HGI
HRVATSKI GEOLOŠKI INSTITUT
CROATIAN GEOLOGICAL SURVEY

44th Annual Congress of the IAH
"Groundwater Heritage and Sustainability"

EXCURSION GUIDEBOOK

Dubrovnik (Ombla) - Blue and Red Lakes (Imotski) - Gacka River - Plitvička Lakes - Zagreb - Ljubljana

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

Groundwater
Heritage&Sustainability

HONORARY PATRONAGE

PRESIDENT OF CROATIA

United Nations Educational, Scientific and Cultural Organization
Organisation des Nations Unies pour l'éducation, la science et la culture

Hrvatsko povjerenstvo za UNESCO
Croatian Commission for UNESCO
Commission croate pour l'UNESCO

REPUBLIKA HRVATSKA
MINISTARSTVO ZAŠTITE OKOLIŠA I ENERGETIKE

Turistička zajednica grada Dubrovnika
Dubrovnik Tourist Board

SCIENTIFIC PARTNERS

United Nations Educational, Scientific and Cultural Organization
International Hydrological Programme

HRVATSKO GEOLOŠKO DRUŠTVO 1951

RGNF

SPONSORS

Ministry of Science and Education

HEP

GRAD DUBROVNIK
CITY OF DUBROVNIK

KOBIS
thermo scientific

ALPHACHROM

Jana
VODA S PORUKOM

DONORS

ponikve.krk VODA

MEĐIMURSKE VODE d.o.o.

Tekija d.o.o. za obavljanje vodnih usluga

USLUGA d.o.o. za vodoopskrbu i odvodnju

DUBROVAČKO-NERETVANSKA ŽUPANIJA

VODOVOD d.o.o. Pula

ŽRNOVNICA

PLITVIČKA JEZERA Nacionalni park National park

LIMES plus

Editors

Tamara Marković — Croatian Geological Survey, President of the Croatian National Chapter of IAH

Kristijan Posavec — Faculty of Mining, Geology and Petroleum Geology, University of Zagreb

Authors of guidebook (in alphabetic order)

Tomislav Paviša	HEP
Jadranka Barešić	Ruđer Bošković Institute, Croatia
Branka Brčič Železnik	Water supply of Ljubljana, Slovenia
Ines Bronić Krajcar	Ruđer Bošković Institute, Croatia
Ozren Hasan	Croatian Geological Survey, Croatia
Nikolina Ilijanić	Croatian Geological Survey, Croatia
Jasmina Lukač Reberski	Croatian Geological Survey, Croatia
Tamara Marković	Croatian Geological Survey, Croatia
Slobodan Miko	Croatian Geological Survey, Croatia
Tomislav Paviša	HEP, Croatia
Kristijan Posavec	Faculty of Mining, Geology and Petroleum Geology, Croatia
Martina Šparica Miko	Croatian Geological Survey, Croatia

Publisher

Croatian Geological Survey, Milana Scahsa 2, 10 000 Zagreb, Croatia

Print

Luna grafika

Issued: September, 2017.

CIP zapis je dostupan u računalnome katalogu Nacionalne i sveučilišne knjižnice u Zagrebu pod brojem 000972206 ISBN: 978-953-6907-68-2

Excursion: Dubrovnik - Blue and Red Lakes (Imotski) - Gacka river - Plitvička lakes - Zagreb - Ljubljana

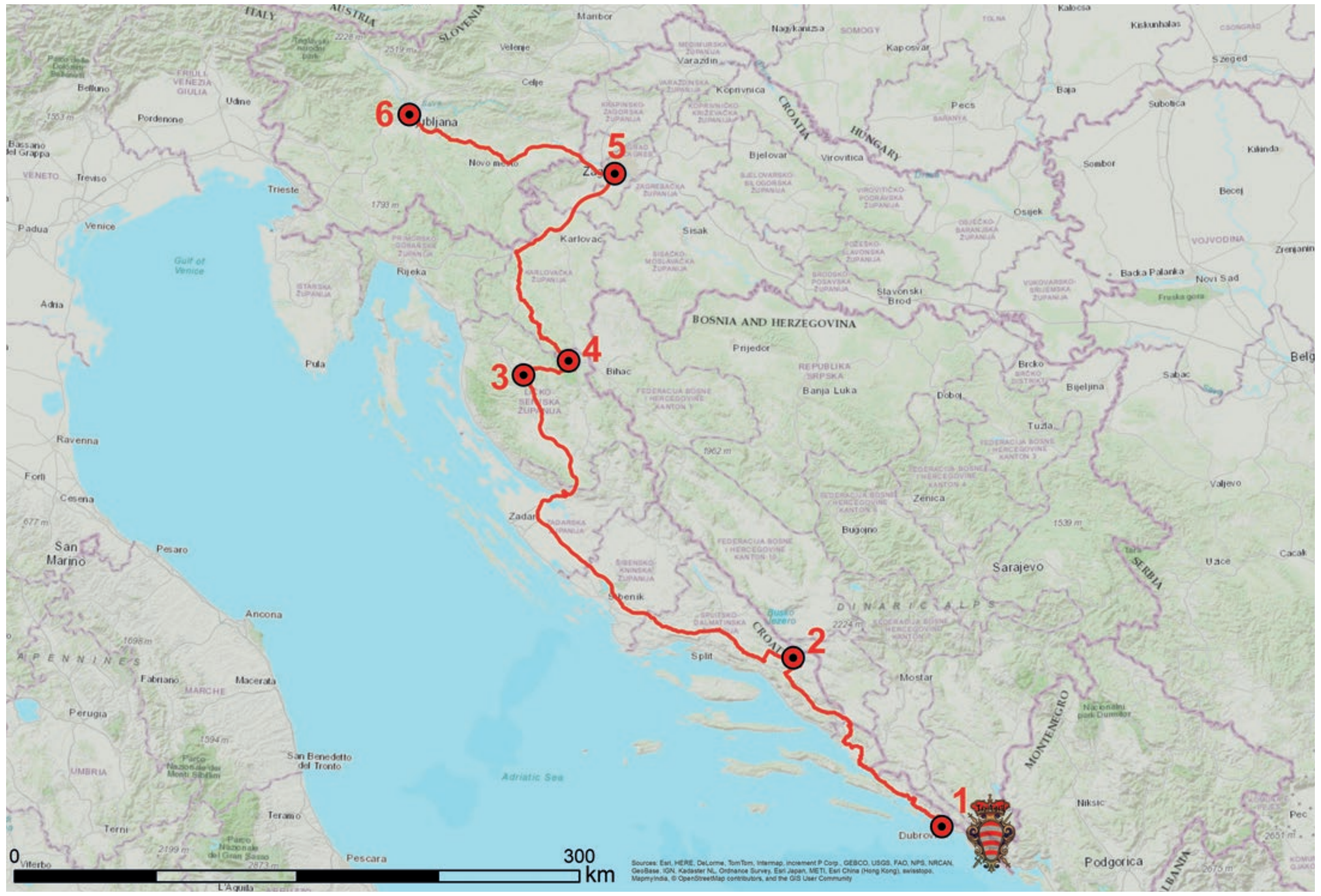

Fig. 1 Map of the area with field trip stops

STOP 1: DUBROVNIK - OMBLA

STOP 2: BLUE AND RED LAKES

STOP 3: THE GACKA RIVER

STOP 4: PLITVIČKA LAKES

STOP 5: ZAGREB

STOP 6: LJUBLJANA

STOP 1: THE OMBLA SPRING

Tomislav Paviša[7]

Rijeka Dubrovačka Bay is located some five kilometres from the centre of the City of Dubrovnik. The Ombla spring is situated at the far end of the bay. It is the discharge point of a large drainage system conveying water from the mountains in the hinterland, through underground conduits, and into the sea. The entire course of the Ombla River is below ground, from the underground retention (reservoir) to its spring in Rijeka Dubrovačka. The Ombla catchment covers an area of about 600 km^2.

Fig. 3 Hydrogeological characteristics of the Ombla spring catchment area

[7]HEP, Dubrovnik, Croatia

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

Hydrogeological characteristics

The Ombla spring catchment area is composed of three rock categories:

- Eocene flysch representing an impermeable hydrogeological barrier;
- Triassic dolomite, a poorly permeable rock with local deviations and
- Jurassic limestone, permeable rock dominated by typical karst porosity with conduits and caverns of large sizes (acting as hydrogeological collectors/aquifers).

Mean annual discharge.......................Qmean= 23.9 m^3/s

- max 100-year discharge...................Qmax/100 = 113 m^3/s
- min 100-year discharge...................Qmin/100 = 2.4 m^3/s

The average annual precipitation is 1,400 mm in the coastal belt, and over 2,400 mm in the mountainous zone of the catchment area.

Dry periods in the Ombla spring catchment area can last more than 90 days. The Ombla spring has never dried out.

Compared to other major springs in the Dinaric karst, the Ombla spring represents an exception. Due to occasional occurrences of water it has great turbidity, which always occurs after heavy rain, and due to the uneven temporal and spatial distribution of water in the catchment area, and especially because of the existence of a dolomite barrier, it is divided into two parts, each with different hydraulic flow conditions.

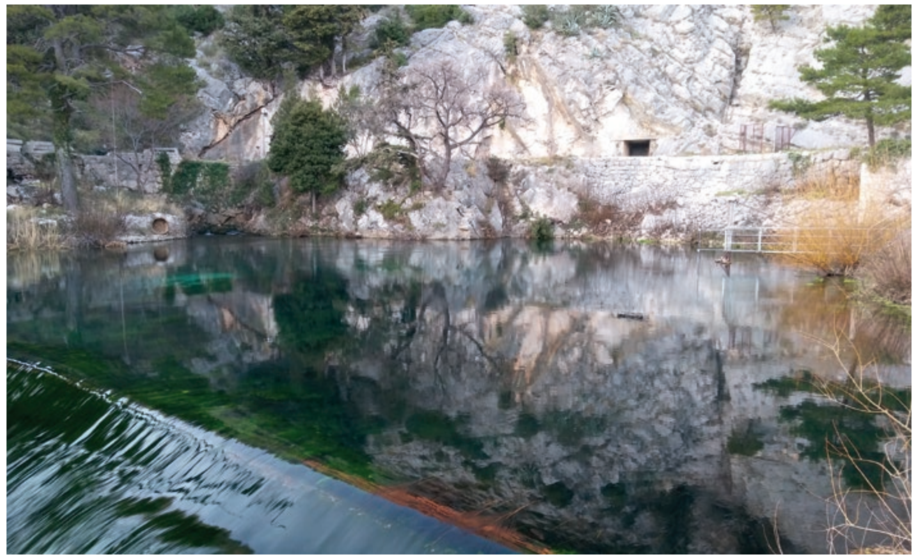

Fig. 4
The Ombla spring and the Rijeka Dubrovačka Bay in conditions of laminar flow

Fig. 5
Periodic phenomena of high turbidity at the Ombla spring and in the Rijeka Dubrovačka Bay in conditions of turbulent flow

The storm water penetrates the soil and creates an underground reservoir in the Ombla spring catchment area of 600 km^2. The underground retention basin is emptied through the damaged dolomite barrier and the main conduit is situated in the southern part of the catchment area. The difference between the minimum and maximum groundwater levels can be up to 200 m. The groundwater stream running from the sinkholes toward the spring may be up to 30 km long. The Ombla catchment area can be subdivided into two typical sections:

- to the north of the dolomite barrier
- to the south of the dolomite barrier

The drainage conduit area downstream of the damaged dolomite barrier, with the main conduit system of the Ombla spring and neighbouring Zaton and Zavrelje springs is shown in Figure 6.

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

Today, the underground reservoir of the Ombla spring is filled only by precipitation. The afore-mentioned subdivision determines the hydraulic diagram of underground reservoir behaviour. The northern part of the catchment area is built of limestone and covers about 90% of the total catchment area. Because of the high porosity of the area, precipitation infiltrates the ground and creates the underground reservoir. The dolomite barrier, which is a poorly permeable rock by its hydrogeological characteristics, encloses the underground reservoir from the south. However, the central portion of this barrier is damaged so that water seeps into the southern part of the catchment area. Downstream of the dolomite barrier is an area of limestone rocks which on the southern side meets the narrow belt of dolomite rocks overthrown onto impermeable flysch. The encountered limestone is characteristic for cave conduits through which the underground retention basin is emptied. The main conduit releases about 90-95% of the total Ombla water.

The first step was to investigate the underground reservoir, and determine the reservoir filling and emptying regime, which together with the behaviour of the underground retention basin was considered and clarified in the numerical model prepared by Jović (2003).

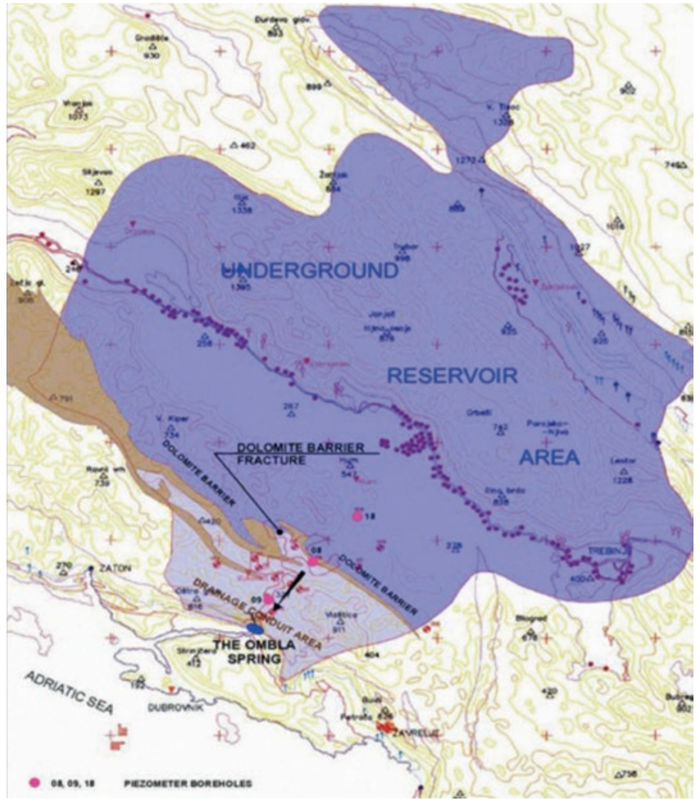

Fig. 6
Underground retention basin and drainage conduit area

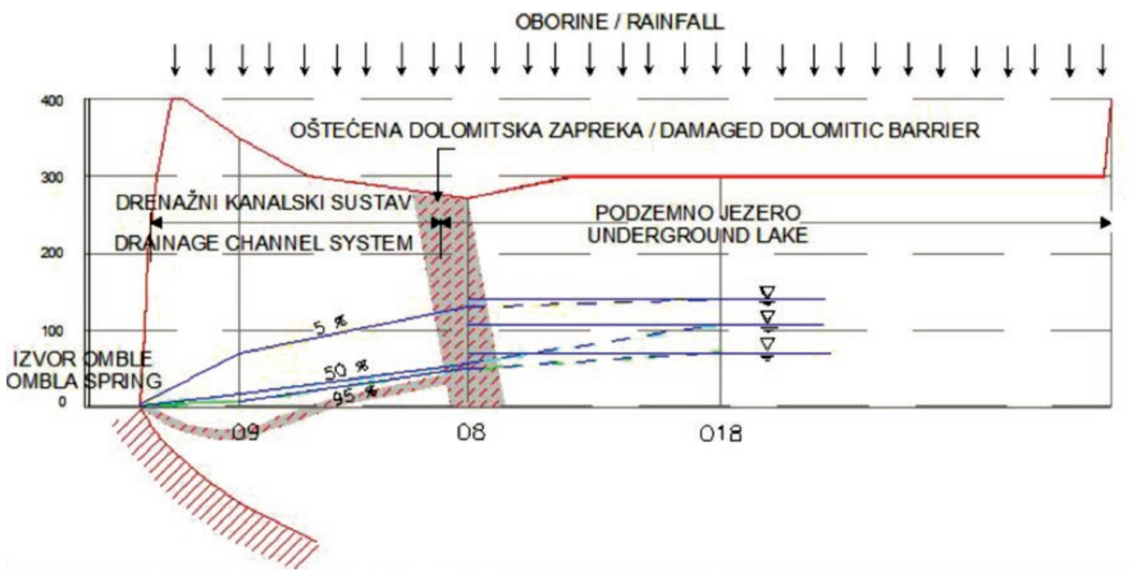

Fig. 7 Schematic illustration of water levels in natural conditions (Jović, 2003)

A numerical model of flows in the underground storage reservoir Ombla in both the natural state and the state planned by the project shows significant changes in the output hydrograph:

- the maximum flow rate reduces,
- the water evacuation time increases and,
- in the period when "the spring gets dry", backwater needs to be lowered to achieve spring outflow (Jović, 2003).

The Ombla flow duration curve under natural conditions and the transformed flow duration curve for the simulated Ombla HPP behaviour at the pool level of 130 m a.s.l. and at biological minimum discharge of Q=4 m^3/s is shown in Figure 8.

