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The conceptual hydrogeological model of the Plitvice Lakes

Božidar Biondić, Ranko Biondić and Hrvoje Meaški

Faculty of Geotechnical Engineering, University of Zagreb, Hallerova aleja 7, 42000 Varaždin, Croatia; (bbiondic@usa.net; rbiondic@gfv.hr; hmeaski@yahoo.com)

doi: 104154/gc.2010.17

Geologia Croatica

ABSTRACT

The Plitvice Lakes National Park, founded in 1949, is located in the central part of the Dinaric karst region in Croatia. Large karst springs and 16 lakes separated by tufa barriers and waterfalls are the fundamental natural phenomenon of the national park, which has a million visitors a year. Lakes are recharged by water from the mountainous region of Lika, and the runoff is directed towards the Black Sea catchment. The whole area of the National park is composed of carbonate rocks with different levels of natural permeability and very complex tectonic relationships, which allowed discharge of groundwater, maintaining the lake and finally partial loss of water to the karst underground after passing through the lake system. Prošćansko and Kozjak are the two largest lakes which dominate and by their internal dynamics ensure maintenance of the high water quality of the whole system. A conceptual hydrogeological model of the Plitvice Lakes was the result of complex research in the framework of international cooperation between the University of Zagreb and the Joanneum Research Institute in Graz. The research identified completely new data about the genesis of the water system, the hydrogeological characteristics of the karst water catchment, the dynamics of the water in the lakes, locations of water loss from the Plitvice Lakes system, the "hanging" position of Lake Kozjak in relation to groundwater and a whole range of other data important for the preservation and protection of water resources in the National Park. Throughout the project were made 3022 measurements of different physico-chemical parameters, 7885 of the chemical analysis of water and 1082 analysis of stable isotopes.

Keywords: National Park Plitvice Lakes, conceptual hydrogeological model, hydrogeochemical analyses, water quality, lake dynamics, lake sustainability

1. INTRODUCTION

The Plitvice Lakes National Park is located in the central part of the Dinaric karst area in Croatia (Fig. 1). Many nature lovers and researchers at the end of the 19th and in the early 20th century had already noticed this naturally attractive area with water, karst forms, forests and biodiversity. The Plitvice Lakes water system consists of 16 lakes separated by tufa barriers, differing in altitude by 160 m over a length of 8.2 km (Fig. 2).

The Plitvice Lakes were proclaimed as a national park in 1949 and by 1979 had entered the UNESCO World Heritage List. Water resources, and sediments formed by water (tufa), are the fundamental natural phenomena of the park because all other natural resources (flora, fauna, aquatic ecosystems), largely depend on maintaining the water quality and water balance. The basic question of the research project was "how to ensure the sustainability of water resources and assess the visitor capacity of the park". This is an important issue because the number of visitors is approaching one million a year, with daily numbers during weekends of the tourist season reaching over ten thousand. All visitors are generally retained in the narrow area of the lakes and the loads are excessive at times. There are three basic objectives of the project: (1) protection of the catchment area of the huge karst springs, which discharges most of the water for the lakes, (2)

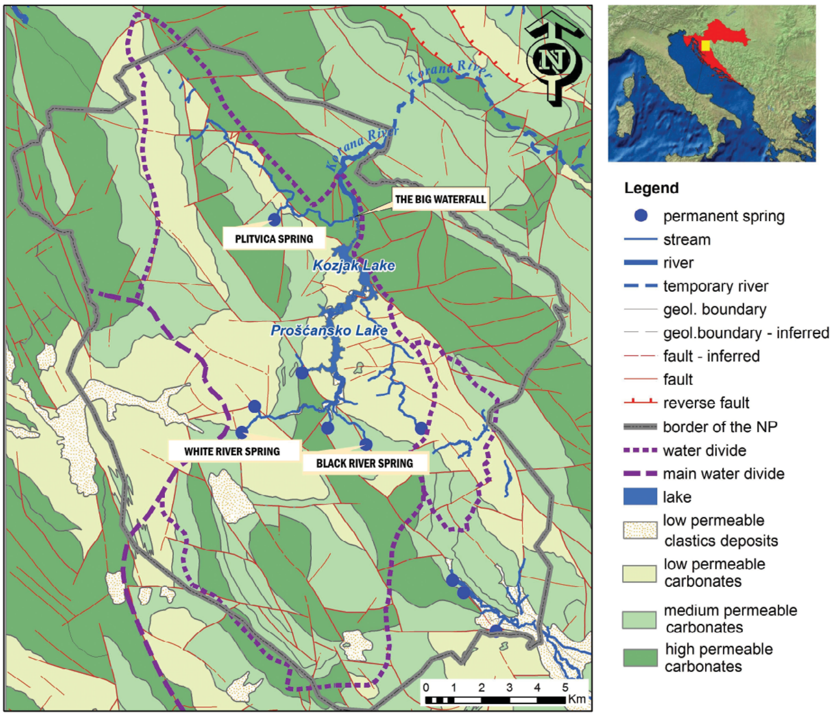

Figure 1: Schematic hydrogeological map of the Plitvice Lakes catchment area.

protection of the lakes and waterfalls overloaded by numerous visitors and tourist facilities and (3) the broader protection of the karst environment from the impact of the National Park (BIONDIĆ et al., 2008).

The Plitvice lakes are fed by waters of the three biggest karst springs – the Black River, the White River, and the Plitvice springs. The River Korana, which belongs to the Danube basin, originates from the Plitvice Lakes system. The main characteristic of the Korana River downstream from the Plitvice Lakes is a gradual but steady loss of water along the river bed and during summer dry periods the river remains completely without water from about 1 km downstream of the spring zone.

