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HYDROGEOLOGY OF THE SINKING ZONE OF THE KORANA RIVER DOWNSTREAM OF THE PLITVICE LAKES, CROATIA

HIDROGEOLOGIJA PONORNEGA OBMOČJA REKE KORANE DOLVODNO OD PLITVIŠKIH JEZER, HRVAŠKA

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Ranko Biondić, Hrvoje Meaški & Božidar Biondić: Hydrogeology of the sinking zone of the Korana River downstream of the Plitvice Lakes, Croatia

Downstream of the Plitvice Lakes National Park, water that pass through the water system of the lakes begins its flow as the Korana River. A few hundred meters downstream of the source zone, during the summer dry periods, there are losses of water in the riverbed resulting in its total drying. The sinking zone in that area is built of high permeable carbonate rocks and with the appearance of less permeable dolomite rocks, about 17 km downstream, the Korana River becomes a permanent river. This paper focuses on the explanation of hydrogeological relations in the zone where losses of water occur in the riverbed, relationship to the neighbouring Una River catchment, as well as possibilities of relocating the source of water supply from the Kozjak Lake (Plitvice Lakes) to the new site in the sinking zone of the Korana River. For this purpose hydrogeological researches were performed, with drilling of several piezometric boreholes and two tracing tests to determine the direction of groundwater flow during the dry season. The results show that during the dry periods in the sinking zone of the Korana River the groundwater level with active aquifer is about 25 m below the riverbed. This opens up the possibility of additional research to solve the problem of water-supply and relocation of water-supply capture in this area. Two tracing tests showed a connection with the Klokot spring (Bosnia and Herzegovina) in the neighbouring Una River catchment, which points to the transboundary character of this aquifer. At the source of the Klokot minimum discharge is around 3 m^3/s and the maximum more than 75 m^3/s. The capturing of about 60 l/s for water-supply in the Korana River sinking zone will not have impact on the amount of discharge at the Klokot spring.

Key words: Dinaric karst, Korana River sinking zone, Plitvice Lakes, tracing test, transboundary aquifer, groundwater capturing.

Izvleček UDK 556.3(497.56)

Ranko Biondić, Hrvoje Meaški & Božidar Biondić: Hidrogeologija ponornega območja reke Korane dolvodno od Plitviških jezer, Hrvaška

Dolvodno od Nacionalnega parka Plitviška jezera vode, ki tečejo skozi sistem jezer, oblikujejo reko Korano. Nekaj sto metrov pod to izvirno cono v času poletnih sušnih obdobij voda v strugi ponika in s časom povsem presahne. Ponorno cono gradijo zelo dobro prepustne karbonatne kamnine in šele po prehodu na manj prepustne dolomite približno 17 km nižje po strugi Korana postane stalna reka. V članku so obravnavane hidrogeološke razmere v coni ponikanja vode v strugi in odnosi s sosednjim porečjem reke Une, pa tudi možnosti prestavitve vira oskrbe s pitno vodo iz jezera Kozjak (Plitviška jezera) na novo lokacijo v ponorni coni reke Korane. V ta namen so bile izvedene hidrogeološke raziskave, izvrtanih je bilo več piezometrskih vrtin in izvedena sta bila dva sledilna poskusa za določitev smeri podzemnega toka v času nizkih vod. Rezultati so pokazali, da je v sušnih obdobjih v ponorni coni reke Korane nivo podzemne vode z aktivnim vodonosnikom približno 25 m pod strugo. To odpira možnost dodatnih raziskav za rešitev problema oskrbe z vodo in prestavitve zajetja vode na tem območju. Oba sledilna poskusa sta dokazala povezavo z izvirom Klokot (Bosna in Hercegovina) v sosednjem porečju reke Une, kar kaže na čezmejni značaj vodonosnika. Minimalni pretok izvira Klokot je približno 3 m^3/s, maksimalni pa več kot 75 m^3/s. Zajetje za oskrbo z vodo v ponorni coni reke Korane z izdatnostjo približno 60 l/s ne bo imelo vpliva na pretok izvira Klokot.

Ključne besede: Dinarski kras, ponorna cona reke Korane, Plitviška jezera, sledilni poskus, čezmejni vodonosnik, zajetje podzemne vode.

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INTRODUCTION

The discharge zone of the Korana River is located within the Plitvice Lakes National Park in the central part of Croatia (Fig. 1). This is a typical part of Dinaric karst area, which belongs to the Danube River catchment.

Fig. 1: Geographical position of the Plitvice Lakes National Park and the Korana River source zone.

The Korana River rises from the Plitvice Lakes water system (Fig. 2) which due to its beautiful landscapes and exceptional biodiversity has been proclaimed a national park in 1949, the first one proclaimed in Croatia, and in 1969 accepted on the UNESCO World Heritage List of nature. The fundamental natural phenomenon of the Plitvice Lakes National Park is the water – rock relation and 16 visually attractive lakes with numerous waterfalls over tufa barriers. Yearly visit of the National Park is about a million people. The elevation difference between the main Plitvice Lakes karst springs and the Korana River source is about 160 m at the distance of 8.2 km.

The origin of the Korana River as well as its hydrology and water quality, are directly related to the genesis of water resources in the National Park. However, the quality of the water in the Korana River source zone is very good and certainly is not the problem. A much bigger problem is the water loss into karst underground, beginning practically from the Korana River source zone, which reduces the water quantity in the riverbed up to the complete drying up during summer dry periods already 1.5 km downstream (Fig. 3). In that zone riverbed is without water about 30 days per year. About 10 km downstream, the duration of the period when the riverbed is completely dry increases on over 120 days per year. Drying up of the Korana River creates significant problems for the downstream villages. Due to lack of water along riverbed there is also the reduction in the attractiveness of that area, and for the expansion of visiting zone of the National Park.

Fig. 2: Beginning of the Korana River in the Plitvice Lakes National Park.