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

The curve is smoothed, extreme discharges reduced and the share of discharge in the central part of the curve increased. The right-hand side of the curve, with constant discharge required to maintain the biological minimum, indicates that, in order for this discharge to be achieved, the pool level has to be lowered during one part of the year, as confirmed by the flow duration curves of the water level in the reservoir.

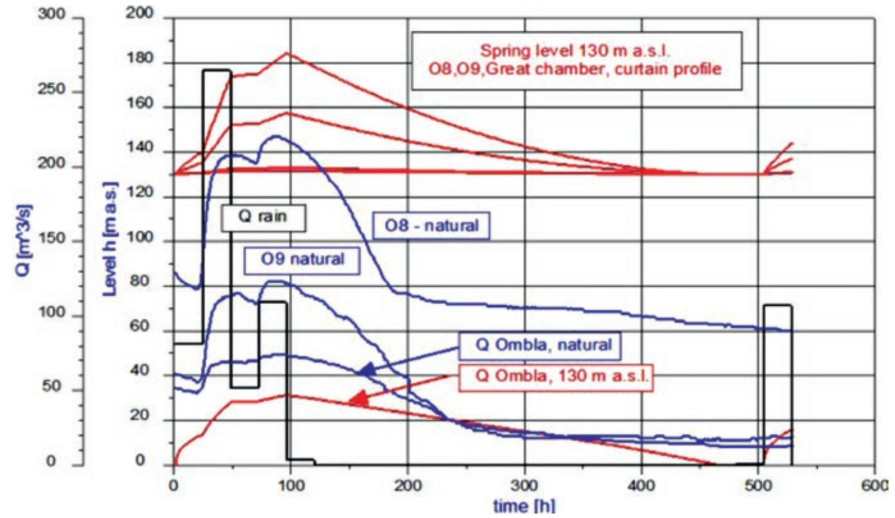

Fig. 8
Water levels in both the natural state and the state planned by the project (Jović, 2003)

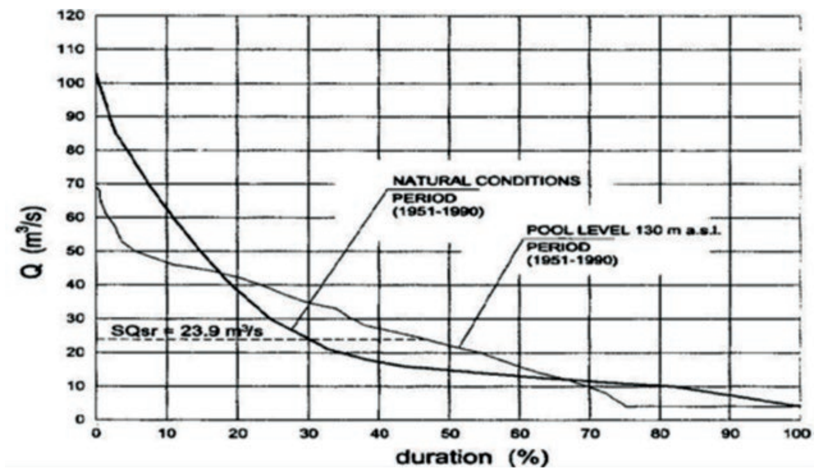

Fig. 9
The Ombla flow duration curve under natural conditions and the transformed flow duration curve for the simulated Ombla HPP behaviour at the pool level of 130 m a.s.l. (Jović, 2003)

Fig. 10 Water level in the underground reservoir in a specific situation of high water levels in the spring zone (November 2010.)

In extremely rare conditions, when a very large amount of rain falls in the immediate hinterland of the Ombla spring, there is a sudden rise in the groundwater level and a subterranean retention basin is temporarily formed, which is partially drained through three waterfalls, as seen in Fig 10.

Basic concept of the Project

The Ombla HPP Multipurpose Hydro Project is a pioneering attempt to build a power plant which will harness the water from an underground karst aquifer for power generation. The dam will be constructed at the Ombla spring to create sufficient water pressure needed for power generation. The underground reservoir is not a large cave, but a labyrinth of interconnected fissures and caves. The dam will be located underground. The idea was to construct a grout curtain as an impermeable barrier and plug the main conduit through which 90% of water is drained, using natural rock mass as the dam body. The grout curtain foundations should be set in flysch. This will enable the water level to rise above the present natural level. It will also turn the present area of the conduit system into a part of the underground reservoir. Figs 11 and 12 show a longitudinal profile of the underground reservoir, the Ombla spring, and the underground dam - grout curtain.

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

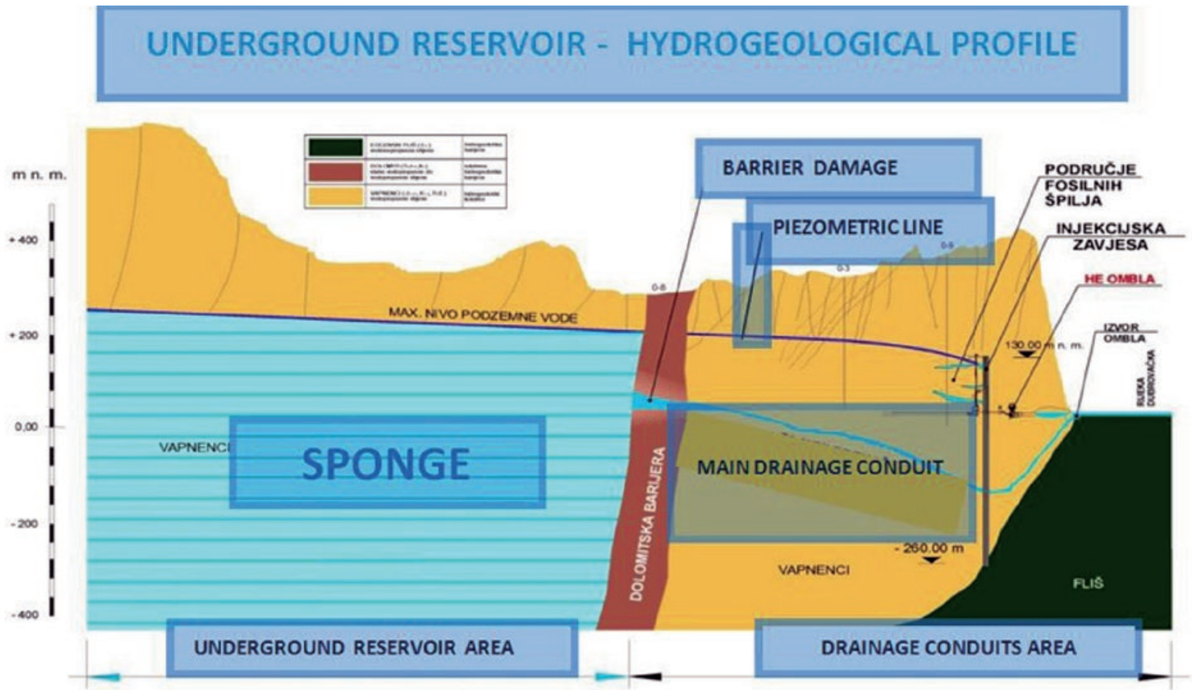

Fig. 11 Underground reservoir - hydrogeological profile (Elektroprojekt - Sever, 2015)

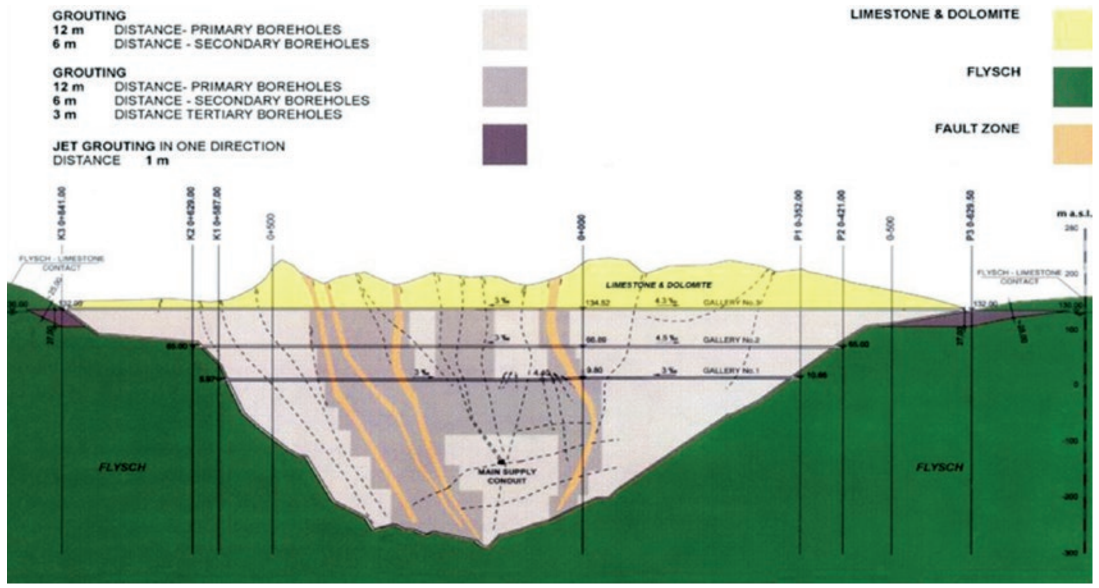

Fig. 12 Underground dam - grout curtain - longitudinal profile (Elektroprojekt - Sever, 2015)

Water intake for Dubrovnik water supply system

The pumping station of the existing Dubrovnik Waterworks is located by the spring pond. The pumps installed in the old and new pumping station pump the water into the municipal network and the water tanks. The Ombla HPP construction will enable a more cost-effective and safer sanitary water supply for the City of Dubrovnik. From the storage water will be conveyed through a special intake by gravity flow into the central water tank of the municipal water supply system without pumping, and without any power consumption. The Dubrovnik Waterworks intake structures are planned to be built at two points, a 560 l/s intake in the natural cave some 500 m under the ground, where the HPP intake structure will also be located, and a 1500 l/s intake in the natural cave - vertical shaft at an elevation of 55.0 m a.s.l.

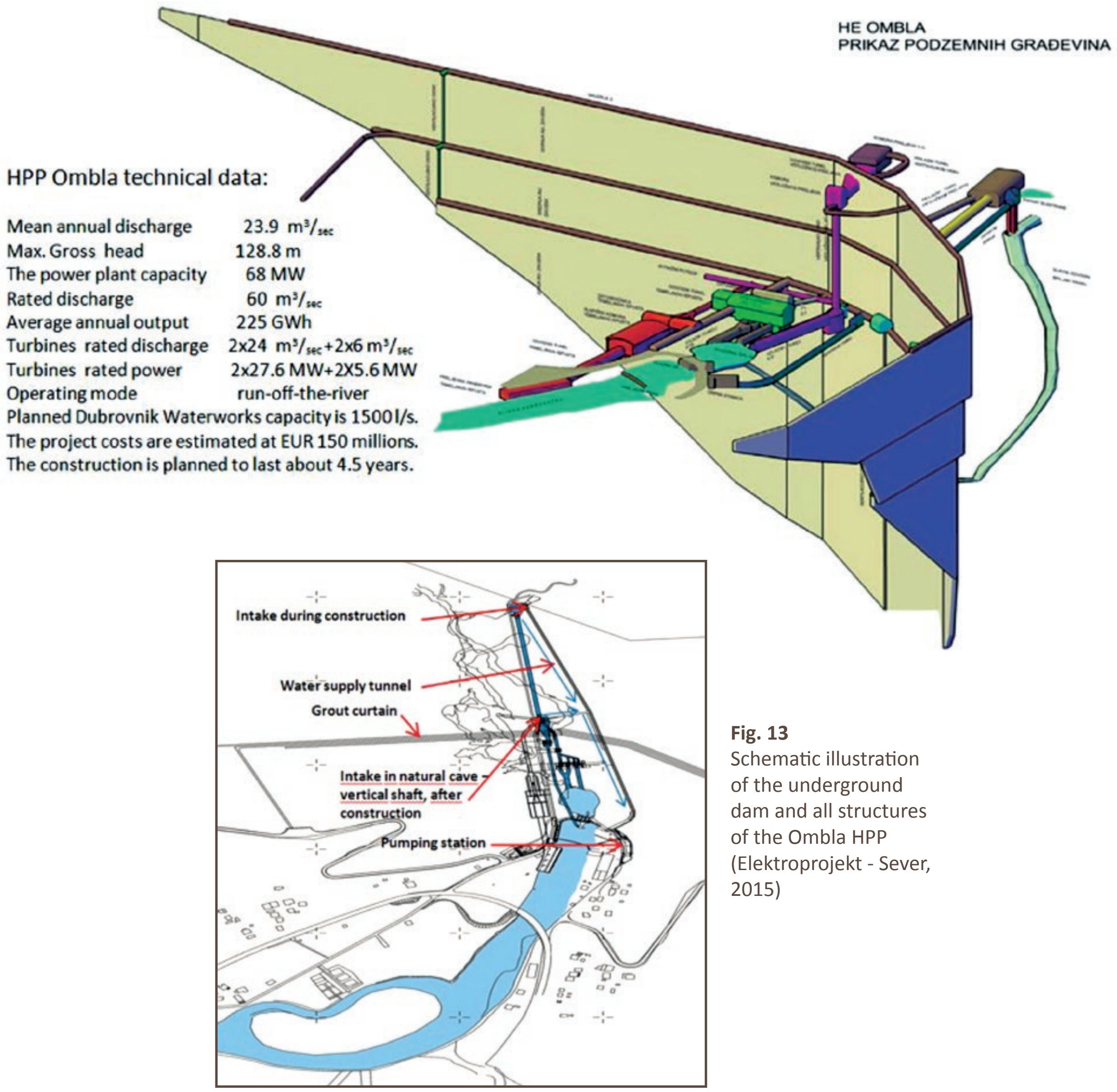

Fig. 13
Schematic illustration of the underground dam and all structures of the Ombla HPP (Elektroprojekt - Sever, 2015)

STOP 2: RED AND BLUE LAKES (CRVENO and MODRO JEZERO)

General overview of the lake genesis

Tamara Marković[1]

Lakes are karstic phenomena and among the top tourist attractions of the Imotski region (Fig 13). The Blue Lake was named after the colour of its water while the Red Lake's name comes from the red stones surrounding it. There is a general disagreement in the literature over defining the Red and Blue Lakes as sinkholes, caves, cenotes, lakes or other karst features. Some of the older researchers argue that both lakes are collapsed dolines. Younger authors argue that the Red Lake is a cave, and their conclusions are based on the classification of the Union International de Spéléologie (UIS). From a hydrological point of view, the Blue Lake has been investigated more extensively, and recent results were published in the paper by Bonacci et al, (2014).

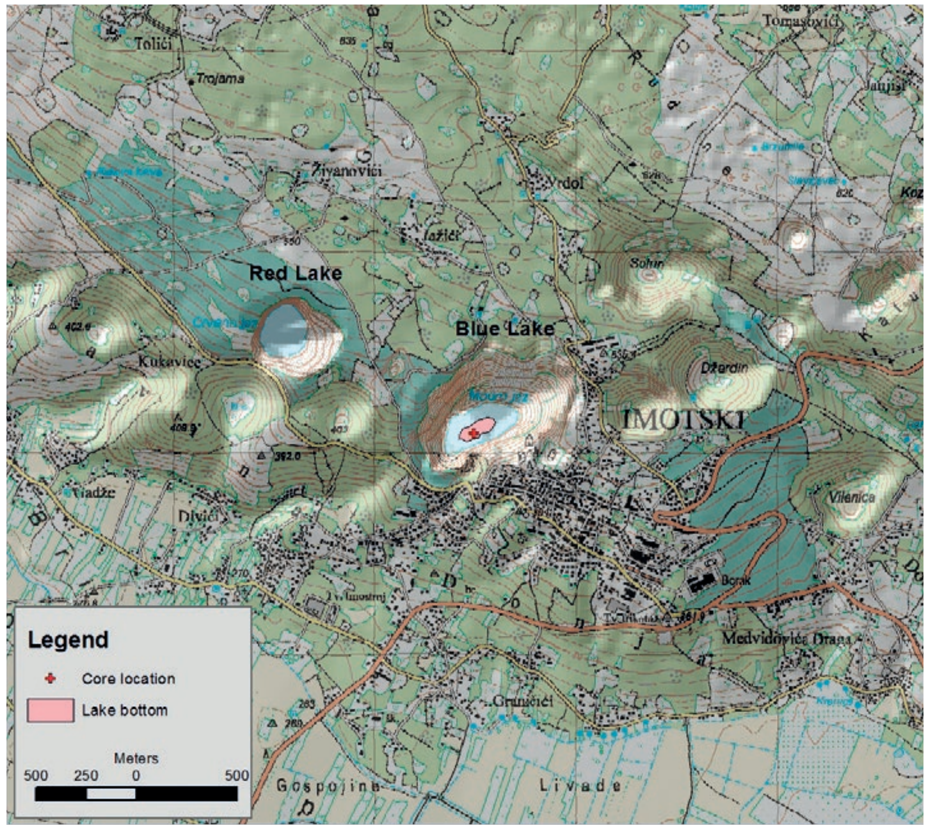

Fig. 13
Map showing the location of the Red and Blue Lakes near Imotski, southern Dalmatia and the coring site in Blue Lake.

