UNIVERSITY OF NOVA GORICA
GRADUATE SCHOOL

SPELEOGENETIC FACTORS AND PROCESSES IN THE KARST CONDUITS OF ZAGORSKA MREŽNICA SPRING CAVE (CROATIA)

DISSERTATION

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I declare that this dissertation is my work of authorship.

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ABSTRACT

Zagorska Mrežnica spring cave is in the Desmerice village, 7.59 km SW from the town of Ogulin. The coordinates of the entrance are X: 399563 m, Y: 5006974 m, and Z: 314 m (HTRS96). The cave system is positioned in the contact zone of Jurassic limestone and the thrust front composed of Triassic Dolomite. The karst drainage system has elements of point recharge through a set of ponors in the hinterland karst poljes and diffuse infiltration through numerous dolines on Velika Kapela Mountain. The karst of Ogulinsko Zagorje area and its epiphreatic and phreatic cave systems have been intensively explored for the last eight years, resulting in the mapping of 1134 m of submerged passages of the Zagorska Mrežnica spring cave. Until 2014 it was the longest mapped submerged system in Croatia explored by cave diving techniques only. Altogether, over 3.5 km of submerged passages in seven caves of Ogulinsko Zagorje (Zagorska Mrežnica spring cave, Spring of Rupečica, Ponor of Rupečica, Cave system Pećine-Veliko vrelo, Spring of Bistrac, Cave Zagorska Peć and Pit Klisura) were explored during 500 hours of diving over a ten-year period. The goal of the research was to determine speleogenetic factors and processes in phreatic conditions. A new methodology for mapping of cave cross-sections, microrelief forms, and structural elements was developed, sediment and petrographic analysis were done, hydrological analysis before and after the building of the accumulation lake Sabljaci, 48 cross-sections of the cave passages and a 3D model of the cave system was created, water chemistry as well as geomorphological analysis was carried out. In the end, a simplified (modified) vulnerability assessment was also done.

The results of my research showed that the distribution of the cave passages is a result of complex tectonic activities that are reflected in the orientation of cave passages. The general orientation of the measured fissures, measured during cave diving, show a dominance of a NWW-SEE direction but also the pattern of cave passages shows a significant dominance of the NE-SW orientation indicating the existence of multiple secondary traverse faults originating from main NW-SE faults. The morphology of the cave passages shows a transition between epiphreatic (possibly vadose) and phreatic phases as well as the presence of paragenetic developments in the ceiling. This indicates the existence of several epiphreatic (possibly vadose) and phreatic speleogenetic phases. The initial shape of the cross-sections was identified by sub-horizontal beds and bedding planes. The mapping of microrelief forms showed that the mechanical erosion was a very intensive process shaping the morphology of the cave passages.

The sediment mineralogy coincides with the lithology of the catchment area, and the sub-angular grains reveal relatively short transport distances. Further analysis of the catchment area’s geomorphology and its relevance for the speleogenesis of Zagorska Mrežnica cave show influence of relief structures that have a Dinaric orientation (NW-SE) with cave structures and passage orientations, great relative relief, steep slopes on Velika Kapela, and flat areas of karst poljes dictate the allogenic and autogenic hydrological regime of the cave. A 3D model of the cave system reveals a relationship between the cave system and the landscape, as well as a possible connection with the nearby Zagorska Peć cave. The modified karst vulnerability assessment shows that the catchment area of Zagorska Mrežnica spring cave has a high vulnerability ranking, mainly due to high doline density and the potential large diffuse capacity of infiltration of pollutants.

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1 INTRODUCTION

Cave diving is a technique that enables us to study still active phreatic caves. Most of the other researchers had been studying “fossil” conduits in the caves. Lauritzen et al. (1985) compare this difference to studying medicine on a corps instead of on a living human. Flooded ((epi)phreatic) systems pose a particular challenge as they are hard to explore and even harder to make any scientific research within. However, they offer insight into active phreatic processes which largely define the whole evolution of the conduit network in the karst (Lauritzen et al., 1985; Jeannin, 2001; Piccini et al., 2003; Ford & Ewers, 1978; Palmer A.N., 1991; Frumkin & Fischhendler, 2005; Palmer 2001, 2012; Audra & Palmer, 2011, 2013, 2015).

Only a few submerged studies have been carried out until now (Grozdicki, 1983; Lauritzen et.al., 1985; Gines et al., 2009; Kincaid, 1999). Knowledge about the morphology, position of cave passages, and pollution in the Zagorska Mrežnica spring cave was unknown until cave divers started the research in 2006 (Jalžić, 2008). From 2006 until 2016, seven cave systems were explored and partially mapped. In 2006, under the organization of the Caving Section Željezničar, the Croatian Biospeleological Society and Caving Club Samobor, a series of expeditions were conducted where teams of cave divers researched and mapped the Zagorska Mrežnica spring cave, Spring-cave Rupečica, Ponor of Rupečica, Zagorska Peć cave, Klisura Pit and the longest researched submerged freshwater cave system in Croatia Pećine-Veliko vrelo. The research and mapping of Zagorska Mrežnica spring cave was carried out continuously from 2006-2016. Due to the complex distribution of cave passages, morphology, and difficult hydrological conditions, cave diving teams had to map it several times. As a result, 1134 m of cave passages were mapped and at that time, it was the longest mapped submerged system in Croatia. For this, it took over 100 hours of diving over a period of 10 years. In the framework of this study, from 2010 until 2014 different components of geomorphological research were done. A geomorphological map of a part of the system was created and 47 cross-sections of cave passages were mapped. Microrelief inventarization of the system was done, along with photo and video documentation. HOBO water level data- loggers were put in the cave which recorded changes in water pressure and temperature. With this information, precipitation and water level, the changes were analysed. The cave-diving techniques enabled *in situ* observation of changes that happened in the cave in the geological past and speleogenetic factors and processes that formed the morphology of the cave in phreatic conditions. The developed methods for underwater data collection in this research as well as the results and presented ideas in the discussion chapter may hopefully result in more use of cave diving for detailed studies of phreatic caves.

2 OBJECTIVES AND GOALS

The main objective of this research was to develop and use new research techniques within a phreatic cave system to bring new insight on its past evolution and its relation to the entire catchment area.

The goals of this research were to:

- develop new techniques of cave surveying, detailed geomorphological mapping, structural mapping, sediment sampling applicable in phreatic caves.
- determinate the phases of evolution of Zagorska Mrežnica spring cave and its past hydrological conditions.
- determinate the role of Zagorska Mrežnica spring cave within the entire catchment area and its relation to adjacent caves.
- compare the observations and conclusions to general conceptual speleogenetic models.

It is not easy to put a single hypothesis which guided this research. However, a plausible hypothesis would be that only detailed mapping by cave diving techniques could give cruicial insights into the past and present speleogenetic phases of Zagorska Mrežnica spring cave and link this phases to known conceptual speleogenetic models (Ford & Ewers 1987; Palmer, 1991; Palmer & Audra, 2015).

3 DESCRIPTION OF RESEARCH AREA

Zagorska Mrežnica spring cave is the main spring of the Zagorska Mrežnica River. Water resurfaces along the contact line of well-permeable Jurassic limestone and less permeable Triassic dolomite. Based on information received from the local population, between 1930 and 1938 a dam was built for the needs of a small sawmill that was constructed next to the spring (Figure 1). This dam created a small accumulation of water in front of the cave. According to the local people, it took seven days for the accumulation to fill. Later the sawmill was destroyed in a fire. Unfortunately, no literature data exists from that period. Construction work for the pumping station started in 1956. They built a dam (Figure 3), which raised the water level in the whole cave system.

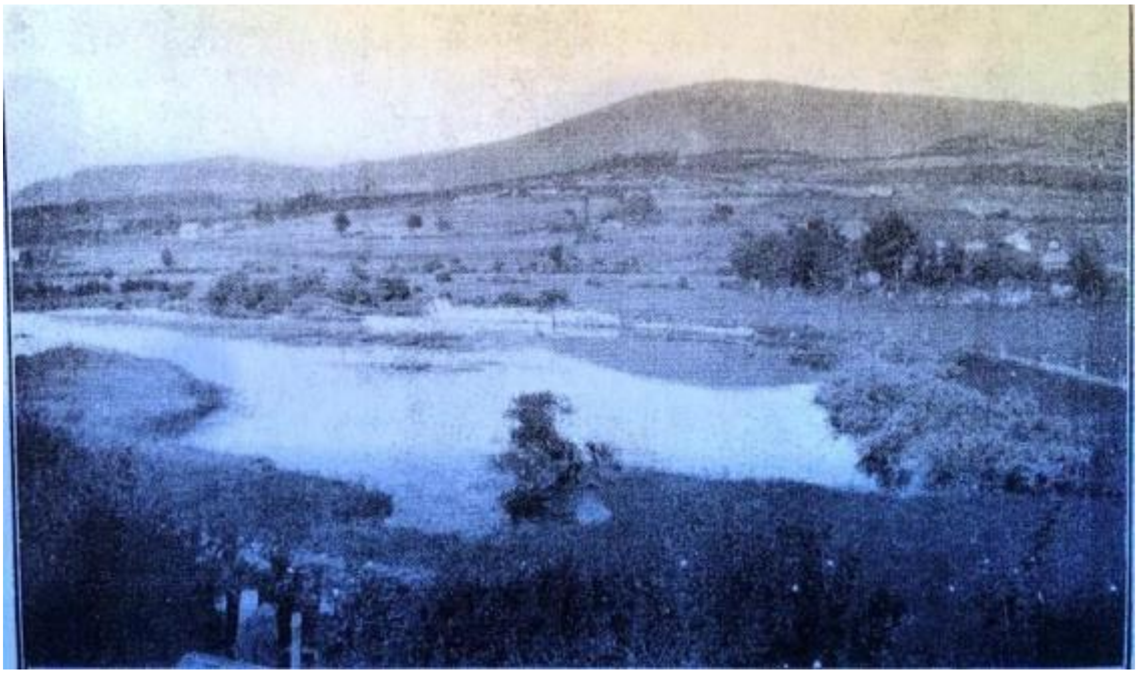


Figure 1: Zagorska Mrežnica spring cave area during high water before construction of the pumping station (Poljak, 1925/26).

The Zagorska Mrežnica River is the first segment of the Mrežnica River. Before the building of the accumulation Lake Sabljaci it was 8.5 km long at its maximum, but now it fills the aforementioned accumulation lake that has a volume of 33×10^6 m^3 (Figure 3). The second segment of the Mrežnica River occasionally flows through its original riverbed towards ponors of which the largest is ponor Ambarac and from there to the Tounjčica spring cave. The third segment is the surface stream Tounjčica River that connects to the Mrežnica River. It is a part of one of the main aquifers of the Ogulin region.

The entrance coordinates of Zagorska Mrežnica spring cave are X: 399563 Y: 5006974 and Z: 314 (HTRS 96, Figure 2). It is the main water supply for over 50,000 people in the Ogulin region.

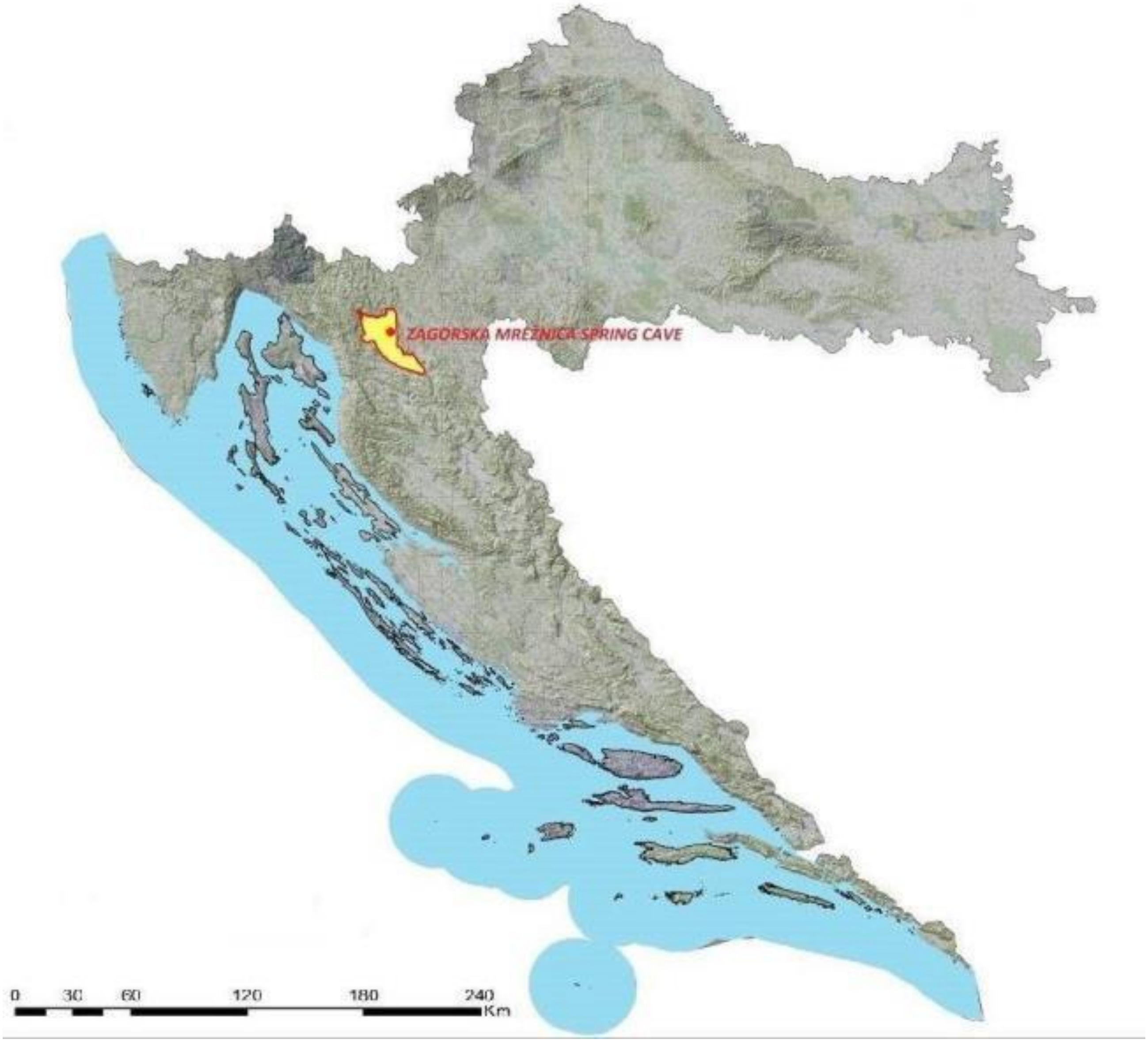


Figure 2: Position of Zagorska Mrežnica spring cave on the map of the Republic of Croatia, yellow marked area is the catchment area of Zagorska Mrežnica spring cave; the red line represents the border of the catchment area.

Figure 3: Zagorska Mrežnica spring cave after the construction of the pumping station.

Before construction of the accumulation lake Sabljaci, the Zagorska Mrežnica River flowed in a northward direction (Figure 4). During high water levels, it flowed to the main ponor – cave Ambarac that is 8.5 km away from the spring (Opala, 2010).

Figure 4: Former natural course of the Zagorska Mrežnica river before the construction of the pumping station.

Today, the Zagorska Mrežnica River does not exist anymore; the natural riverbed is dry, only during high water it is used as an outlet of excess water (Figure 5). The ponors have lost their hydrological function since the water from Zagorska Mrežnica is directed through the tunnel to Gojačka Dobra, where it is used by the Gojak hydroelectric power plant (Opala & Ožančić, 2010).

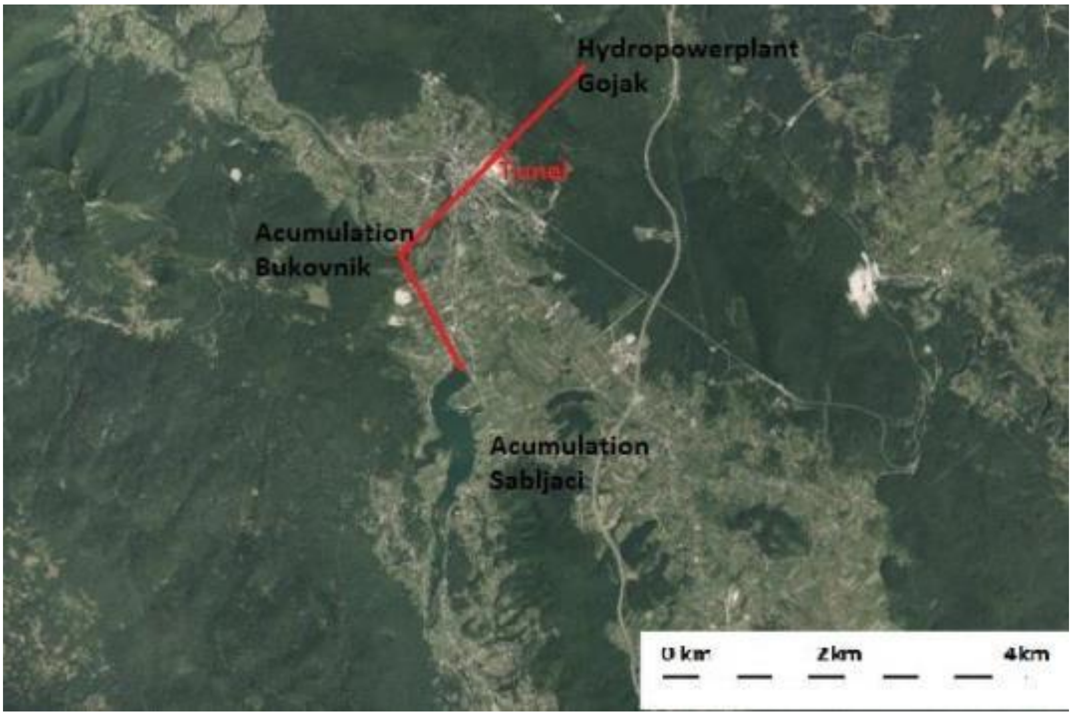


Figure 5: Redirection of water from the Zagorska Mrežnica river to the Gojak hydropower plant through the tunnel.

The first data about springs in Ogulinsko Zagorje was collected for the purpose of making a geological map of the Austrian-Hungarian monarchy in 1868 (Hauer, F., 1867-1871). Franjo Julije Fras (1835) made a written record about a cave near Zagorska Mrežnica spring. E. A. Jurinac, a zoologist who studied the fauna of the Dinaric karst, published an article about caves of the Ogulin and Slunj area (Jurinac, 1887). D. Gorjanović-Kramberger (1912) did the first systematic analysis of karst in the Ogulinsko-plašćanska valley region where he described speleogenesis of Đula ponor and the hydrogeology of the Ogulinsko-plašćanska valley. J. Poljak (1925–1926), who analysed the geomorphology and hidrogeography of Ogulin Zagorje, continued this research. Later on, in his articles, he described Bistrac spring, Zagorska Peć cave, Zagorska Mrežnica spring cave and river Rupečica. He claimed that the underground water from these caves is connected. A substantial contribution to hydrogeological studies was given by S. Bahun (1970). He concluded that the hinterland karst poljes feed the springs in Ogulin Zagorje. M. Kuhta (Kuhta & Blažič, 2005) analysed hydrogeological connections between ponors in Drežničko polje and Stajničko polje and Zagorska Mrežnica spring cave.

3.1 GEOGRAPHICAL SETTING OF RESEARCH AREA

Zagorska Mrežnica catchment area is a part of the Dobra River catchment area and its boundaries are determined based on the hydrogeological connection established with dye- tracing (Bojanić & Ivčić, 1981; Biondić et. al. 1986; see Appendix I). The catchment area of Zagorska Mrežnica spring cave is located in the western central part of the Dinaric karst of Croatia, between 45^{0}03′ and 45^{0} 34′ N and 15^{0}35′ E with the surface of 604 km^{2}, which is akarst of moderate latitudes (Herak, 1972, Appendix I). It is a part of the Karlovac County, thearea of the town of Ogulin. The research area is a part of the Dinaric karst. It is a part of the Dinaric mountain macrogeomorphological region of external Dinarides that is characterized by arched mountain ridges, and a mezogeomorphological region of the Velika Kapela mountain group (Bognar, 2001). The whole area has characteristic karst and fluviokarst morphology and hydrology, with well-developed dolines, poljes, uvalas, vertical and horizontal caves, ponors and karst springs (Pahernik, 2000). The average yearly precipitation is 1520 mm and the average yearly temperature is 10.2°C (Opala & Ožančić, 2010).

The catchment area is constituted of three main geographical regions (Figure 6, Rogić, 1977):

1. Karst poljes that are elongated NW-SE direction on the west side of the Mountain Velika Kapela as a part of the Lika region. They represent a zone of karst depressions of hilly areas of Velika Kapela Mountain. Average annual temperature is between 6-8°C and average annual precipitation is between 1000-1300 mm (Klimatski atlas Hrvatske, DHMZ).
2. Velika Kapela Mountain is a part of the Gorski Kotar region, which is an area of deep karst with some ecological and climatological characteristics important for the hydrological regime in aquifers. It is the coldest region of the research area with an average annual temperature between 2 and 5°C and an average annual precipitation of more than 1400 mm (Klimatski atlas Hrvatske, DHMZ).
3. Ogulinsko Zagorje is a part of the Podkapela sub mountainous valley or Ogulin-Plaški submountainous valley, a fluvio-karst zone below Velika Kapela Mountain. It is a region

that has an average annual temperature between 4 and 6°C and an average annual precipitation of 1000 mm (Klimatski atlas Hrvatske, DHMZ).

Figure 6: Map with position of main geographical regions
(ARKOD, 2016)

Karst poljes are on the west part of the research area. In the central part of the research area is Velika Kapela Mountain, and on the west side is the Ogulinsko Zagorje area. They have a Dinaric alignment and elongated shape. The periodically accumulated water and sinking streams that feed Zagorska Mrežnica spring cave are located in the following karst poljes: Drežničko polje, Jasenačko polje, Stajničko polje, Lug and Krakar polje and Crnačko polje (Biondić et al., 1986). The poljes are depression zones with Dinaric orientation on 650 m a.s.l. (Jasenačko polje) to Stajničko polje 497 m a.s.l. (Figures 6, 7).

Figure 7: Stajničko polje
(Stajnica, 2016).

Jasenačko polje has an area of 2.3 km^2 (Opala & Ožančić, 2010) and it lies between Bjelolasica Mt. (1534 m a.s.l.) on the NW, Debeli vrh Mt. (1050 m a.s.l.) on the SE and Jasenačka kosa (1212 m a.s.l.) on the NE. It consists of Gornje karst polje and Donje karst polje. The lowest elevation of the polje is 610 m a.s.l. Through the karst polje flows a sinking stream – Jasenak. It periodically floods the karst polje. Ponors are situated on the SE part of the polje.

Drežnik Lug and Krakar polje have an area of 8 km^2 (Opala & Ožančić, 2010). On the south part of the poljes lies the village Jezera and springs Vruljčić and Vrujac which flow in a northward direction. During the rainy season, the poljes are flooded. The lowest elevation of the poljes is 468 m a.s.l. The biggest ponor is Sušik, situated at the eastern side of the polje (Figure 8).

Drežničko polje is situated south of Krakar polje. It has an area of 5.25 km^2 (Opala & Ožančić, 2010). Its lowest elevation is 440 m a.s.l. and it has a slight inclination of 0.17% from north to south. On the western part of the polje there are numerous karst springs (Studenac and Kotao are the biggest) and on the eastern and southern parts of the polje there are numerous pits and caves that function as ponors, like Pražića jaruga, Zrnića ponor, Bosnića ponor and Zečev ponor (Kuhta, 2004). When springs flood the polje in the rain season, the polje functions as a natural water accumulation. Stajničko polje is the southernmost of all the karst poljes that constitute the catchment area of Zagorska Mrežnica spring cave. Its lowest elevation is 497 m a.s.l. It is situated between Veliki Panos (1079 m a.s.l.) and Oštri vrh (1164 m a.s.l.) on the north, the hills Kopanje and Veliko and Malo Bilo (631 m a.s.l.), Jelak Mesićev vršak, Petrov i Pavlov vršak, Šašina mala (Plantaš) and Kalun (729 m a.s.l.) on the south and Vršak (656 m a.s.l.) on the east.

Figure 8: Ponor Sušik in Drežnički Lug polje (photo: Ante Sušić).

Crnačko polje is on the west side of Stajničko polje. Its lowest elevation is 448 m a.s.l. and has an area of 3 km² (Opala & Ožančić, 2010). The largest sinking stream is Jaruga, and the largest ponor is cave Rokinka on the NE side of the polje.

Velika Kapela mountain ridge extends from Gorski kotar on the west to Mala Kapela on the east, from the Ogulin-plašćanska valley in the north, to the Glibodol in the south. It has a Dinaric orientation of NW SE, parallel to the Adriatic coastline. The highest peak is Kula on Bjelolasica, part of Velika Kapela 1534 m a.s.l. Other peaks are Mirkovica (1298 m a.s.l.), Smolnik (1219 m a.s.l.), Klek (1182 m a.s.l.), Crni Vrh (1102 m a.s.l.), Kapela (1092 m a.s.l.) and Makovnik (1164 m a.s.l.). The mountain range has numerous dolines and over 30 caves and pits.

Ogulinsko Zagorje is on the eastern part of the catchment area of Zagorska Mrežnica river located between the Gorski Kotar and Lika regions (Pavić, 2009). It is a fluvio-karst region with the lowest elevation of 320 m a.s.l. and a part of Ogulin-plašćanska sub mountainous valley. At the foot of Velika kapela Mt. where it is in contact with Ogulin-plašćanska sub-mountainous valley, Zagorska Mrežnica spring cave is situated along with other springs that are distributed in a N-S direction. The region has one larger urban centre, the town of Ogulin, and 50 smaller villages so the anthropogenic influence is constant and intense. In the past, the area was influenced by agriculture and forestry and during the 2nd half of the 20th Century, the area was substantially modified by a lot of hydro-technical work (accumulation Lake Sabljaci) and deforestation. The eastern part of the area is characterized by numerous ponors from which the largest one is the cave system Đula-Medvedica (16,396 m long), formed by the Dobra river sinking stream.

3.2 GEOLOGICAL SETTING OF THE STUDY AREA

The research area is built of up to 5 km thick carbonate deposits from 12 lithostratigraphic units ranging from Middle Liassic to the Upper Cretaceous (Figure 9, Appendix V). The deposits were deformed by compressive tectonics during the Tertiary and reshaped by weaker neotectonic transpression (Milorad et al., 1982).

Upper Triassic Dolomites are dominant in Ogulin-plašćanska sub-mountainous valley and they represent the oldest deposits in the study area. In relation to hydrogeological characterization, deposits can be classified into five groups (Biondić et al., 1986):

1. Permeable deposits (limestone and dolomite with high tertiary porosity due to high tectonic deformation and a high level of karstification): Middle Jurassic limestone and dolomite ($^1J_2$), limestone and dolomite (^2J), limestone with inlayers of dolomite (J_2), limestone, dolomite, and breccia (K_1) deposits of Cretaceous age constitute the mountain Velika Kapela, and Upper Cretaceous bioaccumulated limestone (K^1_2). The limestone is micritic but also has biogenic components (pellets and algae).
2. Less permeable deposits (limestone and dolomite with tertiary porosity but because of the high component of dolomite it has less permeability): Upper Triassic dolomites and dolomitic limestone ($^2T_3$), Cretaceous bioaccumulated limestone (K_2) present in the Ogulin area and Mt. Mala Kapela, carbonate pellets and sandstone from the Lower Triassic are present in Ogulinsko Zagorje (T_3).
3. Deposits with low permeability (low karstified dolomites with secondary porosity filled with clay and dolomitic sand): Lower Jurassic dolomites with limestone (J_1), Upper Jurassic limestone with algae and dolomite ($^2J_3$), Upper Jurassic foraminiferal limestone with dolomite ($^3J_3$), Upper Jurassic dolomite and limestone ($^1J_3$).

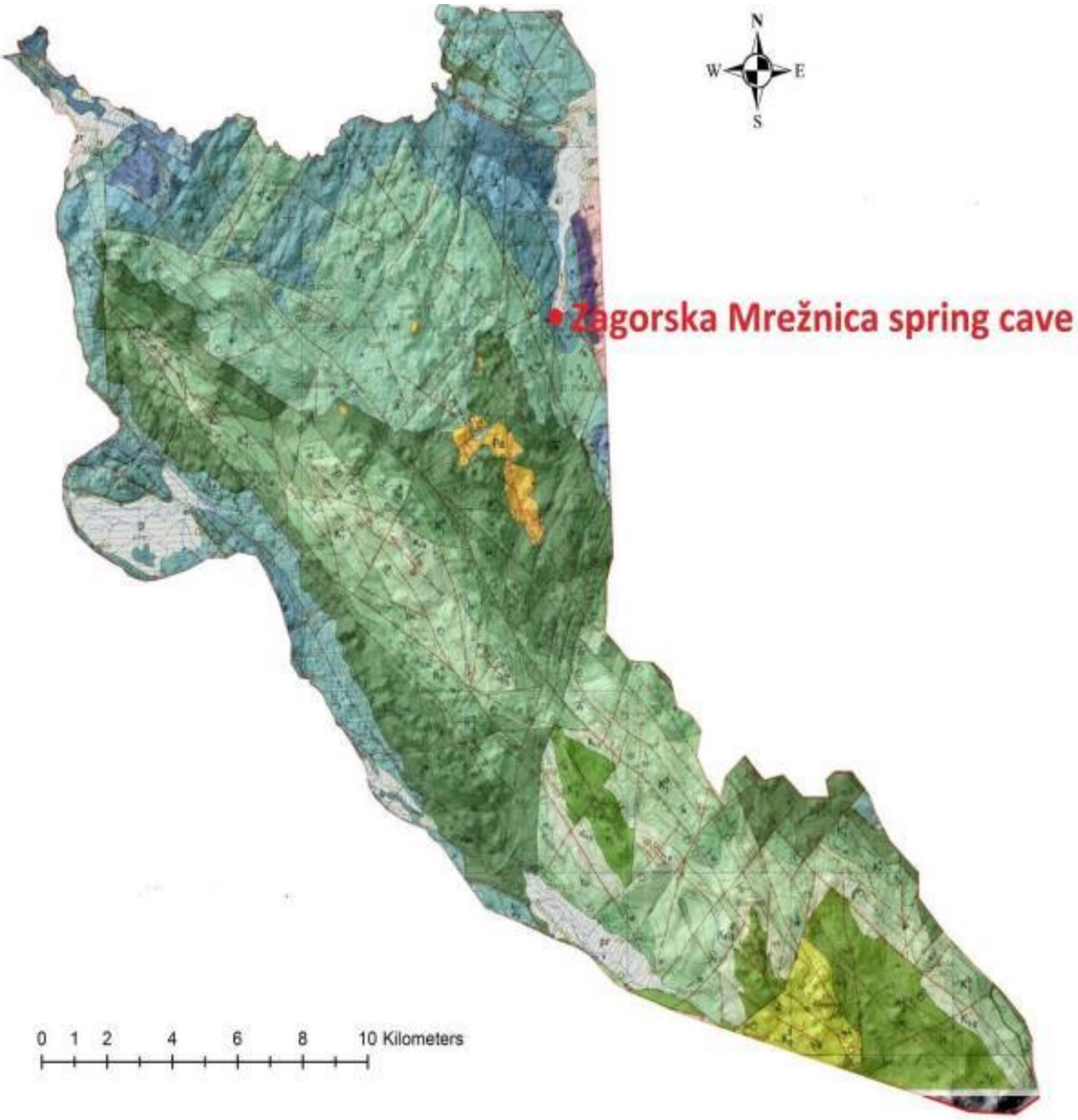


Figure 9: Geological map of the catchment area (Milorad et al., 1982; Velić et al., 1980a; see the map with legend in Appendix V).

4. Non-permeable clastic deposits: (Marl and conglomerate represent aquitards for underground water): Breccia, conglomerates and bioaccumulated limestone (Pc) of Paleocene were found on the west of the catchment area, Silts and dolomite of Lower Triassic age (T_1) are found south of the mountain Klek and part of Velika Kapela, Limestone and conglomerates of Tertiary age (E) were found in the SE part of the catchment area.
5. Deposits that have a variable permeability (Pliocene and Quaternary deposits): Upper Pleistocene proluvial (Pr) and Holocene alluvial (al) deposits are found in karst poljes and river valleys. Deposits of silt sand and gravel are present near the riverbeds of Zagorska Mrežnica, Vrnjika and Dretulja. The catchment area of Zagorska Mrežnica spring cave

belongs to the Adriatic-Dinaridic Carbonate platform area which is a part of the Dinaridic plate and has had several episodes of drowning and emersion (Jelaska, 2002). During the Paleogene, the main thrust-related deformations took place (Schmid et al., 2008) and during Miocene regional complex tectonic structures were formed like wrench tectonics (Prelogović et al., 1995). According to Korbar (2009) the Adriatic-Dinaric Carbonate platform consists of the Dinaridic (DCP) and Adriatic (ACP) domain which are subdivided into five tectonostratigraphic units: Dinaridic NE unit (DNEu) or Inner Karst, Dinaridic SW unit (DSWu) or High Karst, NE Adriatic trough (NEAT), Adriatic NE unit (ANEu) or Dalmatian Karst, and Adriatic SW unit (ASWu) or Istrian Karst. The catchment area of Zagorska Mrežnica spring cave represents one of the most complex tectonic units of the Dinaridic NE unit; Zagorska Mrežnica lies on the border between Gorski kotar unit and Lika unit. It is an orogenic type of karst (Herak, 1980) because it was formed in tectonically (or tectonic) mobile terrain with many tectonic deformations like faults and overthrusting (Figure 10). Parallel reverse faults in a NW-SE direction and transverse faults along Velika and Mala Kapela area are present as well as a dolomite thrust in Ogulinsko Zagorje (Velić et al., 1980b). The most important lithostratigraphic feature of the area is the interchange of limestone and dolomite beds.

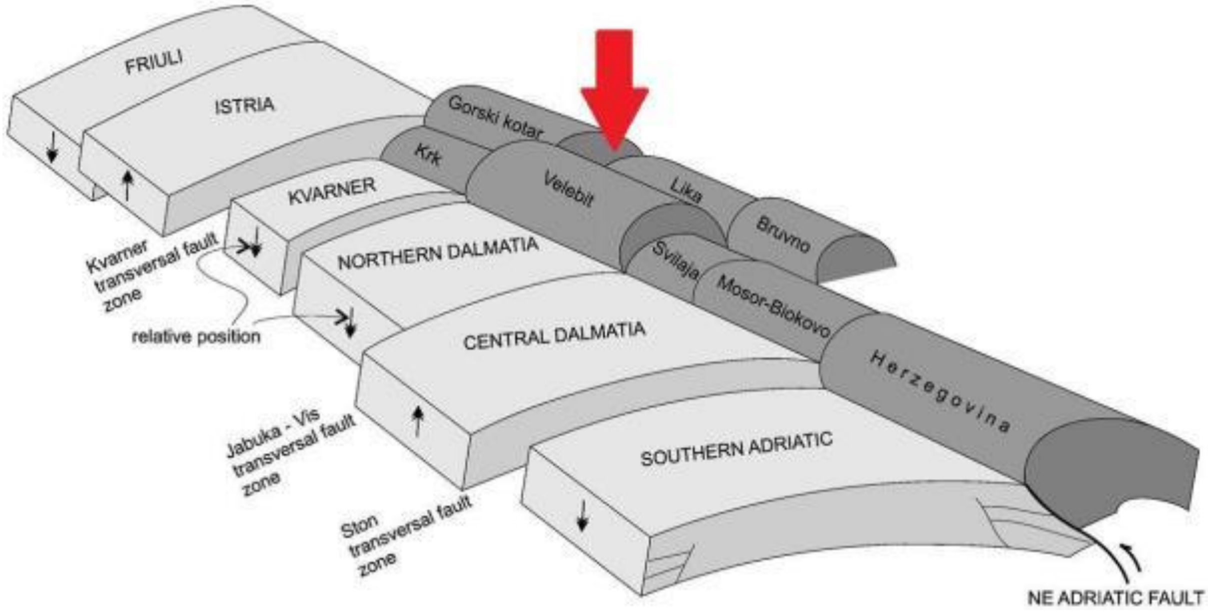


Figure 10: Sketch of spatial relations of the crustal segments and related fragments on different elevations (possible isostatic rebound) in the NE Adriatic region prior to the latest orogenic wrench tectonic deformations (Dinaridic – dark grey, Adriatic – light grey). The superimposed thin-skinned sedimentary cover (early-orogenic) is not shown (Korbar, 2009). Red arrow marks research area.

The deposits were deformed by compressive tectonics during the Tertiary and reshaped by weaker neotectonic transpression during the Tertiary NE-SW compressive movements when they reached their maximum. In the neotectonic period, the stress changed to a N-S direction, resulting in the further uplifting of the Dinarides and further deformation of structures. The Drežnica structural unit represents a deformed syncline composed of Lower Aptian and Albian deposits, pushed from the NE along the fault with approximately 700 m of vertical movement. This fault forms a boundary with the NE part of the Drežnica structural unit (Matičec et al., 1997).

Klek is a tectonically strongly disturbed zone where neotectonic activities caused reactivation of older reverse faults of Dinaric orientation into the dextral strike-slip faults (Korbar 2009).

The Velika Kapela mountain ridge represents a large anticlinal structure composed of Tithonian carbonates and shows no signs of rotation (Korbar, 2009). Due to compression stress, mild faulting occurred. The mountain ridge of Velika Kapela can be separated into two tectonic units, Bijele stijene and Samarske stijene on the north-western part of the catchment area that has an echelon tectonic structure (Pahernik, 2000). The central part of the Velika Kapela

Mt. is an uplifted mountain ridge with a longitudinal NW-SW stretch direction. Between Velika and Mala Kapela, several transverse faults are present. Karst poljes on the western side are a consequence of reverse faulting and pull-apart structures. Their orientation is NW-SE and the Stajničko polje has the NWW-SEE direction because of rotation.

Bahun (1968) related the origin of Ogulin Zagorje valley to a denudation of an anticline that had a very mild curvature. The southern limb of the anticline was completely denudated and the northern limb of the anticline is still visible. The schematic reconstruction from Bahun shows that almost 2500 m of mostly Upper Triassic and Cretaceous deposits have been removed during the Eocene (Bahun, 1960). As a result, the dolomite was exposed to the surface forcing the ground water to emerge. As the surface streams have cut through the deposits, the base level has been lowered leaving river terraces behind (Figure 11).

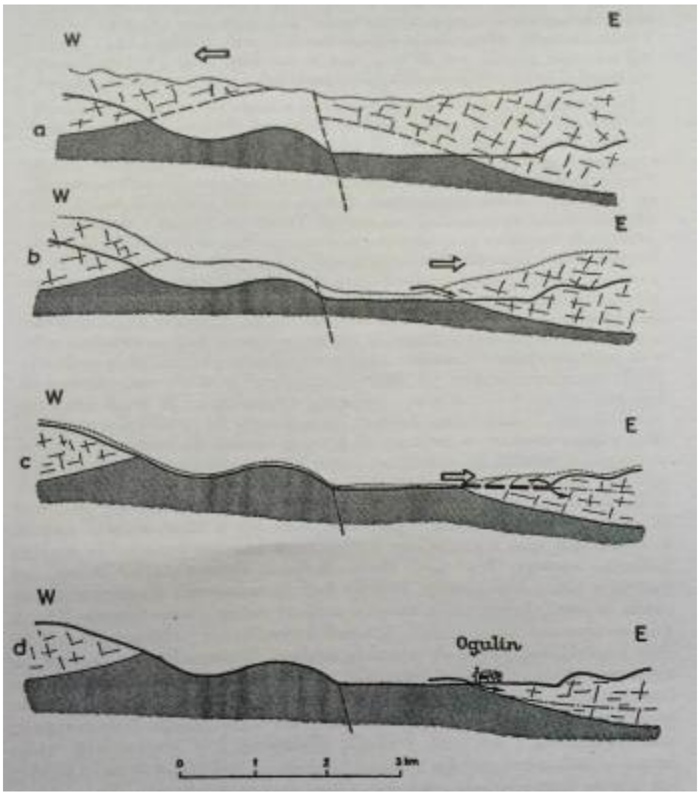


Figure 11: Reconstruction scheme from Bahun (1968) about the origin of the Ogulin Zagorje valley: a) anticline, b) denudation of anticline, c) exposed dolomite strata, the presence of surface streams, d) lowered base level and presence of losing streams.

