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Excursion guidebook

Prud - Narona - Baćina Lakes

25th - 29th September 2017, Hotel Dubrovnik Palace, Croatia

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Excursion: Prud - Narona - Baćina Lakes

Fig. 1 Map of the area with field trip stops

STOP 1: KARST SPRING PRUD
STOP 2: NARONA
STOP 3: BAĆINA LAKES

REGIONAL HYDROGEOLOGICAL SETTINGS OF THE DUBROVNIK - NERETVA REGION

Staša Borović[1] & Josip Terzić[1]

Croatia can, generally, be divided into two very different regions based on their geological settings. The North-eastern part of the country represents the southern margin of the Pannonian Basin System, while the south-western part belongs to the Dinarides. Dubrovnik - Neretva County is the southernmost county in the Republic of Croatia and, in accordance, its structural fabric forms part of the Dinarides. The geological and tectonic settings also dictate the hydrogeological features.

Based on their lithology and age, three dominant types of rocks and deposits can be identified in the area:

1. Carbonate rock complex, encompassing rocks from Upper Triassic, Cretaceous up to Lower Eocene (230 - 40 Ma);
2. Upper Eocene clastic flysch deposits (40 - 34 Ma);
3. Various Quaternary deposits found in karst poljes and the Neretva River delta (<1.8 Ma).

It should be emphasized that carbonate rocks predominate in the region.

The distribution of these deposits reflects the structural and tectonic relationships of the wider area. The regional structural setting is composed of the Dinaric, Epiadriatic and Adriatic structural units of the Dinarides: consecutively positioned from inland toward the shore and islands (Herak, 1991). The current setting is the consequence of the movement of the Adria microplate toward the Dinarides, which resulted in its subduction beneath the Dinarides. In the Dubrovnik-Neretva area, these deposits reach depths of 15-20 km (Aljinović, 1984; Aljinović et al., 1987). On the surface, the Dinaric units are thrust onto the Epiadriatic structural unit. Rock fracturing at the surface is the only manifestation of much greater movements taking place at depth (Prelogović et al., 1999). Hydrogeologically, this area is a typical example of the globally famous karst locus typicus - the Dinaric karst. Geology and tectonics of the Dinaric karst have been described in numerous publications (in addition to those already mentioned see: Prelogović et al., 1995; Vlahović et al., 2005; Korbar, 2009). Due to compressive tectonics dominated by overthrusting and reverse faulting of geological structures, karstification reaches deep horizons in the underground and karstified rock masses are very irregularly distributed. This makes hydrogeological relationships extremely complex; the delineation of catchments is very challenging, and numerical modelling virtually impossible.

[1] Croatian Geological Survey, Zagreb, Croatia

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The Dinaric is the most prominent regional structural unit, composed of thick carbonate deposits. A thrust fault front on the surface consists of Triassic dolomites, upon which there is a continuous sequence of Jurassic and Cretaceous deposits, predominantly composed of limestone. The Dinaric unit was thrust onto Epiadriatic fine-grained flysch deposits. The thrust fault front is a regionally prominent geomorphological feature; visible as a carbonate escarpment reaching maximum heights of 500 m. Sub-horizontal tectonic movements are estimated to be up to 10 km (Marković, 1971), which caused the Epiadriatic flysch deposits to be either completely thrust under the Dinaric unit, or eroded. Their extent on the surface of the terrain rarely reaches 1 km in width.

The regional structural unit of the Adriatic comprises carbonate rocks situated to the south of the flysch deposits. A carbonate rock mass comprising the coastal area and the Pelješac peninsula generally represents a monocline structure of dinaridic strike (NW-SE), dipping toward the NE. Dip angles are mostly between 20° - 50°, but can be up to 70° on the Pelješac peninsula. Geological structures on the islands are characterized by their “Hvar” strike (W-E). Carbonate rocks are folded, and small karst poljes were formed in the synclinal parts of the structures.

Seismic activity in the area proves that tectonic movements have not ceased in the neotectonic phase. Maximum expected intensity is 9-10° on the MCS-scale, while 7.5 is the maximum predicted magnitude on Richter scale (Kuk et al., 1987).

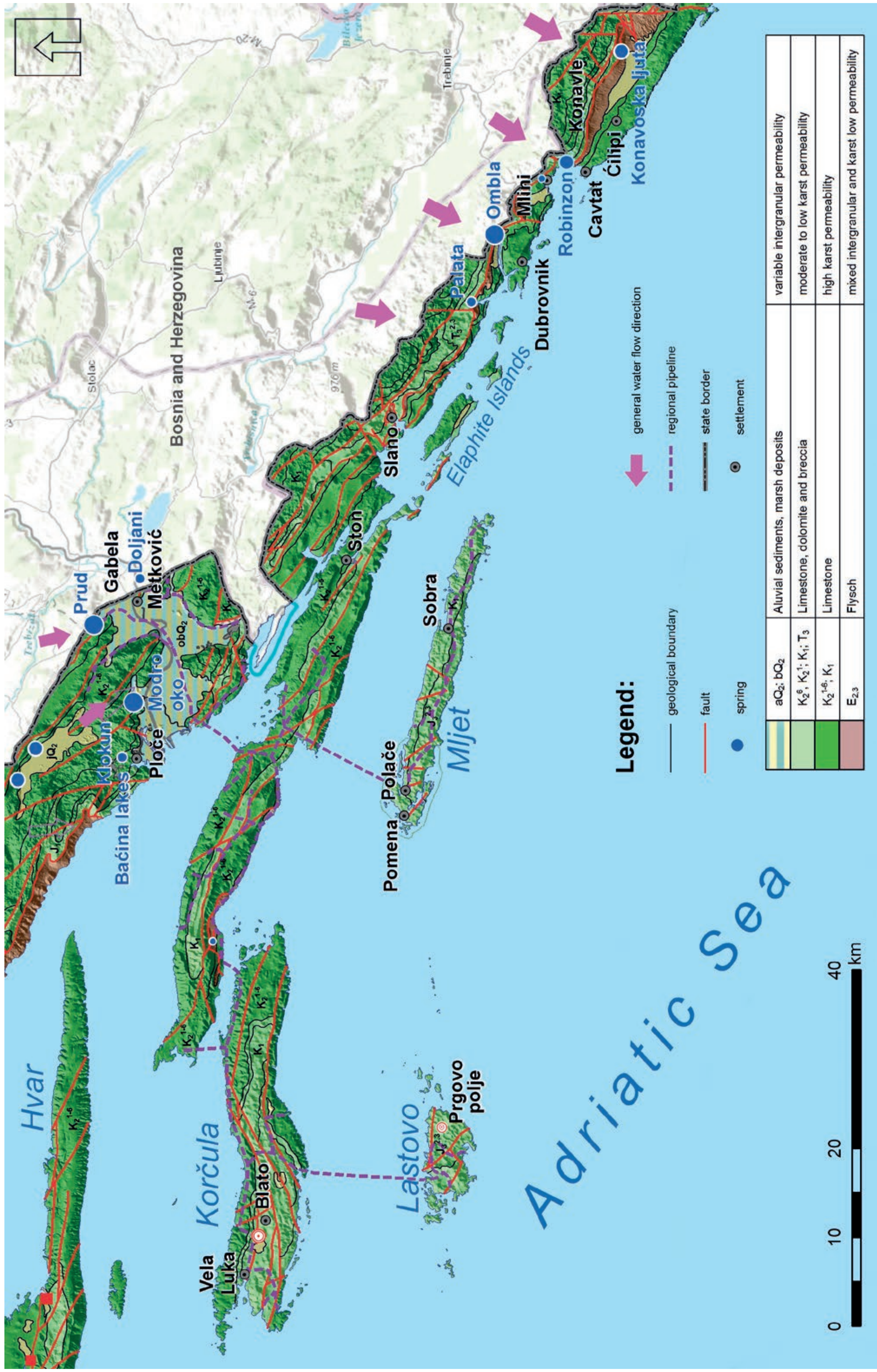

Fig. 2 Hydrogeological map of the area

Deposits in the area can be classified according to their hydrogeological properties into three basic categories: high permeability deposits, low permeability deposits and impermeable deposits.

High permeability deposits are karstified limestones of different ages and they represent the most important aquifers (Fig. 2). Their hydrogeological properties, along with the monocline geological structure and tectonics (which were of paramount importance for the formation of underground flow systems), enabled the formation of large watersheds and high-yield springs in these hydrogeological units.

The carbonate complex also encompasses dolomites in the form of lenses or layers of different thickness. Due to their lithological features, their permeability is lower than that of the limestones. Dolomite zones therefore represent a modifier capable of redirecting groundwater flow within the carbonate complex, which is often called the dolomite barrier.

