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Tracer methods used to verify the hypothesis of Cvijić about the underground connection between Prespa and Ohrid Lake

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Abstract Prespa Lake and Ohrid Lake constitute a hydraulic system shared between Albania, FYR of Macedonia and Greece. Karst rocks separate both lakes. The elevation of Prespa Lake is about 150 m higher than that of Ohrid Lake. Considering these facts, Cvijić formulated in 1906 the hypothesis that Prespa Lake recharges the St. Naum and Tushemisht springs at Ohrid lakeside. Environmental isotopes demonstrated that Prespa Lake recharges about 37–42 and 52–54% of water emerging in St. Naum, and Tushemisht springs, respectively. An artificial tracer experiment carried out in 2002 physically demonstrated the underground connection between both lakes. This experiment confirmed the supposed underground connection and brought important information about the groundwater velocity, transit time, and karst water conduits development.

Keywords Environmental isotopes · Artificial tracer experiment · Karst groundwater velocity · transit time · Karst water conduits · Albania

Geological and hydrogeological characteristics of study area

The small and big Prespa Lake and the Ohrid Lake share their water with Albania, FYR of Macedonia and Greece, and constitute a common hydraulic system (Figs. 1, 2). The elevation of the Prespa Lake is 850 m asl and that of the Ohrid Lake is 695 m asl. The respective surfaces are 274 and 348 km^2. High mountains such as the Mali Thate (2,287 m) in the south and the Galichica (2,262 m) in the north separate them. Geologically these mountains represent a horst constructed mainly of the Upper Triassic–Lower Jurassic massive limestone (AHS 1975). Big graben structures that of Prespa Lake on the east and Ohrid Lake on the west, delimit both sides of the horst. The Pliocene deposits such as clay, sandstone, and conglomerate fill most of the bottom of both lakes. At Ohrid lakeside, in the Albanian-FYROM borderland, are the big karst springs of St. Naum and Tushemisht, which in total