Climatic conditions in the catchment of the Plitvice Lakes are typically mountainous; continental with an average annual rainfall between 1128 and 2113 mm. The upper

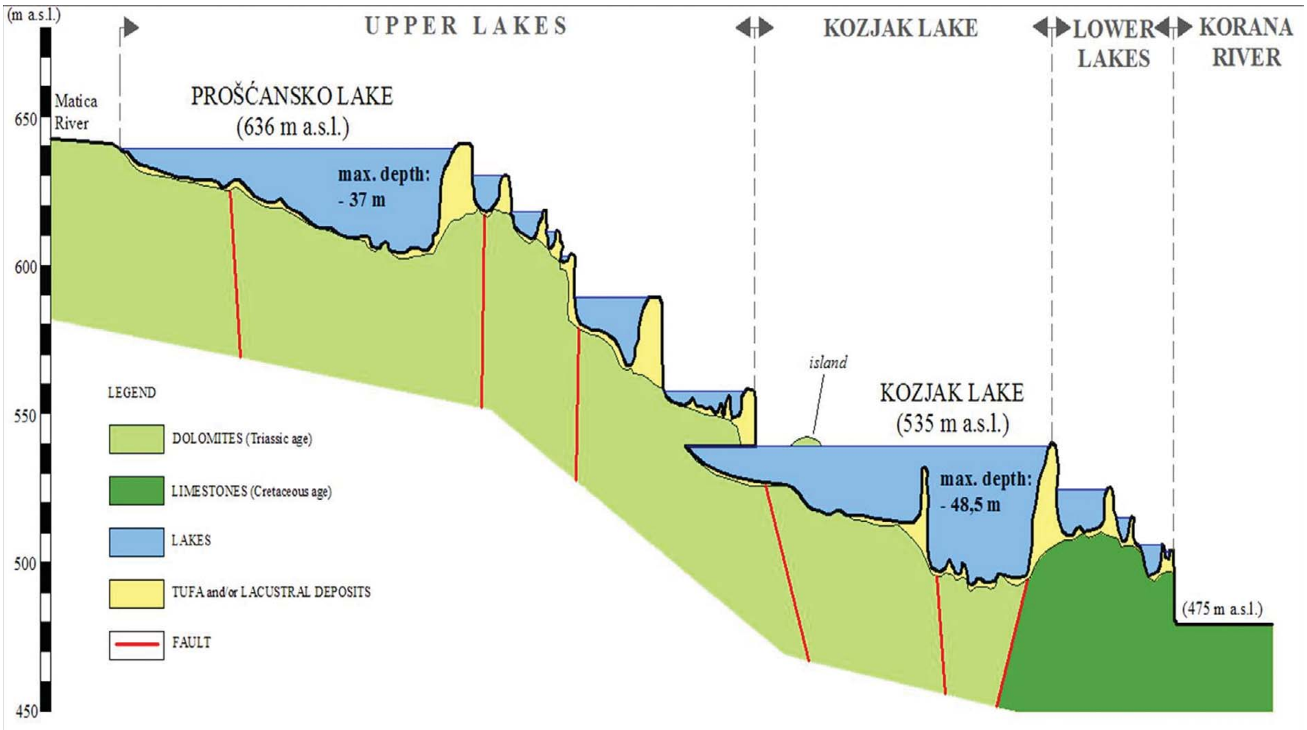

Figure 2: Schematic hydrogeological cross-section of the Plitvice Lakes water resource system.

part of the Korana River, downstream of the lakes, has the characteristics of torrential flow as a result of the concentration of rainfall in the autumn and spring periods. This is particularly pronounced in the springtime, when snow melt overlaps with more extensive precipitation. Average annual air temperature range from 8.9–10.4°C and the wind is predominantly of north-eastern directions.

2. HYDROGEOLOGICAL DESCRIPTION OF THE PLITVICE LAKES

The Plitvice Lakes National Park area is a typical karst environment composed almost completely of carbonate rocks (limestones and dolomites). The age of the basic rock mass is from the Upper Triassic up to and including the Upper Cretaceous (VELIĆ et al., 1974; POLŠAK et al., 1976). Sediments deposited during the Quaternary period are especially important for the identification of the morphostructural and hydrogeological genesis of the area. This was certainly one of the most important geological periods of the development of karst and other erosion processes in carbonate rocks of the Dinarides. Most of the sediments of Quaternary age were formed during the exchange of glacial and interglacial ages and also in the recent period. The researchers have so far mainly focused on exploration of the tufa deposits, which is crucial for the development of lakes and waterfalls, but not on other sediments important for the identification of a genetic model of the system. Firstly, lake sediments occurred during the existence of isolated lakes in the Dinaric karst areas. These can be expected in the bottom of the largest lakes; Prošćansko and Kozjak. Next, layers of tufa of different ages and gravel interbeds occur within the tufa barriers. Recent lake sediments do not have a high value in the identification of a genetic model of the lakes, but the organic load can create problems by reducing the volumes of the lakes and the development of eutrophication in the bottom zone of the lakes.

Tectonic structures are important factors for the formation of surface and especially groundwater systems in the karst area of the Plitvice Lakes National Park. According to HERAK (1986), the Plitvice Lakes area belongs to the Dinarik megastructural unit. The basic feature of that megastructural unit is the existence of a thick sequence of carbonate rocks of complex tectonic structure with the appearance of tangential tectonic forms (overthrusts), interspersed with very deep karstification. Carbonate rocks totalling several thousand metres in thickness are fragmented into tectonic blocks by numerous faults.

The Plitvice Lakes belong to the Black Sea catchment, located in the border area towards the Adriatic Sea catchment. Almost the entire catchment of the Plitvice Lakes is located within the boundaries of the National Park.

The poorly permeable dolomites of the Triassic age, which are essential for the emergence and formation of the so-called Upper Lakes, form a barrier to the discharge of water from the large carbonate basin on the northeastern slopes of Mala Kapela mountain. This surface occurrence of the oldest carbonate rocks of the area is a tectonic phenomenon. After groundwater discharge, flow occurs to longitudinal faults on the north-eastern side of the largest Lake Kozjak without any losses. After this line, there is a gradual loss of water from the system, which eventually results in the complete drying up of the Korana River about a kilometre downstream from the Plitvice Lakes.

The hydrological interpretation of the Plitvice Lakes basin was based on gauge station measurements in the National Park, on the Korana River (taken by the State Hydrometeorological Institute) and data from published papers (ZWICKER & RUBINIĆ, 2005, ZWICKER et al., 2006; RIDJANOVIĆ, 1976). Most of the Plitvice Lakes water flows from karst springs, including the Black River (75%) and the White River (25%). The mean annual inflow into the lake is 2.14 m^3/s, with a maximum of 11.60 m^3/s and a minimum of 0.6 m^3/s. All this water flows through the falls and the Upper Lakes, draining into Lake Kozjak. The largest lake, Kozjak receives on average, an additional 24% of water from the immediate catchment compared to flows from the Upper Lakes. Direct inflow quantities in the mean annual flow rate are 0.67 m^3/s, (maximum 3.4 m^3/s and minimum 0.2 m^3/s). These data show that the flows into the Upper Lakes through the large karst catchment in a mountain area are far greater than direct flows into Lake Kozjak with a far smaller basin and mainly surface runoff. The Plitvica watercourse flows into the Plitvice Lakes system via the highest waterfall in the National Park in the spring area of the Korana River. Water flow from the Plitvica stream reaches a maximum of 5.92 m^3/s, while in average flow conditions it is 0.58 m^3/s, and the measured minimum is only 0.03 m^3/s.

