt cave's temperature within 2.3 km of underground flow. On the contrary, the highest change in annual water

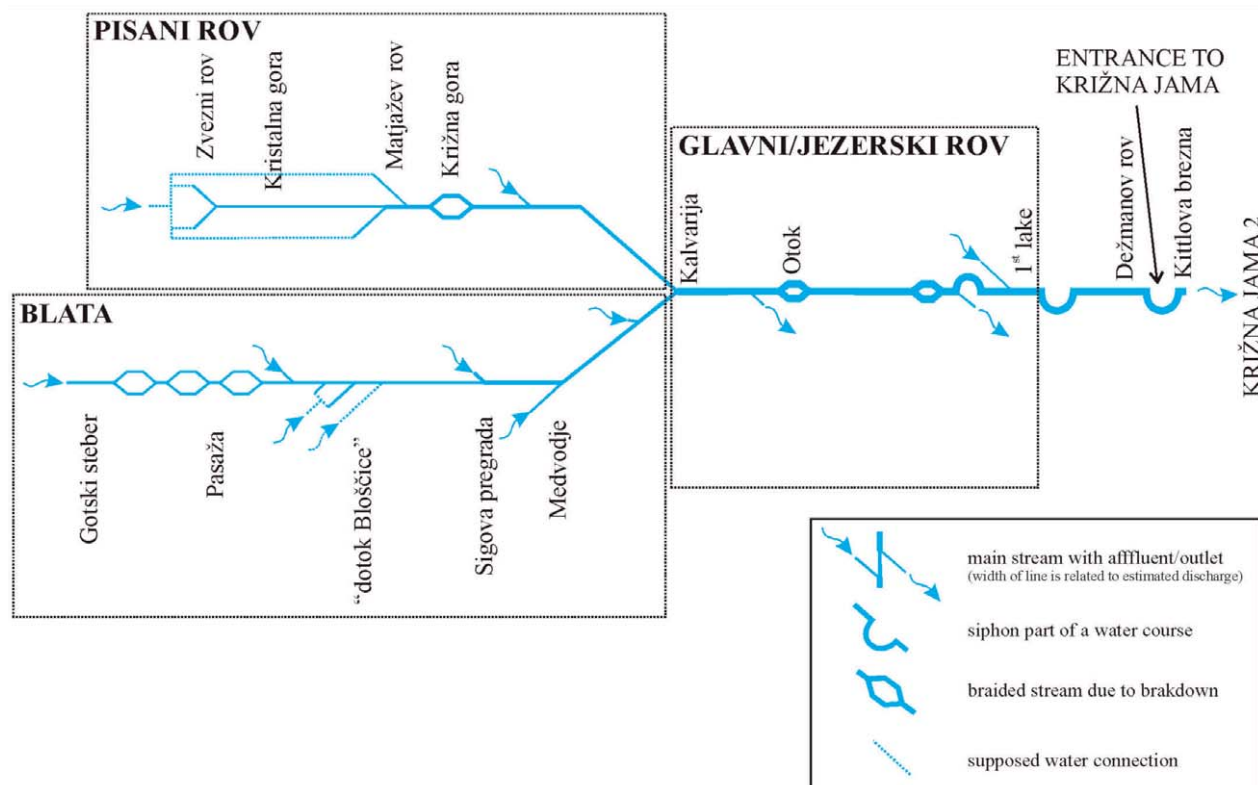


Figure 2: Scheme of hydrological network in Križna jama during low and middle water level. Note that the cave is a collector of autogenic water since it has many inflows and rare outflows.

temperature was observed in Mrzla jama pri Bločicah, where the underground continuation of Farovščica was proved with dye tracing experiment (KOGOVŠEK et al., 2007; KOGOVŠEK et al., 2008). There the annual water temperature variations exceed 4° C. In the past, this northern underground water flow was proposed already by NOVAK (1966) but till 2007 (KOGOVŠEK et al., 2007) never proved by tracing test. In Križna jama we can observe also a strong influence of surface vegetation, which intercept and evapotranspire a lot of precipitation in summer time (fast decline of discharge after the precipitation) and much less in winter time (slow decline of discharge after the precipitation; TROHA, 2005).