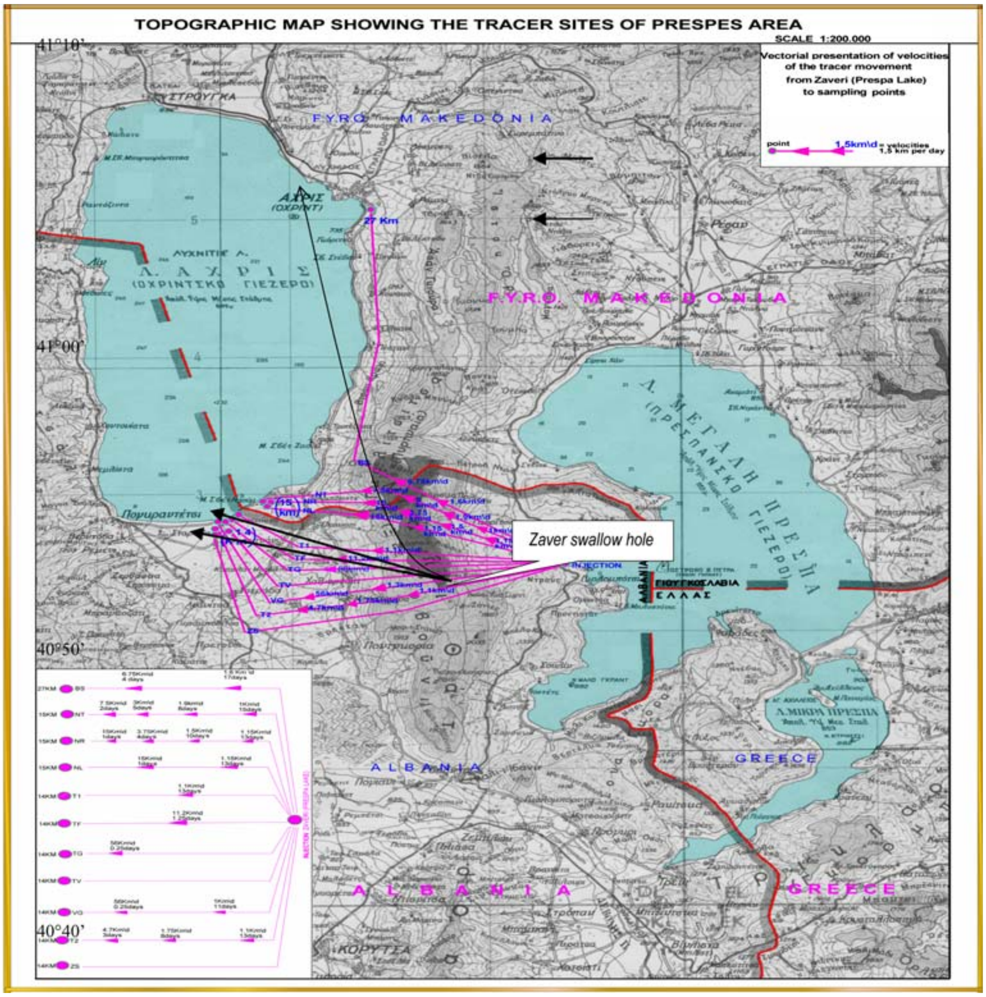


Fig. 1 Underground karst water connection between the Prespa Lake and the springs at the Ohrid lakeside

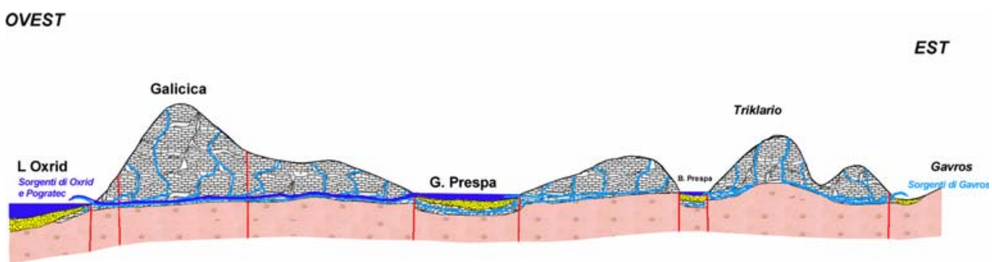


Fig. 2 Cross-section a in the Prespa–Ohrid karst massif

discharge about 255×10^6 m^3/year. Additional quantities of water drain into the lake as sub-lacustrine springs.

The Biljana spring (mean discharge about 0.5 m^3/s), which is about 22 km north of St. Naum spring, is another important karst spring of the area. Cvijić (1906) formulated the hypothesis that Prespa Lake recharges St. Naum and Tushemisht springs at Ohrid lakeside. By means of water balance calculations hydrologists were the first to demonstrate that Ohrid Lake receives about 7–10 m^3/s of water from Prespa Lake.

Environmental tracer approach

The altitude effect of stable isotopes of the meteoric waters (Bradley et al. 1972) was used to identify waters coming from different potential groundwater recharge sources of the study area. Figure 3 shows the correlation between mean δ^{18}O and δD values based on the results of isotope analyses from sampling points on the territory of FYR of Macedonia (Anovski et al. 1991) and Albania

(Eftimi and Zoto 1997). The slope of the Local Meteoric Water Line (LMWL) is 8, which is the same as that of the World Meteoric Water Line (WMWL), but the deuterium excess *d* is 14 instead of 10 of the WMWL. Such 'anomalous' values of intercept are characteristic for Eastern Mediterranean countries (Gat and Dansgaard 1970; Leontiadis et al. 1997). The slope of LMWL of the investigated lakes and springs is 5.4, which indicates that the water of sampled points has been influenced by excessive evaporation relative to the input. Environmentally stable isotopes ^{2}H and ^{18}O demonstrate that the Prespa Lake recharges St. Naum and Tushemisht springs, but the percentage of the lake water is not equal at different springs; it is bigger in Tushemisht spring than in St. Naum spring (Table 1).

Artificial tracer experiment

After the satisfactory results obtained with environmental stable isotopes, IAEA supported an artificial tracer experiment for additional physical confirmation of the connections between both lakes. This experiment also enabled the determination of some karst flow characteristics such as flow velocity, transit time, and character of underground flowpaths. Twenty kilograms of Sulphorhodamine G extra were injected on 18th of September 2002 into Zaveri swallow hole, in the Prespa Lake at 850 m asl. The sampling campaign at Tushemisht spring started on the same day, as well as at Biljana, St. Zaum (about 5 km north of St. Naum spring), and St. Naum springs one day later. The sampling campaign lasted until 10th December 2002. Two types of water sampling were applied, direct manual water sampling and sampling with charcoal bags (filled with activated carbon). Figure 4 shows the most significant tracer events at selected sampling points. The tracer appeared 6 h after the injection in the outlets of the

