International Conference
and Field Seminar

Karst Without Boundaries

In partnership of

In collaboration with

Other supporting partners and organizations

P R O C E E D I N G S

Edited by
N. Kukurić, Z. Stevanović, N. Krešić

11-15 June 2014
Trebinje (Bosnia & Herzegovina)
Dubrovnik (Croatia)

DIKTAS

Protection and Sustainable Use of the Dinaric Karst Transboundary Aquifer System

DELINEATION OF A KARST CATCHMENT AREA USING SEVERAL METHODS – AN EXAMPLE OF PLITVICE LAKES CATCHMENT

Hrvoje Meaški[1], Božidar Biondić[1] and Ranko Biondić[1]

[1]*University of Zagreb, Faculty of Geotechnical Engineering, Varaždin, Croatia;* *hmeaski@gfv.hr*

Key Words: Catchment protection, Karst hydrogeology, Plitvice Lakes, Dinaric karst

INTRODUCTION

The observed Plitvice Lakes Catchment (hereinafter PLC) area is approximately 152 km^2, belongs to the Black Sea catchment area, and is located in the central part of the Dinaric karst. PLC is the largest catchment within the Plitvice Lakes National Park whose total surface area is 296.85 km². This area has been designated a national park since 1949 due to its outstanding natural beauty, and for the same reason, has been included on the UNESCO List of World Heritage since 1979. The most prominent surface water occurrences within PLC are cascading lakes of various sizes. The biodynamic process of tufa barrier growth created those lakes and nowadays there are about 16 lakes, whose surfaces and forms are constantly changing over time (Fig. 1). The largest lakes are Kozjak and Prošćansko. Beside the well-known lake system, there are numerous permanent karst springs in the observed PLC, of which the most important arethe:CrnaRiver, BijelaRiver and Plitvica.Nowadays the Park receives about one million tourists per year; urbanization is encroaching upon the administrative boundaries, causing the human impact to be more pronounced in some parts. Therefore, it is no longer advisable, nor sustainable to restrict the majority of protection only to the narrow area around the lakes system. It is necessary to observe the Plitvice Lakes as a unique hydrogeological unit, composed of a series of interconnected small subcatchment areas. This delineation is not quite simple or unambiguous, and what proceeds is a suggestion of one such division into three subcatchments: Matica, Plitvica and Jezera. Never before have these areas been divided in such way (Meaški, 2011).

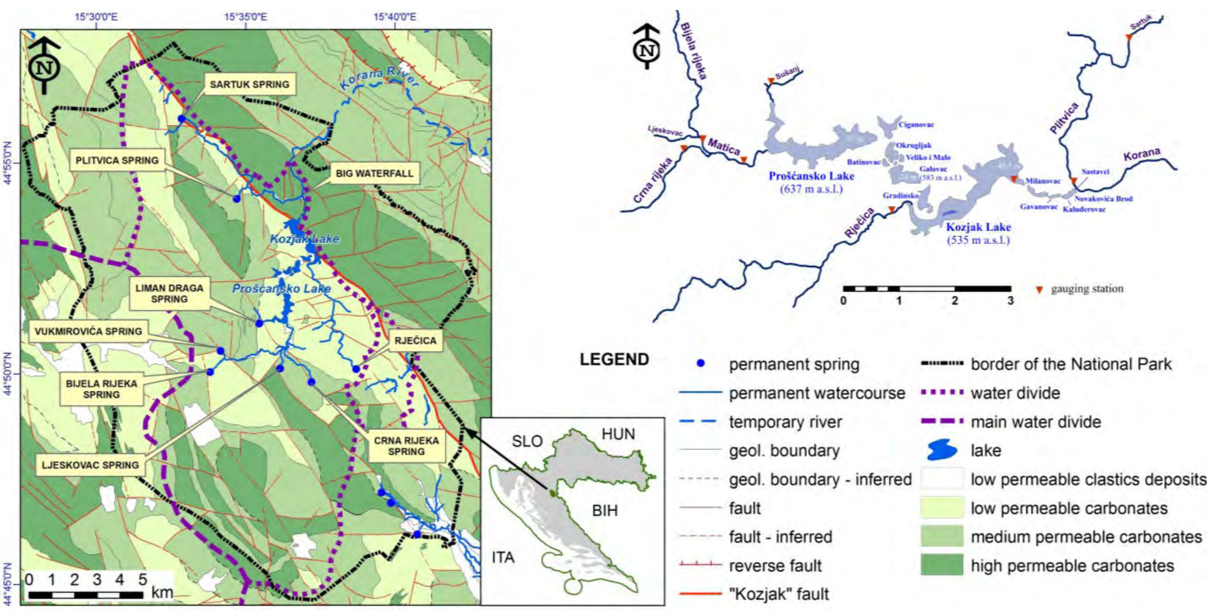


Fig. 1 Hydrogeological sketch (left) and sketch of lakes system (right)