[1]Croatian Geological Survey, Zagreb, Croatia

Bonacci & Andrić, 2014 gave an overview of the existing exploration on the genesis and morphology of the lakes-: ''At the end of the nineteenth and the beginning of the twentieth century Cvijić (1896), Grund (1903), Gavazzi (1903/04) and Daneš (1905) published the first scientific papers about the Red and Blue Lakes. Cvijić (1896) established a hypothesis that both depressions were formed by collapse of the "cave ceiling".

Roglić (1938) suggests that both phenomena are cylindrical shaped dolines. At the same time, he excludes the possibility that both lakes functioned as a sinkhole in the past. According to Roglić (1974) a doline is defined as a simple, solitary funnel-shaped and closed karst depression, which is drained at the bottom. It is always wider than deeper and it is formed by corrosion processes and the mechanical activity of surface water and groundwater in areas of karst fissures crossings, resulting in intense water sinking and limestone dissolution.

Petrik (1960) believes that the Red Lake is the youngest doline of all ten significant dolines around the town of Imotski. Between April 1955 and June 1956, Petrik undertook numerous hydrographic measurements in this region. He measured the highest and the lowest point on Red Lake's rim at 522.9 m a.s.l. and 425.4 m a.s.l. respectively. Estimation was given that the altitude of the base of the Red Lake is 4.1 m a.s.l. At the water level of 254.6 m a.s.l., Petrik (1960) calculated the surface area of the lake as 32,900 m^2.

During the period of measurements, the highest and lowest water levels were recorded at 274.45 m a.s.l. and 252.78 m a.s.l. respectively. The amplitude of water level oscillations of the Red Lake measured by Petrik (1960) was 21.67 m. He calculated that at the water level of 254 m a.s.l. water loss from the lake is 89 l/s.

Petrik (1960) also estimated that at a water level of 268 m a.s.l. the volume of water in the Red Lake is at least 6 x 106 m^3. The hydrological regime of the Red and Blue Lakes is considered different and it is assumed that they have no significant relationship with the hydrological regime of the Imotski Polje and surrounding area.

Milanović (1981) saw the Blue and Red Lakes as dolines, formed in the way that usually occurs as a result of the chemical action of water on limestone.

Bahun (1991) analysed the genesis of the Red and Blue Lakes in his work. For him, whether the Red Lake is a doline or cave is not a problem of terminology, but it is important from the point of view of the formation of karst phenomena. Bahun (1991) believed that both lakes occur in the carbonate environment and that neither lithological nor tectonic characteristics provided predisposition for the development of these features. His conclusions are substantially different from all those previously presented and therefore they will be fully quoted: "The results of analysis of the sequence of geological events and of the present hydrogeological relations and the development of the morphology of the wider area of Red and Blue Lake, allow the reconstruction of the surroundings in the late Miocene. Northeast of today's Imotski Polje existed a vast lake at elevation of 400-500 m. Back then, there was an elevated region between the lake and the sea. Water from the lake flowed through sinkholes to a lower surface level. Neotectonics caused the differential disturbance of terrain and the area of the former lake got dissected so that some parts were relatively elevated to the present level at 900 m a.s.l., and some parts were relatively lowered, such as Imotsko Polje, to the current elevation of 260 m a.s.l. Such movements caused the lake to dry up, sinkholes were left without water so by their exogenous influenced destruction and side collapsing they were turned into a huge sinkhole (Blue Lake) or deep

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

pits (Red Lake). Permanent water and its oscillations in Red Lake as well as the occasional flooding of Blue Lake are the results of the dynamics of underground karst water. It flows through the karst underground of the area from the upper parts in the north and northeast to the erosion base - Neretva River in the east and to the Adriatic Sea in the south."

Garašić (2001, 2012) reports the results of the international cave diving expedition in the Red Lake, which took place during September and October 1998. According to him, the Red Lake is a water reservoir with a minimum of 16 x 106 m^3 of water. He does not specify whether it is a volume of stored water in the lake or the maximum volume as defined by the geometry of the lake. He claims that at the bottom of the Red Lake there is a strong flow, (in other words an underground river). Garašić (2001, 2012) lists the following important results of this expedition: (1) a cave inlet was found east of the lake at a depth of 175 m, measuring 30 x 30 m; (2) new species of cave fish and shrimp as well as frogs and insects in the lake and its immediate environment have been found and specified; (3) the deepest point on the bottom of the lake at an elevation of 6 m below sea level has been measured which established a new maximum depth of the Red Lake after 528.9 m; (4) at depths below 50 m, a constant water temperature of 7.9 °C was measured; and (5) the westward movement of groundwater in the bottom of the lake was registered.

Kovačević (1999) suggests that water from the Red Lake will leak when the level rises up to a cave on the west side, and that the leak stops when the water level drops. Local residents claimed that the water from these caves overflows in the Jažva spring. Gavazzi (1903/1904) documents the existence of this cave and Cvijić (1960) also writes about it. Roglić (1938, 1954) and Petrik (1960) did not register the cave's location during their field research, although its existence was previously documented. The international cave diving expeditions in 1998 recorded more than 300 m of channels in this cave. On November 29th, 2011 cavers from the Imotski Caving Club had the opportunity to explore the very same dried up cave. At that point, the historically lowest water level of the Red Lake was recorded at 228 m a.s.l. The cave's influence on the hydrological regime of the lake can partly explain why the maximum water level in Red Lake is lower than the maximum water level in Blue Lake.

Williams (2004) provides the following information about the Red Lake: "The deepest known case of a collapsed doline containing a lake is the Crveno Jezero (Red Lake) in Croatia, which is 528 m deep from its lowest rim, the bottom of the collapse extending 281 m below the modern level of the nearby Adriatic Sea. The collapse diameter at the surface is about 350 m and at lake level is about 200 m. Recent diving has found an active subterranean river that crosses the doline near its floor. The whole feature is thought to have been formed by progressive upwards collapse of the cave roof, much of the collapse debris having been transported away by the underground river."

Gams (2005) found the reasons for the deep lowering of the bottom of Red Lake in the regional seismic activity that is still present. He notes that a seismic station near Imotski registered in the period 1946-1989 the strongest earthquake of 7 degree of MCS. Gams (2005) mentioned that the earthquake that occurred in 1942 reduced the depth of the Blue Lake and caused a massive rock fall event in the Red Lake. He assumes that the bottom of the Red Lake is covered with a thick layer of collapsed rock material.

Bonacci et al. (2013) mention the Red and Blue Lakes as two exceptional karst phenomena in the complex system of sinking, loss and underground transboundary relationships of karst rivers, lakes and aquifers in the central part of the deep and bare Dinaric karst in Croatia and Bosnia and Herzegovina''.

LATE HOLOCENE ENVIRONMENTAL CHANGE: EVIDENCE FROM THE BLUE LAKE (MODRO JEZERO), CROATIA

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

Introduction

Lacustrine sediments are often outstanding terrestrial archives for the reconstruction of past environments, climate and human impacts. When accurately dated, such a sediment record is a unique opportunity to gain unprecedented insights into coarse- and fine-scale environmental changes and they therefore pose unique challenges for palaeoecologists, palaeoclimatologists and geochemists. The Red (local name Crveno jezero) and Blue (local name Modro jezero) Lakes near the town of Imotski (Fig 13), occur only approximately 500 m away from each other, and represent impressive karst geomorphological forms in the Dinaric karst; collapsed dolines, with extreme dimensions. Karstic depressions are generated by dissolution processes, often involving subsidence and/or collapse, thus leading to the formation of funnel-shaped dolines with steep margins, which generally are very deep for their size. The Red Lake has a rounded shape and is permanently filled with water, whereas the Blue Lake is elongated in a NE-SW direction (195 x 75 m wide) and dries up periodically (Bonacci et al., 2014). The slopes of the Red Lake are much steeper, indicating that the Blue Lake is older than the Red Lake. These systems are very sensitive to regional hydrological balances, resulting in considerable lake level, water chemistry and biological fluctuations in response to changes in the weather, particularly precipitation. They respond dynamically by adjusting their volume and surface area. The highest recorded water level in the Red Lake was at the elevation of 311 m a.s.l., while in Blue Lake it occurred at 342 m a.s.l. (Bonacci et al., 2014,) Fig 14. The Blue Lake dried out 7 times throughout the 20th century based on historical records.

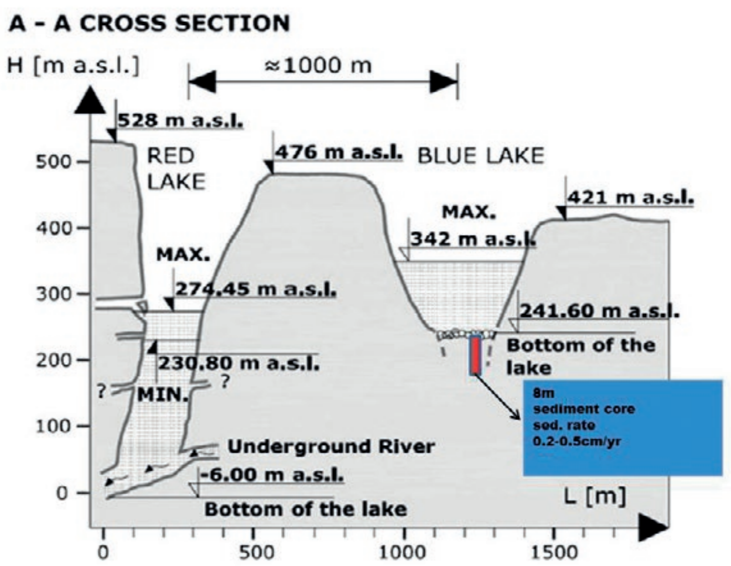

Fig. 14
Cross-section which passes through both the Blue and Red Lakes (from Bonacci et al.,2014). Position of the 2012 coring site (not to scale).

[1]Croatian Geological Survey, Zagreb, Croatia

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

The recent drought period (October 2011 to February 2012) provided access to the lake bottom and the possibility of drilling an 8 metre long sediment core (Figs. 15 and 16). The Blue Lake sediment record is studied using a multiproxy approach to solve chronological questions linked to climatic and environmental changes in the Holocene terrestrial archives. In this endorheic (closed drainage) basin, the combination of great depth and multiple episodes of karstification led to thick deposits with high sedimentation rates, providing a long and continuous sedimentary sequence suitable for palaeohydrological and palaeoclimate reconstructions. The depositional model archived in this lake sedimentary sequence is described using lithological changes with variations in sedimentation rates to reconstruct the Blue Lake history of drought and high water level periods and resolve questions about the sedimentary evolution of the lake.

Fig. 15
The Blue Lake viewed from the south-western slopes and sediment coring in the dried out Blue Lake during the field campaign in January 2012.

Fig. 16 The sedimentary sequence from the Blue Lake. Homogenous carbonate silts dominate in the upper part of the sequence, compared to laminated sediments from 400 cm down-core, indicating lake level variations and the formation of discontinuity surfaces during the low-stand.

The 8 m long sediment core was collected and high resolution images, trends in spectral colour parameters (L*a*b*), magnetic susceptibility, grain size, elemental composition, total nitrogen and total organic carbon were obtained from throughout the core. The sediment is dominated by homogenous carbonate silts (Figs. 4 and 6) in the upper part of the sequence, compared to laminated sediments from 400 cm down-core, indicating lake level variations and the formation of discontinuity surfaces during low-stand (Miko et al., 2015). The sediment core covers the last 2400 years, with the sedimentation rate ranging between 0.2 and 0.5 cm/yr (Fig 17).

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

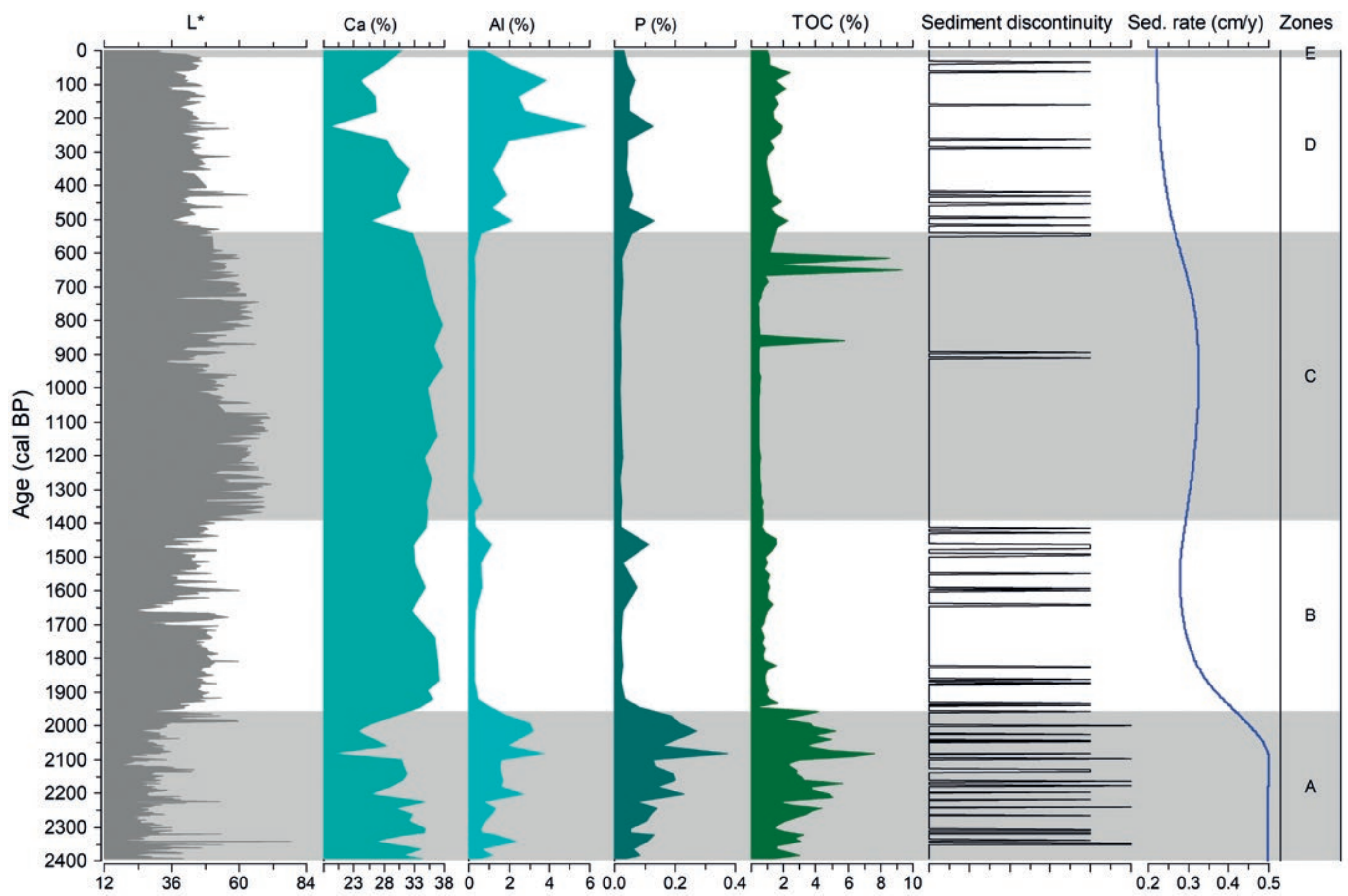

Fig. 17 Downcore colour brightness (L*) and selected geochemical indicators, frequency of sediment discontinuities (interpreted as drought periods) and calculated sedimentation rates.

The sedimentary sequence shows evidence of shallower phase of the lake from 2400 cal BP, and progressive deepening of the lake from app. 2000 cal BP, reaching its maximum during Medieval Warm Period (MWP). The shallow-water sequence is interrupted by several deep water phases and indicates evolution from a wetland prior to 1960 cal BP (lithological zone A). Within this zone, needle-shapes vivianite (iron phosphate mineral) rich layers occur (Fig. 7), which is stable under anoxic conditions, evident in anomalous P-enrichments in this zone. A deeper carbonate producing lake was formed from 1960 to 1390 cal BP (zone B) with frequent drought periods. The deepest lake with no visible discontinuities in sedimentation lasted for the next 850 years (zone C, between 1390 and 540 cal BP). During the LIA and modern period (zones D and E, from 540 to the present) the frequency of drying out of the lake increased but their duration was much shorter without significant organic carbon accumulation. The higher siliciclastic input and erosion into the carbonate producing lake is evident at the beginning of the Little Ice Age (LIA) and intensification of the anthropogenic activities in the town Imotski. Discontinuity surfaces in sediment core were visible in sediment texture and correlated with sediment brightness (L*), elemental composition and organic carbon. Within the core several faults were detected (Fig 8) and correlated with earthquakes which occurred in the time of sedimentation indicating to tectonic activity of the wide area of southern Dalmatia (Miko et al., 2015). The lake deposits, which cover the time-span from ca 2400 cal BP to the present, show that the hydrological balance dominated by groundwater flow. The Blue Lake with its unique position within a karst aquifer and high sedimentation rate will allow the construction of a simplistic climate-hydrology model in which variations in groundwater generation within the lake are recorded in sediments at a three year resolution.