The latest orogenic tectonics resulted in further structural re-arrangements during the Neogene along predominantly reactivated faults of the NE Adriatic fault zone (NW–SE). The most obvious geomorphological evidence of the tectonic activity along the zone is the mountain range characterized by a generally NW-SE (Dinaric) strike. A few mm a year discrepancy between horizontal GPS velocities of the SE part of the Adriatic segment in respect to the Dinaridic one could be accommodated rather by late-orogenic vertical tectonic transport along the NE Adriatic fault zone than by active thrusting (Korbar, 2009).

3.3 GEOMORPHOLOGY OF THE STUDY AREA

According to geomorphological regionalization (Bognar, 2001), the area is a part of the macro-geomorphological region 2.1. *Mountainous part of Croatia*, mezzo-morphological region 2.1.3. *Velika Kapela mountain group*, 2.1.4. *Mala Kapela mountain group* and 2.1.5. *Ogulin-Plaški valley*, and micro-geomorphological regions that have folded-faulted-thrust structures which formed during the Alpine orogenesis (Figure 12). This is a part of External Dinarides where most of the structures and forms are elongated in the Dinaric orientation NW-SE. Due to the change of stress during neotectonic, structures have rotated more N-S. As the Mala Kapela block was rising, valleys developed.

Figure 12: Geomorphological regionalization of Croatia by A. Bognar with marked regions (red square) of the research area (Bognar, 2001).

The type of karst poljes in the study area are structural poljes (Gams, 2005). Structural poljes are associated with fault structures and dolomite rocks (impervious or less permeable rocks). The genesis of structural poljes is connected with pull-apart basin formation and corrosion planation at the piezometric level. Their characteristics are that they are elongated along ridges, overthrust zones and fault zones with a Dinaric orientation. They have numerous karst springs and ponors along fault lines where allogenic sinking streams flow into the underground, and that they often burry irregular topography (synclinal and anticlinal structures). They are typical for Dinaric karst and they represent the fluvio karst landscape in karstic terrain. By geomorphological classification according to Gevozdeckij (1981), this area is predominantly covered karst, and small parts are bare karst areas.

In the research area, all scales of karst landforms are represented (Mcllroy da la Rosa, 2012). Macroforms (larger than 10 m^2) like karst poljes, uvalas and dolines are present. Above Zagorska Mrežnica spring cave there are numerous dolines and several unroofed caves (Figure 13). These features shallow trenches between 10-30 m long. The roofless caves have in general a N-S orientation. They are positioned on more or less the same altitude. Some of them still have part of the ceiling in the northern part. On the bottom, collapsed material is visible in some parts, but mostly the collapsed material is covered in sediment. The position and layout of roofless caves show that some of them are above Prvi Lijevi passage and Novi kanal passage (Figure 14). Roofless caves are remnants of past speleogenetic phases before the development of Zagorska Mrežnica spring cave and Zagorska Peć spring cave.

This is the result of denudation processes and surfacing of the cave (Mihevc, 1996; Mihevc, 1998). In some of them, flowstone deposits are still present. The size of the flowstone suggests that the ceiling was thick.

Mesoforms (1 cm^2-10 m^2), such as different types of karren present in the highest rocky ridges of Velika Kapela Mountain and Bijele and Samarske stijene as well as microforms (1 mm^2-1 cm^2) are present.

Figure 13: Roofless caves positioned above Zagorska Mrežnica spring cave.

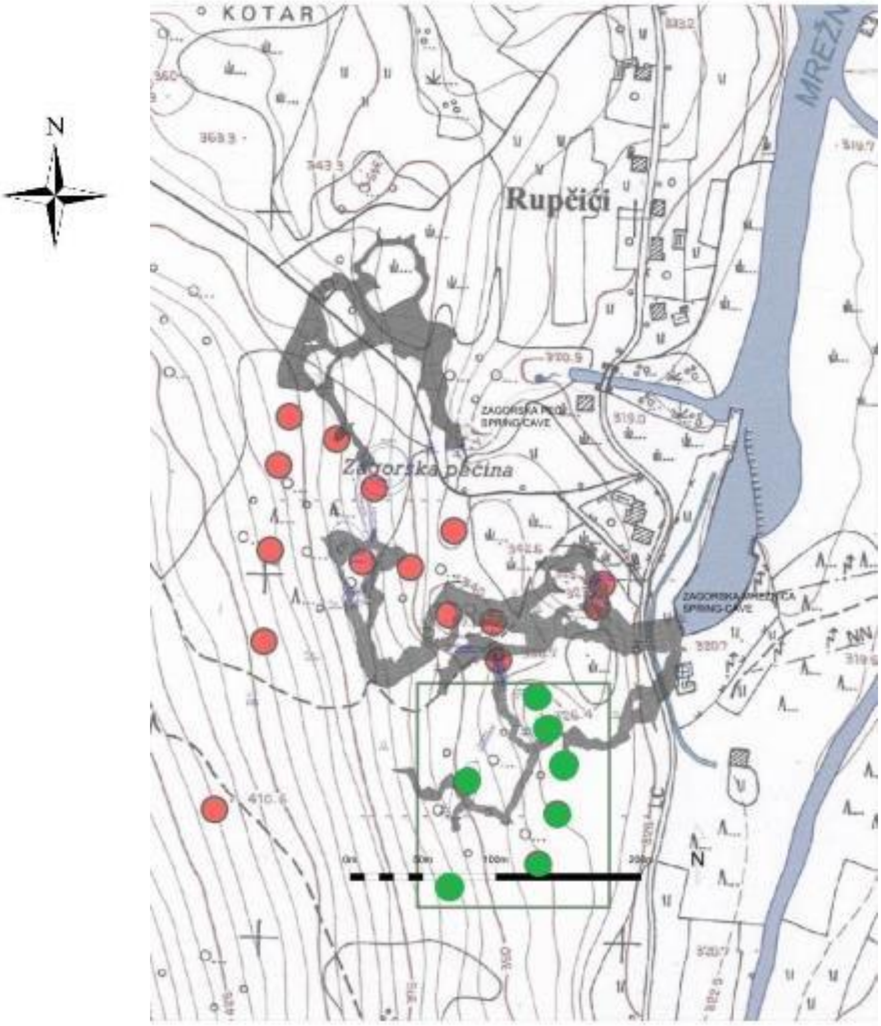


Figure 14: Position of roofless caves (green marks) and dolines (red marks) above Zagorska Mrežnica spring cave and Zagorska Peć cave.

3.4 HYDROGEOLOGICAL CHARACTERISTICS OF THE STUDY AREA

Zagorska Mrežnica spring cave is characterized by both point and diffuse recharge. The point recharge from ponors in karst poljes in the hinterland is transient, recharging a large amount of water in short time periods. During the rainy season, karst poljes are fully or partially filled with water and they represent natural water accumulations. The rainy season lasts from late fall to early spring. The flow-rate of ponors in karst poljes was estimated to be between 18 and 20 m^3/s (Bojanić & Ivčić, 1981). According to measurements by the Water Level Measurement Gauge Stock, the water level in karst poljes is between 3 m and 7 m and the accumulation can last up to 70 days. In 1992 and 2013, the water level was 17 m and it is the highest water level recorded in Drežničko polje. The accumulation of water lasted 75 days (Ivčić et al., 2001).

Bahun (1968) stressed the importance of polje accumulation to the hydraulic response of the whole system. He calls the Velika Kapela Mt. the “upper accumulation and transit/throughout area”. The 1500 m thick, carbonate sequence is highly karstified. The structure of tertiary porosity is largely unknown and therefore the aquifer remains poorly characterized. The residence time is between a few days and a few weeks and the water surfaces again through the numerous springs on the eastern side of Velika Kapela Mountain and on the western side of the accumulation Lake Sabljaci (Bojanić & Ivčić, 1981, Ivčić 1981, Turner, 1954). Large amounts of water flow through Velika Kapela Mountain and surface in contact with the aquitard made of less permeable deposits of dolomite thrust on the eastern side of Velika Kapela Mountain, the Ogulin Zagorje.

Several underground connections were determined by the tracing method using fluorescein (Figure 15, Figure 16, Biondić, 1958).

Pražića jaruga, a ponor in Drežničko polje, is connected with Zagorska Mrežnica spring cave and spring Bistrac (Bojanić & Ivčić, 1981; Ivčić, 1981; Turner, 1954). The tracing was done on 13.5.1985 and the tracer was registered 88 hours later. The flow rate was 3000-4000 l/s. The straight-line distance from the ponor in Drežničko polje to Zagorska Mrežnica spring cave is 11 km and the apparent velocity of water flow is 135 m/h.

Crnačko polje is connected with Zagorska Mrežnica spring cave and spring Bistrac. The tracing was done on 12.4.1985 and the tracer was registered 160-173 hours later. The flow rate was 150-200 l/s. The straight-line distance from the ponor in Crnačko polje to Zagorska Mrežnica spring cave is around 13, 8 km and the apparent velocity of water flow is 150 m/h.

Jasenačko polje is connected with Zagorska Mrežnica spring cave and spring Bistrac. The tracing was done on 12.4.1985 and the tracer was registered 448-457 hours later. The flow rate (discharge) was 13 l/s at the ponor. The straight-line distance from the ponor in Jasenačko polje to Zagorska Mrežnica spring cave is around 14 km and apparent velocity of water flow is 31 m/h.

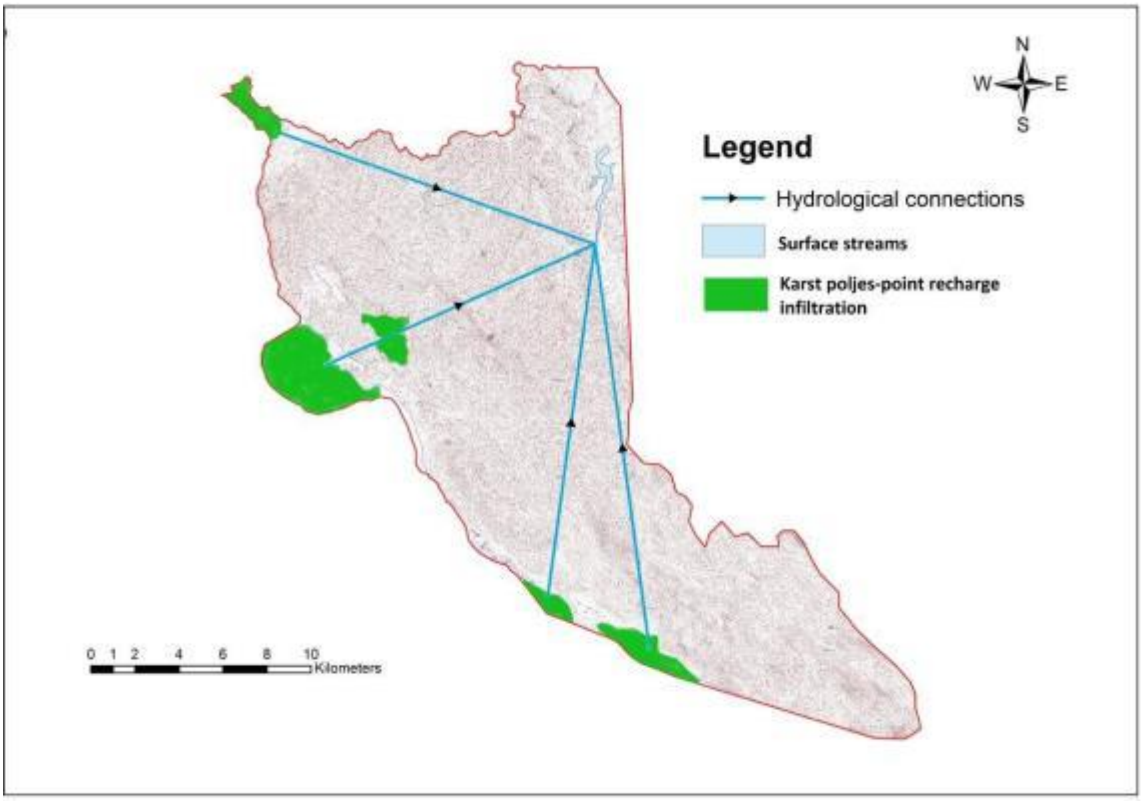


Figure 15: Map showing hydrogeological connections of the catchment area of Zagorska Mrežnica spring cave.

Stajničko polje is connected with Zagorska Mrežnica spring cave and spring Bistrac. The tracing was done on 22.4.1988 and the tracer was registered 320 hours later. The tracing was again done on 8.1.2000, when the flow rate was about 80 l/s (Ivčić et al., 2001). The tracer was detected within 184-308 hours after injection. The flow rate was 80 l/s. The straight-line distance from the ponor in Stajničko polje to Zagorska Mrežnica spring cave is around 16 km and the apparent velocity on 22.4.1988 was 100 m/h and 50 m/h on 8.1.2000. The connection to the cave system Pećine-Veliko vrelo (Stoševo spring) and to the spring Rupečica was not confirmed.

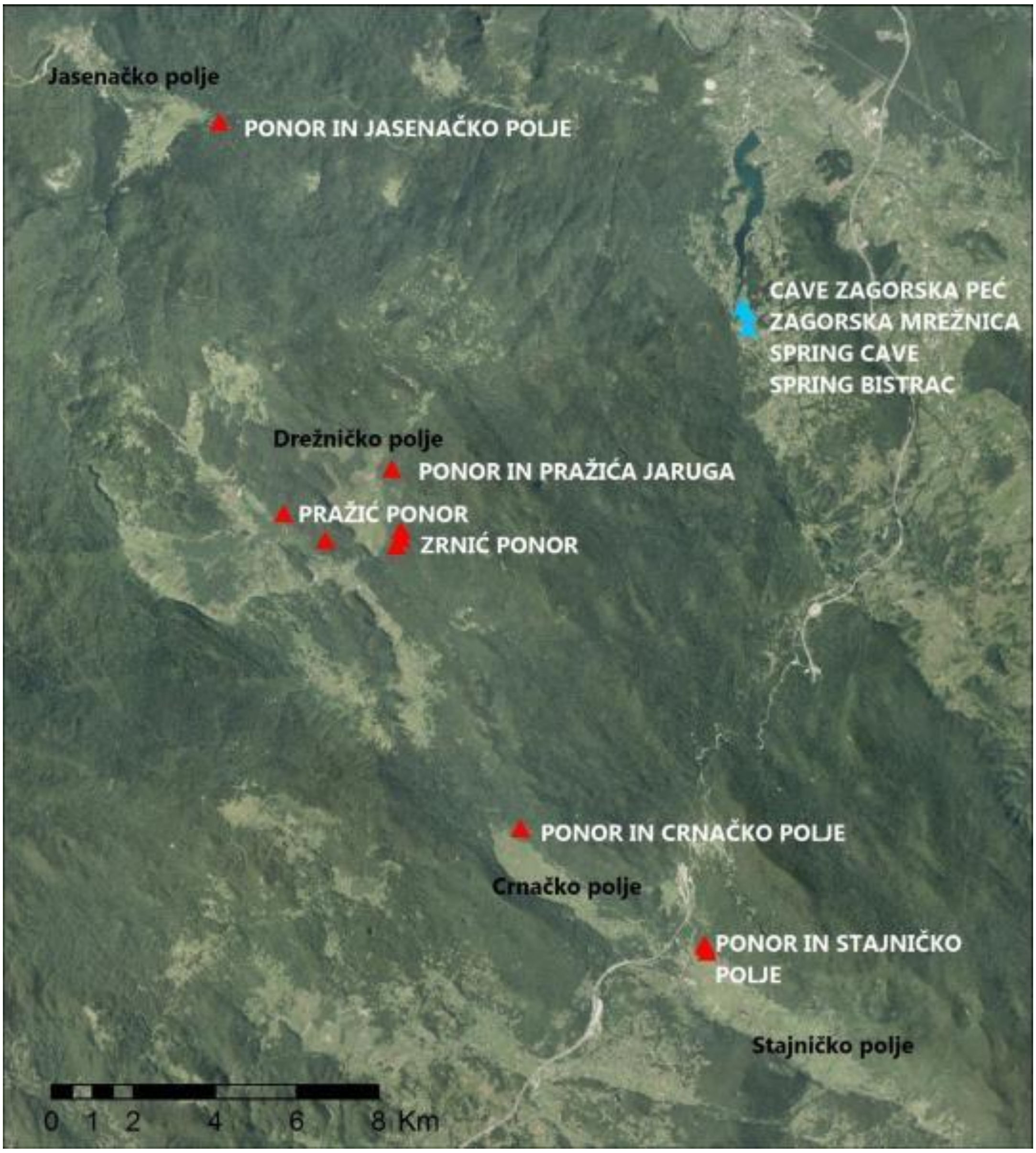


Figure 16: Ponors in which the tracing method using fluorescein was done and springs where the connection was proven.

The diffuse recharge is present through numerous dolines and karst in general in Velika Kapela Mt. area where other surface streams do not exist. The stream of Zagorska Mrežnica River was fed by three springs: Zagorska Mrežnica spring cave, Spring of Bistrac and Pećine-Veliko vrelo spring cave system (also known as Stoševo spring; Figure 16). Karst poljes form four sub-catchments: Jasenačko karst polje, Drežničko polje with Krakar polje and Drežnik Lug on the NW and Crnac polje with Stajničko polje on the SE (Figure 14, Bojanić, 1972). Based on the dye tracing it can be concluded that the conduit flow regime is dominant in the catchment area of Zagorska Mrežnica spring.

3.5 CAVES OF CATCHMENT AREA AND OGULIN ZAGORJE

In the catchment area there are 74 identified caves (Bočić et al., 2016, Basara & Cvitanović, 2012). They are mostly horizontal, short and not deep except for a few, like the pits Rokina bezdana (127 m), Dupla jama (102 m) and Vještičja jama (133 m). The smaller number of caves on this map (47) is the result of lack of data of the cave positions. Speleogenesis of caves and pits on Mt. Velika and Mala Kapela is connected to karst processes in the vadose zone, while the speleogenesis of caves and pits in karst poljes (mostly ponors) is connected to the contact between the dolomite and limestone.

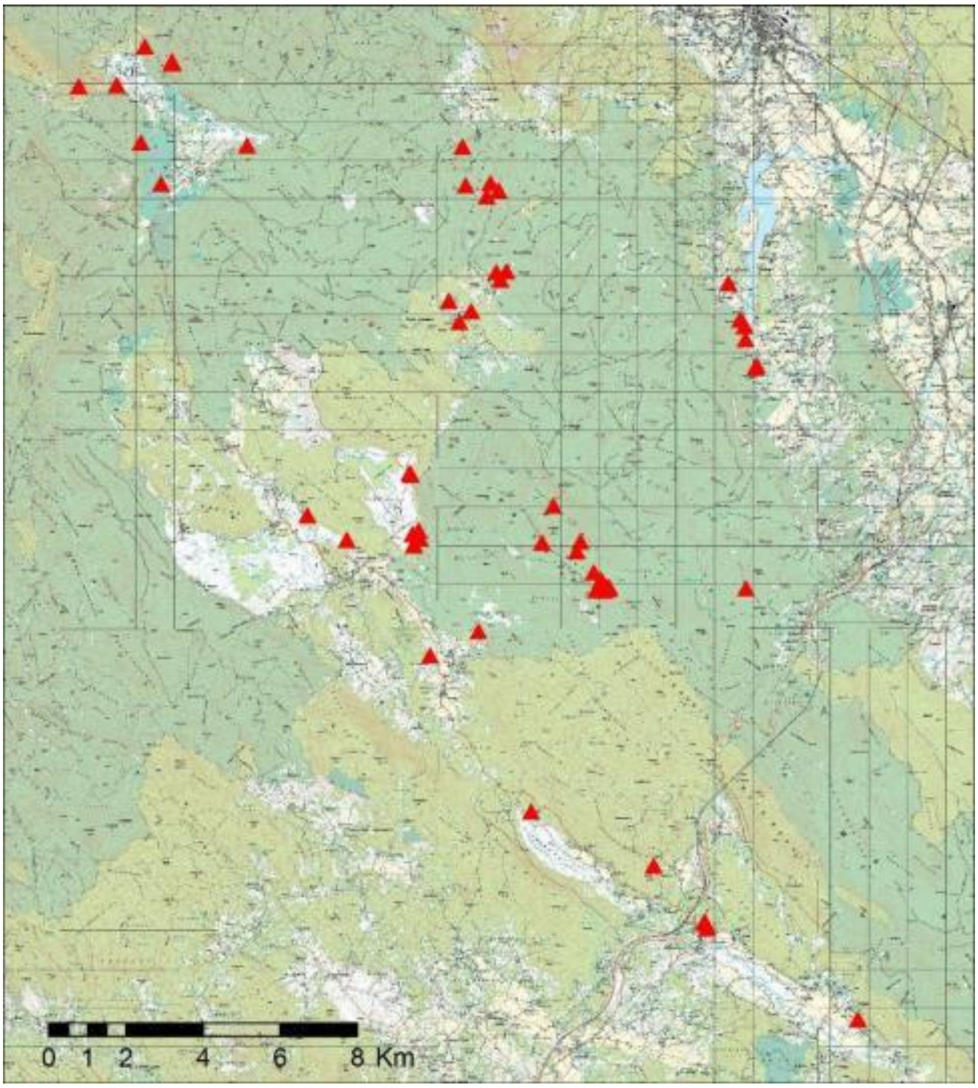


Figure 17: Red triangles represent entrances of identified caves in catchment area of Zagorska Mrežnica spring cave (Basara & Cvitanović, 2012).

The most important caves of Ogulinsko Zagorje are Zagorska Mrežnica spring cave, Zagorska Peć spring cave, Spring of Rupečica spring cave, Ponor of Rupečica, Spring of Bistrac, and the spring cave system Pecine-Veliko vrelo. The caves are aligned along the N-S direction on the west side of the accumulation Lake Sabljaci (Figure 18).

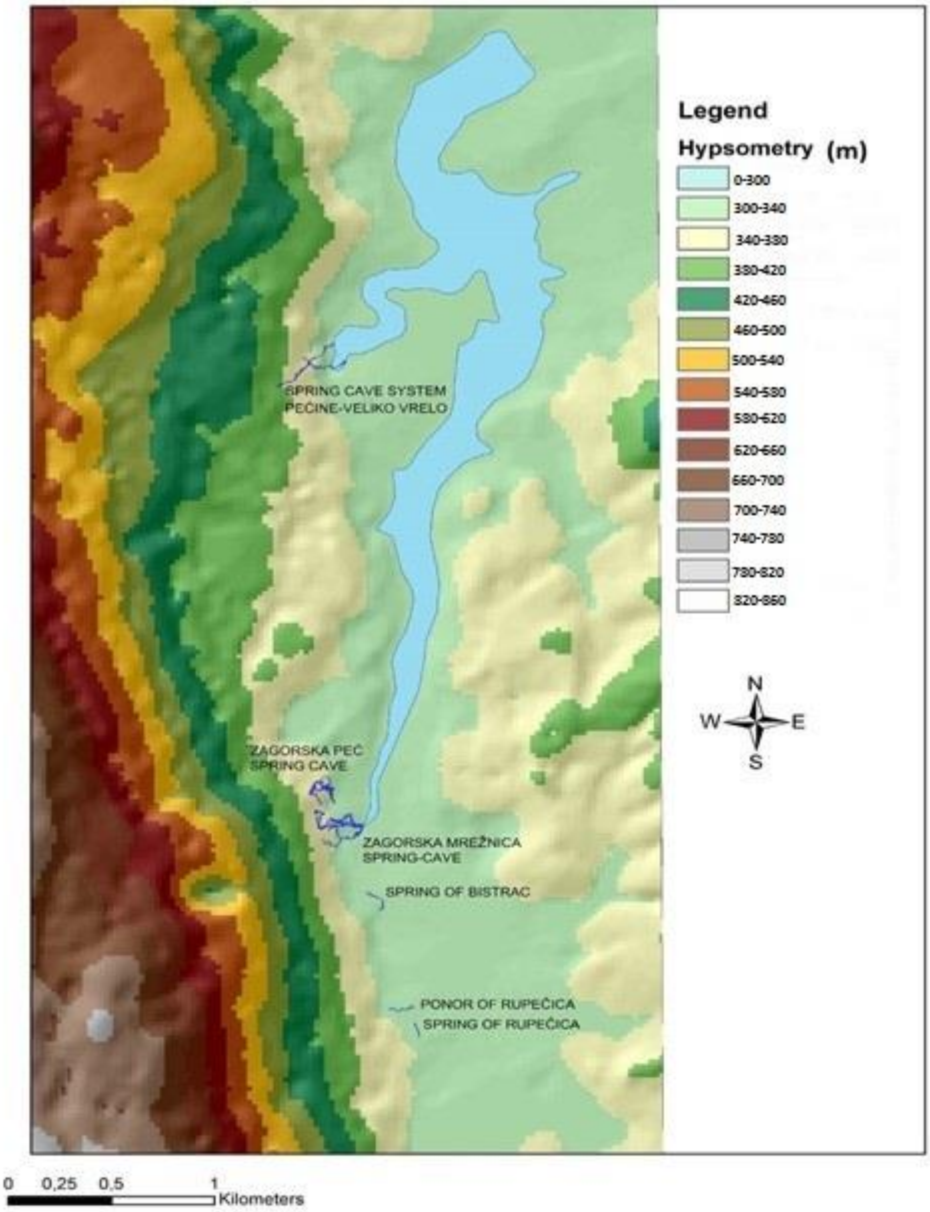


Figure 18: Cave passages on hypsometric map.

Rupečica spring cave is an 80 m long simple cave with a 30m long dry passage and a 50 m long submerged passage (Figures 18, 19). The cave consists of only one cave passage with the average cross-section dimensions of 3 × 3 m. The cave passage ends with a narrowing. In the cave passage, horizontal beds between 0.8 and 1 m thick are visible. A fault is visible at the entrance to the submerged part of the cave, where a lot of collapsed material accumulated. It has a N-S direction along which cave the passage developed. This fault is noticeable on the surface above Zagorska Mrežnica spring cave and Zagorska Peć cave. The underground stream surfaces through collapsed rock blocks at the entrance of the cave and it flows 50 m until it goes into the Ponor of Rupečica. This is a permanent spring where the water level can fluctuate up to 4 meters. According to the hydrogeological classification of Bögli (1980), this is a dammed spring where the outflow is below collapsed blocks during the dry season while during the rainy season, the outflow is through the collapsed blocks.

The Ponor of Rupečica is a 160-m long cave. It has two entrances, one horizontal that is submerged by the ponor stream of Rupečica and a vertical one (Figure 19). The cave also consists only of one passage which has maximum 22 m of depth. The passage often changes its direction, which suggests the influence of tectonics. The main cave passage ends in a chamber on the western side of which is an accumulation pile of collapsed blocks. The water from the Rupečica Ponor flows through the accumulated blocks into Šmitovo Lake, also called Zeleno jezero Lake. Zeleno jezero Lake is a flooded sinkhole probably of collapsed origin. The flow connection between Šmitovo Lake and other springs is anticipated but not confirmed as of yet.

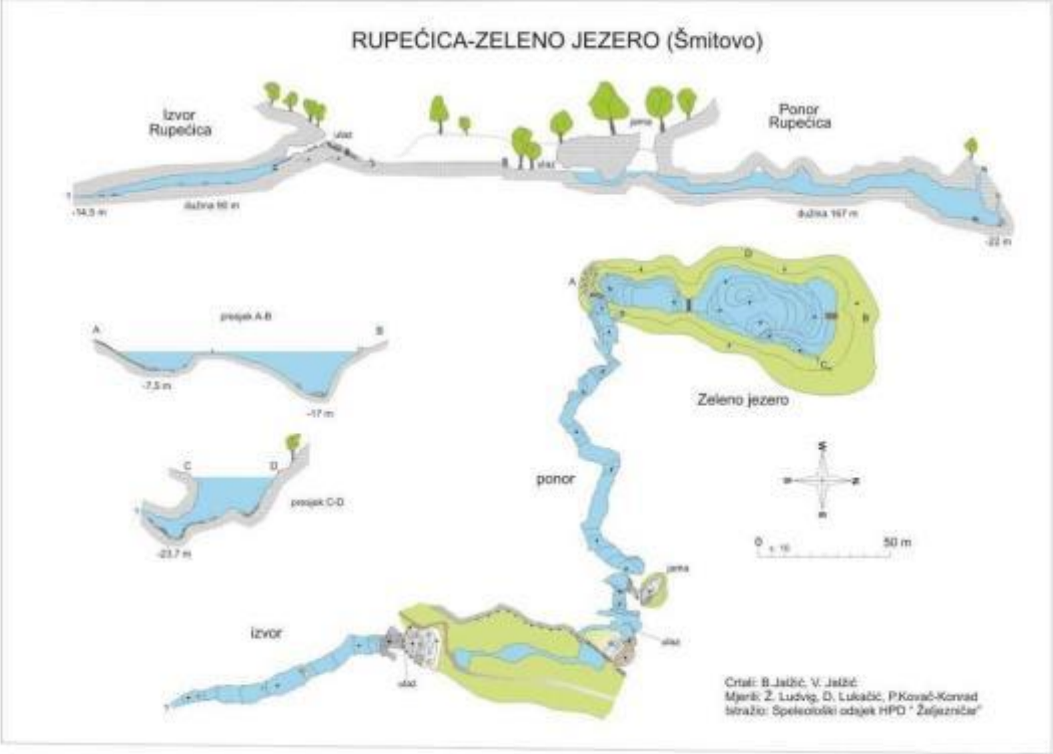


Figure 19: Cave map of Rupečica Spring and Ponor and Zeleno jezero Lake.

(Jalžić & Miculinić, 2008).

The Spring of Bistrac is situated 150 m south from the entrance to Zagorska Mrežnica spring cave (Figure 18). It has three narrow entrances between a lots of collapsed material blocks at a distance of 100 m from the entrance of Zagorska Mrežnica spring cave. Since a road passes next to the spring it is possible that the road’s construction caused the collapse. The cave passage after 100 m from the entrance continues at a depth of 45-50 m. It has a general N-S orientation and continues for another 700 m of which 200 m have been mapped. The exploration of the cave has not yet been finished. The Spring Bistrac is a permanent spring and according to the hydrogeological classification of Bögli (1980), this is also a dammed spring where tectonics caused the surfacing of underground water.

The entrance of Zagorska Peć cave is situated 130 m north of Zagorska Mrežnica spring cave (Figure 20). The cave map shows that it has branched cave passages very similar to Zagorska Mrežnica spring cave (but in smaller size and area) with a total length of 490 m and the main passage has a N-S direction. In the season of high waters during extremely long rainy periods or snow melts the cave floods and becomes an active spring. There is a lake in the cave in which a siphon is located with a depth of 122 m and it continues onwards.

Figure 20: Cave maps of Zagorska Mrežnica spring cave and cave Zagorska Peć.

Pećine-Veliko cave system vrelo consists of about 1350 m of submerged passages and around 150 m of dry passages. 725 meters of passages have been mapped. The entrance passage to Veliko vrelo is vertical and 30 meters deep. After that the passage continues horizontally at a depth of 20 m and after 200 m connects to the main passage of Pećine cave. The entrance to Pećine is at a depth of 3 m. The main passage also continues at a depth of approximately 20 m. The cave system has a fossil level of around 150 m long. The general direction of the main passage is NE-SW. The cave system is still partially unexplored (Figure 21).

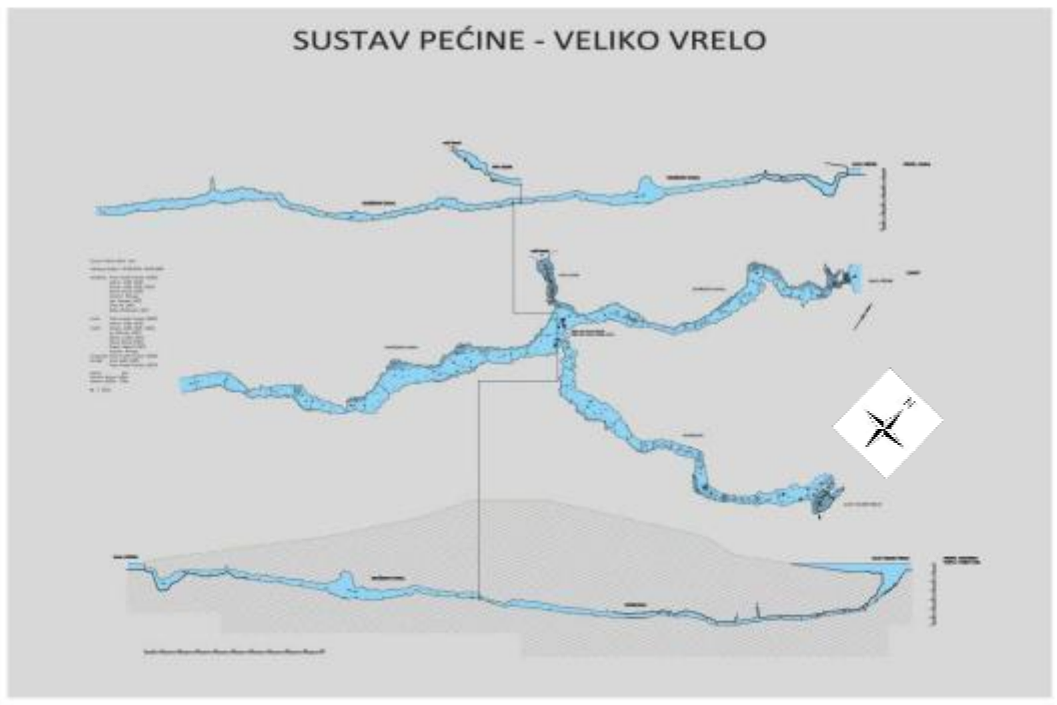


Figure 21: Map of the cave system Pećine–Veliko vrelo (Kovač Konrad, 2010).

4 METHODS

4.1 MAPPING OF THE CAVE, CONDUIT CROSS-SECTIONS, STRUCTURAL AND MICRORELIEF FORMS

To analyse the morphology of cave passages 48 cross-sections were mapped underwater. It took eight dives, two divers per dive. A 1 × 1 cm (1 × 1 m in a cave) grid was printed and laminated in a plastic sheet on an A6 paper format. The mapping was done by measuring the width and height of the cave passage every 10 meters starting from the entrance. At the points of sudden changes in morphology, a cross-section was mapped every five meters. After measuring the height and width of the cross-section, a sketch of the morphology of the cross-section was drawn on the grid. Every cross-section has a number, so it can be positioned on the cave map. After the mapping was done underwater all drawings were scanned as jpg files. Using CorelDraw X7 the cross-sections were digitised, numbered and scaled. Based on these cross-sections an interpretation of the speleogenesis and morphology of cave passages was done (Appendix IV).

The underwater cave mapping was done systematically over several years. The mapping consists of taking measurements for a plane and for a profile. Data collected for the mapping where: distance, direction, and depth of the measuring point. The distance from one point to another (the points are numbered) was measured with a measuring tape. The direction was also measured from the same points with an underwater digital compass. For the width of the cave passage, an underwater laser rangefinder for distance measuring was used. For constructing a profile of the cave, the depth was measured on the bottom and the ceiling at each measuring point. Whenever a cave passage changed in morphology, depth or direction, a measuring point was taken (Kovač-Konrad & Buzjak, 2011).

Geomorphological mapping of the cave was done by underwater mapping of macro- and micro-denudation and accumulation forms. For this purpose, sections of cave map were printed and laminated so they can be used underwater. On these cave maps, all erosional and accumulation forms were mapped. Symbols were assigned for each of the forms. Strike and dip of fissures were measured using a baseplate, a digital underwater compass, and an analogue inclinometer. All the data were written underwater. The gathered data on the cave map was scanned and vectorised in CorelDraw X7.

Pothole (cups on the rocky floor of the cave passages; Slabe, 1995) density analysis was done by underwater photography using a 1 × 1 m frame used as a grid (Figure 22). The frame was placed on the bottom of the cave passage and moved meter by meter. A photograph was taken of each frame. In each frame, the number of potholes was counted. The potholes were counted in 10 m².

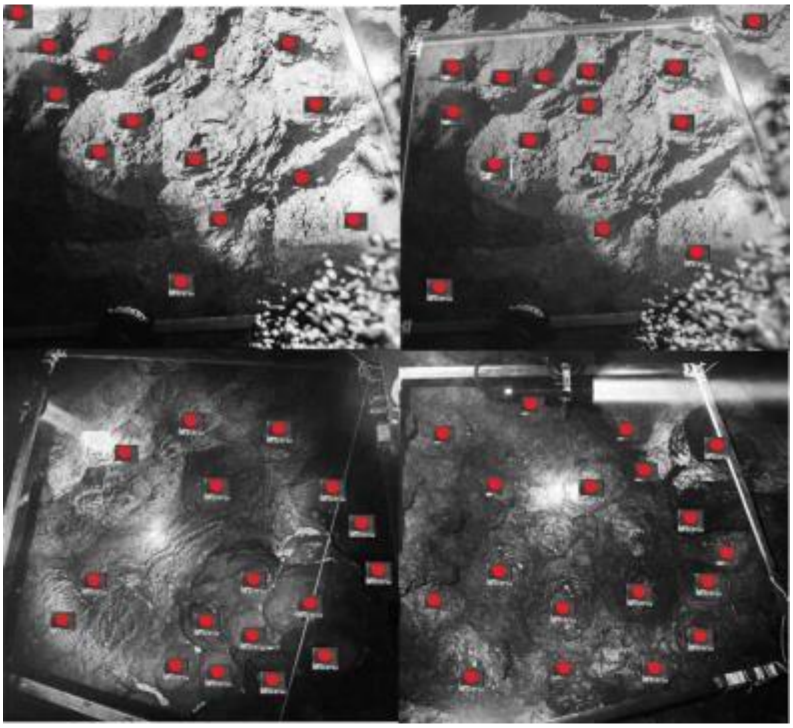


Figure 22: Counting of pothole density with a 1 × 1 m frame.

The measurement of pothole density was done in the area of the intersection of Glavni and Novi kanal passage (Figure 23). This is the part of the cave where two water flows join and a lot of turbulence is created as a result.

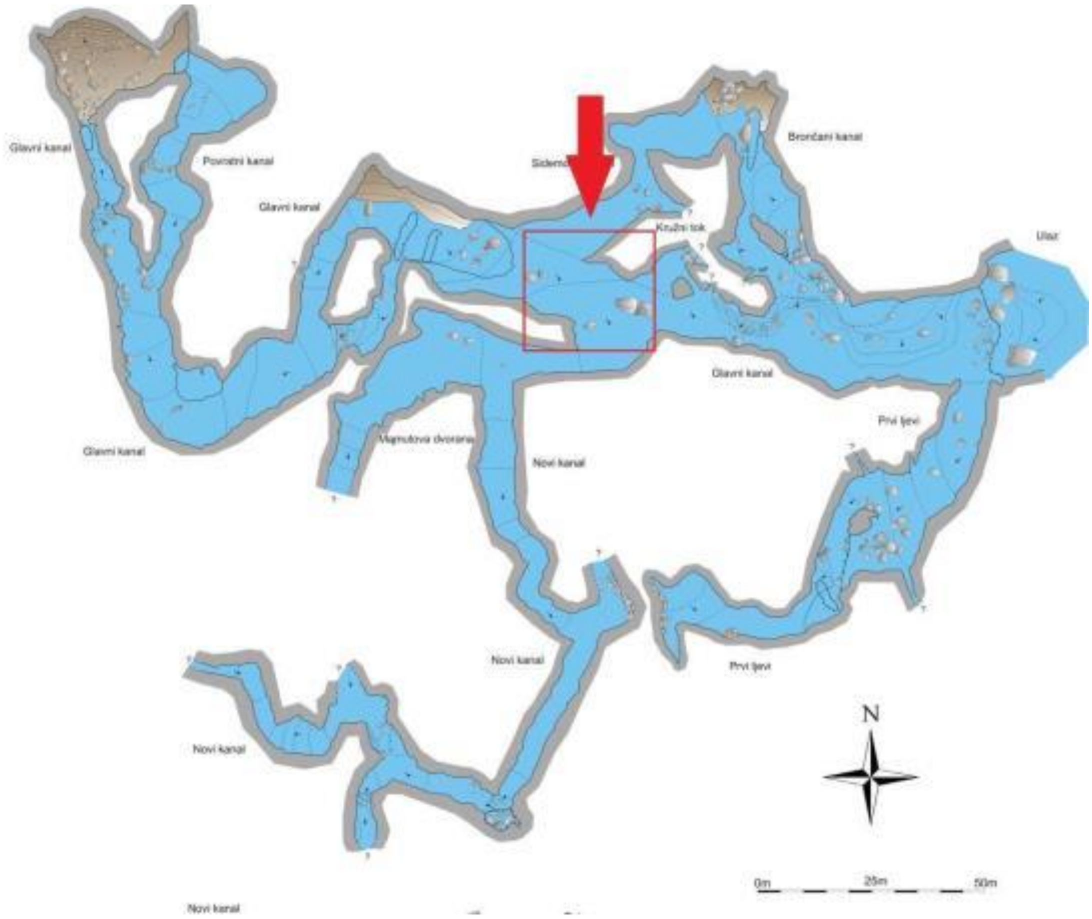


Figure 23: Positions in the cave where potholes were counted.

