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SINKING KARST RIVERS HYDROLOGY: CASE OF THE LIKA AND GACKA (CROATIA)

HIDROLOGIJA PONORNIH REK LIKE IN GACKE (HRVAŠKA)

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Ognjen Bonacci & Ivo Andrić: Sinking Karst Rivers Hydrology: Case of the Lika and Gacka (Croatia)

In this paper a case of very special hydrological behaviour of two neighbouring sinking karst rivers, Lika and Gacka, (Dinaric karst of Croatia), is analysed. The Lika River has a torrential hydrological regime. At the Sklope gauging station its minimum, mean and maximum measured discharges in the 1951-2005 period were: 0 (dry) m^3/s : 24.5 m^3/s : 729 m^3/s. During the same period the Gacka River, at the Vivoze gauging station, had the following characteristic discharges: 2.29 m^3/s; 14.7 m^3/s; 71.0 m^3/s. While the flow regime of the Lika River is characterised by extremely and very quick changes of discharges, the Gacka River flow regime is unusually uniform. The objective of the investigations made in this paper was to analyse the extremely different hydrological behaviour of the two neighbouring sinking rivers in order to find its reasons. Master depletion curves defined for the two analysed rivers shows that the karst aquifer of the Gacka River is much more abundant than Lika's. The difference in the water temperature regime of the two neighbouring rivers is extremely high. At the Lika-Bilaj gauging station the minimum, mean and maximum measured water temperatures in the period of 1964-1991 were: 0.6°C; 9.3 °C; 21.4°C. During the period of 1964-2005 the Gacka River, at the Čovići gauging station had the following characteristic water temperatures: 6.4°C : 9.1°C : 11.6°C. The resident time in the karst underground of water discharging from the Gacka karst springs is much longer than in the case of the Lika River. The most probable explanation for this unusual hydrological behaviour of the two neighbouring karst rivers is that water from the Lika River and its catchment recharges some karst springs of the Gacka River. It is concluded that the Lika River feeds the Gacka River with an average annual discharge of about 5.35 m^3/s. This value is different during each year and depends on the hydrological situation. It is very probably higher during the wet years than during the dry ones.

Key words: karst hydrology, sinking river, water temperature, Lika and Gacka Rivers (Croatia), Dinaric Karst.

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Ognjen Bonacci & Ivo Andrić: Hidrologija ponornih rek Like in Gacke

V članku predstaviva zanimivo hidrološko obnašanje dveh bližnjih ponornic, rek Like in Gacke na Hrvaškem dinarskem krasu. Reka Lika ima hudourniki režim. Pri merilni postajo Sklope je bil v letih 1951-2005 njen minimalni pretok 0 m^3/s, srednji 24.5 m^3/s in maksimalni 729 m^3/s. V istem obdobju so bili ti pretoki na Gacki 2.29 m^3/s, 14.7 m^3/s in 71 m^3/s. Medtem ko so na Liki pretoki izredno spremenljivi in s hitrim odzivom na padavine, je režim Gacke precej bolj monoton. Namen prispevka je analizirati razlike hidroloških režimov obeh sosednjih rek in poikati vzroke teh razlik. Glavne krivulje praznenja (master depletion curves) za obe reki kažeta, da so zaloge vodonosnika zaledja reke Gacke veliko večje od zalog vodonosnika zaledja reke Like. Tudi razlike temperatur obeh rek so velike. Pri merilni postaji Lika-Bilaj so minimalne, srednje in maksimalne izmerjene temperature v letih 1964-1992 0.6°C, 9.3°C in 21.4°C. Na Gacki pri Covićih pa so v letih 1964-2005 namerili 6.4°C, 9.1°C in 11.6°C. Zadrževalni čas vode v vodonosniku, ki napaja Gacko, je precej daljši od tistega, ki napaja Liko. Najverjetnejša razlaga navedenih opažanj je, da del vode iz Like in njenega zaledja napaja Gacko. Ugotovili smo, da Lika napaja Gacko s povprečnim letnim pretokom 5.35 m^3/s, pri čemer se ta količina spreminja glede na hidrološke pogoje. Verjetno je višja v mokrih, kot v suhi letih.

