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Hydrology of Blue Lake in the Dinaric karst

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Abstract:

The aim of this paper is to analyse hydrological measurements obtained from Blue Lake located near the town of Imotski (Croatia), during the period from 6 November 2009 at 10:26 h to 4 September 2010 at 03:26 h (7230 h or 302 days). The water depth, water temperature and electrical conductivity of the water were continuously measured during this period. The measurements were obtained with a CTD DIVER (Schlumberger Water Services). The instrument was fixed at the bottom of Blue Lake, which means that all the measured data refer to a single point of measurement. The data represent the first systematic and continuous monitoring of the hydrological parameters of this fascinating karst phenomenon. The hydrological analysis also involved daily rainfall data and daily mean air temperatures recorded at the nearby Imotski meteorological station. The rate of water level rise and fall and the hourly and daily average inflow and outflow into and from the lake were calculated using the available data. The analysis led to the conclusion that Blue Lake is mainly recharged by water coming from the karst aquifer, the dimensions and the characteristics of which have not yet been adequately studied. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS hydrologic budget; water depth; water temperature; electric conductivity; Dinaric karst

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INTRODUCTION

Blue Lake (local name "Modro jezero") near the town of Imotski (Croatia) represents a fascinating karst phenomena located in the central part of the bare Dinaric karst region. Located in its immediate vicinity, only approximately 500 m to the west, is Red Lake (local name "Crveno jezero"). Red Lake is permanently filled with water, whereas Blue Lake dries up periodically.

Although these two lakes are world-renowned karst features, to date they have not been the subject of detailed interdisciplinary scientific investigations. The available literature consists of a limited number of papers that describe only a few of their geological, geographical and geomorphological characteristics (Cvijic, 1893, 1926, 1960; Gavazzi, 1903/1904; Grund, 1903; Daneš, 1906; Roglic, 1938, 1964; Bögli, 1980; Milanovic, 1981, 2004; Bahun, 1991; Bonacci and Roje-Bonacci, 2000, 2008; Williams, 2004; Gams, 2005; Bonacci, 2006; Palandacic *et al*., 2012). The hydrological and hydrogeological characteristics of these two lakes have not been well investigated, if at all. The main reason for this is the lack of hydrological and hydrogeological measurements.

Because of the inaccessible nature of the karst terrain and the steep slopes above the lake shores, measurements are very difficult to obtain. Taking such measurements is expensive and sometimes even dangerous. The only available measurements (mostly involving topographical and geomorphological surveys) were undertaken during the period 26 April 1955 to 6 June 1956 (Petrik, 1960). At that time, the available technology could not provide reliable measurements and continuous monitoring for karst features that were so difficult to access due to the steep slopes. Today's technology based on CTD divers (Schlumberger Water Services) made it possible for us to collect continuous data from Blue Lake over the study period from 6 November 2009 at 10:26 h to 4 September 2010 at 03:26 h (7230 h or 302 days total). The following parameters were recorded: (i) water depth, H, (ii) water temperature, T_{water}, and (iii) electrical conductivity of the water automatically corrected to a standard temperature of 25°C, EC25. The nearby meteorological station at Imotski (N 43.4459; E 17.2181) provided records of daily precipitation, P, and the daily mean air temperature, T_{air}, that are also used in analysis. These systematic and continuous hydrological and meteorological measurements provide an improved scientific understanding of the hydrological functioning of Blue Lake.

EXISTING FINDINGS REGARDING BLUE LAKE

Figure 1 provides a map of the study area around Blue Lake. Some karst water phenomena in the vicinity, which could have a possible influence on the hydrological regime of Blue Lake, are marked on the map. The positions of the town of Imotski and the Imotski meteorological station are also indicated.

Blue Lake and Red Lake are collapsed dolines (Ford and Williams, 2007; Roglic, 1964; Zdilar, 2001). The processes of side slope degradation and fresh collapses are evident in both lakes. The steeper slopes of Red Lake indicate that Blue Lake is older than Red Lake

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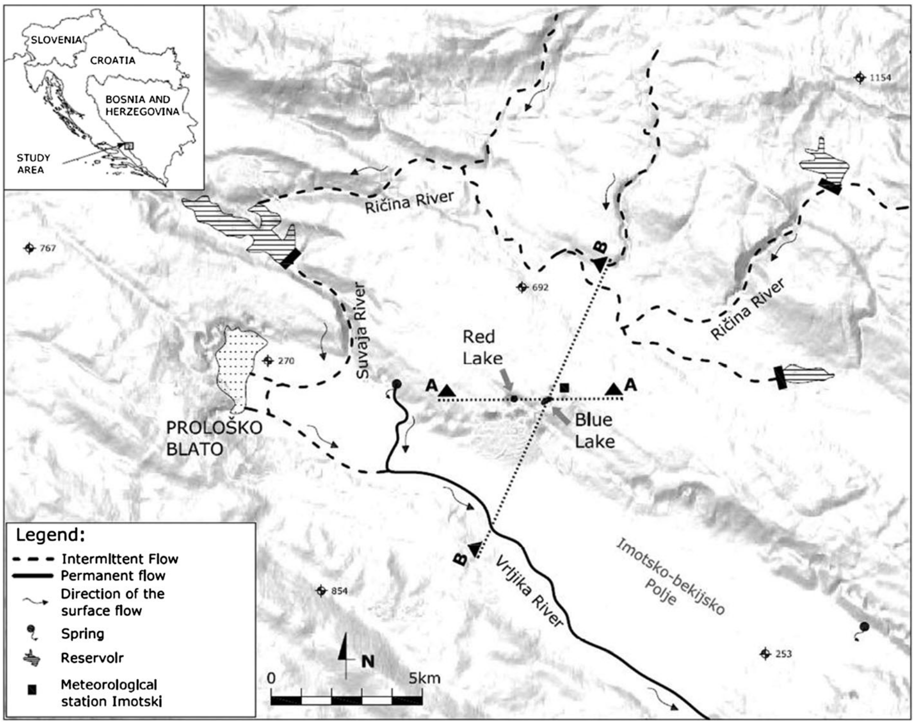