Fig. 3: The dry Korana riverbed (left); the appearances of groundwater (small lakes) in the Korana riverbed (right).

Numerous researches of water resources and genesis of tufa barriers have been conducted in the narrow area of the Plitvice Lakes since the early 20th century, but downstream of the Plitvice Lakes research studies have been very rare. Most of the research studies were related to tufa barriers of the Plitvice Lakes (Pevalek 1924, 1925, 1935, 1938, 1958; Srdoč *et al.* 1985, 1986; Horvatinčić 1985; Habdija & Stilinović 2005; Babinka 2007). Geological, hydrological and hydrogeological research studies were oriented almost to the wider area of the Plitvice Lakes (Koch 1916, 1926; Herak 1962; Polšak 1959, 1960, 1962, 1963, 1965, 1974; Velić *et al.* 1970; Polšak *et al.* 1967; Petrik 1958; Sumina 1988; Srebrenović & Blažeković 1989; Biondić, B. *et al.* 2010, Rubinić *et al.* 2008; Rubinić & Zwicker 2011, Bonacci 2013). Biondić B. (1982) made for the first time the delineation of the catchments in the wider area of Plitvice Lakes and upper part of the Korana River including the water balance calculations. From the recent research studies, the Copernicus INCO project studied possible anthropogenic pollution because of the Homeland War in the area of the Plitvice Lakes and Bihać region in the neighbouring country Bosnia and Herzegovina (ANTHROPOL.PROT 2005).

Very rare projects for building some engineering objects were done in the area downstream of the Plitvice Lakes in the sinking zone of the Korana River. About 7 km downstream of the Korana River source, in the area of the National Park Campsite, there was earlier an idea of building a dam for retaining water in riverbed, but studies have shown that the water would sink from the potential storage during summer dry periods, and storage would quickly stay without water (Srebrenović 1982). Because of that, the project was completely forgotten. That project opens up the problem of the sinking zone.

Drying up of the Korana River during summer dry seasons occurs between the springing in the riverbed and permanent flow of the river about 17 km downstream of the source zone. The basic questions are how much water sinks in the Korana riverbed, the directions of groundwater flows from the sinking zone towards downstream springs, dimensions of influence area of the sinking zone in the National Park, and the possible anthropogenic impacts on the locations of corresponded downstream springs.

There are two possible theses for groundwater directions in the sinking zone of the Korana River. One is the direction toward the downstream part of the Korana River where it became a permanent river, and the other towards the neighbouring Una River Basin.

Multiple water springing and sinking are common and well known appearance in almost all Dinaric karst catchments, but underground connections of big river catchments (bifurcation) as the case of Korana and Una areas are still very rare. There are known and proved the cases of connections between Zrmanja and Krka Rivers in the region of Ravni kotari (Fritz & Pavičić 1982; Bonacci 1985, 1999) and between Mrežnica and Dobra Rivers in the region of Gorski kotar (Bahun 1968). There are also some other cases without confirming with the results of tracing tests, such as Lika and Gacka Rivers in the region of Lika (Bonacci & Andrić 2008).

This paper focuses on the explanation of hydrogeological relations in the sinking zone of the Korana River where losses of water occur in the riverbed of Korana, relationship to the neighbouring Una River catchment, as well as possibilities of relocating the source of water-supply from the Kozjak Lake (Plitvice Lakes) to the new site in the sinking zone of the Korana River. For this purpose hydrogeological researches were performed (Biondić, R. *et al.* 2007; Biondić, B. *et al.* 2008) with drilling of several piezometric boreholes and two tracing tests to determine the direction of groundwater flow during a dry season. Results showed underground runoff toward the Una River catchment area (Klokot spring in Bosnia and Herzegovina) and on a very exact way was for the first time opened the problem of cross-border character of a large karst aquifer and the potential impact of the Plitvice Lakes National Park on the downstream area. During the dry periods in the sinking zone of the Korana River groundwater level with active aquifer is about 25 m below the riverbed. This opens up the possibility of additional research to solve the problem of water-supply and relocation of water-supply capture in this area.

HYDROGEOLOGICAL AND HYDROLOGICAL ANALYSIS

The wider area of the Korana River springing and sinking zones comprises the catchment of the Plitvice Lakes, which includes the catchment and spring of the Plitvica River, and the upper part of the Korana River. It is a typical karst environment located in the border area of main Dinaric geological units built mainly from karstified carbonate rocks of Mesozoic age (Herak 1986, 1991; Biondić B. & Biondić R. 2014). The oldest rocks in the area are the Upper Triassic dolomites, spreading in two main zones (Fig. 4). The first and most important one for the emergence of the Plitvice Lakes is spreading over the lakes in direction from northwest to southeast, and the other on the northeast part of the research area. The Upper Triassic dolomites are followed by younger Mesozoic carbonate rocks – firstly by Liassic limestones and dolomites, and then by Dogger limestones, and finally by Malm limestones and dolomites. For the problems of the Korana River sinking, the most important are the carbonate rocks of Cretaceous age consisting of layered limestones and limestone breccia followed by Upper Cretaceous transitions between limestones and dolomites. An important hydrogeological role in regional directing of underground and surface flow directions have the clastic rocks of Neogene age in the border area between Croatia and Bosnia and Herzegovina. The youngest sediments visible on the surface are the different types of Quaternary clastic sediments, especially tufa and alluvial sediments along Korana River, and occasional appearances of deluvial sediments and terra rossa, which covers a large part of the terrain built from carbonate rocks.