Ključne besede: kraška hidrologija, ponornice, temperatura vode, Lika in Gacka, Hrvaška

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INTRODUCTION

The term “rivers system” is used for the system of connected river channels in a drainage basin (Bridge 2005). For rivers developed in ordinary conditions they are composed of three zones (Schumm 1977): the uppermost or production zone; the central or transfer zone; the downstream or deposition zone. It is well known that conditions which govern flow in karst regions strongly change karst rivers systems. They are generally very different in comparison with ordinary rivers systems which exist in non-karst regions.

Bonacci (1987) mentions that flow regime in open streamflows in karst depends mostly upon the interaction between the groundwater and the surface water. The groundwater levels in karst greatly depends upon the effective porosity of the matrix, while groundwater connections between different parts of karst massive as well as some open streamflows depend on the existence, features, and dimensions of karst conduits. Some of these conduits recharge, while some drain off water from the rivers in karst. Generally, recharging or drainage depends on the groundwater level. The influence of karst differs from one streamflow to another and therefore general conclusions should be carefully drawn.

In this paper the case of very special hydrological behaviour of two neighbouring sinking karst rivers Lika and Gacka will be analysed. Their catchments are located in the central part of the Dinaric karst region of Croatia. Figure 1 represents location maps indicating (a) the study area, and (b) the supposed catchment areas of the Lika and Gacka Rivers up to their swallow-hole zones where they disappear into the karst underground. Their waters reappear on the surface about twenty kilometres away at many abundant coastal karst springs and submarine springs (vruljes) along the Adriatic Sea.

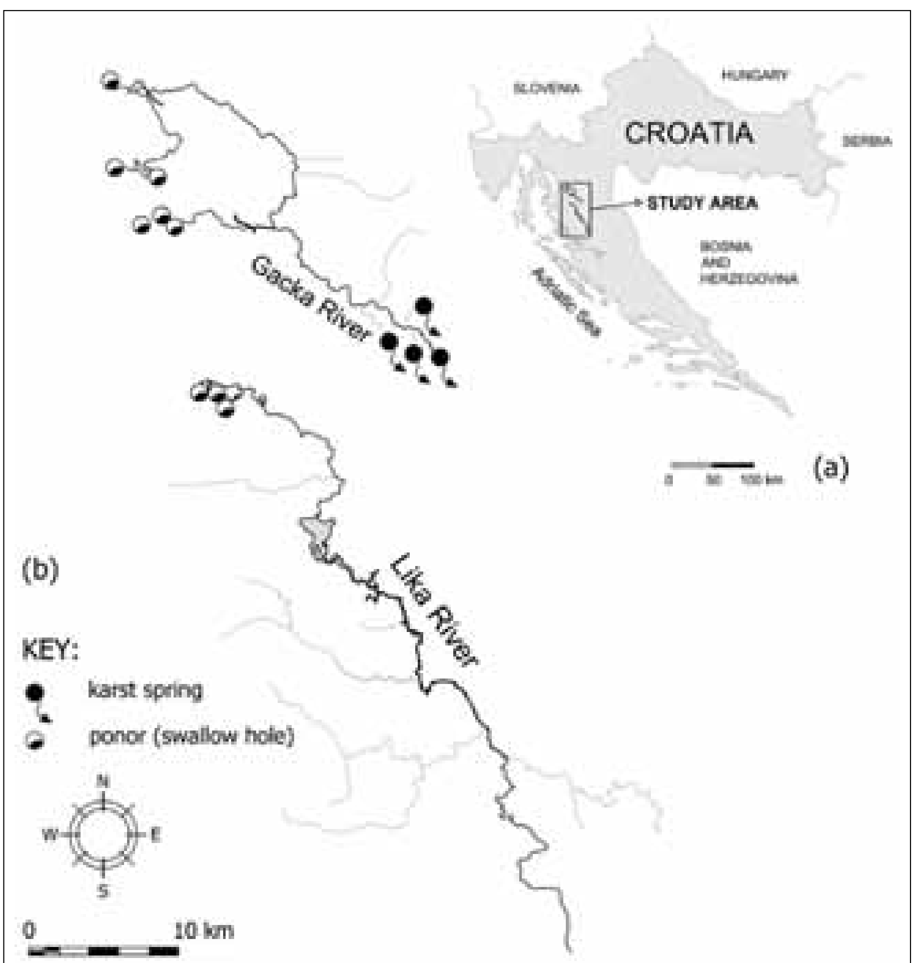

Fig. 1: Location maps indicating (a) the study area, and (b) the supposed catchment areas of the Lika and Gacka Rivers up to the their swallow-hole zones where they disappear into the karst underground.