Figure 1. Location map of the study area

(Roglic, 1938, 1964). Although Gavazzi (1903/1904) and Cvijic (1926) considered the genesis of Blue Lake to be a consequence of the collapse of the roof of a vast cave, Roglic (1938, 1964) stated that Blue Lake presents a cylindrical shaped doline. In addition, he considered that Blue Lake was created by the coalescence of two neighbouring dolines and excluded the possibility that Blue Lake functioned as a sinkhole in the past, assuming that water inflow and outflow takes place only through its bottom. Bahun (1991) classified Blue Lake as a vast doline and Red Lake as a deep cave.

Figure 2 shows cross-sectional A-A, identified on Figure 1, which passes through both Blue Lake and Red Lake. The bottom of Blue Lake is covered by fine mud with the clearly visible funnels through which water runs into the karst beneath (Petrik, 1960). The latest geodetic measurements, performed in 2011, showed that the lake bottom has an altitude of 241.6 m a.s.l. (Figure 3). Petrik's (1960) old geodetic measurements, made more than 55 years ago, set the Blue Lake bottom at 239.0 m a.s.l. This is 2.6 m lower than the recently measured altitude. This significant difference can be accounted for in two ways. First, the discrepancy could reflect a measurement error due to the extremely difficult measuring conditions. Second, it could reflect sedimentation over the intervening 55 years or more. The second possibility is probably the best explanation because the northern side of Blue Lake provides evidence of recent erosion of rock material. On the southern side of the lake, the same processes first became visible after

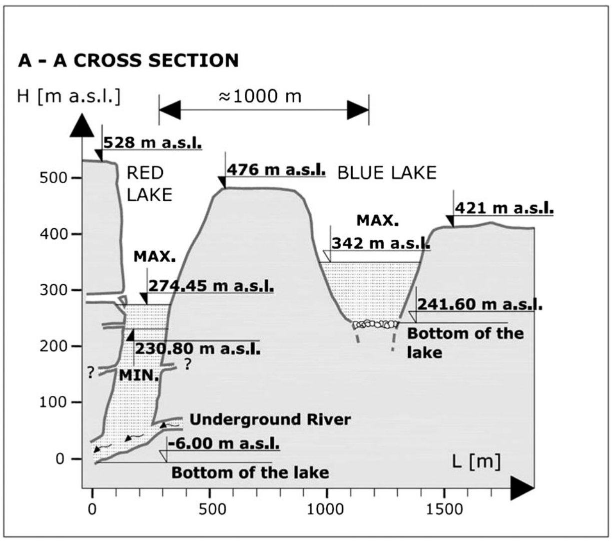

Figure 2. Cross-sectional A-A (Figure 2), which passes through both Blue Lake and Red Lake

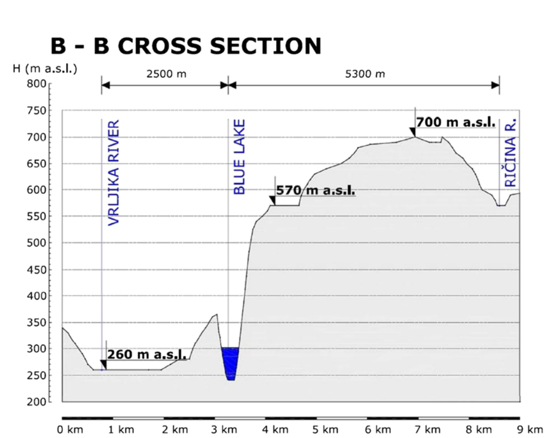

Figure 3. Cross-sectional B-B (Figure 2), which passes through the Ricina River, Blue Lake and the Imotsko Polje

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the 29 December 1942 earthquake, which was rated as magnitude 6 on the Richter scale. This strong earthquake caused large blocks of rock to collapse into the lake.

Ujevic (1991) made the assumption, which was not scientifically proven, that the 1942 earthquake led to the widening of the underground karst conduits, resulting in more frequent as well as longer dry periods when the lake was dry. After this earthquake, Blue Lake was dry for 2 months. Even before the earthquake, the lake would dry up on some occasions, as for example during the very dry year of 1935. The longest dry period for the lake was recently recorded during 2011 and 2012 and extended from 8 October 2011 to 20 February 2012, a total of 135 days.

The previously mentioned information led to the conclusion that Blue Lake belongs to a group of intermittent or periodic karst lakes. Intermittent or periodical karst lakes, or lakes that temporarily dry out, have a relatively high occurrence in the Dinaric karst (Ravbar and Šebela, 2004; Mulec *et al*., 2005). The most frequent reason for their drying out is the lowering of the groundwater level below the lake bottom.