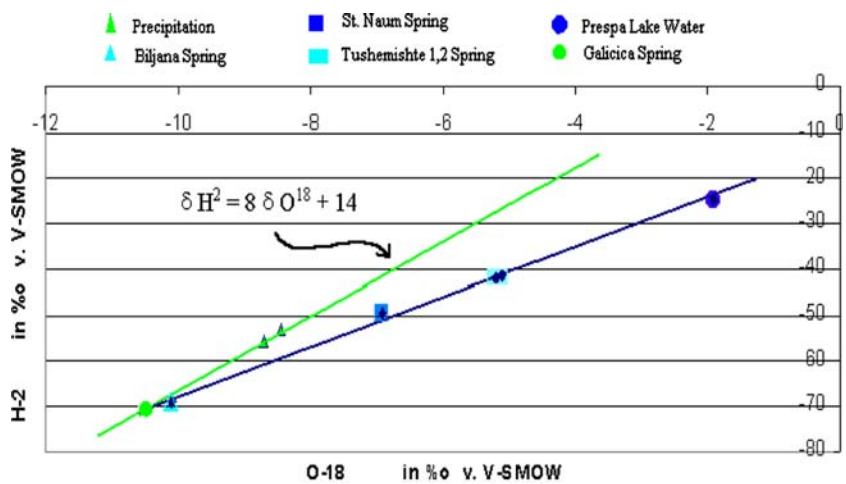
Table 1 The contribution of Prespa Lake to the recharge of karst springs at Ohrid lakeside (*PL* Prespa Lake water, *IP* Infiltrated precipitation in the karst massif)

Spring	Anovski et al. (1991)		Eftimi and Zoto (1997)		IAEA regional project RER/8/008, 2003	
	PL (%)	IP (%)	PL (%)	IP (%)	PL (%)	IP (%)
St. Naum	42	58			37	63
Tushemisht			52	48	54	46

Tushemisht spring and after 24 h in two sampled outlets of the St. Naum spring. The delayed appearance of the tracer in the St. Naum spring is related probably to the delay of one day of sampling at this spring. The concentration peaks at the other sampling points varied within a wide range.

The flow velocity (maximum velocity) toward the sampled points was calculated from air distance and flow time for first arrival of the trace at a particular point. Real velocities thus might be higher. Table 2 presents the measured and calculated values for flow time and flow velocity. The fastest water flow, which essentially differed among the outlets of the same spring, could be observed in Tushemisht and St. Naum springs. The maximum value of the flow velocity toward Tushemisht spring was 81 cm/s, which is much larger than the dominant velocities reported for Croatia (Garašic 1997) and China (Kogovšek and Petric 1997). The lowest flow velocity was calculated for Biljana and St. Zaum springs. Within the observation period of 83 days, the tracer did not appear at two other sampling points of the Tushemisht spring (village and Zagorchan), even though the environmental

Fig. 3 $\delta^{18}\delta D$ plot of waters from the area of lakes Prespa and Ohrid