For the analysis of the fissure orientation, a GEO-orient program software was used to create plots and analyses of stereographic projections and rose diagrams of geological structural data. An excel table was made with the list of fissures and their orientation and then this data was transferred to the program where a rose diagram was created based on frequency and azimuth.

4.2 *GRANULOMETRIC ANALYSIS OF THE SEDIMENT*

Grain size composition of the samples collected in cave passages (Figure 24) of the sampled sediments has been determined by a combination of wet sieving using an ASTM standard sieves set on Fritsch Analysette (for particles > 63 μm) and Micromeritics sedigraph 5100 (for particles < 63 μm, Figures 21 & 22). The analysis was carried out in the Department of Geology at the Faculty of Science, University of Zagreb by dr.sc. Kristina Pikelj. A sample of 20 grams of dried sediment was sieved using the method of wet sieving through sieves with nets with 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm openings.

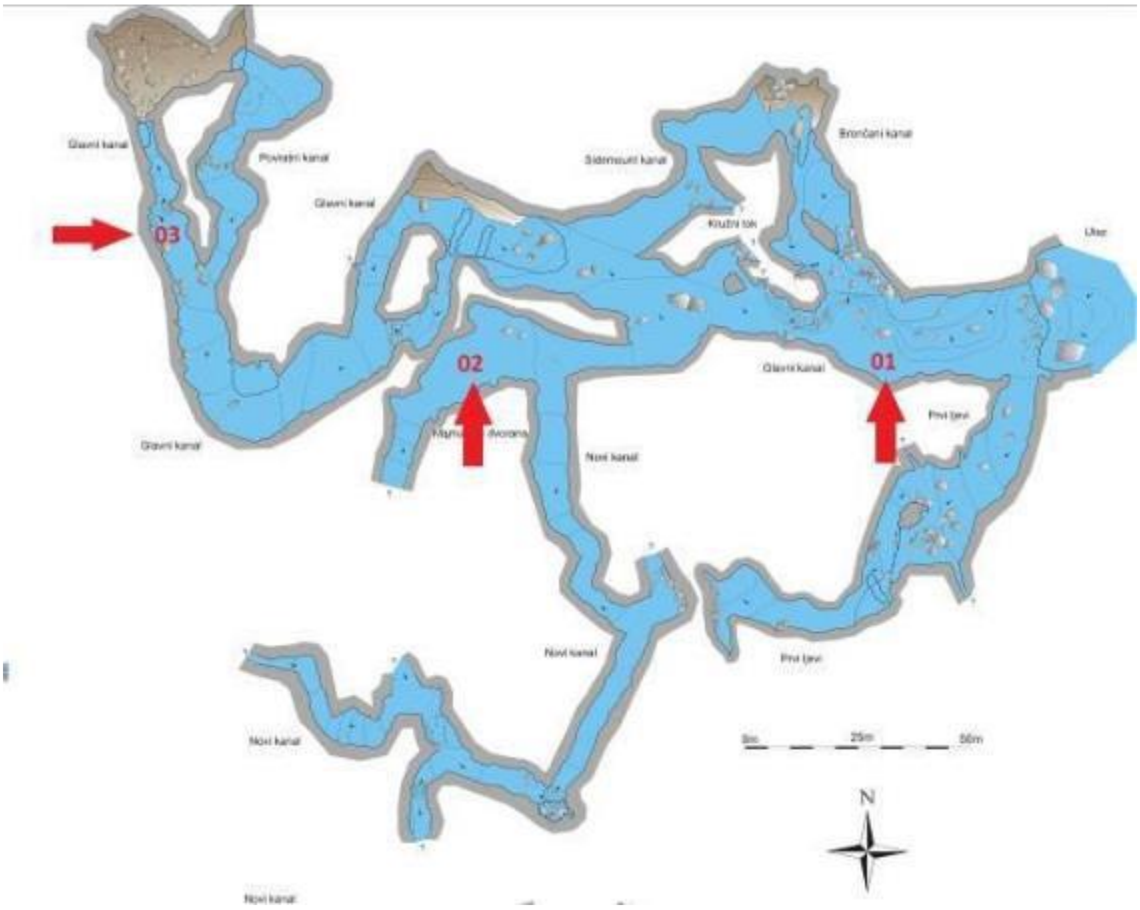


Figure 24: Sediment sampling sites.

Smaller particles were analysed on a sedigraph (Figure 25). After sieving, the fine particles in the suspension were left to settle down. After the suspension settled, the leftover water was removed and the sediment was ready for analysis. Grain size parameters were calculated arithmetically and geometrically (in microns) and logarithmically (using the phi scale) (Krumbein & Pettijohn, 1938). Linear interpolation was also used to calculate statistical parameters by the Folk & Ward (1957) graphical method and derive physical descriptions (such as “very coarse sand” and/or “moderately sorted”). The program Gradistat software also provides a physical description of the textural group which the sample belongs to and the sediment name (such as “fine gravelly coarse sand”) after Folk (1966). The results of sieving and sedigraph analysis were recalculated so that they can be analysed (Blott & Pye, 2001). The result was a percentage of grains falling into each size fraction, modified from Udden (1914) and Wentworth (1922). In terms of graphical output, the program software provides graphs of the grain size distribution and cumulative distribution of the data in both metric and phi units and displays the sample grain size on triangular diagrams.

Figure 25: SediGraph 5100 (Micromeritics Instrument Corporation).

Grain sphericity and roundness were determined on each sediment sample on 300 randomly picked grains (01/01, 01/02, 01/03, 02/01, 02/02, 02/03, 03/01). Sphericity was classified into two categories: high sphericity marked as number 1, and low sphericity marked as number 2.

According to Powers (1953), roundness can be classified into six categories: very angular was marked as number 1, angular was marked as number 2, sub-angular was marked as number 3, sub-rounded was marked as number 4, rounded was marked as number 5 and well-rounded was marked as number 6 (Figure 26).

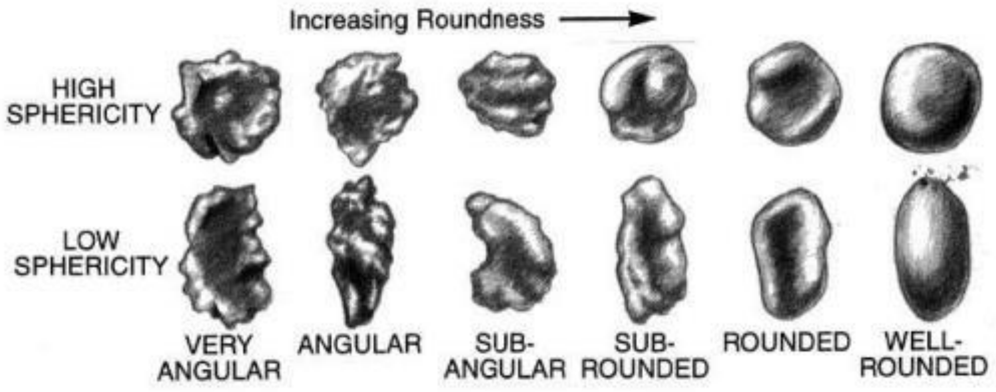


Figure 26: Categorization of sphericity and roundness (Powers, 1953).

4.3 MINERALOGICAL ANALYSIS OF THE SEDIMENT

The qualitative mineral composition of bulk sediment samples was determined using X-ray powder diffraction (XRD). A Philips X'Pert PRO powder diffractometer was employed operating at 40 mV and 40 mA. Semi-quantitative mineral abundance was determined on relative mineral peak intensities. The analysis was conducted by dr.sc. Kristina Pikelj.

A divergence slit of 1/2 and a receiving slit of 1 were used with a graphite monochromator attached in the diffracted beam path. Mineral phases in the samples were identified using the ICDD database. Relative mineral abundances were estimated by using relative intensity ratios (RIR) provided by the powder diffraction files and applying the algorithm of X'Pert HighScore Plus (Panalytical, 2004).

The two sediment samples were divided into three sections, each containing 20 × 10 cm of sediment, the third sediment sample has only one section since the deposition of the sediment was thinner.

Carbonate content was determined twice in each sample by volumetric measurement of CO_2 evolved after digestion in diluted HCl acid, using the Scheibler apparatus (Önorm 1084). Analytical precision was ±2% and the results represent the average of the two measurements.

4.4 LITHOLOGICAL ANALYSIS OF BEDROCK AND MEASUREMENT OF GEOLOGICAL STRUCTURES

The rock samples were taken from four locations in the cave (Figure 27). For identification of the rock type, seven samples were taken. Samples were taken from the bottom and the ceiling of the cave passages (samples 3-7). Sample 1 and 2 are a grain of around 5 cm from the bottom of the Glavni kanal passage. The samples were analysed in the laboratory of the Croatian

Geological Survey, Zagreb, by dr. sc. Vlatko Brčić. From the samples, petrographic samples for the microscope were made. These samples were polished into 0.2 mm thick plates which were then glued to a microscopic slide. Samples were then examined using a petrographic microscope.

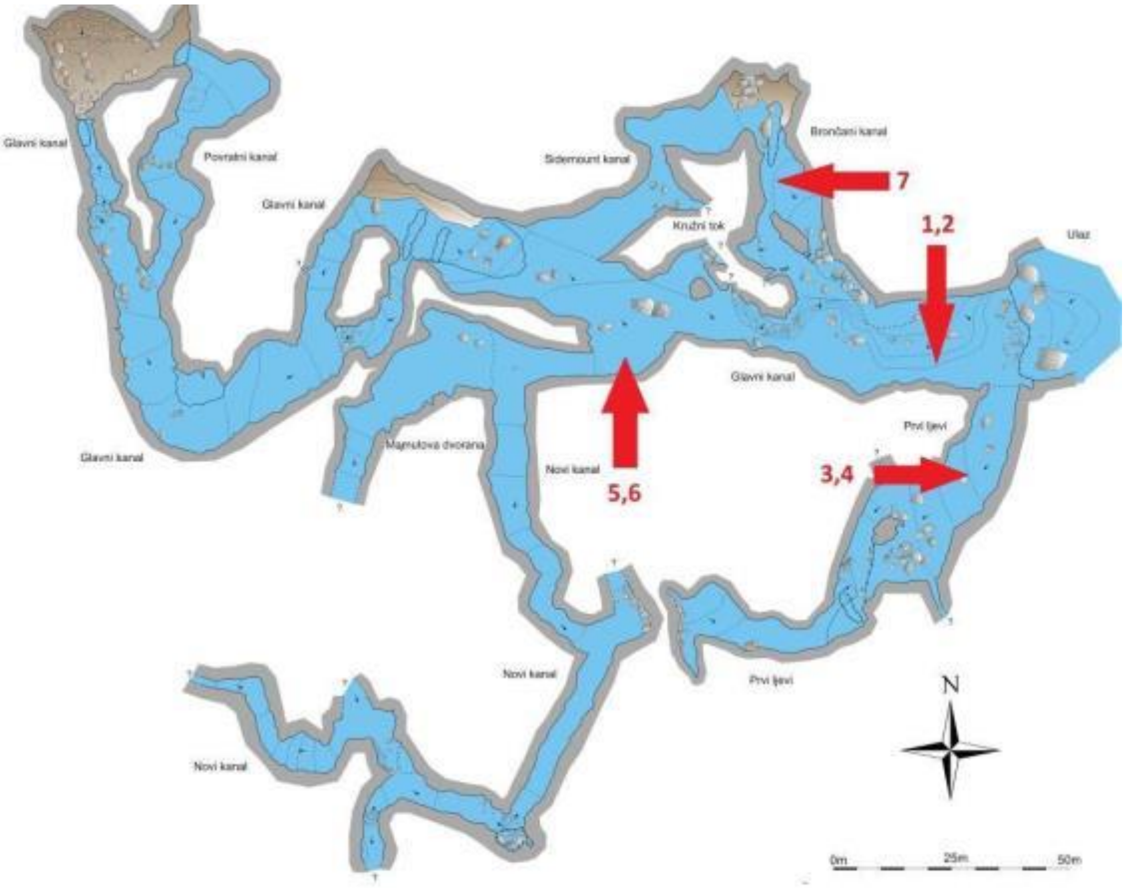


Figure 27: Rock sampling sites.

Above Zagorska Mrežnica spring cave geological samples were examined on nine localities by hand lens and tested with 10% HCl. Structural elements were measured using a geological compass (Figure 28).

Figure 28: Examination and testing of geological samples, along with rock sampling locations.

For stereographic projection, the Georient software was used. In the application, data from measured beds and faults from the surface were put in and for visualisation, a plane was chosen.

4.5 IDENTIFICATION OF THE RELATION BETWEEN PRECIPITATION AND HYDROLOGICAL ACTIVITY OF ZAGORSKA MREŽNICA SPRING CAVE

For analysis of the correlation between precipitation and the average flow of Zagorska Mrežnica spring cave a statistical t-test was used. Such a test is used to determine if two sets of data are statistically significantly different from each other. Here an amount of precipitation and the annual average flow from 1949 until 1990 and from 2009 until 2013 were used as two sets of data.

Precipitation and temperature trend analyses on different temporal scales were also done. The air temperature change was analysed from 1949 until 2013, also by the t-test. The yearly amount of precipitation was analysed to determine whether a trend is present. Most long-term climate series are affected by non-climatic factors like changes in instruments and station location, so an error can be present. For analysis of discharge trends before and after the construction of the accumulation Lake Sabljaci, several sets of data were used. The minimum, maximum and average discharges from January 1949 to October 1952 and from January 2009 to October 2012 were used. These two sets of data were compared using the t-test to determine the difference in discharge before and after the accumulation lake was built. An error may be present due to changes in instruments that gathered the data in different periods.

4.6 WATER CHEMISTRY ANALYSIS

Two water samplings were done in 2 different hydrological conditions. One sample was analysed from a period of high water on 5.10.2014 after rain event occurrence and one from a period of low water on 25.9.2014. The temperature and pH were measured on site. Krešimir Maldini carried out the water chemistry analysis at the Laboratory of Croatian Waterworks (Hrvatske vode d.o.o.).

Physical (hardness, pH, conductivity and turbidity), and chemical (cations and anions concentrations in mg/l and the presence of metals and nitrates) parameters were determined.

For the analysis of saturation index (SI), the programme Phreeqc was used (Appelo & Postma 1993; Parkhurst, Appelo & U.S. Geological Survey, 1999).

For a rough estimation of the cave wall retreat, calculation was done by fourth-order kinetics ($n = 4$, $k_n = 4 \times 10^{-8}$ mol/cm^{2}s) (Eisenlohr et al., 1999; Meteva et al., 1999).

4.7 3D MODEL OF THE ZAGORSKA MREŽNICA SPRING CAVE

For the creation of the 3D model of Zagorska Mrežnica spring cave and Zagorska Peć cave, the plane, profile and cross-section cave maps were used. They were positioned on the topographic map 1: 5000 (HOK5) using references on the map and geographic coordinates. Cave maps were vectorized in CorelDraw in DFX format. For the compilation of data, Autodesk AutoCAD (2014) was used and the file was saved in DWG format. For a three- dimensional cave passages drawing, simplified cross-sections were made in the shape of an octagon and vectorized as 3D polylines. A 3D model was made using the virtual string model technique, where a baseline is represented by octagonal cross-sections positioned along a line- cave polygon, and then connected with a “mantle” (Figure 29). The 3D digital elevation model of the surrounding relief surface area (500 × 500 m) was done by digitalization of izolines of the Croatian topographic base map 1:5000 with an equidistance of 5 m and connected with a “mantle” that represents the relief. The final model was processed using Autodesk 3ds 3D Max. The tool for taking different measurements of distances between 3D models is: »AREA>OBJECT". To calculate all distances from the surface or from one cave to another, the volume of the caves or their surface area, tools MASSPROP, SURFPATCH, 3DFACE, SCULPT, CONVTOSURFACE, UNION, and SLICE in AutoCAD were used (Figure 30).

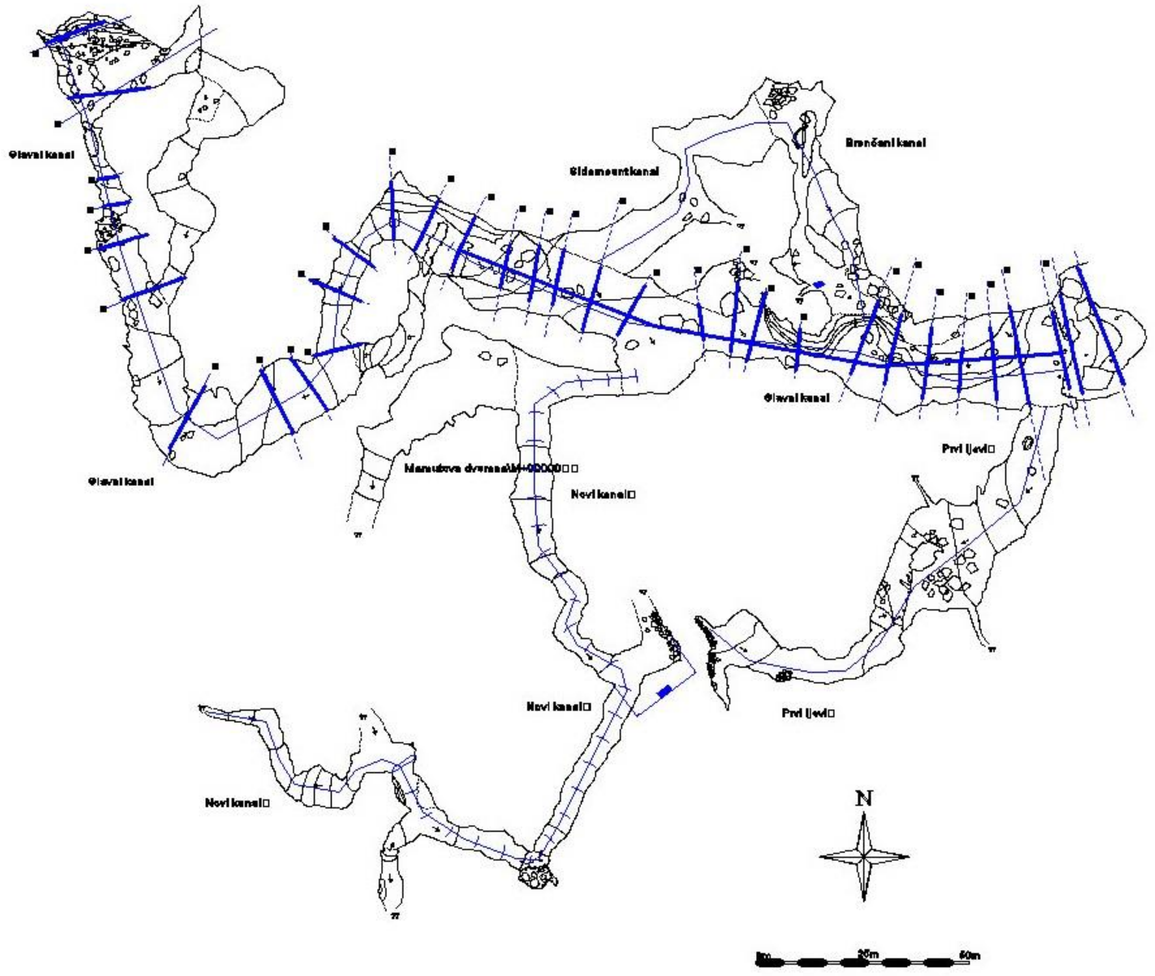


Figure 29: Positioning of octagons on a line, cave polygon for creation of the 3D model.

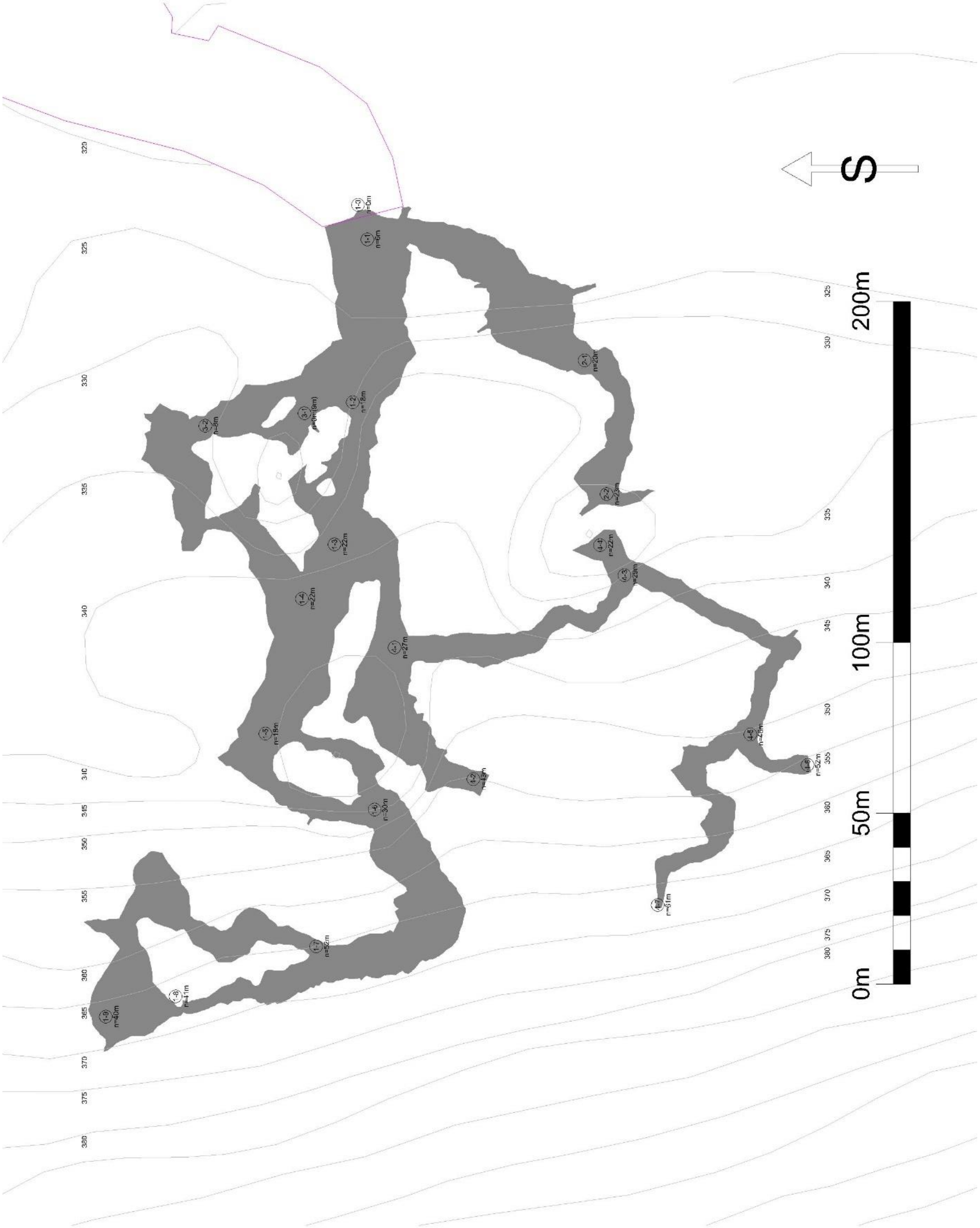


Figure 30: Points in the cave passages where distance to the surface was measured.

4.8 GEOMORPHOLOGICAL CHARACTERIZATION OF RESEARCH AREA

Hypsometric characterization was done based on the digital elevation model based on data from the 1 : 25,000 topographic maps with a resolution of 5 m. The software package used was ArcGIS. For each cell, an altitude value was assigned and based on this data an altitude histogram was developed. A hypsometric classification was done. A total of 14 classes were chosen due to large altitude differences in the study area.

Relative relief analysis was done by using the digital elevation model. The vertical dissection was calculated so that for each cell a radius of 564 m was taken (area P = 1 km^2). In this radius, the difference between the lowest and highest point is calculated (Gams et al., 1981). Four profiles of four karst poljes to Zagorska Mrežnica were made. The start of the profile was from karst poljes over Velika Kapela Mt. ending at Zagorska Mrežnica spring cave. Using the 3D analyst, the Analyst tool terrain profile was made (Figure 31).

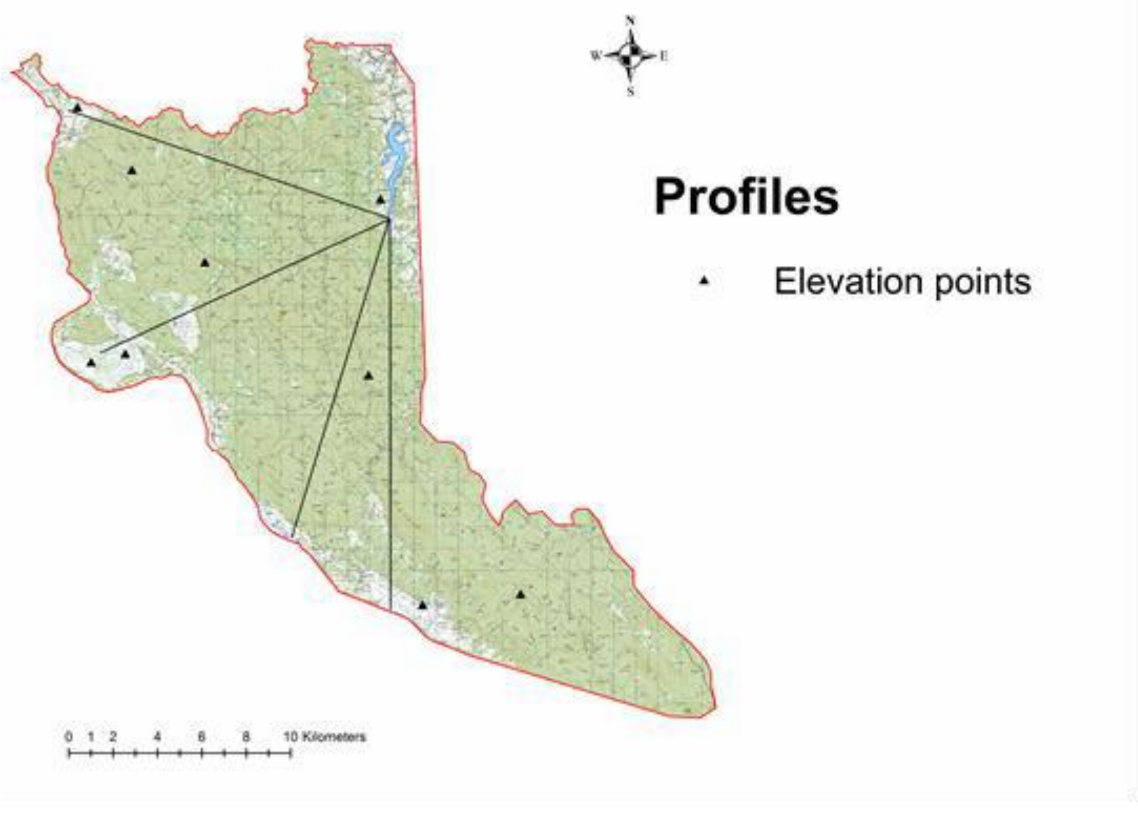


Figure 31: Directions of the profile of relief taken for analysis.

Slope inclination analysis was done using the calculation of the difference of altitude between one cell and eight neighbouring cells (Fairfield & Leymarie, 1991; Pahernik, 2005). Based on the results izolines were interpolated which separate one class from the other. A total of five classes for slope inclination were used.

The doline distribution map was done on a 1 : 25,000 topographic map by marking and digitizing each doline . A pictogram map was made according to methods described in Denizman, 2003. Based on this pictogram, a doline density map was done with the Point density tool (ArcGIS). This map was also done by classification of the number of dolines per km². Slope aspect analysis was done by classifying the orientation of the slopes using DEM.

4.9 VULNERABILITY ASSESSMENT OF THE CATCHMENT AREA OF THE SPRING OF ZAGORSKA MREŽNCA

Although the vulnerability assessment is not the main focus of this work the acquired data allows a simple vulnerability assessment. Such an assessment of this area has not been made so far. Despite that this field of research has advanced during the last 15 years, a very simple method was chosen which gives basic information for future, more elaborate works (Živanović, 2015; Marin et al., 2012). The Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia (2001) were applied. The method mainly focuses on the parameters related to the epikarst and neglects some other parameters for vulnerability such as channel conductivity, groundwater velocity etc. Not every surface or underground karst feature was classified in the GIS database by the degree of vulnerability, but the same types of features were classified together.

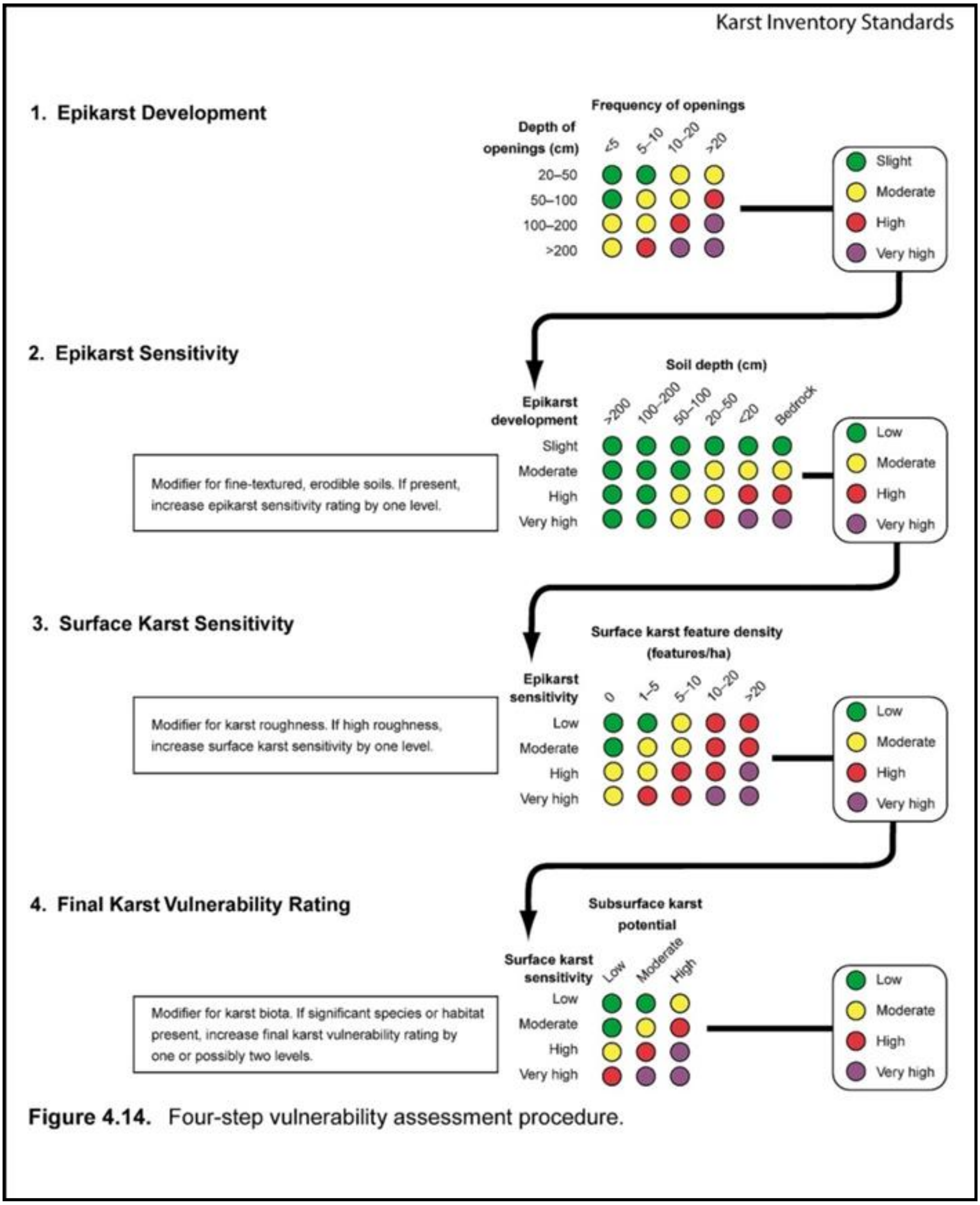
The vulnerability assessment is done in four steps (Figure 32):

Step I of the procedure considers the level of epikarst development derived from the frequency of vertical solutional openings versus their average depth to come up with a rating for epikarst development.

Step II of the procedure integrates the epikarst development rating with the average soil thickness covering the epikarst to obtain a rating for epikarst sensitivity.

Step III integrates the rating for epikarst sensitivity with the density of surface and subsurface karst features to provide a rating for surface karst sensitivity.

Step IV adds the third dimension to the karst polygon by introducing a rating for subsurface karst potential which is integrated with the rating obtained for surface karst sensitivity. If a unique or unusual habitat site for karst flora/fauna is present, the overall karst vulnerability rating is increased by one or possibly two categories.



Karst Inventory Standards

1. Epikarst Development

Depth of openings (cm)	Frequency of openings: <5	5–10	10–20	>20
20–50	🟢	🟢	🟡	🟡
50–100	🟢	🟡	🟡	🔴
100–200	🟡	🟡	🔴	🟣
>200	🟡	🔴	🟣	🟣

🟢 Slight
🟡 Moderate
🔴 High
🟣 Very high

2. Epikarst Sensitivity

Modifier for fine-textured, erodible soils. If present, increase epikarst sensitivity rating by one level.

Epikarst development	Soil depth (cm): >200	100–200	50–100	20–50	<20	Bedrock
Slight	🟢	🟢	🟢	🟢	🟢	🟢
Moderate	🟢	🟢	🟢	🟡	🟡	🟡
High	🟢	🟢	🟡	🟡	🔴	🔴
Very high	🟢	🟢	🟡	🔴	🟣	🟣

🟢 Low
🟡 Moderate
🔴 High
🟣 Very high

3. Surface Karst Sensitivity

Modifier for karst roughness. If high roughness, increase surface karst sensitivity by one level.

Epikarst sensitivity	Surface karst feature density (features/ha): 0	1–5	5–10	10–20	>20
Low	🟢	🟢	🟡	🔴	🔴
Moderate	🟢	🟡	🟡	🔴	🔴
High	🟡	🟡	🔴	🔴	🟣
Very high	🟡	🔴	🔴	🟣	🟣

🟢 Low
🟡 Moderate
🔴 High
🟣 Very high

4. Final Karst Vulnerability Rating

Modifier for karst biota. If significant species or habitat present, increase final karst vulnerability rating by one or possibly two levels.

Surface karst sensitivity	Subsurface karst potential: Low	Moderate	High
Low	🟢	🟢	🟡
Moderate	🟢	🟡	🔴
High	🟡	🔴	🟣
Very high	🔴	🟣	🟣

🟢 Low
🟡 Moderate
🔴 High
🟣 Very high

Figure 4.14. Four-step vulnerability assessment procedure.

Figure 32: 4 step vulnerability procedure (Karst Inventory Standards and Vulnerability Assessment Procedures for British Columbia, 2001).

The first step included the creation of a map with frequencies of openings (Figure 33). This included dolines and caves as negative relief forms. The methodology requires the depth of the openings. This was approximated for all openings – they were classified as deeper than 200 cm. This approximation was done because the analysis was made using 1: 25,000 topographic maps, where dolines shallower than 200 cm are not marked due to data generalization (TK 1: 25,000, Državna geodetska uprava, Desmerice 4515-2-3-2, 2000).

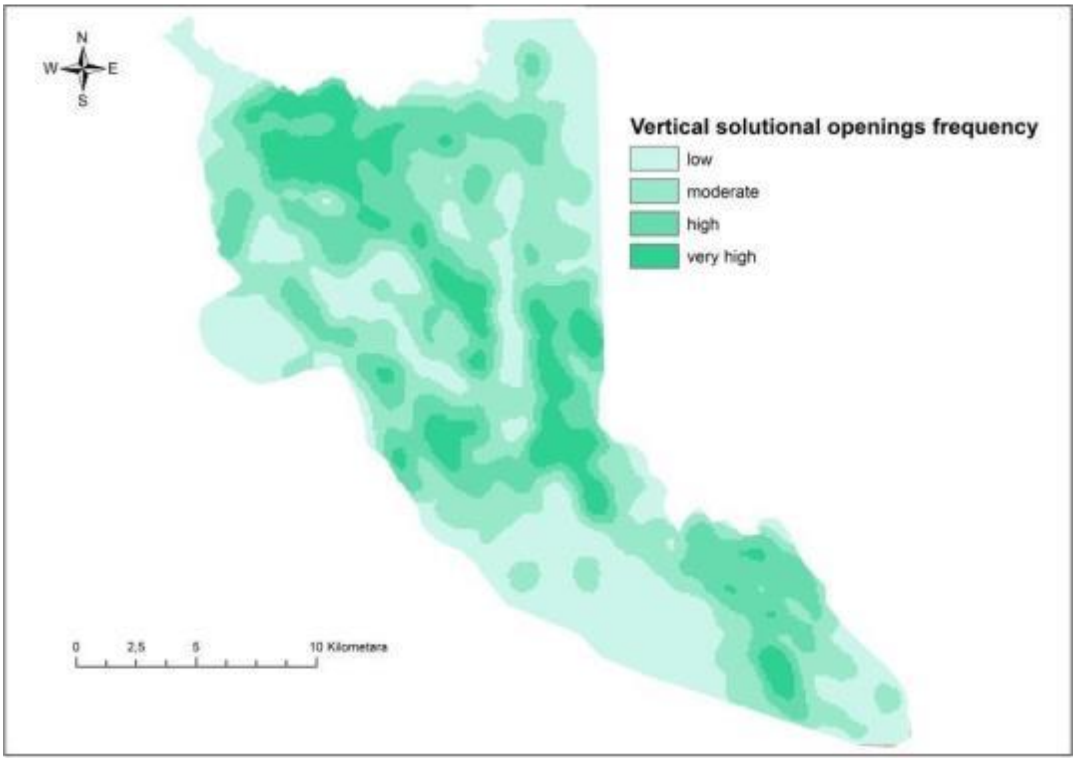


Figure 33: Map of vertical solutional openings frequency (Low < 5/km², Moderate 5-10/km², high 10-20/km², very high > 20/km²).

The Faculty of Forestry of the University of Zagreb, provided the database with soil depths (Figure 34) which was needed for the second step. This included the creation of a map that determined the vulnerability in regard to soil depth (Figure 35). For the research area, only 10 samples were taken. The depth of soils was related to the inclination of the terrain, and for most samples it showed that more flat terrain like karst poljes and uvalas have the deepest soil depth (> 100 cm) and steep slopes have the least soil depth (< 20 cm). This related to most of the samples, only 2 out of 10 showed larger soil depths on steeper slopes. Since no other data was available, the assumption was made that slope depth is related to slope inclination (Figure 35).

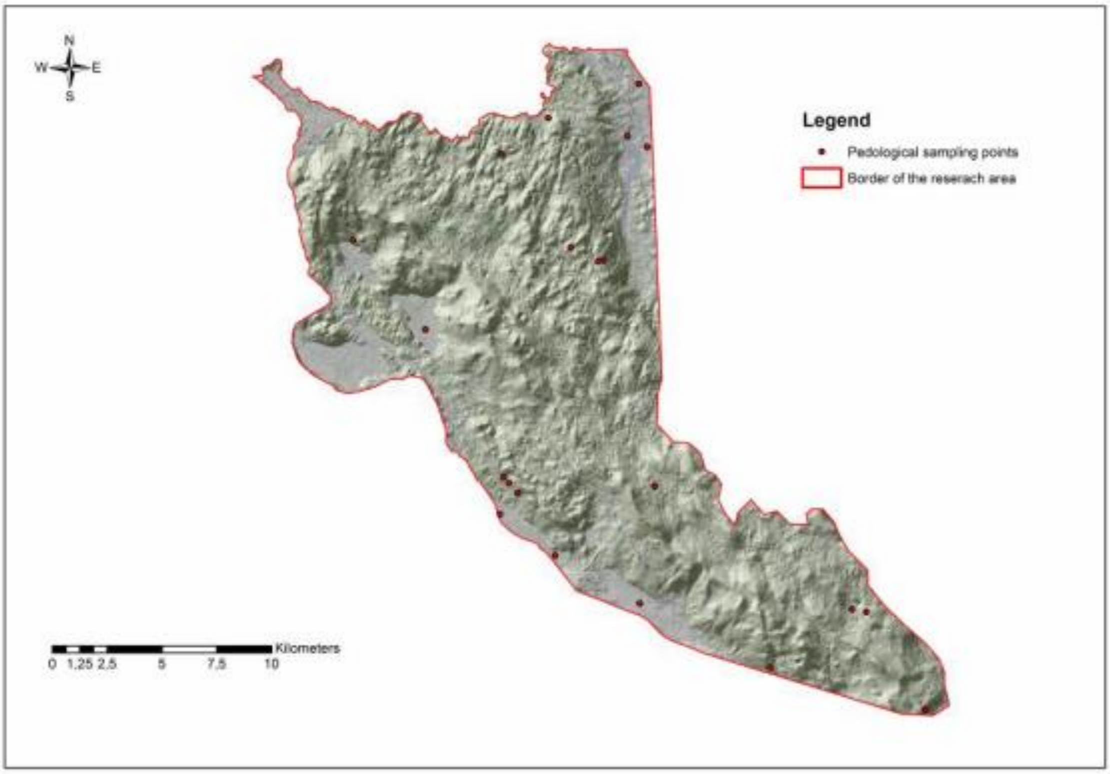


Figure 34: Positions of the soil depth measurements.

