THE VJETRENICA CAVE IN POPOVO KARST FIELD – NEW UNDERSTANDING OF SPELEOGENESIS

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On the edge of the Popovo karst field, through which once meandered in its own coat, the river of Trebisnjica, until then the longest underground river in the world, now ameliorated in a concrete riverbed, in Zavala, is the cave Vjetrenica. By the length of the karts channels, from which 6,300 m has been explored, and by the morphometry and morphography of the cave forms, Vjetrenica is the largest and by the speleodiversity the most famous cave in the outer Dinarides zone. Because of the speleothemes during the middle of the last century (1950.) it was placed in a special protection regime – a natural monument.

The speleogenesis is focused along the main karst caverns in the direction of the Adriatic Sea, i.e. a southerly direction at the beginning and the end of the cave, and in its central parts it has southeast direction. Karst corrosion processes in karst caverns are very active and have a tendency of speleoevolution in the direction of deepening the lower karst erosion base, as evidenced by the constant hydrological activities, especially after flooding of the central cave system that took place in the period from 12 to 16 October 2015.

Since the cave is located on the edge of Popovo karst field, which before the melioration process was periodically flooded by the karst and nival waters, and sometimes during the whole year, and according to the earlier assumptions of speleogenetic scientists in an early stages of development of this holokarst, it was assumed that it was the channel through which the flood waters were leaving Popovo karst field.

Newer caving prospection, especially those relating to the natural processes and phenomena, especially speleoclimatic, hydrogeological and speleovolcanic ones, suggest that the cave is actually hydrological bifurcation, especially in the flooded area, when the excess water forms a temporary flow Lukavac directed towards the Popovo karst field, while the other permanent part has been directed towards the Adriatic Sea through deep karst fissure sinks. Reversible function of the Lukavac flow, with which it drains water from the Popovo karst field to the lower channels of Vjetrenica hasn't been proven so far, and therefore it has no function of the estavelle. This assumption which was narratively propagated by the author of this work has been confirmed this year, when intense rainfall in October, generated from Genoa cyclone, in a very short time exceeded the average two-month amount of rainfall. It caused the flooding of the Vjetrenica cave, reversible and consequential to the decline of the carbonate layers towards the cave's exit. Moreover, from the cave channels, the flood waters were directed at the Lukavac spring, located directly below the cave entrance at the bottom of the Popovo karst field.

Keywords: cave, speleogenesis, decline of the layers, estavelle, bifurcation, water reversibility.

INTRODUCTION

Speleogenesis of the Vjetrenica cave is closely associated with the karstification of the holokarst of the direct and indirect watershed of the Trebisnjica River, which forms the main hydrological backbone of the Popovo karst field. Significant and serious works on the problem of karstification, hydrogeological and hydrological relations of this area within the outer Dinarides, are dated by the geologists and geographers, especially from the time of the Austro-Hungarian reign over Bosnia and Herzegovina as well as afterwards. Those are theoretical discussions about groundwater, which are the key to understanding the ways and depths of karstification. All agree that the underground karst water is produced from the surface drainage water, which through the karst systems of cracks of different diameter and capacity, made by the karst processes, is being infiltrated to the underground aquifers. In defining the aquifer and interconnections of the underground karst systems, there are differences in views; from the common groundwater level that hypsometrically rises from the sea level to the interior, A. Grund (1910), independent hydrological systems at different altitudes F. Katzer (1909) and three hydrological zones in the karst J. Cvijic (1926).

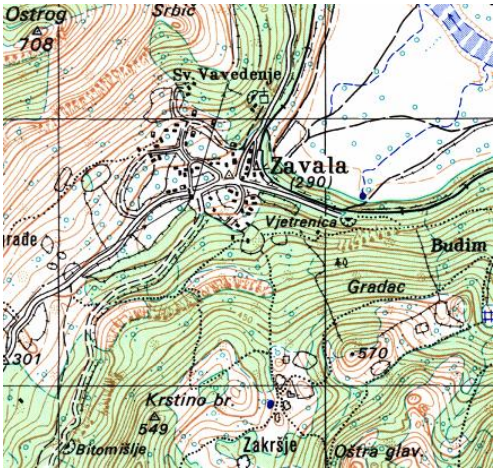

Fig. 1. Topographic location of the Vjetrenica cave in the Zavala of Popovo karst field on the segment topographic map R=1:25 000