A sinking karst river is an open streamflow that disappears into the karst underground, either at a discrete point such as a cave, many ponors (swallow-holes) or gradually along the reach of a stream channel. It may or may not appear on the surface again. In reality there are many very different cases of sinking rivers.

Sinking rivers represent the most direct access to the sensitive and highly vulnerable karst groundwater system. The unique nature of sinking rivers is their development and evolution of conduit flow routes and caves through soluble rocks. The evolution of most of the world’s largest and most significant karst caves and springs are formed as a consequence of large volumes of concentrated recharge from sinking rivers (Ray 2005).

While the Lika River system is composed of three zones (Schumm 1977), the Gacka River system generally has only a downstream or deposition zone. The very

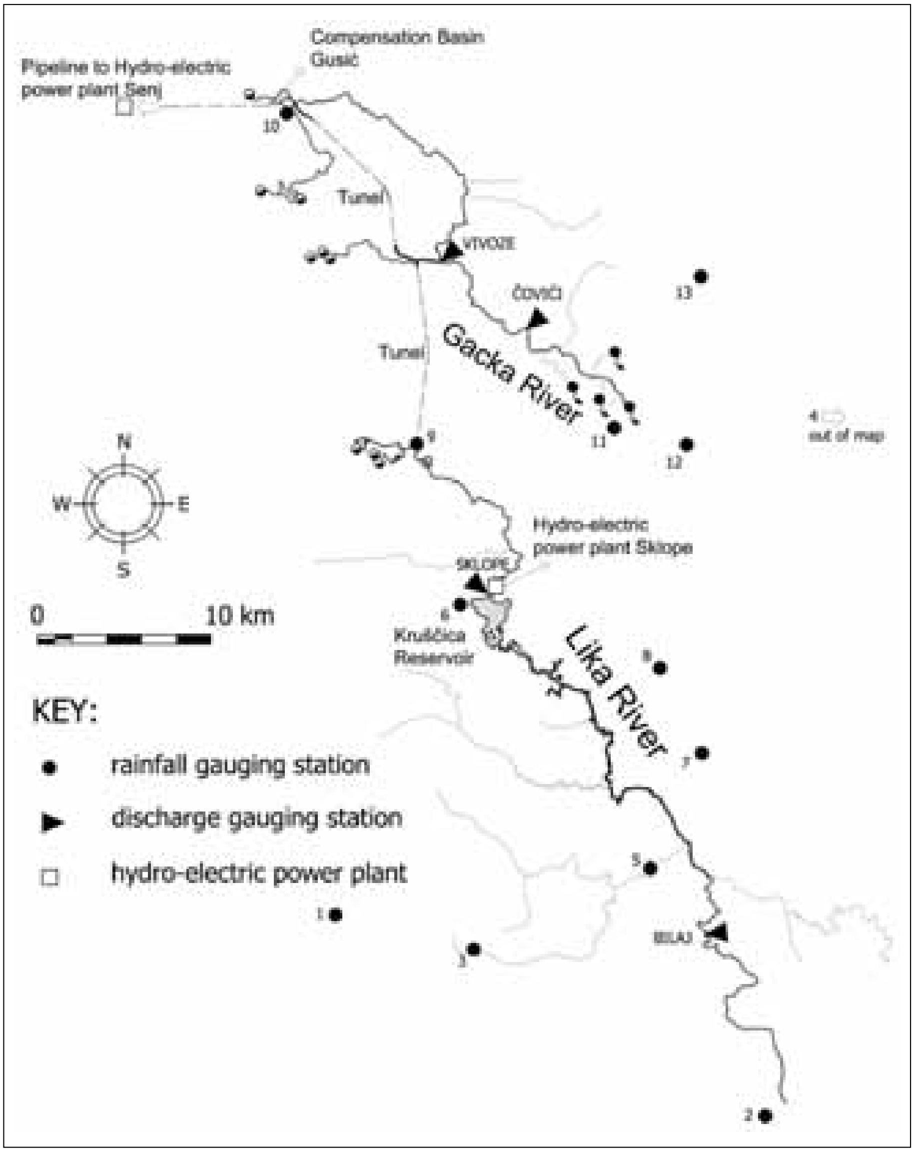

Fig. 2: Location map of the Lika and Gacka Rivers indicating the main ponor zones and karst springs, reservoirs, HEPPs, tunnels, canals, pipeline, and meteorological and hydrological gauging stations analysed in the paper.

