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Hydrogeological study on the sustainable use of the water resources in the Plitvice Lakes National Park, Croatia

Hydrogeologische Studie über die nachhaltige Nutzung der Wässer im Nationalpark Plitvicer Seen, Kroatien

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Zusammenfassung

Die Plitvicer Seen gehören zu den bekanntesten und schönsten Naturphänomenen in Kroatien. Dank ihrer einmaligen Entstehung und landschaftlichen Schönheit wurden die Plitvicer Seen 1949 zum Nationalpark erklärt und 1979 ins Weltnaturerbe der UNESCO aufgenommen. Die Karstquellen und die zahlreich auf unterschiedlichen Höhenstufen liegenden, durch Tuffbarrieren getrennten und durch Wasserfälle miteinander verbundenen, in Kaskaden angelegten Seen sind Hauptattraktion für etwa eine Million Touristen pro Jahr. In diesem Zusammenhang sind die ökologischen Folgen des intensiven Tourismus kritisch zu betrachten. Daher soll die Kompatibilität des intensiven Tourismus mit dem Schutzbedarf des ökologisch sensiblen Nationalparks und dessen Auswirkung auf die Wasserqualität der Wasserressourcen im verkarstetem Einzugsgebiet und den Seen sowie im Unterstrombereich genauer untersucht werden.

Dahingehend wurde zwischen 2005 und 2008 eine detaillierte hydrogeologische Studie im Rahmen des Kompetenznetzwerkes "Wasserressourcen und deren Bewirtschaftung" (Knet Wasser GmbH) mit den Kooperationspartnern Nationalpark Plitvicer Seen, Universität Zagreb und RESOURCES – Institut für Wasser, Energie und Nachhaltigkeit (vormals Institut für WasserRessourcenManagement) der JOANNEUM RESEARCH durchgeführt. Die Hauptkarstquellen im Einzugsgebiet der Seen und die Oberflächenzuflüsse und -abflüsse der Plitvicer Seen sowie die Seen selbst wurden ab August 2005 bis Januar 2006 monatlich und bis Ende 2007 zweimonatlich beobachtet. Dabei wurden Geländeparameter (Wassertemperatur, elektrische Leitfähigkeit, pH-Wert, gelöster Sauerstoff, Redoxpotential) vor Ort gemessen und gleichzeitig Wasserproben zur Bestimmung der Konzentration der Hauptionen und der stabilen Isotope Deuterium und Sauerstoff-18 im Labor gezogen.

Diese Untersuchungen wurden auch in den tiefsten Bereichen der beiden großen Seen (Prošćansko-See und Kozjak-See) an Tiefenprofilen vorgenommen. Zur Klärung der Wechselbeziehung zwischen den in Kaskaden angelegten Seen und den umliegenden verkarsteten Karbonaten wurden im Unterstrombereich der Seen zusätzliche hydrogeologische Geländearbeiten, geophysikalische Messungen und zwei Tracerversuche (mit dem Farbstoff Uranin) durchgeführt sowie zwei Explorationsbohrungen abgeteuft.

Die im Rahmen der gegenständlichen Studie gewonnenen hydrogeologischen, hydrochemischen und isotopenhydrologischen Daten wurden samt der seit den 90er Jahren kontinuierlich registrierten hydrologischen Abflussmessdaten ausgewertet. Durch die kombinierte Interpretation der Daten konnten die Entwässerungsmechanismen, die Seendynamik und die Wechselwirkung zwischen den in

Kaskaden angelegten Seen mit dem dynamischen Karstsystem näher charakterisiert und genauer dargestellt werden.

Mit Hilfe des Höheneffekts des Sauerstoff-18-Isotops (–0.19 ‰/100 m) im Niederschlag in mittleren Lagen und Küstengebieten von Kroatien wurde die mittlere Seehöhe der Einzugsgebiete der großen Karstquellen und daraus entstehenden Abflüsse ermittelt, welche bei etwa 1000 m Höhe liegt. Die hydrochemische Beschaffenheit der Karstquellen, Oberflächenabflüsse und Seen ist durch die Karbonatlösung im Einzugsgebiet und die Entgasung vom Boden-CO_2 nach dem Austritt der Karstquellen, begleitet von der Ausfällung von Kalzit als Kalktuff in den Flussbetten und kaskadenartigen Seen, charakterisiert. Die hydrochemische Zusammensetzung der Wässer ist von den Ionen Ca^{2+}, Mg^{2+} und HCO_3^- dominiert. Die Qualität der Wässer ist generell als sehr gut zu bewerten und aus den hydrochemischen Analysen konnte, zumindest für die Beobachtungsperiode, kein wesentlicher anthropogener Einfluss auf die Wasserqualität der Wässer im Nationalpark Plitvicer Seen nachgewiesen werden.

Die Wasserbilanz der kaskadenartigen Plitvicer Seen ist vorwiegend durch Oberflächenzufluss und Oberflächenabfluss bestimmt. Mit der mittleren Durchflussmenge von etwa 2,81 m^3/s und Verweildauern von etwa drei Monaten erfolgt der Wasseraustausch im gesamten kaskadenartigen Seesystem sehr schnell. Die Seendynamik ist einer starken jahreszeitlichen Veränderung unterworfen. Aus den Temperaturprofil- und gelösten Sauerstoffgehaltsmessungen konnte eine stabile Sommerschichtung im tieferen Bereich des Prošćansko- und Kozjak-Sees festgestellt werden.

Im Seebereich ist der unterirdische Austausch zwischen den Plitvicer Seen und umliegenden verkarsteten mesozoischen Karbonaten nicht gegeben oder vernachlässigbar gering. Erst im Unterstrombereich der Plitvicer Seen erfolgt im Flussbett der Korana eine beträchtliche Infiltration vom Seewasserabfluss in die umliegenden, sehr stark verkarsteten Karbonate. Mit Hilfe von zwei Tracerversuchen wurde nachgewiesen, dass die subterrane Entwässerung der kretazischen Karbonate im Unterstrombereich der Plitvicer Seen vorwiegend in Richtung SE erfolgt. Das im Flussbett der Korana und in vom Flusslauf entfernten Karsterscheinungen versickerte Wasser tritt in der großen Karstquelle Klokot in der Nähe der Stadt Bihać in Bosnien und Herzegowina im Einzugsgebiet der Una (Fluss) aus.

Keywords: Plitvice Lakes National Park, hydrochemistry, environmental isotopes, lake dynamics, sustainable use

Schlüsselwörter: Nationalpark Plitvicer Seen, Hydrochemie, Umweltisotope, Seendynamik, nachhaltige Nutzung

Introduction

The Plitvice Lakes National Park, hereafter named PLNP, is located in the north-eastern Dinaric karst region of the central part of Croatia, close to the border with Bosnia and Herzegovina. With the peculiar karst landforms, series of lakes arranged in a cascade with remarkable waterfalls, huge freshwater reserves and rich biosphere, the PLNP has been proclaimed as national park in 1949 and placed on the UNESCO list of the world heritage of nature in 1979. With its unique natural ambiance the PLNP is an important attraction and a favourite destination for an ever-increasing number of tourists. Nowadays up to one million tourists visit the area each year. The increase of the number of visitors is welcome in terms of income generation for the region. However, the ecological implication of the ongoing intensive tourism needs to be critically viewed and its compatibility with the park's protection requirements examined, and the impacts on the water resources in wider karst environment downstream of the cascade lakes assessed.

In the past decades several hydrogeological and limnological studies have been carried out in the PLNP area, focusing on investigating the hydrogeological setting, water quality of the water resources and limnology of the lake system. As indicated in the geological map sheets Bihać (POLŠAK et al., 1967, 1976) and Otočac (VELIĆ et al., 1974), the area is underlain by dolomites and limestones of Mesozoic age. Karstification of these calcareous rocks determines the surface and underground drainage, thereby the tectonic lineaments traversing the region play an important hydrological role. PETRIK (1958) investigated systematically the hydrology of the area and HERAK (1962) analysed the tectonic setting of the PLNP area. The results of these studies provided an overview hydrogeological framework of the area. Employing a dye tracing experiment, POLŠAK (1974) characterised the groundwater flow condition and figured out the subsurface drainage pattern in the karstified dolomites and limestones of the Plitvice Lakes catchment area. Further hydrological and hydrochemical studies by DESKOVIĆ et al. (1981, 1984) allowed determining the groundwater flow paths in the catchment area, establishing the connection to the lakes and delineating the hydrologic boundaries of the PLNP. In particular, the potential catchment area of the springs Crna and Plitvica was determined. As part of his doctoral dissertation, B. BIONDIĆ (1982) distinguished the hydrogeological catchments of the wider mountainous Lika region in central Croatia, which also partly included the adjoining area of the Plitvice Lakes. By examining the surface drainages and discharges of the major streams flowing into the lake system, RIĐANOVIĆ & BOŽIČEVIĆ (1996) revealed that the setting of the underlying carbonate rocks plays a critical role in the overall hydrogeological setting and the tufa build-up process in the area.

Limnological studies of the Plitvice Lakes go back to the 1940s. The tufa barrier forming process in the Plitvice Lakes was first examined by PEVALEK (1935) and he attributed it to incrustation of bryozoans' genus *Bryum* and *Cratoneuron*. To characterise the calcite deposition processes in the cascade lake system, SRDOČ et al. (1985) determined the ages and growth rates of tufa in the recent time and geological past. Recently, based on ages of tufa sediments from the major lakes, OBELIĆ et al. (2005) and HORVATINČIĆ et al. (2006) revealed a continuous tufa building process in the last 7,000 years in the streams and the lakes. Giving a special emphasis on the bacteriological state of the most nutrient-loaded part of the PLNP, STILINOVIĆ (1979) and STILINOVIĆ & FUTAČ (1985) examined the ecological state of Plitvice Lakes. Based on the assessment of physicochemical and biochemical parameters of Plitvice Lakes monitored in 2006, PAVLUS et al. (2007) classified the water quality of the lakes to be mostly very good; only few water samples from some parts of the PLNP exhibited noticeable anthropogenic influences during summer.

In an effort to understand and solve environmental problems caused by the ongoing intensive tourism in the PLNP, it is crucial to identify the specific activities in the protected area that may have negative effect on the sensitive karst and lake ecosystems. Influx of visitors and the facilities serving them are mainly concentrated in the area adjoining the cascade lake system. Water for drinking and domestic uses is directly abstracted from Lake Kozjak and distributed without any treatment to the hotels, restaurants and other facilities that provide accommodation and catering for visitors and to the adjacent settlements. Wastewater from the PLNP premises is collected with a sewer system and disposed without any treatment directly into a sinkhole downstream of the lakes within the national park area.

To adequately assess the environmental impacts of these activities on the ecologically sensitive PLNP, in particular on the quality of the water resources, it is vital to understand in detail the hydrologic flow condition in the karstified area, the dynamic behaviour of water in the cascade lake basins and the exchange of the Plitvice Lakes with the adjacent karstified area. To this end, comprehensive hydrogeological investigation was carried out between 2005 and 2008. Basic data of the study has been presented in B. Biondić et al. (2008), and additional interpretation of the conceptual hydrogeological model of the Plitvice Lakes was provided in B. Biondić et al. (2010). Data from the mentioned study was also partially used and interpreted by one of the authors, Meaški, for his PhD thesis completed at the University of Zagreb in 2011. The present work is again an outgrowth of the aforementioned hydrogeological investigation and refers to the extensive project data-base. It is specifically aimed at determining the infiltration zones of major karst springs and ensuing streams in the PLNP, examining the exchange of the karst springs, streams and lakes, characterising the dynamic behaviour of the lakes and evaluating the overall hydrologic position of the Plitvice Lakes system and its catchment in the karstified Mesozoic dolomites and limestones. This is achieved by interpreting in a combined way the hydrogeological, hydrological, dye experiment, hydrochemical and stable isotope (δ^2H and δ^{18}O) data collected during the investigation.

Description of the study area

Location

The study area is located in the Dinaric karst region of Central Croatia, extending between the geographic coordinates 44°44’34” and 44°57’48” N and 15°27’32” and 15°42’23” E (Fig. 1). It covers the eastern flank of the Plješivica mountain range that stretches in a north-south direction from Mount Mala Kapela (northwest corner of Fig. 1) further to the south. This region represents the headwater of the Korana river that flows into the Danube. The Plitvice Lakes consist of a chain of 16 lake basins interconnected by a cascade of tufa barriers, arranged in almost a south-north direction over a distance of about 8.2 km between the altitudes of approx. 640 m a.s.l. and 490 m a.s.l. (Δ about 150 m). Figure 2 illustrates the schematic longitudinal section of the cascade lakes.

Locally, the lake basins are divided into two groups:

(1) the Upper Lakes, including the lakes Prošćansko and Kozjak and ten smaller lakes located between them (Ciginovac, Okrugljak, Batinovac, Veliko, Malo, Vir, Galovac, Milinovo, Gradinsko, Buk), and

(2) the Lower Lakes, consisting of four small lakes (Milanovac, Gavanovac, Kaluđerovac and Novakovića brod) located downstream of Lake Kozjak.

The total surface area of the Plitvice Lakes is approx. 2 km^2. The lakes Prošćansko and Kozjak, with a surface area of 0.68 km^2 and 0.82 km^2, respectively, form the largest lake basins. Both lakes comprise about 75 % of the total lake surface area. As indicated in Fig. 2, their max. depth is 37 m and 48.5 m, respectively.