Popovo karst field, the lowest karstified karst level (248 m) in the Zavala, to the Adriatic Sea, to where it drains the surface water in the underground, compared to the highest level (960 m) in the Gatacko karst field, was formed in the outer Dinarides zone, with the same dinaric direction. On the southeast side, Popovo karst field represents the mountainous tectonic-karst valley field, first in the lime-dolomite facies, and then up to the village of Trulje with poorly articulated carbonates with rudists. Quite narrow longitudinal valley of the Trebisnjica river is crossing „The real Popovo karst field" K. Absolon (1916), horizontal articulated morphostructure, which was initially oriented in the meridian direction, passing around the carbonate head of the Bratogosac (871 m), and then again inherits dinaric direction of north-west until its end, by the Hutovo. In the flattened valley of the Popovo karst field, the natural riverbed of the Trebisnjica River was adapted with numerous sinkholes along the longitudinal fairway to its end by the Hutovo. Today, the riverbed is made of concrete and is directed towards the reversible accumulation at Hutovo.

In a segment where popovo karst field valet changes its direction from the dinaric into the meridian one the in the widest part named Zavala, on its southwestern part towards the Slano, the Popovo valley is opened by the low karst valley towards the Slano, which F Katzer (1903) called erosive and which has a surface drainage. According to him, in Zavala, two rivers have met: one larger from the Southeast and the other smaller from the northwest.

Both flew to the west, and for the long time, which is proven by the size of the cove towards the Slano. Separation of the cove from the bottom of the Popovo field E. Katzer explains by the selective tectonics by which it was raised and directed towards the Slano, losing its contact with the Popovo valley. This led to a sudden karstification, through which cracks the surface waters were drained in the underground. This happened, according to the before mentioned author, during the late Pliocene, simultaneously with the formation of the northern part of the Adriatic basin. Therefore, F. Katzer (1909) considers the Popovo karst field a transverse karstic plain.

Popovo karst field morphographically reminds of the blind valley, which is so named by the J. Cvijic (1918.) Its bottom is covered with loose alluvial deposits where, before the melioration, on several places, from the Hutovo, Trebisnjica was disappearing in the underground. Karstified sinkholes in the Popovo field are serially connected across its base. The serial connection of the cracks at the bottom of the Popovo valley caused the fluvial evolution of the surface flow of Trebisnjica, converting it in several places into the dry karstified valleys, and then their connectivity made a typical sinking river.

Vjetrenica cave is located in the part of Popovo field called Zavala. It was formed in the carbonates of the upper Jurassic disc deposits beneath the limestone slope of the Gradac, which ends at the peak at 570 m south. Karstification which generated this cave system has a similar morphogenesis with the karst systems of Popovo field.

MORPHOLOGY OF THE KARST SYSTEM OF POPOVO FIELD AND VJETRENICA CAVE

Popovo karst field morphogenesis

Fig. 2. End of Popovo field valley in Hutovo with visible remains of former abyss. Now karst cracks are injected with concrete basin, which present Trebišnjica's water reservoir, as well as reservoir for reversible water from Svitavsko lake created from HPP "Čapljina"

Carbonate deposits with prevailing limestone, which surround the Popovo field from the south side, affected the northwest orientation of hydrological karst recipients, which affected the creation of the blind karst Popovo valley with the sinking river Trebisnjica. Popovo field valley is tectonically predisposed and divided into smaller individual carbonate units, at least three forms of karst valleys with sinkholes and ponikves of various dimensions and orientation, which are during the Neocene geological period, when simultaneously, in other parts of the Dinarides, isolated and linear valleys were formed, were morphologically the lowest in this karst carbonate habitus, towards which gravitational and fluvial processes were directed. They produced colluvial, proluvial and talus detritus which were used to fill the sinkhole recipients at the bottom of the karst depressions and holes, formed in the series along the Popovo valley. Inundated detritus flattened the bottom of the field, merging the karst depressions and holes in them in a unique flattened form – an

accumulation-type field. Popovo field is different from other karst fields because it, according to the observations by Absolon K. (1916) „bends with numerous curves", like the valley of „every other ordinary river", and he accepts the testimony of J. Cvijic (1918) that the field is „pure result of the river flow". Fluvial genesis of the Popovo field, represented by the K. Absolon, can be accepted only as a hereditary genetic form in the tectonic basis, which predisposed the general look similar to the wedged meander valley. Fluvial processes are corrective morphoform of the predisposed tectonic valley towards the accumulative and flattened form of relief of the field types.