A narrow coastal zone of impermeable (at the regional scale) flysch deposits is locally very thick (up to 500 m). In the coastal area between Slano and Konavle it represents a total hydrogeological barrier to karst groundwater flow, although some lithological members within the flysch can be permeable. Such a continuous flysch belt effectively disables scattered outflow of fresh water from karst aquifers in the hinterland into the sea. This explains why the majority of discharge occurs through a few large karst springs and there are no significant vruljas (submarine fresh water springs). The most important springs in the area are: the Ljuta spring in Konavle (providing the water supply of the Grude area, used for water bottling and acting as a strategic groundwater reserve), the Robinzon spring in Duboka Ljuta/Plat (for the water supply of Župa Dubrovačka, Kupari, Cavtat, Ćilipi and the surrounding area), the Zavrelje spring at Mlini (acting as the water supply for Mlini and a small hydroelectric power plant), the Slavjan spring in Brgat (previously used for the water supply of Dubrovnik - an aqueduct led to Onofrio's fountains in the town), the Ombla spring in Komolac (providing the current water supply of Dubrovnik with the possibility of hydroelectric power plant construction), the Palata spring in Mali Zaton (for the water supply of Zaton, as well as the Elafite islands off the coast), together with springs in Orašac, Trsteno, Slano, and dozens of smaller springs with intake structures supplying smaller settlements.

From Slano to the NW, the flysch barrier tectonically disintegrated so the majority of the groundwater discharge from the hinterland occurs in the form of small coastal springs and vruljas, which results in their low potential for utilization in larger-scale water supply systems. The most significant discharge area is in the Kuti bay in the internal part of the Ston bay, and in Bistrina bay (Bojanić & Ivičić, 1984). The constant inflow of fresh water is lowering the salinity of the bay which, combined with the sparse population and the lack of industrial facilities (i.e. low pollution levels), has enabled ideal conditions for growth of clams, so the aquaculture of mussels and oysters is a significant source of income in the area.

The Neretva River delta downstream from Metković is a marshy cultivated area, suitable for fruit and vegetable production. Both the surface and shallow subsurface deposits are composed of medium and low permeability clastic deposits. On the surface, clayey silt and clayey sand rich in organic materials predominate, while in the lower horizons gravels with conglomerate intercalations are present. There are three identifiable aquifers along the depth of the Neretva River alluvium (Vidović, 1968). The total thickness of the alluvium is 120 m, and it is underlain by carbonate rocks. The water supply of the town of Neum comes from two drilled wells close to Gabela, north of Metković (Slišković et al., 2002).

On the left bank of the Neretva River a number of springs appear: the Doljani spring (providing the water supply for Metković), as well as the Mlinište, Mislina, Bađula, Bili vir and other smaller springs. These are ascending springs in which water upwells through fractures and forms small lakes on the surface. These springs drain the water from a large carbonate watershed extending as far as Popovo polje with the swallow holes in the Trebišljica River Valley and waters from the compensation basin of Hutovo, built for the Čapljina hydroelectric power plant.

On the right bank of the Neretva River the most significant springs are the Klokun (near the Baćina Lakes, providing the water supply of Ploče), the Modro oko (for the water supply of Desne village) and the Prud (supplying both Metković, and the extensive regional water pipeline NPKL: Neretva River - Pelješac Peninsula - Island of Korčula - Island of Lastovo).

In the NE part of Jezero polje there are a number of contact springs, with the largest ones being the Butina, Stinjevac and Lukavac springs. Only the Butina is used for water supply. The Pelješac peninsula has a few sources of water supply. The Ston area receives its water supply from the Studenac spring in the Ston polje. The rest of the peninsula uses small local pumping sites such as Žuljana, Trpanj and Orebić, or water from the regional NPKL pipeline. The Eastern part of Korčula Island also gets its water supply from the regional pipeline, while the central and western parts of the island use the Blato pumping site with dug wells (Terzić, 2006). Lastovo and Mljet islands use desalinated water from boreholes in the Prgovo polje (Lastovo) and blatinas (specific karst lakes on Mljet).

Acknowledgement: The overview of regional hydrogeological settings was written as a review on the basis of published and unpublished materials listed in reference list and the authors would like to thank all colleagues who contributed.

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STOP 1 & 3: KARST SPRING PRUD AND BAĆINA LAKES

Hydrogeological overview of the south Dalmatian dinaric karst catchment system (Karst Spring prud and Baćina Lakes)

Josip Terzić[1] & Tihomir Frangen[1]

Introduction

The Dinaric karst is a locus typicus for karst morphology, and it is quite famous in the hydrogeological community. It is determined by very deep and irregular karstification caused by compressive tectonics and an accumulation of soluble carbonates which can reach up to several km in thickness. The geology, tectonics, and structural framework of the Croatian Dinaric karst region have been reported in numerous publications; however, the evolution of the region is still a matter of debate and fundamental research (Vlahović et al., 2005; Velić, 2007; Korbar, 2009). The area represents the major crustal regions of the Adrian tectonic microplate (Apulia microcontinent). From Triassic to Lower Cenozoic times, this area was characterized by carbonate platform sedimentation. The main Dinaric thrust-related deformations occurred between the Palaeogene and the Eocene or Miocene periods (Tari, 2002; Schmid et al., 2008; Korbar, 2009). However, the present-day geomorphology of the region is rather an expression of wrench tectonics along a zone of steep faults, striking generally NW-SE (Prelogović, 1995). Delineation of catchments in such karstic terrains is very difficult and numerical modelling is practically impossible. Numerous methods should be applied and systems have to be divided into mutually dependent catchments and sub-catchments (Terzić et al., 2012, 2014). The Baćina Lakes have been studied recently within one scientific hydrogeological project funded by Croatian Waters (Terzić et al., 2015) - together with limnological research, and partially within the Drinkadria project (funded by EU within IPA Adriatic Programme) and still ongoing PROLINE-CE project (funded by EU within Interreg CE Programme). Preliminary results have been reported in a few publications (Lukač Reberski et al., 2016, 2016a; Terzić et al., 2015a).

The Prud karst spring (Fig. 4) and Baćina Lakes (Fig. 5) belong to the discharge zone common to both the South-Dalmatian and West-Herzegovinian Dinaric karst catchments. Although the Prud spring is situated in Croatia, most of its catchment is in Bosnia and Herzegovina, which raises trans-boundary issues considering groundwater protection zones and water use. The spring is used for extraction for the water supply of Metković town, and also the more wide-spread water utility NPKL (Neretva River - Pelješac Peninsula - Korčula Island - Lastovo Island). The water is generally of decent quality, and only concentrations of sulfate ions are increased, as a consequence of the dissolution of gypsum and anhydrites in the Herzegovinian underground. Only some 10% of the springs' minimal discharge is used for the water supply. Discharge quantities of the Prud spring vary depending on reference, but according to recent measurements they are between 3 - 10 m^3s^{-1} from the hydrological minimum to maximum.

[1] Croatian Geological Survey, Zagreb, Croatia

The Baćina Lakes are situated to the south of the Prud spring, close to the Adriatic Sea coast near the town of Ploče. They are composed of seven lakes (Crniševo, Očuša, Podgora, Vrbnik, Sladinac, Vitanj and Plitko - Fig. 5). Within their zone there are several springs, and also a tunnel which drives water from the upper zones (karst polje Jezero near Vrgorac; constructed in 1938) and the tunnel which drains water from the lakes into the sea (constructed in 1913). Since such circumstances last for a long period, they can be taken as the new "natural" state. The deepest lake of Crniševo is subject to the underground influence of seawater penetration, and is also polluted by local waste disposal. Other lakes are not endangered at the moment. The local zone lies near the tunnel from the karst polje Vrgoračko polje (Fig. 6). Close to the lakes there is the Klokun karst spring, which is used as a water supply source for Ploče which is used as a water supply source for Ploče town and its surroundings.

Fig. 4 Prud spring - sampling during the high discharge period

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Fig. 5 Location map of the Baćina Lakes with the most important hydrogeological features, as well as the position of the hydrogeological and limnological monitoring (research) points

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Hydrogeological relations of a complex karst catchment system

The discharge zone spreads from the right boundary of the Neretva river valley (Fig. 7). The first spring in Croatia is the Prud, then there are several karst springs, especially in the Desne area with Modro oko (local water supply) as the most important one. Close to the Baćina Lakes there is the Klokun karst spring (providing the water supply of Ploče town) and the zone finishes with the coastal spring Mandina mlinica, after which the flysch rock barrier influences the groundwater flow, also preventing extensive penetration of seawater into the aquifer. Therefore, after Mandina mlinica there is no important karst spring or vrulja (submarine spring) for over 50 km along the coast of the Adriatic Sea.