Tectonics is an important factor in the spatial and depth position of different chronostratigraphic members and directly effects on the disposition of aquifers, springs and sinking zones as well as the directions of groundwater flows inside catchment areas. The catchment of Plitvice Lakes and Korana River is located on the northeastern margin of the Dinarides zone of high karst (Herak 1986, 1991). Basic characteristics of this area are thick layers of carbonate rocks of several thousand meters, complex geological structure and sporadically deep karstification of carbonate rocks along strong tectonic zones. Faults of Dinaric direction (NW–SE) prevail according to its importance and length. Transversal faults generally depreciated the differential movements of large structural blocks. In the Plitvice Lakes catchment area dominates the anticlinal structure of the Mala Kapela, which towards the northeast exceeds in syncline and further to the northeast in the anticlinal structure of the Plitvice Lakes with the core built of Upper Triassic dolomite. The anticlinal core on the north side is cut by the strong regional longitudinal fault, known as Kozjak fault. In terms of hydrogeology, this is a dominant fault in the whole area, which separates poorly permeable dolomites of Triassic age from permeable limestones of Upper Cretaceous age. Synclinal geologic structure of permeable limestones allows deep karstification and water losses from the Korana River immediately after surpassing of water over the dolomite barrier. The next similar longitudinal fault on the northeast side limits the area of the synclinal structure with permeable carbonate rocks that includes the area of mountain Lička Plješivica. This strong longitudinal fault is important for the re-emergence and permanent flow in the Korana River downstream.

The formation and movement of surface and underground waters in the research area is directly related to the lithostratigraphic relationships, tectonic structures and differences in the hydrogeological characteristics of the rocks. Predominantly limestone rocks are generally highly permeable and dolomites are poorly permeable. However, at the Plitvice Lakes region these dolomites have a function of hydrogeological barriers. The catchments of Plitvice Lakes and Korana River belong to the Danube River catchment area, extending to the border of the Adriatic Sea catchment in the mountain area of Mala Kapela. The largest karst springs of the Plitvice

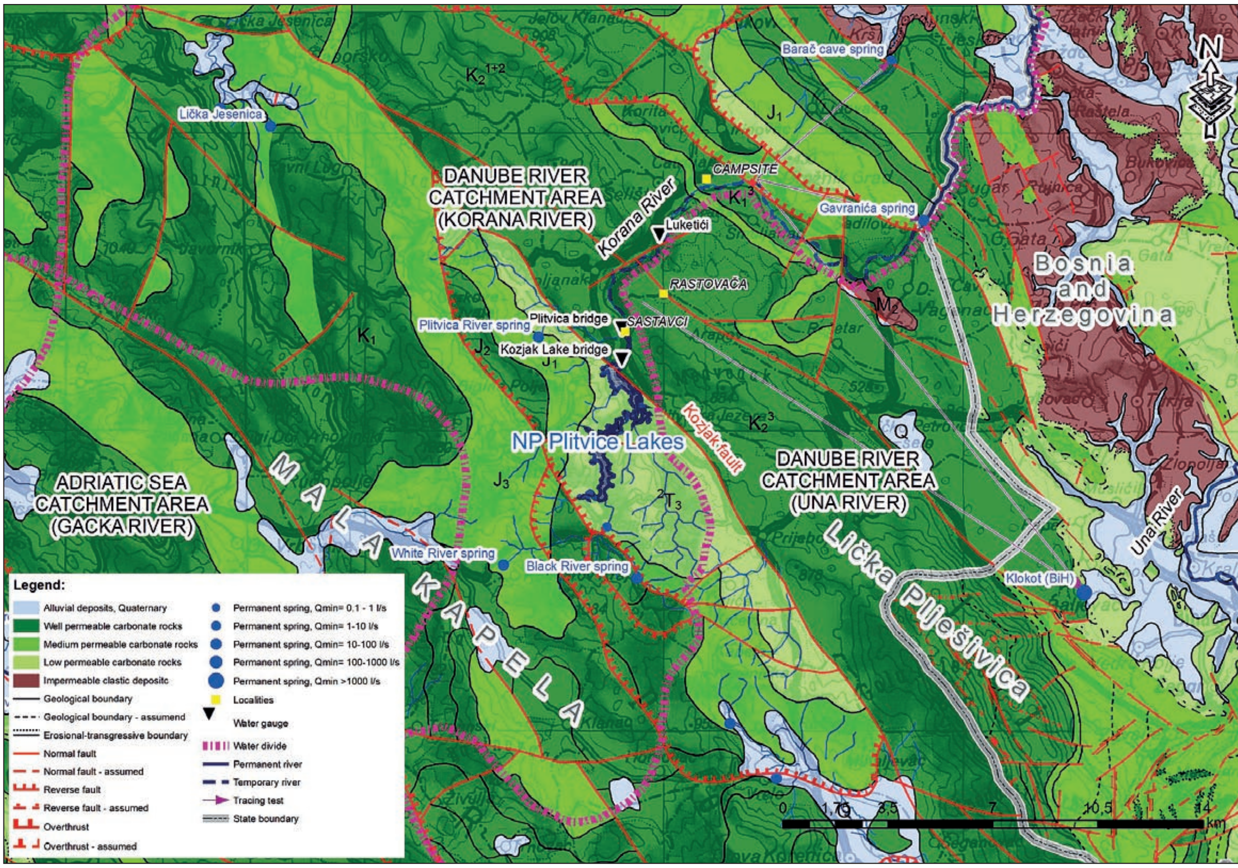

Fig. 4: Hydrogeological map of the Plitvice Lakes and upstream part of the Korana River.

Lakes are the Black River, White River and Plitvica River (Meaški *et al.* 2016). The Upper Lakes and the most of the largest Kozjak Lake are placed on dolomite barrier up to the longitudinal regional fault (Kozjak fault). After the Kozjak fault begins the zone of possible water sinking through the syncline geologic structure of the Lička Plješivica (Fig. 4).

Water from the Kozjak Lake flows over tufa barriers, through the several relatively small lakes (called Lower Lakes) that are formed in a deep canyon inside the permeable carbonate rocks. At the end, water from lakes merges with water that comes over the Big Waterfall from the Plitvica River. Location where these waters are merged is called Sastavci, also known as the beginning of the Korana River.