Figure 2 presents the minimum and the maximum water level recorded in Blue Lake and Red Lake. It should be stressed that these minimum and maximum water levels are not based on reliable and continuous hydrological measurements. According to the unconfirmed historical record, the maximum water level in Blue Lake reached an altitude of 386 m a.s.l. This means that in this case the total maximum water depth of the lake was approximately 145 m. However, this record has not been confirmed, having being first cited by Gavazzi (1903/1904), and then subsequently quoted by numerous authors. According to Petrik (1960), the water level oscillation in Blue Lake is two to five times higher in amplitude than the oscillations in Red Lake. From the hydrogeological–hydrological standpoint, it is important to note that the water level in Blue Lake can be substantially higher than the contemporaneous water level in Red Lake, but it can also occasionally be lower. As there are no simultaneous long-term measurements of water level in both lakes it is impossible to analyse the relationship between the water levels in the two lakes or to formulate reliable conclusions regarding the possible similarities in the behaviour of the two neighbouring karst lakes.

Figure 3 presents the cross-sectional B-B, indicated on Figure 1. This cross section clearly shows the morphological complexity of the study area, which can lead to varying assumptions about the possible directions of groundwater circulation in this complex karst region. Petrik (1960) assumed that at least part of the water in Blue Lake originates from the sinkholes which are located along the thalweg of the Ricina River. He claimed that Red Lake and Blue Lake, as well as many other smaller karst lakes in the vicinity, are recharged by water from the same karst aquifer located in the north. The problem is that there are no tracing tests to confirm or refute his hypothesis. It is important to note that during the dry season, water levels in both lakes can fall below the level of the surface of the Imotsko Polje, which ranges in altitude from northwest to southeast, between 270 and 253 m a.s.l., respectively. Bojanic *et al*. (1981) claimed that the water from both lakes finally ends up in the Adriatic Sea in abundant submarine springs (vruljes) located approximately 23 km to the south, the outlets of which are located at a maximum depth of 38 m below the surface of the Adriatic Sea.

Figure 4 presents the relationships between (i) water depth, H, and water surface area, A; and (ii) water depth, H, and volume of water, V, for Blue Lake. The relationship between depth, H, and volume, V, is plotted in blue, whereas the relationship between depth, H, and the water surface area, A, is plotted in violet. According to these data, when the depth of the water in the lake reaches 85 m, which is at an altitude of approximately 427 m a.s.l., the volume of water stored in Blue Lake is approximately 645,000 m^3 and the water surface area is approximately 133,000 m^2.

THE ANALYSIS OF RECENT MEASUREMENTS CONDUCTED IN 2009 AND 2010

Using the CTD DIVER (Schlumberger Water Services), continuous hydrological measurements were undertaken during the period extending from 6 November 2009 at 10:26 h to 4 September 2010 at 03:26 h. An instrument fixed 20 cm above the bottom of Blue Lake (mount fixed to a concrete pedestal) recorded the following parameters: (i) water depth, H, (ii) water temperature, T_{water}, and (iii) the electrical conductivity of water, EC25, at hourly intervals.

Figure 5 presents a time series of Blue Lake daily mean water depths, H, water temperature, T_{water}, and air temperature, T_{air}, and daily precipitation, P, measured at the Imotski meteorological station over the period. Although the daily mean water temperature, T_{water}, varies within a narrow range, the daily mean air temperature, T_{air}, exhibits greater variability during the period of observation. The strong influence of precipitation on increases of water level can be seen. The precipitation measured at the Imotski meteorological station represents the rainfall regime of the wider region within which the still undefined catchment of Blue Lake is situated. The rainfall in the cold and wet part of the year, from November (beginning of the measurements) to the end of

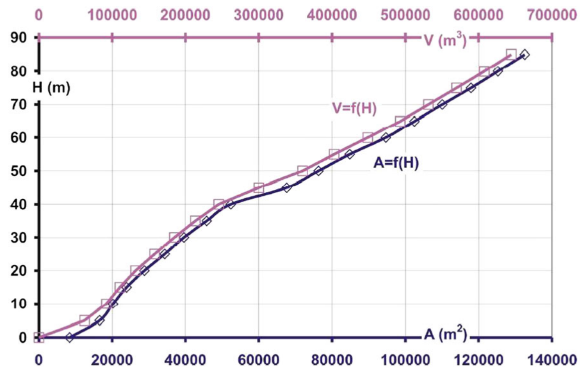

Figure 4. Two curves which characterise the morphometry of Blue Lake: (i) relationship between the water depth, H, and the water surface area, A, and (ii) the relationship between the water depth, H, and the volume of water, V

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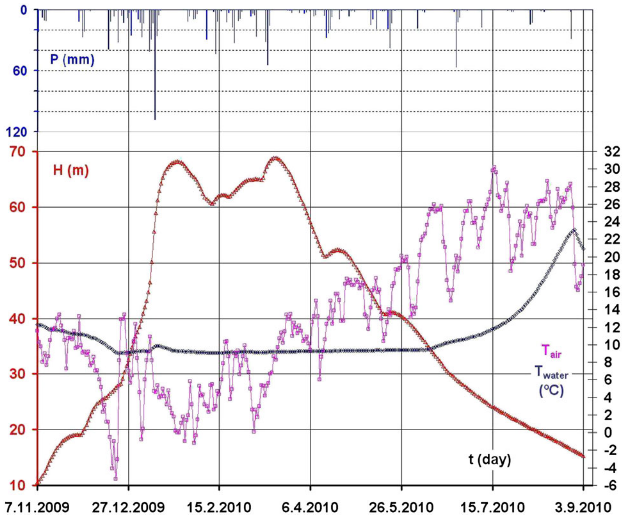

Figure 5. Time series of the daily mean water depth, H, water temperature, T_{water}, air temperature, T_{air}, and daily precipitation, P, measured at the Imotski meteorological station measured over the study period

May, caused the water level to rise at different rates. It should be noted that the rainfall in June, especially the 77.9 mm, measured during the period between 20 and 23 June 2010, did not cause the water level in Blue Lake to rise.