Fig. 6a Inflow tunnel in August, 2014.

Fig. 6b Inflow tunnel in April, 2014.

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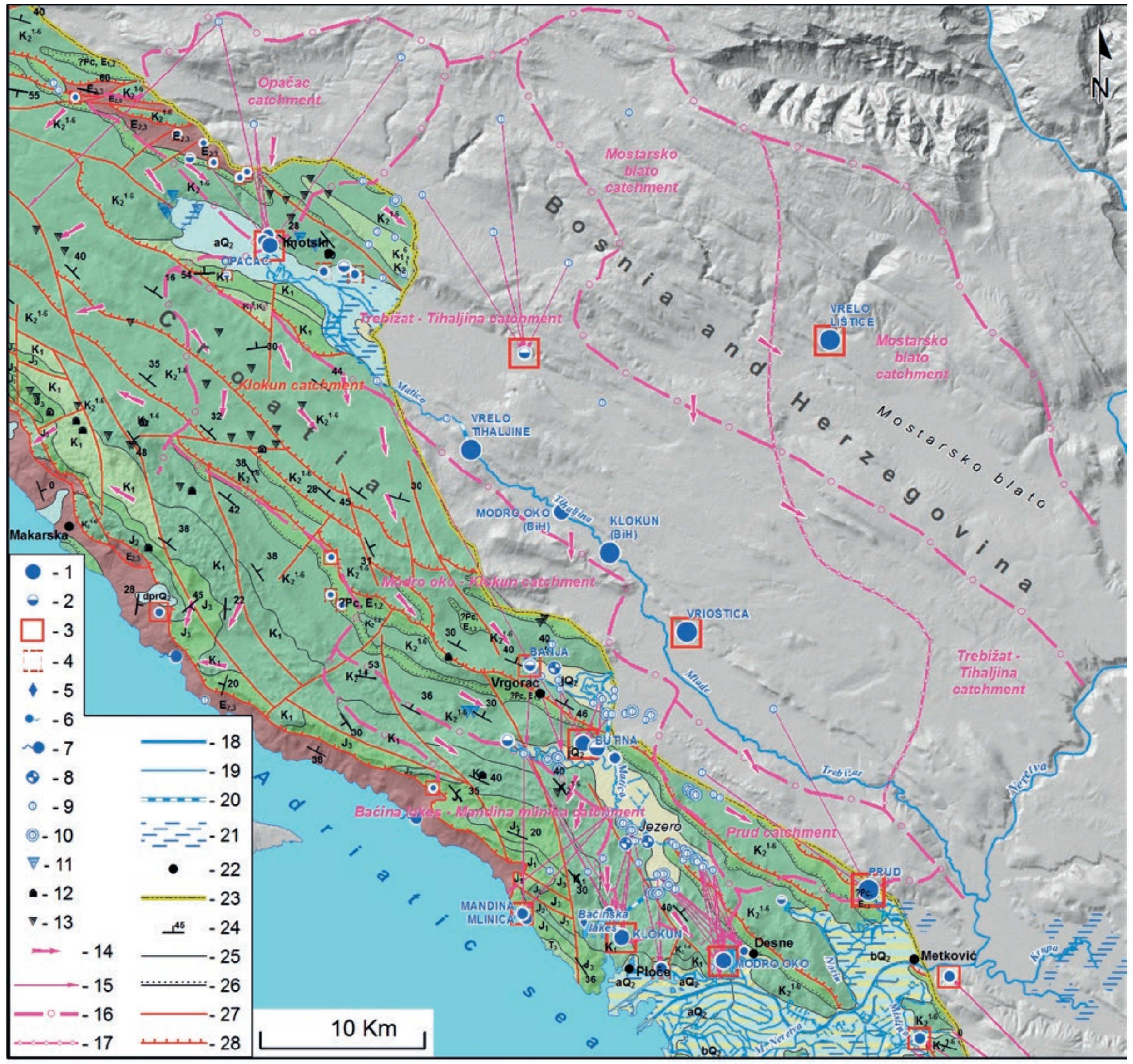
Fig. 6c Inflow tunnel in November, 2013.

Fig. 6 Inflow tunnel (from the karst polje to the Baćina Lakes - constructed in 1938) in three very different hydrological conditions (at the end of every summer, the tunnel is usually completely dry, sometimes for a few months)



aQ₂; dprQ₂	Aluvial sediments, Deluvial-proluvial deposits	moderate intergranular permeability
jQ₂	Lake sediments	very low intergranular permeability
aQ₂; bQ₂	Aluvial sediments, Marsh deposits	variable intergranular permeability
K_2^6, K_2^1; K_1; T_3	Limestone, dolomite and breccia	low karst permeability
?Pc, $E_{1,2}$; K_1; J_3; J_1	Liburnian deposits, transitional beds, limestone, dolomite	moderate karst permeability
K_2^{1-6}; K_1; J_2	Limestone and dolomite	high karst permeability
$E_{2,3}$	Flysch	mixed intergranular and karst low permeability

Fig. 7 Schematic hydrogeological map of the Prud - Baćina discharge zone catchment.

(Legend: 1 - spring; 2 - temporary spring; 3 - extraction site; 4 - primitive extraction site; 5 - spring in lake (coastal); 6 - coastal spring; 7 - vrulja; 8 - estavelle; 9 - swallow hole (ponor); 10 - swallow hole zone; 11 - karst feature (pit) with water; 12 - cave; 13 - pit; 14 - general groundwater flow direction; 15 - underground connection proven by tracing; 16 - groundwater divide; 17 - divide (boundary) between sub-catchments; 18 - river; 19 - river (lower discharge); 20 - tunnel; 21 - marshy area; 22 - settlements; 23 - state boundary; 24 - bedding; 25 - normal geological boundary; 26 - transgressive geological boundary; 27 - normal fault; 28 - reverse fault)

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Hydrogeological relationships in this karst terrain are very complex and interrelated. Although there has been lots of exploration to date (including tracing experiments), many uncertainties and problems with interpretation still exist. Groundwater, surface flows which sink and reappear, karst springs, poljes, estavelles, vruljas and swallow holes, speleological features, and their mutual relationships represent big challenges for hydrogeological researchers even today (Bonacci et al., 2013; Ivičić, 2000; Slišković, 2014; Terzić et al., 2015). Within the most recent study, this big catchment area (total surface 1757 km^2) was taken as a hydrogeological system and divided into several sub-catchments which interrelate depending on any given moment in a hydrological cycle. To make this terrain even more complex, there are quite a lot of man-made interventions: a network of canals in karst poljes, tunnels draining water from karst poljes, and artificial barriers such as small dams. This recent delineation has to consider big parts of terrain in Bosnia and Herzegovina, although most of the hydrogeological and hydrochemical exploration has been performed in Croatia. This area covers the Mostarsko blato karst polje catchment and the Tihaljina-Trebižat karst river catchment in Bosnia and Herzegovina. The discharge zone is in Croatia, and extends from the Mandina mlinica coastal karst spring (Fig. 9) and the Baćina Lakes (Fig. 5), to the Prud karst spring (Fig. 4). The river Trebižat sinks in its riverbed, and this water rises mostly at the Prud spring. All these issues raise questions of trans-boundary protection of spring water which is being extracted for public water supply use (Prud, Klokun, Modro oko, Butina, Banja). Some of the springs have water protection zones, but their implementation is poor.