On the north side of Kozjak Lake the occurrences of active water sinking were not observed, but piezometer wells have shown a negative gradient from the lakes, especially during dry periods. The reasons for the stability of the water system should be the positive hydrogeological function of tufa that fulfils the fossil sinkholes (Biondić, B. *et al.* 2010; Biondić, B. *et al.* 2011). The amount of tufa isolation sediment is slowly reduced downstream of the Korana River source zone, what diminish possibilities of keeping water in the riverbed. Water is gradually losing in karst underground, and during extreme summer periods already 1.5 km downstream begin the problems of complete drying up of the Korana River.

Hydrological conformation of such situation has been obtained by analysing results of measurements on three relevant hydrologic profiles (gauge stations): Kozjak Lake Bridge, Plitvica River and Luketići (Fig. 5).

For the hydrologic analysis available data on discharges measured at water gauging stations within the Plitvice Lakes catchment were used (DHMZ 2009). It also should be noted that most of the gauging stations at Plitvice Lakes area started operating in the early 1980, at the time when on the majority of streams in the Croatian karst region had begun long dry period (Žugaj 1995). In the case of the Plitvice Lakes, it is especially important because the water has a decisive role in the forming sensitive lake system. Therefore, alerts of researchers on the lowering trend of flows in Plitvice Lakes and Korana River have the special value for the sustainability of whole environment (Zwicker & Rubinić 2005; Bonacci 2012).

The main inflow in the Korana River is related to the Plitvice Lakes, respectively outflow from Kozjak Lake. The average annual flow rate at the gauging

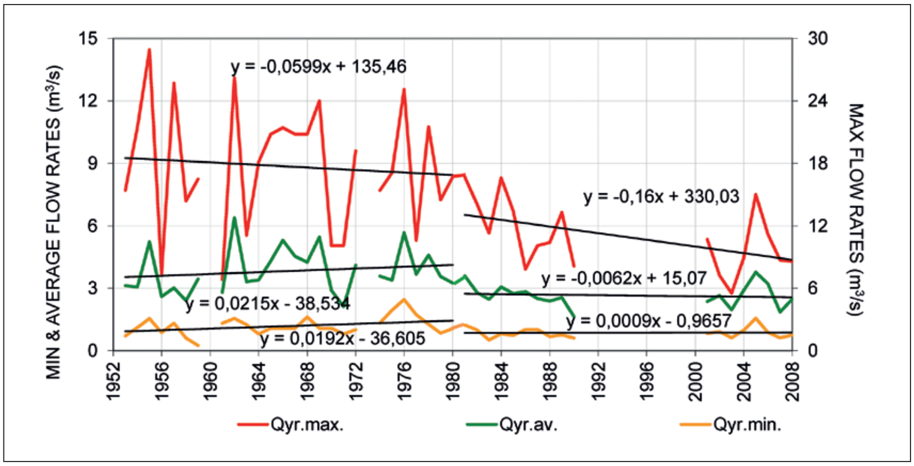

Fig. 5: Time series of minimum, average and maximum annual outflow from Kozjak Lake for the period 1953–2008 (Meaški 2011).

station Kozjak Lake Bridge for the period 1953–1980 was 3.83 m^3/s, the minimum 2.12 m^3/s (1971) and the maximum 6.38 m^3/s (1972). The average annual flow rate for the period 1981–2008 was 2.65 m^3/s, what is much lower than in previous analysed period (Fig. 5). Data for dry period 1981–2008 shows that the average minimum flow rate of 0.861 m^3/s is much lower than for period 1953–1980. Significant reduction of average minimum flow rates is becoming the big problem for the sustainability of the Plitvice Lakes (Fig. 5).

Hydrologic analysis at the Kozjak Lake Bridge (Fig. 5) have shown that the time series of minimum, average and maximum annual flow rates in the period from 1953 to 2008 are not homogenous. Therefore, this time series were divided into two homogeneous period, taking also into account the beginning of the long dry season (Žugaj 1995). The first period is from 1953 to 1980 (with the missing data for 1960 and 1963) and the second period is from 1981 to 2008 (with the missing measurements during the Homeland war in Croatia).

The average maximum annual flow rate for the period 1953–1980 was 17.7 m^3/s and the highest measured was 28.9 m^3/s in October 1955. In the period 1981–2008 the average maximum flow rate was significantly lower 11.0 m^3/s and the highest measured was 16.7 m^3/s in March 1981. A strong negative trend between the first and second period is evident.

The second significant inflow in the Korana River source zone (Sastavci) is the Plitvica River with the gauging station Plitvica Bridge active in period 1981–2008. From the Plitvica River spring to the location of gauging station placed above the Big Waterfall, there is a significant water loss from the Plitvica riverbed. Water sinks at many places along the riverbed. In dry periods, these losses can reach up to 40 % of the total flow rate (Biondić, B. *et al.* 2010; Meaški 2011).

The average annual flow rate at the gauging station Plitvica Bridge for the period 1981–2008 was 0.65 m^3/s. The lowest measured was 0.327 m^3/s in 2003, and the highest measured was 0.983 m^3/s in 1981. The average minimum annual flow rate for the period 1981–1990 was 0.098 m^3/s, and in the period 2001–2008 it was reduced to 0.059 m^3/s, what is approximately 40 % lower. The minimum measured flow rate in this period was

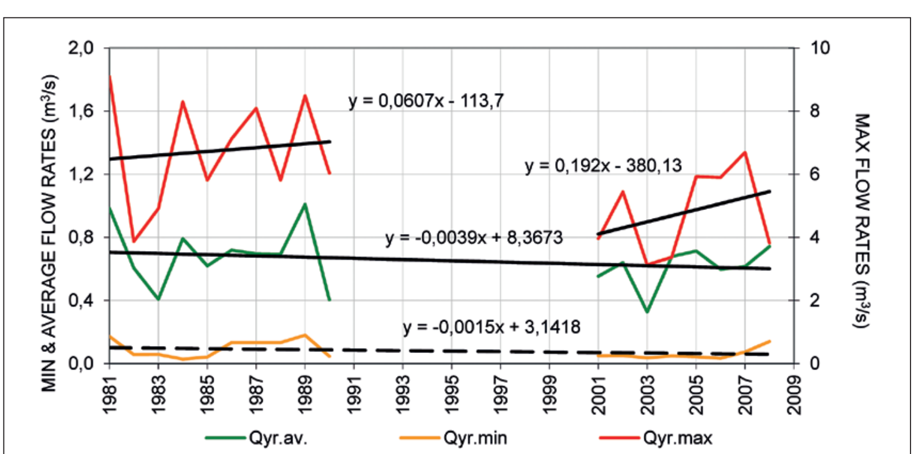

Fig. 6: Time series of minimum, average and maximum annual flow rates at the gauging station Plitvica Bridge for the period 1981–2008 (Meaški 2011).