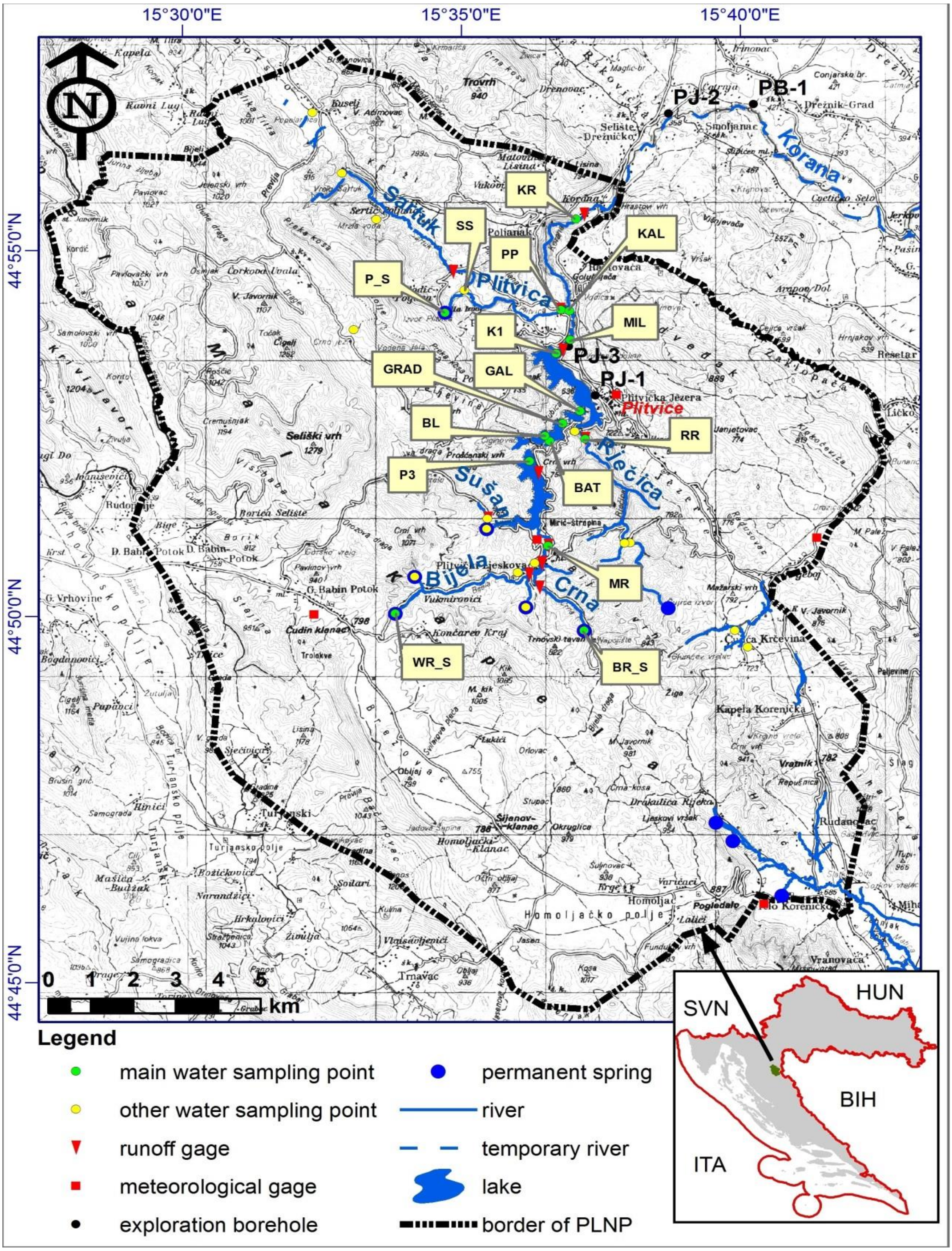

Figure 1: The study area Plitvice Lakes National Park (PLNP) with locations of exploration boreholes (PJ-1 and PJ-3) and observation points (runoff and meteorological gauges, and water sampling points for hydrochemical analysis and environmental isotope determination). Base map source: Topografska karta M 1 : 100.000, List 420, Bihać, 1979–1981. Designations/abbreviations of sampling points are given in tab. 1.

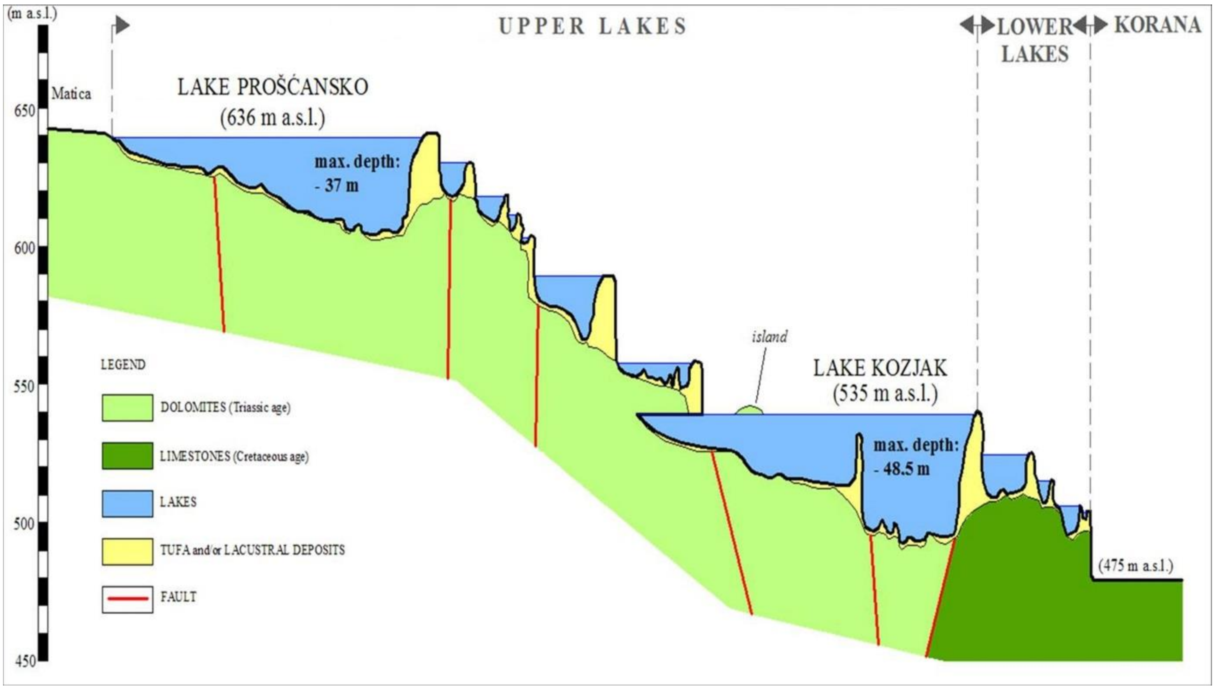

Figure 2: Schematic longitudinal section of the cascade system of Plitvice Lakes (adapted after Petrik, 1958).

Climate

Situated in the central part of Croatia, the study area exhibits a typical mountainous continental climate with Mediterranean influence. It is characterised by a comparatively high amount of precipitation (P) with autumn maxima and summer minima, and low average annual temperature with distinct seasonality (winter minimum and summer maximum). Meteorological data recorded at Plitvice station for the period 1997–2005 revealed an annual precipitation range between 1,148 and 2,113 mm (annual mean of 1,592 mm) and annual air temperatures between 8.9 and 10.4 °C (annual mean 9.4 °C).

Using the meteorological data from the same station as input parameters, evapotranspiration parameters have also been determined from the TURC equation (Turc, 1954, 1955) and the HAUDE equation (Haude, 1955). The mean annual actual evapotranspiration (ET) calculated from the TURC equation was approximated at 538 mm and the resulting climatic water balance (P – ET) about 998 mm. The annual potential evapotranspiration (ET_P), estimated from the HAUDE equation employing monthly factors obtained by Ellinger et al. (1990), considering the different land-use covers in the study area, ranged between 480 and 542 mm, and the resulting climatic water balance ($P – ET_P$) showed a variation range from 946 to 1,008 mm.

The steep limestone terrain bounding the Plitvice Lakes is covered by dense forests of mainly deciduous and coniferous trees, where pure stands of beech dominate at lower altitudes and mixed stands of beech and fir trees at higher levels.

Geological and tectonic outline

In Fig. 3 the schematic geologic map of PLNP and its vicinity is presented, modified after the geological map sheets Bihać (A. Polšak et al., 1967, 1976) and Otočac (I. Velić et al., 1974). The area is mainly underlain by dolomites and limestones of Triassic to Cretaceous age. Also, recent calcareous tufa deposits occur locally in the cascade lake basins and the streambeds of the major streams feeding the lakes and the river Korana. Tufa deposition commenced in the Quaternary period

(Pleistocene and Holocene) and is still in progress. In the Plitvice Lakes, deposition of the recent calcareous sediments resulted in the formation of tufa barriers that separate the numerous cascade lakes basins. The origin of the tufa deposits is attributed to a dynamic karst geomorphologic phenomenon, involving dissolution of the calcareous bedrocks in the lakes' catchment area and subsequent deposition processes.

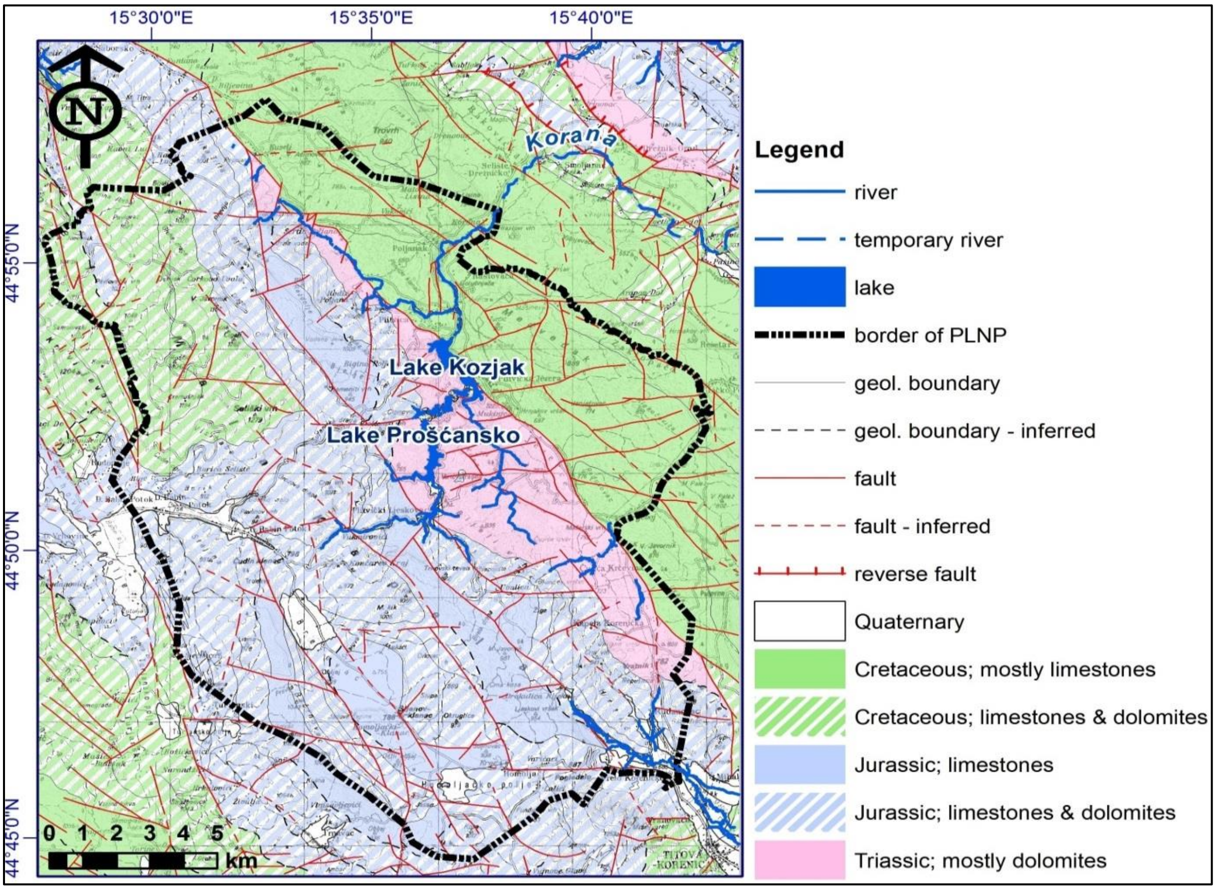

Figure 3: Schematic geologic map of Plitvice Lakes National Park (PLNP) and its vicinity, modified after the geological map sheets Bihać (A. POLŠAK et al., 1967, 1976) and Otočac (I. VELIĆ et al., 1974).

As indicated in the basic geological map of the Republic of Croatia (the Bihać sheet, POLŠAK et al., 1967, 1976), the "Plitvička jezera tectonic unit" plays a central role in the geological setting of the Plitvice Lakes and the vicinity. It appears that the intensive tectonic deformation resulted in the upward penetration or shift of older carbonate rocks into geologically much younger units. Ultimately, this placed different carbonate lithostratigraphic units with variable lithological composition (Upper Triassic dolomites, exchanges of Upper Cretaceous limestones and dolomites, and even the youngest part of the Upper Cretaceous (mostly limestones)) in direct contact. The carbonate rock assemblage penetrating the younger units exhibits an anticlinal form, with the flanks comprising carbonate rocks of Lias and Dogger ages. This tectonic unit also played a significant role in the formation of the Plitvice Lakes and emergence of the large karst springs in the area.

Hydrogeological characterisation

Hydrogeological characteristics of the Mesozoic calcareous rocks in the PLNP vary considerably. The limestones of the Middle Jurassic and Lower Cretaceous are highly karstified and permeable but, in contrast, the Triassic dolomites exhibit a low degree of karstification and low permeability. The calcareous rocks representing the exchange of Mesozoic dolomites and limestones show intermediary degrees of karstification and permeability. Also, the Quaternary calcareous tufa exhibits low permeability at some places.

The emergence of the large karst springs as well as the formation of the Plitvice Lakes basins is controlled by the local geological and tectonic setting and the heterogeneous lithological composition of the different Mesozoic calcareous rocks. Subsurface drainage and the outlets of major karst springs in the area is primarily associated with the intensive karstification of the Mesozoic limestones, thereby the underlying poorly permeable Triassic dolomites act as a barrier. The large karst springs Bijela (WR_S) and Crna (BR_S) emerge in deep canyons at about 710 m and 680 m altitude, respectively, at the contact between the karstified limestones and low permeable dolomites. They drain the karstified limestones in the mountainous region of Mount Mala that rises up to 1,200 m in altitude where numerous karst features (dolines and small ponors or sinkholes) commonly occur. The Plitvica karst spring (P_S) emerges at about 610 m a.s.l. in the northwest.