Table 1 Baćina Lakes basic facts

LAKE	SURFACE (HA) (Curić, 1995)	MAXIMAL DEPTH (M) (Curić, 1995)	MAXIMAL DEPTH (M) (Ivičić, 2000)	HGI - PALEOLIMNOLOGIC RESEARCHES MEASURED WITH SONAR - DEEPEST POINT (M A.S.L.)
1.Crniševo (Trniševo)	43,0	31	34	-33
2. Oćuša (Voćuša)	55,4	18	19,6	-18
3. Podgora	11,3	10	10	-8
4. Vrbnik (Vranjak)	3,1	8	8,7	-1
5. Sladinac	16,5	16	16,4	-15
6. Vitanj (Šipak)	9,0 (with Plitko)		-	-4
7. Plitko Lake (Potkušinac)	-	5	-	-3
BAĆINA LAKES - TOTAL	**138,3**	**31**	**34**	**-33**

Within the most recent research, bulk hydrogeological analyses were performed. Using hydrochemical and isotopic study, new tracing tests, mapping and discharge analyses, this huge karst system was divided into sub-catchments (Fig. 7): (1a) the western Mostarsko blato catchment which influences the southern springs, (1b) the eastern Mostarsko blato only influencing the Neretva River, (2) the Tihaljina-Trebižat catchment (also divided into 2a and 2b where only the most distant eastern part does not influence the discharge zone in Croatia, (3) the direct catchment of the Prud spring, (4) the Modro oko-Klokun elongated catchment following geological structures parallel to the coastal flysch barrier, (5) the Baćina Lakes-Mandina mlinica direct catchment, and (6) the catchment of the Opačac spring near Imotski town which directly influences the Tihaljina-Trebižat river. Hydrological balance calculations corroborated this territorial division of the karst system. A significant part of the water infiltrated in Bosnia and Herzegovina drains toward the studied discharge zone in Croatia. Increased concentrations of sulfates in some springs (especially in the Butina and nearby springs, or Prud where they were between 30 and 215 mg/L during our study) indicate that in

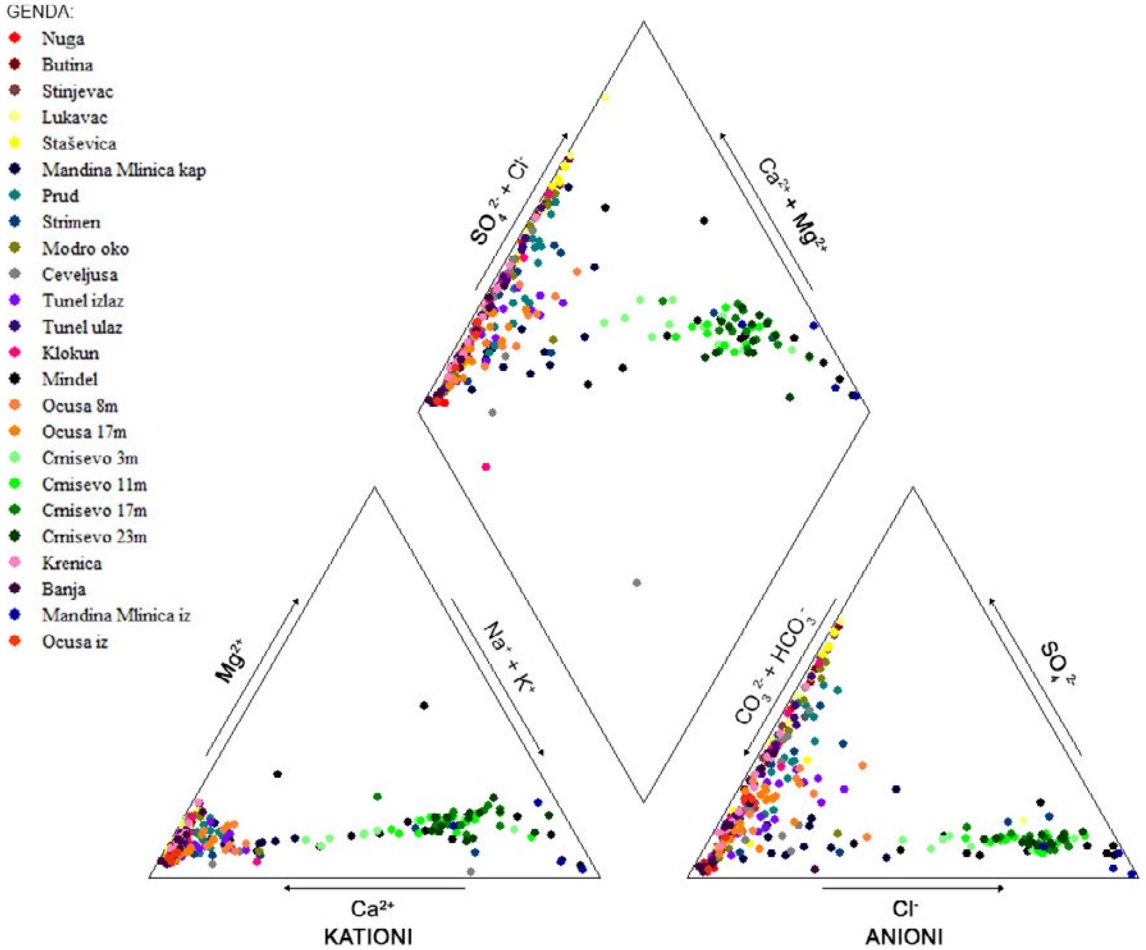

Fig. 8 Piper diagram of the water samples in the research area

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Fig. 9
Mandina mlinica coastal spring - the end of the researched discharge zone

the Herzegovinian underground there is an abundance of sulfate rocks (gypsum and anhydrites). Due to the high solubility of these rocks, outcrops are practically absent, but they represent a big part of the underground, and affect the groundwater quality. Generally, the water is of good quality, and the hydrochemical facies vary from the Ca-HCO_3 type (usual for karst waters), to somewhere close to Na-Cl (mixing with the sea in coastal zones) or Ca-SO (proof of sulfate rocks). This research is being continued and particular importance will be given to stable isotope measurements, especially establishment of the local meteoric water line (LMWL) because there has been no such research in this area before.

Holocene palaeolimnological and palaeohydrological changes in the Baćina Lakes

Nikolina Ilijanić[1], Slobodan Miko[1], Ozren Hasan[1]

Lake sediments provide opportunities to reconstruct aquatic ecosystems through the past. Evaluating the stored environmental information in the sediments depends on the knowledge about the ecosystem and the understanding of the present day lake response to environmental variability. Lake sediments are the result of the input of material from the catchment and the lake productivity itself. Terrestrial input to the lake is carried out through erosional processes and anthropogenic pathways. Knowing the processes driving the terrestrial input is essential to understand for instance carbon deposition and nutrient input, which are linked to climate through weathering and transport processes. On the other hand, understanding the anthropogenic impact is the key to assessing the environmental status of a lake today and its recent history. It is essential to evaluate the environmental status and to assess the use of environmental proxies to estimate the lake's response to climate changes.

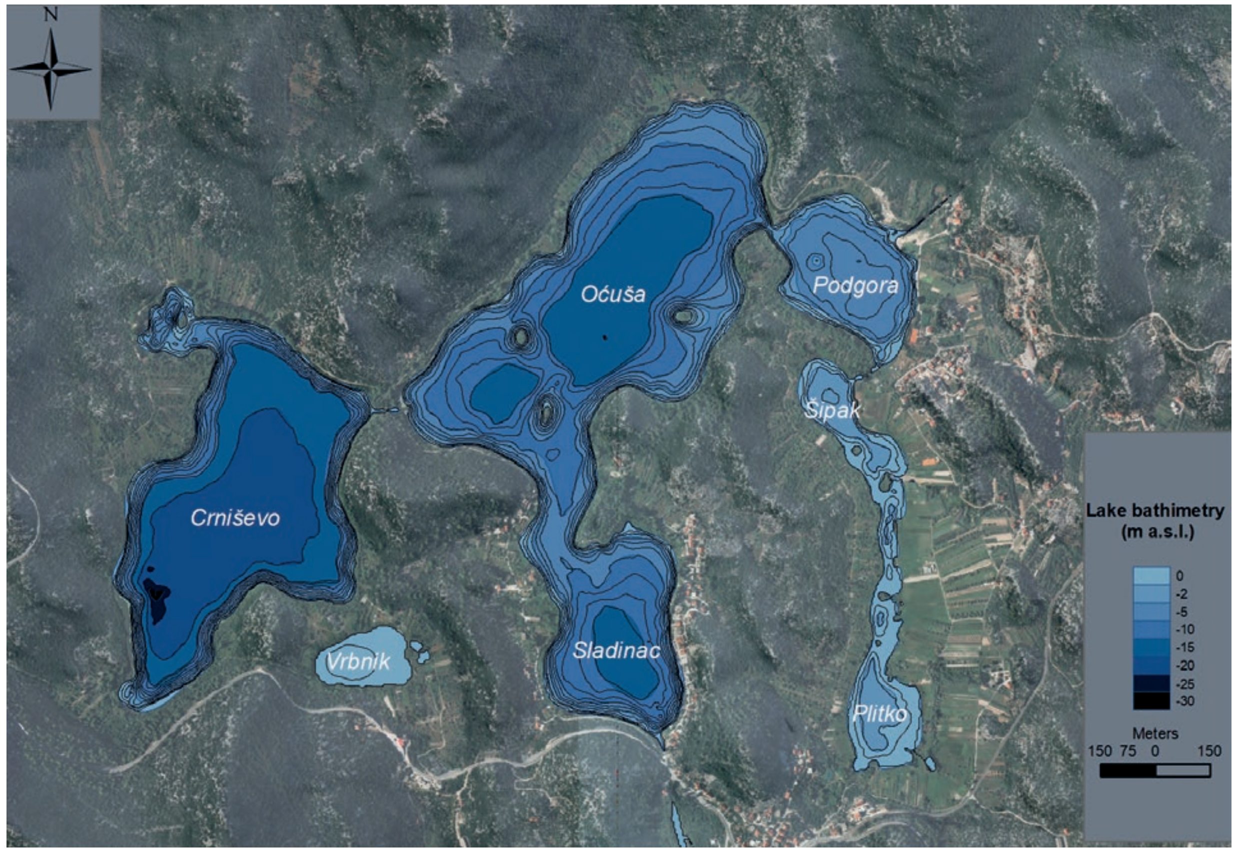

Fig. 10 Bathymetric map of the Baćina Lakes using a Humminbird echosounder (Miko et al., 2015)