The sedimentary sequence shows evidence of a shallower phase of the lake from 2400 BP, and progressive deepening of the lake from app. 2000 BP, reaching its maximum during the Medieval Warm Period (MWP). The shallow-water sequence is interrupted by several deep water phases and indicates evolution from a wetland prior to 1960 BP (lithological zone A). Within this zone, vivianite (needle-shaped iron phosphate mineral) rich layers occur (Fig 19), which are stable under anoxic conditions, and evident as anomalous P-enrichments in this zone. A deeper carbonate producing lake was formed from 1960 to 1390 BP (zone B) with frequent drought periods. The deepest lake with no visible discontinuities in sedimentation lasted for the next 850 years (zone C, between 1390 and 540 cal BP). During the LIA and modern period (zones D and E, from 540 to the present) the frequency of drying out of the lake increased but these periods were much shorter and without significant organic carbon accumulation. The higher siliciclastic input and erosion into the carbonate producing lake is evident at the beginning of the Little Ice Age (LIA) and with the intensification of anthropogenic activities in the town of Imotski. Discontinuity surfaces in sediment core were visible in sediment texture and correlated with sediment brightness (L*), elemental composition and organic carbon. Within the core, several faults were detected (Fig 20) and correlated with earthquakes which occurred at the time of sedimentation indicating tectonic activity over the wide area of southern Dalmatia (Miko et al., 2015). The lake deposits, which cover the time-span from ca 2400 BP to the present, show that the hydrological balance was dominated by groundwater flow. The Blue Lake with its unique position within a karst aquifer and high sedimentation rate will allow the construction of a simplistic climate-hydrology model in which variations in groundwater generation within the lake are recorded in sediments at a three year resolution.

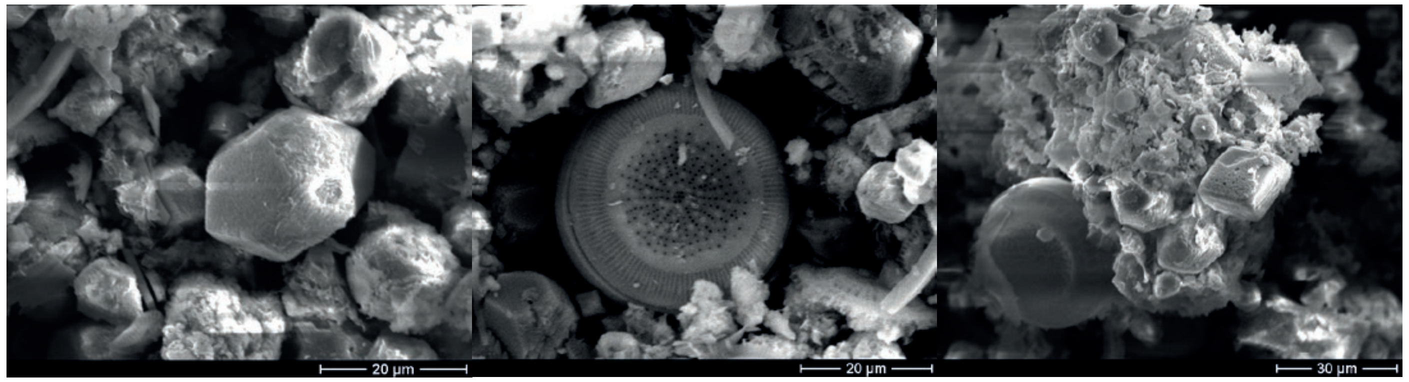

Fig. 18 Homogenous carbonate silts as dominant sediment facies in the sediment record from Blue Lake, composed of endogene calcite crystals and various diatoms.

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

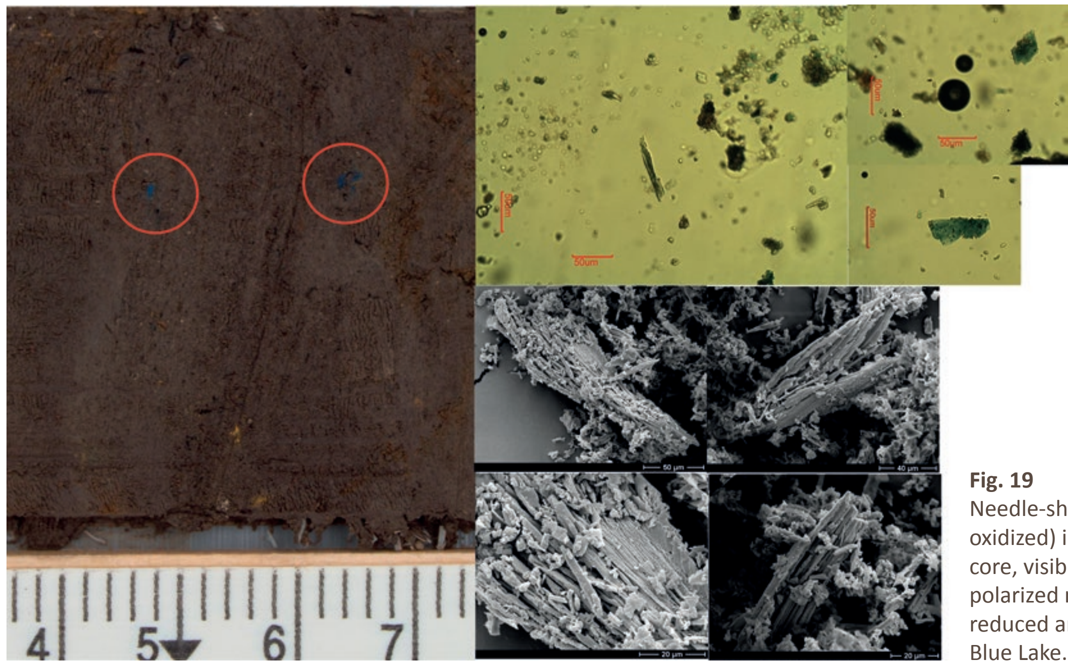

Fig. 19
Needle-shaped vivianite crystals (blue when oxidized) in lower part of the sediment core, visible to the naked eye and under the polarized microscope and SEM, evidencing reduced and shallower environment in the Blue Lake.

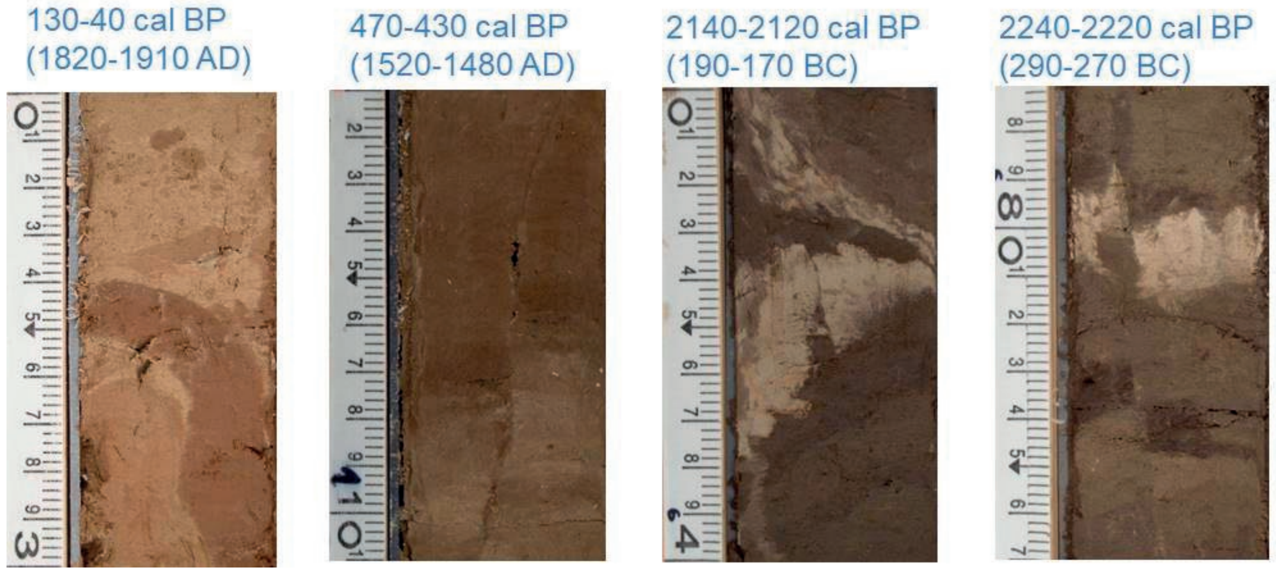

Fig. 20 Different types of disturbed sediments: tiny faults (mm to cm scale), liquefied clayey layers and erosional discontinuities.

STOP 3: HYDROGEOLOGICAL SETTINGS OF THE RIVER GACKA SPRINGS

Tamara Marković[1] & Jasmina Lukač Reberski[1]

Introduction

The catchment of the river Gacka springs is located in the Croatian part of the Dinaric karst, which represents the karst locus typicus. The catchment consists of four major (Tonković, Majerovo Vrilo, Klanac and Pećina) and several minor springs (Jaz, Marusino Vrilo and Graba) with different discharge rates. The Gacka springs are characterised by their high discharge and exceptional water quality, which was why this catchment area was proclaimed by the Water Management Strategy (OG 91/08) as one of the strategically important areas of drinking water reserves in the Republic of Croatia. The research area is characterised by features of typical karst geomorphology. Research and data collection is difficult due to the heterogeneity of the karst aquifer, as well as the unknown geometry of the voids through which the water flows underground to the springs. In addition, with a size of approximately 500 km^2 the river Gacka springs catchment area is categorised as a „big catchment" (Kendall & McDonnell, 1998) which further complicates the study. Results of previous hydrological and hydrogeological studies (Pavičić et al., 2003; Lukač Reberski, 2008) have shown that the river Gacka springs catchment area can be divided into subcatchments of the main springs. Former detailed hydrological analyses were performed on the basis of hydrological data measured only on the profiles of the river Gacka (Bonacci & Andrić, 2008; Lukač Reberski, 2008). Hydrograph analyses performed based on these data are related to the reaction of the entire aquifer system to precipitation, while the characteristics of particular sub-parts of the catchment remain unknown.

General hydrogeology

The study area is composed predominantly of carbonate rocks with fractured and fracture-cavernous porosity. Over the wider area of the river Gacka springs catchment, various Jurassic and Cretaceous limestones and dolomites predominate. The great permeability of the limestone is the direct result of its fragmentation caused by intense tectonics, as well as by the lithological composition which enables dissolution processes. Besides the carbonates, Tertiary clastics, i.e. the Jelar deposits (Bahun, 1974) are also abundant in this area, and can be observed overlying the carbonates, sometimes as erosional remains only a few metres thick, or up to several hundred metre thick deposits. These deposits are represented by limestone breccias formed of unsorted Jurassic, Cretaceous and Palaeogene sedimentary rock fragments (Vlahović et al., 2009). The Jelar formation has specific hydrogeological characteristics and, due to its lithology and spatial distribution, a specific hydrogeological function. The presence of marly-matrix breccias intercalated with marl lenses led to two opposing hydrogeological effects i.e. firstly the unusually well-developed surface and underground karst phenomena, and secondly the formation of relatively low permeable environments (Bahun & Fritz, 1975). These

[1]Croatian Geological Survey, Zagreb, Croatia

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

deposits can be observed at the bottom of the polje near the river Gacka spring, as well as in the western part of the catchment. Fine-grained sediments with intergranular porosity occur in the form of the Quaternary cover in the poljes and depressions and they do not have an important hydrogeological influence.

Lithology played an essential role in the formation of the hydrogeological properties, especially the permeability (LUKAČ REBERSKI et al., 2009). Hence, based on their permeability the deposits are divided into:

- Very permeable carbonate rocks, which are the most common types, and where limestones of Jurassic and Cretaceous ages prevail;
- Predominantly permeable rocks are represented by other Jurassic and Cretaceous carbonates and Palaeogene clastites, i.e. the Jelar deposits. The Jelar deposits exhibit about 50% less permeability than the Jurassic and Cretaceous carbonates, which surround them (Bahun & Fritz, 1975);
- Predominantly impermeable rocks - comprising dolomites of Jurassic and Cretaceous periods;
- Impermeable deposits include the Eocene marls occurring in a very small region in the eastern part of the investigated area;
- Variably permeable deposits include Quaternary deposits with heterogeneous properties, as their permeability varies depending on their thickness and composition. They are represented mostly in the depressions of the karst poljes. One of the most important, and currently unsolved, karst problems is determining the boundaries and the surface of the catchment, for which classical geological and hydrogeological approaches are necessary but not always sufficient. Hydrological approaches may provide answers to some questions regarding the size of the catchment surface but cannot imply the position of the boundaries (Bonacci, 1995). Unlike a topographic water divide, determination of the groundwater divide in karst terrain depends on many factors. Furthermore, the groundwater divide is not constant as its position changes depending on the groundwater level (Žugaj, 2000). Therefore a multidisciplinary research approach and data collection is required in order to precisely determine the location of the divide and the size of the catchment. Several tracing tests were carried out using the Na-fluorescein artificial tracer to determine the apparent velocities and groundwater flow directions as well as the size of the catchment area. Tracing test results, performed between 1957 - 2010, were presented in unpublished technical reports. Recent investigations suggest that the surface of the Gacka catchment up to the Čovići profile extends to 516 km^2 (Biondić et al. 2010). Groundwater-flow directions depend more on the structural relationships than the lithological characteristics because of the relatively monotonous lithology. The study area is characterized by the NW-SE Dinaric strike of the structures. Tracings showed that the groundwater flow direction in the greater part of the catchment area is parallel to these structures. This is due to the position of the main boundary faults, favourable to the stress direction (20°-45°), and along which right transcurrent shifts appear, apart from the opening up of spaces and appearance of structures of a pullapart type (Prelogović, 1989). A fault direction unfavourable to the stress direction leads to local compression by closing of the space and possible prevention of water flow (Fig 21).

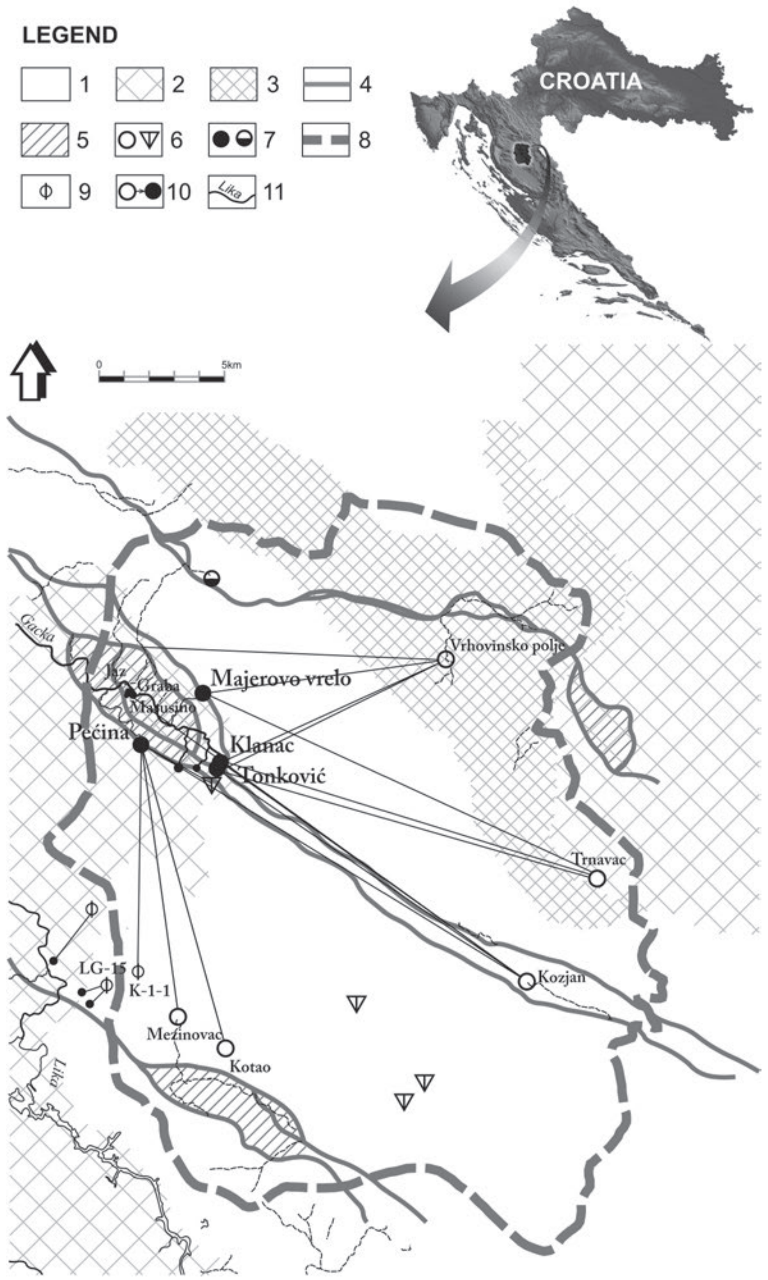

Fig. 21
Schematic hydrogeological map of the study area, showing sampling sites (position of the study area in detail). 1- very permeable rocks, 2- predominantly permeable rocks, 3-predominantly impermeable rocks, 4- most important faults, 5- extension zone, 6- swallow hole (ponor) and vertical cave (pit), 7- spring: permanent and intermittent, 8- groundwater divide, 9- borehole, 10- groundwater connection (tracer test), 11- river, 12- river and rain gauge stations, 13- groundwater velocity determined by tracing tests (cm/s).