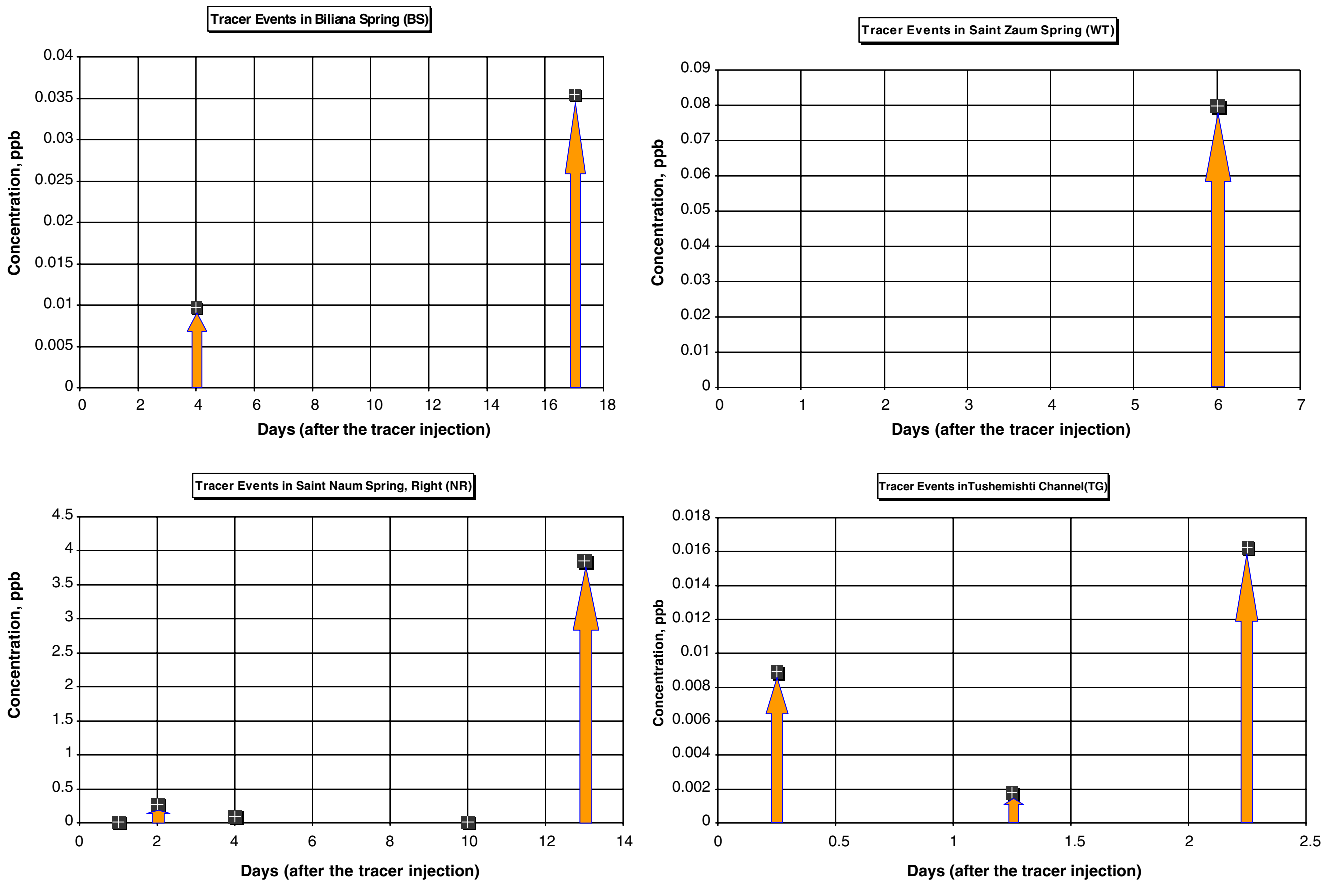


Fig. 4 Tracer events at selected sampling points

isotope study has demonstrated their connection with the Prespa Lake. The karst groundwater connection from Prespa Lake to Ohrid Lake seems to be very complicated. Most groundwater recharging the Tushemisht and St. Naum springs circulates obviously in well-developed bigger conduits, but also differently developed underground water passageways are present within short distances.

Conclusions

Environmental tracer methods (stable isotopes, hydrochemistry) confirmed the hypothesis of Cvijić about the underground connection between Prespa Lake and Ohrid Lake. Environmental isotopes demonstrated that St. Naum spring is recharged to 37–42% from Prespa Lake and Tushemisht spring is recharged to 52–54%, respectively. The results of the artificial tracer experiment showed a very complex groundwater circulation

Table 2 Air distance (*d*), mean hydraulic slope (*I*), tracer travel time for first arrival (*t*) and maximum velocity (*v*) of tracer between observed points

Spring	Sampling point	*d* (m)	*I*	*t* (h)	*v*	
					(m/h)	(cm/s)
Biljana		27.000	0.0056	408	66	1.8
St. Zaum		15.400	0.0099	144	107	3.0
St. Naum	Outlet (right side)	16.300	0.0094	24 (?)	679	18.9
	Outlet (left side)	16.000	0.0094	24 (?)	679	18.9
Tushemisht	Tunnel	17.500	0.0087	314	55.7	1.5
	Fish pond	17.500	0.0087	29	603	16.8
	Main channel	17.500	0.0087	6	2,917	81.0
	Village	17.700	0.0086	No appearance	–	–
	Voloreka	18.300	0.0084	80	229	6.4
	Zagorchan	18.300	0.0083	No appearance	–	–

system in the Galichica-Mali Thate karst massif. Big differences of measured maximum flow velocities indicate the presence of differently developed karst conduits at small-scale distances. Further investigations are necessary to quantify better the connection between Prespa Lake and Ohrid Lake.

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