The third step included the creation of the surface karst feature density map. For this karst poljes, uvalas, dolines, caves, springs and ponors were counted per km^2 (Figure 36).

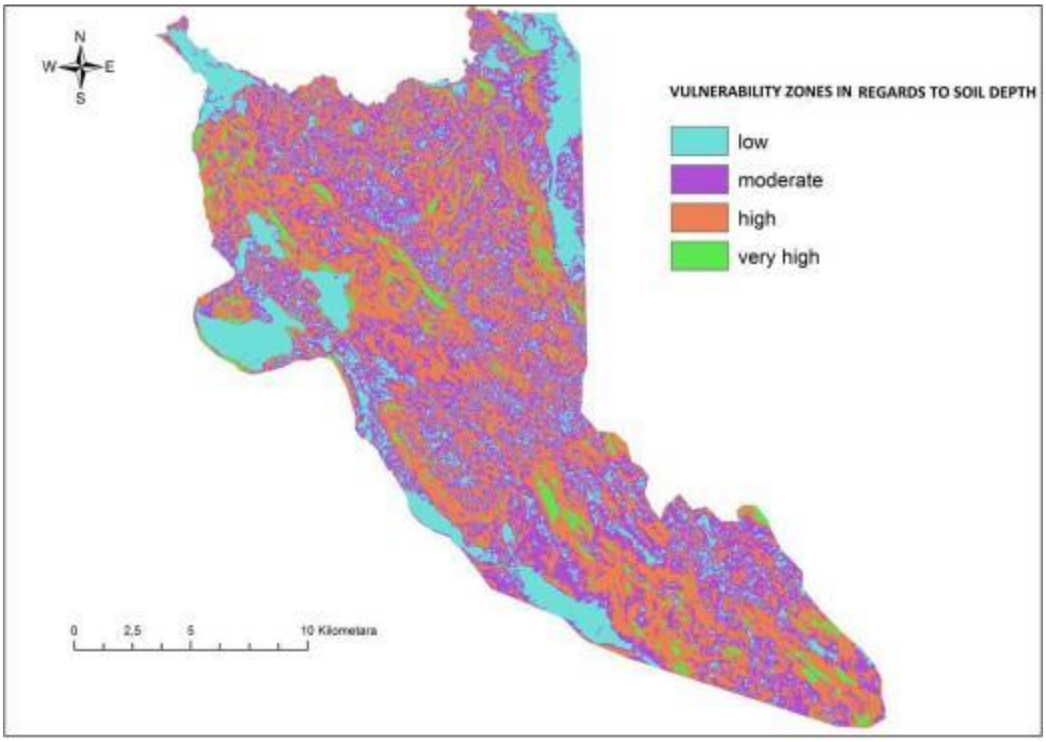


Figure 35: Map of vulnerability zones in relation to soil depth (Low vulnerability > 100 cm soil depth, moderate vulnerability 50-100 cm soil depth, high vulnerability 20-50 cm soil depth, very high vulnerability 0-20 cm soil depth

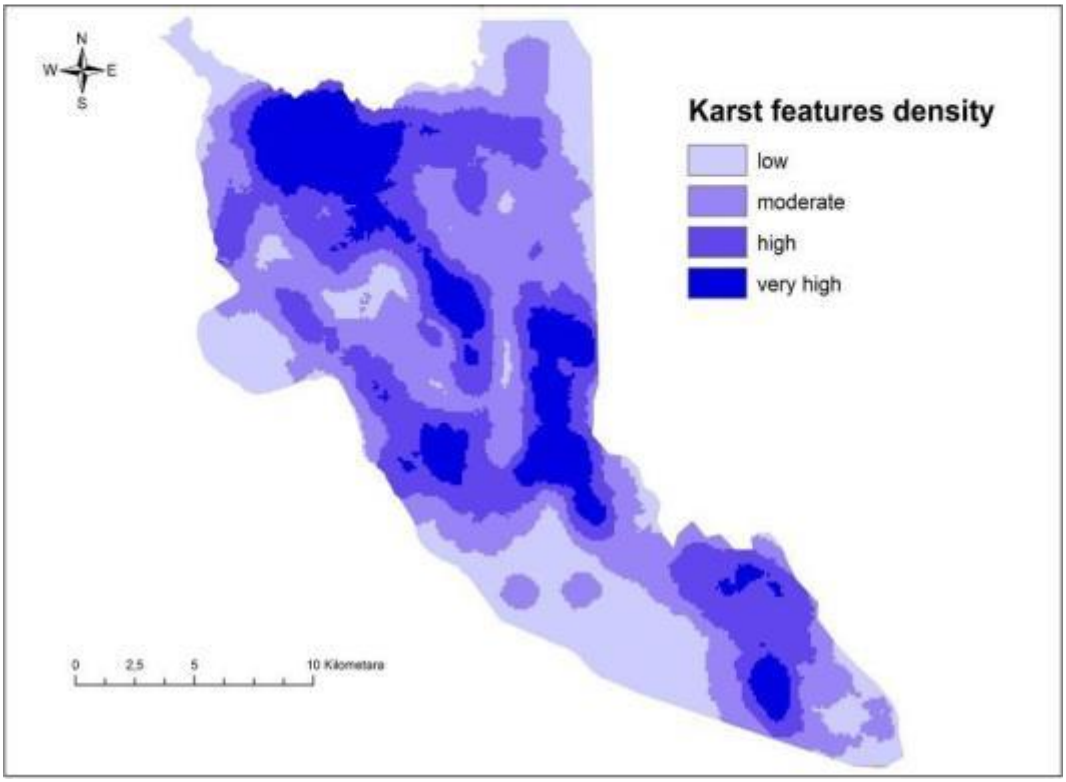


Figure 36: Map of karst feature densities (low 1-5 m²/km², moderate 5-10 m²/km², high10-20 m²/km², very high > 20 m²/km².

The fourth step takes into account unique habitats or species. The Natura 2000 areas cover most of the research area, so the polygons that mark Natura 2000 sites were added as a layer (Table 1).

Table 1. Natura 2000 sites in the Research area (www.dzzp.hr)

FID	SITECODE	SITENAME
144	HR20001295	JEZERANE
245	HR2000609	DOLINA DRETULJE
312	HR2000591	KLEK
396	HR2000645	BJELOLASICA
433	HR2000634	STAJNIČKO POLJE
441	HR2000019	GORSKI KOTAR I LIKA
507	HR2000592	OGULINSKO-PLAŠĆANSKO PODRUČJE
527	HR2000594	PRIVREMENO JEZERO BLATA
528	HR2000633	CRNAČKO POLJE
541	HR2000646	PILJE LUG
542	HR2000648	DREŽNIČKO POLJE
567	HR2000652	JASENAČKO POLJE
611	HR2000078	LUŠKA ŠPILJA
662	HR2001156	ŠPILJA POD MAČKOVOM DRAGOM
687	HR2001126	ROKINA BEZDANA
688	HR2001127	MARKAROVA ŠPILJA

For each map, four classes were added: Low, Moderate, High and Very high with values assigned to them. Each map was then converted to Integer raster data so that the maps could have the same values. Then with a Calculate statistics tool, each raster was converted to numerical values. With this, each class became a mathematical value built into a raster. With the Weight overlay tool, a mathematical analysis of values was done. In this procedure, each raster can be ranked by impact, and for this analysis, the rasters were ranked equally. The result of the geostatistical analysis is the karst vulnerability map.

5 RESULTS

5.1 CHARACTERISTICS OF THE KARST LANDSCAPE OF THE CATCHMENT AREA

5.1.1 HYPSOMETRIC CHARACTERISTICS OF THE STUDY AREA

The flat parts of the study area are karst poljes on the west side of Velika Kapela Mt. and Ogulin Zagorje on the east side. The karst poljes on the west side of Velika Kapela Mt. have an average elevation of 400-500 m a.s.l. and the Ogulin Zagorje has an average altitude of 300 m a.s.l. The highest elevation category is Velika Kapela Mt. (Velika Kapela 1534 m a.s.l., Mala Kapela 1279 m a.s.l. Figure 32). The Jasenačko karst polje to the north has the highest elevation of the rest of the karst poljes (600-700 m a.s.l.). The highest ridges (1000-1400 m a.s.l.) have a Dinaric orientation as do the lowest regions on the western side (300-500 m a.s.l.). Both of the areas' elevations are dependent on the tectonic uplift of Velika Kapela Mt. which is a result of the convergent boundary between Adriatic Plate and the Eurasian Plate. The main faults that determine the geomorphological structure are the Idrija– Čabar–Ogulin–Bihać and Velebit Faults. They have a NW-SE orientation and are parallel to each other (Bognar et al., 2012).

The spatial distribution and orientation of hypsometric classes reflect neotectonic movements and geomorphological evolution. On the east side of the study area, the west coast of the accumulation Lake Sabljaci from the Gavranka ridge and Paljevineto village Ivanci, hypsometric classes are elongated in a N-S direction, which suggests a staircase structure caused by parallel faults (see Appendix V). The two main faults have been identified in that area, the reverse fault Zagorje-Modruš and two parallel thrust fronts show the same position and elongation direction as hypsometric classes (Velić et al., 1980b). The result of these parallel faults in the south part of accumulation Lake Sabljaci is horst as an isolated group of the hills. The elongated hypsometric classes are even more visible on the SW side of Velika Kapela Mt. The orientation of elongated hypsometric classes is also NW-SE (Crnačka kosa, Brezovača and Bijela kosa). They are the result of the large Drežničko-Stajnički fault and probably several parallel smaller faults.

The dominant orientation of the landscape evolution and evolution of karst features is similar to the orientation of structures along which cave passages developed (see Chapter 5.3.). Both surface and subsurface forms have a general NW-SE orientation; but due to neotectonic movements they partially changed their orientation to N-S and NE-SW. A detailed study of speleological objects is needed.

5.1.2 SLOPE INCLINATION ANALYSIS

Erosional processes, such as mass wasting, slope wash, and fluvial activity are present in the research area and they are faster than weathering (soil-forming) processes (Chandler, 1977). Slopes in research area are steep and have a thin layer of soil. This situation is visible in ridges surrounding the karst poljes and in the numerous sinkholes on Velika Kapela Mt.

In the map of slope inclination, an IGU classification has been used that describes seven classes (IGU, 1968, Table 2).

Table 2. Slope inclination classification (IGU,1968).

Angle	Description
0°-2°	Plain
2°-5°	gently inclined
5°-12°	strongly inclined
12°-20°	Steep
20°-45°	very steep
45°-55°	precipitous
55° and greater	Vertical

The map shows the highest slope inclinations on mountain ridges of Velika Kapela. These slopes mark the main geological structures and have a Dinaric orientation. The lowest inclinations are detected in karst poljes that are of depositional origin. The karst poljes are generally surrounded by slopes of higher inclination and the processes of mass movement, terrace formation, slope wash and subsurface water action transport the material into karst poljes that function as depositional regions where colluvium forms. A higher slope inclination is also visible in sinkholes that have a high density between the ridges of Velika Kapela Mt.

The steepest slope classes are also orientated NW-SE and are elongated along the highest hypsometric classes. The parallel structures are concordant with geological structural elements. The map of slope inclination shows (Figure 37) on the west side the highest class in concordance with the Drežničko-Stajnički fault, the central part of the study area shows the steepest inclination on the western part of the Jasenak–Modruš anticline and the NE area has the steepest inclination in the area of Medveljača, Doli, Strane, Paljevine and Pleća as a result of the Zagorska thrust.

In the central south part of the area of the hills Makovnik, Nos Kapele, Visoki vrh and Mala Kapela the highest classes of slope inclination are also present. The SE part of the study area, shows the highest inclination in the area of the hills Markovac, Siminovac, Veliki Javornik, Veliki Lisac and Savića paljevina also elongated in the direction of NW-SE.

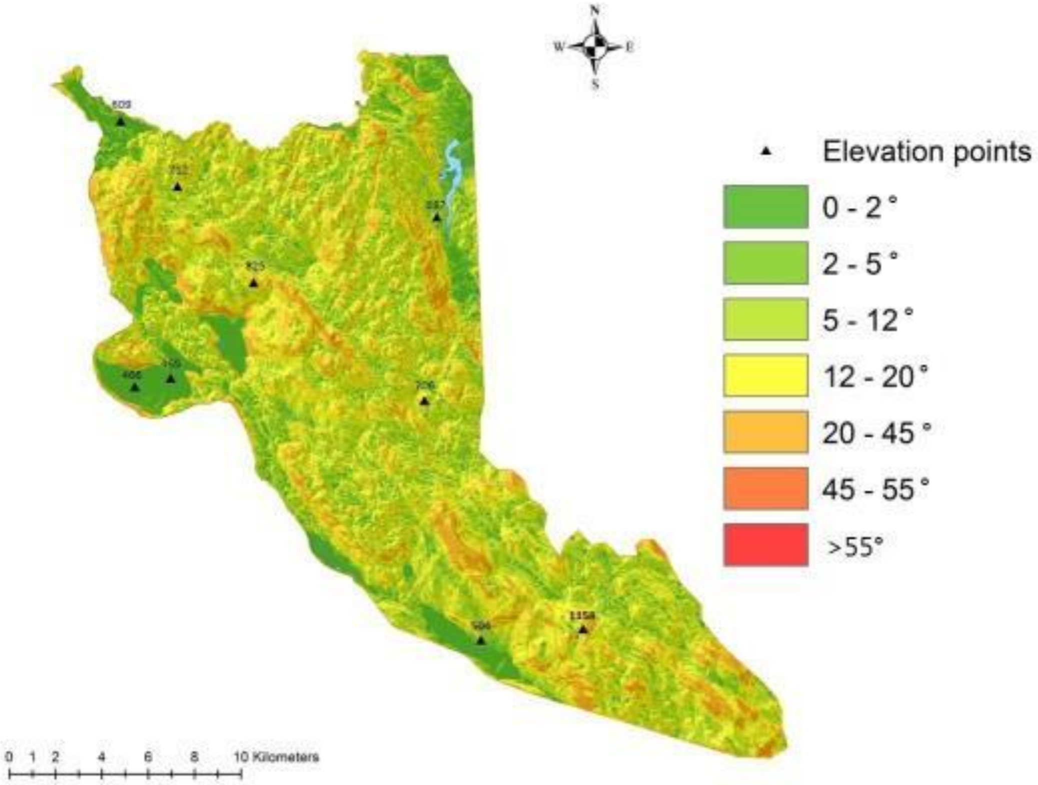


Figure 37: Map of slope inclination of the catchment area of Zagorska Mrežnica spring cave.

5.1.3 RELATIVE RELIEF ANALYSIS

Relative relief is the numerical relief parameter determined by altitude differences between the lowest and highest points within 1 km². It is an indicator of morphogenetic and structural characteristics of the study area. Six classes were chosen for the analysis and they showed that the lowest values are held by karst poljes as flat surfaces and distinctly dissected terrain (Lozić, 1995). The highest category of classification is the result of tectonic and denudation processes. The intensity of soil erosion is higher, which means faster diffuse water infiltration into the underground. In the areas of low energy, like karst poljes and Ogulinsko Zagorje, accumulation processes of denudated material are more intense. The map shows that parallel structures are again orientated NW-SE, except for a discontinuity visible in the central part of the map, between Jezerane-Modruš orientated W-E. This is a result of movements connected to the Idrija–Čabar–Ogulin–Bihać fault (Lozić 1995, Figure 34).

The highest classes of relative relief are concordant with the highest hypsometric classes. Higher classes include also elongated areas of anticlines, while synclinal areas have lower relative relief (Figure 38).

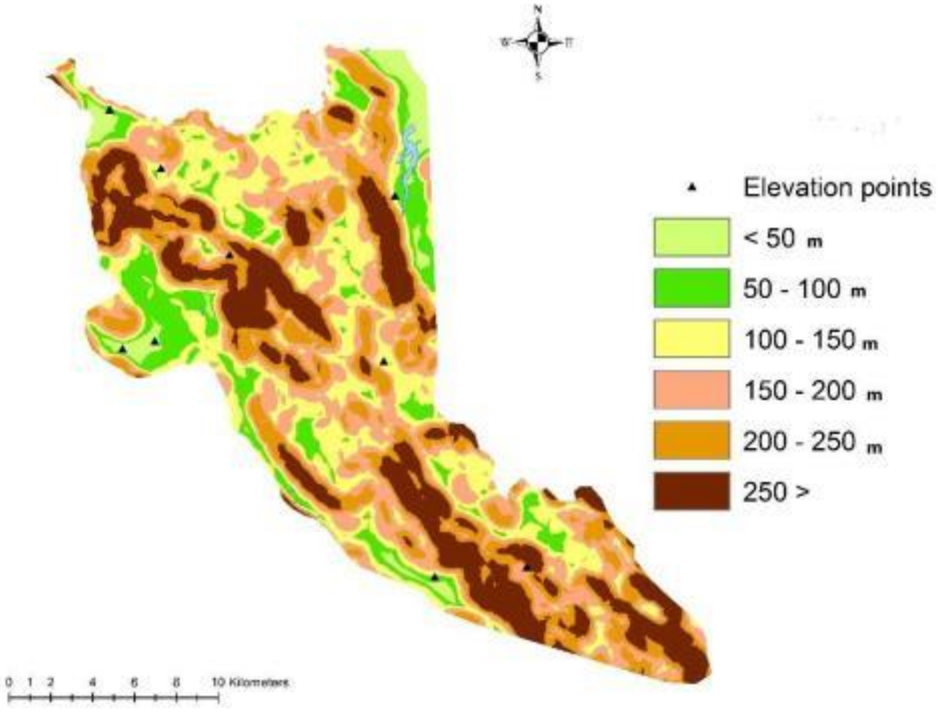


Figure 38: Relative relief map of the research area.

High relative relief is a sign of younger (or more recent) tectonic movements (Lozić, 1995).

5.1.4 DOLINE DISTRIBUTION ANALYSIS

The development of dolines is connected to the geological composition and structures, geomorphological evolution and denudation in general, bedrock breakdown, secondary porosity, and lithology. The morphology of dolines in high altitudes can also be dependent on Pleistocene glacial and periglacial processes (Šušteršič, 1994). Recent research also shows a strong connection between faults and other recent deformations of geological structures and the distribution of dolines (Faivre & Reiffsteck, 1999a). Zones of high doline density are elongated N-S on the east side of the research area. The north central areas show random distribution but the influence of faults is also visible (Figure 39).

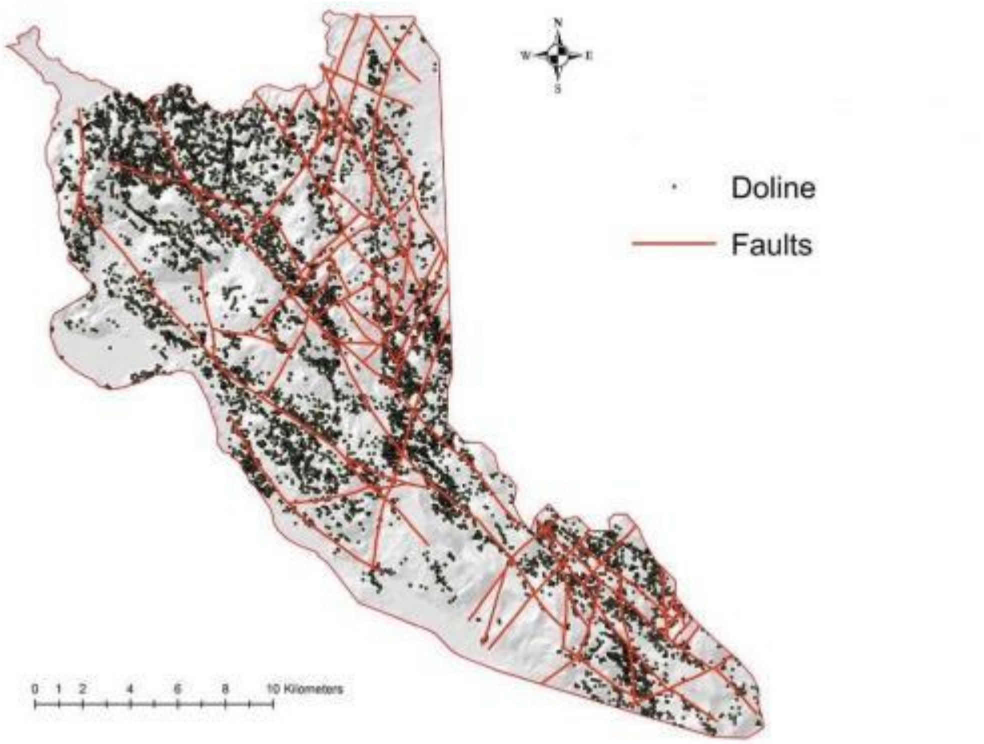


Figure 39: Map of doline distribution with position of the main faults (Velić et al., 1980a, 1980b).

Some NW-SE orientation on the western side of the study area is noticed and can be correlated to the position of the Stajničko-Drežnički Fault. However, generally, the dolines are denser in steep slopes of higher hypsometric classes than on the low flat hypsometric classes. So in karst poljes, and other flat areas, dolines are scattered, without orientation and rare. High doline distribution and linear orientation are usually associated with „older“ faults and neotectonic movements result in a random or partly random, partly linear, not-so-dense doline distribution (Pahernik, 2000). This interpretation only partially explains the doline distribution in the study area. The clustered distribution along the eastern side of the study area suggests that lithology also has a significant impact. The zone of thrust front and contact of limestone and dolomite, combined with several sets of parallel transverse faults resulted in the zones of highest doline density (Figure 40).

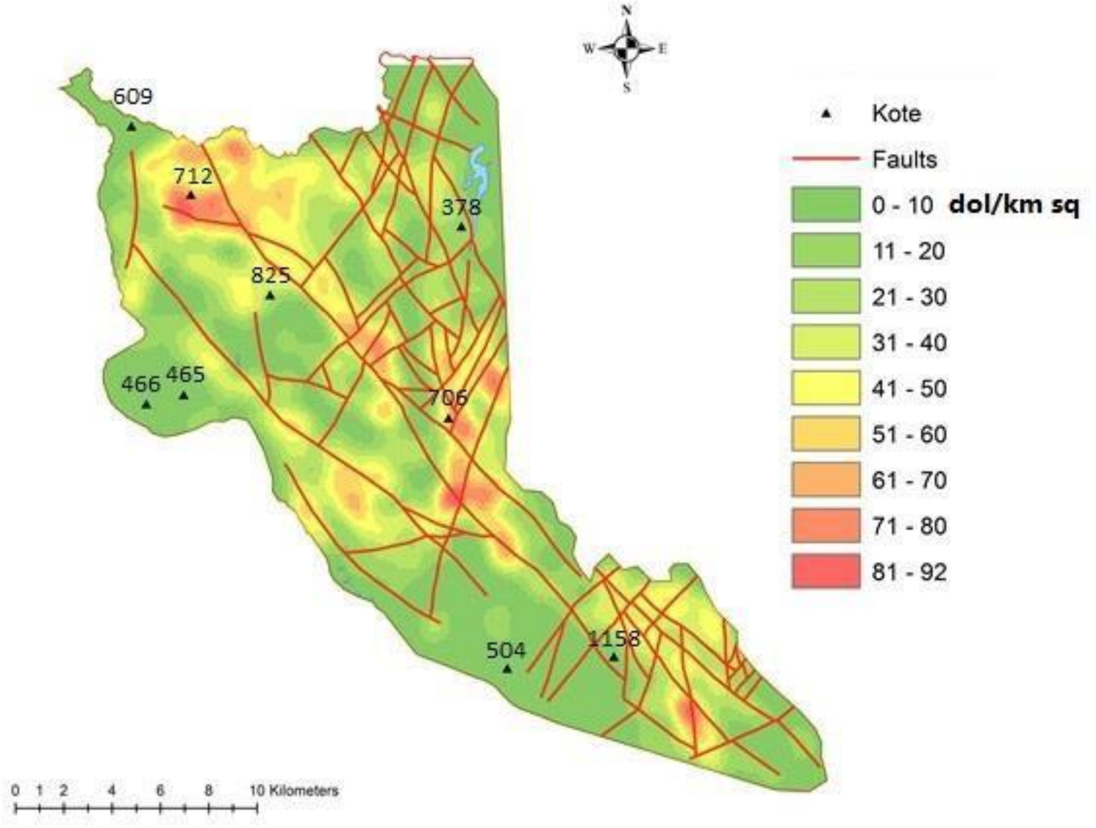


Figure 40: Map of doline density with positions of the main faults (Velić et al., 1980a, 1980b).

5.2 LITHOLOGICAL AND STRUCTURAL CONTROLS OF CAVE DEVELOPMENT

5.2.1 MEZOMORPHOLOGICAL ANALYSIS OF ZAGORSKA MREŽNICA SPRING CAVE

The Zagorska Mrežnica spring cave is 1,134 m long and 22 m deep. The longest passage is Glavni kanal which ends with a large dry chamber (Figure 41, Table 3). The length of Glavni kanal passage is 407 m and it is the widest passage with the strongest water flow in the system. The continuation of the submerged part of the cave system continues through a very narrow N-S oriented passage with a very strong water flow. The dry chamber on its west side has a visible fault plane and a pile of collapsed material originating from the ceiling breakdown in the northern part. The rest of the passages are tributary and they converge with Glavni kanal. The width and the length of the other passages are smaller and they have a role of infeeders to the Glavni kanal passage (Table 41).

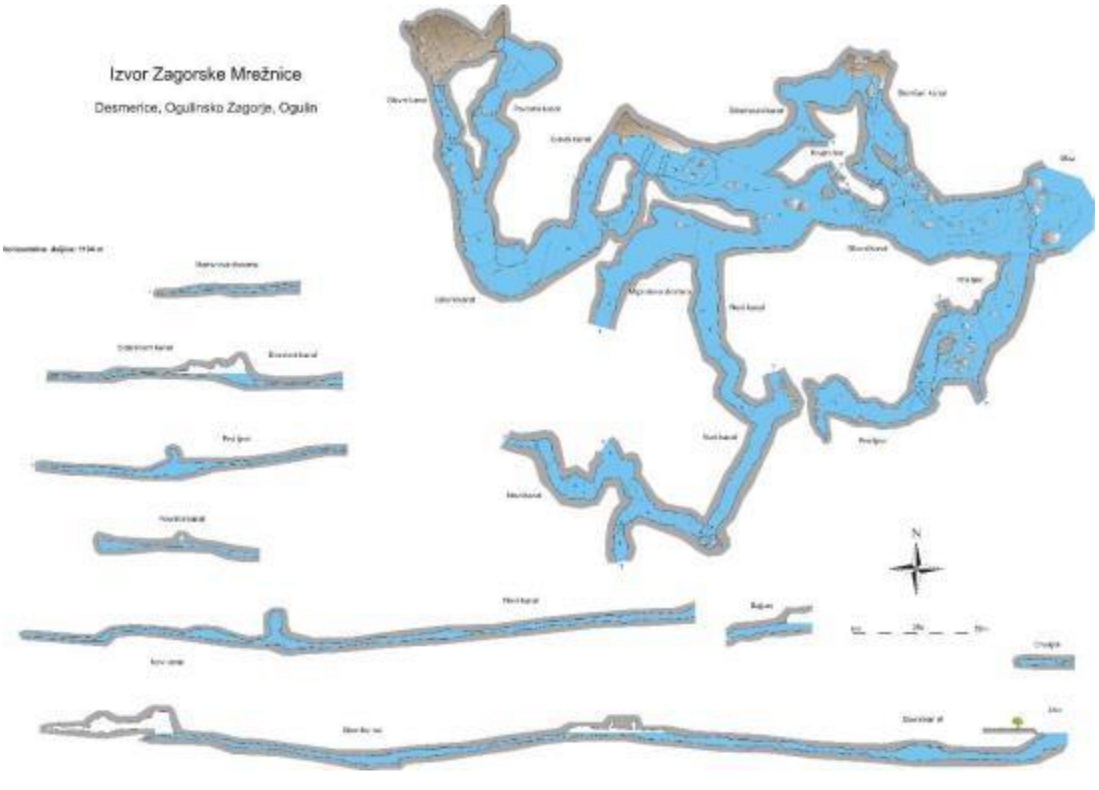


Figure 41: Cave map of Zagorska Mrežnica spring cave (see also Annex III).

Table 3. List of cave passages.

NAME OF THE CAVE PASSAGE	LENGTH (m)
Glavni kanal	407.5
Novi kanal	241
Prvi lijevi kanal	12.5
Povratni kanal	76
Mamutova dvorana	60
Brončani kanal	56
Side-mount kanal	55
Bajpas	33.5
Daleka dvorana	30
Kružni tok	22
Dead-end kanal	16
Crvuljak	15
Dvorana siga	9.5
Short connecting passages	100
TOTAL	1034

The cave form is a combination of curvilinear and rectilinear patterns which origin is linked to bedding-plane partings and fractures as dominant geological structures (Figure 52).

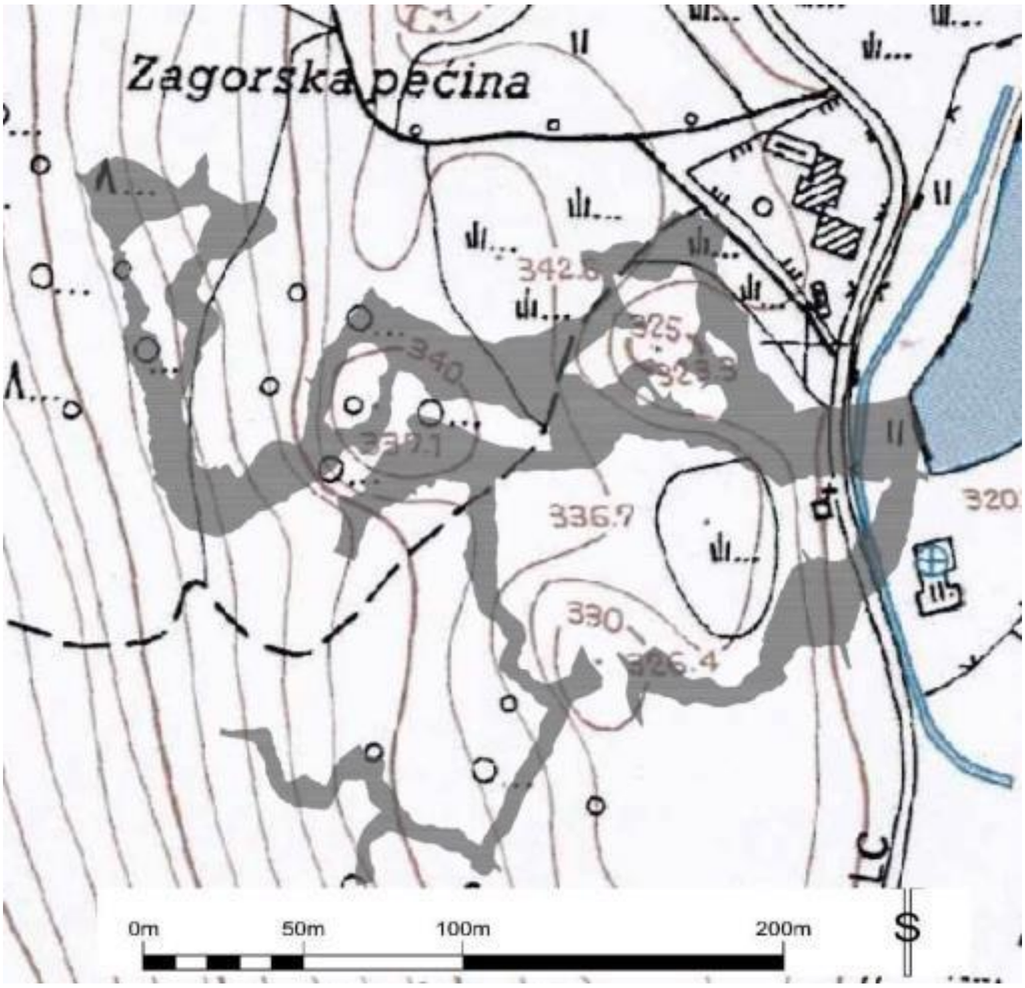


Figure 42: Projection of cave map on the Croatian base map (Base map source: DGU, Croatia).

Different parts of the cave system have slightly different forms. The Novi kanal passage and the distant part of Glavni kanal passage have more angular turns and the rest of the system has a more sinusoidal turn. Angular turns are the result of fracturing and sinusoidal turns can be attributed to a specific randomly distributed aperture field within the primary bedding plan (Rajaran et al., 1999) or neotectonic movements (Klimchouk et al., 2000, Figure 70).

Since connections between ponors in the hinterland and poljes and spring of Zagorska Mrežnica have been proven, it is expected that explored cave passages are just a small part of the cave system suitable for cave-diving explorations (Figure 42).

The pattern of the cave system is obviously controlled by fissures or an intersection of two or more of them. Today Zagorska Mrežnica spring cave is in an epiphreatic zone but on the other hand, the passage of Spring Bistrac extends over 500 m at a depth of 45-50 m. This points to a well-developed conduit system at a greater depth to which the vertical infeeder in Zagorska Peć cave can also be related.

The Left passage ends with a collapse of the bedrock, which is an indicator of the weakening of rock due to tectonic movements (Figure 43).

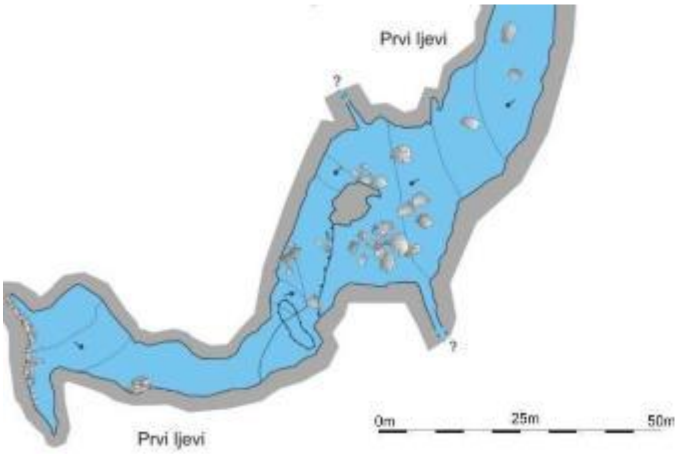


Figure 43: The curving form of Prvi lijevi passage.

There are two more parts of cave passages with curving forms in the Glavni kanal passage (Figure 44).

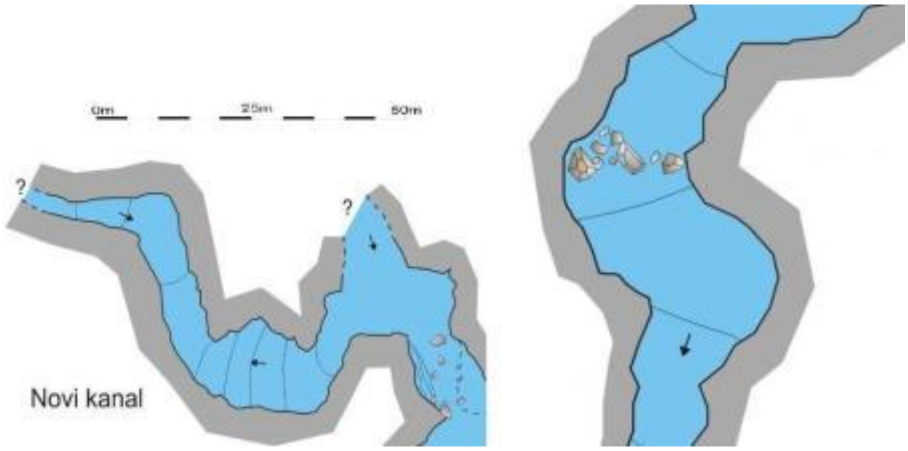


Figure 44: The curving form of part of the Glavni kanal (left) and curving form of Povratni kanal passage.

To analyse the morphology of cave passages 48 cross-sections were mapped underwater. The passages have lenticular, elliptical or semi-circular cross-sections. Generally, phreatic passages enlarge around their entire parameters. The cross-sections are guided by gently dipping the bedding-plane parting. Atconnection of two passages, collapses have formed conical piles that often extend to the ceiling. The general morphology indicates that the cave passages have developed along the systems of fissures and bedding planes (Figure 43).

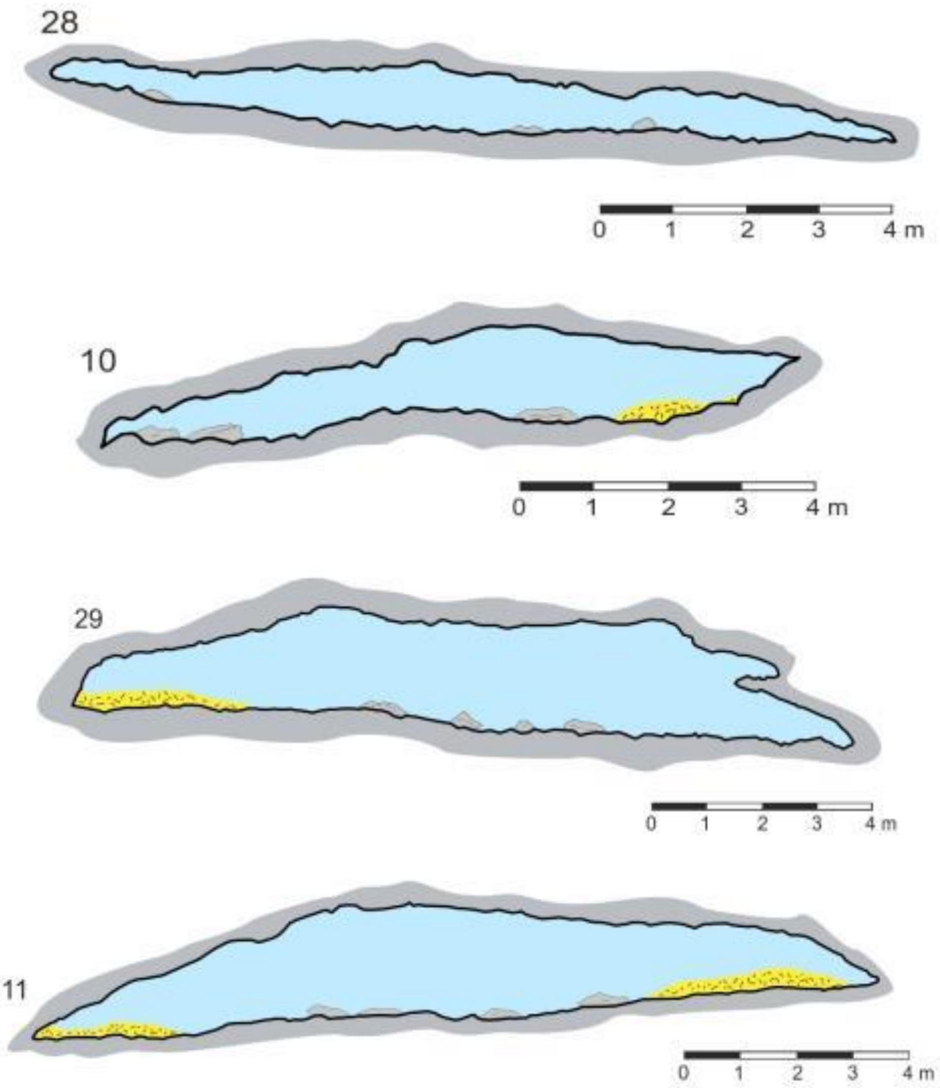


Figure 45: Cross-sections indicating development along the bedding plane and distribution of the sediment.