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

The river Gacka is characterized by favourable hydrological conditions. The flow regime is standardized compared to other karst rivers, and considerable variations of the flow quantities through its river bed do not occur. The ratio of the lowest, medium and highest discharge is 1:4:20, whereas the ratio of the neighbouring Lika river is 1:100:800 (Bonacci, 1987), which vividly shows its torrential character. During the monitoring period (2008 - 2010) the amount of precipitation varied, with 2008/09 being considered as an average year when compared to the long term average, whereas 2009/10 was wetter. The average annual discharge during the monitoring period, (determined from data collected on the Gacka river gauge at Čovići Podgora, Fig 21), was 13.44 m^3s^{-1} of which 29% is related to the Tonković spring, 26% to the Klanac spring, 24% to the Majerovo Vrilo spring, 15% to the Pećina spring and 6% to the remaining springs (Fig 22).

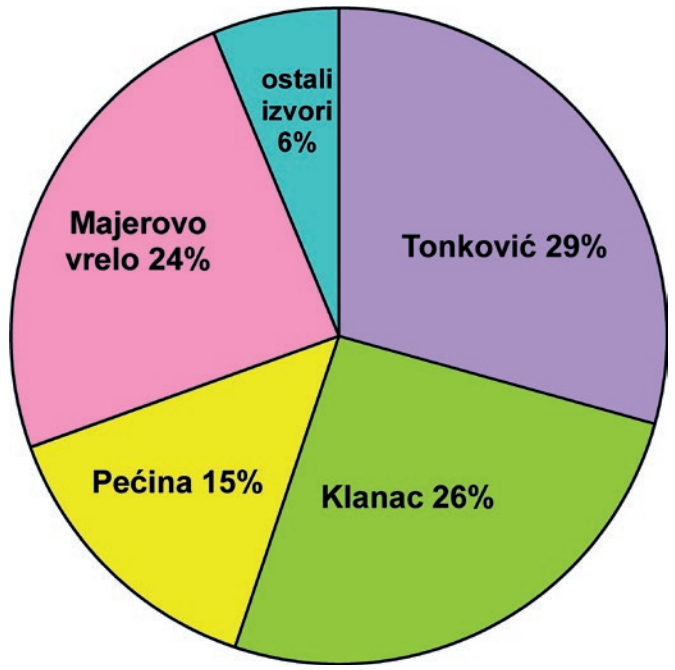

Fig. 22 Proportion of discharge from the river Gacka springs between 2008 - 2010.

Recent investigations of the hydrological balance of the catchment indicated the significant retention properties of the karst underground system in the river Gacka catchment (Lukač Reberski, 2008). Therefore the water balance of the catchment should be prepared over longer time periods because it provides more reliable discharge coefficient information. Due to the inadequate distribution of rain gauge stations (Fig 21) in the river Gacka springs catchment, mean annual precipitation was calculated using the regression equation defined for the research area (Gajić-Čapka et al., 2003). This equation also takes into account the precipitation change with altitude as all the rain gauge stations in Lika are below 760 m.a.s.l. and most of the catchment is located at higher altitudes. Mean annual precipitation is

1383 mm while the mean catchment discharge is determined from 30 years of daily discharge data (1972 - 2002), so the mean annual discharge in the profile of the hydrologic gauge station Čovići-Podgora is 14.2 m^3/s. The discharge coefficient of the catchments calculated using the above formula is 0.63, which means that 63% of total precipitation in the catchment infiltrates into the ground and flows towards the river Gacka springs.

Based on their chemical composition the spring waters of Majerovo Vrilo belong to the Ca-HCO_3 to CaMg- HCO_3-type of water, i.e. to the hydrochemical facies (Fig 23). Waters of the Tonković, Klanac and Pećina springs belong to the Ca-HCO_3 type of water. These water types are the result of the dissolution of carbonate minerals (calcite and dolomite) which are the main constituents of the catchment area of the springs.

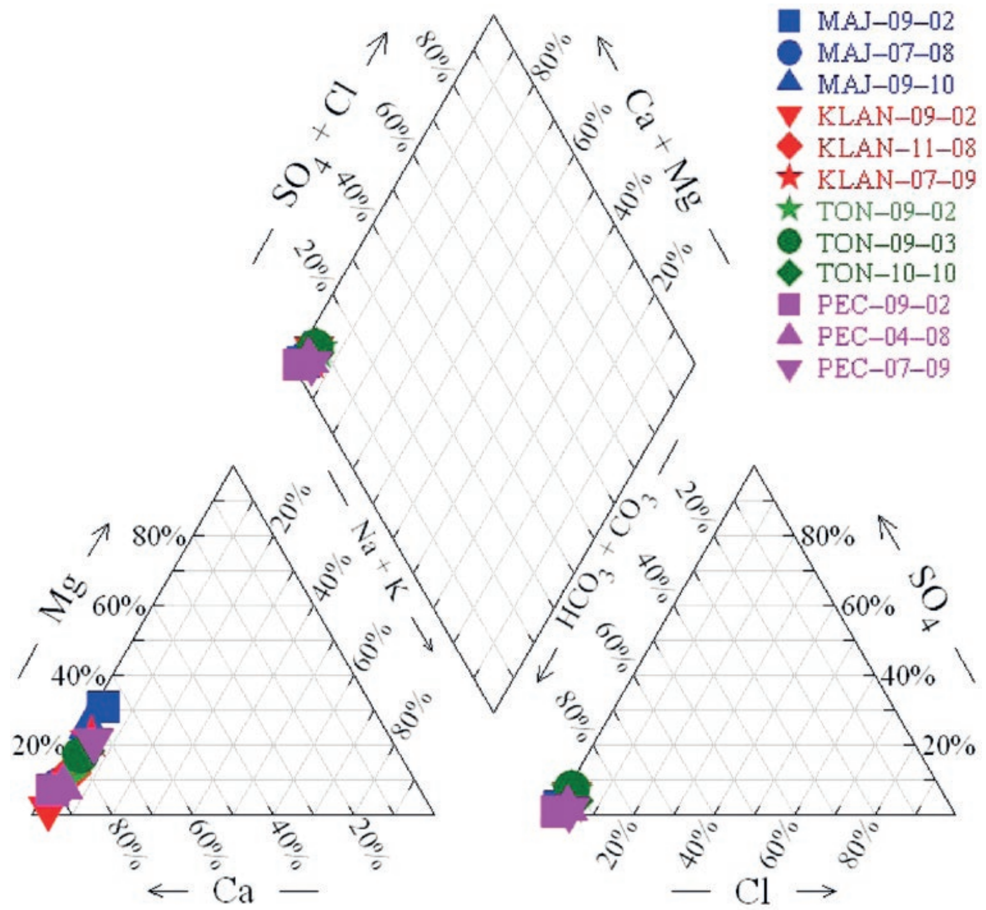

Fig. 23 Piper diagram showing the hydrochemical facies of the observed springs (e.g. KLAN-11-08 means SPRING-month-year).

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

The temperature of the spring waters, was measured periodically during the research period, and varies from 8.4 to 10.0 °C. This is generally in accordance with the mean annual air temperature of the recharge area of the spring. The lowest average measured temperatures were recorded at Majerovo Vrilo, which is in accordance with the data suggesting that this spring is recharged from the highest altitudes, where the temperatures are the lowest. Temperatures measured at the Tonković and Pećina springs are also compatible with the calculated altitudes of their recharge area. The oxygen content measured in the spring waters, as well as the model determined carbonate saturation level, is advantageous, from the water quality protection standing point. A high oxygen concentration was measured in the waters which enables oxidation processes useful as water autopurification reactions. Spring waters are mostly saturated with calcite, which enables deposition of any existing metals in the water due to their affinity with carbonates. Hence, in saturated conditions these reactions could be initiated, which also has a water autopurification role. The measured nitrate concentrations are below the Croatian drinking water standard. (OG. 125/13) and range from 1.3 to 5.2 mg/l with small seasonal oscillations. The highest concentration was measured at the Pećina spring in the autumn and winter. This is the consequence of both anthropogenic influences and degradation of the plant material in the highly karstified aquifer of this spring. Ammonium and orthophosphate concentrations are very low in all the springs and sometimes they are below the detection limit. Sulphate concentrations range from 3.4 - 12.9 mg/l and are below levels for the Croatian drinking water standard (OG. 125/13). Concentrations of chloride range from 1.3 - 14.1 mg/l with the highest concentration being observed at the Tonković spring in March (14.1 mg/l) and April (8.9 mg/l). Furthermore, concentrations of chloride at other springs are higher in March and April, than during other months. These high concentrations are most likely to be a consequence of de-icing of the roads, because the springs are located near them. Waters of the river Gacka springs are still characterised by their excellent quality and are classified as strategically important water reserves of the Republic of Croatia (OG. 91/08).

STOP 4: PLITVICE LAKES NATIONAL PARK

Jadranka Barešić & Ines Krajcar Bronić

Plitvice Lakes are situated at 44°51’N 15°37’E in central Croatia in the eastern part of the mountainous region of Lika-Senj County, between the high forrested mountains of Kapela and Plješivica. A series of sixteen beautiful lakes of a crystal blue-green colour is fed by many small streams and brooks descending from the mountains. The lakes extend over a distance of some eight km, aligned in a south-north direction (Fig 24). The whole area was proclaimed a National Park in 1949 and as such was included into the UNESCO World Heritage list in 1979. The National Park, ranging in altitude from 1279 m to 367 m a.s.l., has an area of 298 km2, of which 223 km2 are forests (74.8%), 69.6 km2 are meadows (23.3%) and about 2 km2 (0.72%) are water areas (lakes) (Fig 25)(http://en.np-plitvicka-jezera.hr/).

Fig. 24
Geographical position of Croatia and Plitvice Lakes National Park. Green line represents border of the Park. (Obelić, 2013)

Ruđer Bošković Institute, Zagreb, Croatia

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

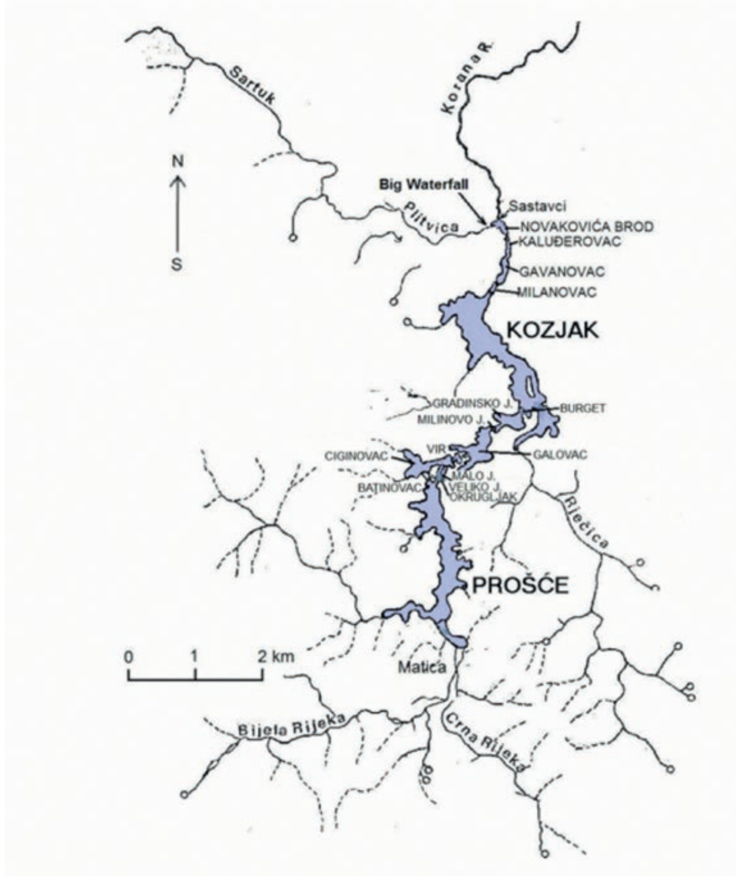

Fig. 25
The lake area of the National Park from main springs (Crna and Bijela Rijeka) along 16 lakes to the outflow of the Korana River.

Geology

The lakes are divided into the Upper and Lower Lakes (Figs. 26 and 27) by a large fault, which strikes northwest - southeast along the northeast edge of the Kozjak Lake (Butko et al., 2013). The Upper Triassic dolomites have low permeability, low primary porosity and stronger secondary porosity. Below them there are impermeable layers of clastic rocks, so these dolomite layers are saturated with water and act as a hydrological barrier. As a consequence, a dense surface hydrographic net and larger Upper Lakes were developed in this area (Figs. 26 and 27). Twelve upper lakes lie in a dolomite valley and are surrounded by thick forests and interlinked by numerous waterfalls. Four lower lakes (Figs 28 and 29), are smaller and shallower, located in a very permeable and karstified Upper Cretaceous rudist limestone, characterized by many caves, pits, cracks and other karstic forms and are surrounded only by sparse underbrush. The lakes spill over from an altitude of 636 to 503 m into each other in foaming cascades and thundering waterfalls separated by the natural dams of tufa, (calcium carbonate deposited from water by the action of moss, algae and cyanobacteria).

The lakes receive water from two main springs (the Bijela Rijeka and Crna Rijeka springs) and two tributaries (the Rječica and Plitvica brooks). The Rječice Brook discharges into the biggest Lake Kozjak, while Plitvica Brook, which also carries water from the Sartuk Brook, forms the Big Waterfall (78 m) (Fig 25) at the end of the Lower Lakes. The Plitvice Lakes feed the Korana River which issues from the lakes and forms a deep canyon (Fig 30).

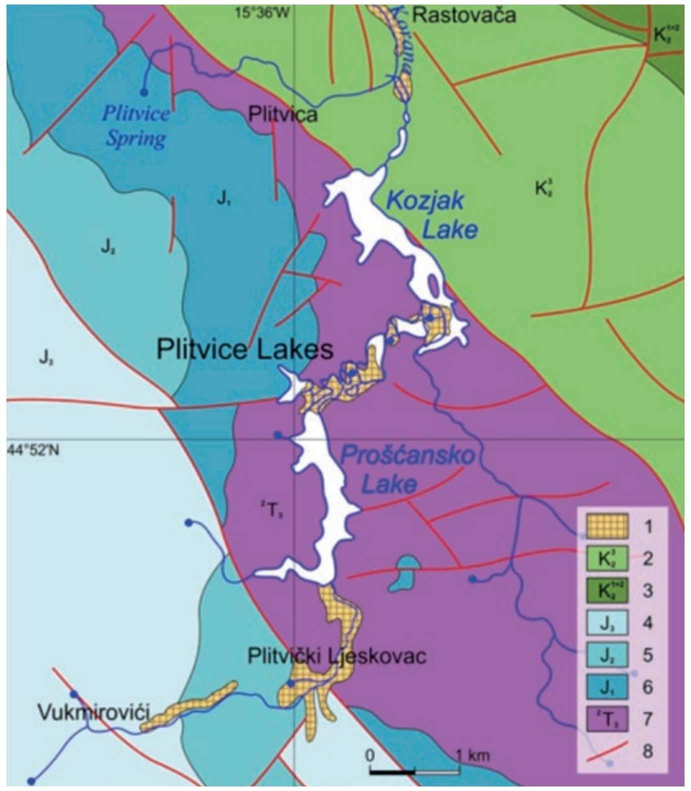

Fig. 26
Schematic geological map of the Plitvice Lakes area (simplified after Polšak et al., 1976); 1 - tufa, 2 - Upper Cretaceous rudist limestone, 3 - Upper Cretaceous limestone, marl and dolomite, 4 - Upper Jurassic dolomite and platy limestone, 5 Middle Jurassic limestone and dolomite, 6 Lower Jurassic limestone and dolomite, 7 Upper Triassic dolomite, 8 - fault. (Butko et al., 2013)