METHODS AND RESULTS

Determination of the catchment area is the basis for all water balance calculations. It enables the estimation of groundwater and surface water quantities, as well as the identification of possible sources, the direction of water, etc. Delineation of the sub-catchment areas was carried out using three basic sets of data: hydrogeological, hydrometeorological and hydrochemical. Hydrogeological data represents the basic data that is needed to define the conceptual position of the catchments and subcatchments. Hydrological and meteorological analyses were used to quantify the presumed hydrogeological catchments, which were then confirmed by the iteration principle. Hydrochemical data was used for verification, mainly discrete data that is influenced by catchment area, i.e. by spatial data.

Hydrogeological research. The PLC is a part of the Dinaric karst area, an area in which the dynamics of groundwater are related to the process of karstification of carbonate rocks of Mesozoic age. Geotectonic and geodynamic evolution of the Dinarides (Dimitrijević, 1982; Herak, 1986; Korbar, 2009, etc.) has had a great impact on those processes. Hydrogeological characteristics and water permeability assessments of layers were determined according to existing structural data and the lithological composition of rocks. For this Basic Geological Map (Polšak et al., 1967; Velić et al., 1970), Geological Map of Plitvička jezera (Polšak, 1969)and other relevant data of this area was used (Herak, 1962; Biondić, 1982;etc.). Data collected in the field, the position of sources and sinks, karst geomorphological features as well as the results of tracing the wider area were taken into consideration during hydrogeological analyses. So far, research of the direction of groundwater flow in the Plitvice lakes has been performed on several occasions. By the end of 2012 in the PLC, and the immediate area, 17 tracing groundwater flows were carried out. More details about these tracing tests are available in Biondić et al., 2008 and Meaški, 2011.

Water balance determination. Spatial and temporal distribution of rainfall, particularly effective rainfall, runoff and evapotranspiration amount are the basic elements that are needed to calculate the water balance after assuming the hydrogeological catchment area. *Spatial distribution of rainfall* was obtained with respect to the available data of rainfall recorded in the reference period 1961-1990 (DHMZ, 2009). Point data was interpolated using the Spatial Analyst Tools module (ArcGIS software). Obtained mean annual precipitation (P) in the PLC area varying from 1200 mm to 1900 mm (Meaški, 2011). Isohyets have emphasized a NW-SE provision, which also coincides with the dominant provision of major mountains in this area. Effective precipitation (Pe) is part of the total precipitation that drains from the study area and can be obtained through the application of an empirical formula. In the PLC area the empirical formula of Žugaj (1995) was applied, which is especially suitable for the Dinaric karst catchments. Furthermore, based on the analysed precipitation data the runoff coefficient (c), which is very often used in scientific hydrological analysis (BonacciiJelin, 1988; Bonacci, 1999; Žugaj, 1995), was determined. In the analysis of the *spatial distribution of air temperature* is defined correlation between altitude and normal annual air temperature in the wider area for the reference period 1961-1990. The obtained result is the vertical temperature gradient of 0.5°C per 100 m of altitude (Meaški, 2011), which is in line with previous research (Zaninović et al., 2004). In order to calculate evapotranspiration (Et) in the research area the empirical formula of Turc (1954) and Coutagne (1954) was used. When using the Coutagne method it is essential that the correct equation in accordance with Coutagne parameter $\lambda$is chosen. In the case of the PLC the equation that satisfies the condition- precipitation $\geq 0.5/\lambda$, was selected. The resultant values of evapotranspiration are in the range of 420-540 mm according to Turc, and 400-520 mm according to Coutagne (Meaški, 2011).For the *hydrologic analysis* available data on discharges measured (Q) at water gauging stations within the PLC (DHMZ, 2009) were used. Most of them started operating in the early 1980s at a time when the majority of streams in the Croatian karst region had observed a long dry period (Žugaj, 1995). To obtain a sufficiently long time series of annual flow, analyses of homogeneity of time series were carried out using Wilcoxson (1945) nonparametric test and the relevant literature. The length of the hydrological series is validated according to the error size of the variation coefficient using the equation of UNESCO (1982) and Kritsky-Menkel (1961). More details can be found in Meaški (2011).