Table I presents the characteristic (minimum, average and maximum) hourly and daily values of the five hydrological and climatological parameters recorded for Blue Lake and at the Imotski meteorological station. The characteristic air temperature, T_{air}, and precipitation, P, parameters are shown in italics.

Table II presents the 20 highest rates of water level rise and fall, r, expressed in centimetres per hour. It should be noted that the rate of water level rise is greater than the rate of lowering. This can be explained by the fact that the water level in the lake is primarily controlled by groundwater recharge, for which the rate of rise is significantly higher than the rate of lowering (Bonacci, 1995; Bonacci and Roje-Bonacci, 2012).

Figure 6 represents a time series of the characteristic (maximum, average and minimum) monthly water temperature, T_{water}, of Blue Lake, the air temperature, T_{air}, at Imotski and the water depth of the lake, H, measured between November 2009 and August 2010. Table III presents the monthly mean values of three parameters measured in Blue Lake (H, EC25 and T_{water})

Table I. Characteristic (minimum, average and maximum) hourly and daily values of the five hydrological and climatological parameters recorded in Blue Lake and at the adjacent Imotski meteorological station

	H (cm)	EC25 (μS/cm)	T_{water} (°C)	T_{air} (°C)	P (mm)
Minimum	1032	301	8.95	*−5.30*	*0*
Average	4027	411	10.99	*13.52*	*9.84*
Maximum	6896	438	23.27	*30.20*	*107.8*

Daily values are italicized.

Table II. The 20 highest rates of water level rise and fall, r (cm/h), measured in Blue Lake over the study period

No.	r (cm/h) Rising	Falling
1	35	−19
2	34	−19
3	34	−18
4	33	−17
5	32	−17
6	32	−16
7	31	−16
8	30	−16
9	28	−15
10	28	−15
11	28	−15
12	26	−15
13	26	−15
14	25	−14
15	24	−14
16	24	−14
17	24	−14
18	24	−14
19	23	−14
20	23	−14

and two parameters measured at the Imotski meteorological station (P and T_{air}) for the 10 months of continuous measurements (between November 2009 and August 2010). Figure 6 illustrates the behaviour of the differences between air and water temperatures for the study period more clearly than Figure 5. When the water depth is greater than 35 m the water temperature measured at the bottom varies over a very narrow range from 9.05°C to 9.50°C. The influence of air temperature on the water temperature is evident for the water depths lower than approximately 27 m. This influence increases as the depth decreases. The air temperatures are lower than the water temperatures in the cold season. In March, both temperatures are similar, and from April onward, the air temperature is greater than the water temperature measured at the bottom of Blue Lake.

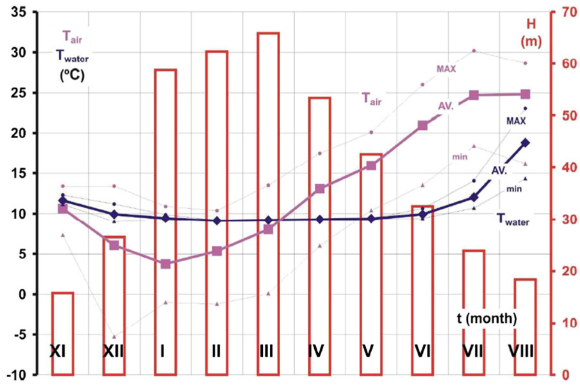

Figure 6. Time series of the characteristic (minimum, average and maximum) monthly water temperature, T_{water}, of Blue Lake, the air temperature, T_{air}, at Imotski and the water depth of the lake, H, measured between November 2009 and August 2010

Table III. Monthly mean values of the three parameters measured in Blue Lake (H, EC25 and T_{water}) and the two parameters measured at the Imotski meteorological station (P and T_{air}) for the study period

Month and year	H (m)	EC25 (μS/cm)	T_{water} (°C)	T_{air} (°C)	P (mm)
November 2009	16.00	346	11.7	10.6	62.3
December 2009	26.76	377	9.93	6.06	223.8
January 2010	58.99	423	9.42	3.75	310.7
February 2010	62.60	422	9.12	5.35	227.3
March 2010	66.09	424	9.19	8.02	153.2
April 2010	53.64	424	9.28	13.1	115.1
May 2010	42.79	424	9.37	16.0	134.4
June 2010	32.76	429	9.93	20.9	100.6
July 2010	24.11	432	12.0	24.7	34.7
August 2010	18.48	404	18.8	24.8	44.3

A more detailed analysis of the relationship between water and air temperature during the study period is provided by Figure 7, which presents the relationship between the contemporaneous values of daily mean water temperature for Blue Lake, T_{water}, and the air temperature at Imotski, T_{air}. The existence of three subperiods can be seen. In the first subperiod (between 7 November and 20 December 2009), when the water depths in the lake varied within the range 15.04 m to 35.10 m, the water temperature decreases when the air temperature decreases. The second subperiod (between 21 December 2009 and 8 June 2010) is characterized by essentially stable water temperatures at the bottom of the lake. Here, the water depth ranged from 27.66 to 68.65 m. For the subperiod between 9 June and the end of the observation period, the water temperatures vary between 9.43°C and 23.06°C, and the water depth is less than 27.66 m. At the same time, the air temperature ranges from 15.07°C to 35.09°C.