The measured data show that at high and medium water flow rates, water losses from the system are not obvious, but at low water even small losses from the system are evident. Thus, for example, in Lake Kozjak, which does not suffer major water loss, a deficit is incurred by the exploitation of water for the water supply (60 l/s), which is evident and measurable. However, the Plitvica watercourse has large problems with water, as during the summer dry period, almost nine tenths of the total amount of water is lost through sinks along the riverbed. This reduces the attractiveness of the largest waterfall in the park during the peak visiting period in the summer months. Increasing water losses occur along the river Korana, so that during summer dry periods, the river completely dries out from about 1 km downstream of the spring zone. At next 10 km from the spring zone, the river bed is completely without water for more than 4 months of the year. Analysis of many years worth of hydrological data shows that water loses from the Korana River are about 0.85 m^3/s on average, lower during high water (~ 0.6 m^3/s), due to saturation of the karst underground and higher in the summer dry periods (~ 1.15 m^3/s).

According BABINKA (2007) the total volume of the lakes is 22.95 x 10^6 m^3 and this was the basis for calculating the average water flow through the cascade system of the lakes over about 3 months. This calculation did not take into account the seasonal stratification of the lakes Kozjak and Prošćansko, which significantly extends the average length of water retention in the Plitvice Lake system.

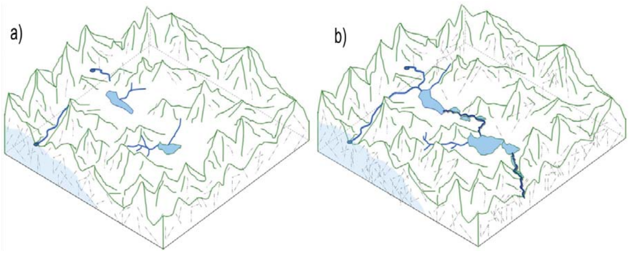

Figure 3: A conceptual model of the genesis of the Plitvice Lakes system. a) Phase of isolated lakes; b) Phase of connected lake system and canyon.

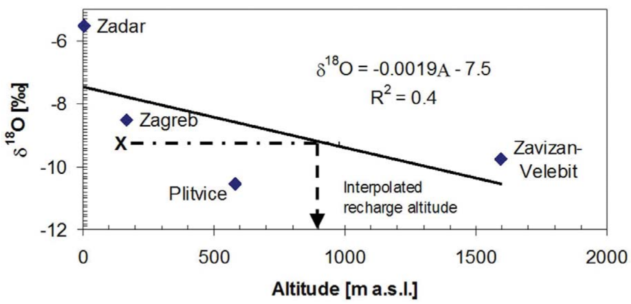

Figure 4: Altitude effect of $\delta^{18}O$ content in rainfall from the area of Plitvice Lakes.

As the Quaternary period included lengthy terrestrial periods in its two million year extent, it is rather significant for the interpretation of recent hydrogeological relationships. Upon completion of deposition of the Neogene sediments in the Pannonian basin (the margins of which almost extend to the Plitvice lakes), there was a period of intensive surface and groundwater erosion with the transport and selective deposition of sediments by surface streams. At the Neogene/Pleistocene boundary in the karst area of the Dinarides, there were many isolated lakes (now karst fields), and surface-water flows into the lakes from the immediate catchments (HERAK, 1962; BIONDIĆ & GOATTI, 1976; BIONDIĆ, 1982). This is analogous to the existence of the individual (unconnected) lakes Prošćansko and Kozjak in the Plitvice Lakes area (Fig. 3).

The terrestrial phase resulted in development of surface and underground karstification and expansion of surface catchment areas where possible according to the geological structure. The catchment of Lake Prošćansko (636 m) extended to Mala Kapela Mt., while Lake Kozjak (535 m) only experienced mild expansion of the surface watershed because of the prevailing largely impermeable dolomites. Consequences of this included increased flows of water to Lake Prošćansko, the carrying capacity of which was no longer able to maintain the water balance of such a large karst catchment, which caused erosional water penetration towards Lake Kozjak, 100 m below. In this manner, these two lakes, only 1700 m apart, were hydrologically connected. The increased amount of water in Lake Kozjak resulted in the opening of the sinks in the area downstream of the dolomite barrier, collapse of relatively thin arches of underground cavities and erosional opening of the Korana River canyon.

The Plitvica spring and watercourse had a development cycle similar to that of Lake Prošćansko, with a catchment extended to the carbonate area of Mala Kapela with a gradual increased quantity of water flowing to the canyon of the Korana River.

3. HYDROGEOCHEMICAL RESEARCH

Stable isotope analysis is an important research tool in the interpretation of the origin of groundwater and processes in the karst underground. This primarily refers to the calculation of the average altitude of the recharge area of the springs, the mean residence time in karst underground, the process of water exchange and the effects of evaporation on the lakes. In the process of research on the Plitvice Lakes area, 1082 samples of water collected over a two-year period were analysed. Correlation of $\delta^{18}O$ and $\delta^{2}H$ with elevation produces an inverse linear regression (BORTOLAMI et al., 1979; FONTES, 1980; ABBOTT et al., 2000; JAMES et al., 2000; YEHDEGO & REICHL, 2002), which enables the calculation of average altitude of recharge of aquifer. It is possible to specify the average altitude of a catchment with a graphical and mathematical regression equation (Fig. 4).

Mean residence time is usually provided by analysis of tritium ^{3}H, however, due to a short sampling period this is of questionable accuracy, and the stable isotope method using an exponential "flow model" was used (MALOSZEWSKI et al., 1983; STEWART & MCDONNELL, 1991). The results of calculations for the karst springs supplying the Plitvice Lakes system show values ranging between 2.1 and 2.9 years (Table 1).

Analyses of $\delta^{18}O$ stable isotopes were also undertaken for water samples from the lakes (Fig. 5). Higher contents of $\delta^{18}O$ were established in the surface parts of the lakes Kozjak and Prošćansko, while the deeper parts of the lakes had a stable content of $\delta^{18}O$, which is a result of high evaporation from the free surface of the lakes. In the cold part of the year, the isotopic content is equalized throughout the depth because of the substantially reduced evaporation and the effect of vertical mixing of water in the lakes.

The cascade system of Plitvice Lakes is reflected in the changes in $\delta^{18}O$ and $\delta^{2}H$ content and by the changes in evaporation effects (Fig. 6). The effects of evaporation increases downstream of the springs due to temperature changes associated with the effects of altitude.