Questionableness of water connection between Farovščica and Križna jama was confirmed by dye tracing experiment at middle water level from the Farovščica ponor – among 88% of recovered tracer we detected only 1.3% of tracer in Križna jama (KOGOVŠEK et al., 2008), Fig. 1. First of all the dye appeared in Mrzla jama pri Bločicah, then in Križna jama 2 (which is lying downward of Križna jama) and only then at 1st lake in Križna jama. This proved that waters of Farovščica flow northern from Križna jama and partly join Križna jama – Križna jama 2 water course between caves. Since the waters of Bloščica most likely flow northern from Farovščica-Štebrščica underground water flow, Križna jama seems to be fed by autogenic recharge from the surrounding of passages. In spite of this findings of polystyrene (TROHA, 2005) and occasional occurrence of polluted waters (foams) doubtlessly prove, that at high water level catchment area of Križna jama extends also on the catchment area of Farovščica (Fig. 3).

Downstream from Križna jama water flow was never questionable. In 1965 NOVAK (1966, 1969, 1990) proved

by means of dye tracing experiments the connection between Ponor, Dežmanov rov, northern sump of Kittlova brezna and Štebrščica passage. At middle water level average flow velocity was 0.9 cm/s (NOVAK, 1990). Between northern sump of Kittlovo brezna and Štebrščica spring water very likely flows through Križna jama 2. This connection seems to be logical due to suitable hydraulic gradient, distance (240 m), similar physical and chemical characteristics of water (PRELOVŠEK, 2006), similar composition of allogenic sediments, *Ursus spelaeus* bones and charcoal findings in Križna jama 2.

3. The Hydrological Network in Križna jama

Brooks from Pisani rov and Blata passage and its uniform watercourse from Kalvarija through Jezerski/Glavni rov, Dežmanov rov and northern sump of Kittlova brezna represent the skeleton of hydrological network in Križna jama (Fig. 2). Both brooks appear under the breakdowns beyond which probably some unknown passages exist. At the upstream end of Pisani rov, brook is dammed with two breakdowns (Kristalna gora and breakdown at the end of Matjažev rov). These breakdowns probably divide uniform water flow into the four chemically very similar springs under the breakdowns. 450 m downward from Križna gora a left tributary joins the major brook in Pisani rov. At lower-middle water level contribute about 16% of water into the Pisani rov water course. Dissimilarity of this tributary according to SEC, pH and T proves different catchment area in comparison with main water course in Pisani rov. In spite of all that, the hydrologic network in Pisani rov seems to be quite simple.