Slope processes were precipitated by a hot humid climate, especially during the Pleistocene interglacials, when nival effects from the high dinaric morphostructures from the hinterland increased sub aerial processes, which was determined by the O. Zubcevic (1976), relying on the theoretical understanding of formation of karst fields of Slovenia in the works of A. Melik (1955). Popovo field valley with peripheral morphostructures went through the geological periods of Pleistocene, and, because of the zonal features; expressed through the proximity of the Mediterranean and azonal ones; defined by a low height–band structure, were not covered by ice-firn phase as a direct basin from the karstified hinterland towards the southeast dinaric highlands of Bosnia and Herzegovina. Glacial cold phases of Pleistocene geological period have reduced the hydrological function in the Popovo field valley, and the warm interglacial periods of the same geological period increased the fluvial income. Glacial phases limited the surface runoff of the water, and consequently karst processes were expanding and deepening karst cracks, whether it was a lateral or deep karstification. Interphase warm periods increased the income of water and thus the increased production of extruded debris entering the karst sinkholes which resulted in the transformation of the Popovo field valley into the lacustric phase, when the fine silts and clay politic were excreted over the surface of the field.

The recent climate of this area has similar characteristics and is different from the climate of internal Dinarides and is characterized by hot dry summers and moderately warm and very humid winters. Such climatic conditions are favorable for the accelerated decomposition of the crust, which ends in Popovo field valley. Open slope vales are unquestionable proof that their deficit of the slope mass, with gravitational and fluvial processes was transferred in the immediate basis. The underlying stratum detritus of different forms and grit on the sides of the Popovo valley was affected and transferred by the smaller periodic tributaries, towards the central parts of the field. Trebisnjica adapted its riverbed, both in transverse and longitudinal profiles, as evidenced by the fragment remains of paleofluvial riverbeds at the bottom of the Popovo field. Since Trebisnjica has changeable river regime, conditioned by the pluvial impacts from the indirect, and nival impacts from the direct hinterland of the Popovo field which goes back to the Dinaric highlands in the northeast, it floods the Popovo field with deep waters. In the Pleistocene and recent limnic stages Popovo bolje was flattened by the powerful fluvial and slope deposits, whereby the fine sediments, of the pelitic structure, were deposited on the surface, from the dimly waters, which originated from the immediate catchment area. The clay deposits were made of them, with which the accumulating detritus was cemented and precipitated in thin series of deeper horizons of Popovo valley, which can be noticed on the open sinkholes profiles.

Karstification on the bottom of the Popovo field even in the accumulation phase of uplift and flattening of its bottom had a function of the underground drainage from the surface of the endoreic system of Trebisnjica. With the series of sinkholes, of different

capacities the waters of Trebisnjica were absorbed in the upstream succession from the end of the blind valley. In times of high water levels the ultimate sinkholes were fully active, and during the reduction of water levels, the sinkholes would stay without hydrological function, and their role was compensated by the upstream smaller sinkholes at the bottom of the Trebisnjica riverbed. Trebisnjica had surface function at the time of the high karst water level in the sinking zone, which J. Danes (1906) called the stagnant water. Given that some sinkholes, during the intense siltation of the Popovo valley, very likely, were clogged by the transported detritus which elevated the bottom of the field, so their functions were taken by the hanging karst holes, now in the level of the bottom of the field, on the slopes, and were transformed from once dry or at times wet to the constantly wet karst zones. Given that some sinkholes in the karst interior had narrowed karst channels, towards the incoming karst network from the Popovo field direction, they had the function of estavelle then; in the times of high water levels as the springs and in the times of droughts as sinkholes.

The processes of karstification widening of the sinkholes and their clogging with detritus show the usual trend. Humization periods correspond to the clogging of the sinkholes and aridation period to their openings. This regularity is present in the interior of the carbonate rocks, true to a far lesser extent.

Morphogenesis of the Vjetrenica cave system

Fig. 3. Geological base of Vjeternica in Zavala
Source: BGM Ston 1: 100000

Vjetrenica is a karstified system in Zavala, which is located at the end of the carbonate section of plate to the banked limestone of Kimmeridgian-Portland part of Jurassic era, of dinaric orientation and northeast decline of the layers in the direction of the Popovo field. Inner carbonate layers generally change the directions of declines to the southeast. These deposits, towards the lower Cretaceous carbonates, have the characteristics of overthrust which is defined, by the geological map 1:100 000 Ston sheet, with the tip of the onlay just above the entrance od the cave channels at the 570 m of relative height. Karstification included mainly banks and layered carbonates of Jurassic age as well as Lower Cretaceous limestone at the contact layer of the tip of the onlay.