Figure 8 presents the relationship between the hourly average water depth, H, and the water temperature, T_{water}, for the study period. Looking at the data presented in Figure 8, it is possible to observe the three subperiods similar to those identified for the relationship between water temperature and air temperature shown in Figure 7. In the first subperiod, between 6 November and 20 December 2009, the water temperature at the bottom of the lake decreased with increasing water level. In the second subperiod between 21 December 2009 and 8 June 2010, when the water depth is greater than approximately 27.5 m, the water temperature at the bottom of the lake did not change with changes of water depth. In the last subperiod, between 8 June and 4 September 2010, the decrease of water level is followed by an increase of water temperature. The decrease in water

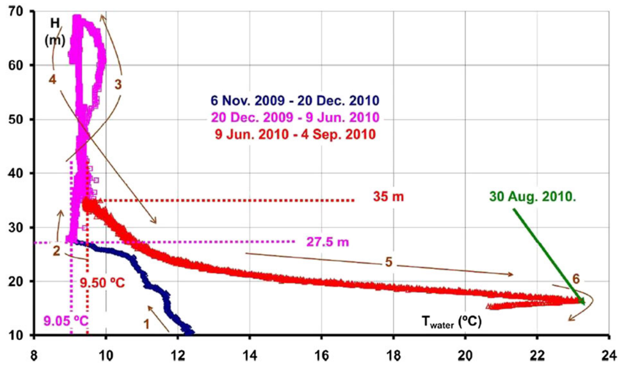

Figure 8. The relationship between the hourly average water depth, H, and water temperature, T_{water}, for the study period

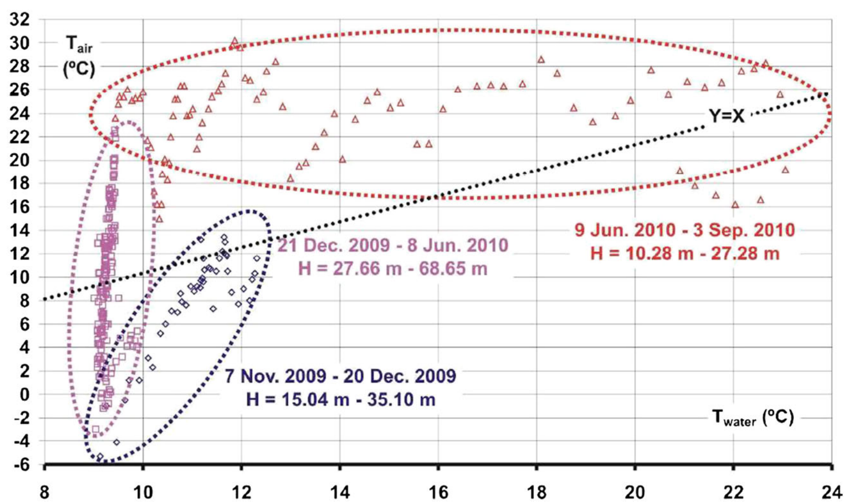

Figure 7. The relationship between contemporaneous values of daily mean water temperature in Blue Lake, T_{water}, and the air temperature at Imotski, T_{air}, for the study period

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temperature began on 30 August 2010, when the air temperature suddenly dropped by more than 10°C.

In accordance with the previous analysis, which was based on the information presented in Figures 5–8, it is possible to conclude that changes in the water temperature at the bottom of the lake depend on the air temperature and the water depth in the lake. In autumn, after a long exposure of relatively shallow water ($H < 27.5$ m) in Blue Lake to high air temperatures, the decrease in water temperature coincides with the decrease in air temperature. The water temperature at the bottom of the lake is not affected by the air temperature during the winter and spring. In the late spring when the air temperature rises and the water depth of Blue Lake is relative high for a long period, the increase of the water temperature at the bottom begins when the water depth reduces to less than approximately 35 m and when the air temperature is higher than 22°C. The lake water temperature at high stage is very stable at 9.3°C. This is the expected mean temperature of the aquifer. The above conclusions should be confirmed by further measurements made under different conditions and at different locations. For a complete understanding of this process, it is of particular importance to obtain a temperature profile of the whole lake water depth under different climatic conditions.

Figure 9 presents a time series of the hourly average water depth, *H*, and the electrical conductivity of the water, EC25, for the study period. It can be seen that the electrical conductivity of the water and thus the chemical properties of the water flowing into the lake change several times over the study period. For the period between 6 November 2009 at 10:26 h and 13 January 2010 at 10:26 h, EC25 values increased with an increase of water depth, *H*, which can be explained by the inflow of water into Blue Lake with a relatively long residence time in the karst aquifer. For the period between 13 January at 11:26 h and 9 August 2010 at 18:26 h, the electrical conductivity of the water remained relatively constant. A decrease in the electrical conductivity of the water was recorded for the period between 9 August 2010 at 19:26 h and 28 August 2010 at 01:26 h, when the electrical conductivity of the water began to increase again.