[1] Croatian Geological Survey, Zagreb, Croatia

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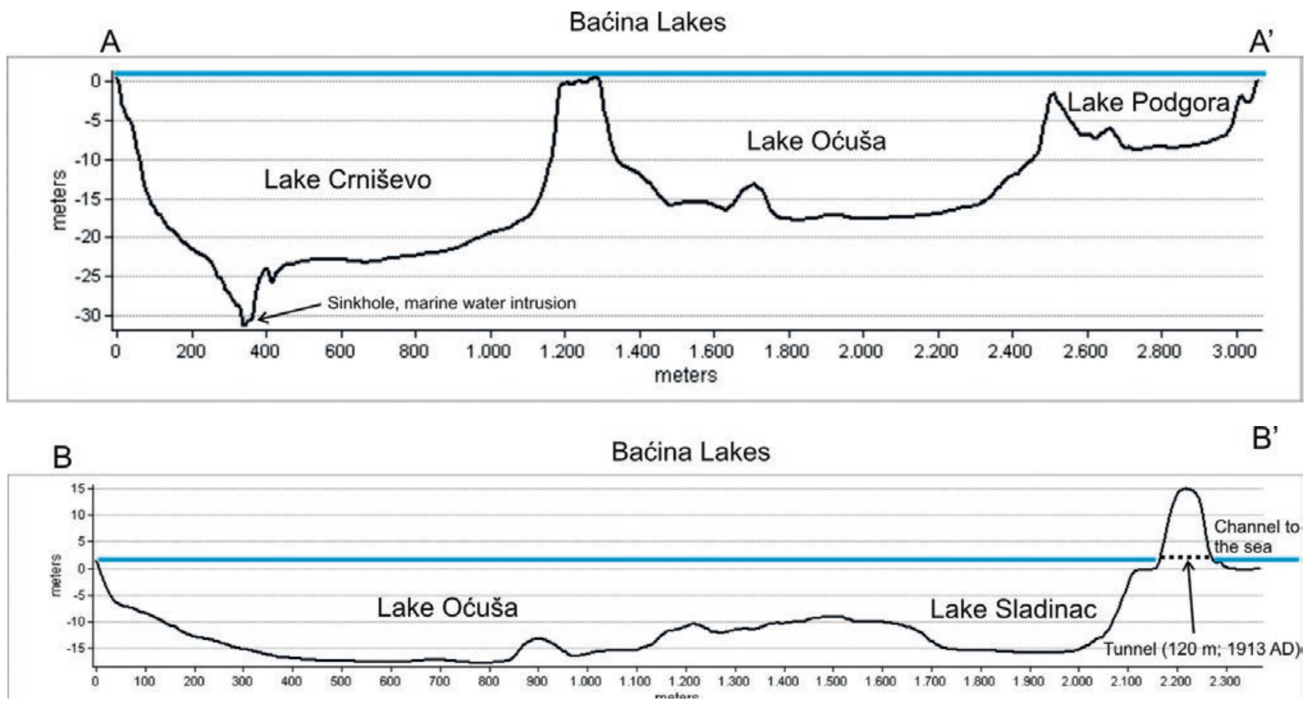

Fig. 11 Profiles through the Baćina Lakes which emphasize the irregular shape of the lakes developed on karst palaeorelief

In the summer of 2011, the research group for environmental geochemistry, palaeolimnology and marine geology from the Croatian Geological Survey cored the lacustrine sedimentary sequences in six connected Baćina Lakes, in the lengths ranging from 2 - 8 m (Fig. 5, from the text "Hydrogeological overview of south dalmatian dinaric karst catchment system"). The Baćina Lakes represent a unique ecosystem due to its irregular shape developed on karst (Fig. 10 and 11) and the influence of the sea due to Holocene sea level rise and human interventions which change lake levels significantly. Here we demonstrate palaeolimnological analysis of the Baćina Lakes sediment record, each spanning a few thousand years to the whole Holocene. Using palaeolimnology, various information about the past can be obtained, including watershed disturbance, climate change, evolutionary history of terrestrial basins, sediment source dynamics and human impact. Sediment cores were dated using radiocarbon absolute dating of the shells, charcoal or plants, deposited therein. Sedimentation rates and the geochronology of the cores vary through time and hence are fundamental to understanding changes in the physical and geochemical properties of the sediment. A bathymetric map was made using a simple Humminbird echosounder (Side Imaging/Down Imaging sonar with DualBeam), which provided a snapshot of the varying water depth and, by inference, climate and human intervention (Fig. 10).

The Baćina Lakes receive water mainly through precipitation and freshwater to brackish springs and submerged springs manifested as pockmarks or sinkholes on the lake bottom (Fig. 12). Only Lake Crniševo is influenced by sea water intrusion, especially during dry periods of the year (Fig. 14). On the western shore of Lake Crniševo there is an inflow of brackish waters from the Mindel spring. The sea water also enters the lake through a sinkhole at the bottom of the lake which is also the deepest point of the Baćina Lakes at 35 m depth (approximately 10 m in diameter) located in the south-western part of the lake (Fig. 12).

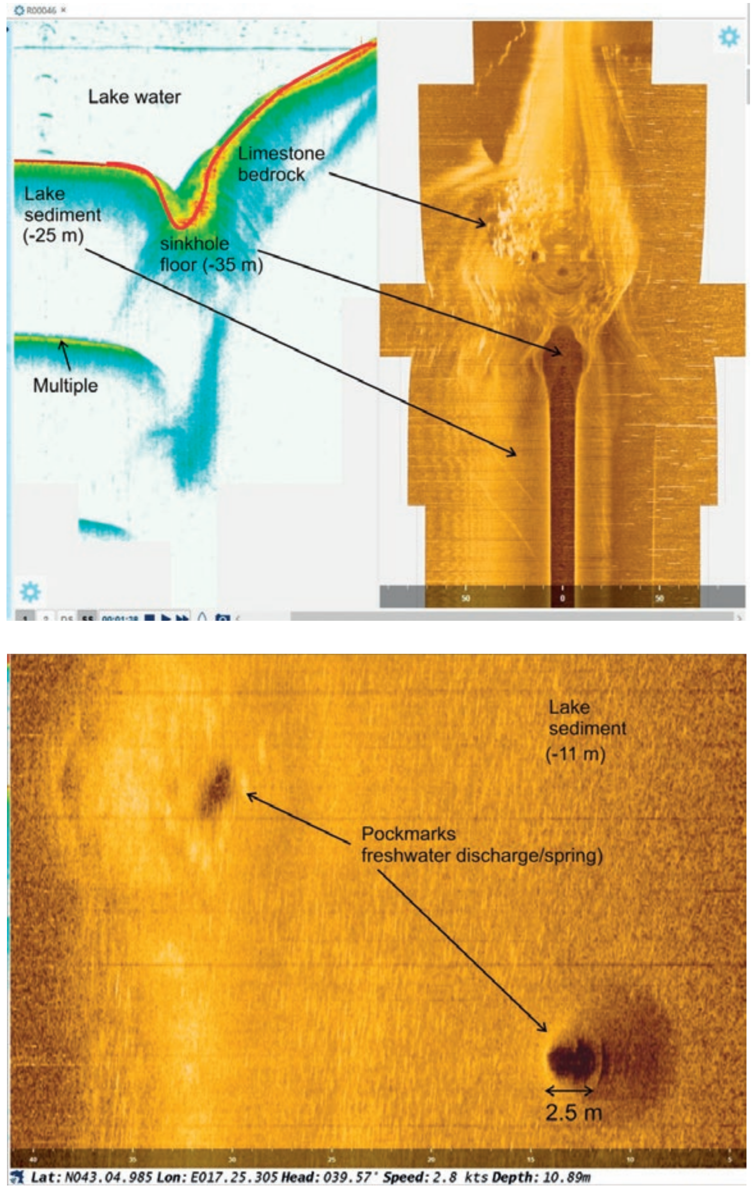

Fig. 12 Side-scan image of the depression in Lake Crniševo, approximately 10 m in diameter; and side-scan image of pockmarks (app. 2.5 m in diameter) along the northern shores of Lake Oćuša