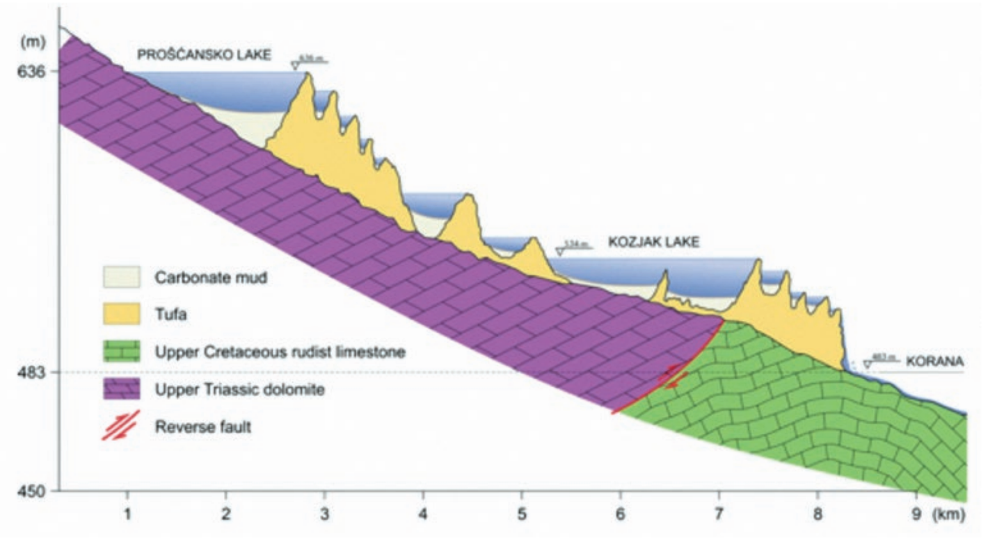

Fig. 27
Schematic hydrogeological profile through the Plitvice Lakes. (Butko et al., 2013)

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

Fig. 28
Lake Prošće, first lake of Plitvice Lakes system formed on dolomite

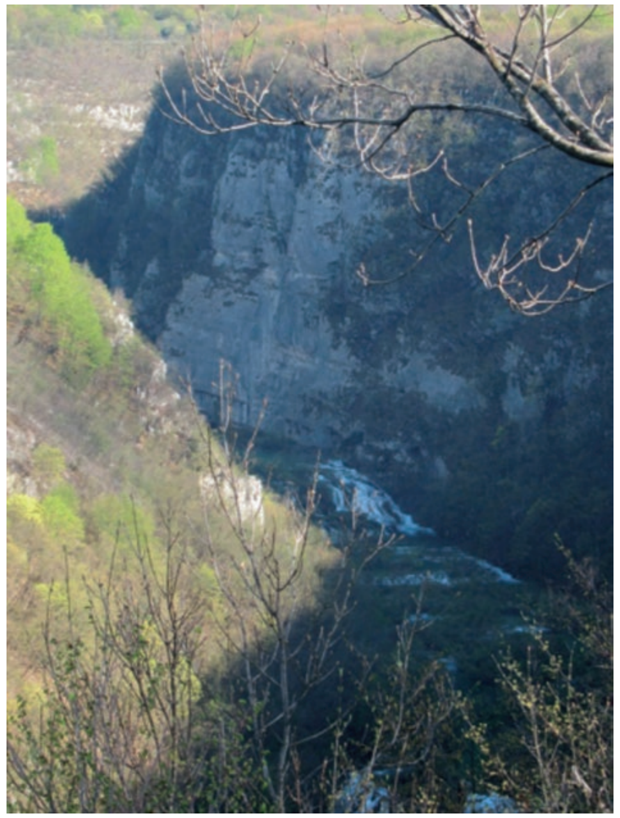

Fig. 30
Canyon of the Korana River

Fig. 29
Lake Novakovića Brod, Sastavci waterfalls and Big waterfall have been formed in limestone

Climate

The climate of the Plitvice Lakes area is typically continental, classified according to the Köppen-Geiger climate classification as climate type Cfb - temperate humid climate without a dry season with a warm summer (Filipčić, 1998; Peel et al., 2007). The mean annual temperature is about 8°C, with January being the coldest (average temperature about -1°C) and July the warmest month (average temperature about 18°C). The average relative air humidity is 82%. The annual precipitation rate at the Plitvice Lakes is about 1480 mm. The largest precipitation amounts are measured in the autumn (accounting for ~ 32% of the annual total) and the lowest in summer (19%). Snow falls from November until March.

Tufa and lake sediments

Tufa is a freshwater calcium carbonate that precipitates very intensively in the presence of macrophytes and microphytes forming spectacular waterfalls and barriers. Barrier deposits form dams, behind which the lakes of the Plitvice Lakes complex are located. Tufa barriers grow at the average rate of about 1 cm per year (Srdoč et al., 1985). Calcium carbonate also precipitates as fine-grained lake sediment at the bottom of the lakes. Lake sediment is mainly authigenic calcite (80 - 95%), while the amount of organic matter is low in Plitvice Lakes sediment (Horvatinčić et al., 2013; Barešić, 2009).

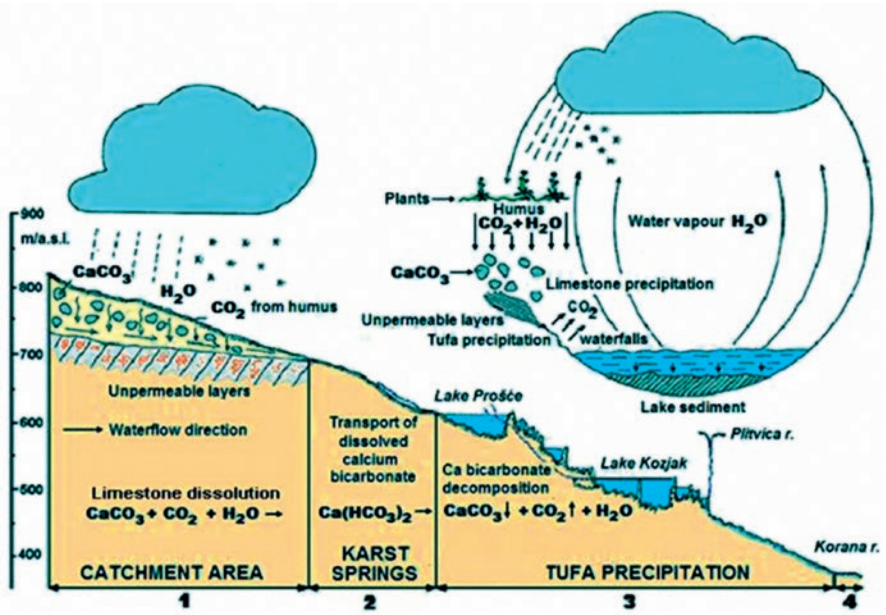

Fig. 31
Geochemical processes of tufa and lake sediment precipitation presented at the cross-section of the Plitvice Lakes. (Horvatinčić, 2013)

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

The first step in the formation of tufa and carbonate lake sediment occurs when precipitation dissolves CO_2 produced by the decomposition of organic matter and root respiration in the topsoil. Percolating water rich in CO_2 dissolves carbonate rocks and forms bicarbonate ions. When water containing calcium and bicarbonate ions emerges in the form of a karst spring, precipitation of calcium carbonate occurs either due to the degassing of CO_2 from solution or by evaporation or by consumption by plants for photosynthesis (Fig. 31). Precipitation of carbonates in the form of lake sediment or tufa depends on the physico-chemical conditions of the water. It is enhanced by the photosynthetic activity of aquatic primary producers (algae, cyanobacteria and higher plants) indicating that the interaction between the atmosphere and biosphere determines the CO_2 - HCO_3 - $CaCO_3$ system (Horvatinčić, 2013).

The lake waters are characterized by a high seasonal temperature variation of ~20°C. The pH values increase downstream and range from 7.3 - 7.6 in the springs to 8.2 - 8.6 in the lakes area. CO_2 concentration decreases rapidly in the spring area, while the concentration of bicarbonates as a main component of dissolved inorganic carbon steadily decreases downstream from 5.2 to 3.5 $mmolL^{-1}$ due to intensive calcite precipitation. In the area of the lakes where the process of calcite precipitation is very intensive, the waters are oversaturated with $CaCO_3$, the saturation index (I_{sat}) ranges from 4 to 10 (Horvatinčić, 2013; Srdoč et al., 1985; Barešić, 2009; Barešić et al., 2011).

Biota have an important role in tufa precipitation for two reasons: the plants remove CO_2 during photosynthesis and favour calcite precipitation, and at the same time act as a convenient substrate for precipitation. They trap and bind calcite seed crystals within a biofilm which is a by-product of the microbial metabolic activity of diatoms, bacteria and/or cyanobacteria (Chafetz et al., 1994). Tufa formation is favoured where well-developed plants exist in streams and waterfalls resulting in different morphological forms of tufa.

Geochronology

In order to determine the age of tufa deposits, more than 500 samples of tufa from active barriers and old deposits from the entire area of the Plitvice Lakes National Park were collected during more than 30 years of scientific studies (Obelić & Horvatinčić, 2013). The Plitvice lakes, in the form that we know them today, were formed in the Holocene after the last glacial maximum (LGM) when favourable (warm and wet) conditions for their development occurred, mostly in the area between the Prošće and Kozjak lakes. The present relief of the Plitvice Lakes was formed in the last 7000 years, as shown by ^{14}C dating of 12-m deep lake sediments and active tufa deposits (Srdoč et al., 1985, 1986).

Outcrops of old tufa deposits discovered at three locations within the Park resulted in a ^{14}C age in the range from 20 000 years to the limit of the ^{14}C method. Such samples were dated by the ^{230}Th/^{234}U dating method (Srdoč et al., 1994, Horvatinčić et al., 2000). The results showed that most of old tufa samples clustered around the interglacial marine ^{18}O stage 5, and then interglacial stages 7 and 9 (Fig. 32). The ^{14}C and ^{230}Th/^{234}U ages of tufa in the Plitvice Lakes area demonstrate that the formation of tufa barriers was stimulated by changing climate, e.g. during interglacial periods with warm and humid conditions (Horvatinčić et al., 2000; Horvatinčić et al., 2003).

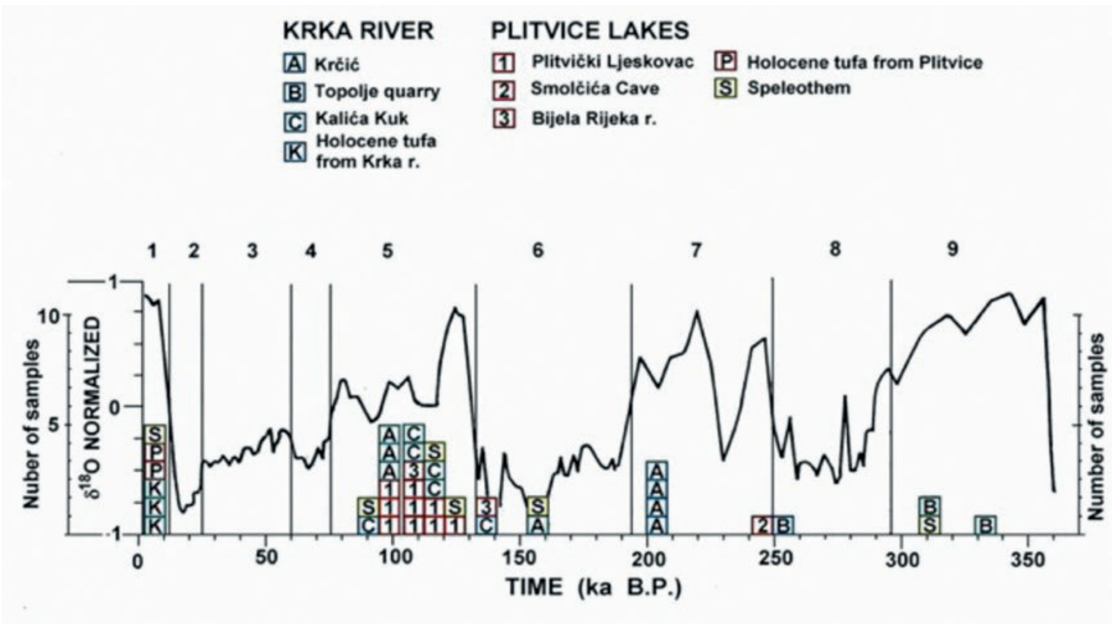

Fig. 32 Histogram of 230Th/234U ages of tufa and speleothem samples from Dinaric Karst (Plitvice Lakes and Krka River areas) compared with the palaeoclimatic δ18O stages (Horvatinčić et al, 2000). (Obelić & Horvatinčić, 2013)

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

STOP 5: ZAGREB VISIT TO THE WEIR TE-TO ON THE SAVA RIVER (N 45°46’43’’, E 16°00’49’’)

Kristijan Posavec

Introduction

The Zagreb aquifer (Fig. 33) is an unconfined alluvial aquifer with a water table permanently connected to the Sava River, which is a perennial river. Therefore, groundwater levels are strongly dependent on the Sava river water levels. This aquifer is mainly composed of gravels and sands which the Sava river transported from the Alpine regions during the Holocene period. During the Pleistocene the aquifer area was covered with lakes and marshes while the neighbouring mountains (Mt. Medvednica, Vukomeričke gorice hills, Marijagorička Brda hills and Mt. Samoborska gora)

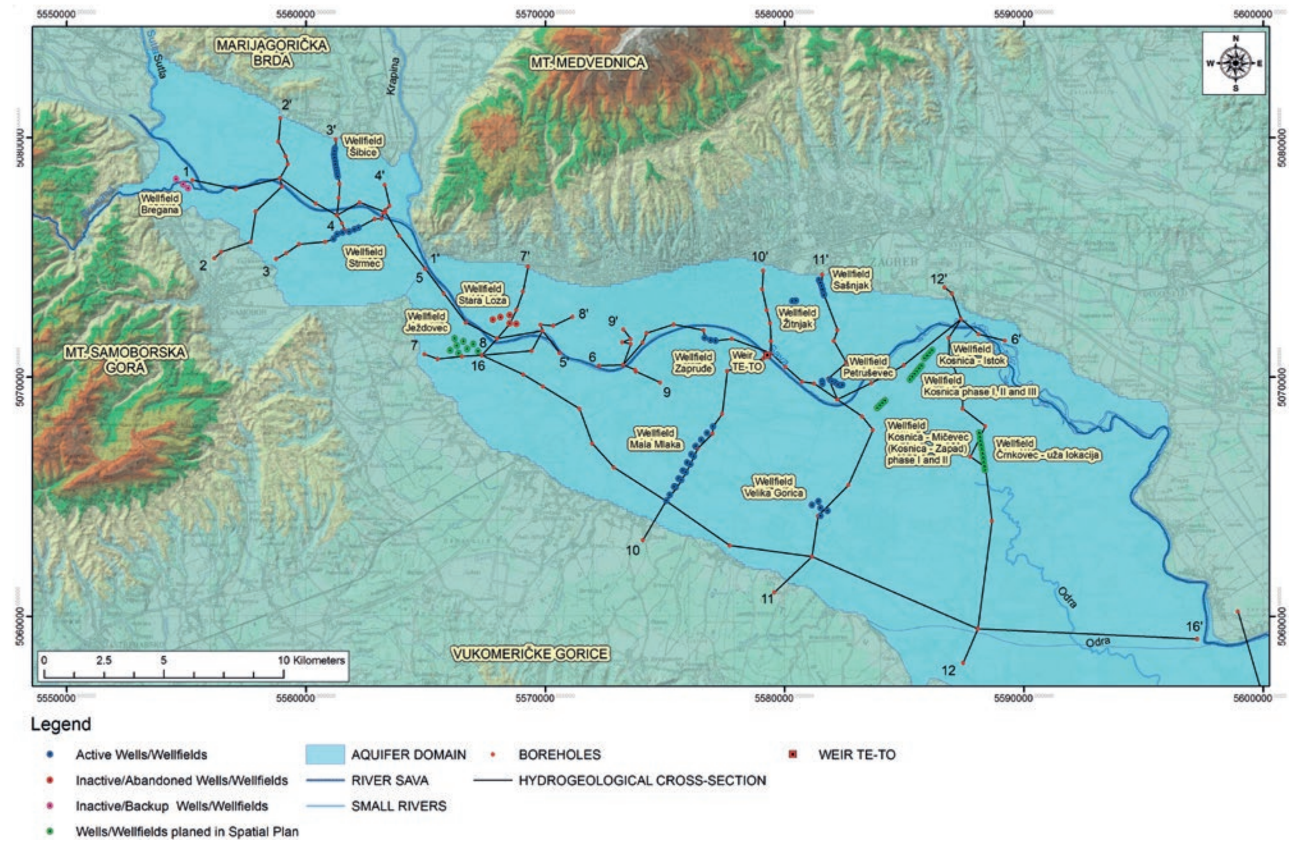

Fig. 33 Zagreb aquifer

University of Zagreb, Faculty of Mining, Geology and Petroleum Geology, Zagreb, Croatia

were susceptible to intensive erosion. Weathered material was carried along the streams and deposited in the lakes and marshes (Velić and Saftić, 1991). At the beginning of the Holocene, climate and tectonic processes enabled the river Sava to excavate its course and transport of material from the Alps began (Velić and Durn, 1993). This transport occurred at varying intensity due to frequent changes of climate conditions. During warm and wet periods, it was intensive while transport fell during dry and cold periods. Besides climate changes, tectonic movements also influenced the depositional processes (Velić et al., 1999). A consequence of such deposition conditions was the pronounced heterogeneity and anisotropy of the aquifer sediments as well as unequal distribution of aquifer thicknesses (Fig. 34). Quaternary aquifer deposits are divided into three basic units: aquifer system overburden composed of clay and silt, a shallow Holocene aquifer formed of alluvial deposits i.e. medium-grain gravel mixed with sands and a deeper aquifer of Middle and Upper Pleistocene age comprising lacustrine-marshy deposits, with frequent lateral and vertical alternations of gravel, sand and clay. Differentiation between the shallow and deeper parts is stratigraphic since they are hydraulically connected and form a single aquifer from the hydrogeological point of view.