The cross-sections indicate that structural elements (bedding planes) are subhorizontal to horizontal (maximum 10°-12° of inclination) and the points of outcrop of these beds are the spring point, not only for Zagorska Mrežnica spring cave but for other springs nearby. In dips less than 20° the ceiling and the bottom of cross-sections reflect the inclination of beds (Davies, 1960). The height of the cave passage in the first group of cave cross-sections shows a dominant lateral development in some stage of cave development (Figure 44). The different solubility of individual beds determined which bedding planes were more favourable to the development of the passages (Ford & Ewers, 1978).

The cave passages were formed in well-bedded limestone (0.5-1.5 m) and the height of the cave passages in cross-sections is 0.7-1.5 m, indicating that the whole bed portion has been removed by erosion and corrosion. In some cross-sections, it is visible that they end in niches (cross-sections no. 26, 21, 22, 54, 60). These niches are sometimes several meters long and show the future lateral development of the cave passage (Figure 45, cross-section no. 28). The niches also serve as sediment traps with observed accumulation. The sediment indicates the presence of mechanical erosion in the whole cave system. Two cross-sections were made in a large dry chamber (Figure 46). The chamber developed in the fault zone with a fault plane dip of 80-90°. From the cross-sections, it is visible that the fault and thrusts orientated NE to SW determine the cross-section morphology. The large blocks on the bottom of the chamber also confirm neotectonic movements, which resulted in instability and collapse of the bedrock.

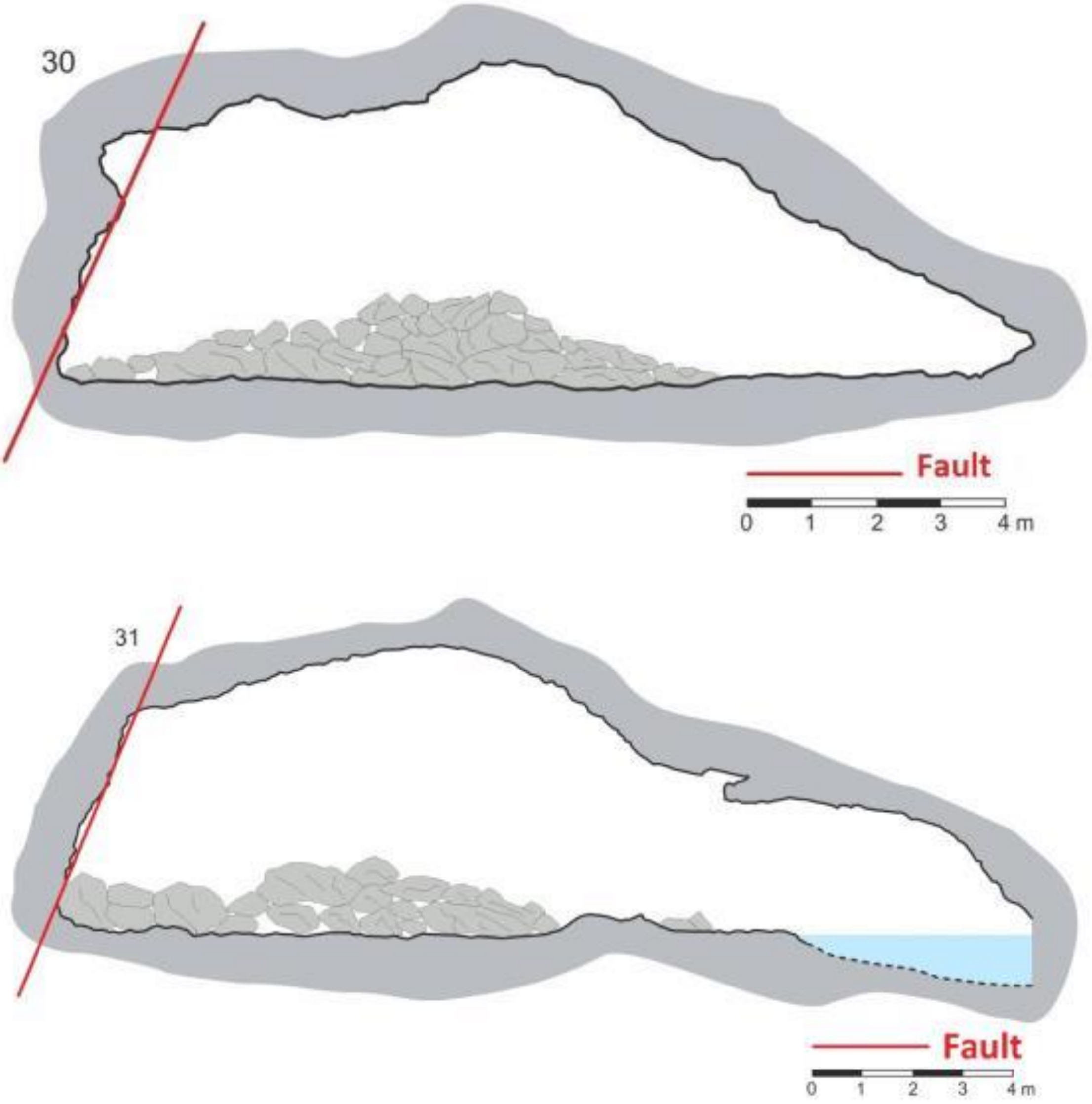


Figure 46: Cross-sections of the dry chamber.

The cross-sections (No. 6, 20 and 22) of Novi kanal passage and Lijevi kanal passage have a dominantly lenticular shape (Figure 47) with a clearly incised bottom in Novi kanal passage. The initial lenticular shape suggests that the cave passage developed below the water table in phreatic conditions.

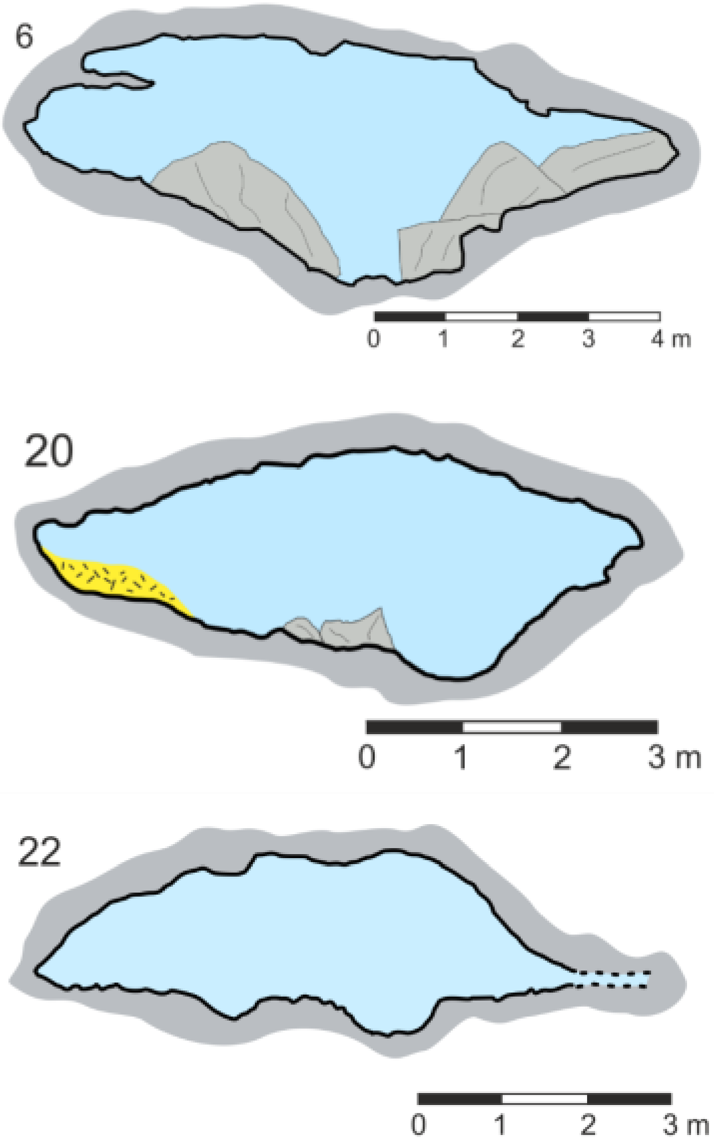


Figure 47: Lenticular-shaped cross-section with an incision on the bottom.

This incision in Novi kanal passage extends for 20 m or more, from 0.2 to 0.7 m in width and points to a past phase of epiphreatic and/or vadose conditions. Novi kanal passage is the deepest part of the cave so if the incision is an indication of a vadose phase it would mean that the whole cave was once above the water-table. On the ceiling of the cross-sections No. 13, 17, 38 and 43 ceiling niches are present (Slabe, 1989, 1995). They are oriented in the same direction as the cave passages (Figure 48). Such ceiling niches are often of paragenetic origin but there is no clear evidence of that.

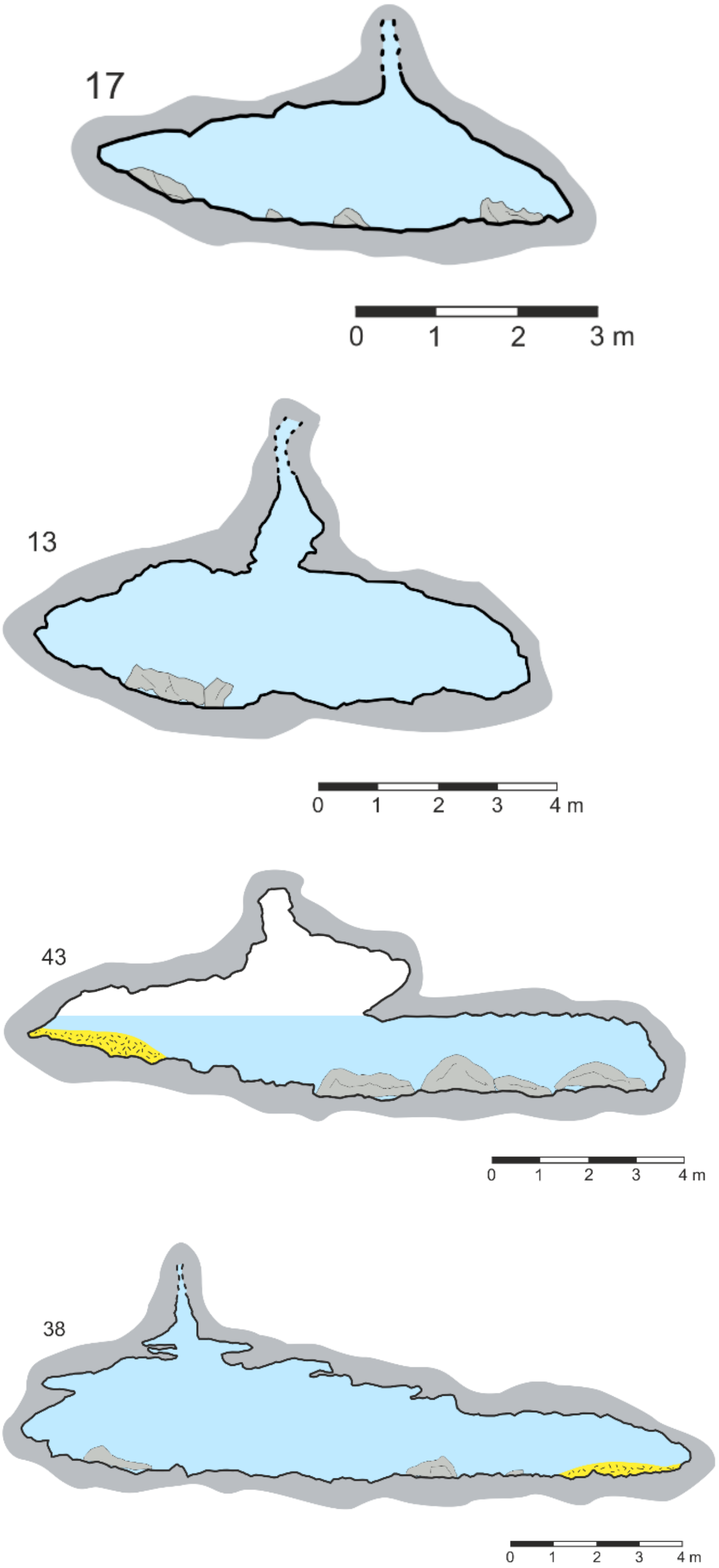


Figure 48: Influence of fissures on the cross-section of passages.

When young, phreatic passages have sub-circular cross-sections or are slightly elongated along the fissure. This shape is preserved in the cross-sections although they have enlarged over time (Figure 49).

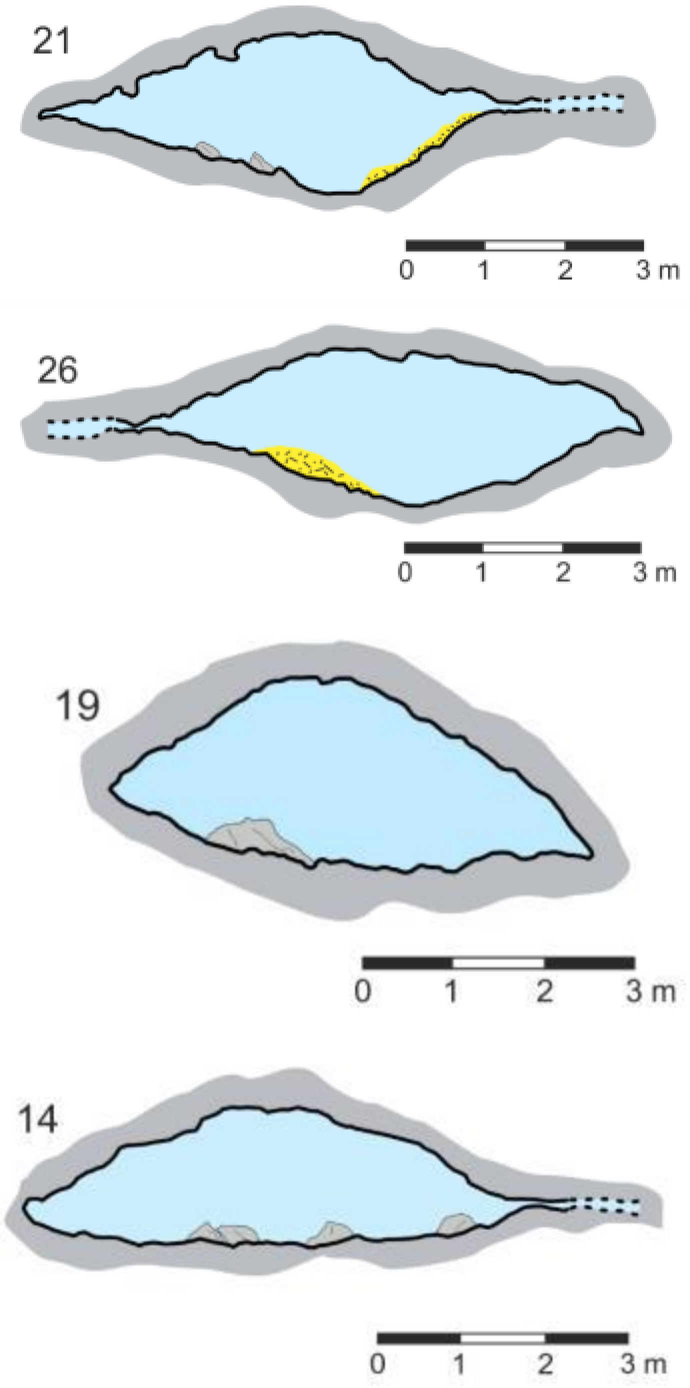


Figure 49: Lenticular shape of passages with niches.

These cross-sections (No. 21, 26, 19, 14) are typical for the deepest part of the cave system in Novi kanal where dimensions of the passages vary from 0.5-1 m.

The cross-sections found in the part of the Glavni kanal passage show a more irregular form (Figure 50). Some cross-sections of the cave system are 16-17 m wide.

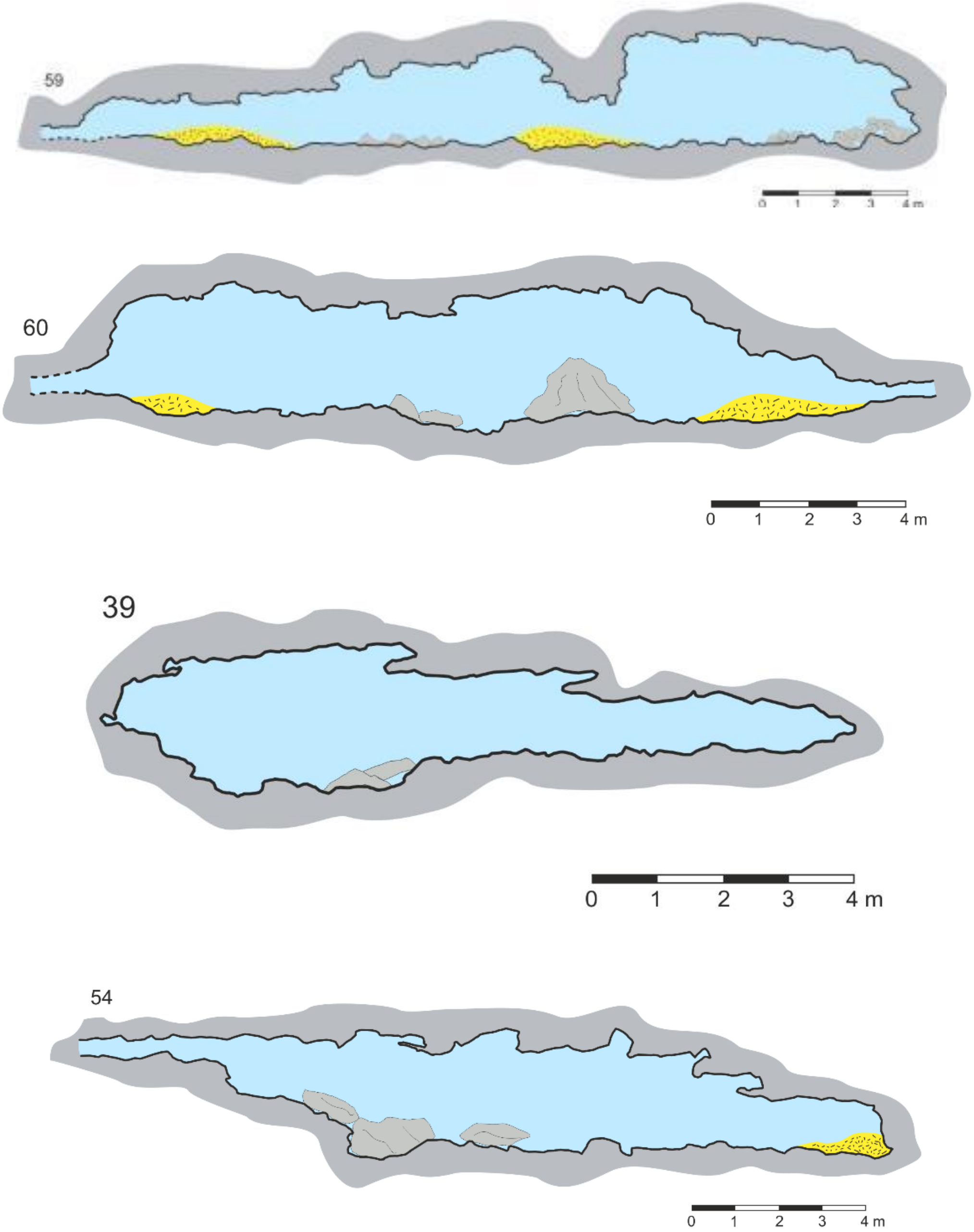


Figure 50: Irregular cross-sections in Glavni kanal passage.

This irregular shape in the proximity of the entrance is connected to the stronger influence of surface processes. This is the point of contact between surface climate conditions and slowing of outflow due to the dam that has been built. The influence of surface climate causes denudation processes, especially cryofraction and mechanical erosion of the bedrock surrounding the entrance. This causes more intense bedrock fractioning those results in more irregular and wider cross-section. In the entry part of Glavni kanal passage, there is a large conical pile beneath a large sinkhole pond. This is clear evidence how denudation of terrain influences cave morphology. Moreover, 15 m from the conical pile is the second entrance to the cave situated at the bottom of a doline.

At the entrance part, there is also a large amount of sediment and rock blocks (Figure 51). The breakdown of the cave ceiling occurred at the contact of underground flow with the surface. The breakdown is common at the points where water loses its pressure and the slight buoyant effect of water is removed (Palmer, 2007).

Figure 51: Collapsed bedrock at the bottom near the entrance (photo: V. Jalžić).

Also, there is a natural rock dam several meters high that disables gravel to be carried out of the cave. Therefore, at the first 70 m of Glavni kanal passage there is a large amount of gravel, but outside of the cave system, there is a large amount of sand sediment on the bottom. In phreatic conditions, the buoyancy of water can support up to 42% of the weight of the passage ceiling (Veni, 2005). Maybe the switch between vadose and phreatic periods and the loss of water pressure on the bedrock resulted in gravitational stress and rock ceiling breakdown. At the bottom in the Glavni kanal, Sidemount kanal and Brončani kanal where epiphreatic conditions are present, large blocks of thick bedded rock are on the bottom.

5.2.2 INVENTARIZATION OF MICRORELIEF FORMS

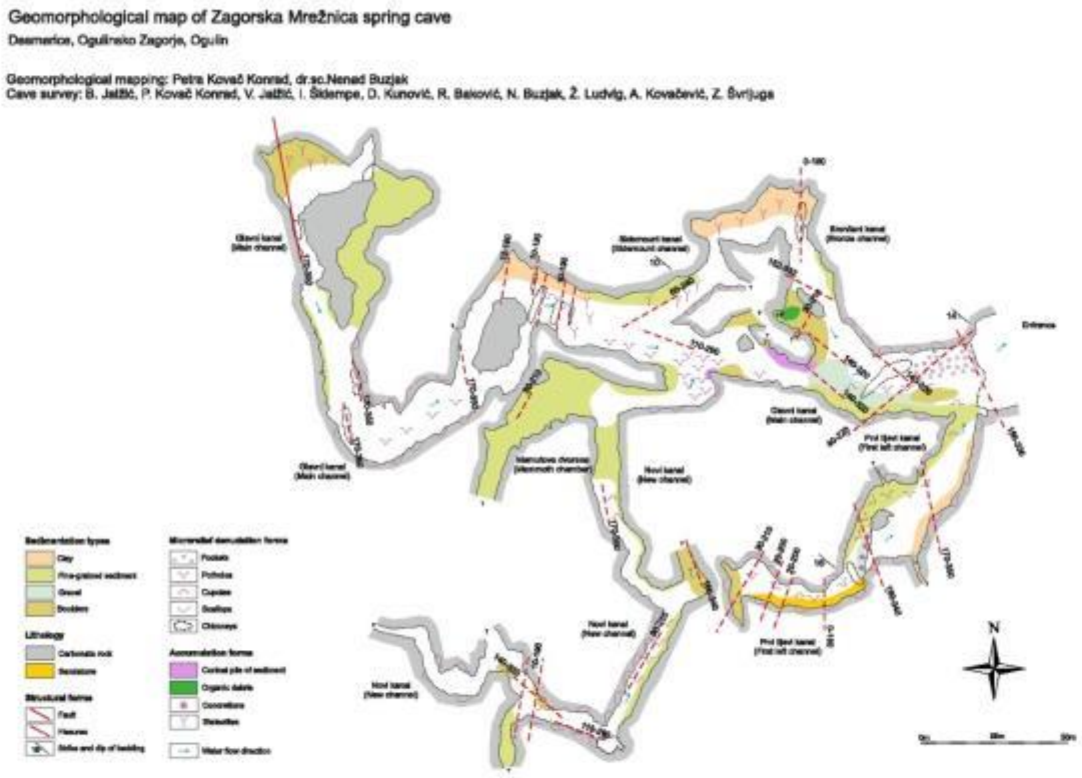


Figure 52: Geomorphological map of Zagorska Mrežnica spring cave (see Appendix II).

5.2.2.1 Rocky features due to turbulent water flow

In Zagorska Mrežnica spring caves, scallops are present mostly on the bedrock on the bottom of the cave passages. They are shallow with a diameter between 20 and 30 cm (Figure 53). Their orientation indicates flow towards the entrance, and at the entrance of the cave some of them are jointed into sets. The evolution of the scallops is controlled by lithology, velocity and pressure of the water flow. The shape, size, and distribution are mainly controlled by local hydraulic conditions (Slabe, 1995). Since scallops are mainly solutional forms (Grm et al., 2016) one can conclude that no transport of sediment with significant erosional power has been present and confirms the conclusions from the analysis of sediment.

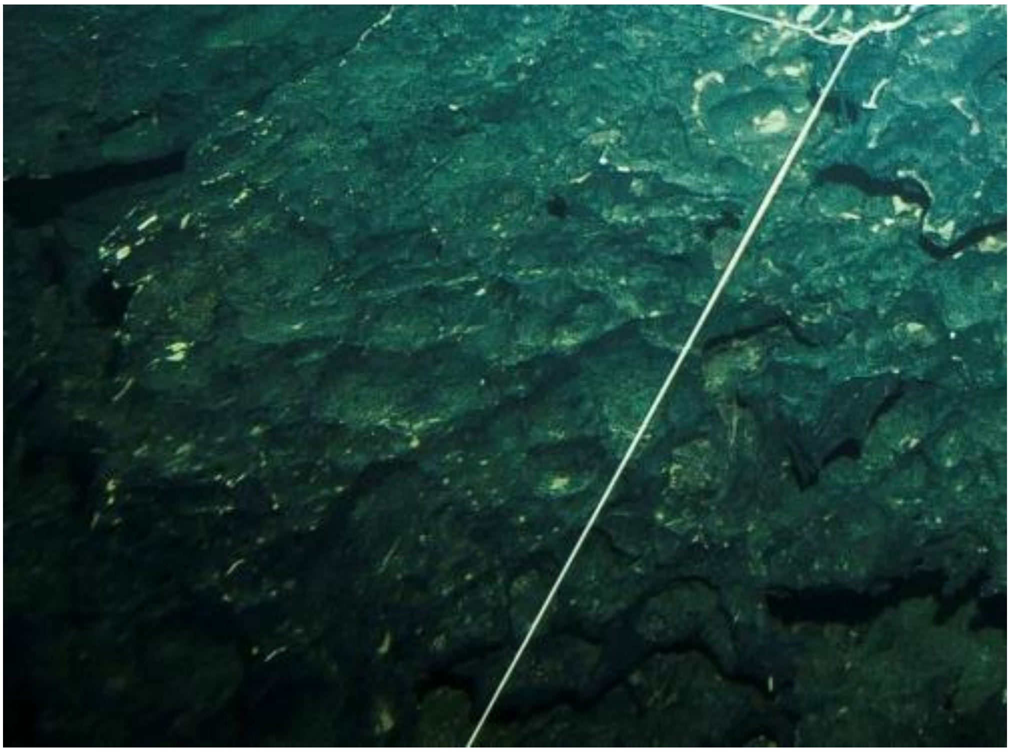


Figure 53: Scallops at the Glavni kanal passage.

Potholes are most dense in the crossing of Novi kanal and Glavni kanal passage (Figure 54). Their average density is 16 potholes per m^2 in this part of the cave. They are both simple and in line, semi-spherical and composite (Slabe, 1995) with semispherical bottoms. Their walls are inclined and their diameter (24-35 cm) is larger than their depth (15-20 cm). The conical narrowing towards the bottom in some of the potholes suggests a decrease of waterpower at depth (Slabe, 1995). Scallops surround them and in many of them, secondary potholes developed (composite type). The high density of potholes in the part of the cave where Glavni kanal and Novi kanal connect is the result of the intersection of two strong flows and thus intensive turbulence of water and transported sediment. One flow is coming from the Novi kanal passage from the direction S and the other flow is coming from Glavni kanal passage from the direction W, both then flowing to the exit direction E.

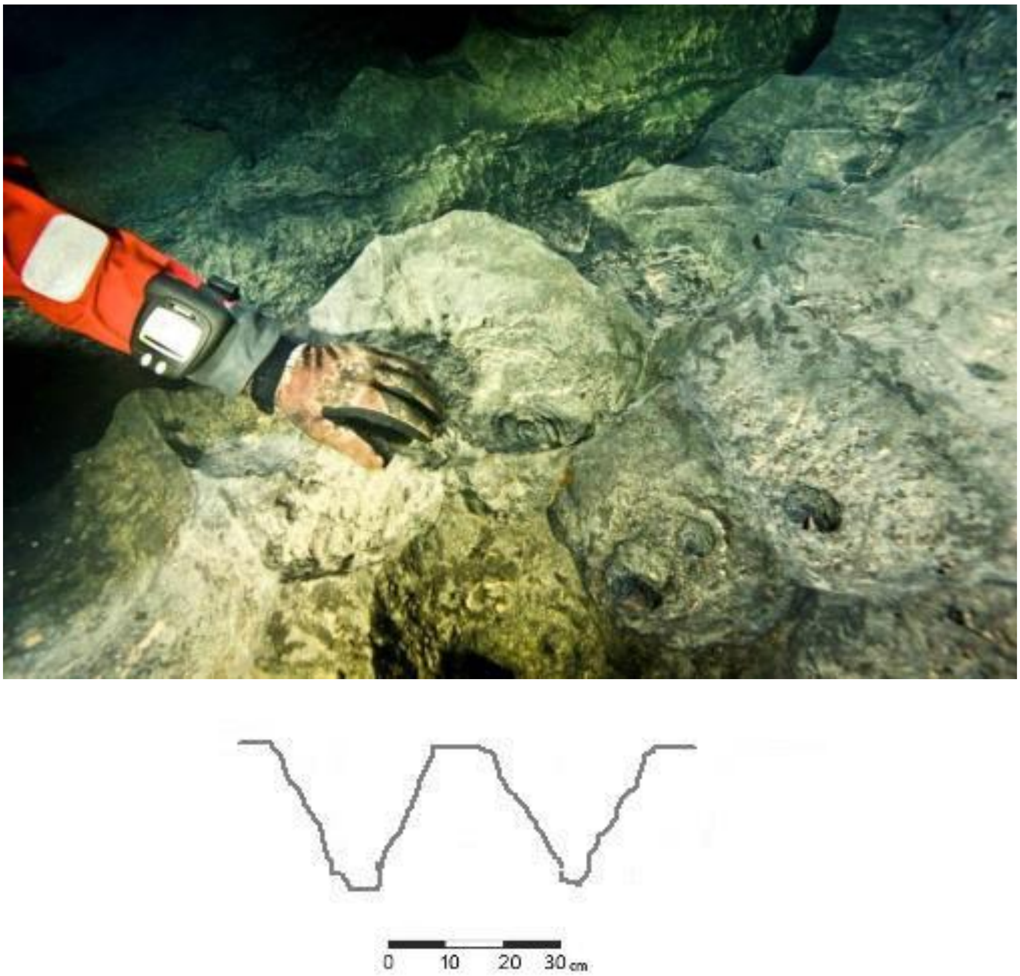


Figure 54: Potholes in Zagorska Mrežnica spring cave and scheme of their cross-section.

Ceiling pockets are mostly present in the Glavni kanal passage in the epiphreatic zone. They vary in size (Figure 55). They developed in phreatic conditions due to slow water turbulence (Slabe, 1995). They are both independent and composite semi-circular or elongated into ellipses, the cross-section narrowing inwards. The composite ones are in-line direction NE-SW made of several smaller ceiling pockets connected into a series.

Figure 55: Ceiling pocket in Prvi lijevi kanal passage.

Chimneys are present in the entire cave system. They developed along the fissure(s) in the ceiling. Sometimes they are over 7 m high. The biggest one is in Novi kanal Passage and is over 4 m wide at the entrance and 10 m high. All chimneys end like narrow fissures and they function as sediment traps. In all of the chimneys, a lot of sediment is present because of low or no flow velocity.

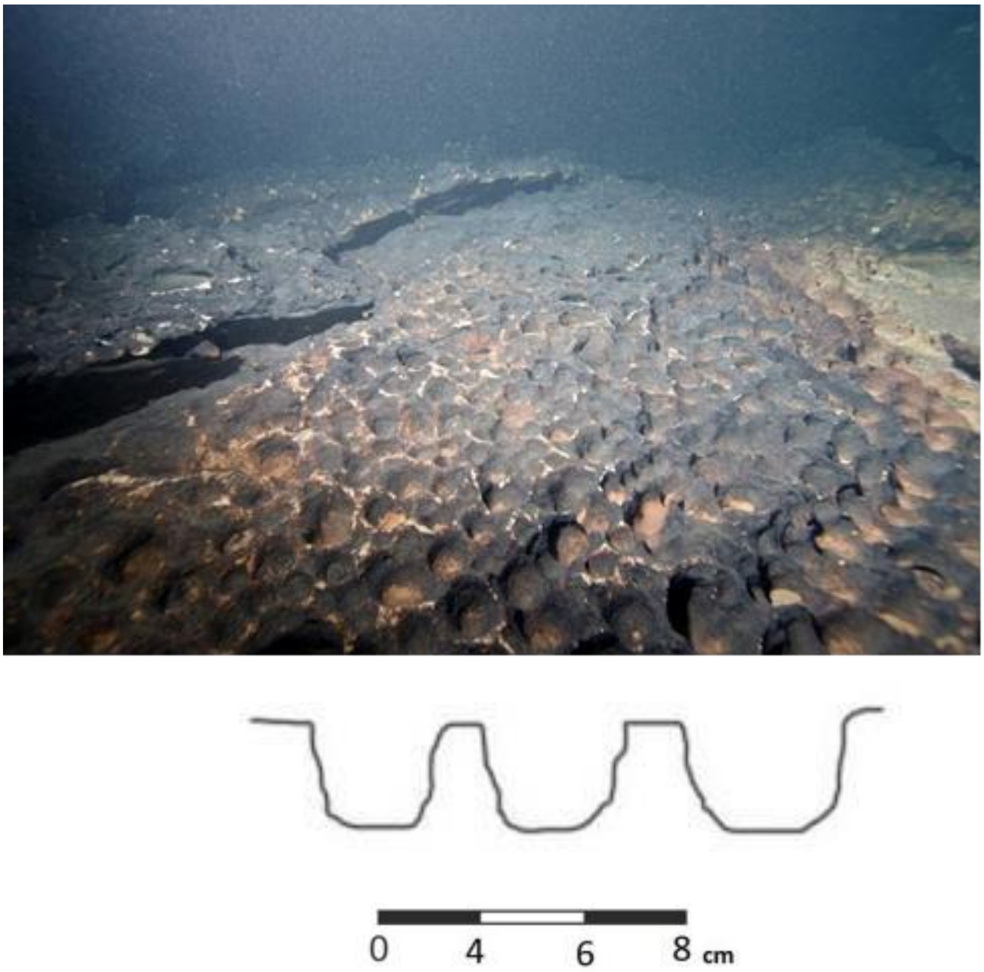


Figure 56: Photograph and cross-section of solution pockets at the entrance of Zagorska Mrežnica spring cave.

Pockets or floor pits are present on the bedrock on the bottom first 30 m from the entrance of the cave (Figure 56). So far, this form has never been recorded in any other submerged cave in Croatia. They are 4-5 cm in diameter and 3-5 cm deep. Their origin can be connected with the below-sediment solution (Slabe, 1995). If it is developed below sediment, it means that it is developed in epiphreatic conditions. They have vertical walls and the bottom is almost flat. The pits develop from corrosion below sediment, which was deposited on concave parts of the rock. For this to happen, the water level in Zagorska Mrežnica spring cave had to be lower than today, and the cave system had to be an epiphreatic system.

5.2.2.2 Accumulation forms

The transport and sedimentation processes in Zagorska Mrežnica spring cave are dependent on its hydrological characteristics, the morphology of cave passages and changes of the water table level in the geological past (mainly epiphreatic-phreatic stages).

There are two ways of sediment transport throughout the cave, as a bed-load and as suspension load. As the hydrological conditions change in the conduits, as well as the morphology of cave passages, one type of transport can change to the other. The type of flow carrying the sediment in Zagorska Mrežnica cave passages is mostly turbulent. The sediment cover found in the fissures and chimneys across the ceiling are not the result of laminar flow but due to reduced water velocity.

The composition of the sediment (Chapter 5.2.2.) suggests that sediment is similar to deposits in the catchment area and thus there was no past (fossil) inflow from other areas. The cross-sections of the cave passages show that the size of the cave narrows in the lateral sides of the passage. The subhorizontal passages often end in subhorizontal fissures several meters long. Such morphology results in the highest water flow in the widest part of the cave passage and a great loss of energy on the sides of the passages due to friction.

The sediment types we can find in the cave are:

1. gravel at the entrance part of the cave
2. silt and sand deposits along the whole cave system
3. clay deposits in epiphreatic parts of the cave
4. concretions in the Left passage
5. chemical sediments such as speleothems in epiphreatic parts of the cave system

CLASTIC SEDIMENT

GRAVEL

The origin of gravel found along the first 70 m of the cave passage of Zagorska Mrežnica spring cave is from local origin because its mineralogy is identical to the mineralogy from the bedrock, which was determined by petrographic analysis of the gravel and bedrock (see Chapter 5.6.). It is a product of physical disaggregation of bedrock from weathering, a bedrock breakdown (incision) and transport and mechanical erosion. Water flow with suspended particles erodes cave walls by plucking and corrosion (White, 2007). The collapse of cave bedrock walls and ceilings results in accumulation of the material that is angular, and ranges in size from debris to boulders (Sasowsky & Mylroie, 2007). On the bottom of the cave at some parts of the passages, there are boulders that could fit up to the ceiling of the cave. On the sides of the cave passage, there are very thin eroded beds that are a future source of clasts and gravel (Figure 57). The collapse of the ceiling happened due to denudation processes on the surface, which weakened the bedrock. This type of sediment could only be found at the first 70 m of the cave because here water loses a lot of its velocity and due to the wider passage, backflow occurs due to entering the entrance lake.

Figure 57: Portion of denudated limestone bed in the spring of Zagorska Mrežnica.

The gravel pebbles are sub-rounded due to interclast friction, rolling and transport. They are from 4 to 6 cm in diameter (Figure 58). Most of them are oriented with the longer axis parallel to the water flow.

Figure 58: Gravel near the entrance of the spring.

SAND DEPOSITS

Sand deposit is found on the sides of the passages, as previously mentioned. Symmetrical ripple marks are visible on sand deposits indicating the direction of the water flow (Figure 59). Ripples have relatively continuous but sinuous crests and uniform height and spacing. Ripple marks found near the entrance show a different orientation because of constriction on the entrance of the cave where the back-flow on the sides of the passage is present. The Mammoth chamber (Mamutova dvorana) has the largest sand body at over 1.5 m thick. In the hydrological sense, the Mammoth chamber functions as a vent for the water flow coming through Novi kanal passage. It is a sediment trap. The sources of the sediment are insoluble residues formed during the phreatic enlargement and erosion of bedrock and the sandstone-bed found in the Prvi lijevi passage and fragments found in Novi kanal passage and from the inflow through ponors and the erosion of epikarst that consists of limestone and dolostone. The sediment deposits are also found in the places where the cave passage widens, where the water flow is reduced (Appendix II).

Figure 59: Sand ripples on the sand accumulation found on the sides of the cave passage.

The distribution of sand deposits along the cave system is visible on the geomorphological map (Appendix II) of the Zagorska Mrežnica spring cave and it can be related to high and low water flow energy present in the cave system.

FINE GRAINED SEDIMENT

Fine-grained sediments found in the cave are mud, silt and clay. Large deposits of fine-grained sediment are found in two places in the cave system. Both places are in the epiphreatic zone of the system (Figure 60), in the Brončana dvorana chamber and Glavni kanal passage. The strong water flow rapidly reduces in the wide chambers thus allowing the fine particles to settle. The fine-grained sediment can have several origins: the sediment was transported into the cave from a surface source, dissolution of limestone during speleogenesis resulted in the liberation of trace constituents and accumulation of insoluble residue or the minerals formed by microbiologic alteration of bedrock or other materials (Foos et al., 2000). Since the cave is close to the surface, sediment could have originated from the washed-down surface soils and transported through numerous fissures.

Figure 60: Large clay deposits in Brončani kanal passage.

The deposits are 1-1.5 m thick indicating long calm hydrological periods allowing the deposition of fine-grained sediment. Due to the effect of compaction, the clay particles encircle the sand grains and form an uneven sediment surface forming small spherical forms (Figure 61, Tišljar, 1994).