In the karst evolution of the Popovo polje, the morphogenesis of the Vjetrenica cave should be sought, where the main entrance is at the 268 m above the sea level and it's higher about 20 m in height from the bottom of the Popovo field. The concept of techtogenesis, with which the karst valley was predisposed, and simultaneous process of karstification of carbonate rocks at the valley bottom, on the edges and slopes that were used for the surface water flow from the endoreic blind end to the inside and the fact that the subsequent accumulation of slope-fluvial detritus in the Popovo field remained on the recent heights, excludes its direct genetic link with the Vjetrenica cave system. From the review of floods in the Popovo field, maximum recorded floods were in 1915. when the amount of water reached the height

of 259.8 meters above the sea level, reliably tells us that the level of the flood water never went up to the main entrance of the cave, and thus the cave's entrance could never be the drainage sink of flood waters from the field.

Vjetrenica cave system, especially in its lower horizons in relation to the open cave system, establishes a connection with the Popovo field, i.e. Trebisnjica's periodic flow Lukavac, which originates in the periphery of the field from the karst crack in which the water ascendently balances at an altitude of 248 m, which is the height of the lower karst aquifers in the lower channels of Vjetrenica. Lower Vjetrenica is a karst system of cracks, fissures and channels below today's level of the open cave system. Based on the same altitudes of the well spring of Lukavac and the level of karst aquifer in the system of karst caverns of lower Vjetrenica, their direct hydrological connection was confirmed.

Fig. 4. Spring Lukavac, which is in the karst terminology called "eye". It has a connection with the lower Vjeternica and its lakes. Lake water levels correspond with the amount of water in the well. Through this spring a large mass of flood water from the cave system poured through the chasm that connects the upper to the lower Vjetrenica. It forms the occasional river flow Lukavac. In times of low water levels, water from the springs is used for the water supply of local residents.

The Lukavac spring increases its level and the water outflows to the surface only during and immediately after exceptionally heavy rainfall, when the cave systems are filled with the incoming waters from the upper cave horizons. Then the bifurcation of water takes place in the lower karst fissures, except towards the Adriatic Sea, even to the upper cave halls from where the water is directed through the sinkhole towards the lower Vjetrenica, and then the Lukavac spring, which represents the periodic tributary of Trebisnjica. The Lukavac spring doesn't have reversible function and it doesn't „swallow" floodwaters from the Popovo field, because the water in the Lower Vjetrenica cave system doesn't correspond with floodwaters in the Popovo field.

Karstification of the Vjetrenica cave system was held at the existing relative height and it functions within a separate operating cave system with the karst system of cracks, fissures and channels in the cave ceiling. Filtering of the rainwater from the topographic surface is carried out intensively only in a few places, while the dripping is sporadically, especially in its entrance area, to such an extent that the small stalactites known as „cave macaroni", became dry and are subject to the coronation, which produces dripstone loess. The before mentioned cracks from the cave system have been transferred to the inside and have the same hydrological orientation towards the Adriatic Sea, just like water from the Popovo field. Internal systems of the Lower Vjetrenica are hydrologically very active in inlet and the drainage karst channels. Supply karst channels have the possibility of karst opening due to intensive corrosive dissolution of carbonates, erosion expansion of the cracks, as well as the reduced transport of the decaying detritus from the surface.

Thorough the karstified and extended cracks from the surface, in addition to rainwater infiltration, abundant aeration is done, the trade of the external with the internal cave air though the karst cracks. At a time when the atmospheric air outside of the cave system is heated, and therefore is lighter and vertically expansive, the same air inside the cave is cold, thick and thus heavy; the baric inequality is established that is normalized by the air flow from the cave through the cave cracks outside. The larger the thermic differences between the air on the outside and inside the cave the baric inequality is bigger and the wind towards outside, especially through the entrance, becomes stronger. Baric conditions in the cave and outside of it may be equal, and during those times there is no air flow. In winter, especially when temperatures above the Popovo field are low and lower than the temperatures of the air in the cave, the inverse baric state is formed, so the airflow direction is reversed as well – the wind blows through the entrance of the cave. Such air currents are present in all the caves, and are stronger in those cave systems that have narrow entrance, as is the case with Vjetrenica cave. Speleonim Vjetrenica was named after the bidirectional wind in the first place.