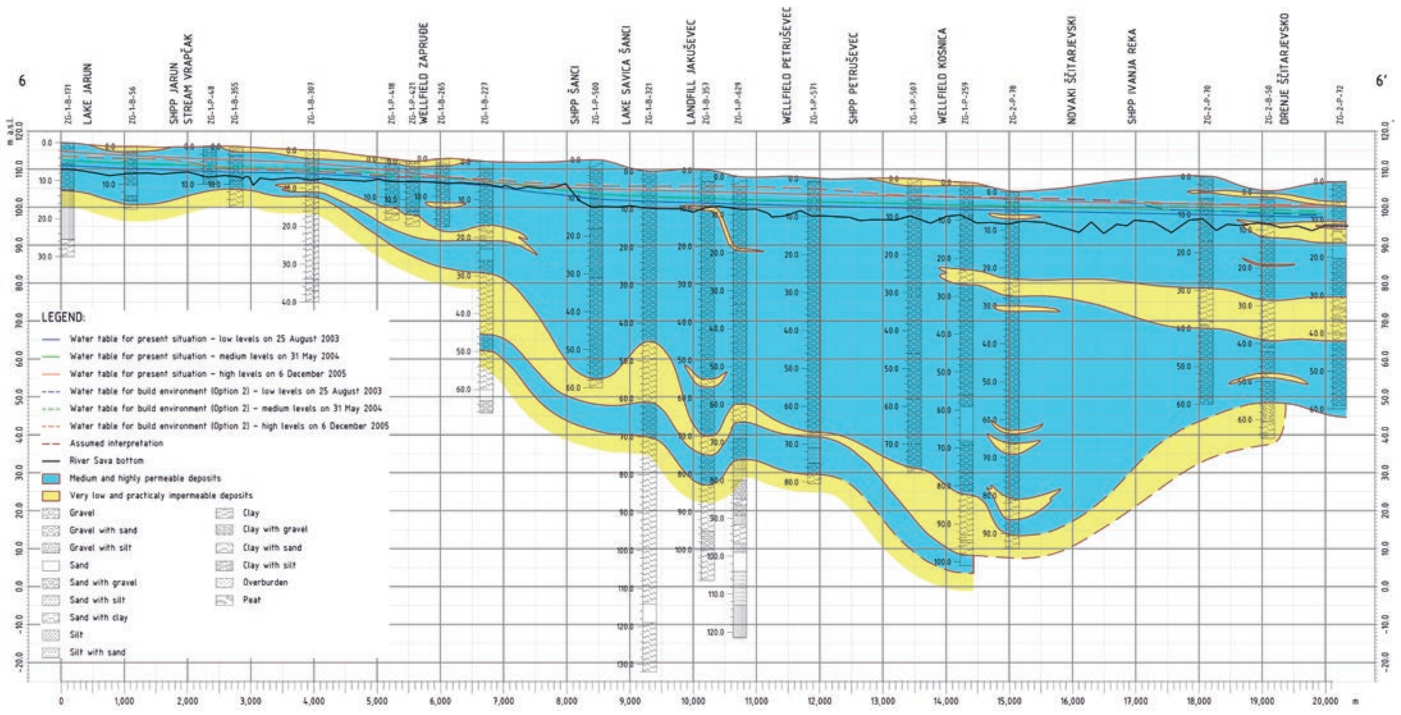

Fig. 34 Hydrogeological cross-section 6-6'

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

Negative trend of groundwater levels

The transport of gravels and sands ceased with the building of hydroelectric powerplants (HPP's) in the upstream parts of the Sava river course in the Republic of Slovenia. Since then, the Sava riverbed faces a continuous decrease in its downstream parts due to the dominantly erosional processes of the riverbed. Riverbed decrease causes a decrease in the Sava water levels, which further causes a decrease in groundwater levels due to the hydraulic connection of the Sava water levels and the aquifer water table (Fig. 35). This is an ongoing process, which has led to a drop in groundwater levels below the top of the screens in shallower pumping wells of public wellfields, causing a decrease in their capacities (Posavec, 2016).

Currently, active well fields of the City of Zagreb pump some 3.5 to 3.8 m^3s^{-1} in order to satisfy the total water demand of the City of Zagreb. Presently, the stated amounts of pumped water can be provided by Zagreb well fields without major problems if the hydrological year is average or favourable in terms of sufficient rainfall in the upper parts of the Sava river basin, primarily in the Republic of Slovenia, which can in turn ensure average or longer durations of medium and high water levels of the Sava river in the area of the Zagreb aquifer. Furthermore, such durations of the Sava river water levels ensure ground water levels in the aquifers are higher than the screen top elevations in the wells of the Zagreb well fields, which enables pumping according to the designed capacities.

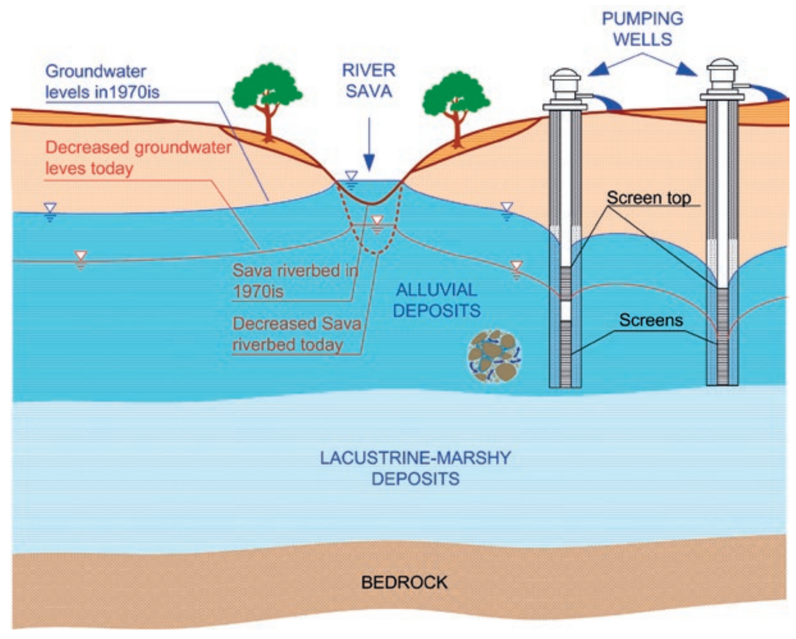

Fig. 35
Schematic hydrogeological cross-section showing decrease in riverbed and groundwater levels

However, in hydrologically drought periods, in which rainfall are absent in the upper parts of the Sava river basin, and which in turn results in longer durations of the low Sava water levels with dominant drainage of the aquifers, ground water level drops below the screen top elevations in some wells, which considerably reduces their capacities and consequently capacities of the well fields as well as total available capacity in the Zagreb water supply system. If we consider the analysis of minimum ground water levels on well field Mala Mlaka (Posavec, 2013.), it can be seen that, for example, the capacity of the well B-9 dropped some 60% during drought year 2003 when ground water level in a nearby observation well dropped below the screen top elevation in the well. Beside well field Mala Mlaka, a drop in well capacity during hydrological droughts is also present on well fields Sašnjak and Zapruđe due to drop of ground water levels, which fall below the screen top elevations in the wells.

Fig. 36 Weir TE-TO on the Sava river, Zagreb

Analysis of pumping rates on the active Zagreb well fields during the drought year 2003 have shown that capacity is significantly decreased in well fields Mala Mlaka (-18%), Sašnjak (-20%) and Zapruđe (-11%) while it is simultaneously increased on well fields Petruševec (+17%) and Velika Gorica (+37%). The same analysis during drought year 2011-2012 show that capacity is even more significantly decreased in the well fields Mala Mlaka (-30%), Sašnjak (-26%) and Zapruđe (-4%) while it is simultaneously increased on well fields Petruševec (+31%), Velika Gorica (+44%) and Žitnjak (+6%) (Posavec, 2013). In well fields Petruševac, Žitnjak and Velika Gorica, screen top elevations are generally a few metres below the ground water table, which currently ensures the normal/designed pumping of wells/well fields even during drought periods.

The active well fields of the Zagreb water supply system, as currently designed, can only supply the City of Zagreb during hydrological droughts with the required 3.5 to 3.8 m^3/s with significant increase of pumping rates in the well fields Petruševac and Velika Gorica, taking into consideration the assumption that the hydrological drought does not last longer than historically recorded ones. If the present negative trends of ground water levels continues, the well fields Petruševac and Velika Gorica will also experience a drop in

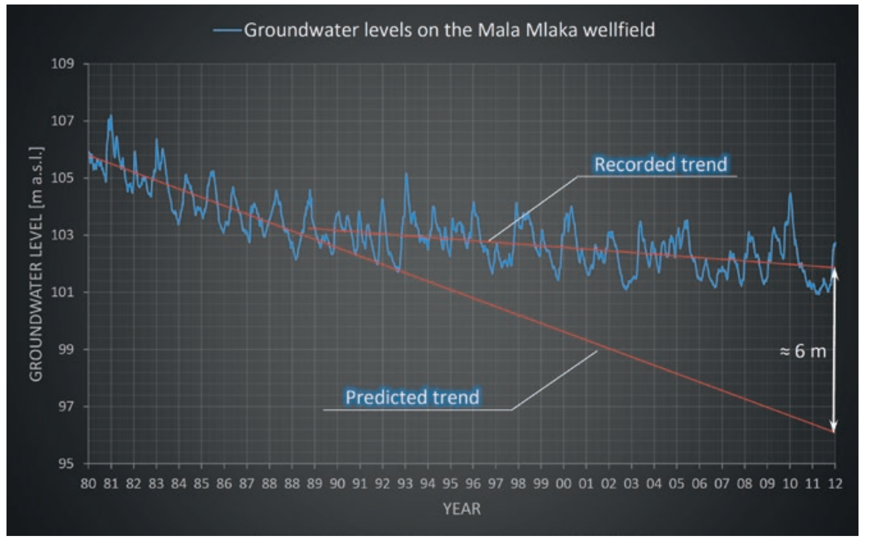

Fig. 37 Impact of weir TE-TO on groundwater levels

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY
iah aih

well capacities during hydrological droughts as this is currently the case with the well fields Mala Mlaka, Zapruđe and Sašnjak. Furthermore, in such a situation, the well fields Mala Mlaka, Zapruđe and Sašnjak can expect an even greater drop in capacity due to continued lowering of the water table and future global climate predictions, which suggest an increase in the intensity of droughts and less rainfall.

Potential solutions for the public water supply, which would ensure a stable water supply during hydrological droughts, include drilling of deeper wells in the existing wellfields or building new wellfields. However, these solutions are temporary since they do not stop the negative trend of groundwater levels and they do not solve the impact on groundwater dependent ecosystems. Potential permanent solutions for a stable water supply during hydrological droughts as well as groundwater dependent ecosystems, include the building of dams or weirs on the Sava river, which would stop further erosion of the Sava riverbed and stop negative trends of groundwater levels. An example of the impact of a single weir (TE-TO) on groundwater levels, built on the Sava river in the middle and late eighties, shows that the negative trend of groundwater levels has slowed down in the upstream parts of the aquifer, enabling the wellfield Mala Mlaka to remain one of the leading public wellfields (Fig. 37 and 38).

a	-0.000172943		
b	107.7562283		
	Lower 95% prediction	Trendline	Upper 95% prediction
HEAD 31.12.2015. (m a.s.l.)	98.64	100.43	102.22
HEAD 31.12.2025. (m a.s.l.)	98.00	99.80	101.59
HEAD 31.12.2035. (m a.s.l.)	97.36	99.17	100.97
HEAD 31.12.2045. (m a.s.l.)	96.72	98.53	100.34
P-value (0.05)	5.69984E-90	Trend is statistically significant.	

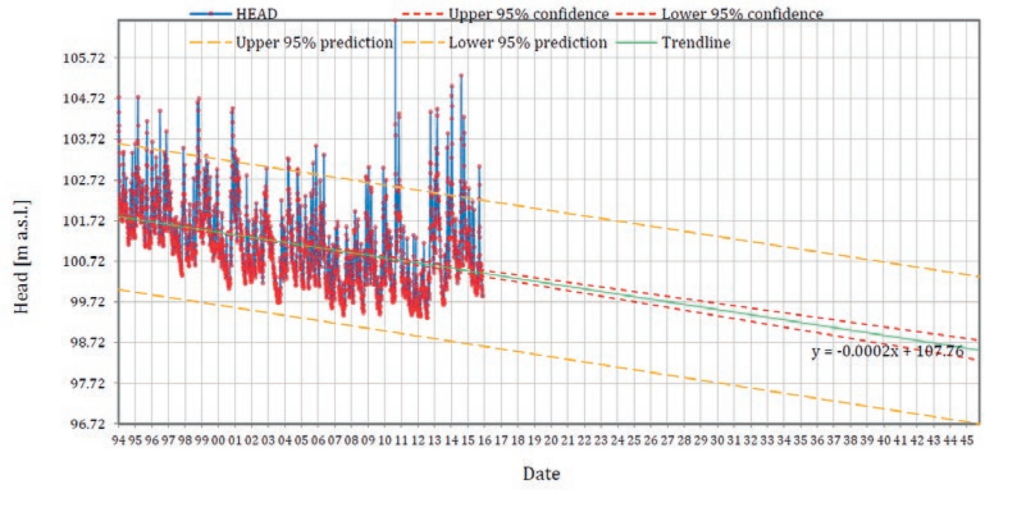

Fig. 39
Observation well 81 located in central part of Zagreb aquifer, right bank

In order to solve problems caused by a decrease of the Sava riverbed and continuous negative trends of groundwater levels, a project led by Program Sava d.o.o. supported by a number of stakeholders, among which are HEP Group (the national energy company), Croatian Waters, City of Zagreb, Municipality of Zagreb and Sisak as well as several Ministry departments, is currently ongoing. Three options are being considered for future regulation of the Sava river, Option 0 which includes a number of weirs, and Options 1 and 2 which include HPP's. Option 2 also has an alternative conceptual solution named Option 2A.

Multipurpose project Programme Sava

Option 0 represents a technical solution that would achieve the defence from flooding and regulation of the Sava River and considers the construction of sixteen control weirs in the Sava River. Option 1 considers the construction of four hydropower plants, HPP Drenje, HPP Zagreb, HPP Prečko and HPP Podsused along with the Sava - Sava channel, while Option 2 considers the construction of two hydropower plants, HPP Prečko and HPP Zaprešić as well as four small hydropower plants (SHPP), SHPP Jarun, SHPP Šanci, SHPP Petruševec and SHPP Ivanja Reka and envisages the Sava - Sava channel, the same as Option 1. An alternative conceptual solution named Option 2A considers the construction of 9 small hydropower plants in the Sava river and also envisages the Sava - Sava channel as for Options 1 and 2. A regional groundwater flow model for the present state as well as prediction models for the built environment were developed for all options in order to identify the impact of the built environment on the groundwater levels of the Zagreb aquifer as well as active well fields. Fig. 8 shows the impact of Option 2A on groundwater levels. Negative trends are fully stopped while groundwater levels are raised to their historic levels. Such a solution would enable a long-term stable water supply under all hydrological conditions.