The origin of the cascade lake basins is also linked to the heterogeneous hydrogeological setting of the carbonate bedrocks. As shown in Fig. 3, the entire Upper Lakes (including Lake Kozjak and all upstream-lying basins) are embedded in the low permeable dolomite bedrocks, whereas the Lower Lakes (small lake basins downstream of Lake Kozjak) are enclosed by the relatively narrow canyon cut in the highly permeable Cretaceous limestones.

The main source of inflow to the Plitvice Lakes system comprises surface inflow, including the streams Matica, Sušanj and Rječica, and to some extent small channelised and non-channelised inflows from the steep calcareous terrain bordering the lakes. The streams Matica (confluence of Crna and Bijela karst springs) and Sušanj drain the adjacent karstified limestones in the southern part of PLNP. Both streams enter into Lake Prošćansko, the upstream lake basin. From Lake Prošćansko the water flows through the smaller lake basins into Lake Kozjak. Another significant inflow to Lake Kozjak comes from Rječica, which drains numerous diffuse and focused small springs that appear from the underlying predominantly poorly permeable dolomites. Finally, the water leaves Lake Kozjak and flows through the smaller Lower Lakes and confluences with the Plitvica (Plitvica karst spring as the main source), ultimately forming the river Korana.

Water sampling and laboratory analysis

Monitoring of the Plitvice Lakes system commenced in August 2005 and continued regularly on monthly basis until January 2006 and, subsequently, bi-monthly until the end of 2007. Field parameters were measured in situ, and water samples were collected for hydrochemical analysis and stable isotope determination from large karst outlets in the lakes' catchment area as well as streams inflowing to the lake system, different lake basins and the river outflowing from the Plitvice Lakes. The locations of the sampling points are shown in Fig. 1.

The inflow components regularly monitored during the whole observation included: the karst springs WR_S and BR_S (Bijela and Crna, respectively) as well as the streams MR (Matica) and RR (Rječica). Profiles of physico-chemical parameters and stable isotope contents were performed on monthly basis during the first two years and on bi-monthly basis during the final year on the deepest parts of the largest lake basins, Lake Prošćansko and Lake Kozjak, at P3 and K1, respectively. Additional depth profiles of physico-chemical parameters and stable isotope contents were done on quarterly basis on two points along the longitudinal axis of each of these lakes. Within the smaller lake basins, notably at BL, BAT, GRAD, GAL, MIL and KAL (Veliko, Batinovac, Gradinsko, Galovac, Milanovac and

Kaluđerovac lakes, respectively) field measurements and water sampling were performed at one point near the lake surface (about 0.5 m depth). On the western flank of the Plitvice Lakes catchment, the karst spring (P_S) of the Plitvica and the stream itself (PP) were also regularly observed. The start of the river Korana (KR), downstream of the confluence between the lake water outflow and the stream Plitvica, has also been monitored for its physico-chemical parameters and stable isotope contents. Additionally, numerous small carbonate springs emanating at higher altitudes in the wider catchment area of the lake system were mapped and monitored periodically in 2007 in order to obtain insight into their hydrochemical composition and stable isotope contents.

Measurement of field parameters (water temperature, pH, specific electrical conductivity and dissolved oxygen content) was done in situ, using the respective WTW probes at the springs, rivers and the small lakes and using SEBA probes in the lake profiles of Lake Prošćansko and Lake Kozjak. At the same time, raw water samples were collected in two polyethylene bottles (each with one litre capacity) for the analysis of major ions (HCO_3^-, SO_4^{2-}, NO_3^-, Cl^-, Na^+, K^+, Mg^{2+} and Ca^{2+}) and phosphate content. HCO_3^-, Mg^{2+} and Ca^{2+} ions were measured by the standard titrimetric method with a Hach Digital Titrator in the hydrochemical laboratory of Ivo Pevalek, PLNP. Also, other major anions were analysed in the same laboratory by standard methods using the Hach Spectrophotometer: NO_3^- using low and medium range Cadmium Reduction Methods, Cl^- using Mercuric Thiocyanate Method and SO_4^{2-} using Barium Sulphate Method. The Na^+ and K^+ cations were analysed by flame atomic emission technique on AAS, Perkin Elmer Analyst 800 at the chemical laboratory of the University of Zagreb.

Together with the hydrochemical samples, a 100 ml polyethylene bottle of raw water sample was collected for stable isotopes (^2H and ^{18}O). Determination of stable isotopes was done at the Isotope Laboratory of RESOURCES – Institute for Water, Energy and Sustainability (formerly the Institute of Water Resources Management), JOANNEUM RESEARCH Graz, Austria, using a Finnigan DELTAplus light stable isotope ratio mass spectrometer, with an overall precision for 0.1 ‰ for oxygen-18 and 1 ‰ for deuterium. Stable isotope content is conventionally expressed and reported in δ-notations as ‰ deviation from the internationally accepted standard V-SMOW (Vienna Standard Mean Ocean Water).

The long-term mean values of field parameters, major ions and stable isotope contents (δ^2H and $\delta^{18}O$) are summarized in tab. 1. The table also contains the saturation indices of calcite (SI_c), dolomite (SI_d), gypsum (SI_g) and anhydrite (SI_a), and theoretical equilibrium partial pressure of CO_2 (P_{CO2}), which were computed using the NETPATH speciation computer programme by processing the complete hydrochemical dataset of the observation points.

Investigation results

Borehole drilling data

Downstream of the Plitvice Lakes Cretaceous limestones outcrop (Fig. 3), characterised by appearances of different karst features. Two exploration boreholes were drilled on the littoral zone of Lake Kozjak to investigate the hydrogeological condition, especially to determine the hydrologic connection between the lake and the adjacent karstified limestones. The drilling sites were selected based on detailed hydrogeological mapping (1 : 5,000 scale) and different geophysical surveys (shallow seismic reflection, geoelectrical tomography, electromagnetic sounding and electromagnetic profiling).

The first borehole (PJ-1) was drilled at about 115 m downstream of the shore of Lake Kozjak (Fig. 1). The exploration borehole is 95 m deep. During the drilling progress, a strong water loss was encountered, indicating good permeability of the drilled carbonate rocks. Retrieved drill cores revealed typical Upper Cretaceous rudiste limestone until 34.6 m depth (about 10 m above the water level surface of Lake Kozjak), laminated and bituminous limestones (representing an exchange of limestones and dolomites) until 62 m depth, and again typical Upper Cretaceous rudiste limestone until 95 m depth. The laminated and bituminous limestones are characterised by low permeability and they act as a barrier that limits the vertical percolation and seepage of lake water into the downgradient carbonate rocks. As a result, despite the large negative gradient to the lake, the drilled piezometric borehole was dry although the piezometric borehole penetrated about 50 m below the surface of Lake Kozjak. Between 49.1–49.3 m and 55.0–58.6 m borehole depth, just about 5 m below the deepest part of Lake Kozjak, a cavernous zone filled with tufa sediments was encountered. This indicates a prior existence of lake water sinking into the adjacent karstified carbonate rocks via the cavernous openings. The cavernous openings were subsequently plugged by tufa sediments and the lake water flow into the Cretaceous limestones interrupted.

A second 70-m-deep exploration borehole (PJ-3) was drilled in the Korana river canyon at a distance of about 90 m from the Veliki slap and tufa barrier at the Kozjak bridge, close to Lake Milanovac. Indicating a good permeability of the carbonate rocks in the area, similar to the first exploration borehole, a strong water loss was encountered starting from 11.7 m depth. Drill cores from the entire borehole depth exhibited moderately fractured Upper Cretaceous rudiste limestones. From LUGEONE tests, permeability values ranging between 0.10 and 38.50 LU were determined. These values reflect the high permeability of the calcareous rock mass and direct exchange with the adjacent lakes Milanovac and Kozjak. Showing negative gradients from the lakes towards the karst underground, the groundwater levels in the piezometric borehole were always below the water levels of these lakes. Linked to snow melting in the area, the groundwater level was high (53.30 m depth) in the piezometric borehole in March 2008. During the dry period of 2007, the borehole was without water, signifying the drop of groundwater level below the bottom of the borehole. It is noteworthy that during the time span of 1995 to 2008 the adjacent river bed segment of Korana was intermittently dry between August and November 2000, August and October 2003 and July and September 2007. But during 2008 the river flow was continuous.

Dye tracing experiments

Several groundwater tracing experiments were carried out in the PLNP and adjacent area (e. g. POLŠAK, 1974; DEŠKOVIĆ et al., 1984) with the objective to establish the connection between karst features (dolines and sinkholes) and springs and other water features, to determine the overall subsurface drainage pattern and to define the hydrologic boundaries of the national park. During the present investigation two tracing experiments were performed downgradient of the Plitvice Lakes, employing uranine fluorescent dye (Fig. 4). They were designed to trace the flow direction from the sink hole where the wastewater from the PLNP premises (hotels, restaurants, and settlements) is disposed, and to ascertain the sinking condition and flow direction of groundwater in the area close to the Korana river canyon. The first experiment was carried out on April 21, 2005 by injecting 30 kg of uranine (adding 10 kg NaOH to elevate the pH) into the sinkhole at the village called Rastovača at 515 m a.s.l., where the domestic or sanitary wastewater from the PLNP is directly discharged without treatment. The uranine concentration in the water samples was measured at the dye tracer laboratory of the Institute of RESOURCES – Institute for Water, Energy and Sustainability, JOANNEUM RESEARCH Graz, Austria, using a Shimadzu RF-5000 spectrofluorophotometer with a detection limit of 1 ng/L. The dye was quantitatively determined using the synchron-scan method (BEHRENS, 1970), where the excitation and emission wavelengths are varied with a constant wavelength separation.

The second dye experiment was carried out on 25 September 2007 near the village of Drežnik Grad, the prospective site for the injection of treated wastewater. Twenty-five kg of uranine (adding 3 kg NaOH to elevate the pH) were injected into the karstified underground via the exploration borehole PB-1 (Fig. 4). The uranine concentration in the water samples was measured at the Environmental Geochemistry Laboratory of the Faculty of Geotechnical Engineering, University of Zagreb, using PerkinElmer LS 55 Fluorescence Spectrometer with a detection limit of 10 ng/L.

From the tracing experiment at the village called Rastovača, uranine first appeared on May 9 2005, 428 hours (about 8 days) after the tracer injection, on a large karst spring called Klokot. This spring emerges at 216 m a.s.l. and about 17.6 km southeast of the injection point in Bosnia and Herzegovina in the Una river catchment. Also, the uranine dye injected into the piezometric borehole near Drežnik Grad reappeared on the same karst spring, which is about 18 km southeast from the injection point. First appearance of uranine was registered on 12 October, 443 hours (about 18.5 days) after the injection.

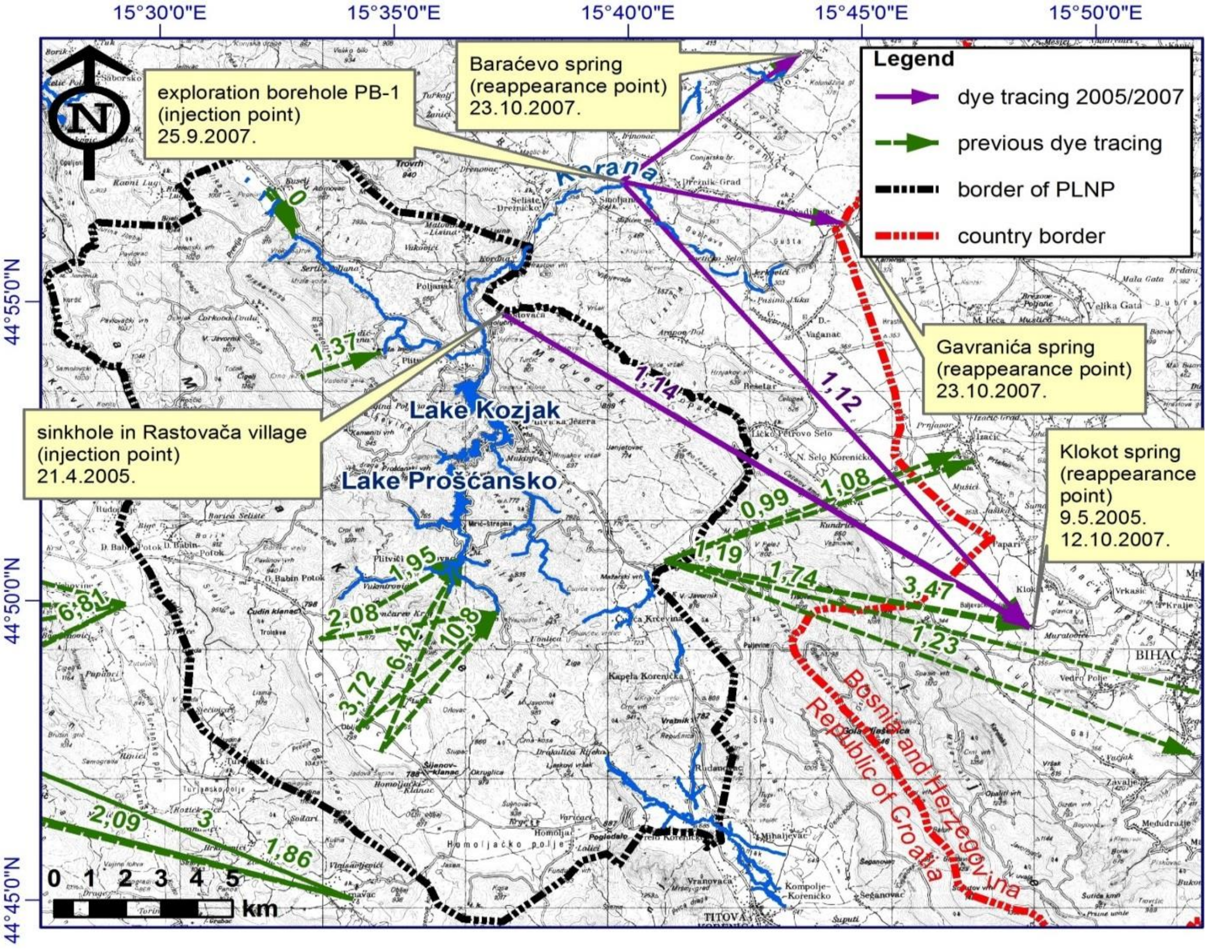

Figure 4: Map showing the injection and reappearance points of two dye tracer experiments performed on 21 April 2005 and 25 September 2007, with solid arrows showing the groundwater flow direction and the connection between injection and reappearance points. Tracer experiments carried out prior to the present investigation (e. g. POLŠAK, 1974, DEŠKOVIĆ et al., 1984) are indicated with dashed lines. Base map source: Topografska karta M 1 : 100.000, List 420, Bihać, 1979–1981.