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Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

Fig. 13 Photograph of the lake sediments around Lake Vrbnik and lacustrine molluscs on the shores of Lake Crniševo, suggesting higher water levels in the past

Two man made interventions in the 20th century significantly changed the ecosystem of the Baćina Lakes. In 1913, the tunnel that drains the Baćina Lakes fresh water to the sea was constructed for approximately 120 m and it hydrologically opened the Baćina Lakes and lowered the lake-level for a max. of 10-12 m. Until this intervention, the Baćina Lakes had no surface water outflow, the only outlets were the depression in Lake Crniševo that probably acted as a ponor and another ponor south of Lake Vrbnik (a connected lake at that time). Due to this intervention the lakes lost approximately 40% of their water. The second tunnel was built in 1938 and connected the Baćina Lakes (Lake Podgora) with the Vrgoračko polje in order to drain an excess of water from Vrgoračko polje to reduce the duration of spring flooding and drain the intermittent lake that formed in the polje. The exposed lake sediments surrounding the lake shores (approximately +9 m a.s.l. on the shores of Lake Crniševo (Fig. 13) are evidence of higher lake levels in the past. Discovery of lacustrine molluscs in tufa deposits on the steep limestone lake shores (+ 9 m a.s.l.) are also indicative of pre-existing higher lake-levels (Fig. 14).

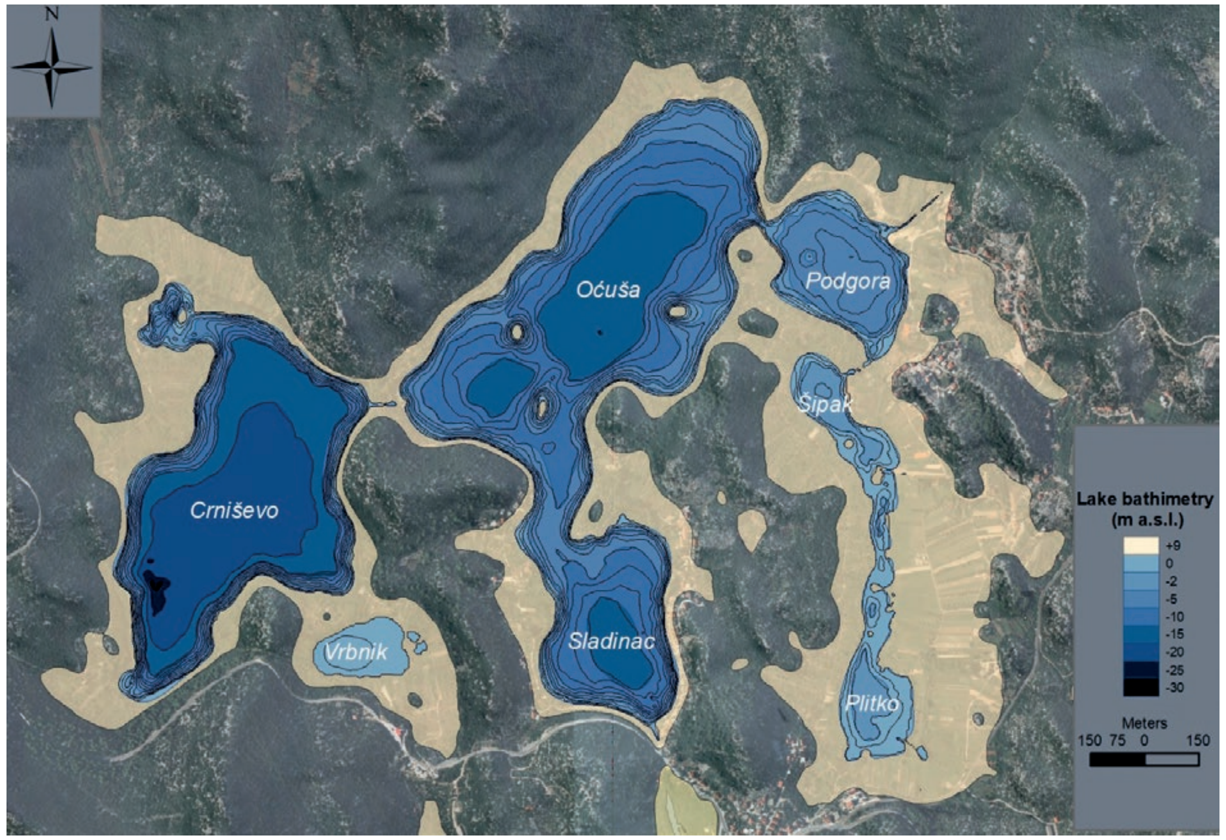

Fig. 14 Bathymetric map of the Baćina Lakes with the highest possible average lake-level (+9 m asl), marked in yellow (lake sediments around the lake), reached before the construction of the lake-sea tunnel in 1913 from Lake Sladinac.

According to biological productivity, the Baćina Lakes are classified as a mesotrophic type of lakes, and according to their thermal classification they are polymictic lakes (Fig. 15). The Baćina Lakes are subject to endogenic carbonate production during the dry summer periods, triggered by aquatic productivity, as is the case for most karstic freshwater lakes (Lake Vrana on the Island Cres, Lake Vrana in Dalmatia; Ilijanić, 2014). In contrast to homogenous carbonate sedimentation, laminated sediments are evidenced in the first ~5 cm of the sediment core in Lake Crniševo in the Baćina Lakes (Miko et al., 2015). These laminations are varves composed of black organic matter rich layers and white endogenic calcite layers. They are the result of the whitening processes in Lake Crniševo due to its high production and algal blooms during summer months, followed by the bottom water anoxic conditions during winter. The deposition of laminated sediments started approximately 50 years ago, probably caused by eutrophic conditions that favour the formation of anoxic bottom water, which is the result of oxygen depletion related to decomposition of organic matter near the sediment surface. This is a result of past anthropogenic activities, nutrient rich waters (due to extensive agriculture activity in Vrgoračko polje in the 1960's - 1990's) and the relative isolation of Lake Crniševo due to the artificial lake level drop after the tunnel construction in 1913. Prior to 1913 and construction of the drainage tunnel to the sea, the only outlets were the ponor zones on the southern shores of Lake Sladinac and Lake Vrbnik. The laminated sediments and anoxic conditions are not detected in other lakes from the Baćina Lakes complex, since

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their bottom waters are oxygenated throughout the whole year and water circulation is more pronounced. The diatom assemblage in the sediment-water interface is characteristic of fresh, relatively nutrient rich waters (Miko et al., 2015). Higher concentrations of total organic carbon and nitrogen in surface sediments from all the Baćina Lakes indicate eutrophication of the lakes (Miko et al., 2015).