Hydrochemical research has consisted of a total of 3022 measurements of physico-chemical parameters and 7885 analysis of karst spring, river and lake water samples, of which only a small part, in our opinion showing the char-

Table 1: Calculated residence time data from deuterium analyses.

	Max. $\delta^{2}H$ amplitude (‰) in spring and stream water	T (year) using max. $\delta^{2}H$ amplitude in precipitation	Storage volume (*10^6 m^3)
White River spring	–3.65	2.1	18
Black River spring	–2.60	2.9	70
Plitvica River spring	–2.80	2.7	28

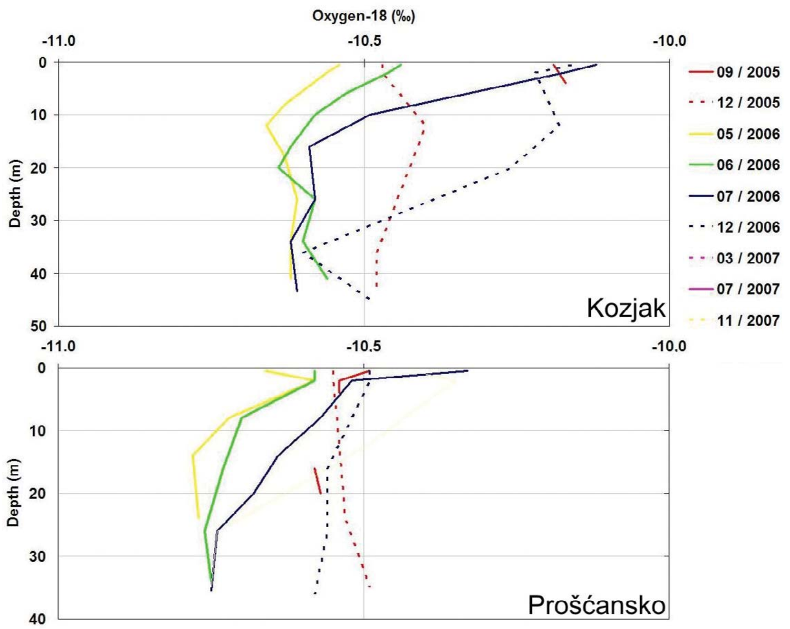

Figure 5: Changes of stable δ18O isotope with depth in both lakes.

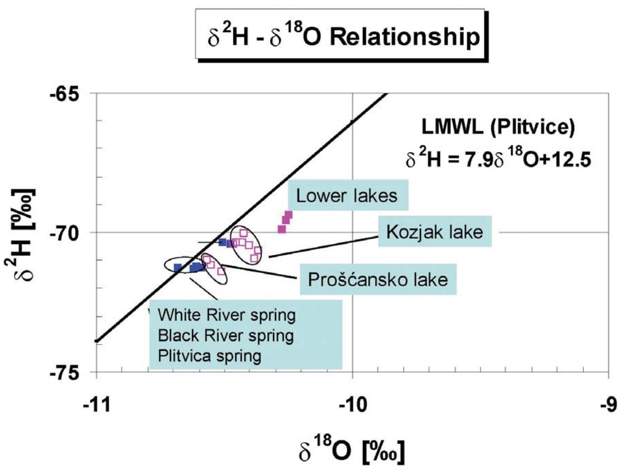

Figure 6: The δ^2H - $\delta^{18}O$ relationship – evaporated lake basins and river outflow.

acteristics of the water system of Plitvice Lakes, is presented here. It is important to show the changes in pH, specific electrical conductivity and Ca^{2+}, in order to understand how the whole system functions. However, the situation with the lakes is far more complex due to the internal dynamics related to seasonal climatic changes and the functions of the lakes in preserving the water quality of the system.

The pH values vary between 7–8 along the water system in the carbonate terrain (FREEZE & CHERRY, 1979). Rivers and lakes generally have higher values due to the reduction of carbon dioxide dissolved in the water. In the case of the Plitvice Lakes, spring waters are in the range of 7.2 and 7.6, and lakes between 8.0 and 8.4. Specific electrolytic conductivity gradually decreases from the springs downstream by about 500 μS/cm, which indicates a loss of calcium carbonate by precipitation of tufa. This is particularly evident from the analyses of Ca^{2+} (Fig. 7), the values varying from 60-70 mg/l at the springs to 40-50 mg/l at the exit from the Plitvice Lakes system. The permanent process of tufa precipitation is an indicator of high water quality and important for the stability of tufa barriers and waterfalls.

A large part of the hydrochemical research was focused on the two biggest lakes – Prošćansko Lake (636 m asl, area 0.68 km^2, depth 37 m) and Kozjak Lake (535 m asl, area 0.83

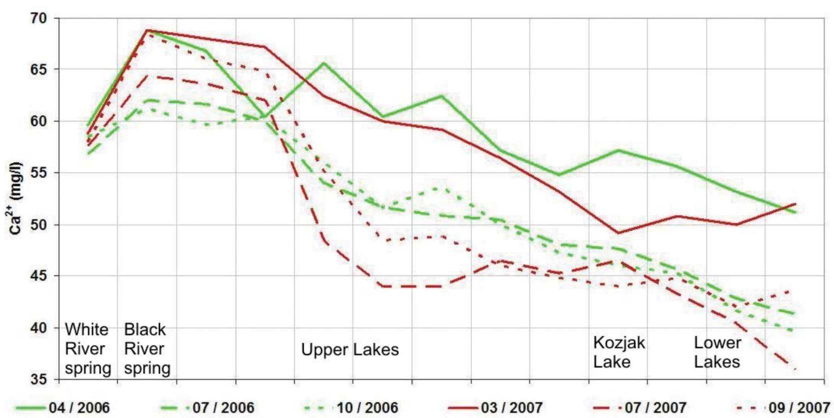

Figure 7: Seasonal change of Ca^{2+} in the various water features adjacent to the Plitvice Lakes for the period 2005–2007.