Both tracing experiments revealed closely resembling results. From the first tracing experiment the travel time until the first appearance of the dye tracer in Klokot karst spring was about 18–18.5 days and the apparent flow velocity computed in the range 975–987 m/day (1.12 cm/sec–1.14 cm/sec). Pursuant to the Croatian Water Laws (NN 55/02 and amendments made in NN 66/11), the sinkhole in the village Rastovača and the karstified underground lies within the III sanitary protection area of Klokot karst spring, which is the source of water supply for the town of Bihać. Thus, disposing untreated wastewater into the sinkhole contravenes the Croatian Water Law and the need to find a solution to the problem is evident. Concentration of uranine dye registered in Klokot karst spring from the second tracing experiment was significantly lower than from the first experiment. The peak value registered (27.39 ng/L) was more than 1000 times diluted. This could be partly explained by migration of the injected dye to other places. For instance, the injected fluorescent dye was traced in the karst springs Gavranića Vrelo and Baraćevo Vrelo, which emanate at about 6.3 km east-northeast and 6.2 km east-southeast of the injection borehole. Uranine dye first appeared on 19 October after 571 hours (about 24 days) and on 23 October after 679 hours (about 28 days) at the karst springs Gavranića Vrelo and Baraćevo Vrelo, respectively. However, it should be remarked that this tracing experiment was carried out under a dry condition, i. e. when the river Korana (just the adjacent river segment downstream of Plitvice Lakes) stopped flowing and the groundwater level in the injection borehole was low (10 m below Korana river bed). The dye tracer began appearing at the later karst springs after nearly a month after tracer injection, following precipitation events in the area that led to the rise of the groundwater level in the karst aquifer and to the water flow in the Korana river. This suggests that groundwater flow bifurcation occurs during high flow conditions. Given this hydrologic condition, the travel time to the karst springs may not reflect the real groundwater flow velocity. For this reason, calculation of flow velocity to the spring outlets Gavranića Vrelo and Baraćevo Vrelo has been avoided.

Figure 4 illustrates the uranine tracer injection and reappearance points, accordingly the subsurface groundwater flow directions and calculated flow velocities. Also, the results of groundwater tracing experiments carried out prior to the present investigation within PLNP and adjacent area (e. g. POLŠAK, 1974; DEŠKOVIĆ et al., 1984) are shown in the map. The connections between tracer injection and reappearance points are indicated by dashed lines.

Hydrochemical and environmental isotope data

Hydrochemical composition of the karst springs and lakes and the state of water quality of the water resources in the Plitvice area have been characterised based on the dataset of field parameters and hydrochemical analyses of major ions. Employing the stable isotope data (δ^2H and $\delta^{18}O$), the mean recharge altitude of the karst springs and ensuing streams has been estimated, the provenance of the different water features in the PLNP interpreted, and the mean residence time of water in the lake cascade lake system approximated. Furthermore, the seasonal dynamic behaviour of the lake system has been examined.

Hydrochemical composition of springs, streams and lakes

The hydrochemistry of the springs, streams and lake water in PLNP is determined by carbonate mineral dissolution/precipitation reactions. It is weakly basic and dominated by Ca^{2+}, Mg^{2+} and HCO_3^- ions. Mean values of the field parameters and concentrations of major ions of the observation points regularly monitored between 2005 and 2007 are given in tab. 1. They show a distinct systematic spatial variation from the carbonate spring sources to the Plitvice Lakes' outflow in pH and concentration of carbonate species, in particular in Ca^{2+} and HCO_3^- contents. The pH successively increased from 7.4–7.5 in the spring outlets to about 8.3 in the surface water outflow from the lake system. Conversely, concentration of the dominant ions Ca^{2+} and HCO_3^-, respectively, decreased from approx. 58–66 mg/l and 267–305 mg/l in the karst springs to 44 mg/l and 228 mg/l in the lake outflow. Linked to this, the specific electrical conductivity also dropped from > 415 µS/cm to 354 µS/cm. This hydrochemical change is mainly attributed to the drop of the high pedologically derived P_{CO2} due to degassing of dissolved CO_2 after the emergence of the karst springs and subsequent flow in the streams and through the cascade lakes. Degassing of CO_2 from the waters leads to oversaturation with respect to calcite and dolomite minerals. This hydrochemical state ultimately brought about precipitation of mainly calcite in the river beds and cascade lakes.

Combined interpretation of the saturation indexes of the carbonate minerals (SI_{cal} and SI_{dol}) and the equilibrium partial pressure of CO_2 (P_{CO2}) in the sampled waters provided a better insight into the hydrochemical change taking place from spring emergence to lake water outflow. This was particularly evident in the plot of the mean values of P_{CO2} versus SI_{cal} and SI_{dol} (Fig. 5). Reflecting the presence of high soil-derived dissolved CO_2, the water samples from the karst springs exhibited a higher P_{CO2}, close to approx. $10^{-2.2}$ atm, and their SI_{cal} values were slightly positive. Thus, data points cluster slightly above the equilibrium line SI = 0. On the other hand, SI_{dol} values were negative. Therefore, the data points fell below the equilibrium line, indicating the undersaturation of these waters with respect to dolomite. Comparatively, the SI_{dol} values of the water samples from BR_S and P_S were more negative and thus the data points clustered distinctly below the equilibrium line. It is worth to note that the Mg^{2+} concentration in the karst springs varied to some extent, which is attributed to the inhomogeneities of the calcareous bedrocks in the catchment areas. The springs WR_S and RR contained a comparatively higher Mg^{2+} concentration (ranging from 28 mg/l to 33 mg/l, respectively). Hence, it appeared that these springs drain calcareous rocks consisting of significantly more dolomites compared to the karst spring BR_S, which contained a lower Mg^{2+} concentration (approx. 15 mg/l).

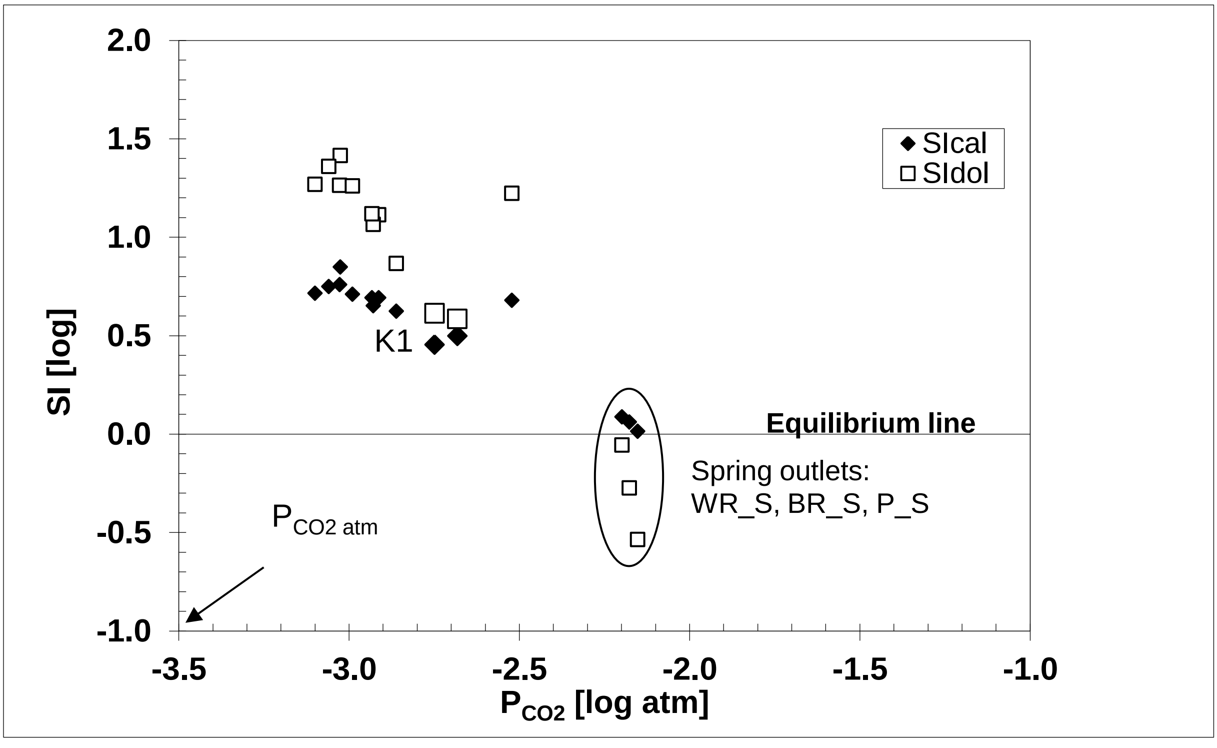

Figure 5: Plot of the mean values of saturation indices of calcite and dolomite (SI_{cal} and SI_{dol}) vs. the corresponding mean partial pressure of CO_2 (P_{CO2}). The larger open squares and filled rhombus represent the data points of the depth- and time-

averaged deep profiles P3 and K1 of the lakes Prošćansko and Kozjak, respectively. For the designations/abbreviations of sampling points refer to tab. 1.

In the ensuing rivers and lake basins, P_{CO2} dropped to $10^{-2.5}$ to $10^{-3.1}$ atm and the water samples were oversaturated with respect to both calcite and dolomite. The data points of these waters thus fell far above the equilibrium line. As shown in tab. 1, the average SI_{cal} values in the stream waters and lake basins rose as high as 0.5–0.85 and the SI_{dol} values to 1–1.5. The prevailing hydrochemical condition (with biological mediation due to the presence of mosses, algae and bacteria) induced deposition of mainly calcite as tufa sediments in the streambeds and within the cascade lakes. This ultimately resulted in a considerable decrease of Ca^{2+} and HCO_3^- concentrations in the downstream direction, while the Mg^{2+} concentration remained without any significant change in the streams and lakes. As a result, as shown in Fig. 5, the degree of dolomite oversaturation significantly surpassed that of calcite in the streams and lakes. Most likely, the invariability of the Mg^{2+} concentration is attributed to the kinetic hindrances to dolomite precipitation. As stated in FREEZE & CHERRY (1979), in a carbonate groundwater system dolomite precipitation is so sluggish that the ions involved persist to remain in solution for long periods of time with little or no dolomite precipitation.

Table 1: Average values of field parameters, hydrochemical composition and stable isotope contents of the measuring points in the Plitvice Lakes system and adjacent to it, monitored regularly during the period 2005–2007. P3 and K1 represent the values of lake profiles from the deepest part of the lakes Proščansko and Kozjak, respectively. KR (river Korana) represents the confluence of outflow from the Plitvice Lakes and Plitvica river.

	Flow catagory	Desig.	Name in English/Croatia	Temp.	pH	SEC	Dis. O_2	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-
				[°C]	[-Log]	[µS/cm 25 °C]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
Plitvice Lakes system and its adjacent area	Inflows to lake	WR_S	White River (source)/Izvor	7.59	7.54	473	10.23	0.99	0.41	28.20	58.03	2.87	5.44	1.99	304.58
		BR_S	Black River (source)/Izvor Crne rijeke	7.94	7.42	417	10.53	0.80	0.27	15.12	65.64	2.16	4.06	2.09	266.67
		MR	Matica (stream)/Rijeka Matica	9.28	8.10	430	9.92	0.74	0.29	19.41	63.11	2.10	3.10	1.59	278.20
		RR	Rječica (stream)/Potok Rječica	8.97	8.14	486	9.54	0.48	0.28	32.65	57.24	1.59	2.91	1.13	327.08
	Upper Lakes	P3	Lake Prošćansko /Prošćansko jezero	9.08	8.00	400	8.93	0.74	0.29	17.90	60.32	2.14	2.41	1.49	264.81
		BL	Lake Veliko /Veliko jezero	12.83	8.29	391	9.80	0.69	0.29	18.72	51.46	2.06	1.73	1.53	242.00
		BAT	Lake Batinovac/Batinovac jezero	12.53	8.22	395	10.38	0.69	0.28	19.31	52.66	2.03	1.62	1.19	249.15
		GAL	Lake Galovac/Galovac jezero	12.64	8.23	382	9.74	0.69	0.28	19.16	51.41	2.00	1.43	1.45	244.89
		GRAD	Lake Gradinsko/Gradinsko jezero	13.04	8.20	373	9.21	0.70	0.31	19.05	49.34	2.03	1.50	1.47	236.68
		K1	Lake Kozjak/Kozjak jezero	8.40	8.09	387	9.27	0.68	0.30	21.05	51.15	1.93	3.21	1.95	251.99
	Lower Lakes	MIL	Lake Milanovac/Milanovac jezero	14.05	8.28	374	9.00	0.66	0.27	20.56	46.66	1.92	1.43	1.77	237.81
		KAL	Lake Kaluđerovac Lake/Kaluđerovac jezero	13.67	8.35	364	9.65	0.67	0.28	20.83	45.14	1.95	1.58	1.81	234.59
	Tributary to lake outflow	P_S	Plitvica (source)/Izvor Plitvica	7.45	7.51	443	9.49	0.54	0.31	21.49	62.71	1.50	6.49	2.74	285.48
		SS	Sartuk (stream)/Sartuk	10.83	8.55	428	9.92	0.49	0.28	29.55	54.50	1.92	0.51	0.35	302.87
		PP	Plitvica (stream)/Potok Plitvica	9.78	8.35	426	9.65	0.47	0.27	22.42	56.48	1.53	3.31	2.38	275.66
	Lake outflow	KR	Korana (river)/Rijeka Korana	12.81	8.34	354	9.25	0.65	0.29	20.49	43.63	1.87	1.82	1.92	227.84