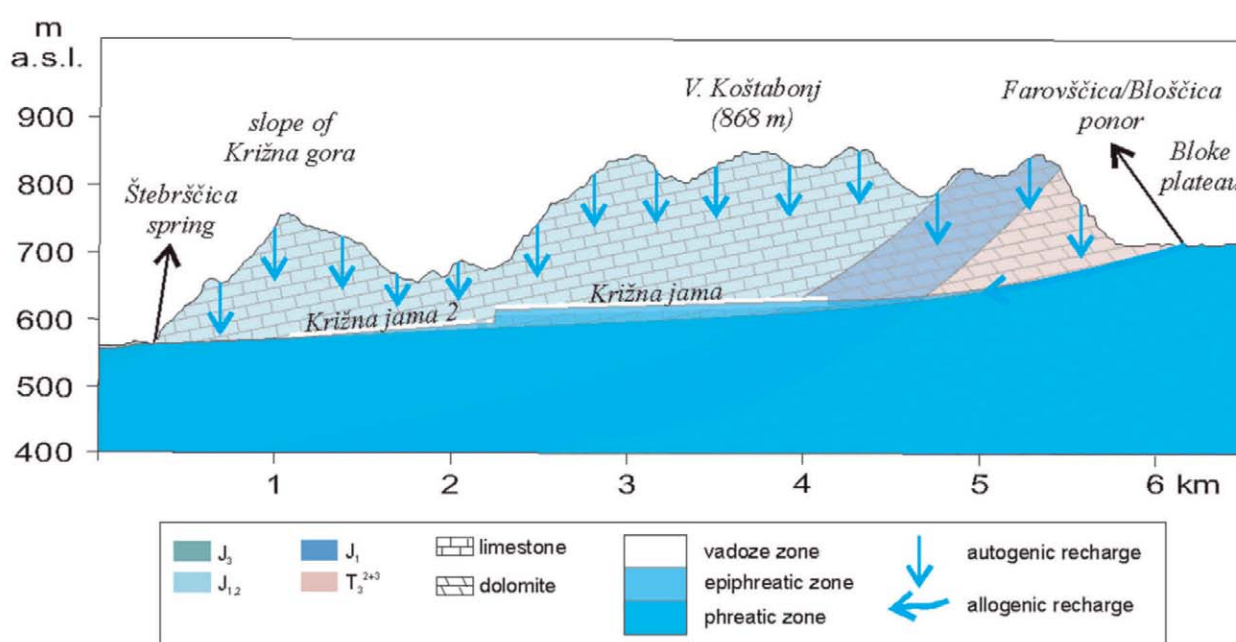


Figure 3: Underground flow of allogenic water from Bloke plateau to Cerknica polje. Note that Križna jama is generally fed by autogenic water since it is slightly above the flow of allogenic water.

Hydrological situation in Blata passage is more complex since the major water course gets at least six tributaries. The main, but not always the strongest spring in Blata passage originates under the ending breakdown. Some 200 m downward, this brook with discharge of several liters per second gets left tributary from the dolomite. At low-middle water level its portion is about 25%. According to morphological observation main stream and dolomite tributary does not contribute much water even at high water level. Few tens of meters downward from dolomite tributary usually not more than 1% of water in Blata passage flows from two right springs, which are due to similar chemical characteristics connected in the hinterland. Besides them lie more than 3 m wide and more than 20 m long side passage which terminates in the sump. At middle water level it does not contribute any water, but according to wash out breakdown at the junction with main stream and dimension of passages discharge can reach several m^3/s at high water level. Since it lies in the direction of Bloščica ponor and becomes active only at high waters, cavers named this tributary "dotok Bloščic" (= afflux of Bloščica). Sump was not dived yet and this connection was never proved by tracing tests but it seems to be possible. Near Vratca the main water course gets unusual underwater tributary that is well detected with SEC, T and pH measurement. Origin of this water is not interpreted yet. Lower downstream, right tributary at Medvodje contributes majority of water flow in Blata passage especially at middle water levels. According to water chemistry measurements (PRELOVŠEK, unpublished) the portion to the all quantity of water in Blata can be from 43% at low water levels and up to 92% at high water levels. Just before the confluence with the brook from Pisani rov water course in Blata passage gets quantitatively quite unimportant left tributary from Markov rov.

Outflows of water in Pisani rov and Blata passage are unknown due to lack of discharge measurements. If they exist they are at least not visible. Contrary to Pisani rov and Blata passage water in the Jezerski/Glavni rov is lost at least at two places and probably joins the major water course between Ponor and Dežmanov rov, maybe also through V-rov. The latter contributes only few litres per second of water at low water levels. At middle-low discharges this water is very similar to the water which flows through Jezerski/Glavni rov. But in the case of heavy storms above Križna jama it erupts some m^3/s of turbid water. Clear water from the Jezerski/Glavni rov at the same time proves different catchment areas at high water levels. Water is therefore gathered through unknown passage between Lož polje and southern part of Bloke plateau.

Gradient of water flow in Križna jama is extremely low. Between 1st lake and Kalvarija the vertical difference equals only 2.6 m in the 1,200 m long Jezerski/Glavni rov (PLANINA, 1985). Thus the gradient is only 0.2%. In Pisani rov and Blata passage the gradient is due to some breakdowns some tenth of percent higher. The highest gradient is between 1st lake and Ponor (about 10%) and downstream from Dežmanov rov (about 5%).