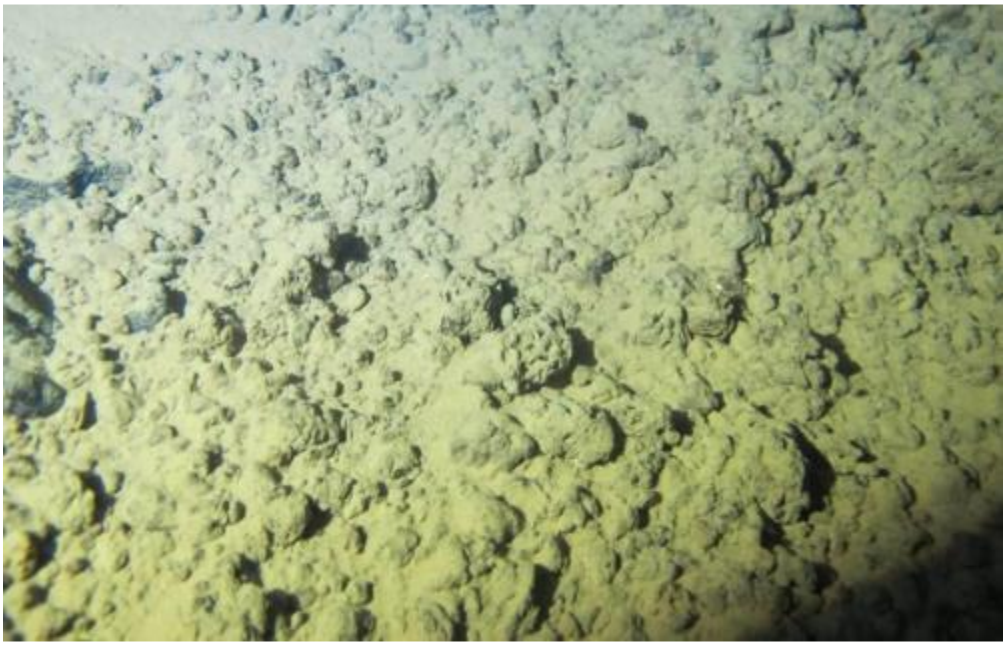


Figure 61: Uneven sediment surface in Prvi Lijevi kanal passage.

CONCRETIONS

Concretions were found in the Prvi Lijevi passage, in and on the sediment (Figure 62). Their size varies from 5 to 15 cm. They are spheroidal in shape, some flat like plates and ovoid in shape, and most of them are irregular. Concretions are the result of partial cementation of cave sediment that can be seen in cross-sections of the concretion (Figure 63). This process probably occurred above the water table what again indices existence of vadose or epiphreatic phases of the cave.

Figure 62: Concretions in Prvi lijevi kanal passage.

Irregular concretions were formed by cementation of larger, sometimes laminated material, which is visible in the form of concretion (spheroidal layers).

Figure 63: Cross-section of concretion showing lamination.

CHEMICAL SEDIMENTS

SPELEOTHEMS

Speleothems are formed in two chambers where vadose/epiphreatic conditions are present. Stalactites, stalagmites, draperies and flowstone are found on the ceiling and walls. In these chambers, as stated before, a thick layer of fine-grained sediment is found. All this indicates that these parts of the cave are never completely flooded. Soda-straws are common as are stalactites on the ceiling. Some stalactites and flowstone can be found below water level indicating longer periods of very low water levels (Figure 64). This is another indicator that Zagorska Mrežnica spring cave has had periods in its geological past when it was mostly an epiphreatic system and had some parts in the vadose zone. The vadose zone became reduced due to neotectonic and changes in the hydrological regime after the construction of the accumulation lake Sabljaci or/and because of aggradation of the valley.

Figure 64:Speleothems in the epiphreatic part of Brončani kanal passage.

5.2.3 STRUCTURAL CONTROLS OF CAVE DEVELOPMENT

Structural elements in caves are important due to the influence on cave morphology, passage morphology, microrelief from evolution and speleothem evolution (Palmer, 2009, 1991; Klimchouk et al., 2000; Ford & Williams, 2007; Figure 65). Two major fault sets were identified on the surface above Zagorska Mrežnica spring cave and Zagorska Peć cave, and one was identified inside the Zagorska Peć cave. One set has an N-S orientation; the other has a NE-SW orientation (Figures 66). The fault sets identified on the surface are also marked on the geological map (Velić et al., 1980b). As a part of the Dinaric NE Inner Karst unit, it is a part of a zone of steep faults striking generally NW-SE, affected by the latest orogenic wrench tectonics (Korbar,2009). Due to stress change over time to N-S, the structures also changed their orientation.

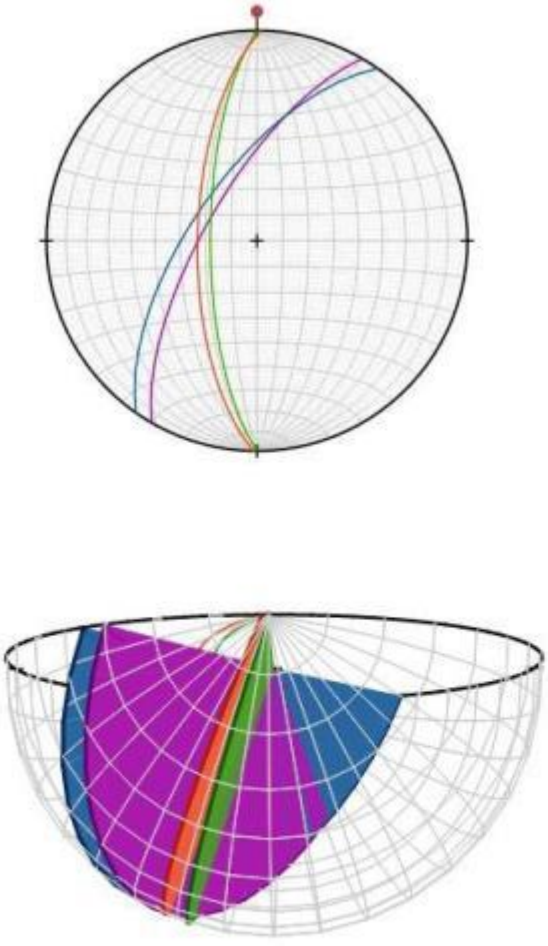


Figure 65: Stereographic projection of identified faults.

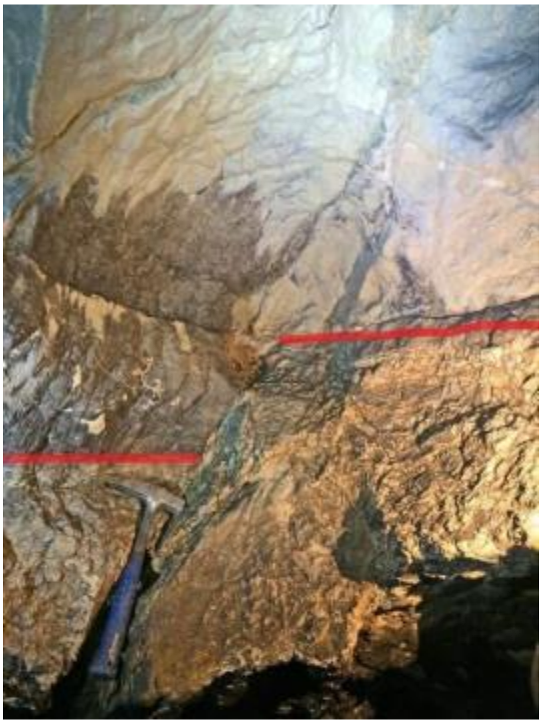


Figure 66: Identified fault in Zagorska Peć, red lines indicate the shift along the bedding plane.

In the Zagorska Peć cave a fault was identified in the NE-SW direction, the same as the surface fault. So, this structure obviously has an impact on the speleogenesis of Zagorska Peć cave and probably on the Zagorska Mrežnica spring cave since they are one system.

This can also be seen in Figure 67, where the rose diagrams show a close correlation between the direction of passages and the direction of fissures with a dominant NE-SW direction.

Beds are also dominant geological structures which influenced the speleogenesis and morphology of all caves of Ogulin Zagorje. Measurements done on the surface and in the underground show that beds have a slight inclination in the range of 4° to 16°. Their orientation ranges between directions 180° and 240°, meaning that the beds are dipping towards the S-SW. The whole cave system is dipping towards the S as well where Spring of Bistrac is positioned (Figure 67).

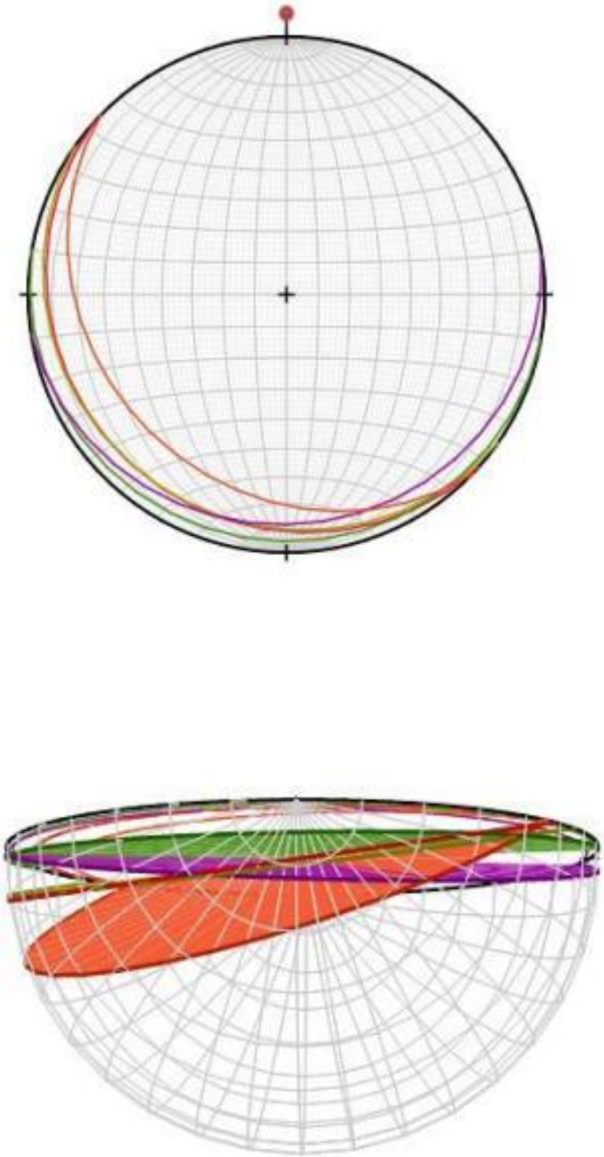


Figure 67: Measured beds on the surface and in Zagorska Peć.

The Ogulin Zagorje caves mostly consist of horizontal passages that are on one level (except Zagorska Peć cave) and show the influence of subhorizontal beds (Figure 68). Zagorska Peć cave is the only cave that has a deep subvertical submerged passage penetrating into the phreatic zone. This passage developed along a steep fault observed also on the surface.

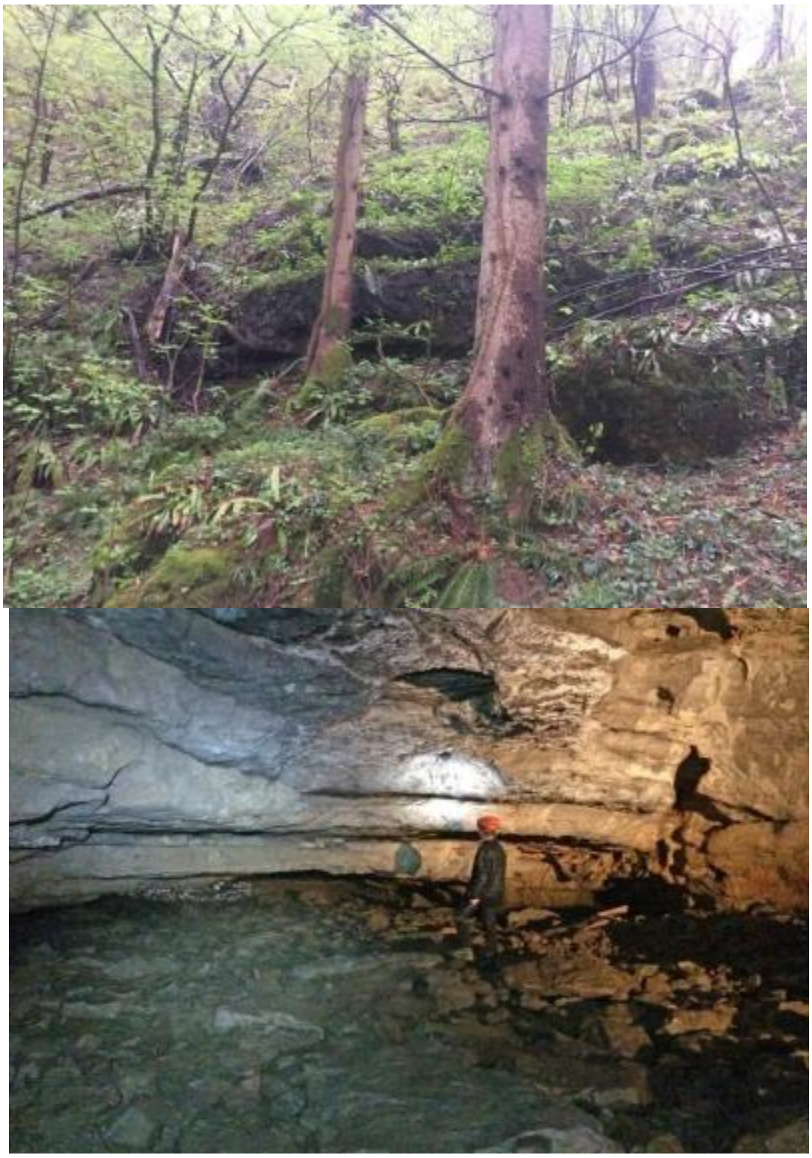


Figure 68: Subhorizontal limestone and dolomite beds on the surface and in Zagorska Peć cave.

It can be observed that the whole cave system is developed more or less along a single plane dipping to S corresponding to a few neighbouring bedding planes. The cave systems dip to S along the guiding bedding plane. The only exception is a flooded shaft in Zagorska Peć cave, which will be discussed later.

According to measurements of the orientation of fissures and cave passages in cave systems of Ogulin Zagorje, the beds and bedding planes played an important role in speleogenesis, and this guided the majority of the initial cave development (Figure 69).

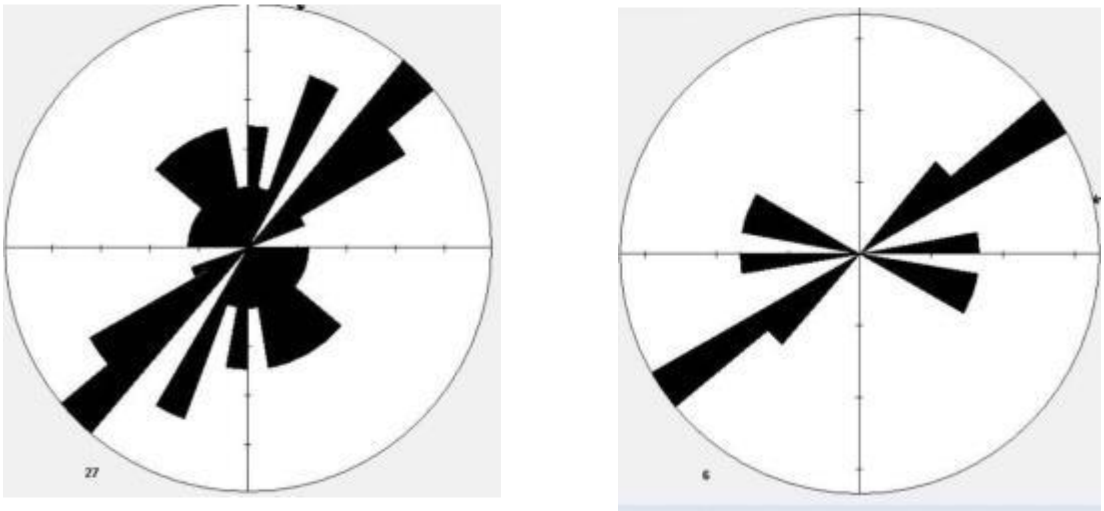


Figure 69: Rose diagrams of cave passages (left) and fissures (right) of Zagorska Peć cave.

The rose diagrams of cave passages in Zagorska Peć cave show that the dominant orientation is along the NE-SW. In Zagorska Mrežnica spring cave fissures are present along all of the cave system. 31 fissures have been mapped (Figures 70, 71, 72). The NNE-SSW orientation of measured fissures is dominant and that is concordance with the general structural elements of the study area. The cave passages show different orientations, W-E and WWE-EES being dominant, indicating the existence of a complex relationship between fissure orientation and cave passage distribution, which probably results from time-varying tectonic situations (Chapter 5.1.). The development of cave passages is greatly influenced by the structure. The classification of fissures in groups by their orientation shows two dominant sets, one a N-S direction and the other NW-SE. This is in accordance with two major fault systems that are mapped on the geological map and have been confirmed in the field (Figure 64, see Appendix V). According to the classification of joint networks, this is a complex asymmetric network, which is dominant in karst areas and karst aquifers (Chernyshev, 1983). The two main sets of fissures in NNE-SSW and NW-SE directions intersect at an angle of approximately 60°. This kind of intersection is usually associated with shear fracturing and compression (Klimchouk et al., 2000). Regionally, the orientation of fissures to fold axes of the Ogulin Zagorje anticlinal is perpendicular.

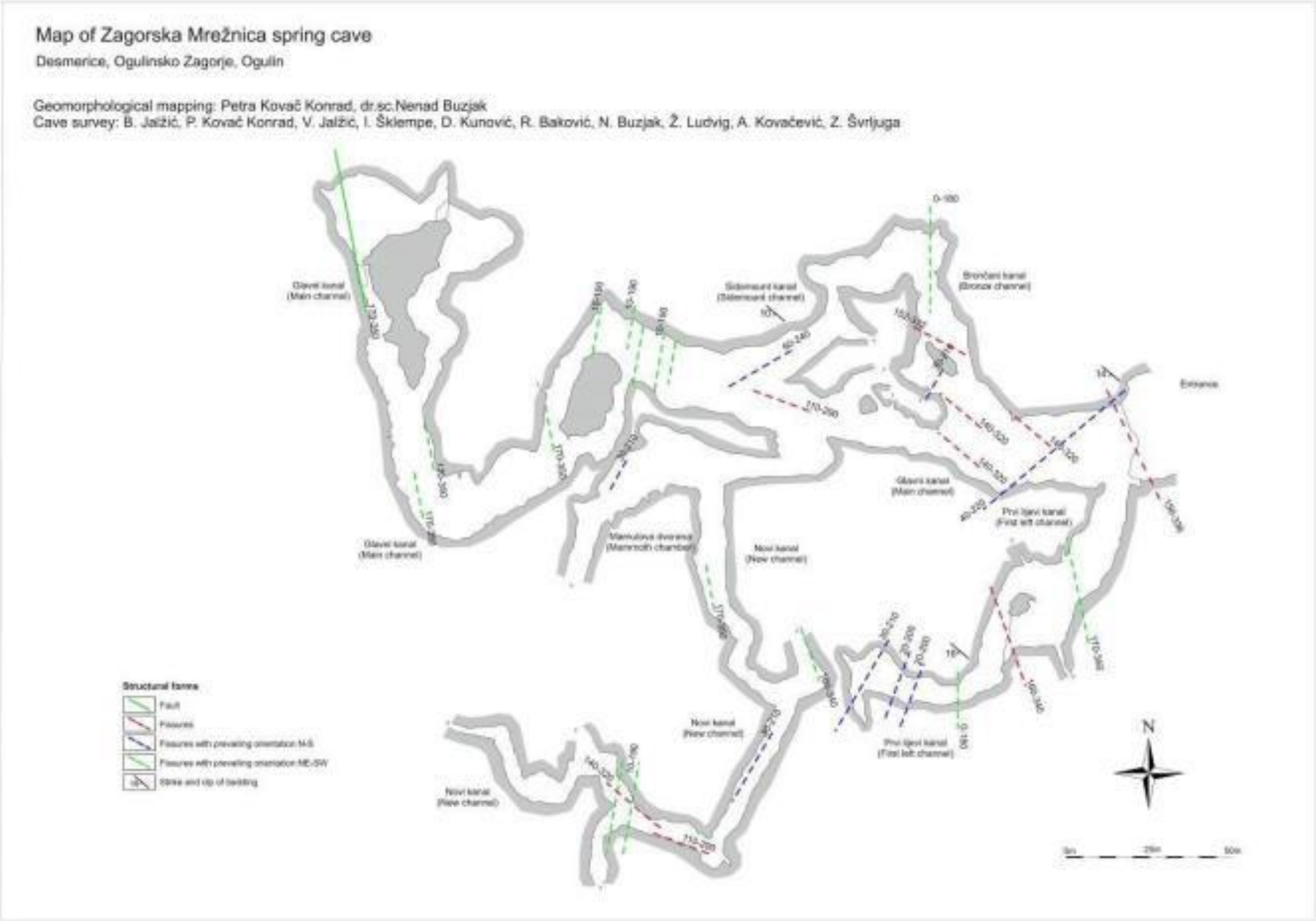


Figure 70: Classification of fissures in groups by their orientation (Appendix VI).

The fault plane has been identified in the chamber at the end of the Glavni kanal passage and stretches in the NNW-SSE direction.

Beds found in the area of Zagorska Mrežnica spring cave and in the cave system are well-bedded dolomite between 0.4-0.7 m thick. They are positioned at a mild inclination of 10-12°, N-S general direction. They are one of the main structural elements that have defined the morphology of the cave passages and their development.

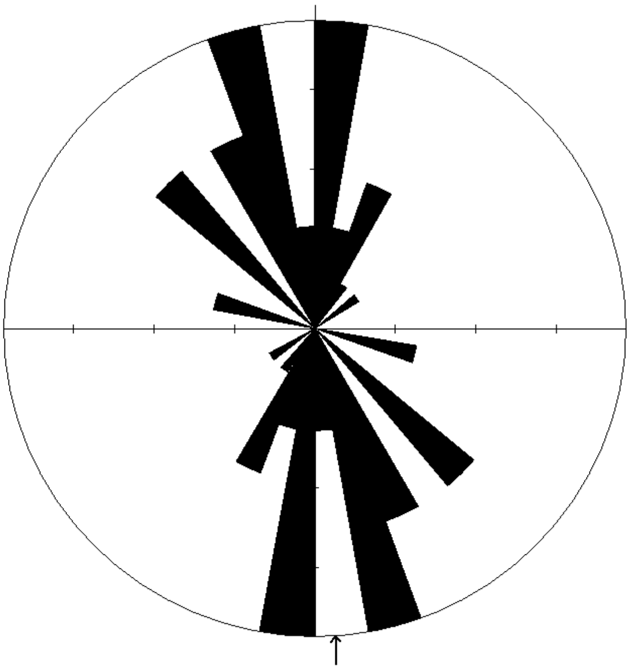


Figure 71: Rose diagram of measured fissure orientation in the Zagorska Mrežnica spring cave.

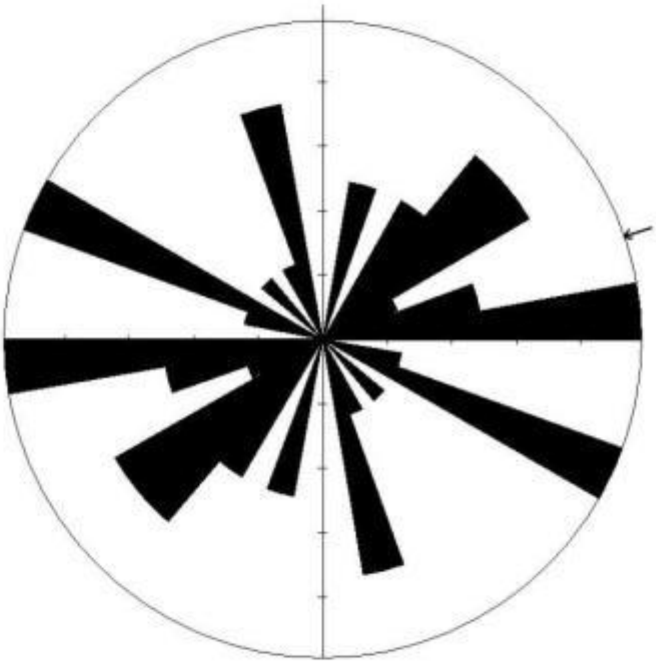
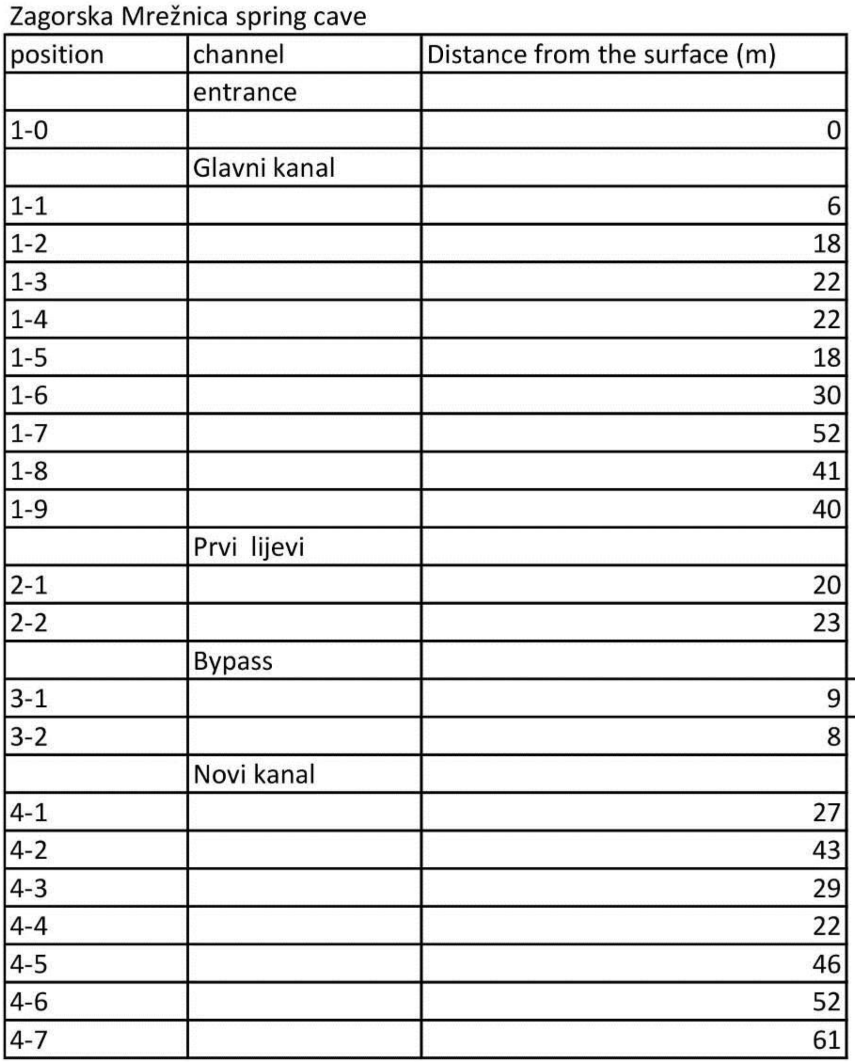


Figure 72: Rose diagram of Zagorska Mrežnica spring cave passage orientation.

5.2.4 MACROMORPHOLOGICAL ANALYSIS FROM THE 3D MODEL OF ZAGORSKA MREŽNICA SPRING CAVE AND ZAGORSKA PEĆ

The average water level is at 319 m a.s.l. The lowest part of the cave passages is at 300.7 m a.s.l. and the highest is at 322.1 m a.s.l. so the whole cave system spans 21.4 m of vertical distance. The average height of the cave passages is 1.20 m and the average inclination is 4.5°. The estimated volume of the cave is about 13,650 m^3. Based on the 3D model, the distance of the cave passages from the surface was calculated (Table 4).

Table 4. Vertical distances from the ceiling of cave passages to the surface.



Zagorska Mrežnica spring cave

position	channel	Distance from the surface (m)
	entrance	
1-0		0
	Glavni kanal	
1-1		6
1-2		18
1-3		22
1-4		22
1-5		18
1-6		30
1-7		52
1-8		41
1-9		40
	Prvi lijevi	
2-1		20
2-2		23
	Bypass	
3-1		9
3-2		8
	Novi kanal	
4-1		27
4-2		43
4-3		29
4-4		22
4-5		46
4-6		52
4-7		61

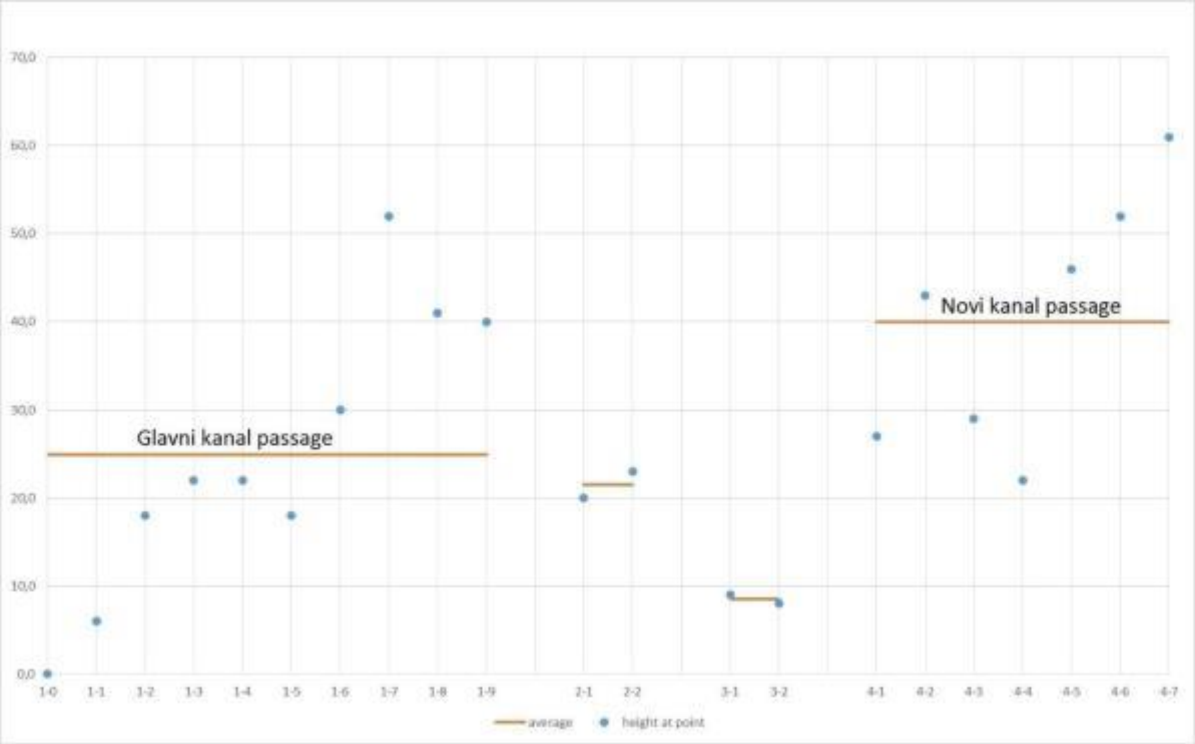


Figure 73: Graph showing the average distance of measured points in cave passages to the surface.

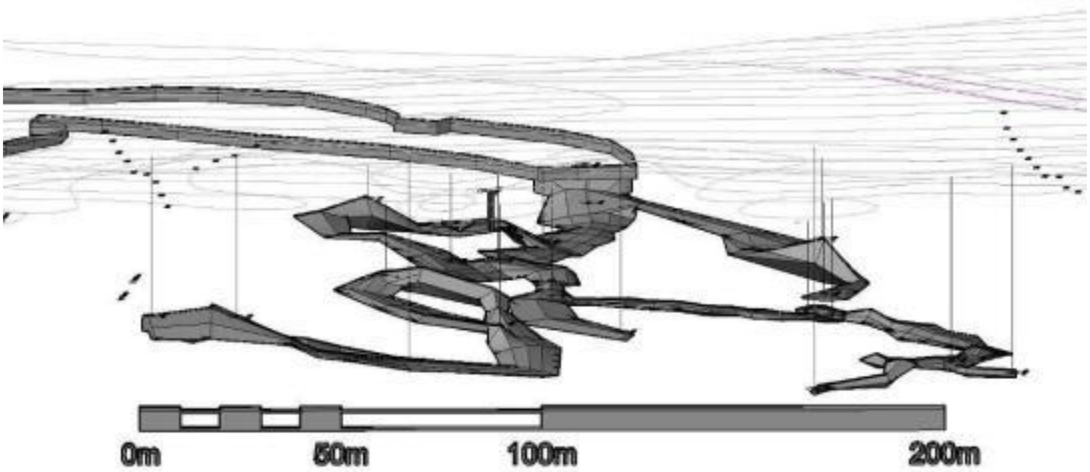


Figure 74: Relation of cave passages to the surface in the 3D model.

Based on the data in Table 5 and Figure 73 it is evident that the cave is under the direct influence of surface processes due to the short distances to the surface and presence of dolines. The average distance from the surface is between 25 and 40 m (Figure 74). The collapse of the ceiling is noticed in several places in the cave system and on the surface in these places are dolines. These conical piles of collapsed rocks blocked parts of the cave passage and probably caused water to reroute and widen cave passages in other parts.

The mapping of cave systems and the 3D model show that the distance between the closest part of Zagorska Mrežnica spring cave and Zagorska peć cave is only 25 m. The geometry of cave passages is very similar (branchwork) so these two caves can be considered as one system. All passages can be encircled by the surface of 57,744 m^2 but the surface of the plan projection of cave passages is 11,339 m^2, which makes up only 19.64% of the described encircled area. Zagorska Peć cave lies below an area of 24,614 m^2 and passages have an area of vertical projection of 5,776 m^2, which makes up 23.47 % of the described circle area (r = 177 m). The two cave systems are distributed below the circle area of 132,081 m^2 (r = 410 m) with the surface of the vertical projection of cave passages making up 13.01% (Figure 68). Based on this information it can be concluded that the two caves have a very similar distribution of cave passages. Cave passages are distributed in different directions with sudden turns and roundabouts, spreading below a large surface area.

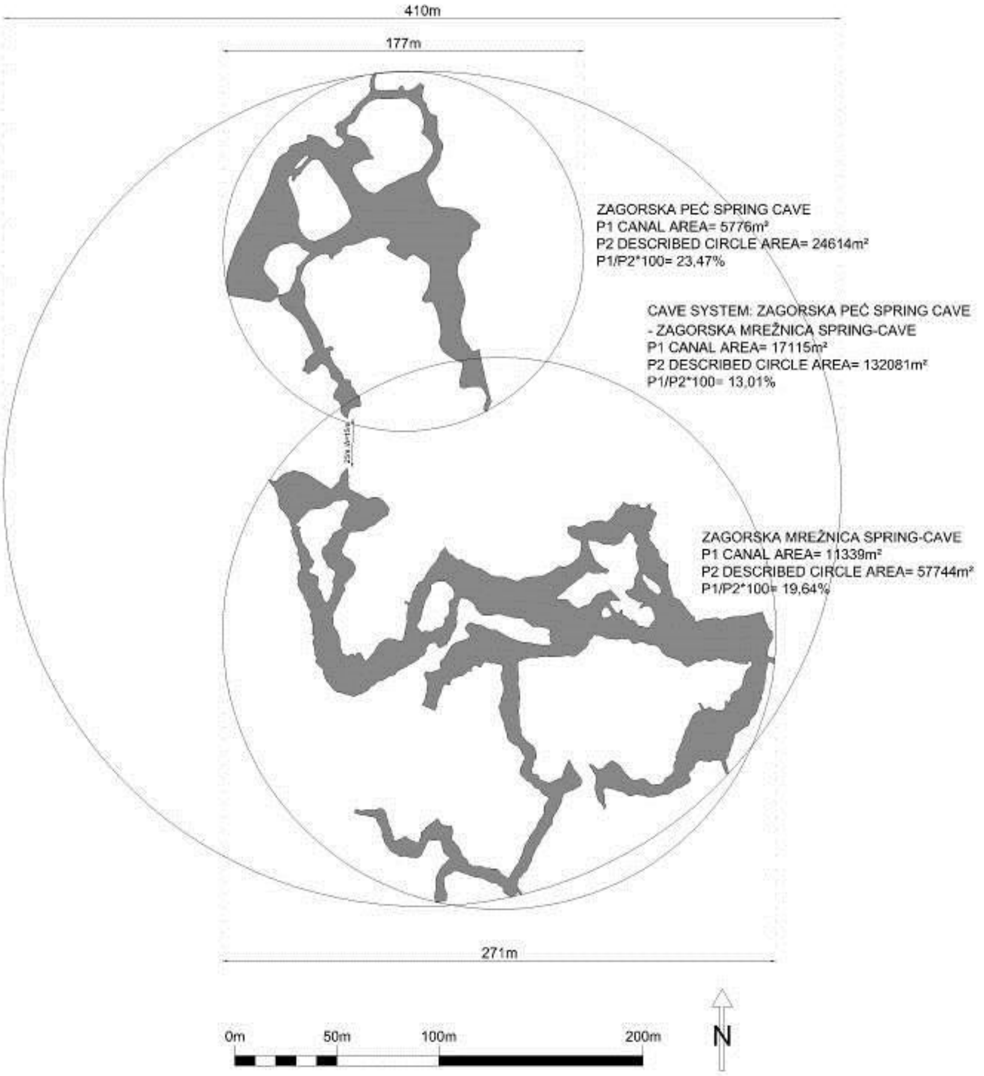


Figure 75:Surface area of cave passages.

The vertical distance between the two closest points is 14 m (Figure 75). It can be concluded that the two individual caves once formed one cave system separated by collapse of surface where now a sinkhole is formed.

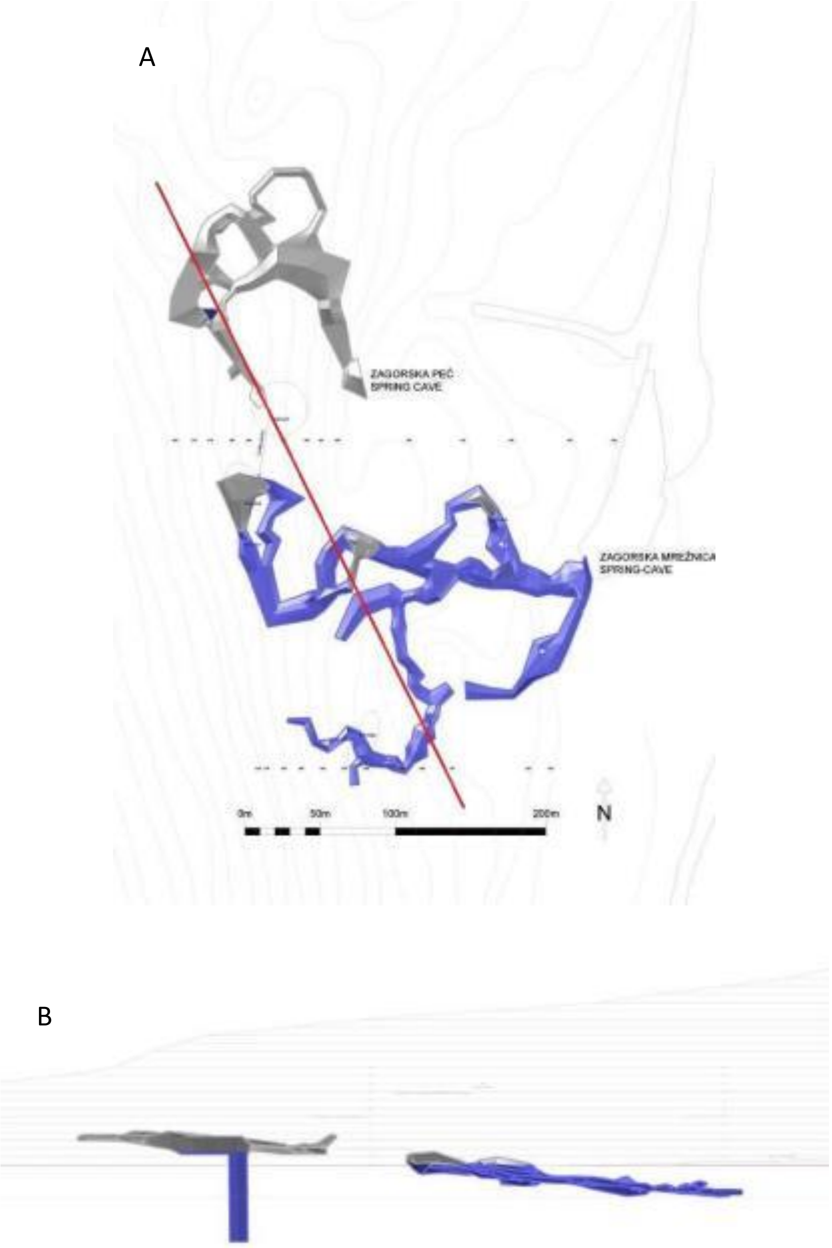


Figure 76: The 3D model from different views, the figure above is the plan-A (red line indicates where profile is taken, figure below is the profile –B (NW-SW).