Drainage channels in the karst cave system of the lower Vjetrenica belong to the later phase of the speleogenesis and are, thus, narrower and have limited power of water drainage from the cave. Its hydrological activity is evident in the lowest parts, the ones below the today's cave channels and halls in which the cave lakes, ponds and submerged channels are present, while the middle part of Vjetrenica is the transitional hydrological zone which receives water during floods and, during the reduced seeping and trickling from the topographic surface it reduces the presence of water in the cave and cave baths plates. (Pjates)

At the time of the flood, when cave drainage channels with their capacity cannot accept and drain the incoming water, then they are filled and sunk. The water in them vertically pulsates; during the floods ascendant, when the channels of the cave are filled with the water, and descendent in times of drought, when the water in the channels sinks down to the lower levels. The water level pulsing in the cave channels are more pronounced during the humid weather conditions.

DISCUSSION

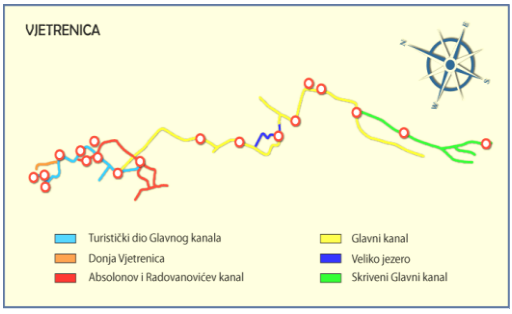

Fig. 5. Vjetrenica cave system
Source: www.vjetrenica.ba/index.php/hr/mapa

Based on the recent seeping and trickling of the karst waters from the cave ceilings and its waste through the sinkholes into the lower system of the karst fissures, we can assume that the Vjetrenica cave is hydrologically very active underground karst system. Evolutionary development is directed towards the lower karst erosion base which has general southeastern orientation towards the Adriatic Sea.

The cave system is fully developed and is characterized by a system of channels that hold general orientation of the main channel in the horizontal direction. The first 150 meters, after the entrance the main channel has east then south direction, through which the airflow takes place. After that, the cave

extends into the cavernous hall, and then at about 600 m, it follows the general direction and continues with the hidden main channel.

The extended parts of the cave halls represent the tectonic-karst expansion compared to the cave channels and were named mostly after the known speleologists who gave their contribution in the study of the cave. Cave halls are internal, tectonically predisposed and subsequently karstified extended cave openings, where the main feature is the presence of the speleothemes. Inside the cave halls there are accumulations of water in the calcite baths, plates or pjates, how the locals call them. The amount of water can vary; during the colder periods of the year they are filled with the water, and during the warmer periods, they almost dry up. Cave halls are mutually connected with the cave channels, some of which are at an advanced stage of speleoevolution.

Web of the cave channels in the Lower Vjetrenica is at the younger phase of the speleoevolution, which can be concluded on the basis of their reduced capacity for cave water filtering. The lower cave channels are hydrologically richer and in them cave river flows and cave lakes can be found. This undoubtedly proves that the entrance to the cave and cave system are evolutionarily older than the lower cave channels, which has already been discussed.

If we follow the chronology of caving there is no doubt that the cave entrance systems from the top of the topographic surface, through which the constant seepage and infiltration of rainwater is taking place, are older and belong to an advanced stage of speleoevolution of cracks porosity within the occasional humid zone. Above the cave ceiling, there is a dense network in karstified carbonates, most of which were dry and occasionally wet during the flood. Main seeping was associated with the systems of karst caverns from the high upper horizons and, very likely, from the cave systems of Bitomislja in the southern hinterland of Vjetrenica.

The lower levels of the Vjetrenica cave system are hydrologically active and completely characterized by the visible hydrological functions within a patent system of channels. Since the cave water, under normal hydrological conditions, stays for the short time in the cave morphoforms, it undoubtedly leads to the conclusion about an advanced process of the cave sinkholes towards its lower levels.

Fig. 6. Vertical tunnel which links middle levels of the cave to the lower systems of karst cracks which form the lower Vjeternica

Poor throughput power of the lower karst horizons reflects the retention of water during the floods in the cave channels defined by the cave system, as evidenced by the formation of the cave lakes and occasional water flows. At a time of increased inflow of cave water, the karst cracks, due to the limited flow capacity, are rising the water level, and again at the time of reduced water income, they reduce the karst level. In this way, the water level in the cave channels vertically pulsates. It is caused by a disproportion of the inflow and outflow of the filtrated waters through the inlet and outlet interconnected cave

fracture systems.