different regulatory influence of karst at the closed locations could be seen from the Lika and Gacka Rivers hydrological behaviour. The Lika River has torrential hydrological regime. At the Sklope gauging station (Figure 2) its minimum, mean and maximum measured discharges in the period of 1951-2005 were: 0 (dry) m^3/s; 24.5 m^3/s; 729 m^3/s. During the same period the Gacka River at the Vivoze gauging station had the following characteristic discharges: 2.29 m^3/s; 14.7 m^3/s; 71.0 m^3/s. While the flow regime of the Lika River is characterised by extremely and very quick changes of discharges, the Gacka River flow regime is unusually uniform. Due to this reason as well as due to the high quality of water, it represents an exceptionally valuable regional strategic water resource (Ožanić & Rubinić 1999). The objective of the investigations made in this paper is to analyse the extremely different hydrological behaviour of the two neighbouring sinking rivers in order to find its reasons.

STUDY AREA

The Lika and Gacka Rivers are located in the central part of the Dinaric karst region of Croatia (Figure 1a) between 44°17’ and 44°58’N and 15°07’ and 15°48’E. Their precise hydrological catchment areas and boundaries are not known. The main reasons for this are the very deep, highly developed and unknown underground karst forms as well as a complex surface topography.

These two rivers belong among the largest sinking karst rivers in Europe. They have been regulated for hydroelectric power production since 1961. Figure 2 shows a location map of the Lika and Gacka Rivers indicating the main ponor zones, the main karst springs, reservoirs, hydro-electric power plants, tunnels, canals, pipeline, and meteorological and hydrological gauging stations analysed in this paper.

In natural conditions, before the hydroelectrical development, the total length of the Lika and Gacka Rivers from springs to the mouths in the large swallow-hole zones were about 70 km and 60 km respectively. The altitude of the swallow-hole zones of the Lika and Gacka Rivers are at about 430 m a. s. l. and 415 m a. s. l. respectively, while the springs are at 600 m a. s. l. and 460 m a. s. l. respectively.

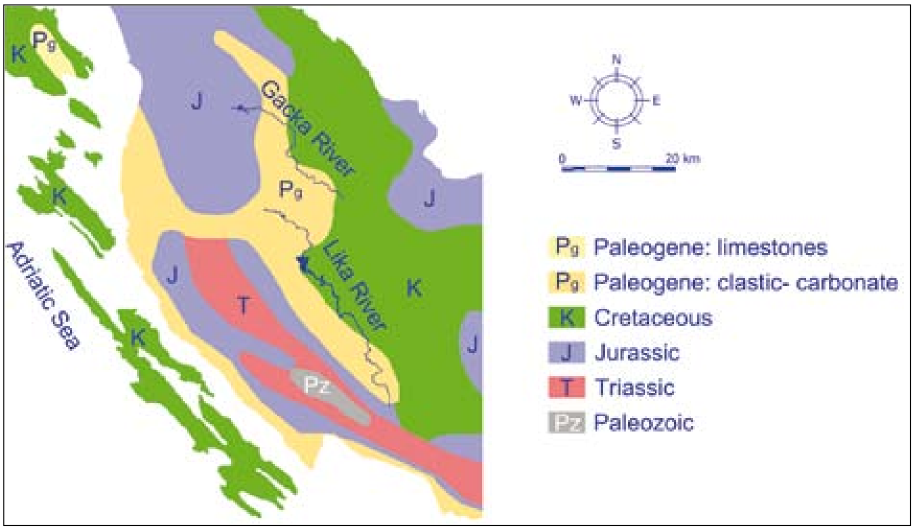

Fig. 3: Geological map of the study area.