	Flow catagory	Desig.	Name in English/Croatia	NO_2^-	NH_3	PO_4^{3-}-P	SiO_2	$SI_{cal.}$	$SI_{dol.}$	$SI_{gyps.}$
				[mg/l]	[mg/l]	[mg/l]	[mg/l]	log	log	log
Plitvice Lakes system and its adjacent area	Inflows to lake	WR_S	White River (source) /Izvor Bijele rijeke	0.00	-0.11	0.01	2.22	0.09	-0.06	-3.46
		BR_S	Black River (source) /Izvor Crne rijeke	0.00	-0.11	0.01	2.34	0.01	-0.54	-3.34
		MR	Matica (stream)/Rijeka Matica	0.00	-0.11	0.00	1.88	0.62	0.87	-3.54
		RR	Rječica (stream)/Potok Rječica	0.00	-0.10	0.00	1.16	0.68	1.22	-3.79
	Upper Lakes	P3	Lake Prošćansko /Prošćansko jezero	0.00	-0.07	0.00	1.57	0.50	0.59	-3.56
		BL	Lake Veliko/Veliko jezero	0.00	-0.11	0.00	–	0.76	1.26	-3.74
		BAT	Lake Batinovac /Batinovac jezero	0.00	-0.11	-0.01	–	0.69	1.11	-3.69
		GAL	Lake Galovac/Galovac jezero	0.00	-0.11	-0.01	–	0.69	1.12	-3.55
		GRAD	Lake Gradinsko /Gradinsko jezero	0.00	-0.11	0.00	–	0.65	1.07	3.24
		K1	Lake Kozjak /Kozjak jezero	0.00	-0.10	0.00	1.63	0.45	0.61	-3.53
	Lower Lakes	MIL	Lake Milanovac /Milanovac jezero	0.00	-0.11	0.00	–	0.71	1.26	-3.48
		KAL	Lake Kaluđerovac Lake/Kaluđerovac jezero	0.00	-0.11	0.00	–	0.75	1.36	-3.55
	Tributary to lake outflow	P_S	Plitvica (source) /Izvor Plitvica	0.00	-0.11	0.00	1.33	0.06	-0.27	-3.21
		SS	Sartuk (stream) /Sartuk Potok	0.00	-0.09	-0.01	–	–	–	–
		PP	Plitvica (stream) /Potok Plitvica	0.00	-0.11	0.00	–	0.85	1.42	-3.33
	Lake outflow	KR	Korana (river) /Rijeka Korana	0.00	-0.11	-0.01	–	0.72	1.27	-3.49

Interpretation of stable isotope contents

Recharge areas of karst springs using $\delta^{18}O$-altitude effect

In areas with a high relief, recharge areas of springs and groundwater bodies can be determined employing the altitude effect on the distribution of $\delta^{18}O$ and $\delta^{2}H$ contents. This technique has been widely applied in numerous groundwater studies (e. g. Bortolami et al., 1979, Fontes, 1980, Abbott et al., 2000, James et al., 2000, Yehdegho & Reichl, 2002). In tectonically complicated geological environments and karstified calcareous terrains, the infiltration zones of springs and groundwater bodies often do not correspond with and often extend far beyond the topographic boundaries. Hence, they cannot be reliably determined by classical hydrological methods. In such cases, the altitude gradient of $\delta^{18}O$ and $\delta^{2}H$ provides an alternative means for determining the mean recharge altitude of springs and groundwaters.

To do this, first the altitude effect on the distribution of stable isotope contents in the study area needs to be determined. This is done by evaluating the isotopic composition of precipitation in different elevations or of small reference springs that closely reflect the distribution of stable isotope contents in precipitation and whose mean recharge altitudes can be determined from hydrogeological data. Mean recharge altitudes of springs and other groundwater bodies can be determined in two ways. Graphically, the average recharge altitude is inferred by extrapolating from the data point X, corresponding to the isotope content of a spring or another groundwater body and its elevation at emergence, to the stable isotope content vs. altitude regression line and then dropping a perpendicular to the abscissa (Fig. 6). Mathematically, it is predicted from the linear equation describing the regression line, using the stable isotope content in the water sample as input parameter.

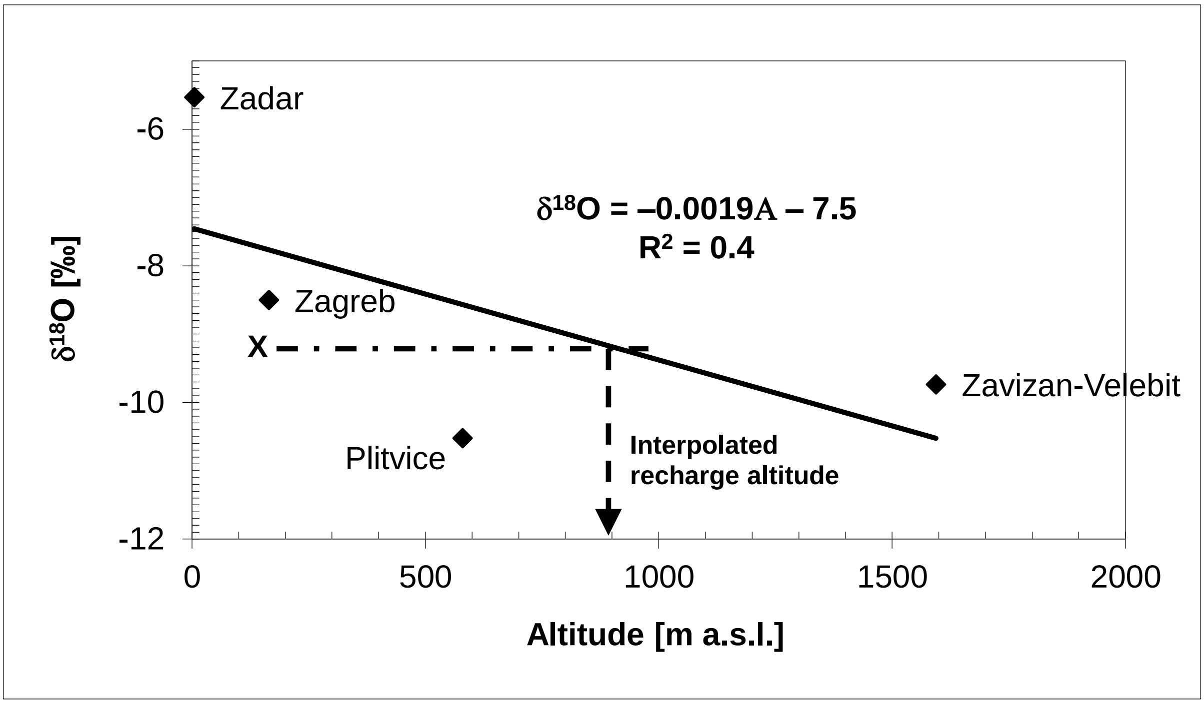

Figure 6: Altitude effect on $\delta^{18}O$ content of rainfall in the Plitvice Lakes National Park and adjacent region.

Mean recharge altitude of the springs in the PLNP area has been determined employing the $\delta^{18}O$-altitude effect obtained by correlating the stable isotope data of GNIP stations (Global Network of Isotopes in Precipitation) located at different altitudes in the central and Adriatic coastal area of Croatia. The GNIP stations considered for determining $\delta^{18}O$-altitude effect include: Zagreb (165/157 m a.s.l., 1980–2002), Zadar (5 m a.s.l., 2001–2002), Plitvice (580 m a.s.l., 2004–2005) and Zavizan-Velebit (1594 m a.s.l., 2001–2002). The linear regression equation is given as: $\delta^{18}\mathrm{O} = -0.0019 * \mathrm{A} - 7.5$ with a correlation coefficient of (R^2) 0.4, where A represents altitude in m a.s.l. From this equation an altitude effect –0.19 ‰ $\delta^{18}O$/100 m was derived. It should be remarked that the observation period of stable isotope contents of precipitation in the GNIP stations was short and heterogeneous, and the correlation of the regression equation rather poor. In spite of these uncertainties in the determination, the altitude effect on the distribution of $\delta^{18}O$ appeared to be representative for the study area. The value lies within the range of typical gradients reported in many isotope studies carried out in the Alps (-0.2 ‰ $\delta^{18}O$/100 m to -0.4 ‰ $\delta^{18}O$/100 m, e. g. SIEGENTHALER et al., 1970; BORTOLAMI et al., 1979; SIEGENTHALER & OESCHGER, 1980; YEHDEGHO & REICHL, 2002). It also closely resembles the isotopic gradients reported from isotope studies carried out in other temperate zones. As reported by FONTES (1980), the altitude effect on oxygen-18 in temperate zones (mid latitudes) is in the order of –0.3 ‰ $\delta^{18}O$/100 m. A decrease in $\delta^{18}O$ of 0.18 ‰ / 100 m rise in elevation was reported by JAMES et al. (2000) in the central Oregon Cascades, and ABBOTT et al. (2000) determined $\delta^{18}O$ gradients of –0.25‰/100 m in Vermont, USA.

At any rate, as there is no other better result, the specific altitude gradient of stable isotopes of $\delta^{18}O$ (–0.19 ‰/100 m) has been used to determine the mean recharge altitudes of the karst springs and ensuing streams in PLNP. The mean recharge areas of the large karst springs WR_S, BR_S, P_S and the streams MR, PP and RR were in the range 980–1,020 m a.s.l. This average recharge altitude determined from the δ^{18}O altitude effect suggested that the infiltration zone to the karst springs and ensuing streams is located in the highly karstified limestone rocks in the catchment area of the Plitvice Lakes, at higher elevations to the south and west in the mountainous region of Mount Mala Kapala that rises up to 1,200 m in altitude. The carbonate rocks there are characterised by the occurrence of distinctive surface karst features (dolines or sinkholes), where intensive infiltration of precipitation easily takes place and, as a result, the surface runoff is almost nil. It should be remarked that the δ^{18}O values and the resulting mean recharge altitudes of the streams Matica and Plitvica (MR and PP) closely resembled the respective karst spring outlets. This most likely illustrated that these streams drain mainly a karst groundwater system with a recharge altitude similar to the spring outlets and that the contribution from the mountain slopes downstream of the springs' emergence was rather negligible.

δ^2H/δ^{18}O-plot analysis

Distribution of the mean stable isotope contents of the sampled springs, rivers and lake basins has been plotted in δ^2H-δ^{18}O diagrams using the Local Meteoric Water Line (LMWL) of the PLNP as key reference (Fig. 7). The LMWL has been determined from the monthly δ^2H and δ^{18}O values of the composite precipitation samples collected at the Plitvice station (580 m a.s.l.) during the period July 2003 – September 2006. It is given as: $\delta^2\mathrm{H} = 7.9 * \delta^{18}\mathrm{O} + 12.5$ (n = 38, R^2 = 0.99). The slope of the LMWL closely resembles that of the Global Meteoric Water Line (GMWL). The slightly larger δ^2H intercept (12.5) is ascribed to the influence of water vapour originating from closed basins. It is generally known that water vapour from closed basins exhibits a larger δ^2H intercept. For instance, FONTES (1980) revealed the δ^2H intercept in the eastern Mediterranean to be as large as +22 ‰.

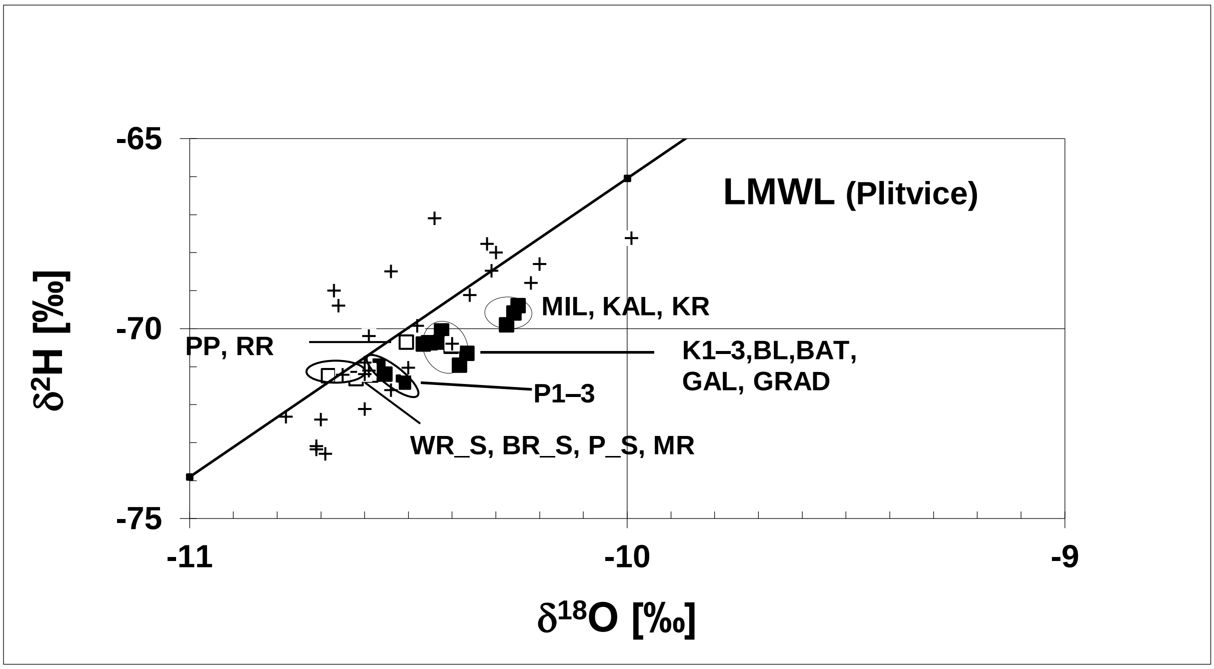

Figure 7: δ ^{2}H vs. δ ^{18}O plot analysis for the Plitvice Lakes National Park: + symbolizes stable isotope contents of springs in the wider catchment of the Plitvice Lakes (overview sampling and analysis carried out in May and June 2007), □ non-evaporated water features – springs and streams (regularly monitored sampling points) and evaporated lake basins and lake outflow (river Korana). The stable isotope contents of the sampling points adjacent to the lake represent averages for the period 2005–2007, where the data-points P1–3 and K1–3 correspond to the averages of the three profiles carried out at Lake Prošćansko and Lake Kozjak, respectively. For the designations/abbreviations of sampling points see tab. 1.