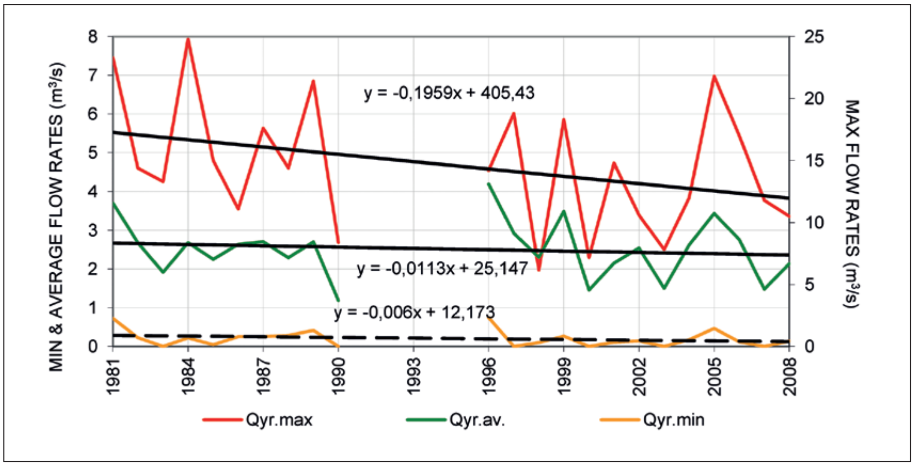

Fig. 7: Time series of minimum, average and maximum annual flow rates of the Korana River at the gauging station Luketići for the period 1981–2008 (Meaški 2011).

0.028 m^3/s (in August 1984). The average maximum annual flow rate for the period 1981–1990 was 6.75 m^3/s, and in the period 2001–2008 it was 4.78 m^3/s, what is much lower.

The gauging station Luketići (located in the village of the same name) summarizes the total amount of runoff in the Korana River, because that is the first gauging station after the Korana River source zone, where the effect of water loss along the riverbed is observed. The average annual flow rate for the period 1981–2008 was 2.51 m^3/s with an obvious negative trend (Fig. 7).

The average minimum annual flow rate for the period 1981–1990 was 0.242 m^3/s, and for the period 1996–2008 it was 0.174 m^3/s, what means a reduction of the average minimum annual flow rate for approximately 29 %. According to measurements of flow rates in the village Luketići, the Korana River was in the period 1981–2008 completely dry for 17 months in total (Meaški 2011). The decreasing trend of the average minimum annual flow rates indicate that either there was a prolongation of the dry periods or the increased amount of sinking into the Korana riverbed from the source zone to the gauge profile Luketići. The average maximum annual flow rate for the period 1981–2008 was 14.6 m^3/s, and the largest 24.8 m^3/s in April 1984. Time series of maximum annual flow rates have a negative linear trend, too.

From presented data it can be concluded that at the time of maximum flows in the Korana River source zone (Sastavci) about 65 % of water comes from the lakes system and about 35 % from the Plitvica River. According to the data from the gauging station Luketići, during the period of high waters from the Korana River source zone up to the station Luketići sinks about 2.3 m^3/s of total water amount. Furthermore, at the time of minimum flows in the Korana River source zone about 91 % of water inflows from the lake system, and only 9 % from the Plitvica River. During this period average minimum flow rate at the gauging station Luketići was 0.200 m^3/s, and the river occasionally dried up. It can be concluded that the losses of water in the average minimum conditions at the distance of around 1.5 km from the source are approximately 79 %, and occasionally even 100 % (Meaški 2011). Water losses in the Korana River downstream from the source occur in all hydrological conditions throughout the year, but the most obvious are during dry seasons because of the complete drying up of the Korana River.

Hydrogeological and hydrological analyses have showed that the Plitvice Lakes catchment area is a separate hydrogeological unit down to the Korana River source zone. Downstream of the source zone, it becomes a part of the wider karst water system, including the possibility of belonging partly to the Una River catchment area in the neighbouring state Bosnia and Herzegovina.

Hydrogeochemical investigations gave also very interesting results concerning groundwater distribution after sinking in the Korana riverbed. In the frame of a previous investigation project, the stabile isotopes and tritium parameters of the springs in the area of Plitvice Lakes in Croatia and some springs along the left bank of the Una River in Bosnia and Herzegovina were analysed. Those analyses confirmed the possible hydrogeological connection of the Plitvice Lakes and the Korana River in Croatia with the Una River in Bosnia and Herzegovina (ANTHROPOL.PROT 2005).

Measurements of stabile isotopes δ^2H and δ^{18}O along the Plitvice Lakes (Biondić, B. *et al.* 2010) showed that water overflowing the lakes and waterfalls was enriched with stabile isotopes because of the evaporation processes. The Korana River source in such a way has a water of the highest level of concentration of stabile isotopes. One part of that water sinks along upstream part of the Korana River and becomes the part of the Una River catchment area.

TRACING TESTS

In spite of previous analyses that indicated possible connection of the Korana River and the Una River catchment areas, two basic questions stay open:

1. Does the prevailing karstification processes have occurred along the Korana River as in the cases of other rivers in the area of so-called shallow karst?