From the third column of Table I, it can be seen that the hourly values of the electrical conductivity of the water range between 301 μS/cm to 438 μS/cm with an average value of 411 μS/cm. Figure 10 presents the frequency, *N*, of the

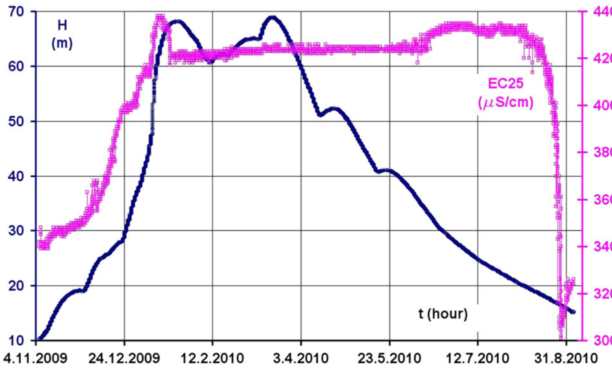

Figure 9. Time series of the hourly average water depth, *H*, and the electrical conductivity of the water, EC25, for the study period

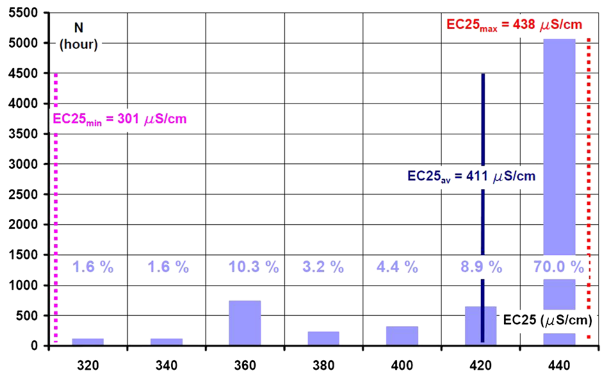

Figure 10. Frequency, *N*, of the hourly values of electrical conductivity of the water, EC25, for the study period

hourly values of electrical conductivity of the water. It can be seen that for 70% of the time, the value of the electrical conductivity of the water is higher than 430 μS/cm. Electrical conductivity is a measure of the concentration of ions in water or the concentration of dissolved solids it contains. The higher the water hardness, the greater is its electrical conductivity. Water that resides longer in the underground karst dissolves more minerals than water with a shorter residence time in same area. Ford and Williams (2007) emphasize that the analysis of changes in electrical conductivity over time can lead to a better understanding of the aquifer from which the water enters the karst water phenomena under investigation (spring, estavelle, lake, etc.).

Bakalowicz and Mangin (1980) measured the electrical conductivity of the water of several karst springs in France, which are recharged from deep karst aquifers, including the Fontaine de Vaucluse spring. The electrical conductivity of water values, EC25, ranged between 220 and 470 μS/cm with the most common value being 380 μS/cm. The distributions of the electrical conductivity of the water that were obtained were multimodal, which can be explained by the different residence times of water in the karst matrix and the different origins of the water from different parts of the karst aquifers with different mineralogical compositions. The recorded values for the electrical conductivity of the water measured in the Jadro Spring (Croatia) in 2011, which is fed by a deep karst aquifer, ranged between and 350 μS/cm. Based on the data presented, it can be concluded that the values of the electrical conductivity of the water at the bottom of Blue Lake correspond to the values characteristic of water which originates from a deep karst aquifer.

HYDROLOGICAL BUDGET OF THE BLUE LAKE

Figure 11 presents a schematic representation of five components of the hydrological budget of Blue Lake. The outputs from the lake are designated with the letter O and the inputs (water inflow) with the letter I.

The evaporation from the water surface of the Blue Lake, O_1, depends on the climatic conditions, mainly air temperature and wind, but also on the depth of the water. When the water level is low, the water surface is small and

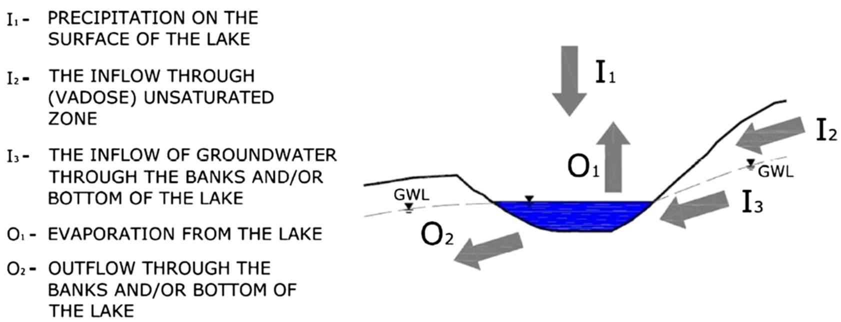

Figure 11. Schematic presentation of the five components of the Blue Lake hydrological budget

the water in the lake is deeper in a doline. This affects the decrease of evaporation. Although the evaporation process is continuous, the amount of water evaporated from the lake is probably less significant than the amount of water that flows out of the lake through its bottom and sides.