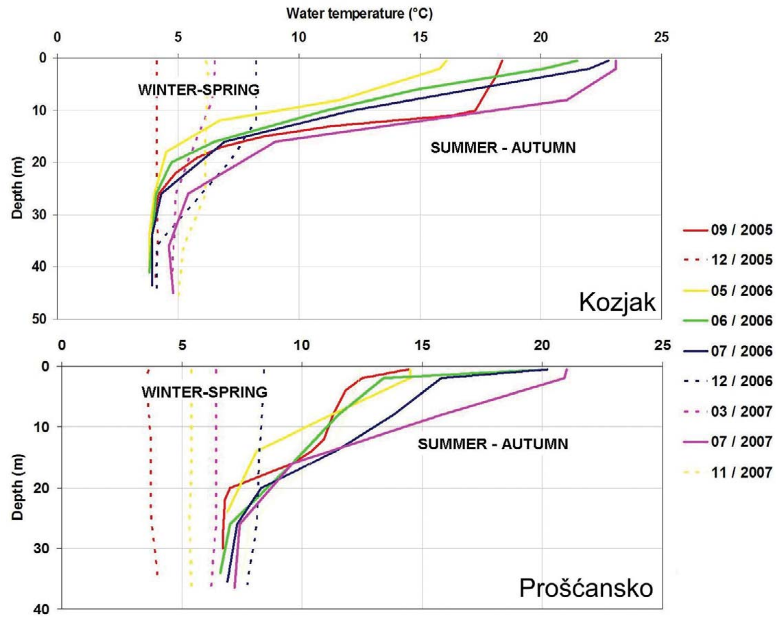

Figure 8: Seasonal temperature stratification of water in the Prošćansko and Kozjak lakes.

km^2, depth 48.5 m). Three locations per lake were determined where typical hydrochemical parameters were measured at different depth - temperature (T), specific electrical conductivity (SEC), dissolved oxygen (O), pH, and Eh, and samples were taken for laboratory analysis of the water for Ca^{2+}, Mg^{2+}, HCO_3^-, SI_{cal}, SI_{dol}, P_{CO2} , and $\delta^{18}O$. Water temperature in the lakes is a very important parameter in determining the internal dynamics of the lakes.

Figure 8 indicates seasonal temperature stratification of both lakes with differentiation of epilimnium zones (0–10 m), thermocline zones (10–20 m) and hypolimnium zones (deeper than 20 m). In Lake Kozjak during December vertical water exchange begins with isotherm process, which lasts until the end of the February. Then, a new cycle of lake stratification begins. The same effect is present in the hypsometric higher Lake Prošćansko, but due to climatic conditions, it begins a month earlier and lasts almost a month longer in the spring.

Hydrochemical investigations of the lakes were conducted several times, but were mostly related to the lake surface (PETRIK, 1958; STILINOVIĆ et al., 2004) and to the sanitary condition of surface parts of the lakes. Significant improvements over previous studies were observed because of renovations to the waste water system in the most loaded part of the park. Research in this project was focused on identification of hydrogeological conceptual model of the Kozjak and Prošćansko lakes. From the previous researches which pointed out the problem of eutrophication of the lakes, with this research thinking about the lakes role in the natural model is completely changed.

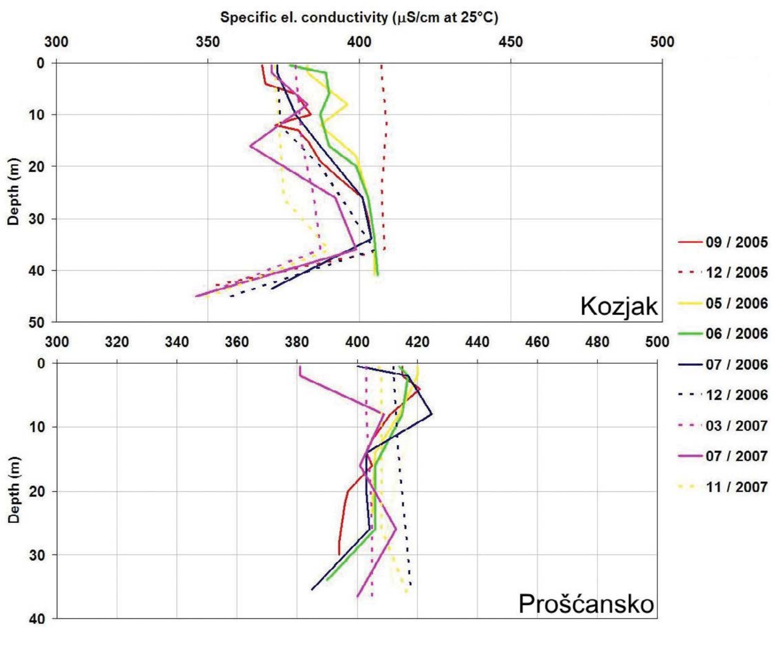

Figure 9: Specific electric conductivity in the Prošćansko and Kozjak lakes.

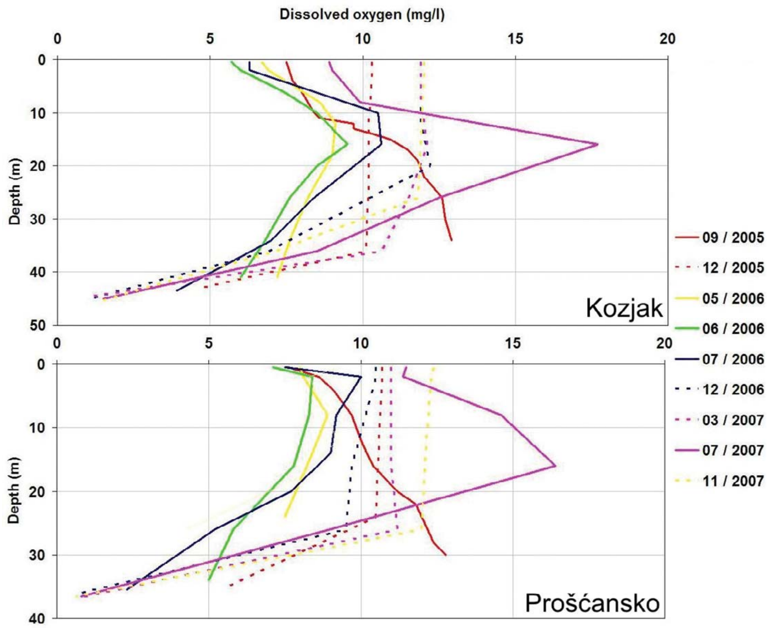

Figure 10: Distribution of dissolved oxygen content in the Prošćansko and Kozjak lakes.

In order to illustrate the positive changes in thinking about the function of the large lakes, the results of depth measurements of specific electrical conductivity (SEC), the content of dissolved oxygen, pH, redox potential (Eh) and the content of carbonate species are presented. SEC has generally shown a slightly higher value in Lake Prošćansko in relation to Lake Kozjak due to precipitation of calcium carbonates on tufa barriers between the two biggest lakes (Fig. 9). In the depth profiles of the lakes, SEC rises slightly from the surface to depths of about 20 m (thermocline zone), while there is a slight downward trend in the hypolimnium.