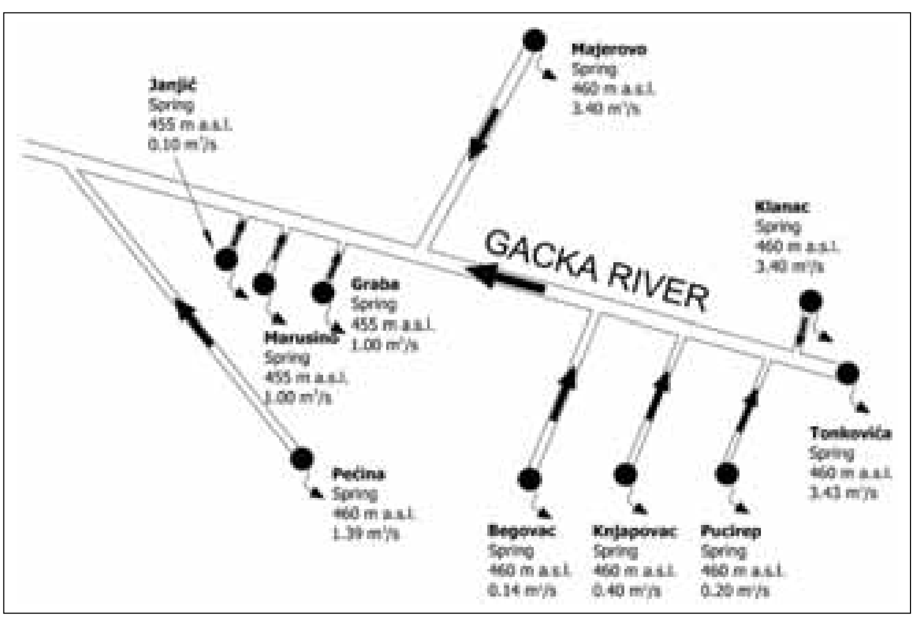

Fig. 4: Schematic presentation of the Gacka River main karst springs indicating their altitudes and mean annual discharges.

The Velebit Mountain (max. altitude 1758 m a. s. l.) separates their catchments from the Adriatic Sea. The joint hydrologic catchment area up to their swallow-hole zones for both rivers is estimated to cover about 2450 km^2. With regard to hydrogeology and hydrology this catchment should be divided into "direct" and "indirect" parts. The western "direct" part represents the topographic catchment. In the "indirect" part of the catchment surface water infiltrates and reaches the Lika and Gacka Rivers flowing through various karst underground forms (joints, fissures and karst conduits of different sizes). The catchment boundaries between the two analysed rivers have not yet been defined. The hydrologic catchment areas up to the swallow-hole zones of the Lika and Gacka Rivers are roughly estimated to cover about 1600 km^2, and 850 km^2 respectively. The accuracy of these estimations is about ± 15 %.

A geologic map of the study area is given in Figure 3 (Sokač *et al.* 1967). In the Gacka River catchment carbonate rocks predominantly occurs: limestone and dolomites. Tertiary breccias and limestone as well as Quaternary sediments occur with various hydrogeological characteristics (Božičević 1984). Pavičić *et al.* (2001) stress that the specific geological composition of the Velebit Mountain causes certain hydrogeological phenomena in the values of the Lika and Gacka catchments, which differs from those occurring in the neighbouring karst areas. The problem is that till now they are not discovered and explained well enough from the hydrogeological point of view. It should be mentioned that few sections are found on both rivers in which surface water disappears into the karst underground (Božičević 1984; Bahun and Fritz 1972; Pavičić *et al.* 2002).

The Lika River has a well-developed, and for the Dinaric karst region an unusually dense, network of permanent and intermittent tributaries. The slopes of their beds are very steep. The Gacka River stream network characteristics are quite different. This is a consequence of fact that the Gacka River is formed as a confluence of ten permanent and more or less abundant karst springs. Figure 4 is a schematic representation of the ten Gacka River main karst springs indicating their altitudes and mean annual discharges. On the water most abundant springs discharges are continuously measured, while on other springs discharges are measured occasionally. From the data given in Figure 4 it is seen that the altitudes of the Gacka River's spring exits varies within a very narrow range, from 455 to 460 m a. s. l. The Gacka River mainly flows through flatland, which represents the bottom of the polje in karst, and at the same time represents a wetland area.

CLIMATOLOGICAL CHARACTERISTICS

According to Köpen's classification of climatic regime, the lower part of the studied area has a temperate humid climate with a warm summer. The mean monthly air temperature in winter is -3°C and 18°C in summer. The highest parts of the Lika River catchment (higher than 1200 m a. s. l.) have a humid boreal climate (Filipčić 1998).