The projection of the vertical plain (Figure 76) shows that Zagorska Peć cave and Zagorska Mrežnica spring cave are aligned along a single structure (bedding plane, or set of bedding planes). The only exception is the vertically protruding shaft in Zagorska Peć cave which is an infeeder and may represent a phreatic jump (Šušteršić, 1998). Based on current information the shaft is more than 120 m deep, approximate dimensions 10 × 7m.

5.2.5 LITHOLOGICAL CONTROLS OF CAVE DEVELOPMENT

The geological analysis of samples 1 and 2 (see locations in Figure 27) show that the mineralogical composition of the rocks is late diagenetic dolomite, probably of Jurassic age (Appendix V). The dolomite is bedded. The dolomites are dark grey without fossils with very clear grains of hypidiomorphic shape. Sample 1 has a grain size of 400 µm, while sample 2 (the sample size 5 cm gravel pebbles taken from the bottom of Glavni kanal passage) has the same grains but of 250µm (Figure 77). The same mineralogy of sample 2 and other samples indicate the local origin of gravel that is found in Glavni kanal passage.

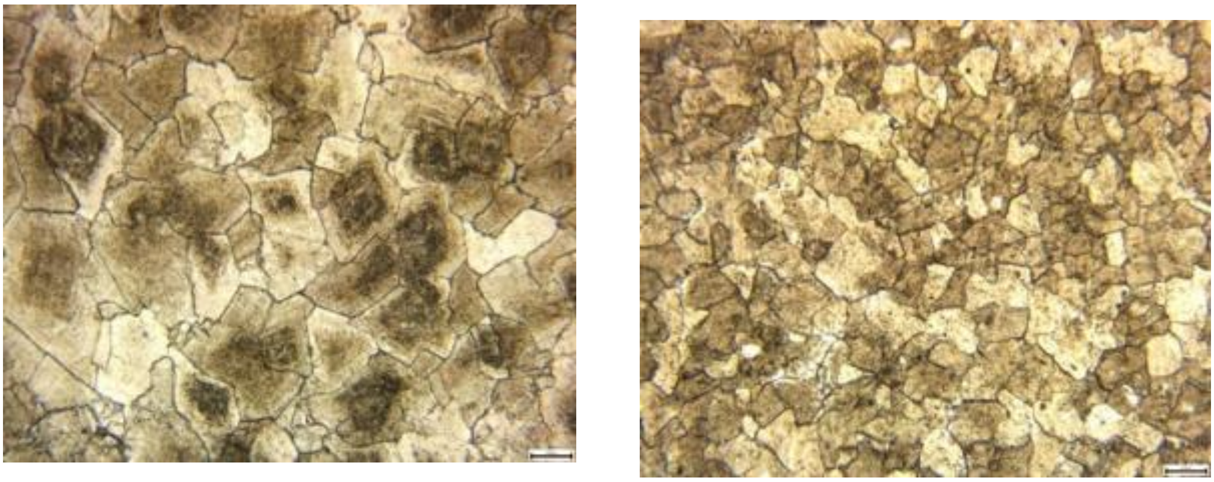


Figure 77: The dolomite structure of samples 1 and 2: Late diagenetic dolomite of Jurassic age.

Samples 3 and 4 are limestones, they contain Foraminifera fossils (Figure 78). They are categorized as bioclast-peloid packstone, a type of limestone. The matrix is micrite. Bioclasts are fragments of foraminifera, Ostracod, algae, *Teumetoporele* sp. and *Eolisakus* sp.. The sample has been recrystallized, homogenised and unconsolidated. The deposition environment was probably shallow with low energy.

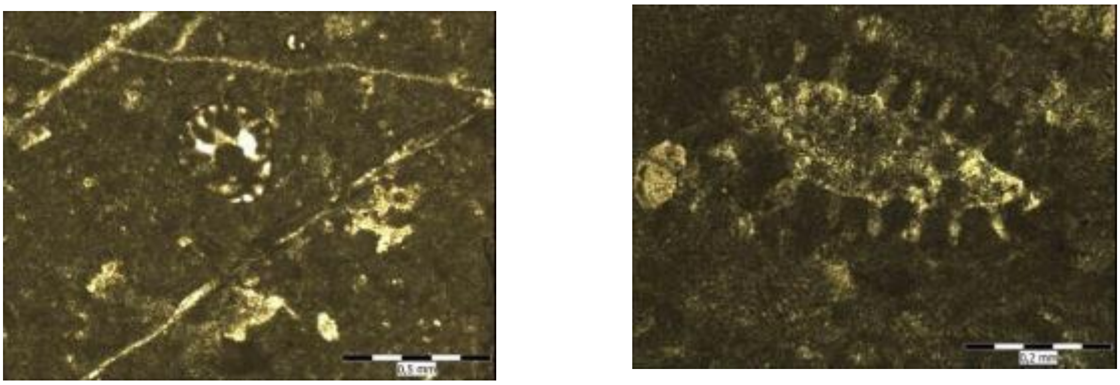


Figure 78: Bioclasts in samples 3 and 4.

The result of surface sampling shows two different strata: dolomite and limestone. Limestone covers dolomite. This is in accordance with the geological map that shows an interchange between limestone and dolomite deposits (Milorad et al., 1982).

Although there are two types of carbonate rocks, there are no distinctive morphological features between passages in limestone and passages in dolomite (see Chapter 5.5). It can be concluded that petrological composition has no or minimal influence on wall rocky relief.

5.2.6 MINERALOGICAL COMPOSITION OF THE SEDIMENT

The most abundant minerals in most of the samples are quartz, dolomite and calcite. Other identified minerals were clinochlore, muscovite, albite, margarite and microcline in traces (Table 5).

Table 5. Identified minerals in the sediment (see Figure 24 for sampling locations).

Sample	**Identified minerals indicated according to their abundance**
01/01	quartz, dolomite, calcite, muscovite, clinochlore, albite, microcline
01/02	quartz, dolomite, calcite, clinochlore, muscovite, albite
01/03	quartz, dolomite, calcite, clinochlore, muscovite, diaspore, albite
02/01	quartz, dolomite, calcite, clinochlore, muscovite, diaspore, albite, tremolite
02/02	quartz, dolomite, calcite, clinochlore, muscovite, microcline
02/03	quartz, dolomite, clinochlore, muscovite, calcite, microcline, nontronite
03/01	quartz, dolomite, calcite, muscovite, illite, clinochlore, margarite

The most dominant mineral sequence is Quartz, Dolomite and Calcite. According to the geological map of the Ogulin area (Velić et al., 1980 a, 1980b), the catchment area mostly consists of dolomite rock and limestone but this is not a detailed study. Dolomite and calcite particles are *in situ* or transported locally into the cave. Dolomite rock contains silicate minerals like quartz and clay minerals, so the origin of quartz could be the same as the origin of dolomite and limestone. Quartz can also be from autochthonous origin. Quartz has the lowest potential to weather and has preserved a dominant content in the cave sediment of Zagorska Mrežnica spring cave. Physical properties of quartz grains enable it to survive multiple recycling events, while also allowing the grains to display some small degree of rounding (Sasowsky & Mylroie, 2007, Figure 79). As the sediment is transported, the more soluble minerals are abraded or dissolved to leave the more stable mineral – quartz. Clay minerals are found in small or trace amounts.

Figure 79: Subangular sediment grains.

It can be concluded that the quartz sequence in the sediment can be of local origin, transported as an insoluble residual of bedrock (dolomite and limestone) found in the catchment area or it was produced *in situ* by weathering of fine-grained cave sediment found in the spring. So part of the quartz sequence can be considered autochthonous, derived within the cave and possibly moved inside the same cavity. The destruction of fine-grained cave sediment is caused by a change in the environment (Frumkin, 2001). The cave sediment was deposited in a still environment and has been destructed by erosional action of the water current. This can be also concluded because of the presence of muscovite in small amounts as a common mineral in sandstone that was found in the Zagorska Mrežnica spring cave.

Only fragments of cave sediment can be found along the cave passages. Biggest amount of sediment is found in Lijevi kanal passage with minimal water current. Sediment is partially concreted and the thickest deposit is now 1 m. Smaller fragments are found in other parts of the cave. Most of it has been washed out of the cave system by now (Figure 80).

Figure 80: The remains of cave sediment in the Lijevi kanal passage in Zagorska Mrežnica spring cave.

In one of the sediment sections (02/03) clinochlore mineral has been found as one of the important minerals. These kinds of deposits are present in large amounts in the spring in places where the cave passage suddenly widens, resulting in the reduction of water flow, allowing for the particles to deposit. The fine-grained nature of these deposits could suggest that the sediment was transported in suspension with the inflow of surface water (Deer et al.,1966). It could originate from soil wash-down from the epikarst that is washed into the cave through solutionally widened fractures as gravitational debris, or it could be transported into the cave system through ponors (White, 2007). As one of the typical minerals of clay soils in the Ogulin-Karlovac region (Šaban, 2012) the presence of clinochlore was to be expected since its origin is connected to a broader area.

Other minerals found in the sediment are muscovite, albite, margarite and microcline in traces depending on the sample. Muscovite is commonly present in sedimentary rocks. Since it is not especially resistant to chemical weathering, it is quickly transformed into clay minerals. That is why there are only small amounts of this mineral found in the sediment. Tiny flakes of muscovite sometimes survive long enough to be incorporated into sediments and immature sedimentary rocks. This shows that these sediments and rocks have not been subjected to severe weathering (Willet, 2011).

Table 6. Results of the analysis of carbonate content.

Sample:	Carbonates (%):
01/01	69.14
01/02	75.82
01/03	84.01
02/01	66.84
02/02	77.46
02/03	83.68
03/01	43.41

The local sources (bedrock, sediment) of carbonate are the main factor of carbonate content in the sediment sample (Table 6). The uniform carbonate content of these sediment samples (except sample 02/03) can be explained as the result of deposition of carbonate-rich sediment containing dolomite and calcite minerals (Table 4, Bohrmann et al., 1998). A 10% variation in increase by sediment segment (01/01 is the bottom of the sediment sample, 01/02 is the middle and 01/03 is the top of the sediment sample) is noticeable.

The sample 03/01 contains less carbonate content since this sample possibly partly originates from surface soils and the clay fraction is dominant.

Since there is a large amount of Quartz, and a lower content of carbonates in the sediment and no rock in the catchment area which would have a larger content of Quartz. There is no mineral that is not related to local origin. If the cave was just a conveyor belt, there would be higher amounts of carbonates. This proves that sediment stays in the cave for some time, and carbonates are partially dissolved.

Much of the sediment originates from eroded cave sediment. There are parts of the cave that have a hydrological function of a vent where a large amount of sediment is deposited. The sediment deposition does not re-sediment.

5.2.7 GRANULOMETRIC ANALYSIS OF SEDIMENTS

Grain size distribution depends on the local environment. The sediment sorting depends on the ratio between time-rate of supply of detritus and efficiency of the sorting agent (Folk, 1980). The environment of sedimentation in the spring of Zagorska Mrežnica experiences high flow variability with a rapid increase during rain events and slow recession and periods of stagnant flow.

According to Folk’s (1980) classification, the first subsample (01/01), which is the bottom of the sediment sample (01), is silty sand where the sand fraction is 79.1% and the mud fraction is 20.9%. Coarse sand comprises 0.8%, fine sand comprises 56.9% and medium sand is 21.4% of the sediment, while coarse silt is 10.5%, medium silt is 3.9%, and fine silt is 3.6%. Clay represents only 2.8% of the sediment (Figure 81).

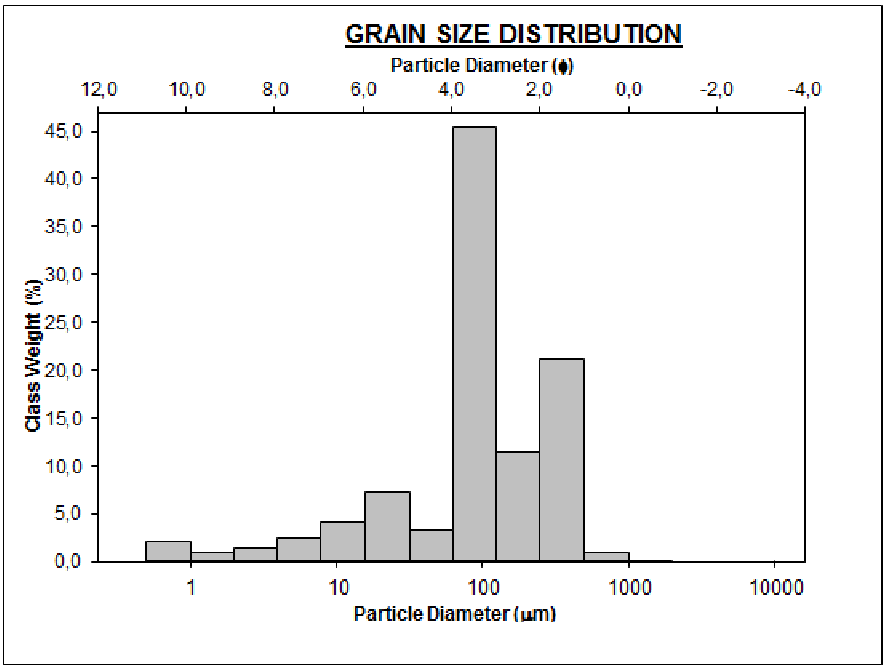


Figure 81: Grain size distribution in sample 01/01.

The next subsample (01/02), which is the middle of the sediment sample 01, is poorly sorted muddy sand where the sand fraction is 84.9% and the mud fraction is 15.1%. From the sand, the fraction of coarse sand comprises 1.6%, fine sand comprises 46% and medium sand is 37.2% of the sediment, while coarse silt is 7.2%, medium silt is 2.7% and fine silt is 2.8%. Clay represents only 2.2% (Figure 82).

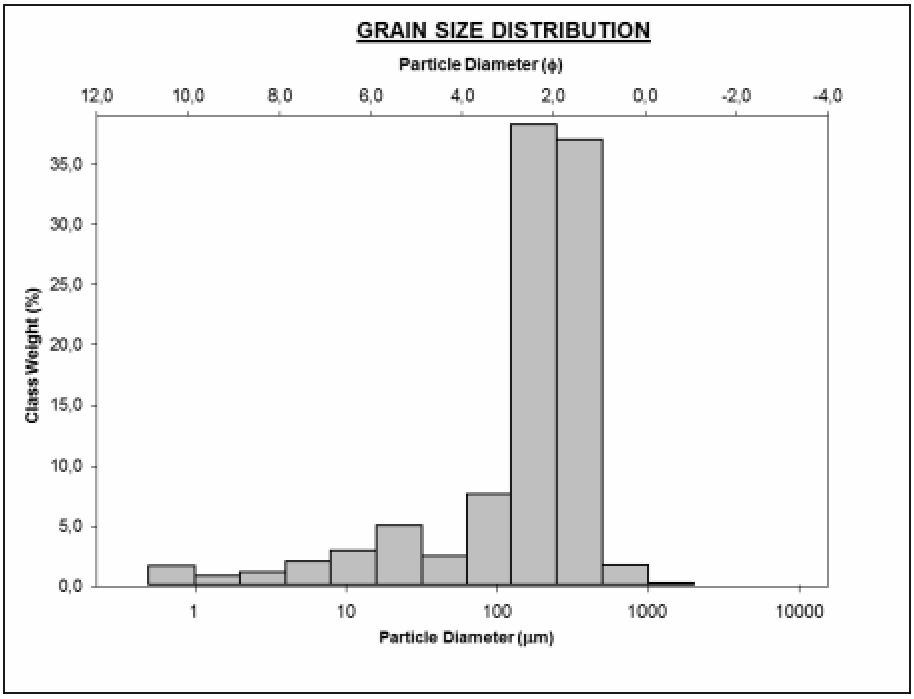


Figure 82: Grain size distribution in sample 01/02.

The third part of the first sample (01), subsample 01/03, which is the top of the sediment body, is also poorly sorted muddy sand where the sand fraction is 88.2% and the mud fraction is 11.8%. From the sand fraction, coarse sand makes up 0.9%, medium sand 25.6% and the fine sand fraction comprises 61.7%, while coarse silt is 6% and medium silt is 2.0%. Clay represents 1.8% (Figure 83).

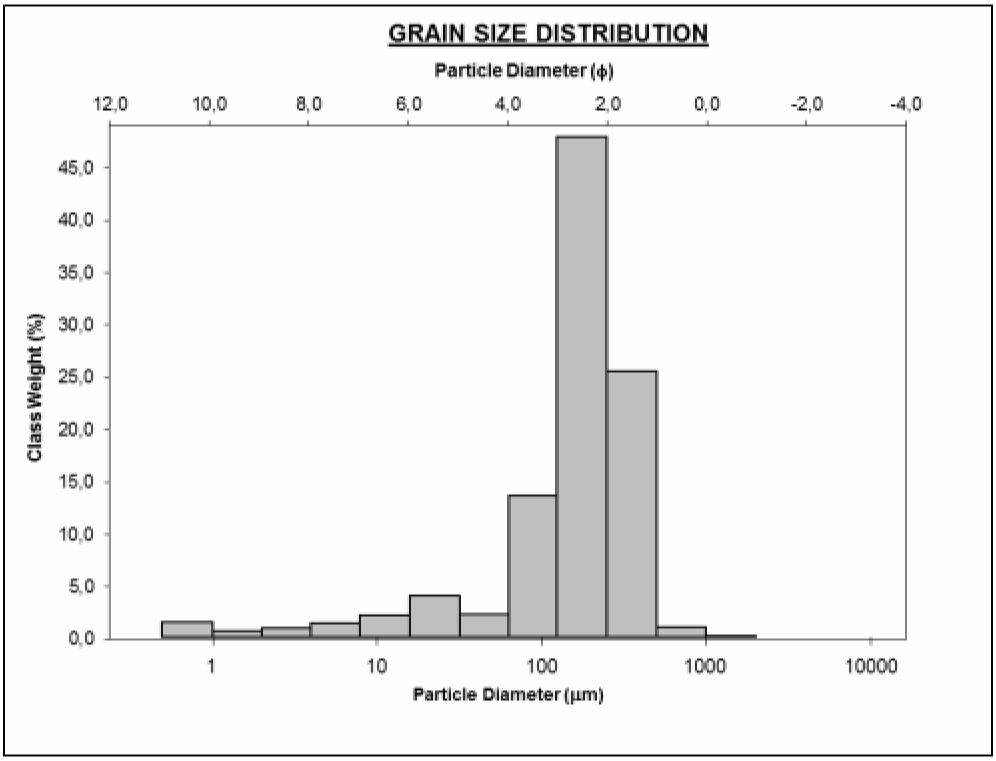


Figure 83: Grain size distribution in sample 01/03.

The second sediment sample 02 differs from sample 01. This sample was taken in the Mammoth chamber (Mamutova dvorana) where there are large deposits of sediment showing the low-energy conditions of sedimentation environment compared to sample. As in sample 01, sample 02 is divided into three subsamples according to the depth of the sediment (02/01, 02/02, 02/03). Subsample 02/01 represents the deepest part of the sediment. The sediment is characterized as muddy sand and poorly sorted, where the sand fraction is 71.8 % and the mud fraction is 28.2% (Figure 84). From the sand fraction, coarse sand makes up 1.6%, medium sand is 1% and fine sand comprises 69.2% of the sediment, while coarse silt is 16.5%, medium silt is 4.0 % and fine silt is 3.5%. Clay represents 4.1%.

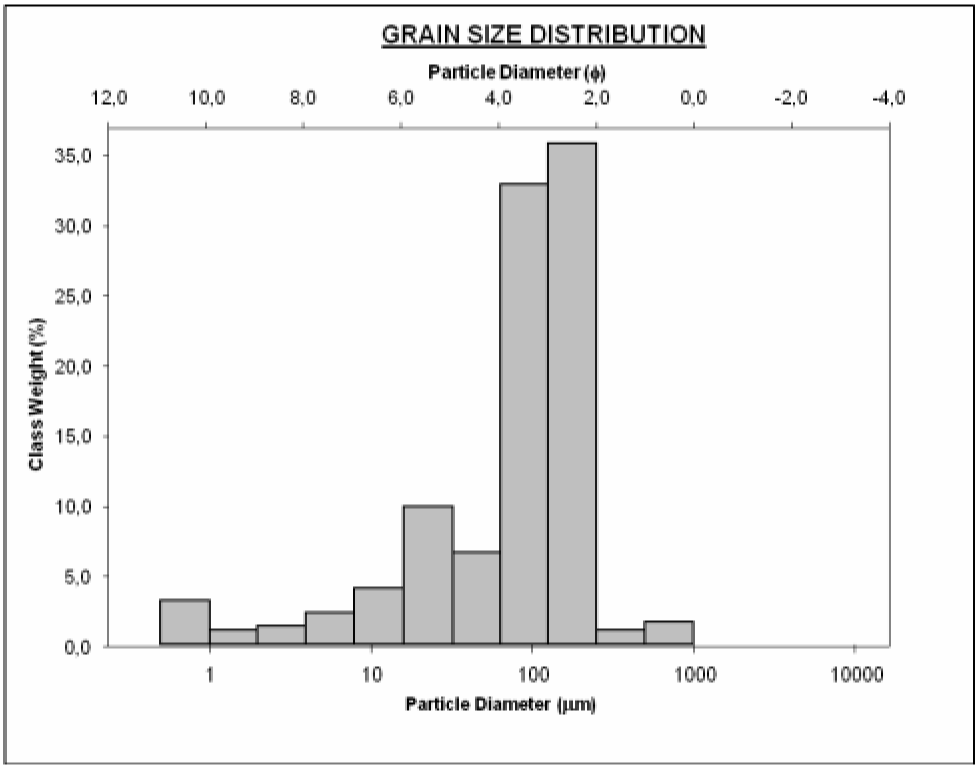


Figure 84: Grain size distribution in sample 02/01.

The middle part of the second sediment sample is subsample 02/02 and is characterized as poorly sorted muddy sand, where the sand fraction is 57.3 % and the mud fraction is 42.7% (Figure 85). From the sand fraction, medium sand is 1.9%, and fine sand comprises 55.4% of the sediment. Coarse silt is 17.4%, medium silt is 9.5 % and fine silt is 7.8%. Clay represents 8.3%. In this sediment section, the amount of fine-grained fraction is increasing, indicating periods of either no or very little water flows. For these particles to settle it takes time due to the viscosity of water and gravitation. These conditions are very rare in the Zagorska Mrežnica spring cave due to the high discharge of the spring.

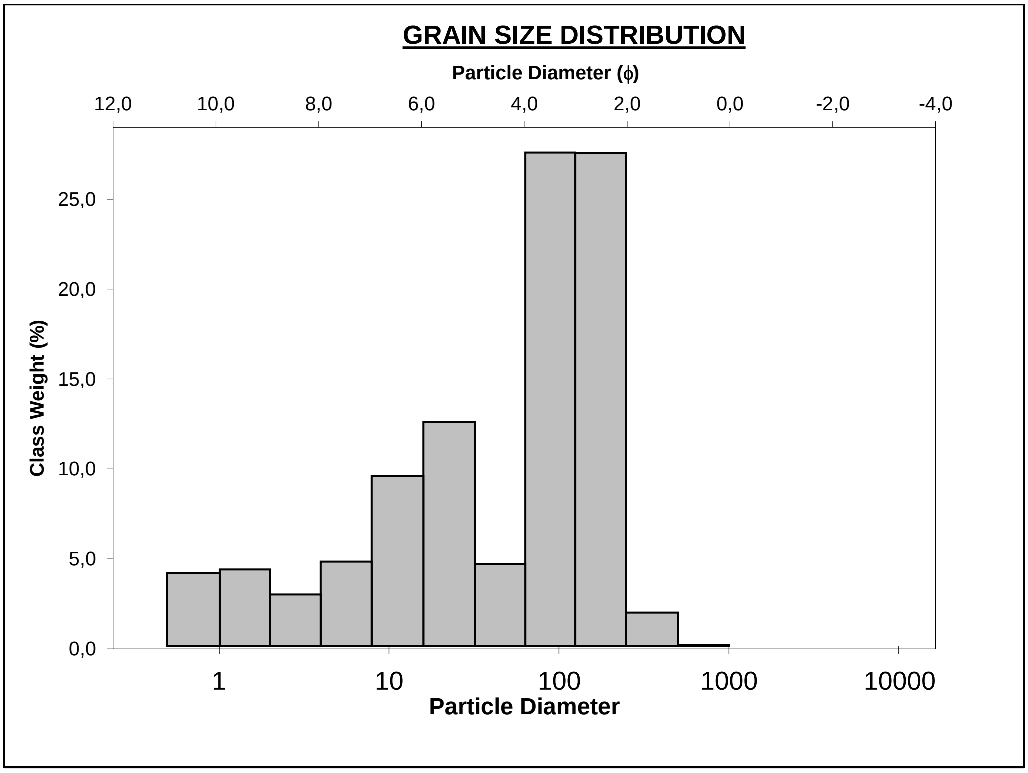


Figure 85: Grain size distribution in sample 02/02.

The top part of the second sediment sample is subsample 02/03 and is characterized as sandy mud, poorly sorted where the sand fraction contains 30% and the mud fraction contains 69.2% (Figure 86). From the sand fraction, medium sand is 0.6%, fine sand comprises 30.2% of the sediment, while coarse silt is 36.3%, medium silt is 13%, and fine silt is 10.6%. Clay represents 9.3%.

It can be concluded that the second sample, although it is poorly sorted, shows some sorting of material. The ammount of smallest particles increases from the bottom to the top of the sediment. The Mamutova dvorana chamber where the sediment was collected is the place in the cave system with the largest sediment deposits. It has the function of a sediment trap.

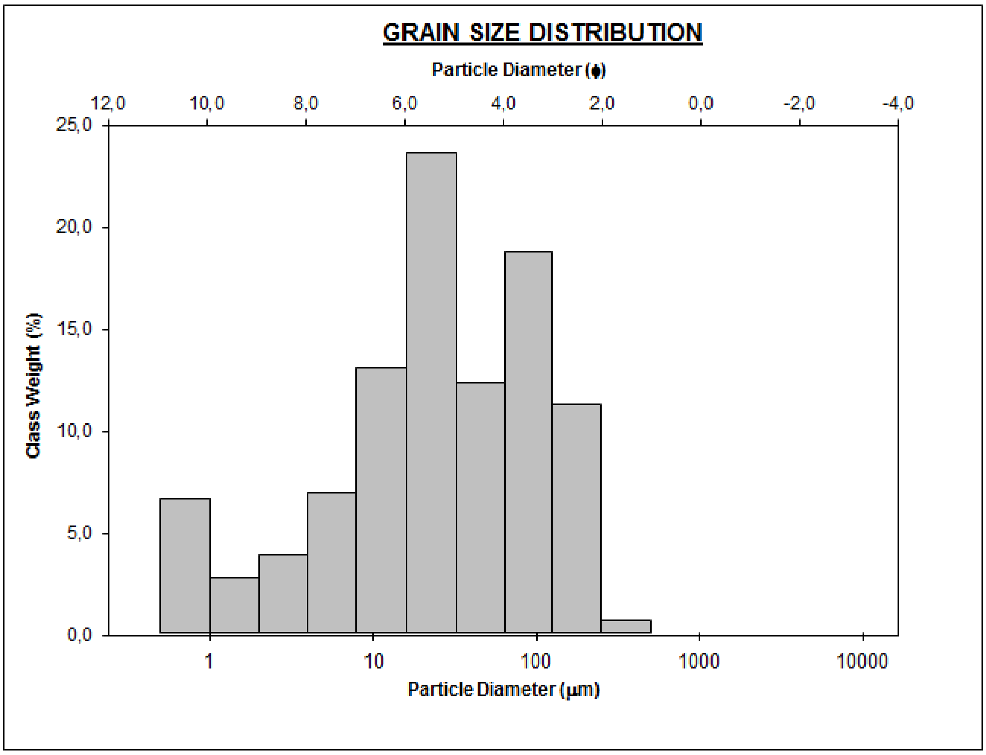


Figure 86: Grain size distribution in sample 02/03.

Sediment sample 03 was not divided into subsamples due to the small amount and it is characterized as slightly gravely muddy sand. The gravel is 1%, sand fraction is 87.9 % and the mud fraction is 11.1% (Figure 87). From the sand, the fraction coarse sand is 9.1%, medium sand is 42.4% of the sediment, and fine sand comprises 33%, while coarse silt is 5.7%, medium silt is 2.7%, and fine silt is 1.7%. Clay represents 1%. This sediment sample was taken in the farthest part from the entrance in the main passage. Water-flow here is always quite strong, based on observations during the cave-diving research. This can be seen from the sediment in a way that there is a very little ammount of small particles and the gravel is found only in this sample. Conditions for sedimentation in this part of the cave are turbulent water flows carrying debris. Due to the morphology of the cave passage and the increase in friction on the sides, the water flow velocity drops so the sediment can be found only on the sides of the passage.

The results of granulometric analysis of sample 03 show that the sediment is poorly sorted (Figure 87). The main sedimentation process is debris flow and fluidized flow as a part of the underground water flow.

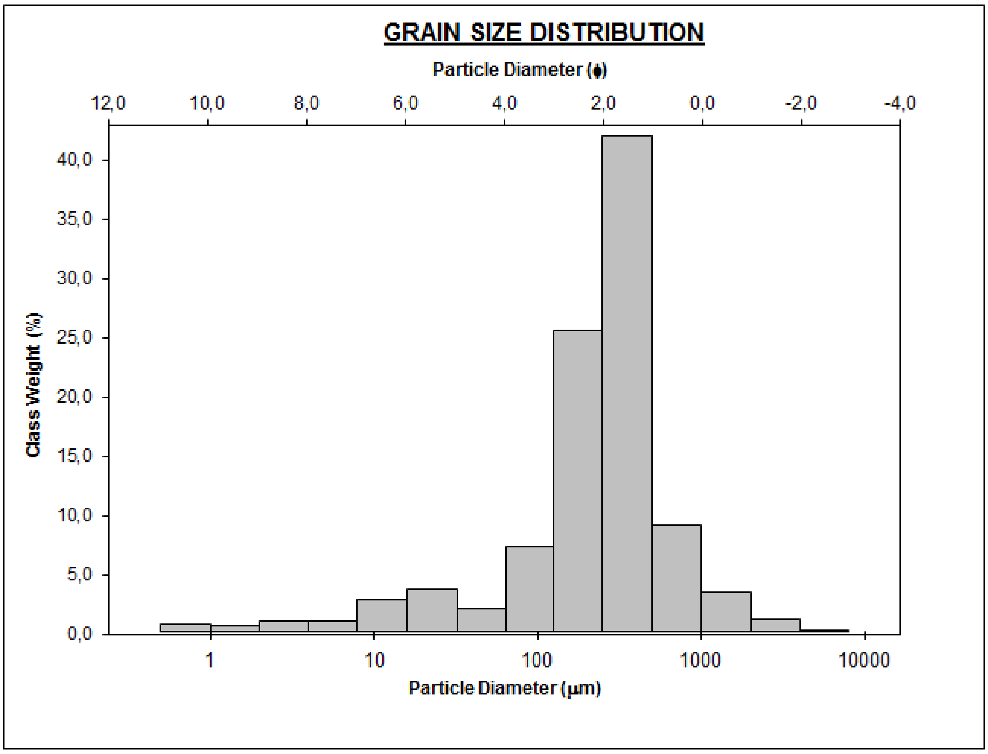


Figure 87: Grain size distribution in sample 03/01.

The main sedimentation process is debris flow and fluidized flow as a part of underground water flow. Fluidization of cave sediment in Zagorska Mrežnica spring cave has occurred when the upward drag exerted by moving pore fluid exceeded the effective weight of the grains. According to Selley (2000), when this upward movement exceeds the minimum fluidization velocity, the bed expanded rapidly, porosity increased, and the bed became liquefied and fluid supported, rather than grain supported.

The cross-section of the Glavni kanal passage is about 30 m². Considering that most of the water flows through this passage and that the monthly average discharge often surpasses 35 m³/s, one can conclude that the average flow velocity in the Glavni kanal is often higher than 1 m/s (data from Gauging Station 4181). From the interval of grain sizes and the Hjulström diagram one would expect that such sediment would be eroded (Hjulström, 1935, Figure 88).

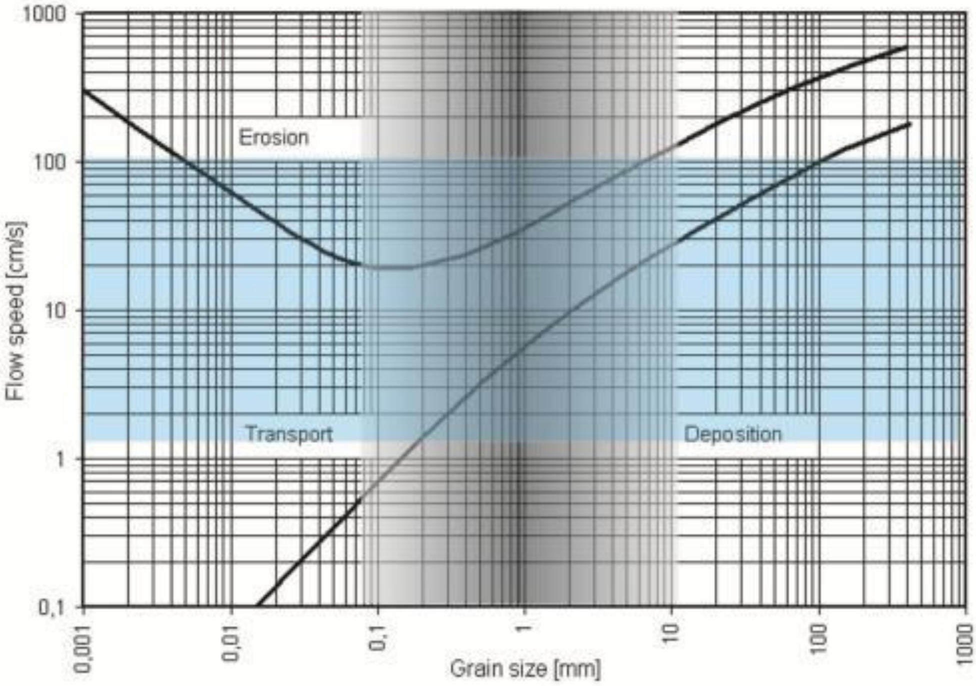


Figure 88: Hjulström curve with marked grain size and flow speed.

On the other hand, the relative abundance of quartz indicates that the sediment is *in-situ* for a longer period since dolomite and calcite minerals have largely been dissolved. It also means that no new sediment is being deposited. This might indicate that sedimentation occurred in a much calmer period or that exact sampling location acts as a sediment trap due to very uneven velocity distribution in an irregular passage cross-section.

5.2.8 GRAIN-SHAPE SPHERICITY AND ROUNDNESS ANALYSIS

Grains are mostly spherical but very angular or angular (Figure 51). The speed of rounding depends on the composition, hardness and mineral cleavage. Grains of other minerals found in the sediment sample are more rounded because during transport they rounded much faster, and over a shorter distance than a more resistant quartz pebble. The rate of rounding is also affected by the grain size and energy conditions (Grippo, 2013).

The sphericity of a particle influences erosion, transportation, and deposition patterns. The roundness of a particle is a measure of the distance that the particle travelled and the harshness during transportation. Roundness defines how "smooth" a grain is. The roundness of carbonate grains starts over distances of just a few kilometres (Flügel, 2010). More resistant minerals like quartz need much longer fluvial transport. Quartz also becomes well rounded but at a much slower rate, equalling the roundness of limestone after about 240 km (Folk, 1980). Downstream roundness increases more rapidly for carbonate grains than for other lithologies (Mills, 1979).

Figure 89: Angular sediment grains from sample 01/01.

Larger grains are rounded more easily than smaller grains. Also, quartz grains differ in shape from carbonate grains (Folk, 1980). Rock fragments > 32 mm in diameter became rounded after traveling a short distance, whereas those between 8 and 32 millimetres remained angular for comparatively long distances, partly due to the contribution of fragments broken from larger particles. Grains below 8 mm in diameter showed little change even after longer transport (Russel, 1939). Almost all grains in the sediment samples from the spring of Zagorska Mrežnica are smaller than 0.5 mm, so transport did not affect their roundness so much (Figure 89).

Figure 90: Angular sediment grains from sample 02/01.

On analysis of sediment subsamples 01/01, 01/02 and 01/03, an increase in sphericity can be observed from top to bottom, along with a slight increase in roundness, from the bottom to the top of the sediment (Figures 90, 91). When combined with granulometric and mineralogical analysis, it is shown that an increase in clay and mud fractions in the sediment increases from the bottom to the top.

The subsamples 02/01, 02/02 and 02/03 have a higher increase in clay and mud compared to the first sample. It shows almost no difference in sphericity but roundness decreases from the bottom to the top of the sediment (Figure 91, 92). This can be correlated with the granulometric analysis in a way that the top section of the sediment sample has the finest grains, but the smaller the grain, the slower the rounding (Pettijohn et al., 1987).

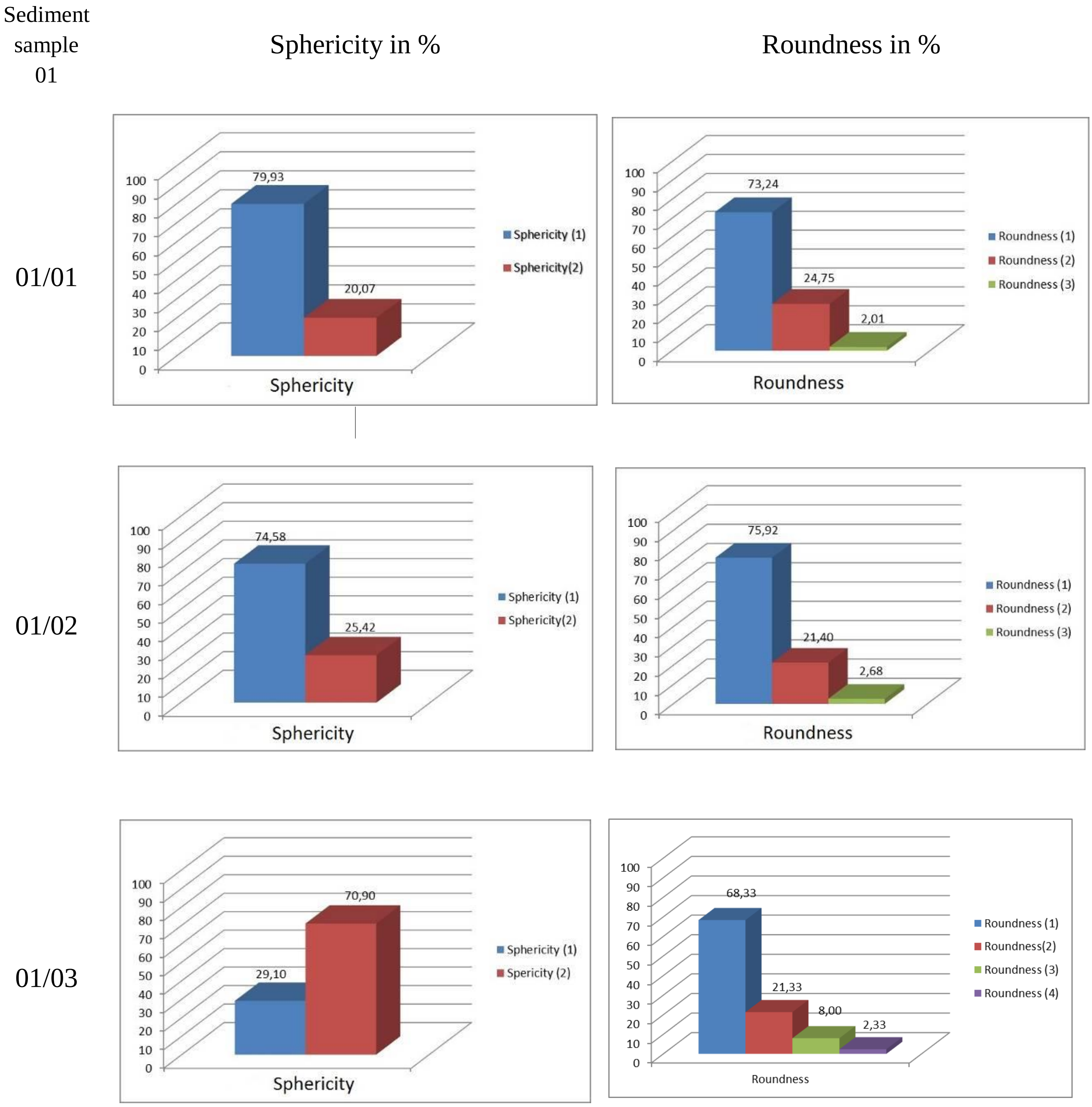


Figure 91: Sphericity and roundness of sediment grains in sample 01.