The outflow of water through the lake bottom and sides is designated as O_2. This is the main component of water outflow from the lake. Its magnitude depends on the water level in the lake and the position of the groundwater table (how much lower the groundwater level is than the water level in Blue Lake) in the surrounding karst aquifer.

The precipitation which has fallen on the lake water surface is labelled I_1. Because the surface of the lake is relatively small (especially when compared with the unknown catchment area) and the duration of the precipitation is usually short, this component cannot play a significant role in the recharge of the lake. The component I_1 plays a significant role only for a short time during extremely heavy precipitation. For example, there was an occasion on 9 January 2010 when, in a few hours, 107.8 mm of rainfall was recorded at the Imotski meteorological station.

The water budget component, which represents the water inflow through the vadose zone, is labelled I_2. The banks of Blue Lake consist of highly fractured carbonate layers; therefore, the water circulation through them is rapid.

The label I_3 refers to a component of the Blue Lake recharge in which the lake is recharged by groundwater from the karst aquifer. The inflow of groundwater into the lake takes place through its bottom and banks. This recharge component of the lake hydrological budget operates for the longest period and is quantitatively the most significant. It directly depends on the groundwater level in the Blue Lake karst aquifer.

It is important to note that under different hydrogeological conditions, various combinations of the five previously explained components of the hydrologic budget can occur. Figure 12 presents four scenarios representing some of the possible features of the water budget of Blue Lake. Figure 12a provides a schematic representation of the case when the groundwater level around the site is higher than the lake water level. Because of this the inflow into the lake occurs through the banks and the bottom of the lake, with simultaneous input from heavy rainfall. The only losses that occur are caused by evaporation from the surface of the lake. A variant of this case could involve the exclusion of direct precipitation input.

A schematic representation of the case when the groundwater level in the surrounding karst aquifer is higher on one side of the lake is shown in Figure 12b. During this situation, the water flows into the lake from the side of the lake where the groundwater level is higher than the lake level. At the same time, water outflow from

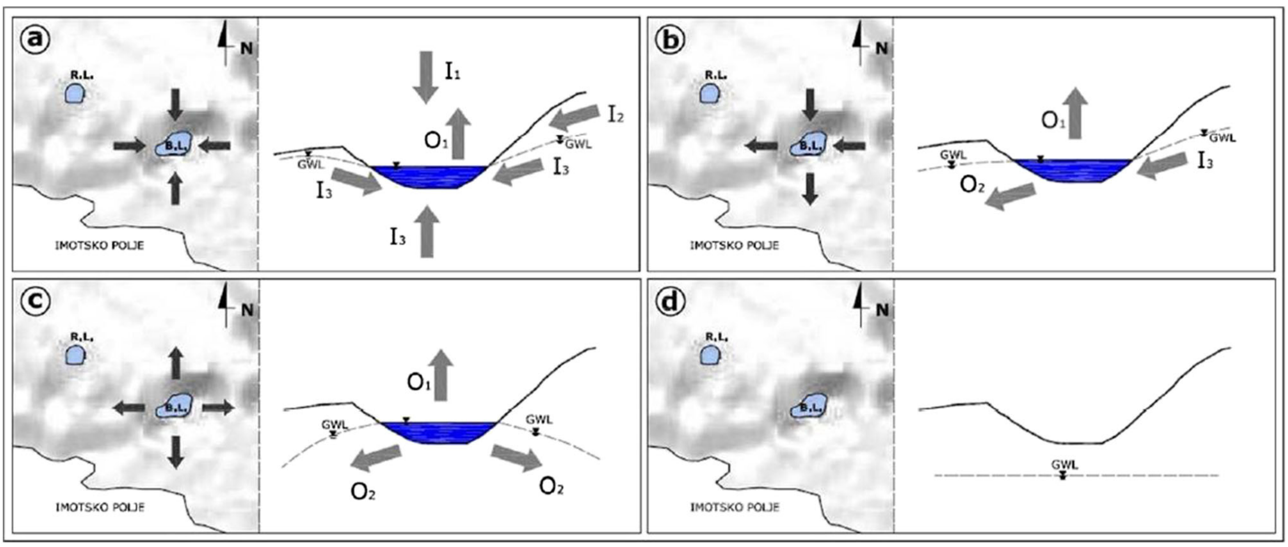

Figure 12. Four diagrams that represent some of the possible water budget scenarios for Blue Lake

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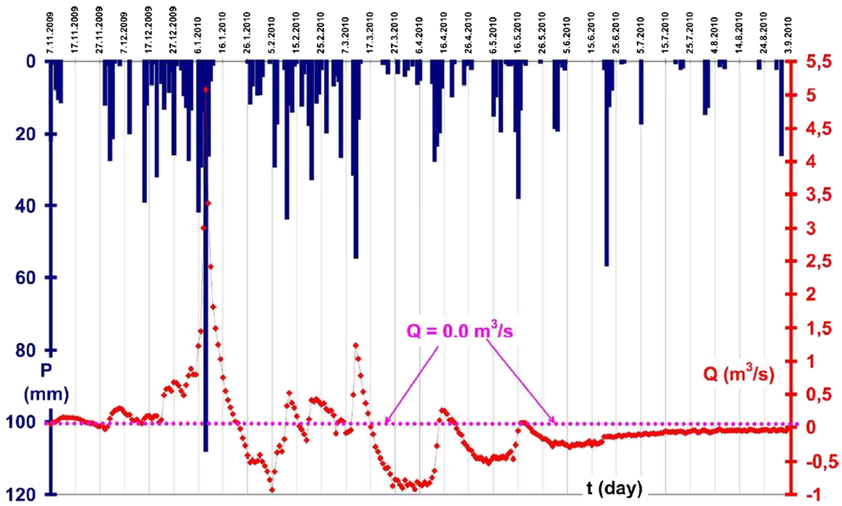