Table 1 gives some characteristics of 13 analysed precipitation gauging stations showed on Figure 2. Due to incomplete measurements in the period of 1951-2006 for some gauging stations data are completed by correlation and regression analyses with neighbouring stations. During the analysed period (1951-2005) the average annual precipitations measured at these stations varied from a minimum of 1149 mm (at Lički Osik gauging station) to a maximum of 2270 mm (at Baške Oštarije gauging station). Figure 5 represents a isohyetal map of annual rainfall for the study area for the period of 1961-1990 (Gajić-Čapka *et al.* 2003).

Table 1: Characteristics of 13 analysed precipitation gauging stations showed on Figure 2 and used for analyses in this paper.

No. on Fig. 2	Station name	Altitude – H (m a. s. l.)	Average annual rainfall (1951-2005) - H (mm)
1	Baške Oštarije	924	2270
2	Breznik	560	2019
3	Brušane	589	2248
4	Bunić	665	1183
5	Gospić	564	1385
6	Kruščica	557	1254
7	Lički Osik	579	1149
8	Perušić	603	1198
9	Selište	498	1293
10	Gusić Polje	438	1180
11	Ličko Lešće	463	1165
12	Ramljane	760	1238
13	Vrhovine	736	1170

Air temperature is measured only at the Gospić meteorological station. During the period of 1902-2006 (missing 1943-1945) the mean annual temperature varied between 7.0 and 10.5°C with an average value of 8.7°C. A maximum temperature of 38.8°C was measured on 30 Jul. 1947, and a minimum of -33.6°C on 17 Feb. 1956.

The annual precipitation data series measured from 1873 to 2006 (missing 1891, 1898-1900, 1943-1945) for the Gospić meteorological station is presented in Figure 6. An average trend of precipitation decrease of 2.7 mm per year is noticed. It should be remarked that average annual precipitation in the period of 1873-2006 (missing 1891, 1898-1900, 1943-1945) was 1508 mm, while in the last 55 years (1951-2005) it dropped by 123 mm to 1385 mm. An increasing trend of minimum annual temperatures of 0.04°C per year in 1902-2006 (missing 1943-1945) is found at the Gospić station, while for maximum annual temperatures no trend was found.

A time series analysis can detect and quantify trends and fluctuations in records. In this paper the Rescaled Adjusted Partial Sums method (RAPS) (Garbrecht and Fernandez 1994; Bonacci *et al.* 2008) was used for this purpose. A visualisation approach based on RAPS overcomes small systematic changes in records and the variability of data values. The RAPS visualisation highlights trends, shifts, data clustering, irregular fluctuations, and periodicities in the record (Garbrecht and Fernandez 1994). It should be stressed that the RAPS method is not

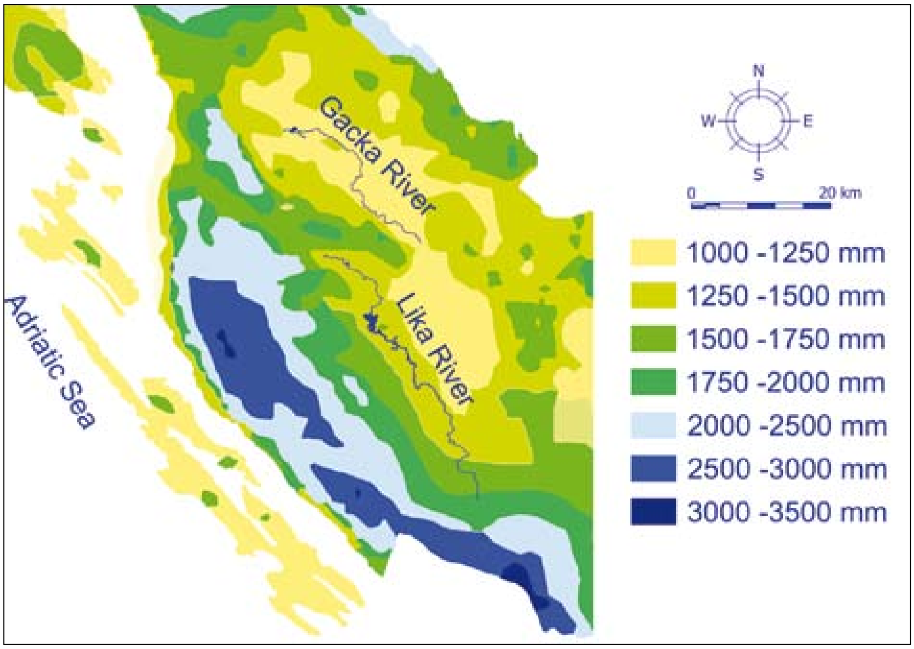

Fig. 5: Isohyetal map of annual rainfall for study area for the period of 1961-1990.