The dissolved oxygen content (Fig. 10) is a particularly important parameter for the assessment of water quality, and a good indicator of the degree of eutrophication of the lake. Seasonal changes in dissolved oxygen are evident in the depths of both lakes. During the thermal stratification phase, high dissolved oxygen levels are linked to the epilimnium and thermocline zones, and a continuous decrease is observed in the hypolimnium. This indicates on the activation of the process of eutrophication. During the winter, vertical mixing results in the gradual disappearance of the differentiated zones of stratification, and oxygen enriched water from the shallow parts of lakes migrates to the depths thus enriching the entire mass of the lake water with oxygen, thereby interrupting the processes of eutrophication in the bottom parts. Then a new cycle of stratification begins and the gradual process of eutrophication of the bottom part of the lakes is resumed in spring.

Acidity (pH) is an important parameter in the assessment of water quality and the hydrochemical development of the

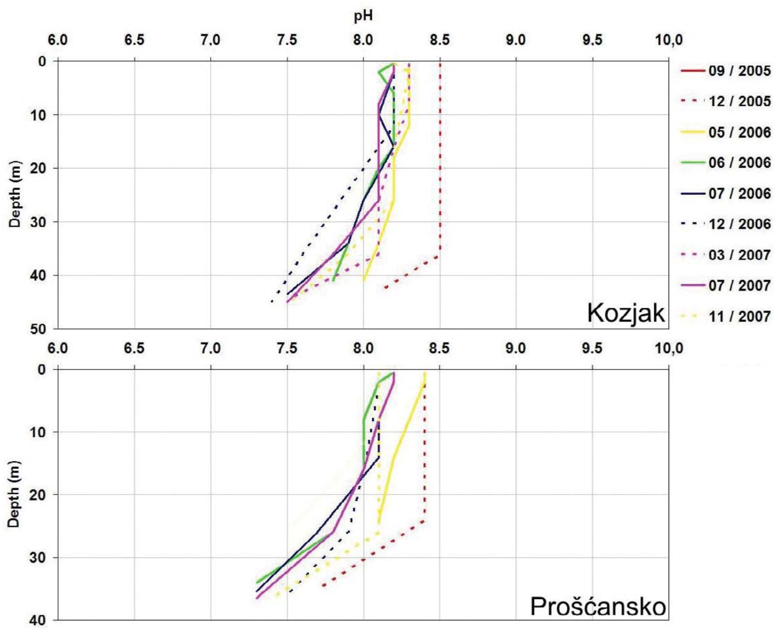

Figure 11: pH value with depth in the Prošćansko and Kozjak lakes.

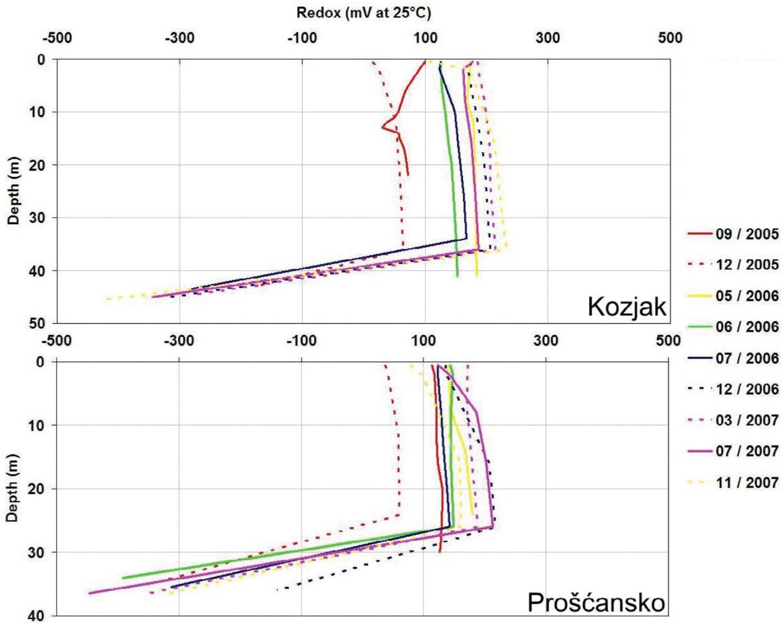

Figure 12: Distribution of redox potential with depth in the Kozjak and Prošćansko lakes.

whole environment. The consequence of dissolution of limestone and dolomite are relatively high pH values of water in the range of 8.0–8.5. During the thermal stratification of the lakes, pH values are stable in the epilimnium and thermocline zones, while slightly decreased values are observed at depth in the hypolimnium. This can be associated with the increase of dissolved CO_2 produced by the decay of organic matter. In the isothermic phase, pH values are equalised throughout the depth of the lake (Fig. 11).

The redox potential (Eh) characterises the oxidation-reduction state of natural waters. Values are influenced by the dissolved oxygen content. Redox potential in the lakes is stable in the epilimnium, thermocline and in most parts of hypolimnium zones, and this is an indicator of the expressed oxidation conditions. In the bottom parts of the lakes near the contact with the lake sediments (mud), Eh values fall drastically into negative values, which is an indication of reducing conditions (Fig. 12).

The content of the carbonate species (Ca, Mg, HCO_3) in the lakes varies from time to time. During vertical mixing of the water masses, concentrations of Ca and Mg are generally uniform throughout the depth of the lake. During periods of temperature stratification, a decrease of Mg and increase of Ca concentrations are observed with depth. Lake water is generally oversaturated with calcite and dolomite throughout the monitored period.

Hydrogeochemical research clearly shows the dynamic model of the lake water mass with the pronounced effect of thermal stratification and vertical mixing of water masses during the isothermal period. The importance of vertical mixing of water masses is evident in the enrichment of the bottom part of the lake with oxygen. Without such water mixing, the lakes would gradually become fully reducing.

4. WATER RETENTION IN KOZJAK LAKE

Lake Kozjak has a vital role for tourists visiting and being accommodated in the Plitvice Lakes National Park. Up to 100 l/s of water are exploited from the lake for the supply of the National Park and numerous villages on its north side. It is important to emphasize that Lake Kozjak is located on the north-eastern edge of the so-called Plitvice barrier (dolomite), in the zone of strong longitudinal regional faulting. The lake includes some very permeable carbonate rocks with the potential for water loss from the lake system. While this is a large area for tourism, it is also one with previously poorly understood hydrogeological relationships between the lake and very permeable underground karst areas to the north – east that are potentially very vulnerable. Therefore, part of the research project was directed towards identification of these relationships between Lake Kozjak and groundwater on the northeastern side of the lake. Two exploration-piezometric boreholes were drilled in this area, located on the base of the detailed hydrogeological map at 1:5.000 scale, and geophysical surveys (shallow seismic reflection, tomography, electromagnetic sounding and electromagnetic profiling) (Fig. 13).