Tab. 1 Calculated hydrometeorological valuescompred with measured mean flowrates for the period 1981-2008

DESCRITPION	% of PLC	Area (km^2)	P (mm)	Pe (mm)	Et (mm)	c (Pe/P)	Q_{calc} (m^3/s)	$Q_{sr81-08}$ (m^3/s)
Bijela rijeka with Ljeskovac	13	20	1224	774	449	0.63	0.501	0.448
Crna rijeka	41	62	1245	791	454	0.64	1.54	1.364
Matica (direct catchment)	1	2	1273	798	475	0.63	0.042	*no data*
Sub-catchment MATICA	**55**	**84**	**1247**	**788**	**459**	**0.63**	**2.09**	
Average flow rate for the period 1981-2008 at the Matica River gauging station: 2.09 m^3/s								
Upper lakes (direct catchment)	10	10	1376	893	483	0.65	0.276	*no data*
Sušanj	3	5	1257	797	460	0.63	0.125	0.055
Rječica River	8	12	1455	969	486	0.67	0.383	0.426
Sub-catchment JEZERA	**18**	**28**	**1363**	**886**	**477**	**0.65**	**0.784**	
Average flow rate for the period 1981-2008 at the Kozjak Lake gauging station: 2.45 m^3/s								
Sartuk	7	10	1475	998	477	0.68	0,325	0.094
Plitvica spring	18	28	1374	919	455	0.67	0.807	*no data*
Plitvica River (direct catchment)	2	3	1452	959	493	0.66	0.077	*no data*
Sub-catchment PLITVICA	**27**	**41**	**1434**	**959**	**475**	**0.67**	**1.21**	**0.655**
Average flow rate for the period 1981-2008 at the Plitvica River gauging station: 0.655 m^3/s								
PLC TOTAL	**100**	**152**	**1348**	**878**	**470**	**0.65**		

Hydrochemical analyses

Measurement of physico-chemical parameters, water sampling and laboratory analysis of chemical composition in the PLC area were performed within the international research project (Biondić et al., 2008) during two hydrological years2005-2007. All observed points are shown in Fig. 3, and just some of the results in Tab. 2. Within isotope research, sampling and analysis of stable isotopes of water was carried out, which aimed to complete the picture of the natural water system; the identification of the mean recharge altitude of springs, the determination of the mean residence time of groundwater as well as understanding the processes of ionic changes in water and evaporation. The Local Meteoric Water Line (LMWL) was also obtained (Fig. 2). The content of stable isotopes $\delta^{18}O$ and δD in precipitation was determined from a composite sample of rainwater for the period 2003-2007.

Tab. 2 The average concentrations of major ions at certain observations points in the period IV/2005-XI/2007

DESCRIPTION & MARK	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	TDS
	shown as % of total dissolved solids								meq/l
Bijela rijeka spring (BR-I)	28	22	0.4	0.1	48	0.4	0.8	0.6	10.55
Crna rijeka spring (CR-I)	36	14	0.4	0.1	48	0.5	0.7	0.5	9.08
Matica River (M-R)	33	17	0.3	0.1	48	0.3	0.6	0.4	9.46
Rječica River (R-R)	26	24	0.2	0.1	49	0.2	0.4	0.3	11.16
Plitvica spring (PL-I)	32	18	0.2	0.1	48	0.6	0.4	0.8	9.78
Sartuka spring (SAR-I)	27	24	0.2	0.1	48	0.1	0.4	0.6	10.26
Ljeskovac spring (LES-I)	33	18	0.2	0.1	47	0.2	0.5	0.7	10.31
izvor Rječice (RJ-I)	27	24	0.1	0.1	49	0.0	0.4	0.0	11.22
PLC average based on all data (Biondić et al., 2008)	**29**	**21**	**0.3**	**0.1**	**49**	**0.4**	**0.5**	**0.4**	**9.73**