As illustrated in Fig. 7, the δ^{18}O vs. δ^{2}H data points of the water samples representing non-evaporated water bodies are clustered along the LMWL. This included the karst springs WR_S and BR_S, the ensuing streams that inflow to Plitvice Lakes (MR and RR) and those of P_S and PP. Also, the δ^{18}O vs. δ^{2}H data points from the small spring outlets (about 15 in number) in the wider catchment area of the Plitvice Lakes monitored periodically (once or twice during spring and autumn 2007) are distributed around the LMWL, but the data points showed a wider scatter. On the other hand, the water samples collected from the different lake basins and the surface water outflow from the Plitvice Lakes system were isotopically heavier. Reflecting the evaporation effect on the lakes, the δ^{18}O vs. δ^{2}H data points came to lie on the right side of the diagram, below the LMWL.

Though small in magnitude, a successive evaporative enrichment in stable isotope content was noticed in the downstream direction of the cascade lake system. Showing the smallest evaporation effect, the data points from the upstream Lake Prošćansko (P3) plotted close to the LMWL. The δ^{18}O and δ^{2}H values (approx. –10.5 and –71.0 ‰, respectively) represented depth and time averages from the three profiles P1–3. In contrast, the water samples from MIL, KAL and KR constituted the most isotopically enriched waters in the studied system. Their long-term mean δ^{18}O and δ^{2}H contents were close to –10.3 and –70.0 ‰ and the data points thus plotted far to the right on the δ^{2}H vs. δ^{18}O diagram. Mean isotopic values of Lake Kozjak (depth- and time-averaged values of the depth profiles K1–3) and those from the remaining smaller lake basins, including BL, BAT, GAL and GRAD, fell in between. Using the long-term average δ^{18}O and δ^{2}H values from the MR (Matica representing the main inflow to the lake system) as initial concentration, the isotopic enrichment (in %) in the different cascade-arranged lake basins has been quantified. This revealed a successive isotopic enrichment from approx. 0.7 % in Lake Prošćansko to slightly over 3 % in most of the downstream lakes (MIL and KAL) with respect to δ^{18}O and, accordingly, from 0.2 % to 2.4 % with respect to δ^{2}H (Tab. 2).

Table 2: Mean values of stable isotope contents and evaporative enrichment in the different cascade lake basins calculated assuming the isotopic composition of the stream Matica (MR) as a starting point. For designations/abbreviations of sampling points refer tab. 1. Mean stable isotope contents of the three profiles (depth and time averaged) performed in each lake.

Sampling points	**δ^{18}O [‰]**	**δ^{2}H [‰]**	**Stable isotope enrichment [%]**	
			δ^{18}O	**δ^{2}H**
MR	–10.62	–71.32	0	0
Lake Prošćansko*	–10.54	–71.20	0.7	0.2
BL	–10.45	–70.38	1.6	1.3
BAT	–10.47	–70.41	1.4	1.3
GAL	–10.43	–70.36	1.8	1.3
GRAD	–10.40	–70.47	2.0	1.2
Lake Kozjak*	–10.39	–70.56	2.2	1.1
MIL	–10.28	–69.90	3.2	2.0
KAL	–10.26	–69.59	3.4	2.4

Dynamic behaviour of the cascade lake system

Hydrometeorological data from the stream gauges adjacent to the Plitvice Lakes and from the precipitation station at Plitvice station collected during the period 1995–2006 has been analysed and the hydrological flow characterised. Signifying the fast hydrologic response of the karstified limestone catchment area to precipitation, the seasonal and annual variations in stream flows and lake gauges closely matched with the distribution pattern of precipitation in the region. The peak stream discharges observed in the runoff gauge stations closely corresponded with high precipitation events, and the base flows coincided with periods of low precipitation. Some delay in the peak stream discharges was observed in some cases and can be attributed to snow accumulation in winter and subsequent delayed melting in spring.

Estimation of lake water budget

Hydrologic influxes in the Plitvice Lakes system included direct precipitation, stream inflows and non-channelised inflows, whereas water loss from the lake occurred due to evaporation, river outflow and direct withdrawal from Lake Kozjak for water supply. On a long-term basis, the lake system is assumed to be in a hydrologic steady-state condition where inflow to the lake system equals their outflow.

The water balance equation for the studied lake system is given as:

$\Delta V = P + I_{Sg} + I_{Sug} - OS - E - Q = 0$,Where
P = precipitation,
I_{Sg} = inflow rate from gauged streams,
I_{Sug} = inflow rate from channelised and non-channelised ungauged inflows,
OS = stream outflow,
E = evaporation,
Q = water withdrawal for water supply,
ΔV = change in lake volume (about 0).

The lake water budget of the Plitvice Lakes system was calculated employing the mean values of the water flow components for the period 2001–2006. The results of the calculated inflow and outflow components are summarised in tab. 3. The total stream water inflow to the lake system via the gauged streams Matica, Rječica and Sušanj (Figs. 1 and 3) amounted to 2.61 m^3/sec, and the contribution of precipitation falling directly on the lake surface was only about 0.10 m^3/sec. The stream Matica represents the major surface water inflow to the lake system (about 74 % of total inflow). Whereas, the surface water outflow from the lake system is measured at the gauge at the outlet of Lake Kozjak and is approximated at 2.81 m^3/sec, making up approx. 97 % of the total outflow from the whole cascade lake system, and the evaporation flux amounts to 0.06 m^3/sec. Withdrawal from Lake Kozjak for water supply was about 0.06 m^3/sec.

The aggregation of ungauged channelised and non-channelised inflow to the lake system (I_{Sug}) has been estimated indirectly by comparing the inflow and outflow components so far computed. On the inflow side of the lake water budget a water deficit of about 0.20 m^3/sec arose and this corresponded to the magnitude of I_{Sug} contribution. This lake water budget estimate fairly reflects the situation in the Plitvice Lakes system. Considering the climatic water balance (P – ET) of the area, the magnitude of runoff can be generated from a surface area as large as 3.5 times of the Plitvice Lakes (with approximately 2 km^2 surface area). This fairly matches with the topographic setting and surface drainage pattern of the steep limestone terrain confining the cascade lake system. It should be noted that the altitude effect on the distribution of precipitation and evaporation could not be considered in the estimation of I_{Sug} during water balance calculation due to lack of measurement of meteorological parameters in different elevations in the catchment area of the Plitvice Lakes.

Mean residence of water in the cascade lake system

Besides the hydrologic and solute fluxes, the residence time of water is a critical parameter in controlling the hydrochemical processes and water quality of lakes. The mean residence time of lake water is determined by simply dividing the lake volume by the flow in or out of the lake. Recently, Babinka (2007) recalculated the volume of the Plitvice Lakes for her PhD thesis using the bathymetric maps from Petrik (1958) and approximated it at 22.95 million m^3. Employing this lake volume and long-term mean total inflow to the lake (2.91 m^3/sec, tab. 3), the mean residence time of water in the lake system has been approximated at three months. Apparently, the water entering the lake system leaves it after a relatively short residence time in the cascade lakes.

Table 3: Estimation of the lake water budget of the Plitvice Lakes.

	Lake budget components	Flux [m^3/sec]	Flux [%]
Inflow	P – precipitation	0.10	3
	I_{Sg} – sum of gauged stream inflows: Sušanj Matica Rječica	2.60 0.06 2.14 0.40	90 2 74 14
	I_{Sug} –sum of channelised and non-channelised ungauged inflow	0.20	7
Outflow	O_S – gauged stream outflow at Lake Kozjak	2.81	97
	E – evaporation	0.03	1
	Q – withdrawal from Lake Kozjak	0.06	2

Depth profiles in the lakes Prošćansko and Kozjak

As air temperatures rise, so does the water temperature of the upper layer of lakes and vice versa. Hence, due to the seasonality of meteorological conditions in the area, lakes in temperate zones experience a major variation in their thermal regime. Temperature profiles in the lakes undergo seasonal changes with a cyclical pattern repeated every year. This also brings about seasonal changes of the vertical distribution of hydrochemical parameters as well as the stable isotope composition of the lakes.

During 2005 to 2007, depth profiles of water temperature, hydrochemical parameters and stable isotope contents were measured regularly in the Plitvice Lakes at the deepest points of the lakes Prošćansko and Kozjak (at P3 and K1, respectively). Selected profiles are illustrated in Figs. 8–10. Combined interpretation of the depth profiles of the different parameters enabled characterising the seasonal and the overall dynamic behaviour of the lakes.

Water temperature profiles

Water temperature profiles measured at the deepest points of the lakes exhibited a distinct thermal stratification during summer. As illustrated in Fig. 8, the stratification of the upper warm lake layer (epilimnion) extended up to approx. 10 m below the lake surface (m b.l.s.), the gradational zone (thermocline) continued to about 20 m b.l.s., and below it there is the cold water layer (hypolymnion). In summer 2006 and 2007, the water temperature range at the surfaces of the lakes lay between 20 and 25 °C. Two additional profiles were measured in a shallower part of the lakes along the longitudinal axis on quarterly basis. But the profiles depicted no clear summer stratification, although a tendency to develop a thermocline was evident.

In autumn the lakes started to cool, ultimately undergoing complete mixing during late autumn to winter, depending on the meteorological condition that prevailed in the region during the year. In Lake Prošćansko the onset of the lake turnover was about one to three months earlier than in Lake Kozjak. During the complete mixed state (homothermal condition), the water temperature in Lake Kozjak was about 4–6 °C, and in Lake Prošćansko about 6.5–8.5 °C. Complete mixed state persisted during winter in both lakes. Furthermore, the water surface of both lakes was frozen during winter.

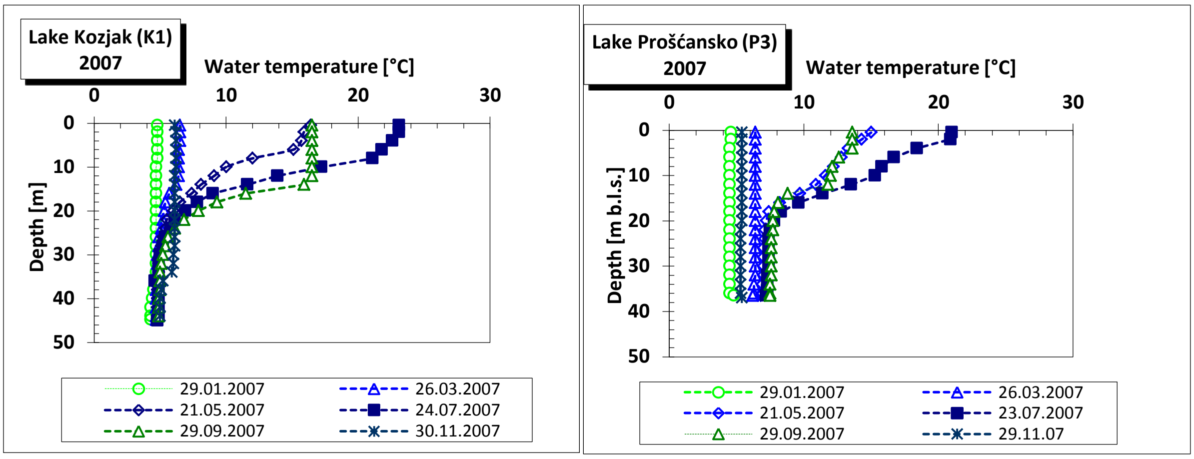

Figure 8: Depth profiles of water temperature in the deepest part of Lake Prošćansko and Lake Kozjak.

Dissolved oxygen content profiles

The vertical profiles of dissolved oxygen measured in the deepest parts of the lakes also depicted a distinct seasonal change (Fig. 9). Coinciding with the summer thermal stratification, concentration of dissolved oxygen content increased from about 10 mg/l at the lake surface to 16–18 mg/l in the middle part of the thermocline and then decreased downward. This was particularly evident in the profiles measured at K1. Dissolved oxygen concentration dropped to less than 5 mg/l at the lower lake depths. In fact it was almost completely depleted at the lake bottom. This was attributed to the consumption of dissolved oxygen content in oxidation reactions in the hypolimnion and to mud at the lake bottom containing organic matter. During the lake turnover time (late autumn – winter) the dissolved oxygen content was uniform for most of the lake water column (about 11–12 mg/l).

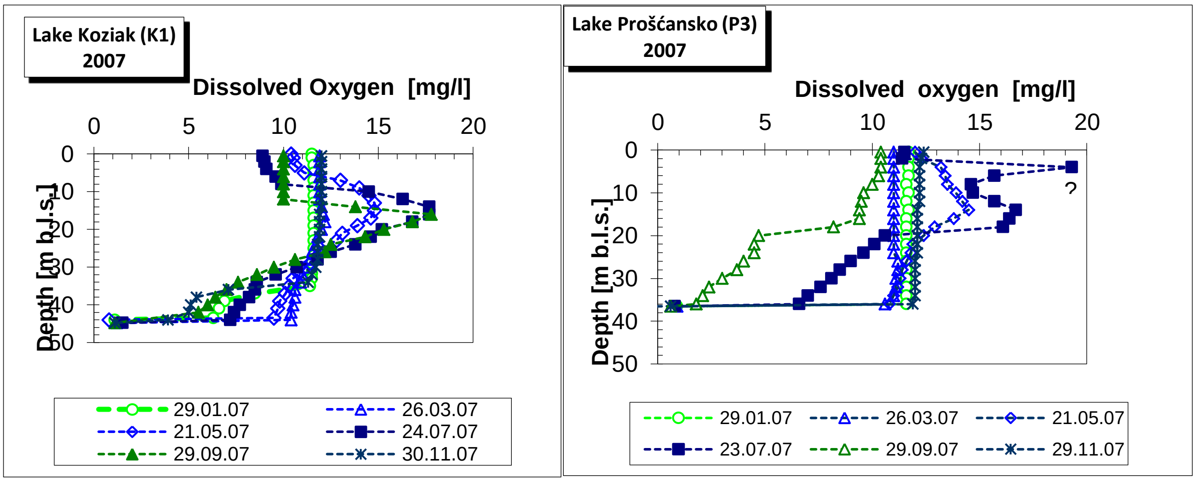

Figure 9: Depth profiles of dissolved oxygen content in the deepest part of Lake Prošćansko and Lake Kozjak.