2. Is the role of geological structure crucial for the water runoff through deep karst underground towards the adjacent catchment of the Una River in the neighbouring country?

The answers to these questions were clarified by two tracing tests from the Korana River sinking zone performed during dry periods in time of evident water losses along the Korana riverbed. The first tracing test was performed from the sinkhole in the village Rastovača (Fig. 8a) in the zone of syncline structure Lička Plješivica about 1 km southeast from the Korana River sinking zone (Biondić, B. *et al.* 2008). The second tracing test was performed through piezometer well on the left bank of the Korana River (Fig. 8b) near the village Drežnik Grad (Biondić, R. *et al.* 2007). Both locations were in a certain way defined by the necessity of the Plitvice Lakes National Park and local community. The first location is the location of the wastewater discharge from the National Park and the second location was foreseen for the construction of the new wastewater treatment plant for the National Park and local community.

Tracing test through the sinkhole in the village Rastovača was done as a part of the international project "Sustainable use and protection of water resources in the area of Plitvice Lakes" in cooperation between the University of Zagreb – Faculty of Geotechnical Engineering, Joanneum Research Institute from Graz and the National Park Plitvice Lakes – Centre "Ivo Pevalek". The injection place was the small dry valley (Fig. 8a), in which National Park discharges practically untreated wastewater in karst underground. The aim of the tracing test was to define possible groundwater connection with downstream parts of the Korana riverbed, some karst springs in the Una River catchment and some springs in a wider karst area. The observation network included three profiles along the Korana riverbed, two temporary springs on the northern side of Lička Plješivica Mountain, a permanent spring downstream in the Korana riverbed, and the Klokot spring in the Una River catchment in the neighbouring country Bosnia and Hercegovina.

30 kg of Na-fluorescein together with 60 m^3 of potable water was injected on 21 April 2005 in the sinkhole. Samples for laboratory analyses were collected every 8 hours in the period of two months; 840 samples in total have been taken and analysed. At each observation site the active carbon as the security indication of tracer appearances was set. The tracer appeared only at the Klokot spring 428 hours after the injection (Fig. 9).

Fig. 9: Sampling for the tracing test on the Klokot Spring.

Fig. 8: Places of tracer injections – (a) in the sinkhole near the village Rastovača; (b) in the piezometric well near the village Drežnik Grad.

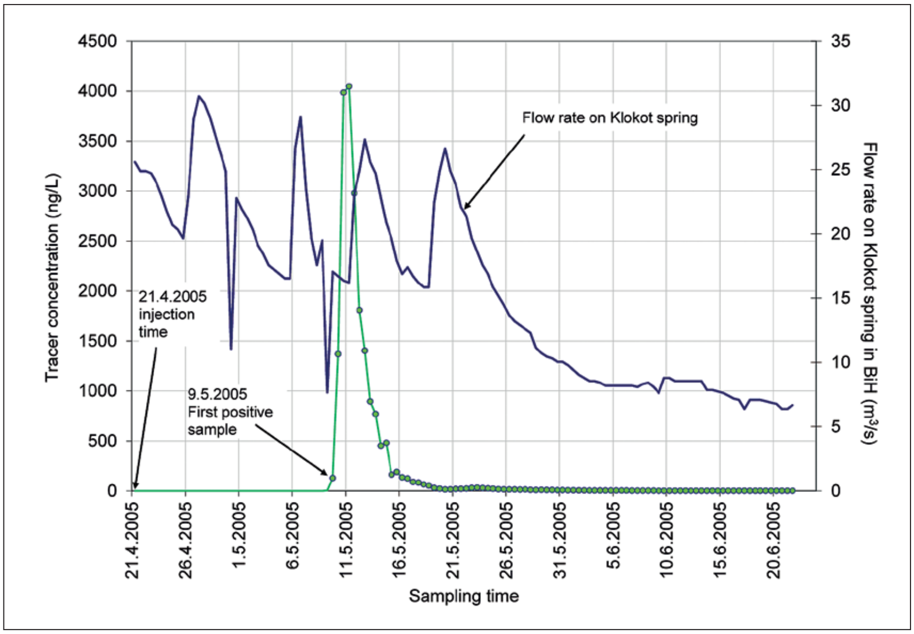

Fig. 10: Tracing test of the Rastovača doline and appearances at the Klokot spring (Biondić, B. et al. 2010).

The maximum concentration of the tracer was recorded on 11 May 2005 and was 4047 ng/L (Fig. 10). Tracer continues to discharge up to the end of the observation period in very low concentrations.

The maximum apparent groundwater flow velocity of 1.14 cm/s between the injection place in the village Rastovača and Klokot spring was calculated from the results. The calculation of the tracer mass recovery in the Klokot spring was approximately 17.1 kg, which is 57 % of the injected quantity.

The second tracing test was performed on 25 September 2007 by injecting tracer in the piezometer well near the village Drežnik Grad. This location was proposed as a potential place of a central unit for the wastewater treatment plant of the National Park Plitvice Lakes and local municipality (Biondić, R. *et al.* 2007). 25 kg of Na-fluorescein together with 25 m^3 of potable water was injected. At the time of tracing the Korana riverbed was dry, which means just underground runoff of the tracer from the zone of injection.