Piezometric boreholes were drilled to depths greater than the deepest part of Lake Kozjak. The first (PJ–1), is upstream, near the hotel, and the other, (PJ–3) is located at the downstream end of the lake towards the Lower Lakes. In the upstream borehole, no active groundwater was found to a depth greater than 40 m below the lake, regardless of the hydrologic conditions, suggesting the “hanging” nature of Lake Kozjak in relation to the environment. It is possible to expect the existence of a negative gradient of the lakes in relation to groundwater, but such a large gradient means there is a latent risk of loss of water from the largest lake system. The surprise was the appearance of caverns filled with tufa at depths below Lake Kozjak, suggesting the existence of fossil sinks during the development of the youngest Quaternary period. Sinks are filled with tufa, which has enabled a significant increase in the water retention capability of the north-eastern flank of Lake Kozjak and practically makes active water losses from the lake impossible. However, fossil sinks filled with relatively porous tufa certainly increase the high risk status of the northeast side of Lake Kozjak. A

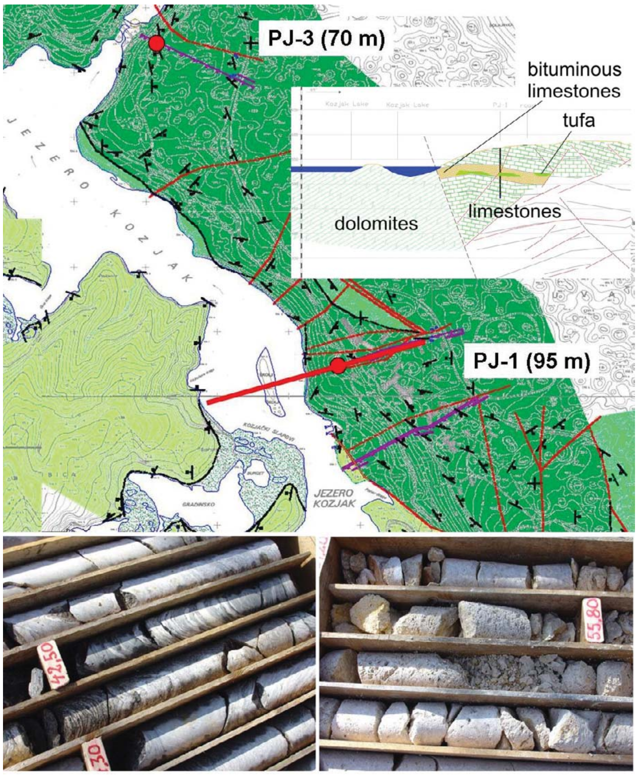

Figure 13: Locations of piezometric boreholes PJ-1 and PJ-3, hydrogeological cross-section and core of cavern with tufa from borehole PJ-1.

similar situation occurs with the downstream borehole, where groundwater has been registered, but with a pronounced negative gradient with respect to Kozjak Lake and the Lower Lakes.

Detailed hydrogeological research has highlighted the previously unknown high risk to the survival of Lake Kozjak. In addition, it has highlighted the importance of tufa and active processes of tufa precipitation in maintaining the northeast margin of the lake, and the openness of the karst underground on the northeast side of the lake with the wider environment. The direction of groundwater runoff from the area of the Plitvice Lakes was determined by groundwater tracing tests. In a natural cave, 30 kg of uranine dye tracer was injected with about 60 m^3 of water. After 19 days, the tracer registered in the samples and visually occurred in the Klokot spring near Bihać in neighbouring Bosnia and Herzegovina, 17.6 kilometres from the place of injection (Fig. 14).

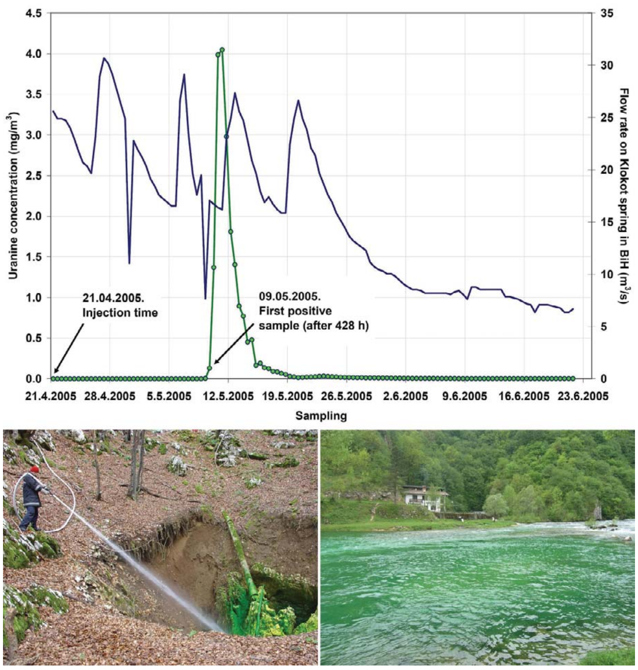

Figure 14: Results of the tracing test of the doline in Rastovača in the Plitvice Lakes National Park.

5. WATER LOSES RESEARCH ALONG THE PLITVICA STREAM

The Plitvica stream is a very significant part of the water resources of the Plitvice Lakes National Park, as it supplies the Big waterfall with water. The Big waterfall is a visually very attractive part of the park, which, together with the waters of the lakes forms the spring zone of the Korana River. In the last ten years, the amount of water flowing over the Big waterfall in periods of drought has been severely reduced and this is a big problem for the park, because one of the most beautiful waterfalls of the park practically disappears (Fig. 15).

The Plitvica spring is the third largest karst spring in the Plitvice Lakes system. Water from karst underground springs on contact with very permeable carbonate rocks of the Mala Kapela mountain area and the dolomite barriers of the Plitvice Lakes. The maximum amounts of discharge are about 6 m^3/s and in such conditions the water losses along the river bed upstream of the Big waterfall are practically invisible. However, during the summer dry periods, the flow just before the Big waterfall is reduced to the minimum of 30 l/s, which is disastrous for the Big waterfall, meaning that it is practically dry. Flow measurements were made at three places along the Plitvica stream, mainly during the dry periods, when the effects of sinking are visible (Fig. 16). Thus, for example, in an extremely dry period in the month of October 2006 265 l/s of water (100%) flowed from the spring zone. On the measuring profile downstream in the central part of the watercourse, there was 140 l/s (53%), and before the Big waterfall only 74 l/s (38%) was measured.