Figure 13. Time series of the daily mean inflow and outflow discharge, ±Q, and daily precipitation, *P*, for the study period

Table IV. The 20 highest hourly and daily mean inflow and outflow discharges, ±Q (m^3/s), estimated for Blue Lake over the study period

	+Q (m^3/s) inflow		−Q (m^3/s) outflow	
No.	Hourly data	Daily data	Hourly data	Daily data
1	7.52	5.09	−5.04	−0.932
2	7.52	3.36	−4.54	−0.923
3	7.14	3.01	−4.39	−0.905
4	6.96	2.41	−4.34	−0.872
5	6.88	1.81	−4.07	−0.862
6	6.79	1.49	−3.97	−0.860
7	6.62	1.45	−3.78	−0.858
8	6.59	1.25	−3.71	−0.855
9	6.29	1.24	−3.69	−0.848
10	6.06	1.23	−3.68	−0.844
11	6.04	1.04	−3.62	−0.836
12	5.91	1.03	−3.58	−0.825
13	5.77	0.885	−3.58	−0.811
14	5.74	0.801	−3.50	−0.810
15	5.45	0.797	−3.43	−0.788
16	5.41	0.781	−3.43	−0.785
17	5.36	0.780	−3.41	−0.778
18	5.27	0.752	−3.35	−0.773
19	5.27	0.681	−3.33	−0.747
20	5.15	0.672	−3.31	−0.690

the lake occurs through the banks and the bottom where the groundwater level is lower than the water level of the lake. In most cases, the side with the higher groundwater level is likely to be northeast side of the lake, which is backed by the mountainous region of Bosnia and Herzegovina. The lower groundwater levels are likely to occur on the western side of the lake towards Red Lake and the Imotsko Polje.

Figure 12c represents the scenario where the groundwater level all around the lake is lower than the water level in the lake. In this case, the water from the lake feeds the surrounding karst aquifer. The two key components of the budget in this case are the outflow through the banks and the bottom of the lake and evaporation. There is no recharge of the lake water. The last scenario is shown in Figure 12d. It shows the case when Blue Lake is dry and the groundwater level is well below its bottom.

The hourly and daily mean discharges into, +Q, and out of, −Q, the lake were estimated using the depth, *H*, volume of water, *V*, the morphometry of Blue Lake represented in Figure 4 and the hourly and daily data on lake water depth (Figures 5 and 10). Figure 13 presents a time series of the daily mean inflow and outflow discharges, ±Q, and the precipitation, *P*, measured for the study period.

Table IV presents 20 of the highest values of hourly and daily mean inflow and outflow discharges, ±Q (m^3/s), estimated for Blue Lake over the study period. It can be seen that the inflow values are greater than the outflow values. The greatest values of inflow and outflow were triggered by the heavy, intense rainfall recorded on 9 January 2010 when a total of 107.8 mm was recorded.

CONCLUSIONS

From the perspective of karst geomorphology, the Blue Lake and the neighbouring Red Lake represent some of the most impressive karst forms on Earth. The underground circulation of water (hydrogeology) and the hydrological budgets of these two lakes and their interrelationships have not been adequately investigated to date because of the lack of systematic measurements. Analysis of the data collected during an incomplete hydrological year extending from 6 November 2009 at 10:26 h to 4 September 2010 at 03:26 h (7230 h or 302 days total) has provided an improved understanding of functioning of the lake and to some extent of the processes of water circulation in the wider area. Blue Lake is mainly fed by the water from the karst aquifer located in the northeastern part of the catchment in the high mountainous region where precipitation is much higher than the

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precipitation in Imotski. The dimensions of this aquifer and its properties currently remain unexplored.

These new measurements and related conclusions do not provide a detailed understanding of the hydrogeological–hydrological processes occurring in Blue Lake and its catchment, but they do provide a better insight into the complex processes water inflow and outflow. The measurements obtained have facilitated the establishment of a scientifically based strategy for organizing future monitoring, which is essential for a detailed explanation of water budget of this impressive karst phenomenon.

The need for additional and better-organized measurements is crucial. First, it is necessary to implement continuous measurement of the hydrological parameters of both lakes, and maybe even of some additional water features (which are numerous) in the wider area. The necessity to drill several deep piezometers near Blue Lake and Red Lake to determine the direction of local and regional groundwater circulation and to determine the process of water movement between the two lakes is of special importance (see Figure 2). Temperature and electrical conductivity profiles of the water in Blue Lake need to be documented for different water levels and at different times of the year. Measurements of these parameters should also be obtained from piezometers. Additional dye tracing from the Blue Lake bottom outlets should be carried out as well as frequent sampling of basic water geochemistry (Ca, Mg, K, Na, HCO_3, SO_4 and Cl). For a more detailed analysis, data on precipitation in the mountainous parts of the hinterland of the Blue Lake are required. In short, important karstic features deserve a much greater level of scientific attention.

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