Extreme pulsation of the levels of karst source water corresponds to extremely increased quantity of precipitation, what happened at the beginning of the second decade of October this year, when the huge amounts of rainfall were extracted on the basin of the Vjetrenica cave system; 270 mm/m^3 of rain in only three days. The bad weather was generated by the Genoa cyclone, triggered by the southward streaming, when in the period of only three days, the Vjetrenica basin received the amount of rainfall almost identical to the average maximum amount of rainfall for the month of October. Rainwater from the topographic surface is transferred through the karst fissures in the interior of the open cave system towards the lower karst base. As the lower level of the cave system is certified less than the middle and the upper level, so the throughput capacity is limited and the ascendant, ascending, pulsation of the water starts with which the central cave system was flooded, even its entrance. Excess water from the lower cave channels was transferred into the main cave channel and thus the flood occurred which lasted from the 12 to 16 October 2015. Flood waters went through the vertical corridor, which leads to lower Vjetrenica. Vertical channel has taken the role of the sinkhole through which huge amount of water disappeared, moving stone blocks weighing several hundred kg. These waters disappeared through the underground fissures towards the Lukavac spring, the temporary tributary of Trebisnjica. Through the main spring of Lukavac, the huge amount of water was ejected, estimated at around 8m^3/s. The flow of the water lasted as long as the flooding of the main cave channel.

The consequences of the sinking of the cave are evident. In addition to infrastructure devices and objects being temporarily disabled, the cave channels at the middle tourist cave floor are intruded with the cave mud that slowed the flowing of the filtered water. The floods of the Vjetrenica cave confirm the basic assumption that the cave is a separate karst system, that it performs bifurcation of karst water in the direction of the Adriatic Sea, which ends up as the submarine springs and through the Popovo field through a series of springs, of which the most important is Lukavac, in which the pulsation o karst water is performed.

CONCLUSION

Speleogenesis of the Vjetrenica cave is closely associated with the karstification of the holokarst of the direct and indirect watershed of the Trebisnjica River, which forms the main hydrological backbone of the Popovo karst field. Significant and serious works on the problem of karstification, hydrogeological and hydrological relations of this area within the outer Dinarides, are dated by the geologists and geographers, especially from the time of the Austro-Hungarian reign over Bosnia and Herzegovina as well as afterwards.

Popovo karst field morphographically reminds of the blind valley, which is so named by the J. Cvijic (1918.) Its bottom is covered with loose alluvial deposits where, before the melioration, on several places, from the Hutovo, Trebisnjica was disappearing in the underground. Karstified sinkholes in the Popovo field are serially connected across its base. The serial connection of the cracks at the bottom of the Popovo valley caused the fluvial evolution of the surface flow of Trebisnjica, converting it in several places into the dry karstified valleys, and then their connectivity made a typical sinking river.

Vjetrenica cave is located in the part of Popovo field called Zavala. It was formed in the carbonates of the upper Jurassic disc deposits beneath the limestone slope of the Gradac, which ends at the peak at 570 m south. Karstification which generated this cave system has a similar morphogenesis with the karst systems of Popovo field.

Vjetrenica was in the beginning of the second decade in October flooded with waters, drained from the surface, which belong to the Vjetrenica catchment system. Huge amount of rainfall was extracted on the karstified basin of Vjetrenica, triggered by the southern Mediterranean flow, and in particular, the Genoa cyclone which caused a flood of the middle cave system, which is arranged for the tourists.

Flood waters of Vjetrenica cave system and its leakage from the lower hydrological catchments in the north, confirm the assumptions of its internal hydrological bifurcation which partly gives water, not only towards the Adriatic Sea, but the Popovo field as well. In addition, a mutual internal hydrological connection of the cave system was shown, whose capacity was reduced from the upper levels towards the lower levels following the processes of karstification towards the lower karst base. The cave system of Vjetrenica shows the large correspondence of the amount of waters at the same hypsometrical levels. Thus, the water level in the well spring in the bottom of the rim of Popovo polje corresponds to the water level of the lake in the lower channels of Vjetrenica. Onflow of the recent flood waters from the Vjetrenica cave have shown the complete separation of karst processes of Vjetrenica and Popovo field.

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