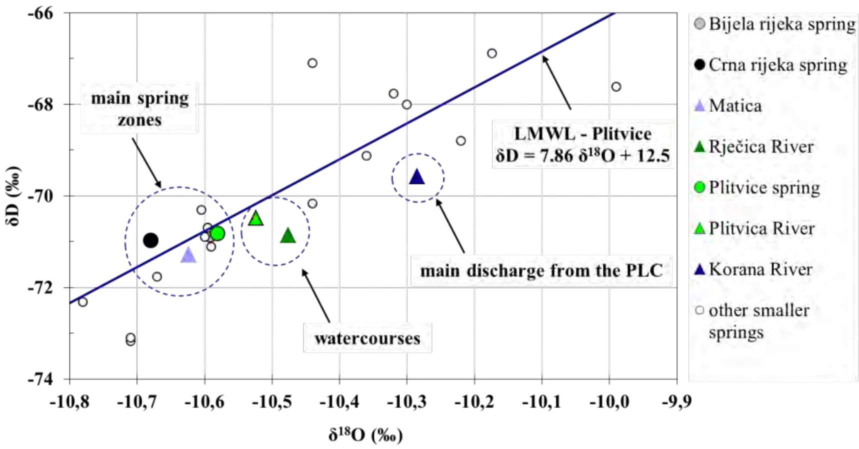
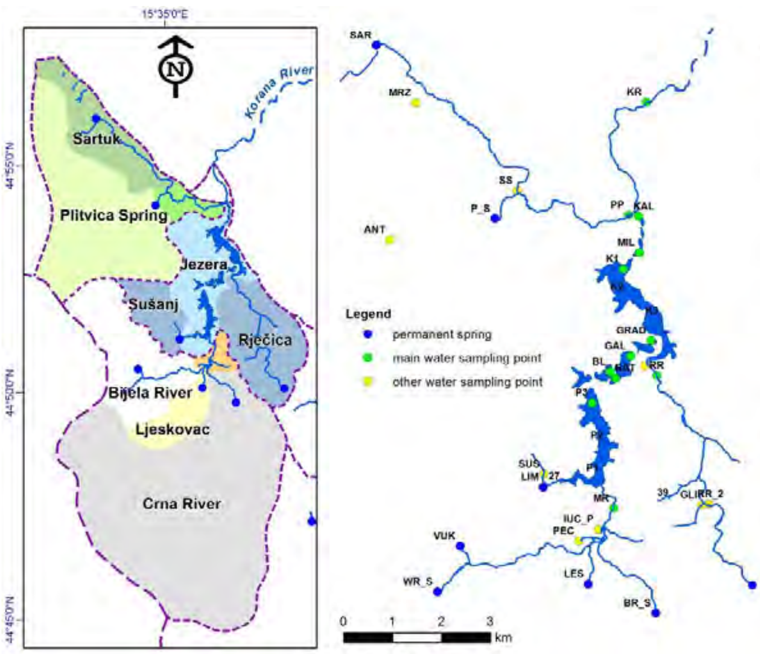


Fig. 2 Analysis of $\delta^{18}O/\delta D$ values for all major and some minor sources and streams in the PLC area

CONCLUSIONS

The PLC is a unique hydrogeological catchment because all waters are directed toward the lakes system, or the source area of the Korana River. However, due to specific hydrogeological conditions it can be divided into three main subcatchments: Matica, Plitvica and Jezera. Determination of smaller subcatchments within the PLC through the synthesis of research results that include: hydrogeological characteristics of the area, hydrochemical and isotopic analysis of water springs, and hydrological analysis of the surface water system. It should be noted that the final subcatchment surface area and its divides needs further confirmation in the future throughnew or detailed hydrogeological investigations.



LABEL	DESCRIPTION
ANT-I	izvor Antino vrelce
BAT-J	jezero Batinovac
BR-I	izvor Bijele rijeke
CR-I	izvor Crne rijeke
CU1-I	izvor na području Čujića Krčevine
CU2-I	izvor na području Čujića Krčevine
GAL-J	jezero Galovac
GLI-R	površinsko mjerenje Glibovitog potoka
GRA-J	Gradinsko jezero
IUK-I	izvor uz Kozjak
IUP-I	izvor uz Prošće kod PL.Ljeskovca
K-R	površinsko mjerenje rijeke Korane, selo Korana
KAL-J	jezero Kaluđerovac
KOZ-J	dubinski profil na Kozjaku
KUS-I	izvor u mjestu Kuselj
LES-I	izvorišna zona potoka Ljeskovac
LIM-I	izvor u Liman Dragi
M-R	površinsko mjerenje rijeke Matice
MIL-J	jezero Milanovac
MRZ-I	izvor Mrzla voda, pritok Sartuka
P-R	površinsko mjerenje potok na Plitvici
PEC-I	izvor Pećina
PL-I	izvor potoka Plitvice
PRO-J	dubinski profil na Prošću
R-R	površinsko mjerenje potoka Rječica
RJ-I	izvor uz Rječicu
SAR-I	izvorišna zona Sartuka
SAR-R	površinsko mjerenje potok na Sartuku
SUS-R	otvoreni vodotok potoka Sušanj
VEL-J	Veliko jezero
VUK-I	izvor Vukmirovića potoka