The first appearance of the tracer was registered on 12 October 2007 at the Klokot spring, and it continued until the end of the sampling period on 20 November 2007 as a result of groundwater washing after heavy

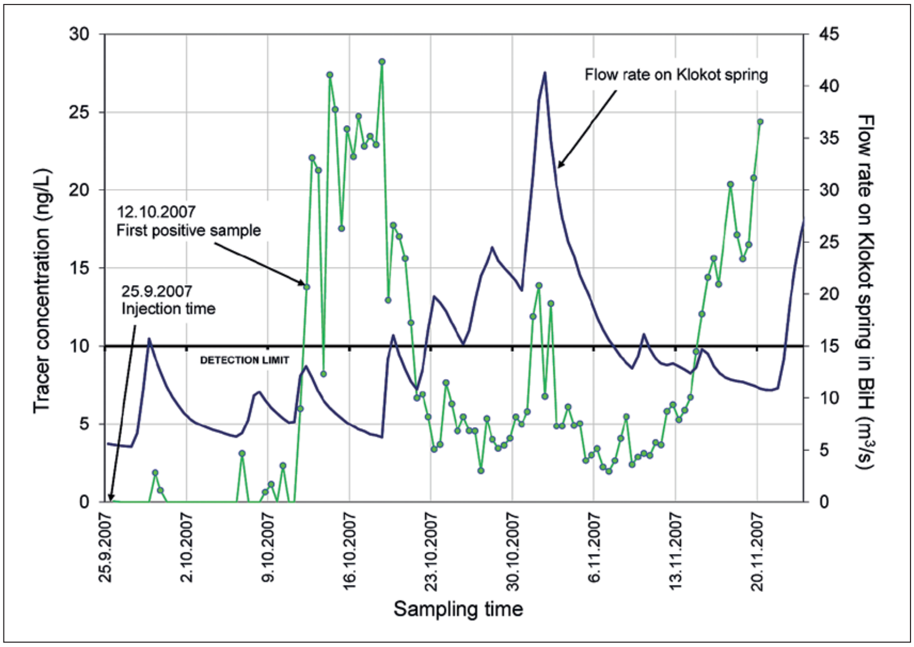

Fig. 11: Tracing test from Drežnik Grad and appearances at the Klokot spring.

rains. Tracer concentrations were much lower than in previously described tracing test, but continuous tracer discharge indicated a connection of the injection location with the Klokot spring (Fig. 11).

The observation network included the Klokot spring, downstream permanent spring of the Korana River, and the spring from the Barač cave (open for visitors). Tracer was firstly registered in the Klokot spring about 18 km far from the injection place after 432 hours (18 days). The calculated maximum apparent groundwater velocity was 1.13 cm/s. What is interesting to be mentioned is that the recovery rate of the tracer on the Klokot spring was only 0.5 kg of the total injected 25 kg of tracer, or approximately 2 %. The reason for this is that the Korana riverbed was completely dry for 28 days after the tracer injection. With the first rise of water in the Korana River, the tracer appeared in the riverbed near the injection place, and by surface stream majority of tracer was transferred in the zone of the downstream permanent spring of the Korana River. However, it is interesting what happened with the tracer further downstream from the permanent spring of the Korana River. Part of the water from the Korana River sinks along the canyon of the Korana River, and through karst underground flows towards the spring from Barač cave, which is separated from the injection place with a natural hydrogeological barrier (Fig. 4).

POSSIBLE WATER CAPTURING IN THE SINKING ZONE

Knowledge of the groundwater levels in the Korana River sinking zone downstream of the gauge station in the village Luketići in dry seasons, when the river is without water on the surface and spreading of the catchment area far away to the mountain area towards northwest opened a series of new assumptions.

However, the basic assumption for further investigation was that the sinking water from the Korana River is just a small part of groundwater that flow through that aquifer toward the Klokot spring. This opens an opportunity for a possible alternative groundwater capturing in this area for water supply of the Plitvice Lakes National Park and nearby touristic developed municipality. Drinking water is now pumped from the Kozjak Lake (approx. 60 l/s), which during dry periods seriously effect on the water quantity overflowing the tufa barriers, and indirectly the stability of tufa barriers in the lakes downstream of the Kozjak Lake and in the springing zone of the Korana River. To solve this serious problem with water in the National Park it is necessary to find an alternative solution for water supply by capturing groundwater on some other location. The actual idea is water capturing outside the Korana River catchment area at the spring Lička Jesenica, which is located about 20 km north-west from the Plitvice Lakes National Park in a neighbouring community. This is a large and economically challenging project because of the difficult mountainous morphology, which requires the construction of long hydrotechnical tunnel, and during the wintertime very challenging maintenances due to the relatively low consumption and hard climatic conditions. Unfortunately, groundwater capturing in the area of the Korana River sinking zone has not been previously considered, although such possibility is practically in the centre of consumption without the need of long transport of water and construction of demanding and expensive hydro facilities.

The potential location of groundwater capturing in the Korana River sinking zone has been investigated in the period 2007–2008 (Biondić, B. *et al.* 2008) (Fig. 12). A detailed hydrogeological mapping was performed and the combination of three geophysical methods was used: shallow seismic reflection method, geoelectric tomography and electromagnetic profiling. The results were the definition of spatial distribution of faults and the indications of stronger karstified carbonate rocks in the underground. In one of such zones a 159 m deep exploratory borehole with the bottom at approximately 120 m bellow the Korana riverbed was located and drilled. The performed borehole permeability tests showed the enhanced permeability at the Korana riverbed level. The enhanced permeability was registered again at the depth of 25–50 m bellow the Korana riverbed. Measurements of water temperature, electrical conductivity and dissolved oxygen along the borehole together with tested degree of karstification showed significant activity of water down to the depth of 60 m bellow the Korana riverbed – lower level of electrical conductivity and higher concentration of dissolved oxygen (Fig. 12). Concerning the measured minimum groundwater levels during dry periods at the depth of about 25 m bellow the bottom of the canyon, can be concluded that about 35 m of the saturated part of aquifer is very active even in the condition of droughts. In this way was opened a possibility of further investigations and finally capturing of an alternative water source for the exploitation of drinking water for the National Park and surrounding municipality