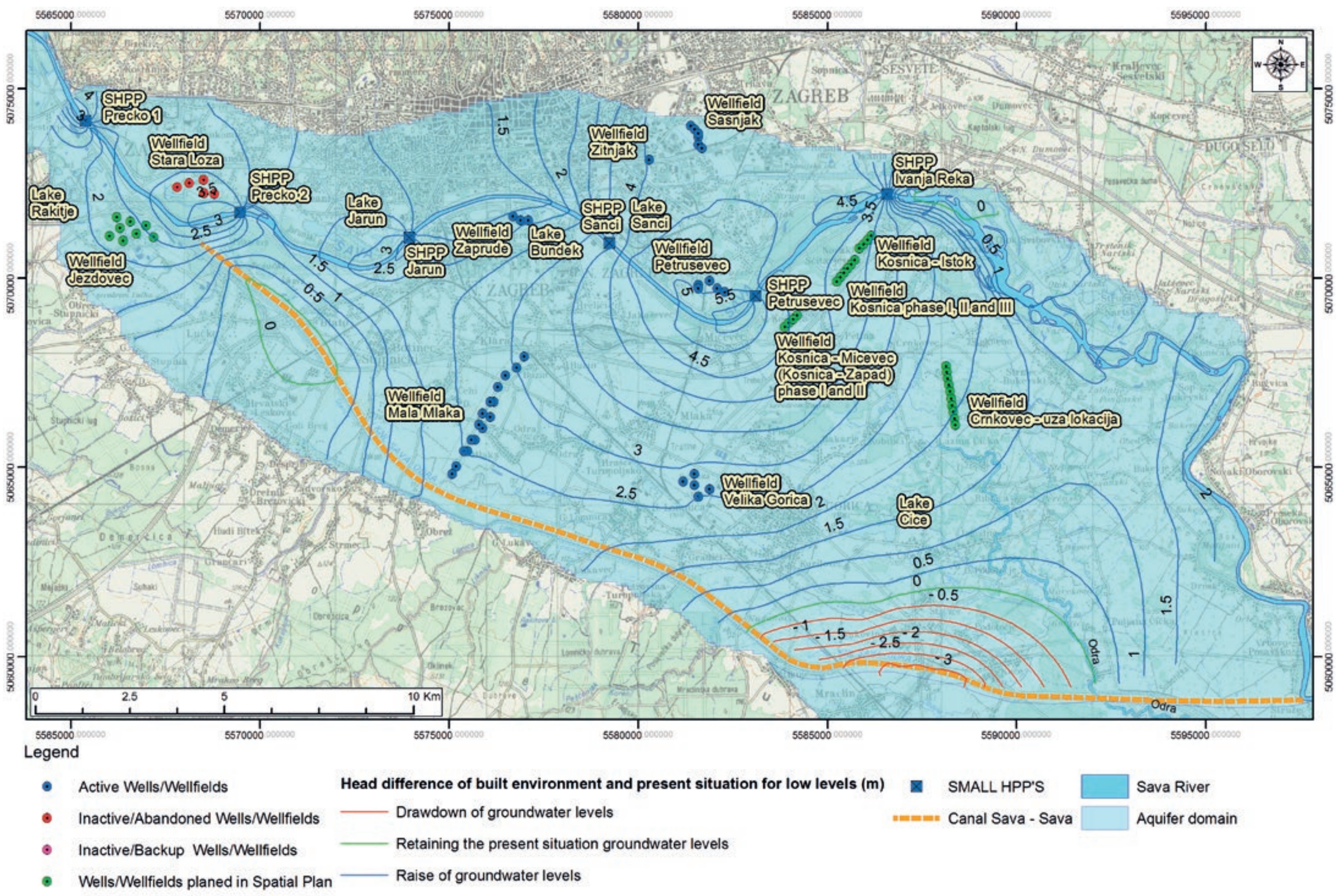

Fig. 40 Impact of alternative conceptual solution Option 2A on groundwater levels

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017
HGI HRVATSKI GEOLOŠKI INSTITUT CROATIAN GEOLOGICAL SURVEY

STOP 6: WATER SUPPLY OF LJUBLJANA

Branka Brčič Železnik

The public water supply in Ljubljana has a long and respectable tradition. In May 1890 a 27 km long water distribution system delivered drinking water to 606 houses in Ljubljana for the first time. 127 years later the same wells are still in operation. We pumped the groundwater from a gravel, sandy unconfined aquifer that lies beneath the city of Ljubljana. Like the Zagreb aquifer, the Ljubljansko polje aquifer is also composed of gravel and sands, which the Sava River transported from mountainous areas during the Holocene period. It is 130 km upstream and the gravel is coarser and in the upper part of aquifer we have conglomerate lenses. The central water distribution system includes five water plants with 44 wells, 1100 kilometres of water distribution network, 40500 connections that supply water to 315000 users.

Drinking water is our natural resource - priceless and indispensable. The water that reaches users in Ljubljana comes from the natural environment; it does not undergo technical treatments and is only chlorinated occasionally. On its journey from the water plants to users, water never stays in the water supply network for more than couple of hours.

Fig 41 The Pumping station of Ljubljana

REFERENCES:

Andrić, I & Bonacci, O (2014): MORPHOLOGICAL STUDY OF RED LAKE IN DINARIC KARST BASED ON TERRESTRIAL LASER SCANNING AND SONAR SYSTEMS, ACTA CARSOLOGICA 43/2-3, 229-239

Bahun, S. & Fritz, F. (1975): Hidrogeološke specifičnosti Jelarnaslaga [Hydrogeological specificities of the Jelar breccias - in Croatian].- Geol. vjesnik, 28, 345-355.

Bahun, S. (1974): Tektogeneza Velebita i postanak Jelar naslaga [The tectogenesis of the Mt. Velebit and the formation of Jelar deposits - in Croatian].- Geol. vjesnik, 27, 35-51.

Bahun, S., 1991: O postanku Crvenog i Modrog jezera kod Imotskog (Genesis of Red and Blue Lakes near Imotski). Geološki Vjesnik, 44, 275-280.

Barešić J., Horvatinčić N. & Roller-Lutz Z. (2011): Spatial and seasonal variations in the stable C isotope composition of dissolved inorganic carbon and in physico-chemical water parameters in the Plitvice Lakes system. - Isotopes in Environmental and Health Studies 47/3, 316-329.

Barešić, J. (2009): Primjena izotopnih i geokemijskih metoda u praćenju globalnih i lokalnih promjena u ekološkom sustavu Plitvička jezera. PhD Thesis. Zagreb, University of Zagreb, Fakultet kemijskog inženjerstva i tehnologije, 16. 02. 2009., 163 str.

Biondić, R., Biondić, B. & Meaški, H. (2010): Novelacija granica zona sanitarne zaštite izvorišta Gacke [Gacka spring sanitary protection zone novelation - in Croatian]. Geotehnical faculty, University of Zagreb, 115 p.

Bonacci, O. & Andrić, I. (2008): Sinking karst rivers hydrology: case of the Lika and Gacka/Croatia.- Acta Carsologica, 37/2, 185-196

Bonacci, O. (1987): Karst Hydrology with Special Reference to the Dinaric Karst.- Springer-Verlag-Berlin-Heidelberg, 9/4, 328-338.

Bonacci, O. (1995): Međuzavisnost geologije, hidrogeologije i hidrologije pri rješavanju hidrotehničkih problema. [The interdependence of geology, hydrogeology and hydrology in solving hydraulic proble - in Croatian].- First Croatian geological congress, Book of Proceedings, 1, 105-108.

Bonacci, O., 2006: Crveno i Modro jezero kod Imotskog (Red and Blue Lakes near Imotski). Hrvatske Vode, 14(54), 45-54.

Bonacci, O., Andrić, I. & Y. Yamashiki, 2014: Hydrology of Blue Lake in the Dinaric karst. Hydrological Processes, 28(4), 1890-1898, DOI:10.1002/hyp.9736.

Bonacci, O., Andrić, I. & Y. Yamashiki, 2014: Hydrology of Blue Lake in the Dinaric karst. Hydrological Processes, 28(4), 1890-1898, DOI:10.1002/hyp.9736.

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

Bonacci, O., Andrić, I., Yamashiki, Y. (2014): Hydrology of Blue Lake in the Dinaric karst. Hydrological Processes 28(4), 1890-1898.

Bonacci, O., Željković, I. & A. Galić, 2013: Karst rivers' particularity: an example from Dinaric karst (Croatia/Bosnia and Herzegovina). Environmental Earth Sciences, 70(2), 963-974, DOI:10.1007/s12665-012-2187-9.

Butko, I., Felja, I. & Juračić, M. (2013): Geology of the Plitvice Lakes. In: STRAVAL Case Study: Croatia. Selected site: Plitvice Lakes National Park (Obelić, B. & Krajcar Bronić, I., eds.). Marie Curie Actions - IRSES Project STRAVAL, Barcelona, 2013. ISBN: 9788461629909. pp. 24-26.

Chafetz H., Srdoč D. & Horvatinčić N. (1994): Early diagenesis of Plitvice Lakes waterfall and barrier travertine deposits. - Geographie physique et Quaternaire 48/3, 247-255.

Cvijić, J., 1893: Das Karstphänomen (Karst phenomena). Versuch einer morphologischen Monographie. Geographischen Abhandlung Wien V(3), pp 218-329, Vienna

Cvijić, J., 1926: Geomorfologija 2 (Geomorpholgy 2).- Srpska Akademija Nauka i Umetnosti, pp. 587, Belgrade.

Cvijić, J., 1960: La géographie des terrains calcaires (Geography of carbonate terraines). Naučno Delo, pp. 164, Belgrade.

Filipčić, A. (1998): Climatic regionalization of Croatia according to W. Köppen for the standard period 1961-1990 in relation to the period 1931-1960 [in Croatian]. - Acta Geogr. Croat. 33, 1-15.

Gajić-Čapka, M., Perćec Tadić, M. & Patarčić, M. (2003): Digitalna godišnja oborinska karta Hrvatske. [A Digital Annual Precipitation Map of Croatia - in Croatian] Hrvatski meteorološki časopis (Croatian Meteorological Journal), 38, 21-33.

Garašić, M., 2001: New speleohydrogeological research of Crveno Jezero (Red Lake) near Imotski in Dinaric karst area (Croatia, Europe): International Speleodiving expedition "Crveno Jezero 98".- In: 13th International Congress of Speleology, 15th-22nd. July 2001, Brasilia Speleo Brazil, 168-171, Brasilia.

Garašić, M., 2012: Crveno jezero - the biggest sinkhole in Dinaric Karst (Croatia).- In: EGU General Assembly 2012, 22th-27th April 2012, Vienna, COPERNICUS, 7132, Vienna

Horvatinčić, N. (2013): Tufa and lake sediment formation. In: STRAVAL Case Study: Croatia. Selected site: Plitvice Lakes National Park (Obelić, B. & Krajcar Bronić, I., eds.). Marie Curie Actions - IRSES Project STRAVAL, Barcelona, 2013. ISBN: 9788461629909. pp. 33-40.

Horvatinčić, N., Čalić, R. & Geyh, M.A. (2000): Interglacial Growth of Tufa in Croatia. - Quaternary Research 53, 185-195.

Horvatinčić, N., Krajcar Bronić, I. & Obelić, B. (2003): Differences in the 14C age, δ13C and δ18O of Holocene tufa and speleothem in the dinaric karst. - Palaeogeography, Palaeoclimatology, Palaeoecology 193/1, 139-157.

Kendall, C. & McDonnell, J. J. (1998): Isotope Tracers in Catchment Hydrology.-Elsevier Science B.V., Amsterdam, 839 p.

Lukač Reberski, J. (2008): Hidrogeološka i hidrogeokemijska osnova za defi niranje slijeva Gacke i zaštita njenog izvorišta [Hydrogeological and hydrogeochemical basis for the catchment area definition: River Gacka springs catchment area - in Croatian].- Unpubl.

Lukač Reberski, J., Kapelj, S. & Terzić, J. (2009): An estimation of groundwater type and origin of the complex karst catchment using hydrological and hydrogeochemical parameters: A case study of the river Gacka springs.- Geol. Croat., 62/3, 157-178, doi: 10.4154/ gc.2009.15.

Master's Thesis. Rudarsko-geološko-naftni fakultet, Sveučilište u Zagrebu (Faculty of mining, geology and petroleum engineering, University of Zagreb), 118 p.

Miko, S., Ilijanić, N., Jarić, A., Brenko, T, Hasan, O., Šparica Miko, M., Čućuzović, H., Stroj, A. (2015): 2400-year multi-proxy reconstruction of environmental change: the Blue Lake (Modro jezero, Imotski) sediment record - Knjiga sažetaka, 5th Croatian geological congress Horvat, M. & Wacha, L. (ed.). Zagreb: Hrvatski geološki institut, 2015, 177-178.

Milanović, P. T., 1981: Karst Hydrogeology.- Water Resources Publications. pp. 434, Littleton

Obelić, B. & Horvatinčić, N. (2013): Geochronology. In: STRAVAL Case Study: Croatia. Selected site: Plitvice Lakes National Park (Obelić, B. & Krajcar Bronić, I., eds.). Marie Curie Actions - IRSES Project STRAVAL, Barcelona, 2013. ISBN: 9788461629909. pp. 41-46.

Obelić, B. (2013): Introduction to Plitvice Lakes National Park. In: STRAVAL Case Study: Croatia. Selected site: Plitvice Lakes National Park (Obelić, B. & Krajcar Bronić, I., eds.). Marie Curie Actions - IRSES Project STRAVAL, Barcelona, 2013. ISBN: 9788461629909. pp. 6-23.

OG 125/2013: Pravilnik o parametrima sukladnosti i metodama analize vode za ljudsku potrošnju

OG 91/2008: Strategija upravljanja vodama [Water Management Strategy - in Croatian].

Pavičić, A., Kapelj, S. & Lukač, J. (2003): The influence of the Highway on the protected spring of Gacka river.- RMZ - Materials and geoenvironment, 50/1, 289-292.

Peel, M.C., Finlyanson, B.L. & McMahon, T.A. (2007): Updated world map of the Köppen-Geiger climate classification. - Hydrol. Earth Syst. Sci. 11, 1633-1644.

Petrik, M., 1960: Hidrografska mjerenja u okolici Imotskog (Hydrographic measurements near Imotski).- Ljetopis JAZU, 64, 266-286.

Posavec, K. (2013.): Zagreb - Possibilities for groundwater abstraction from Zagreb alluvial aquifer using wells on active Zagreb wellfields - analysis of the present and future situation. Croatian Waters archive, Zagreb.

Posavec, K. (2016): Zagreb on the Sava River - Significance of the Project for Public Well Fields and Strategy for the Development of Zagreb Water Supply System. Proceedings of Papers, Conference on the Strategic development of the water supply and sewage systems of the City of Zagreb, May 17 and 18, 2016, Zagreb, 49-66.

Groundwater Heritage&Sustainability
44th ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

Posavec, K. (2017): Mathematical Modelling of Option 2A, Groundwater flow and contaminant transport modeling. Regulation and Development of Sava River in Zagreb - Feasibility Study, SEA and CBA. Multipurpose project for Sava River, WB8-HR-ENE-11. IPA 2011 WBIF - Infrastructure Project Facility, Technical Assistance 3.

Prelogović, E. (1989): Neotektonski pokreti u području sjevernog Velebita i dijela Like [Neotectonic movements in northern Velebit and part of Lika - in Croatian]. Geol. vjesnik, 42, 133-147.

Roglić, J., 1938: Imotsko Polje -Fizičko-Geografske Osobine. (Physical-Geographic Characteristics of Imotski Polje).- Posebno Izdanje Geografskog Društva 21, pp. 125, Belgrade.

Roglić, J., 1954. Polja zapadne Bosne i Hercegovine (Karst poljas of Western Bosnia and Herzegovina).-In: III Kongres geografa Jugoslavije, 1953, Sarajevo, Geografsko društvo NR BiH, Sarajevo.

Roglić, J., 1974: Prilog Hrvatskoj Krškoj Terminologiji (Contribution to Croatian Karst Terminology).- Carsus Iugoslaviae 9/1, 72.

Roglić, J., 1974: Relationship between surface and underground of Dinaric karst).- Acta Carsologica, 6, 11-19.

Srdoč, D., Horvatinčić, N., Obelić, B., Krajcar Bronić, I. & Sliepčević A. (1985): Calcite deposition processes in karstwaters with special emphasis on the Plitvice Lakes (in Croatian). - Krš Jugoslavije [Carsus Iugoslaviae] 11/2-6, 101-204.

Srdoč, D., Obelić, B., Horvatinčić, N., Krajcar Bronić, I., Marčenko, E., Merkt, J., Wong, H.K. & Sliepčević, A. (1986): Radiocarbon dating of lake sediments from two karst lakes in Yugoslavia. - Radiocarbon 28/2A, 495-502.

Velić, J. and B. Saftić (1991): Subsurface Spreading and Facies Characteristics of Middle Pleistocene Deposits between Zaprešić and Samobor. Geološki vjesnik, 44, 69-82.

Velić, J. and G. Durn (1993): Alternating Lacustrine-Marsh Sedimentation and Subaerial Exposure Phases during Quaternary: Prečko, Zagreb, Croatia. Geologia Croatica, vol. 46, no. 1, p. 71-90.

Velić, J., B. Saftić and T. Malvić: (1999): Lithologic Composition and Stratigraphy of Quaternary Sediments in the Area of the "Jakuševec" Waste Depository (Zagreb, Northern Croatia). Geologia Croatica, vol. 52, no. 2, p. 119-130.

Vlahović, I., Tišljar, J. & Velić, I. (2009): Tercijarne karbonatne breče (paleogen-neogen- Pg, Ng) [Tertiary Carbonate Breccia, PGNg - in Croatian]. - In: VELIĆ, I. & VLAHOVIĆ, I. (2009): Tumač Geološke karte Republike Hrvatske 1:300000 [Explanatory Notes of the Geological Map of the Republic of Croatia in 1:300.000 Scale]. Croatian geological survey, 141 p.

Žugaj, R. (2000): Hidrologija [Hydrology - in Croatian].- Rudarskogeološko- naftni fakultet, Sveučilište u Zagrebu (Faculty of mining, geology and petroleum engineering, University of Zagreb), 407 p.

Notes

Groundwater Heritage&Sustainability
44TH ANNUAL CONGRESS OF THE INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
Dubrovnik, Croatia, 25th - 29th September 2017

ISBN: 978-953-6907-68-2