Carbonate species (Ca^{2+}, Mg^{2+} and HCO_3^-) profiles

Concentration of Ca^{2+} and HCO_3^- in the lake water columns exhibited a significant temporal variability. In contrast, most likely attributed to the kinetic hindrances to dolomite precipitation in the lakes, Mg^{2+} concentration was seasonally invariable. As mentioned elsewhere, dolomite precipitation in a carbonate groundwater system is so sluggish that the ions involved persist to remain in solution for long periods of time with little or no dolomite precipitation (FREEZE & CHERRY, 1979).

Vertical profiles of carbonate species in the lakes are illustrated in Fig. 10. In general, the seasonal variability of Ca^{2+} and HCO_3^- concentration is more manifested in the shallow parts of the lakes and lower in the bottom parts of the lakes. Profiles measured in summer showed an increasing tendency from the lake surface to the lake bottom. Concentration of Ca^{2+} and HCO_3^- increased from approx. 50 mg/l to 60 mg/l and from 245 mg/l to 270 mg/l, respectively, in Lake Prošćansko, and from about 45 mg/l to 50 mg/l and from 230 mg/l to 255 mg/l, respectively, in Lake Kozjak. During the lake turnover (late autumn to winter) the vertical distribution of the Ca^{2+} and HCO_3^- was more or less uniform throughout the whole lake water column.

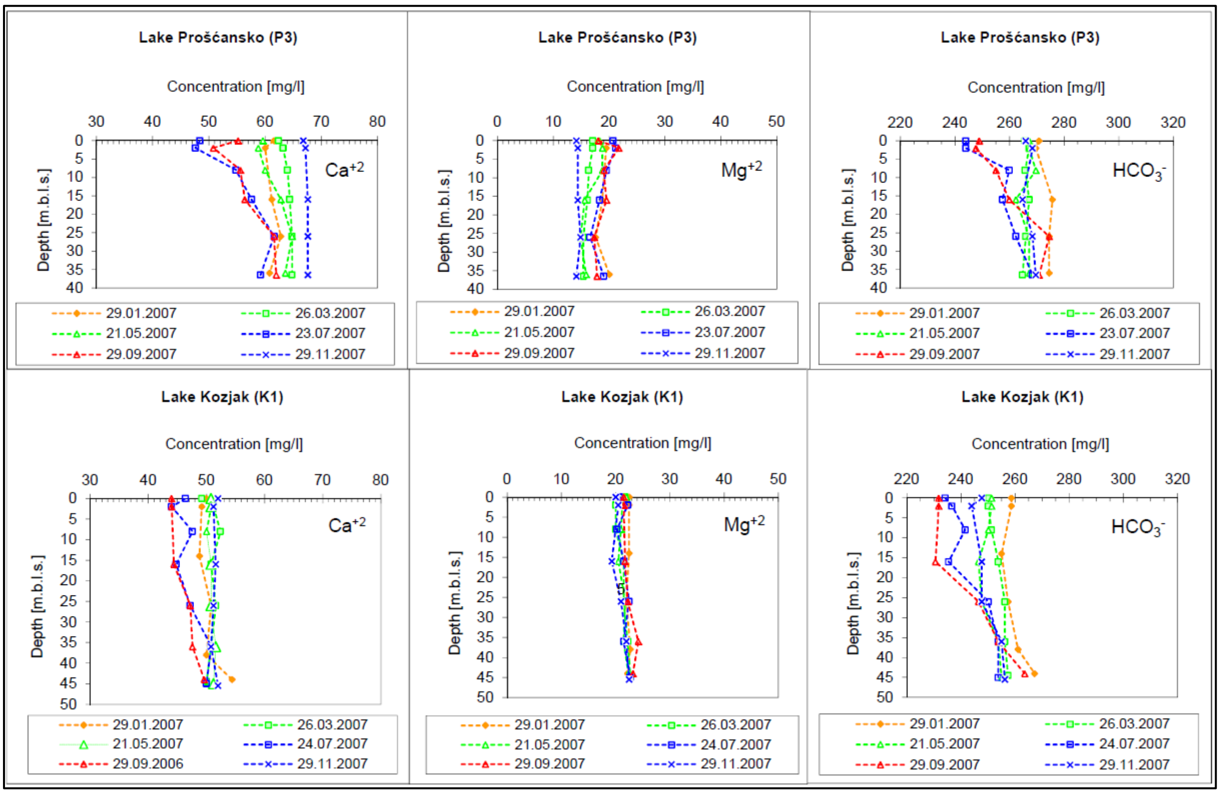

Figure 10: Depth profiles of carbonate species (Ca2+, Mg2+ and HCO3–) in the deepest part of Lake Prošćansko and Lake Kozjak.

SI_{cal}, SI_{dol} and P_{CO2} profiles

Vertical profiles of the computed parameters SI_{cal}, SI_{dol} and P_{CO2} (functions of the pH, concentration of the carbonate species and water temperature) are shown in Fig. 11. Seasonal changes of these parameters were small in Lake Kozjak, whereas in Lake Prošćansko a larger variability of these parameters was observed, especially in middle part of the lake.

Except in the bottom part of the lakes, the lake water column was oversaturated with respect to calcite and dolomite (SI values > 0). The degree of oversaturation with respect to dolomite exceeded that of calcite in the upper part of the lakes in the spring to summer profiles. In general, the degree of oversaturation of calcite and dolomite minerals decreased towards the bottom of the lakes. At the lake bottom the lake water was most of the time quasi-saturated with respect to calcite (values close to SI = 0), but undersaturated with respect to dolomite (negative SI_{dol} values, and data points fall left of the vertical dashed line SI = 0). The vertical dashed line in the diagrams, corresponding to the equilibrium value SI = 0, served as a reference to elucidate the variation of the degree of saturation state of carbonate minerals in the lake water column.

The calculated equilibrium CO_2 partial pressure in the lake water column exceeded that of the CO_2 partial pressure in the air ($10^{-3.5}$ atm indicated as dashed line in the diagrams as reference). In the upper part of both lakes, the calculated P_{CO2} values were consistently close to –3 log atm and they increased from about 25 m depth to the bottom of the lakes. Also, the pH was low in the lower part of the lakes. Most likely decomposition of organic substances in the hypolimnion induced CO_2 release (P_{CO2} increase) and ultimately the drop of pH in the lower part of the lakes. This hydrochemical condition favoured the dissolution of carbonate minerals. In agreement with this, lower SI values of carbonate minerals were computed at the bottom part of the lakes.

During the lake mixing in January 2007 the vertical distribution of SI_{cal}, SI_{dol} and P_{CO2} was more or less consistent throughout the whole lake water column in Lake Prošćansko. But this was not the case in Lake Kozjak.

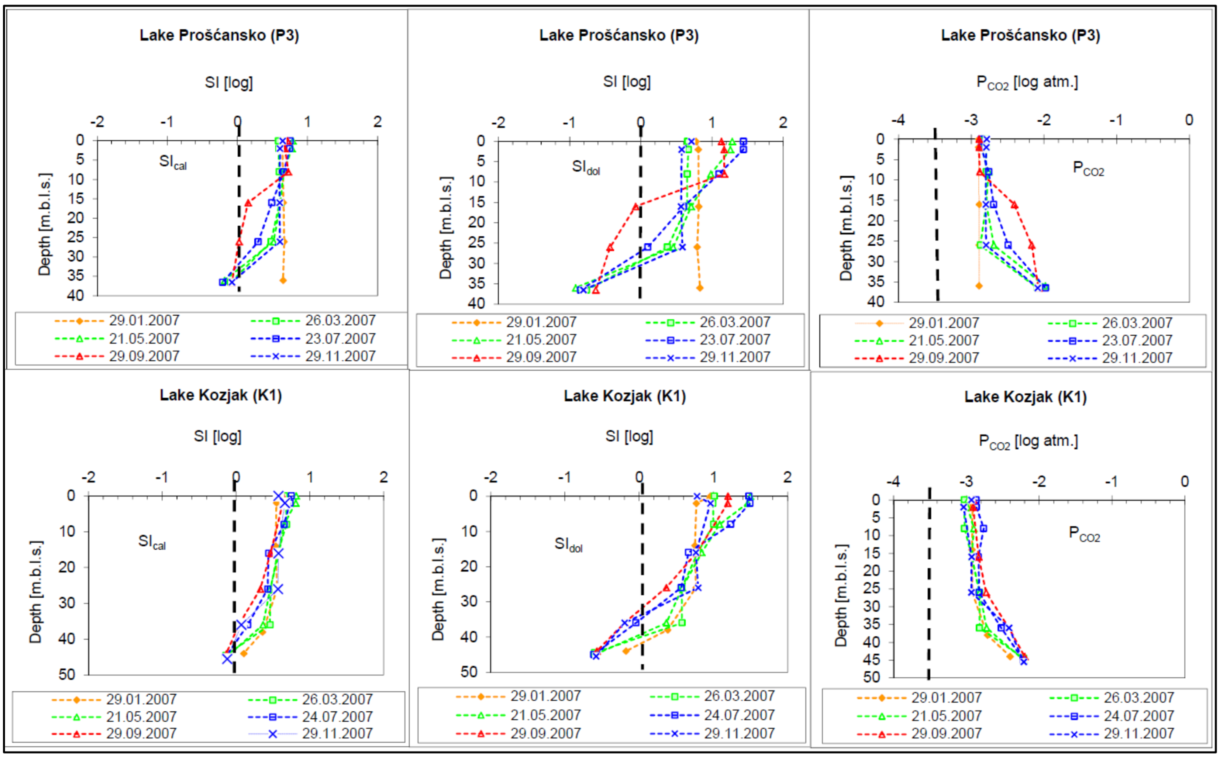

Figure 11: Depth profiles of SI_{cal}, SI_{dol} and P_{CO2} in the deepest part of Lake Prošćansko and Lake Kozjak.

Stable oxygen-18 isotope profile

Owing to stronger evaporation effects on the lake surface, the shallow part of the lake was enriched in heavy stable isotopes during summer. Vertical profiles of oxygen-18 from 2005 (during which stable isotope determination on lake profiles was performed regularly) are illustrated in Fig. 12. Consistent with the temperature profiles, the upper zone of Lake Kozjak (0–10 m depth) was relatively enriched in oxygen-18 content during summer (with $\delta^{18}O$ about –10.2 ‰), while the water samples from deeper lake columns were rather depleted (with $\delta^{18}O$ about –10.5 ‰). A similar trend was also observed in the shallower profiles (K2 and K3). In the case of Lake Prošćansko no clear isotopic stratification was observed, indicating a low evaporation effect in this lake. During the lake turnover time (late autumn – winter) the $\delta^{18}O$ content was consistent throughout the lake depth.

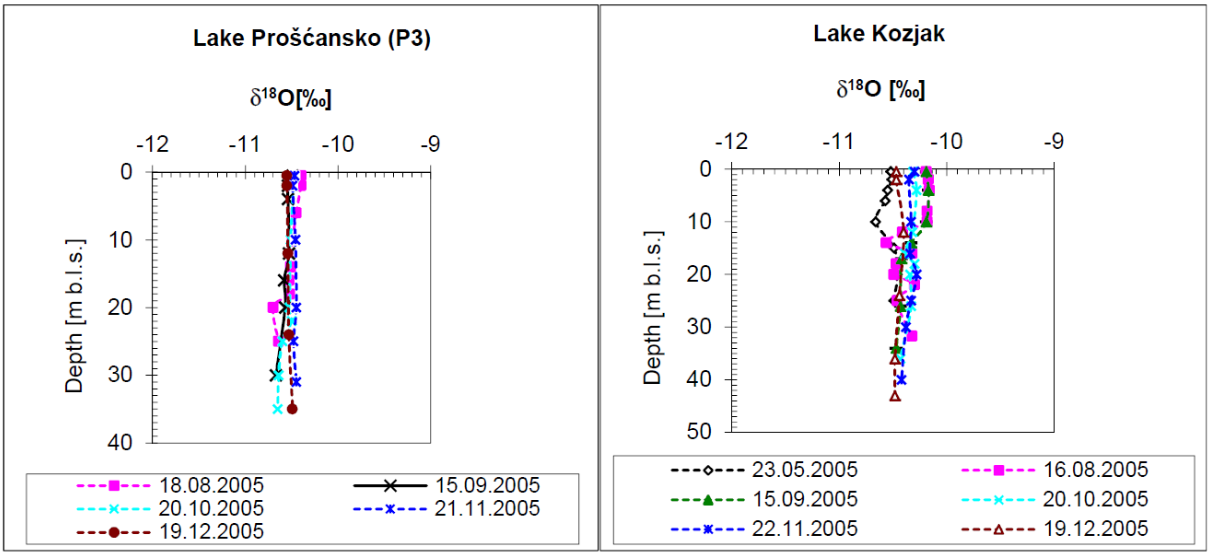

Figure 12: Depth profiles of stable oxygen-18 isotope content in the deepest part of Lake Prošćansko and Lake Kozjak.

Summary and concluding remarks

The Plitvice Lakes National Park (PLNP) is located in the Dinaric karst region of Central Croatia, close to the border with Bosnia Herzegovina. It is a very famous tourist destination, with up to one million tourists visiting the area every year. However, it must be underlined that the PLNP constitutes an ecologically highly sensitive area with its peculiar cascade lakes and the tufa barriers. Hence, prudence is absolutely necessary when exercising tourist activities. In this context, it is critical to figure out if the ongoing intensive tourist use of the PLNP is ecologically sustainable and is compatible with the park's protection requirements. To adequately evaluate these environmental issues, detailed understanding of the hydrologic characteristics of the karst springs and streams, the dynamic behaviour of the cascade lake basins and the overall hydrologic position of the Plitvice Lakes system is required.