4. Basic Physical and Chemical Characteristics of Waters in Križna jama

Physical and chemical characteristics of waters are the results of geological settings and hydrological conditions in different part of an aquifer. In Križna jama they are significantly influenced also from meteorological conditions outside the cave (PRELOVŠEK, 2007).

A basic factor that defines physical and chemical properties of water in Križna jama is the origin of water. Since the water is autogenic by origin, we know that at the beginning it has to be infiltrated through epikarstic and vadose zone until it reaches the phreatic or epiphreatic zone near Križna jama. Due to the depth of roof (usually 150–200 m) such waters have very constant temperature through the year, they have high pressure of CO_2 and because they are near the equilibrium with respect to Ca^{2+} they have also a lot of dissolved carbonates.

Permeability of all four hydrological zones (soil, epikarstic, vadose and phreatic) is relatively high and mitigation of precipitation is weak in the case of Križna jama. Rapid response is possible because of the intensively karstified limestones and also dolomites above Križna jama. At the water level water flow is also not restricted because of well organized system of dendritic drainage system. Also more than 70 m sump between Križna jama and Križna jama 2 has an appropriate dimension to conduct low and middle discharges without special damming. Rapid reaction to strong precipitation in the Jezerski/Glavni rov was often observed by guides (TROHA, 2005). But since the aquifer is also composed of fracture-matrix system with high water capacity, discharge after precipitation decrease very slowly. This leads to torrential character of waters in Križna jama with relatively long decline of discharge.

Water level at 1st lake fluctuates for several meters. In the case of extreme drought water level decreases for more than 5 m under the normal water level and the 1st lake can lose almost all water. At such hydrological condition the discharge in Jezerski/Glavni rov is between 1 l/s and zero. At high water levels water can rise for about 1 m in the 1st lake and flows into the Dežmanov rov under the Čimboraso. In such case discharge is about 2 m^3/s . In the case of extremely high water levels at 1st lake can rise up to 4 m. Water appears also in Cerarjeva dvorana and can flow over tourist path toward Kittlova brezna (TROHA, 2005). Discharge at such water level is unknown since it occurs very rarely (about twice per hundred years) and it is extremely hard to be measured. Since the velocity of water is much reduced at such water levels, estimated discharge can be some m^3/s higher than at high water levels (2 m^3/s). A high saturation index and a lot of dissolved carbonates are a result of infiltration through soil and epikarstic zone. Water that is flowing through the soil absorbs higher quantity of CO_2 than it is able to retain in the cave's atmosphere. Because of this we can expect oversaturated water. This is exactly the case of Križna jama where the flowstone deposition process is increased by intensively aeration of cave during the winter time (PRELOVŠEK, 2007). Such aeration reduces CO_2 concentration in the karst massive

(around Križna jama is about 2.000 ppm; PRELOVŠEK, unpublished data) to nearly open atmosphere concentration (about 360 ppm). Just the opposite, underground waters of Bloščica and Farovščica has lower CO₂ concentrations due to superficial flow and therefore less dissolved carbonates. They does not deposit any flowstone even during low and middle water levels and but they can become slightly corrosive at high water levels (PRELOVŠEK, 2006). Since these waters are not able to deposit flowstone we have another proof that water stream in the Križna cave is fed by primary infiltration through vadose zone.

The pH value is inadequately studied but an important chemical parameter in Križna jama. According to some periodical measurements it corresponds to water level fluctuation and meteorological conditions. At very high water levels pH value can be below 7.5. Lower pH values are observed also in summer time although the water level can be quite low. This is probably related to weaker degassing of CO₂ from the water. Higher pH values (above 8.0) were recorded at low water levels usually in winter time. If the water level is low and outside temperatures stays below 0° C for some days, pH value can rise even above 8.3. In such conditions we recorded also vast flowstone deposition.