The subsamples 02/01, 02/02 and 02/03 have a higher increase in clay and mud compared to the first sample. It shows almost no difference in sphericity but roundness decreases from the bottom to the top of the sediment (Figure 91, 92). This can be correlated with the granulometric analysis in a way that the top section of the sediment sample has the finest grains, but the smaller the grain, the slower the rounding (Pettitjohn et al., 1987).

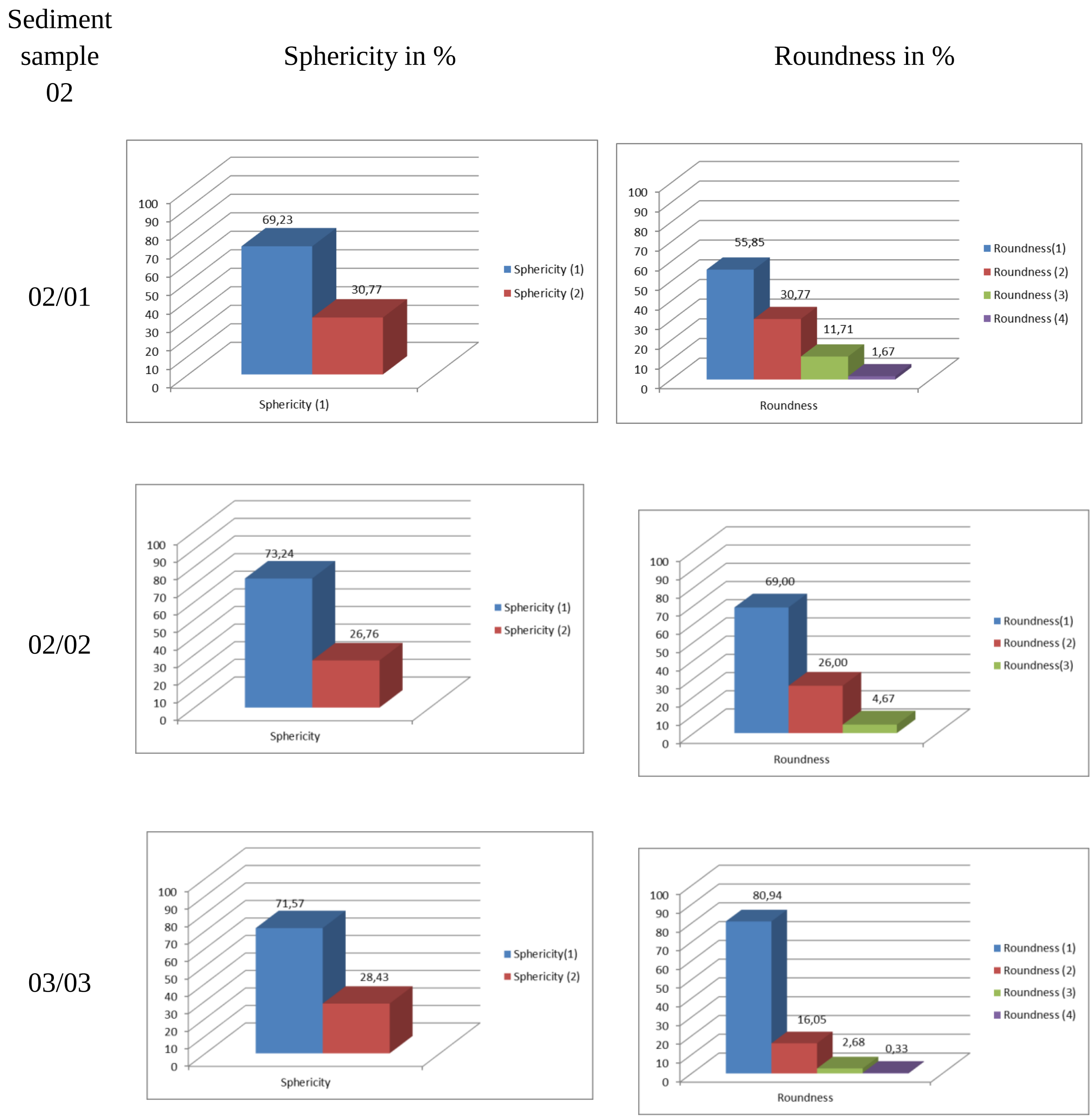


Figure 92: Sphericity and roundness of sediment grains in sample 02.

Sample 03 shows results similar to the first sample. This also correlates with the granulometric analysis that shows the same results as the first sample (Figure 93).

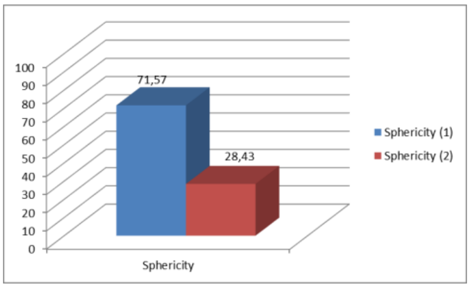
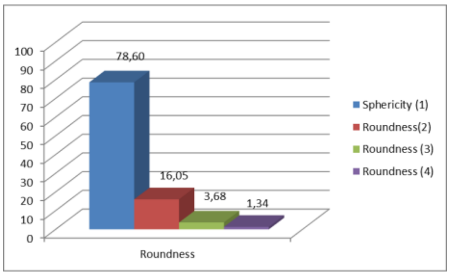
Sediment sample 03	Sphericity in %	Roundness in %
03		

Figure 93: Sphericity and roundness of sediment grains in sample 03.

All sediment samples, regardless of mineralogy, show high angularity, which is an additional indication of their local origin since they have not been transported for longer distances.

5.2.9 ESTIMATION OF PRESENT WALL RETREAT RATE BASED ON WATER CHEMISTRY

The Ca^{2+}-to-Mg^{2+} ion ratio indicates the rock type in the catchment and spring areas. Samples exhibit a rather higher ratio of Ca ions. The reason for this result lies in several factors: the dissolution rate of dolomite is considerably smaller than calcite (Appelo & Postma, 2005), and a high concentration of Mg ions would mean that Zagorska Mrežnica spring cave has a long ground water residence, which is not the case. Zagorska Mrežnica spring cave is a fast throughput aquifer. The second factor is the general lithology of the catchment area, which is mostly Jurassic limestone and dolomite. Because most limestone contains some Mg, Ca/Mg ratios for limestone, springs are typically in the range of 6 to 8. Intermediate values would indicate that both limestone and dolomite are present along the flow path leading to the spring.

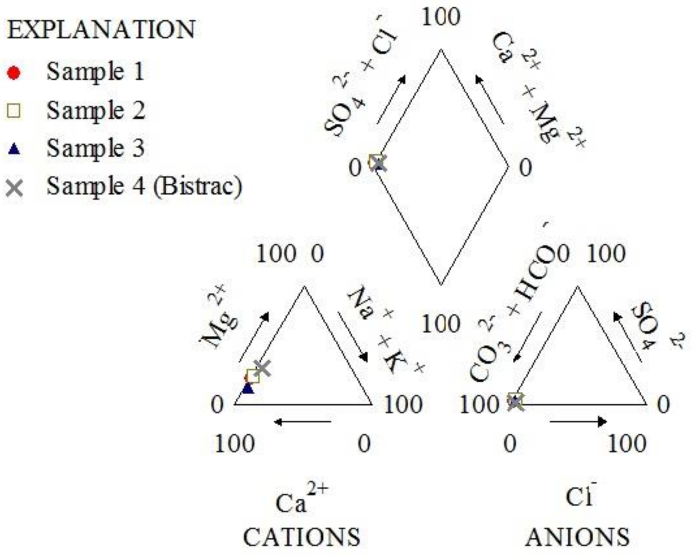


Figure 94: Piper diagram illustrating the water chemistry of Zagorska Mrežnica spring cave and Bistrac.

The histogram (Figure 94) shows a slight difference in composition in the low water and high water period. During the low-water period on 25.9.2014, concentrations of solutes were slightly higher than after a sudden rainfall occurrence due to dilution in the high water period. Therefore, it can be concluded that chemical reactions in the aquifer do not cause significant and rapid changes in the concentration of Ca and Mg cations (Figure 95).

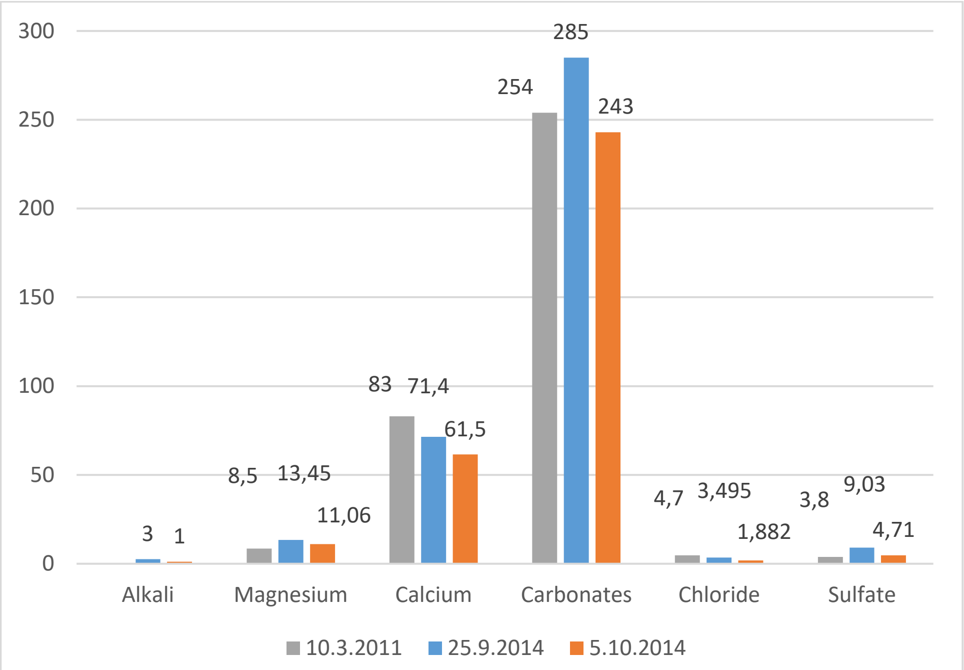


Figure 95: The result of water chemistry analysis in mg/l.

The slightly higher concentrations in low water indicate longer groundwater residence times and thus higher saturation rates.

The same is with sulphates which originate from agriculture. Their concentrations are slightly higher during low water periods, and lower during high water periods, because of dilution.

The total dissolved solids values vary in range from 199 to 234 mg/l, which classifies the water as hard. The pH ranges between 7.3 and 7.4, which is also typical for karst waters. Metals and nitrates are present in very low amounts indicating that the water is of high quality and anthropogenic influence regarding land use. Water runoff and air pollution is very low (Narodne Novine 125/13, 77/98).

The Phreeqc (Appelo & Postma, 1993) simulation give SI values of solution between –0.1 and 0, which means that solutions are slightly undersaturated. The saturation ratio is therefore between 0.9 and 1. According to (Eisenlohr et al., 1999) this, the saturation ratio dissolution proceeds under the non-linear law:

$F= k_n(1-c/c_{eq})^n$,

Where n is the rate order, k_n is the rate constant and c/c_{eq} is the saturation ratio.

For a rough estimation, fourth order kinetics were taken ($n = 4$, $k_n = 4x10^{-8}$ mol/cm^{2}s) (Eisenlohr et al.1998). For the saturation ratios obtained in samples this yields a dissolution rate in the order of 10^{-12} mol/cm^{2}s, which is equivalent to a dissolution wall retreat rate in the order of a few cm per ky.

The chemical composition of water at the spring depends on the lithology type of the catchment area, recharge mechanism, flow paths and the climate (Hunkeler & Mudry, 2007). Based on the ratio of cations and anions, the water from Zagorska Mrežnica spring cave can be classified as bicarbonate water where Ca^{2+} and Mg^{2+} are dominant cations (Figure 57; Krešić & Stevanović, 2010).

5.3 HYDROLOGICAL CHARACTERIZATION OF THE SPRING

The time series of precipitation and average and maximal discharge between the periods of January 1949 to October 1952 and January 2009 and October 2012 have been compared. The same number of months through the same seasons have been compared. It was found that there is no statistical difference between precipitations in both periods. The t-test for averages gives a p-value of 0.84, meaning that there is a high probability that no significant changes in precipitation occurred. On the other hand, the discharge has changed severely, the t-test returning to 0.27 for the maximal discharge. If there had been no change it would be a value close to 1.

Furthermore, analysing the correlation between precipitation and discharge for the period of 1949-1952 and the period of 2009-2012 (Figure 96) shows:

1. The maximum discharge was larger in the period before the damming of Zagorska Mrežnica River and the construction of the artificial accumulation.
2. Minimum discharge did not change significantly.
3. The correlation between precipitation and the maximum discharge is stronger in the period of 1949-1952.

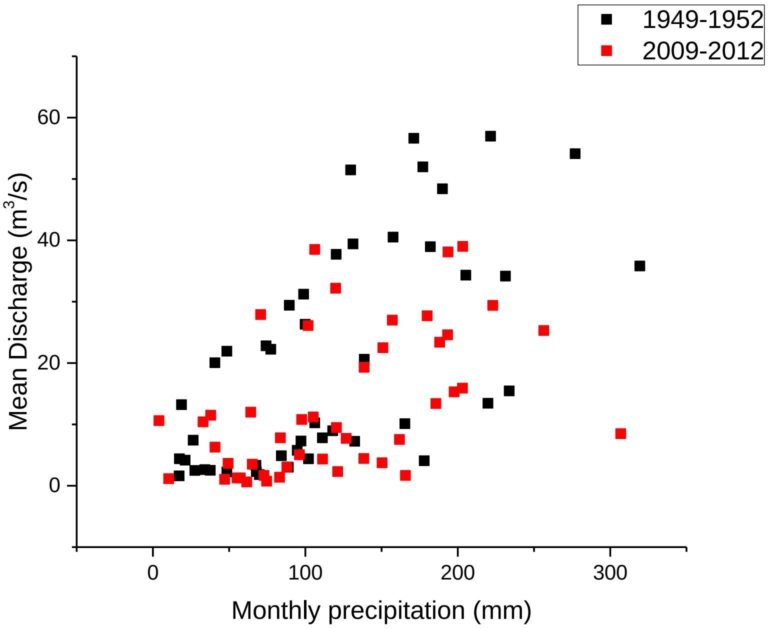


Figure 96: Correlation graph of precipitation and discharge for 1949-1952 and 2009-2012.

The correlation between precipitation and maximum discharge of Zagorska Mrežnica spring cave shows that there is a very good conduit development/tertiary porosity so the underground water flow paths have no delay and no significant influence of soil cover or matrix storage that would serve as a retainer of water.

The Velika Kapela Mt. has a rugged terrain with steep slopes. The karst poljes are between 130-200m higher a.s.l. than Zagorska Mrežnica spring cave. The high massif of Velika Kapela allows a lot of diffuse infiltration of precipitation. On the hypsometric profiles from karst poljes to Zagorska Mrežnica spring cave it is visible that there is a large vadose zone with numerous vertical shafts and fractures (Figure 97). This represents a large zone of diffuse autogenic recharge. Significant role in this zone represents a zone of epikarst providing probably more long-term diffuse autogenic recharge and has the most significant input during the melting of snow and intensive rainfall. Then it feeds the Zagorska Mrežnica spring cave for weeks, depending on the amount of snow on the mountain. It can be concluded that the thick vadose zone represents a significant recharge zone and water storage capacity during snow melt and rainy season with good hydraulic conductivity of under-laying transmission zone.

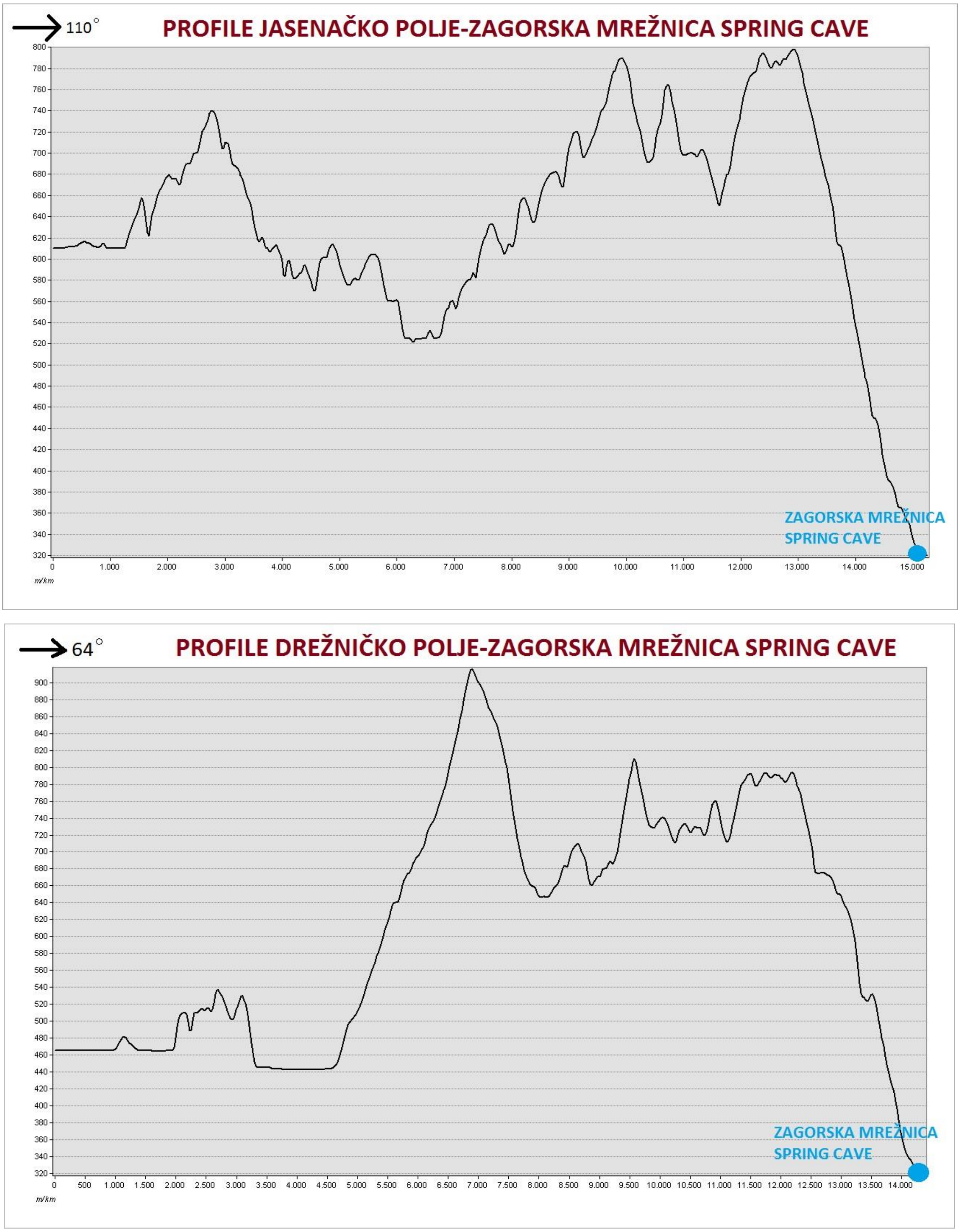
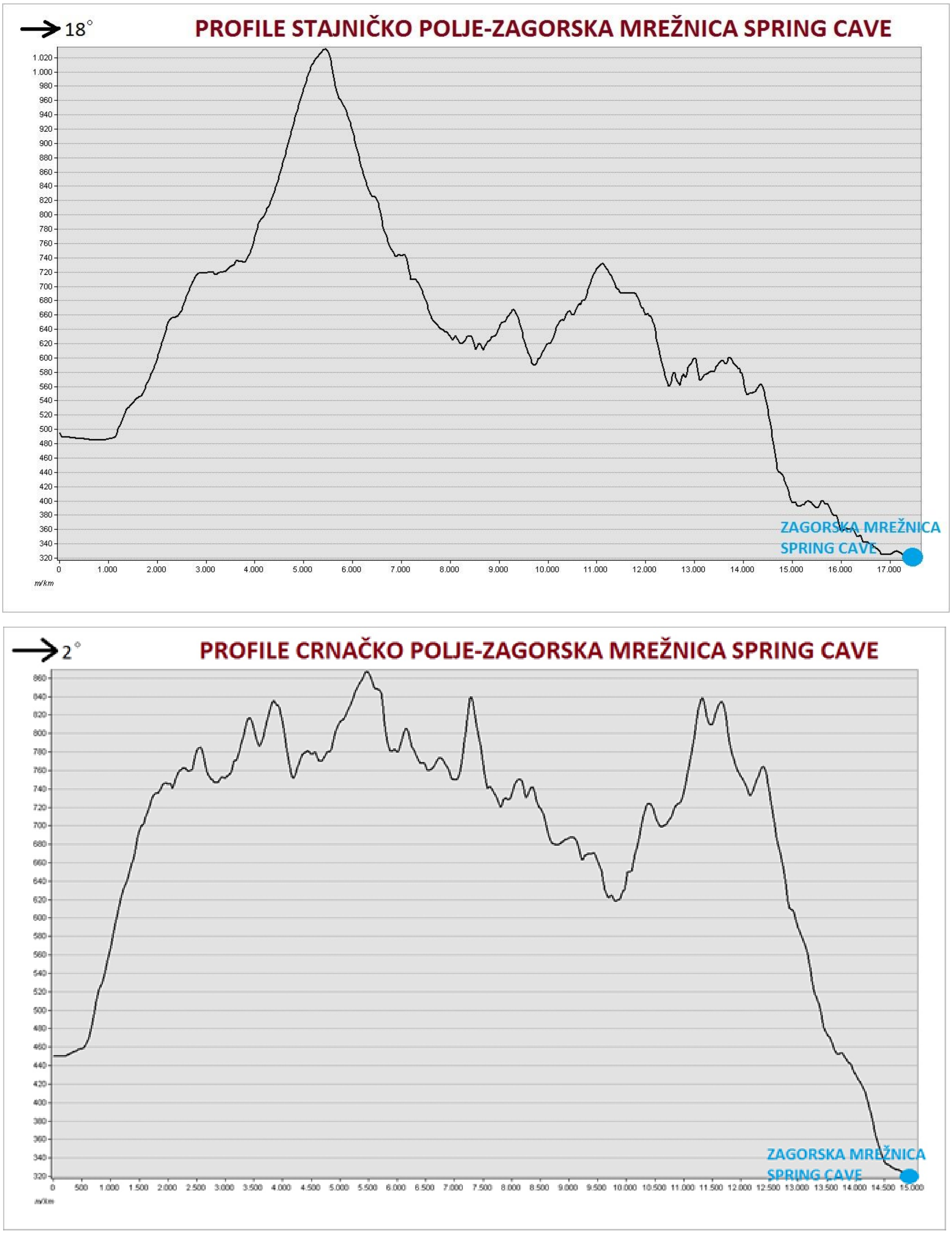


Figure 97: Hypsometric profiles of karst poljes in the hinterland of Zagorska Mrežnica spring cave.



PROFILE STAJNIČKO POLJE-ZAGORSKA MREŽNICA SPRING CAVE

PROFILE CRNAČKO POLJE-ZAGORSKA MREŽNICA SPRING CAVE

Figure 98 (continued): Hypsometric profiles of karst poljes in the hinterland of Zagorska Mrežnica spring cave.

There is no data on the water-level in Zagorska Mrežnica spring cave before the construction of the pumping station and accumulation Sabljaci, but what is visible is that the discharge is “buffered” by the accumulation Lake Sabljaci. This results in the increase of the water level at the discharge point that resulted in an increase in the hydraulic head inside the aquifer and blockage of the discharge point. This is a classic retention effect (Krešić & Stevanović, 2010). The Sabljaci accumulation was constructed to maintain the water level at the highest position, and create an accumulation of water for the Gojak Hydropower plant. In such a way, the retention of water of the aquifer is increased. The lake also represents a local barrier that raised the karst water level within the Velika Kapela Mt. aquifer (Bonacci & Andrić, 2010). The deepest caves of this area are over 100m, which indicates deep karstification processes in Velika Kapela Mt.

6 VULNERABILITY ASSESSMENT OF THE CATCHMENT AREA OF ZAGORSKA MREŽNICA SPRING CAVE

The pumping station is in a protected zone, but the rest of the cave system that goes under the pumping station, road and nearby houses and dolines is not. Cave divers reported to the water supply staff that waste was illegally dumped in dolines above cave passages, and some of it in the cave system. The resulting map provides an inventory of the potential hazards, their location in the catchment area and the degree of harmfulness (Figure 98). The assessment shows that aquifer vulnerability ranges from low to very high. The area is characterized by a dispersed rural population. Since the research area has no bigger urban centres except Ogulin, only one state road and a part of a highway, no industries, and very little agriculture, the highest contribution to vulnerability are karstic features such as dolines, swallow holes, caves, and sinking streams. The well-developed epi karstic zone and a thin layer of soil results in a lack of effective attenuation mechanisms and can be the cause of fast infiltration of pollutants through a network of fissures (Doerfliger et al., 1999).

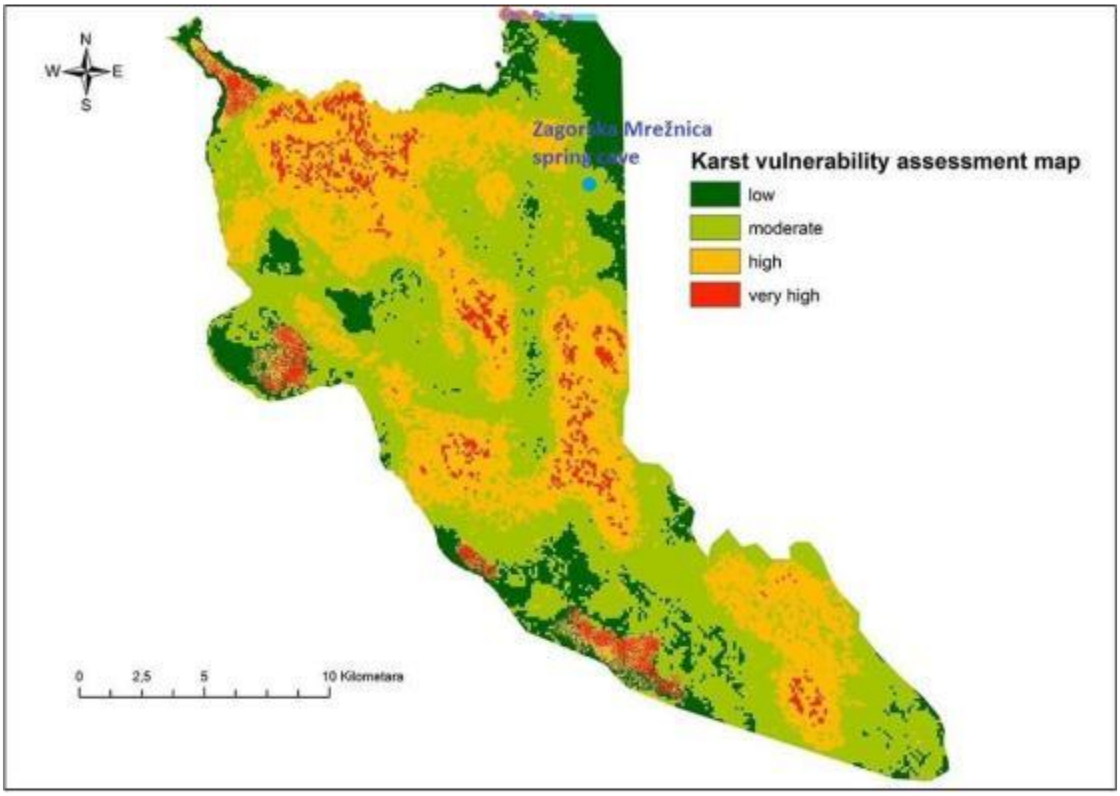


Figure 99: Karst vulnerability assessment map of the research area of Zagorska Mrežnica spring cave.

According to Quinlan et al. (1991), the degree of intrinsic vulnerability depends on four main characteristics:

1. The existence or absence of a soil and debris cover, which is crucial for the protection of the karst groundwater from contaminants;
2. The infiltration characteristics. Diffuse, spatial infiltration on covered karst generally results in a lower vulnerability. A linear or point infiltration, which is typical for karst, leads to a higher vulnerability;
3. The intensity of epi karst, and
4. The development of the karst system.

High vulnerability potential areas have high epikarst development, high subsurface feature density, and high subsurface potential. The map shows that the areas with the highest doline density have the highest vulnerability category because it has a great capacity for diffuse infiltration of precipitation and no pollutant filtration function. The karst poljes are areas of point recharge infiltration, and potentially have the possibility of a fast input of pollutants into the aquifer (Polemio et al., 2009) and that is why they were also classified as high vulnerability areas. Hydrological regime of the catchment area shows that response of recharge from ponors in karst poljes and diffuse infiltration in epikarst of Velika Kapela Mountain is fast and strong. The short travel time of water represents the potential for fast bacteriological contamination. Since the water is used for public water supply, the whole catchment area has to be specially protected.

Any subsequent changes of land use may introduce additional hazards. This has to be taken into consideration for future projects like construction of the railroad, building of retention of water in Drežničko polje. This area is currently under a construction project which purpose is building an accumulation in Drežničko polje for better regulation of the discharge of Zagorska Mrežnica spring cave. Ponors in Drežničko polje will be partially sealed with concrete and large amounts of concrete will be injected into the underground to create water accumulations.

7 CONCLUSIONS

1. Speleogenesis of 74 caves in the catchment area of Zagorska Mrežnica spring cave can be related to numerous faults present in the area, but further research is needed to determine this. Dominant orientation of the landscape evolution and evolution of karst features is similar to the orientation of structures along which cave passages developed. The steepest slope classes are oriented in a NW-SE direction and are elongated along the highest hypsometric classes. Both surface and subsurface forms have a NW-SE general orientation but due to neotectonic effects, their orientation changed partially to N-S and NE-SW directions. Two major fault sets were identified on the surface above Zagorska Mrežnica spring cave and Zagorska Peć cave, in a N-S and NE-SW orientation, and this influenced orientation and distribution of cave passages in Zagorska Peć cave and in Zagorska Mrežnica spring cave. Neotectonic are visible in two sets of fissures and have influenced changes in orientation of some passages to NNE-SSW and NW-SE.
2. Although there are two types of carbonate rocks in which passages of Zagorska Mrežnica spring cave developed, there are no distinctive morphological features between passages in limestone and passages in dolomite. It can be concluded that the petrological composition has no or only a minimal influence on wall rocky relief. Slightly inclined beds are dominant geological structures, which influenced the speleogenesis and morphology of Zagorska Mrežnica spring cave, which is well expressed in passage cross-sections.
3. The dominant source of cave sediment is the cave system itself. There is no mineral that cannot be related to local origin. Gravel, boulders, clasts and denudated limestone beds indicate active processes of erosion like plucking and corrosion. Mineralogical composition of the sediment reveals an abundance of the quartz sequence and that points to the local origin of the sediment. Part of the quartz sequence can be considered autochthonous, derived within the cave and possibly moved inside the same cavity. The relative abundance of quartz indicates that the sediment is *in situ* for a longer period since dolomite and calcite minerals have largely been dissolved. It means that no new sediment is being deposited. This might indicate that sedimentation occurred in a much calmer period or that exact sampling location acts as sediment traps due to very uneven velocity distribution in the irregular passage cross-section. All sediment samples, regardless of mineralogy show high angularity, which is an

additional indication of their local origin since they have not been transported for a longer distance.

4. The high massif of Velika Kapela allows infiltration through numerous dolines and fissures so this type of recharge is significant as well as point-recharge in karst poljes. Hydrological conditions in Zagorska Mrežnica spring cave changed over time and several facts confirm that. First is the presence of cave sediment which could have only been deposited in a still environment, second is the presence of stalactites in epiphreatic zones and third is the incision on the bottom of Novi kanal passage that could have been made from a stream. The chemical composition of water in Zagorska Mrežnica spring cave shows that the water is slightly undersaturated. The saturation ratio is therefore between 0.9 and 1 and at this saturation ratio dissolution proceeds under the non-linear law and the dissolution wall retreat rate is present in the order of a few cm per ky.
5. Cave passages of Zagorska Mrežnica spring cave and Zagorska peć cave are distributed in different directions with sudden turns and bypasses spreading below a large surface area. The pattern of the cave systems is controlled by numerous fissures or an intersection of two or more of them. The cross-sections have a lenticular, elliptical or semi-circular shape and are guided by the parting of the gently dipping bedding-plane. Rocky features like scallops and solution pockets are mainly solutional forms, which point to the fact that no transport of sediment with significant erosional power has been actively present, and that epiphreatic conditions were dominant in some part of the geological past. The pot-hole density that is highest in the part of the cave where Novi kanal passage and Glavni kanal passage connect indicates that this is the part of the cave where two water flows join and, as a result, a lot of turbulence is created.
6. The mapping of cave systems and 3D models show that the distance between the closest part of Zagorska Mrežnica spring cave and Zagorska peć cave is only 25 m. The distribution of cave passages is very similar (branch work) so these two caves can be considered as one system. Zagorska Mrežnica spring cave is situated in 21.4 m of vertical distance and the average height of the cave passages is 1.20 m with an average inclination of 4.5° which shows that Zagorska Peć and Zagorska Mrežnica spring cave are aligned along the single structure (one bedding plane, or a set of bedding planes). The only exception is the vertically protruding shaft in Zagorska Peć cave which is an

infeeder and may represent a phreatic jump.

7. The correlation between precipitation and the maximum discharge of Zagorska Mrežnica spring cave shows that there is very good conduit development. Therefore, the underground water flow paths have no delay and no significant influence of soil cover or matrix storage that would serve as a retainer of water. The distribution of sand deposits along Zagorska Mrežnica spring cave can be related to differences in high and low flow energy present in certain parts of the cave system. This means that some parts of the cave system like Glavni kanal passage functions as a primary conduit while Mamutova dvorana (Mammoth chamber) functions as a vent. The discharge is "buffered" by the accumulation Lake Sabljaci. The increase of the water level at the discharge point resulted in an increase in the hydraulic head inside the aquifer and blockage of the discharge point. The water level is raised by approximately 20 m since in the deepest parts of the cave there are indicators of epiphreatic (vadose) periods.
8. The vulnerability assessment of the catchment area of Zagorska Mrežnica spring cave shows that the areas with the highest doline density have the highest vulnerability category because they have a greater capacity for diffuse infiltration of precipitation and no pollutant filtration function. The karst poljes also have the highest vulnerability category because they are areas of point recharge infiltration, and potentially have the possibility of fast input of pollutants into the aquifer.

7.1 THE SYSTEM FROM THE PERSPECTIVE OF STANDARD SPELEOGENETIC MODELS AND FURTHER PERSPECTIVES OF THIS WORK

Results of the research can be discussed within the concept of different speleogenetic models. The observed system is comprised of deep phreatic channels (Spring of Bistrac), a shallow phreatic network (Zagorska Mrežnica spring cave) and vertical connections between both (shaft in Zagorska Peć cave).

The 4-state model of Ford and Ewers (1978, Ford & Ewers) relates resulting cave patterns to fissure frequency. Although one could relate the deep phreatic loop to this model, it is questionable if the system fits into the framework, as the branch work/maze pattern of Zagorska

Mrežnica spring cave and fissure mapping indicate a high frequency of penetrable fissures.

Several works (Palmer & Audra, 2003; Gabrovšek et al., 2014) discussed the influence of base level changes on cave patterns. Generally, the evolving conduit systems adopt to the position of the base levels. It is not yet resolved how the system adopts to the gradual lowering, but step-wise lowering results in multiple levels of conduit systems, each reflecting the past position of the base level. If, for some reason, like valley aggradation or tectonic uplift, the base level rises back, fossil levels can become active or flooded. Such passages may connect via vertical infeeders to the water table cave. Dreybrodt et al. (2005) have demonstrated such a scenario with a numerical model. The concept was also applied to interpret the patterns observed in large systems influenced by base level down-cutting and up-filling as a consequence to the Messinian crisis.

In the observed system, the level of the deep channel of Spring of Bistrac could be related to the past base level. Later aggradation or tectonic uplift of Ogulinsko Zagorje could result in the burial of the lower level of Spring of Bistrac and adaptation of the system to the new base level resulting in the formation of Zagorska Mrežnica spring cave and Zagorska Peć cave and the connection between the deep phreatic and epiphreatic level (Figure 99). This would also explain the good hydrological connection between all 3 springs as illustrated by dye tracing. To confirm these assumptions, a detailed mapping of conduit morphology would be needed within the deep passage of Spring of Bistrac and vertical channel in Zagorska Peć cave. This could give insights into their past hydrological position and role. Furthermore, it is hard to conclude, based on the existing data, whether both down-cutting and up-filling were required to make such a system. Also, additional geological mapping on the surface would be needed to confirm the assumption of base-level changes.

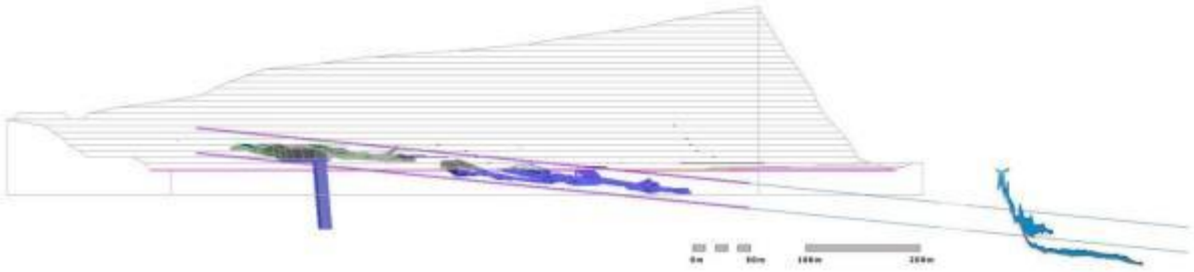


Figure 100: Position of the Zagorska Peć cave, Zagorska Mrežnica spring cave and spring Bistrac from the direction of 80º-260º (Appendix 7).

The inventarization of microrelief forms reveals the changes of vadose-epiphreatic to phreatic conditions in Zagorska Mrežnica spring cave. The presence of concretions in the phreatic passage Lijevi kanal can only be explained by the presumption that at one point Zagorska Mrežnica spring cave became a fossil cave (paleoaquifer) Davis (1999). The incision on the bottom of Novi kanal passage and paragenetic incisions also indicate this. This means that the whole cave was above the water table and the water level raised approximately 20 m. Solutional pockets indicate a presence of longer periods of epiphreatic conditions because of the lower water-level. If these presumptions are correct and the phase of aggradation of the valley continues, Zagorska Mrežnica spring cave will become a deep phreatic system and the cave Zagorska Peć will become a permanent spring.

The water in Zagorska Mrežnica spring cave is slightly corrosive, which indicates its present growth. Also, hydrological characteristics of the spring show irregular recharge and thus discharge which plays an important role in speleogenesis. Gabrovšek et al. (2014) show in their analytical model that the formation of a water table or looping caves is not principally dependent on fracture density but also on the recharge dynamics, valley incision rate and vertical distribution of permeable structures. In the case of Zagorska Mrežnica spring cave, Spring of Bistrac and Zagorska Peć cave a more detailed numerical 2D and 3D model could give more information on the importance of recharge dynamics on cave geometry.

Sediment analysis show that there is no active sedimentation present in the cave and that cave sediments have been altered by dissolution of carbonate fraction within the cave.

The study opened many questions for new research which would confirm some of the above *brave* assumptions. Nevertheless, this work clearly demonstrates that only exploration diving and mapping can reveal important insights into the vertical distribution of cave systems and result in a better interpretation of their evolution.

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