The surface and subsurface drainage, and the overall hydrogeology of the PLNP area are determined by intensive karstification of the Mesozoic limestones and dolomites. Employing $\delta^{18}O$ altitude effect of –0.19 $\delta^{18}O$/100 m, representative for the Plitvice Lakes area, the mean recharge zone of the karst springs and streams was estimated at 980–1,020 m altitude. This isotopically determined average recharge altitude corresponds to the highly karstified limestones in the catchment area of the Plitvice Lakes, to the south and west in the mountainous region of Mount Mala that rises up to 1,200 m in altitude. The carbonate bed rocks there exhibit distinctive surface karst features (dolines or sinkholes), where intensive infiltration of precipitation occurs and, as a result, surface runoff is almost nil. Also, the $\delta^{18}O$ content and mean recharge altitudes of the streams Matica and Plitvica (MR and PP) closely resemble the respective karst spring outlets (WR_S, BR_S and P_S). This indicates that the drainage area of streams is situated at about 1,000 m altitude, which is consistent with the topographic and hydrogeologic setting of the carbonate rocks in the area. From the isotopically determined average recharge altitudes of the karst springs and streams it is clear that preservation of the karstified limestones at the higher mountainous region of Mount Mala Kapala is crucial for the protection of the karst springs, the ensuing streams and, ultimately, the cascade lakes.

The mean δ^2H and δ^{18}O values of the karst spring outlets (WR_S, BR_S), the ensuing streams inflowing to Plitvice Lakes (MR and RR) and those of P_S and PP are clustered along the LMWL. On the other hand, due to evaporation effect the isotope contents of the water samples from the different lake basins and river Korana are heavier and the δ^2H vs. δ^{18} data points plot on the right side of the LMWL. Furthermore, a successive evaporative enrichment of heavy stable isotopes is noticed in the cascade lake system. The upstream Lake Prošćansko is relatively isotopically depleted while the water samples from MIL, KAL and KR are the most isotopically enriched in the cascade lake system. The average isotopic values of the remaining basins, including the mean isotopic values of Lake Kozjak (depth- and time-averaged values of the depth profiles K1–3), BL, BAT, GAL and GRAD, fall in between

Additionally, the isotopic enrichment in the different lake basins has been quantified using the mean isotope content of the stream Matica River (MR), representing the main stream inflow to the lake system, as initial concentration (δ^{18}O and δ^2H contents –10.6 ‰ and –71.3 ‰, respectively). It revealed a successive isotopic enrichment from 0.7 % in Lake Prošćansko to slightly over 3 % in the most downstream lakes (MIL and KAL) with respect to δ^{18}O and from 0.2 % to 2.4 % with respect to δ^2H.

Hydrochemical composition of the various sampled waters in the Plitvice Lakes catchment area is weakly alkaline and dominated by the carbonate species Ca^{2+}, Mg^{2+} and HCO_3^- ions. On average, they are saturated to oversaturated with respect to calcite and undersaturated to oversaturated with respect to dolomite. A systematic spatial variation in the hydrochemical composition is observed from the carbonate spring outlets to the Plitvice Lakes outflow. This is clearly observed in the distribution of pH, Ca^{2+} and HCO_3^- ions, saturation indices of the carbonate minerals and specific electrical conductivity of the waters. On long-term average, the pH successively increased from 7.4 to 7.5 in the carbonate springs to about 8.3 in the surface water outflow from the lake system. On the other hand, concentration of Ca^{2+} and HCO_3^- ions decreased accordingly, from approx. 58–66 mg/l and 267–305 mg/l to 44 mg/l and 228 mg/l, respectively. The saturation indices of calcite increased from about 0 to 0.5–0.85 and dolomite saturation indices from below 0 to values as high as 1 to 1.5. The specific electrical conductivity dropped from > 415 µS/cm at 25 °C to 354 µS/cm at 25 °C. This hydrochemical change is mainly induced by degassing of the high pedologically derived CO_2 contents after the emergence of the karst springs and during the water flow through the streams and the cascade lakes. Ultimately, this brings about oversaturation of carbonate minerals and subsequent deposition of predominantly calcite as tufa (removal of Ca^{2+} and HCO_3^-) along the watercourses of the major streams and in the cascade lake system.

Indicating low man-made impacts on the water resources in the PLNP, the nitrate and phosphate concentration in the sampled waters is low, with average values of 1.5–6.5 mg/l and < 0.1 mg/l, respectively. The concentration of dissolved oxygen in these waters is in the order 8.0–9.5 mg/l. Generally, according to the Croatian regulations (NN 77/98), the large lakes Kozjak and Prošćansko are most of the year oligotrophic. Only after the end of the stratification period the deeper parts of these lakes are quite suboxic to anoxic and eutrophic to hypereutrophic at the bottom.

In the large lakes a distinct thermal stratification was observed during summer, where the upper warm lake layer (epilimnion) extended up to approx. 10 m below lake surface (m b.l.s.), followed by the gradational zone (thermocline) up to about 20 m b.l.s., and below it the cold water layer (hypolimnion) is represented. In autumn the lakes start to cool and ultimately undergo complete mixing during late autumn to winter, depending on the meteorological conditions that prevailed in the region during the year. Closely associated with the temporal variation of water temperature, the vertical profiles of dissolved oxygen measured in the deepest parts of the lakes also show distinct seasonal changes. During the lake turnover time (late autumn – winter) the dissolved oxygen content was uniform for most of the lake water column. Also, the concentration of the carbonate species (Ca^{2+} and HCO_3^-) varied seasonally to some extent in the deepest parts of the lakes, where an increasing tendency is noticed from the surface to the bottom of the lakes in summer. But during the lake turnover (late autumn to winter) they are more or less uniformly distributed throughout the lake water column. In contrast, the seasonal variation of Mg^{2+} concentration in the lakes is relatively small.

Hydrologic influxes to the Plitvice Lakes system include direct precipitation, stream inflows and non-channelised inflows, whereas water loss from the lake occurs through evaporation, river outflow and direct withdrawal from Lake Kozjak for water supply for the PLNP and surrounding settlements. Based on hydrometeorological data for the period 2001–2006, the mean inflow to the lake system is approximated at 2.91 m^3/sec (precipitation falling direct on the lake surface about 0.1 m^3/sec, surface water through the gauged streams Matica, Rječica and Sušanj 2.60 m^3/sec, and 0.20 m^3/sec via ungauged channelised and non-channelised inflow). The outflow from Lake Kozjak is approx. 2.81 m^3/sec, withdrawal from Lake Kozjak for water supply amounts to 0.06 m^3/sec and evaporation flux is about 0.03 m^3/sec. The mean residence time of water in the cascade lake system is approximated with three months.

Extending between 417 m and 1,280 m altitude, the PLNP is characterised by a relatively strong relief. Hence, the altitudinal effect on the distribution of precipitation and evaporation needs to be taken into account to exactly quantify the surface inflow from the ungauged channelised and non-channelised catchment area of the lake. Therefore, it is essential to install and monitor additional meteorological stations at different elevations in the catchment of the Plitvice Lakes. The lake water balance estimate can further be improved by again starting the monitoring of the stream of Sušanj and gauging other larger gorges so far not gauged.

The close match of the total inflow to with outflow from the lake system evidenced nonexistence of subsurface flux to/from the lake system. Also, the detailed hydrogeological investigations and exploration borehole drillings carried out at the downstream shore of Lake Kozjak gave no indication of any significant lake water seepage into the karstified Cretaceous limestone. Therefore, the Plitvice Lakes system acts hydrologically as a bathtub. The water entering the lake outflows into the river Korana after a relatively short stay in the cascade lakes without any significant loss from the lake basin into the adjacent karstified carbonate rocks.

A first significant infiltration into the underground occurs after the water leaves the lake system via the Korana river bed in the canyon between the confluence with the Plitvica and the Korana river gauge. Hydrogeological field investigations and exploration borehole data indicate appearances of karst landforms like caverns and shallow holes in the Cretaceous limestone outcropping in the canyon. This suggests a good permeability of the limestones in this area, an essential condition for intensive water loss through the streambed to the adjacent karst system. On average, approx. 25 % of the river runoff (0.85 m^3/sec) infiltrates the underground. A high water flow occurs at the upstream gauge stations (Kozjak and Plitvica) and at the river gauge Korana during spring and a low water flow in summer. The seasonal dynamics of river water infiltration become more discernible when the difference between long-term monthly water flow sums of Lake Kozjak and the stream Plitvica are compared to those of the river Korana (Fig. 13). Stream water loss is low in early spring, when the overall hydrologic flow condition in the area is high, where not only the surface water flow but also the groundwater level in the adjacent karst aquifer system rises in connection to snow melting. On the contrary, intensive stream water loss occurs during the dry period (in summer), when the overall hydrologic flow in the area recedes and groundwater levels in the adjacent karstified aquifers sink.

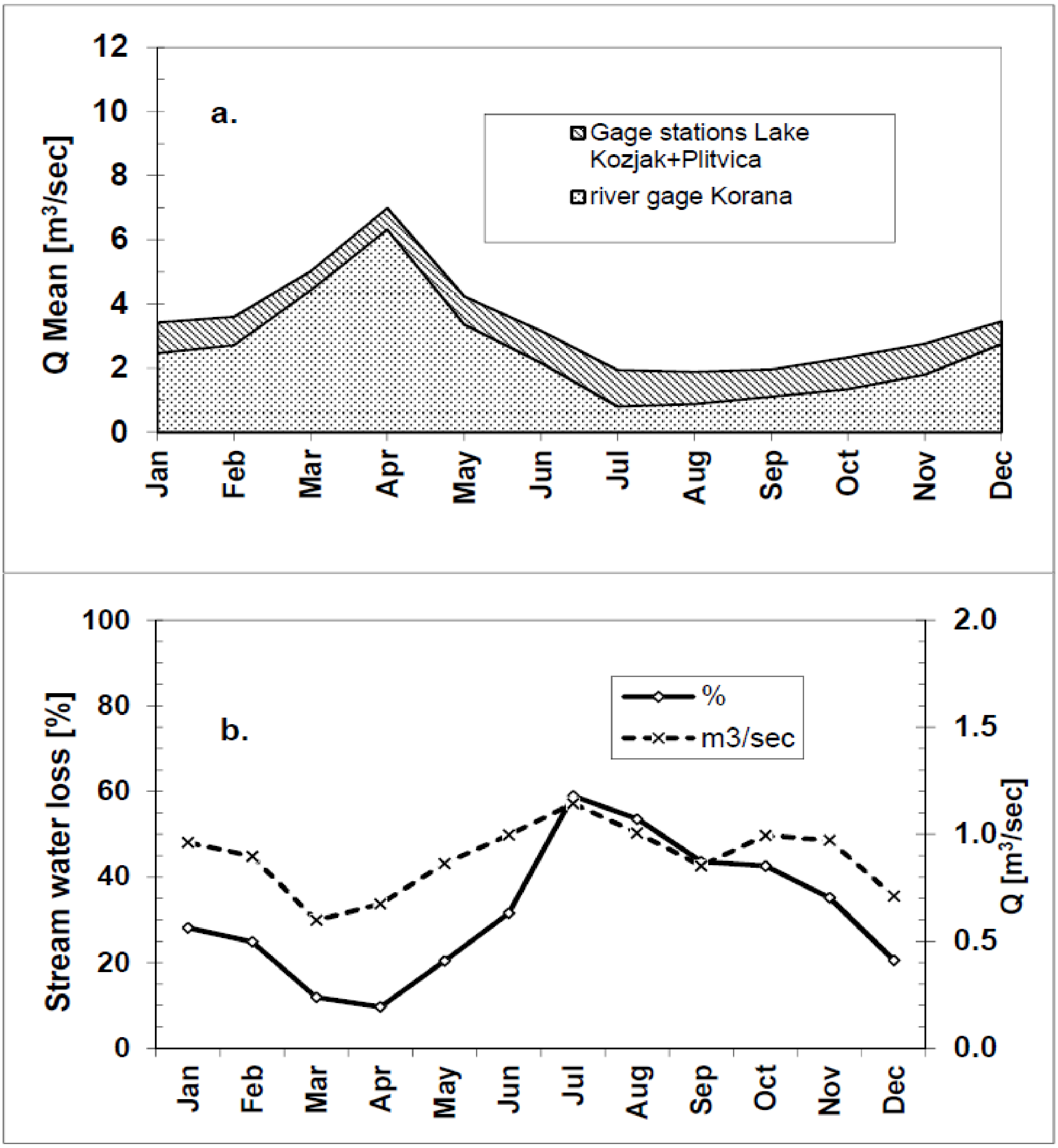

Figure 13a, b: Stream water infiltration through the river bed of Korana into the karstified Cretaceous limestones, downstream of the Plitvice Lakes system between the upstream gauge stations at Lake Kozjak and the tributary stream Plitvica (measured upgradient of Big Water Fall) and at the downstream river gauge Korana. ***a}*** *Comparison of the long-term mean monthly water flows (in* m^3*/sec) of the total of the gauging stations at Lake Kozjak and the stream Plitvica with water flow at the river gauge Korana.* ***b}*** *Water loss in the river bed of Korana determined as a difference between the total flows of Lake Kozjak and the stream Plitvica and that of the river Korana, expressed in* m^3*/sec and %.*

Untreated wastewater from the PLNP premises and adjacent settlements is directly disposed into a sinkhole downstream of the lakes within the national park area. This is threatening the water quality of a large karst spring called Klokot that emerges in the territory of Bosnia Herzegovina, near the town of Bihać. Interconnection of this karst spring with the sinkhole and the karstified Cretaceous limestones downgradient of the Plitvice Lakes has been established by dye tracing experiments. From the results of these tracing experiments an apparent flow velocity close to 985 m/day has been computed for the groundwater flow in the karst system. Hence, according to the Croatian Water Law (NN 55/02), the intensively karstified Cretaceous limestones downgradient of the Plitvice Lakes lie within the III sanitary protection area of the Klokot karst spring. Hence, disposing of untreated wastewater in this area is in contravention to the Croatian Water Law and a corrective solution to the problem needs to be sought.

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