1945), the total data series was divided into three subsequent subsets: 1) 1902-1961; 2) 1962-1987; 3) 1988-2006. These three time data sub-series are shown in Figure 7. The RAPS method proves that a trend for a linear increase in Gospić mean annual air temperatures does not exist over the time series of the whole analysed period of 1902 to 2006. It indicates that increases of air temperature at the analysed meteorological station start in 1988 and last until 2006. During the first two sub-periods (until 1987), a trend of temperature increase does not exist at all. In order to investigate sta-

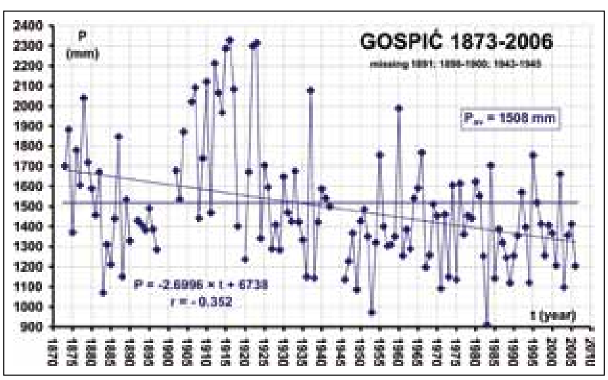

Fig. 6: Time series of annual rainfall at the Gospić meteorological station with a linear trend line for the period of 1873-2006 with data missing for the years 1898-1901, 1919 and 1943-1945.

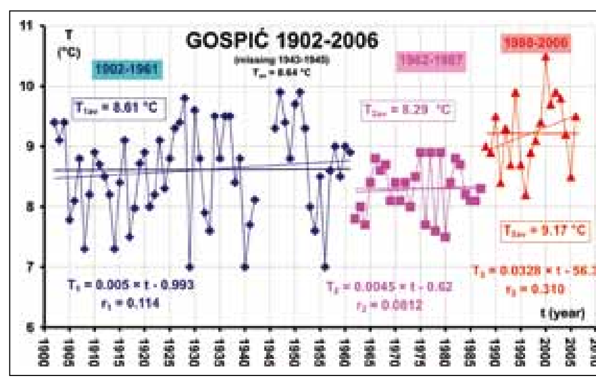

Fig. 7: Trends in annual rainfall of Gospić in the three sub-periods: 1902-1961 (missing 1943-1945); 1962-1987; 1988-2006.

without shortcomings. The values of RAPS are defined by the following equation:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - \overline{Y}}{\sigma_Y} \qquad (1)$$

where $\overline{Y}$ is the sample mean; σ_Y is the standard deviation; n is the number of values in the time series; and (k=1, 2…, n) is the counter limit of the current summation. The plot of the RAPS in time is the visualisation of the trends and fluctuations of Y_t.

Using the RAPS method for the time data series of mean annual air temperature at the Gospić meteorological station for the period of 1902-2005 (missing 1943-

tistically significant differences between the averages of the two most recent sub-series for air temperatures the t-test was used. The averages 8.29°C for the sub-period of 1962-1987, and 9.27°C for the sub-period of 1988-2006 are statistically significant (beyond 1 %). In the last sub-period there exists an average increasing trend of 0.0328°C per year.

HYDROLOGICAL CHARACTERISTICS

Table 2 provides the main characteristics of 4 analysed discharge gauging stations, their altitudes and assessed catchment areas.

Table 2: Some characteristics of 4 analysed discharge gauging stations.