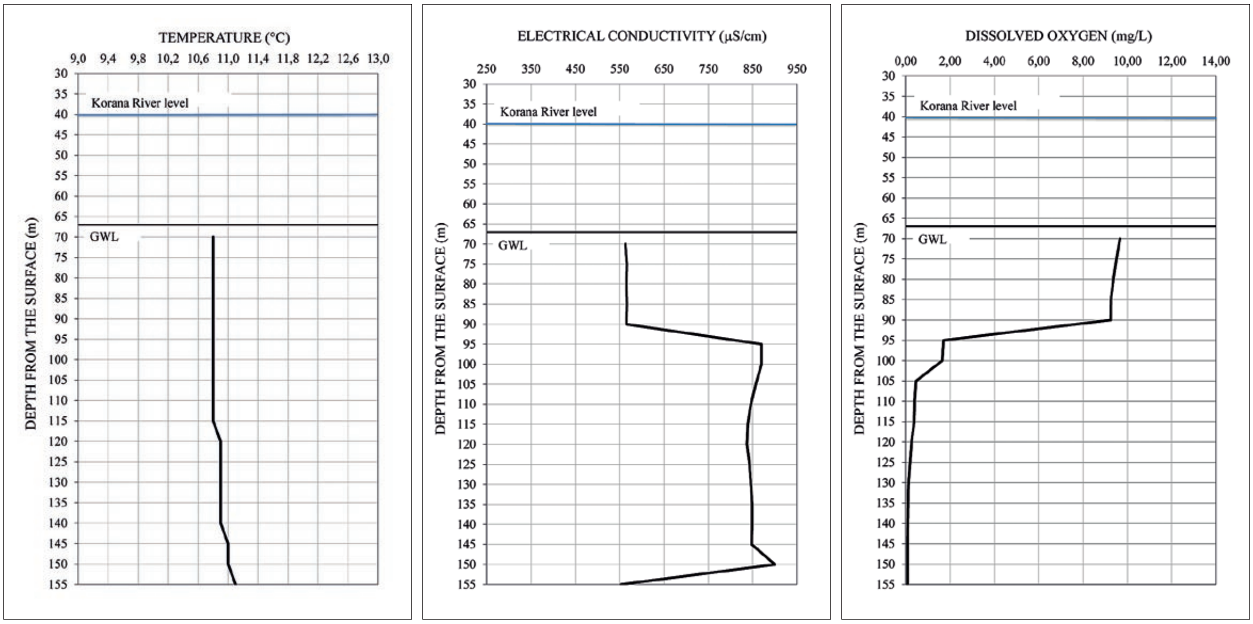

Fig. 12: Measured values of temperature, electrical conductivity and dissolved oxygen concentrations in the piezometric borehole in the campsite of the National Park.

avoiding long water transfer from distant spring zone Lička Jesenica.

The Klokot spring discharge in a minimum is about 3 m^3/s and in a maximum over 75 m^3/s. Groundwater capturing of 60 l/s for the public water supply in the sinking zone of the Korana River would replace that same amount of water captured from the Kozjak Lake. Positive results of detail hydrogeological investigations would lead to relocating the current water capture without taking additional quantities of water from the water system Plitvice Lakes – Korana River. The amount of 60 l/s does not represent the amount that could adversely affect the discharge capacity of the Klokot spring in Bosnia and Herzegovina.

CONCLUSIONS

From presented materials can be concluded that the Korana River from its source zone has all characteristics of a "hanging" river, which due to known hydrogeological relations can be extended on Lower Lakes and north-eastern coast of Kozjak Lake. Water losses in the Korana riverbed are especially pronounced and visible during dry periods, when the Korana River at a distance of 1.5 km downstream from the source zone remains completely dry in the length of about 10 km. After re-emergence in the riverbed downstream, the Korana River becomes the river of permanent flow up to its mouth as tributary at the city of Karlovac. The spreading of geological structures and lithostratigraphic units dictate in a way the difference in intensity of water losses along the riverbed from the source to re-emergence place in the Korana River downstream, what is visible from small and localized appearances of water along the riverbed during dry periods.

Average minimum annual quantity of water sinking in first 1.5 km of the Korana River in the seasons of complete drying is up to 0.940 m^3/s. The losses are increasing during high waters, but they are not visible because of the large quantity of water in the riverbed. Measurements during high waters have shown that up to the gauging station in the village Luketići the sinking in riverbed is approximately 2.30 m^3/s, and the losses downstream certainly increase this amount.

Rivers in Dinaric karst have expressed very often the effect of sinking with even complete losses of water during dry seasons, but very rarely occurrences of water overflow from one large catchment area to another (bifurcation), as is the case with the upstream part of the Korana River. This is very significant and in the same time dangerous situation for the Plitvice Lakes National Park, because the Korana River outflows from the Plitvice Lakes, which are from hydrogeological point of view partly effected by the possible water losses. Namely, the Korana River cuts the spreading of earlier mentioned Kozjak fault, which divides dolomite barrier from the area built of high water permeable limestone. In such a way, northeast part of the Kozjak Lake together with the Korana River up to the re-emergency place (Gavranića spring) are in the endangered zone concerning the water sinking.

The most interesting results are the definition of the directions of groundwater runoff after sinking from the Korana River and the possibility of groundwater capturing as the alternative potable water source to current direct pumping of water from the Kozjak Lake. Tracing tests unambiguously showed that sinking water from the Korana River is drained towards the Klokot spring in the Una River catchment area in the neighbouring state, what means that we are faced with even for Dinaric karst rare natural phenomenon of water bifurcation from one to another large catchments. In such a way the problem of transboundary water management is opened. That is particularly important for the efficient water resources protection of the Plitvice Lakes National Park and water supply systems on both sides of the border between Bosnia & Hercegovina and Croatia. In this paper is also presented a possibility of groundwater capturing in the Korana River sinking zone with the possibility of exploitation even during the drying up of the river as an alternative solution for currently exploitation from the Kozjak Lake that is actually not allowed in the National Park area. Moreover, presented groundwater capturing would enable much more economical solution than distant transfer of water from the Lička Jesenica spring zone. It is important to point out that captured volume of groundwater from the Korana River sinking zone would not have impact on discharge volume of the Klokot spring in Bosnia & Hercegovina.

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