Fig. 3 Main subcatchments in the PLC, also labeled with small hydrogeological parts (left). Name and position of field measurements and water sampling points used for hydrochemical and isotopic analysis (right)

1. Matica subcatchment area includes all sources and watercourses that gravitate to the Matica River, which then inflow into the Prošćansko Lake. The most important are the Crna River, Bijela River and Ljeskovac and accordingly the subcatchment can be divided into three hydrogeological parts, respectively. Natural barrier for discharge from this karst catchment causes the appearance of low permeable dolomite of Triassic age. The total outflow from the subcatchment is measured on the Matica River at the gauging station "Matica". Matica River chemistry is a mixture of hydrochemical characteristics of above-mentioned main watercourses (Tab. 2).*Hydrogeological part of Crna River* consists of Liassic and Malm age limestones and dolomites that vary in the degree of water permeability. The main discharge zone is the Crna River spring (Fig. 3, Tab. 1). Emerging from the spring is an approximately 2.5 km long surface stream of the same name, which connects to the Bijela River and forms the Matica River. Along its course, the Crna River does not receive significant surface runoff. Total outflow is measured on the Crna River at the gauging station of the same name. *Hydrogeological part of Bijela River* almost entirely consists of Upper Malm age dolomites. It is a spatially complex catchment area due to the lack of reliable data on the direction of groundwater movements. The main discharge zone is the Bijela River spring (Fig. 3, Tab. 1), and the largest part of the catchment extends northwest from this zone, along the divide between the Adriatic and Black Sea catchment areas. From the spring emerges an approximately 4.5 km long surface stream called the Bijela River. Along its course, it receives numerous small tributaries, and just before the junction with the Crna River the Ljeskovac Stream flows in, which belongs to *Hydrogeological part Ljeskovac*. This is the only watercourse located betweem the Bijela and the Crna River. It begins as a series of minor karst springs, approximately 2 km before the junction with the Bijela River. Higher parts of the basin consist of Upper Malm age carbonate sediments, while the lower parts mainly consist of Doger age limestones. The total outflow from the Bijela River and Ljeskovac Stream are measured on the Bijela River at the gauging station of the same name.

2. Plitvica subcatchment area includes all waters that gravitate to the Plitvice River, which over the Big Waterfall (78 m height) influences in the area called Sastavci where merges with waters coming from the lakes system. This is also known as the beginning of the Korana River. The total outflow from this subcatchment is measured on the Plitvica River at the gauging station "Plitvica most". Subcatchment could be further divided into hydrogeologicparts of Sartuk, Plitvica Spring and Plitvica River. *Hydrogeologic part of Sartuk* includes the area drained by the small Sartuk stream, which is formed after the merging of several small springs in the area and consists of poorly permeable dolomite of Triassic age. Division is based partly by the topography setting, and partly by the parallel contact of less permeable carbonate rocks of Liassic age and well permeable rock of Doger age. In general, there are plenty of major water loss indications in this part of the PLC area (Tab.1). *Hydrogeological part of Plitvica Spring* consists of Lower Cretaceous and Doger age limestones, which here represent the main aquifers. Hydrogeological conditions are affected by the significant longitudinal fault known as Kozjak fault, which separates Doger and Malm ages carbonate sediments. *Hydrogeological part Plitvica River* includes direct, predominately surface catchment area of the watercourse itself.This separation isdue to the specific problems of water loss along the main river flow, which are the most pronounced at the BigWaterfall; during summer dry periods it almost dries up (Biondić et al., 2010; Meaški, 2011).

3. Jezera subcatchment area includes all surface water inflow into the lakes system. The Matica River flows in this subcatchment, too. However, aside from it, the most significant direct inflows are Rječica River and Sušanj stream. Due to that, this subcatchment can be divided into three hydrogeological parts. *Hydrogeological part of Jezera* covers the area of the lakes themselves and their direct inflow area. In a hydrogeological sense, it consists of poorly water-permeable dolomites of Triassic age, which also form the base ofthe Upper Lakes and the largest part of the Kozjak Lake. The eastern part of this area is confinedby good water-permeable limestones of Upper Cretaceous age, and according to conducted tracing tests those areas belong to the Klokot Spring catchment area located in the neighbouring state of Bosnia and Herzegovina. *Hydrogeological part of Sušanj* mainly consists of lower permeable dolomite of Malm age. The surface water drains to the Sušanj stream, which is intermittent upstream, while downstream it has a permanent flow. Shortly before entering the Prošćansko Lake this stream receives water from permanent source zone in Limanska Draga. *Hydrogeological part of Rječica* is located in an area consisting of low permeable dolomites of Triassic age. There are no greater karst springs in this area but present is a well-developed surface network of streams, which are drained toward permanent surface flow the Rječica River. This watercourse flows into the Kozjak Lake at approximately 535 m a.s.l.