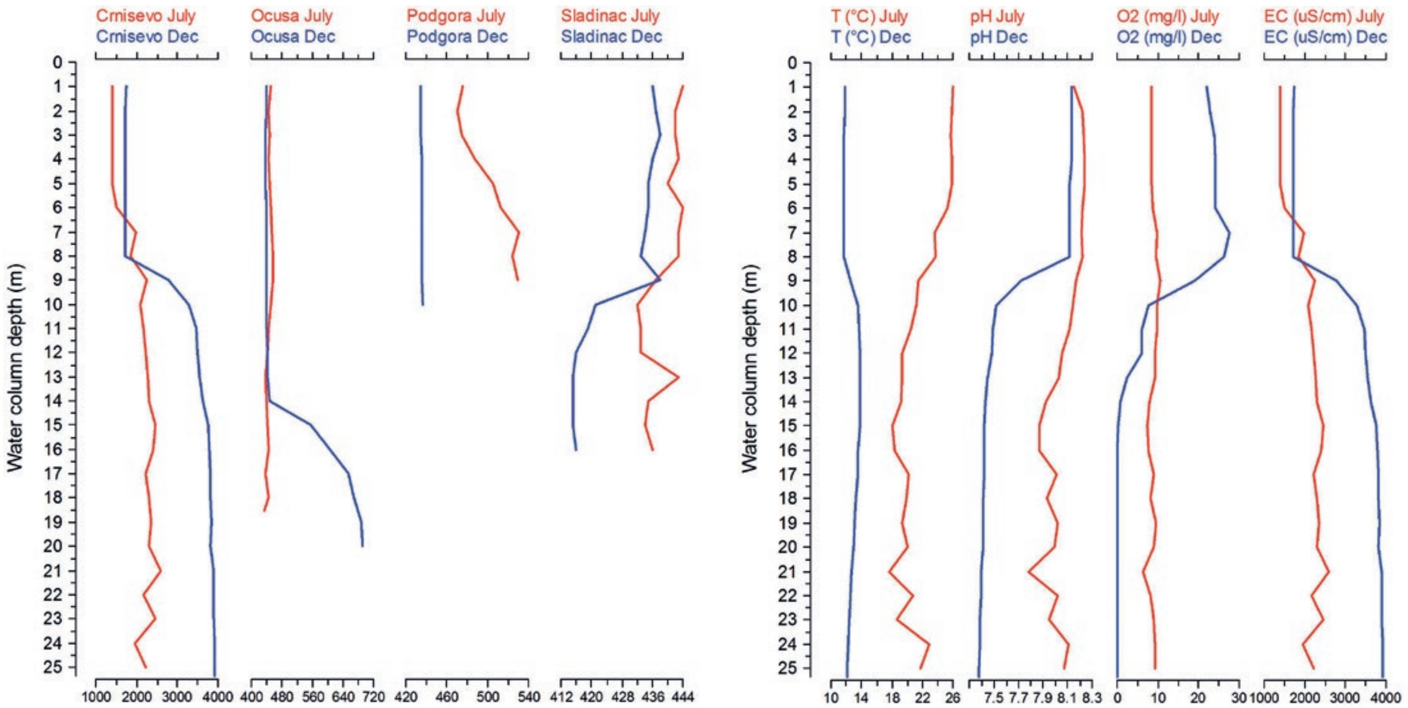

Fig. 15 Electrical conductivity (µS/cm) in the water column from Lakes Crniševo, Očuša, Podgora and Sladinac measured during summer (July) and winter (December) months, show the brackish nature of Lake Crniševo, especially during the summer months. The basic characteristics of the Crniševo lake water (T in °C, pH, O2 and EC in µS/cm) measured during summer (July) and winter (December) months, indicate the winter izothermia and anoxic conditions.

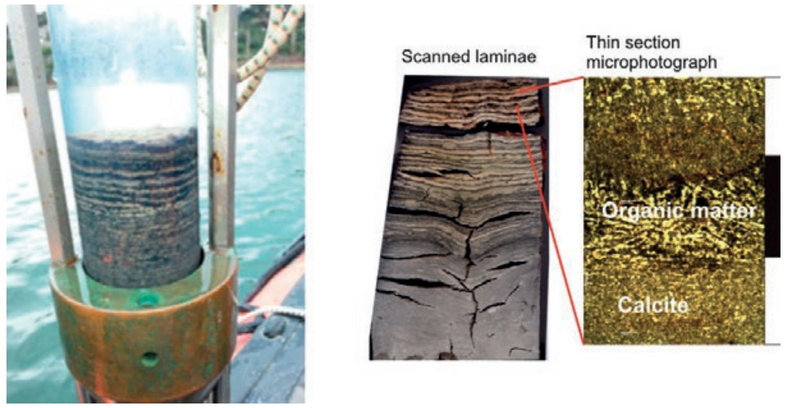

Fig. 16 Laminated sediments - varves in Lake Crniševo, composed of black organic matter layers and white endogenic carbonate layers, evidencing the whitening processes („algal blooms") in Lake Crniševo for the last approximately 50 years as a result of the alternating oxic/anoxic conditions in the lake.

We investigated the lake evolution under the light of sedimentary, geochemical and mineralogical processes; endogenic lacustrine carbonate production/formation; and the association between the limnological evolution, climatic changes and human impact. Analysis of the sedimentary record from Lake Crniševo, the deepest lake, provides a representative palaeoenvironment of the Baćina Lakes from the end of Late Glacial to the Holocene (Fig. 17; Ilijanić et al., 2015; Miko et al., 2015). Sediment records from the Baćina Lakes suggest that lake water levels were low during the early Holocene period when the outflow from the lake was possible only through the karstic underground (ponors) due to the lower sea level. The Holocene sea level rise caused the lake high stand in the Baćina Lakes, which is determined to be up to +9 m asl, by the sediment characteristics in the lake catchment. The Lake level didn't change until the present and recent human interventions, especially the outflow tunnel constructed in 1913, which drained the water from Lake Sladinac to the sea and caused the lowering of the lake level in the Baćina Lakes by up to approximately 40%, representing the biggest human intervention in the lake ecosystem that significantly changed the palaeolimnological conditions (Miko et al., 2015). The water outflow changed from ponors in Lakes Crniševo and south of Lake Vrbnik (connected at that time) to surface outflow from Lake Sladinac to the sea. Lowering the lake level separated Lake Vrbnik from the rest of the lakes, and isolated Lake Crniševo. Generated anoxia in Lake Crniševo initiated formation of recent varved lake sediments as a result of increased lake productivity and eutrophication. The construction of the inflow tunnel from Vrgoračko polje (1938) could be evidenced in the higher content of Pb and Cu in the sediment record from Lake Sladinac (upper 10-30 cm) and Lake Oćuša (upper 20-40 cm). A slight increase of Pb and Cu content in recent sediments is only observed in Lake Podgora. This indicates that the sediments from the Baćina Lakes were influenced by the sediments from Vrgoračko polje and their agricultural activities at the time when the tunnel was constructed, with a decreasing trend at recent times. A high resolution geochemical signal using an XRF core scanner from sediment cores of Lake Oćuša shows a slightly higher Pb content in the upper 20-40 cm and 30-50 cm in Lake Šipak (unpublished), indicating anthropogenic agricultural activities in the Vrgoračko polje after the tunnel opened. The sediment records from all the lakes are correlated using magnetic susceptibility, Al content (% and cps) which indicate erosional processes in the catchment (Fig. 17). The decreasing trend of erosional processes and sediment runoff in recent sediment in lakes close to the tunnel from Vrgoračko polje and agricultural fields in Baćina Lakes catchment can be observed. The Baćina Lakes are not endangered by erosion and sediment runoff from Vrgoračko polje.