5. Hydrological Conditions before the Holocene

From the hydrogeological point of view, passages and sediments in Križna jama show a very dynamic evolution. From the speleogenetical point of view it contains probably several phases of hydrological activity and inactivity of passages that is now reflected in some morphological and sedimentological structures.

The oldest water flow through Križna jama is seen through the dimensions of now inactive passages. Before the formation of Jezerski/Glavni rov water was flowing from Kalvarija through Suhi rov, 1st lake, Medvedji rov, Cerarjeva dvorana toward Kittlova brezna or toward north, where we can follow several collapsed dolines on the surface. This old water course was probably abandoned due to several collapses in Cerarjeva dvorana and especially the big breakdown between Suhi rov and 1st lake. The breakdown is visible also on the surface near the quarry as collapsed doline.

According to the investigations of GOSPODARIČ (1974) we know for sure that Pleistocene water course was characterized by a strong allogenic input of water. This is proved by sedimentological investigation of allogenic sediments found in Pisani rov, Jezerski/Glavni rov and on some places in Blata passage. The origin of this material (chert and Upper Triassic dolomite) is namely northern part of Bloke plateau. It is possible that the ponors of Bloščica near Velike Bloke were blocked by allochthonous sediment and thus hydrologically not active at that time. As a result, Bloščica had to flow further to the south. The ponors of Bloščica and Farovščica were probably near present-day polystyrene deposits (1 km southwestern from Fara), from where it is possible water connection with Pisani

rov in Križna jama. Catchment area of waters that flew through Križna jama was not just on Bloke plateau since GOSPODARIČ (1974) detected also gravel from the near surrounding of Križna jama (Lower Jurassic dolomite and oolitic bauxite). The age of this phase is definitely older than the oldest dated sediment in Medvedji rov, this is 146,000 ± 14,000 B.P. (FORD & GOSPODARIČ, 1989; ZUPAN HAJNA et al., 2008) or 46,700 +2,400/-1,800 B.P. (RABEDER & WITHALM, 2001; POHAR et al., 2002). In that time, velocity of water was much higher since the cave was without dams and other restrictions. Lower parts of the passage were covered with more than 2 m thick gravelly sediments (to the altitude 617 m a.s.l. near 1st lake). Pebbles more than 10 mm in diameter also show that they were moved as bedrock and not in suspension like now. Water velocity has at least 1 m/s, this is much higher as today (GOSPODARIČ, 1974). Later, the geomorphological and hydrological conditions changed so severe, that Bloščica probably reactivated previously blocked ponors. Reactivation of present-day ponors of Bloščica has broken off transport of sediment from northern Bloke plateau to Križna jama. In the present time, only very high waters of Bloščica flow further to the south toward polystyrene deposits, but such waters do not transport sand or gravel any more. This change into the slow water flow was sudden, since GOSPODARIČ (1974) nowhere noticed normal graded bedding. In this phase water deposited about 3 m of loamy sediments to the altitude about 620 m a.s.l. Some meters higher deposition took place in side passages (Medvedji rov, Suhi rov, probably Cerarjeva dvorana). All these passages had to be exposed to frequent inundation which deposited fine grained material to the altitude about 624 m a.s.l. near 1st lake and completely blocked Ponor (GOSPODARIČ, 1974).

Later, Križna jama has to be hydrologically inactive and was used as a lair for *Ursus spelaeus*. According to U/Th datations made by FORD & GOSPODARIČ (1989) this happened before 146,000 ± 14,000 a B.P. If the bones were intruded between two dated flowstone, hydrologic inactiveness of Križna jama could happen after 126,000 ± 11,000 a B.P.

The final two hydrologic phases started in Würmian glacial and lasts even now. In the glacial water was erosive and corrosive. As a consequence passages were widened and deepened. Due to climatic changes at the end of Würmian glacial water chemistry changed so much that present-day hydrochemical process is mainly flowstone deposition out of usual underground stream of Farovščica and Bloščica brooks.

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