REFERENCES

Biondić, B., 1982. *Hidrogeologija Like i južnog dijela Hrvatskog primorja*. Doktorska disertacija. PMF, Sveučilište u Zagrebu, Zagreb, 214 p.

Biondić, B., Biondić, R., Meaški, H., 2010. *The conceptual hydrogeological model of the Plitvice Lakes*. Geol. Croatica, 63(2): 195- 206.

Biondić, B., Zojer, H., Yehdegho, B., Biondić, R., Kapelj, S., Meaški, H., Zwicker, G., 2008. *Održivo korištenje i zaštita vodnih resursa na području Plitvičkih jezera, Završno izvješće*. Arhiv Geotehničkog fakulteta, Sveučilište u Zagrebu, Varaždin.

Bonacci, O., 1999. *Water circulation in karst and determination of catchment areas: example of the Zrmanja River*. Hydrol. Sci. J. 44(3): 373-386.

Bonacci, O., Jelin, J., 1988. *Identification of a karst hydrolgic system in the Dinaric karst (Yugoslavia)*. Hydrol. Sci. J. 33(5): 483-497.

Coutagne, A., 1954. *Quelqes considération sur le pouvoir évaporant de l'atmosphère, le déficit d'écoulement effectif et le déficit d'écoulement maximum*. 360-369.

Dimitrijević, M., 1982. *Dinarides – an outline of the tectonics*. Earth Evol. Sci. (1): 4-23.

Državni hidrometeorološki zavod, DHMZ, 2009. *Hidrološki i meteorološki podaci za područje Plitvičkih jezera, razdoblje od 1997. do 2007. godine.*

Herak, M., 1962. *Tektonska osnova hidrogeoloških odnosa u izvornim područjima Kupe i Korane (s Plitvičkim jezerima)*. Referati V. sav. geol. FNR Jugosl., Beograd, (3): 17-25.

Herak, M., 1986. *A New Concept of Geotectonics of the Dinarides*. Acta Geologica 16(1).

Korbar, T., 2009. *Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates*. Earth-Science Reviews, 96: 296-312.

Kritsky, S.N., Menkel, M.F., 1961. *On the regularities of long term river flow fluctuations and on the methods of estimation of lingering droughts*. Hydrol. Sci. J., 6(2): 34-40

Meaški, H., 2011. *Model zaštite krških vodnih resursa na primjeru Nacionalnog parka „Plitvička jezera"*. Doktorska disertacija. RGN, Sveučilište u Zagrebu, Zagreb, 211 p.

Polšak, A.1969. Geološka karta Plitvičkih jezera, M 1 : 50 000. Kartografski laboratorij Geodetskog fakulteta, Arhiv PMF Sveučilišta u Zagrebu, Zagreb.

Polšak, A., Šparica, M., Crnko, J., Juriša, M., 1967. *Osnovna geološka karta SFRJ M 1:100000. list Bihać*, L 33-116. Arhiv Hrvatskog geološkog instituta, Zagreb.

Turc, L., 1954. *Calcul du bian de l'eau evaluation en fonction des precipitations et des temperatures*. IASH Symposium, Rome, 111(38):188-202.

UNESCO, 1982. *Methods of computation of low streamflows*. Paris.

Velić, I., Bahun, S., Sokač, B, Galović, I., 1970. *Osnovna geološka karta SFRJ, M 1:100000, list Otočac*, L 33-115. Arhiv Hrvatskog geološkog instituta, Zagreb.

Zaninović, K., Srnec, L., Perčec Tadić, M., 2004. *Digitalna godišnja temperaturna karta Hrvatske*. Hrv. meteorološki časopis, 39: 51–58.

Žugaj, R., 1995. *Regionalna hidrološka analiza u kršu Hrvatske*. Hrvatsko hidrološko društvo, Monografije br. 1, Zagreb, 139 p.

ISBN 978-99938-52-58-2

DIKTAS