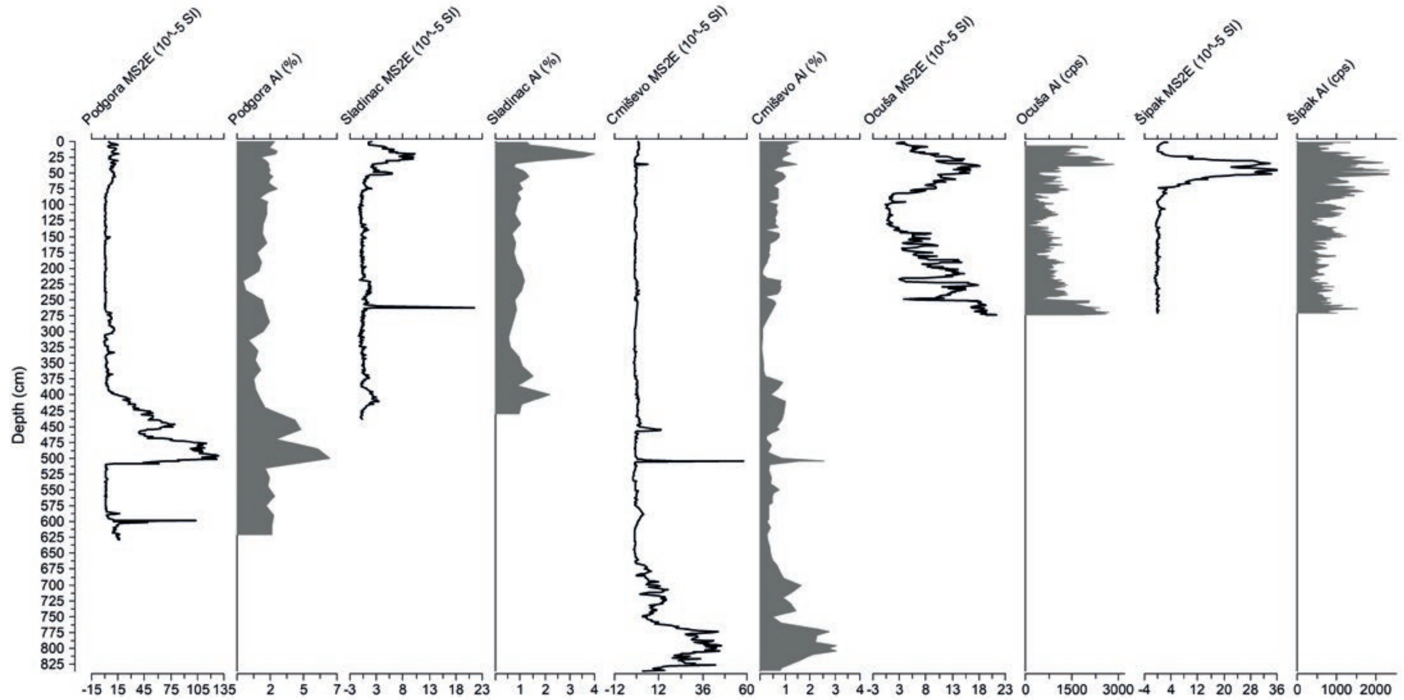

Fig. 17 Downcore variations of high resolution magnetic susceptibility (MS2E) and Al content of the sediment cores from the Baćina Lakes, as erosional and sediment runoff proxies, indicating higher erosion at the time of the construction of the tunnel with a decreasing trend in recent times

STOP 2: NARONA

Ivana Turalija[2]

The remains of the city of Narona, (present day Vid), are located four kilometres northwest of downtown Metković (Fig. 15). Today it is the site of the Narona Archaeological Museum, the first museum in Croatia to be built at the actual locale of an excavation. Throughout history, the Neretva River Valley has always formed a natural route from the Adriatic Sea to the interior. It was by means of this route that the interior of the Province of Dalmatia was linked to the coast and the rest of the Mediterranean during Antiquity. The Neretva Valley is also mentioned in the works of the writers by the fourth century BC. Certainly the most important for Narona are the writings of PseudoScylax and Theopompus, which mention the emporium, or market-town, which developed as a place to trade goods between the Mediterranean and the interior. The emporium at this location continued to thrive during the Roman era, and so grew into the city of Narona, one of the most important cities on the eastern shores of the Adriatic. The city was bordered with ramparts which descended down the slopes of a hill to the banks of the Neretva River, covering an area of approximately 25 hectares, so it can be assumed that a large number of people lived in Narona. The first contacts with Rome are associated with the Roman military incursions to the eastern Adriatic coast, i.e. the first Illyrian War in 229 BC. Archaeological research in Narona commenced at the beginning of the twentieth century, under the leadership of the Austrian archaeologist Carl Patch. After the Second World War, Narona began to be studied by experts from the Archaeological Museum in Split: Ivan Marović, Frane Buškariol, and Nenad Cambi. Nenad Cambi initiated excavations of the city itself and the area of the ancient forum in the 1970s, and research at this site continued until 1995.

Fig. 18 The remains of the city of Narona
(http://www.a-m-narona.hr/amnsite/gradski-bedemi/4-3/)

[1] conTres, Zagreb, Croatia

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REFERENCES

TBonacci, O., Željković, I. & Galić, A. (2013): Karst rivers' particularity: an example from Dinaric karst (Croatia/Bosnia and Herzegovina), Environ Earth Sci 70: 963-974.

Ilijanić, N., Miko, S., Hasan, O., Čupić, D., Mesić, S., Širac, S., Marković, T., Šparica Miko, M., Vlašić, A (2015): Paleolimnološka istraživanja Baćinskih jezera - jezero Crniševo.- Zbornik radova "Hrvatske vode na investicijskom valu"/ Proceedings Croatian waters on the investment wave. Biondić, Danko; Holjević, Danko; Vizner, Marija (eds.). Zagreb: Hrvatske vode, 437-446.

Ivičić, D. (2000): Sliv izvora desne strane donjeg toka Neretve (Catchment of springs on right bank of Neretva River), Vodič ekskurzija 2. hrvatskog geološkog kongresa u Cavtatu (Excursion book, 2nd Croatian geological congress), Hrvatski geološki institut, Zagreb.

Korbar T. (2009): Orogenic evolution of the External Dinarides in the NE Adriatic region: A model constrained by tectonostratigraphy of Upper Cretaceous to Palegone carbonates, Earth-Science Reviews, 96 (4):296-312. doi: 10.1016/j.earscirev.2009.07.004

Iijanić, N. (2014): Clay minerals in lake sediments along the eastern Adriatic coast as proxies of environmental changes during Late Pleistocene and Holocene.- Ph.D. thesis, University of Zagreb, pp. 382. (http://digre.pmf.unizg.hr/894/1/Nikolina_ilijanic_PhD2014.pdf).

Lukač Reberski, J., Terzić, J., Filipović, M., Frangen, T., & Marković, T. (2016): Impact of land use on groundwater quality in south Dalmatia test area. Cross-border drinking water management. Karleuša, B. & Sušanj, I. (ur.). Rijeka: University of Rijeka, Faculty of Civil Engineering, 2016. 153-167

Lukač Reberski, J., Terzić, J., Frangen, T. & Filipović, M. (2016): Analiza stabilnih izotopa δ18O i δD u podzemnim i površinskim vodama šireg slijeva izvora Prud (Stable isotope δ18O and δD analysis in groundwater and surface water in the Prud spring catchment). Međunarodni znanstveno-stručni skup „Čovjek i krš" Knjiga sažetaka (Proceedings of international conference "Man and karst") / Simone Milanolo, Jasminko Mulaomerović (ur.). Sarajevo : Garmond. 38-39

Miko, S., Ilijanić, N., Marković, T., Hasan, O., Hajek Tadesse, V., Bakrač, K., Galović, I., Caput Mihalić, K., Mesić, S. (2015): Hidrogeološka i paleolimnološka istraživanja Baćinskih jezera - Knjiga II. Paleolimnološka istraživanja Baćinskih jezera (Paleolimnological research of Baćina Lakes). Fond stručne dokumentacije 74/15, Hrvatski geološki institut, 485 str.

Prelogović, E., Aljinović, B. & Bahun, S. (1995): New data on structural relationships in the Northern Dalmatian Dinaride Area, Geologia Croatica 48/2:167-176

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K. (2008): The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geoscience 101:139-183. doi: 10.1007/s00015-008-1247-3

Slišković, I. (2014): Vode u kršu slivova Neretve i Cetine (Water in karst catchments of Neretva and Cetina), Hrvatski geološki institut, Zagreb, 171 str.

Tari, V. (2002): Evolution of the Northern and Western Dinarides: A Tectonostratigraphic Approach. European Geosciences Union: Stephan Mueller Special Publication Series, 1:223-236

Terzić, J., Lukač Reberski, J., Frangen, T., Rubinić, J., Boljat, I. & Burić, H. (2015a): Hidrogeološki odnosi dijela južne Dalmacije i Hercegovine (Hydrogeological relations in part of southern Dalmacia and Herzegovina). 5. hrvatski geološki kongres - Knjiga sažetaka (Excursion guidebook, 5th Croatian geological congress). Horvat, M. & Wacha, L. (ur.). Zagreb: Hrvatski geološki institut, 2015. 262-263

Terzić, J., Lukač Reberski, Jasmina, Frangen, T. & Rubinić, J. (2015): Hidrogeološka i paleolimnološka istraživanja Baćinskih jezera. Knjiga I. Hidrogeološka istraživanja Baćinskih jezera (Hydrogeological research of Baćina Lakes - book 1; technical report). Fond HGI 74/15.

Terzić, J., Marković, T. & Lukač Reberski, J. (2014): Hydrogeological properties of a complex Dinaric karst catchment: Miljacka Spring case study. DOI: 10.1007/s12665-013-3031-6. Environmental Earth Sciences 72 (2014) 4. 1129-1142.

Terzić, J., Stroj, A. & Frangen, T. (2012): Hydrogeologic investigation of karst system properties by common use of diverse methods: a case study of Lička Jesenica springs in Dinaric karst of Croatia. DOI 10.1002/hyp.9194. Hydrological processes 26, 3302-3311.

Velić I. 2007. Stratigraphy and Palaeobiogeography of Mesozoic Benthic Foraminifera of the Karst Dinarides (SE Europe). Geologia Croatica 60/1:1-113

Vlahović I, Tišljar J, Velić I, Matičec D. 2005. Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. Palaeogeography, Palaeoclimatology, Palaeoecology 220:333-360. doi: 10.1016/j.palaeo.2005.01.011

http://www.a-m-narona.hr/

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