Figure 15: The Big waterfall during dry and rainy periods.

Figure 16: Meadows adjacent to the Plitvica watercourse where water sinks.

There is several cause of this water loss along the Plitvica stream. Firstly, the stream crosses dolomite barriers in the area composed of very permeable limestone. However, the situation is further complicated by the distribution of the natural tufa sediments, which generally have a positive hydrogeological function of helping to retain water along the bed of the watercourses. Tufa deposition in the bed of watercourse is so intense that the bed is constantly raised with new layers and water outflows from the raised bed to the adjacent meadows without tufa, but with numerous dolines, where water sinks in the calcareous subsoil.

The question can be asked as to why water losses were lower in the past. Reasons include the activities of the local inhabitants, who are now more concerned with tourism and do not care too much for cleaning and cutting troughs in the tufa and releasing the meadows from water. Solutions are to strive to maintain the system at the level of previous use, even without the need to use the meadows. Water that is lost in the underground karst system most likely disappears from the Plitvice Lakes system into the adjacent Una River catchment area or springs downstream in the Korana River.

6. DISCUSSION

The Plitvice Lakes National Park is located in the central part of the Dinarides, an area characteristic of the development of specific surface and underground morphological forms resulting from dissolution by water. Large karst springs, lakes and waterfalls are the fundamental phenomena of the National Park attracting almost a million visitors a year. The catchment of karst springs, which supplies the Plitvice Lakes with water, is composed of carbonate rock of the Mesozoic age. It extends to the northern slopes of the mountain areas of Mala Kapela and is about 150 km^2 in size. Groundwater flow from the catchment is of relatively large apparent speeds towards the springs (POLŠAK, 1974), indicating relatively short periods of water retention in the karst underground, and at the same time suggests a high degree of natural vulnerability for most of the catchment. The consequences are the large variation in discharge in the karst springs, which range from 0.6 m^3/s in dry periods and 11.6 m^3/s in rainy periods. From the total amount of discharge from the spring zone, the Black River spring produces about 75% of the water, with the remaining 25% from the White River spring. Poorly permeable dolomites of the Upper Triassic age form barriers to the discharge. Streams of both springs are combined in a common watercourse and flow into the uppermost Lake Prošćansko. The Plitvica spring varies between 0.3 and 5.92 m^3/s. Water from the Lake Prošćansko flows throughout the numerous lakes and waterfalls created by deposition of tufa to the largest Lake Kozjak. Hydrological measurements show that there are no water losses up to and including Lake Kozjak in the Plitvice Lakes system due to dolomite barriers. Because of the regional fault along the north-eastern side of Lake Kozjak, a part of the lake is located in the permeable part of the geological structure. Thick deposits of tufa and probably lake sediments from the early stages of development of the lake have a positive hydrological function. Downstream from the last lake, the Plitvice Lakes water system is connected by the Big waterfall of the Plitvica stream and the beginning of the Korana River. Along the Plitvica stream, significant losses of water occur in the karst underground with an unknown direction of underground flow, significantly reducing the flow of water over the Big waterfall during summer dry periods. Possible losses of the water prior to the spring zone of the Korana river are minimal due to tufa sediments, which fill the old cracks and sinkholes, but the downstream losses increases and after only 1 km the Korana River is dry during the summer periods. The Korana River remains dry until the flow reaches 1.1 m^3/s and with the increase of flow the river flows over its entire length. Water sinking from the Korana River drains into the catchment of the river Una, towards the main water-supply spring of Bihać (Klokot) located in the neighbouring state (BIONDIĆ et al., 2008). This is the general principle of how the Plitvice Lakes function, but the system is far more complex because of the existence of large lakes, which function independently.

The Prošćansko and Kozjak lakes have a very important position for the functioning of the Plitvice Lakes system. Detailed hydrogeochemical research has discovered that both lakes have very similar internal dynamics, which is very important in preventing eutrophication of the whole Plitvice Lakes system. Annual stratification of the water mass was determined in both lakes together with vertical mixing during the isotherm phase of the lakes. It is important to note that in both lakes during stratification, reducing conditions occur in the bottom waters with greatly reduced amounts of dissolved oxygen due to decay of organic matter. With vertical mixing, in the lakes, water enriched with oxygen migrates from the surface zone towards the bottom and thus oxygen enriches the deepest parts of the lakes and prevents the further spread of eutrophication processes. All the analyses of stable isotopes and hydrochemical parameters in this research project confirm such a state. The height of zones of reducing conditions in the lakes could be an indicator of the sustainability of water quality during the stratification of the lake water mass. The trend of increasing height of that reduction zone can certainly be an indicator of the progress of the process of lake eutrophication, and a warning for the introduction of additional measures to protect the whole system.

The detail research opened the serious problem in the central visiting area of the National park on the north-eastern part of Lake Kozjak. In that area the problem could be opening of the fossil sinks filled with tufa sediments. It is a high risk part of the National Park, where future development should given special attention. Most tourist attractions are located in the area at risk, where each uncontrolled construction activity may cause changes in natural systems.

A significant problem is the water loss along the river bed of the Plitvice stream, where the amount of water in one of the main attractions; the Big waterfall, is severely reduced in the summer. Reduction of losses should be carried out very carefully within the limits of previous activities of the local population.

7. CONCLUSION

Water resources are the fundamental natural phenomenon of the Plitvice Lakes National Park, and their quality and quantity directly affect the exceptional biodiversity of the entire region. Due to the natural dynamics of the lakes, despite the burdens of natural systems with a large number of visitors, hotels and transportation, the exceptional quality of lake water has been preserved.

The research identified completely new data on the genesis of the water system of Plitvice Lakes, hydrogeological characteristics of karst springs and their catchment areas, dynamics of the lake water, and also a whole range of data relating to the preservation and protection of groundwater and surface water in the catchment area. Research has also indicated the most sensitive areas of the water system of Plitvice Lakes to which special attention should be paid.

ACKNOWLEDGMENT

The project "Sustainable utilization of water in the pilot area Plitvice Lakes" was undertaken within the Kompetenznetwerk Wasserressourcen Gmbh, co-financed by the Plitvice Lakes National Park and the Austrian government. The authors wish to thank all associates from Joanneum Research (Graz, Austria) and the Research centre "Ivo Pevalek" from Plitvice Lakes who made significant contributions and enabled the successful execution and completion of the project.

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Manuscript received February 01, 2010
Revised manuscript accepted May 04, 2010
Available online June 28, 2010