Station name	River	Datum plane - H (m a. s. l.)	Assessed catchment area - A (km²)
Bilaj	**Lika**	**556.24**	**210**
Sklope	Lika	481.56	1014
Čovići	Gacka	449.82	492
Vivoze	Gacka	447.08	584

Figure 8 represents time series of mean annual discharges of the Lika at Sklope in the period of 1930-2005. The RAPS analysis indicates that in the whole period there exists the following three sub-periods with different average annual discharges: 1) 32.04 m³/s for the first sub-period 1930-1944; 2) 25.78 m³/s for the second sub-period 1945-1981; 3) 21.68 m³/s for the third sub-period 1982-2005. The average annual discharge for the whole period (1930-2005) is 25.7 m³/s. There does not exist a decreasing trend in any of three sub-periods. In order to investigate the significance of the differences between the averages of the three average sub-period discharges, the t-test is used. This suggests that all three averages are different at the $p < 0.01$ level of significance. The main reason for the mean annual discharges decrease should be found in the reduction of annual precipitation, the trend of which is given on Figure 6.

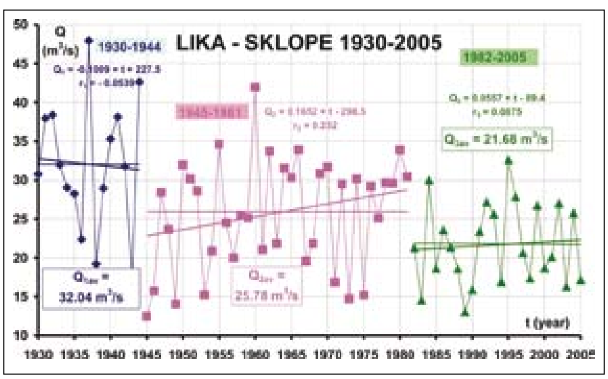

Fig. 8: Trends in mean annual air temperatures in the Lika River at Sklope in the three sub-periods: 1930-1944; 1945-1981 and 1982-2005.

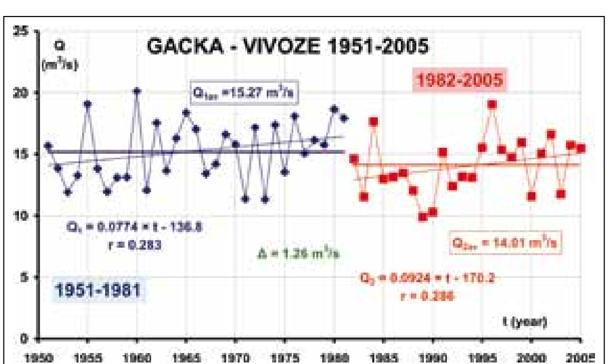

Fig. 9: Trends in mean annual discharges in the Gacka River at Vivoze in the two sub-periods: 1951-1981 and 1982-2005.

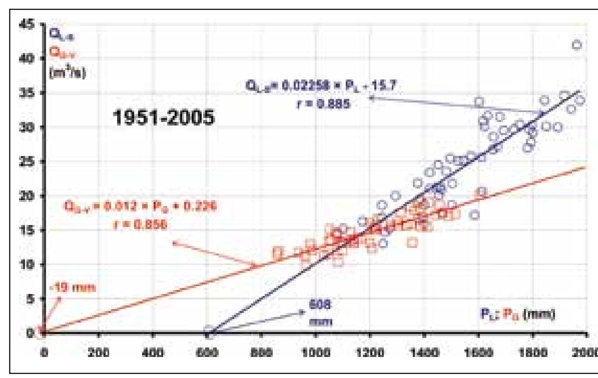

Fig. 10: Relationships between mean annual discharges of Gacka at Vivoze Q_{G-V} and average annual rainfall on the Gacka River catchment P_G and mean annual discharges of Lika at Sklope Q_{L-S} and average annual rainfall on the Lika River catchment P_L for the period of 1951-2005.

A similar behaviour of mean annual discharges is on the profile of the Gacka River at Vivoze. Figure 9 represents time series of mean annual discharges of the Gacka at Vivoze from 1951-2005. The RAPS analysis indicates the existence of two sub-periods with different average annual discharges: 1) 15.27 m³/s for the first sub-period 1951-1981; 2) 14.01 m³/s for the second sub-period 1982-2005. The t-test suggests that these averages are different at the $p < 0.03$. It can be concluded that the decrease of mean annual discharges are significantly less at the Gacka River than at the Lika River.

Figure 10 represents the following two relationships between: 1) Mean annual discharges of Gacka at Vivoze Q_{G-V} and annual rainfall on the Gacka River catchment P_G; 2) Mean annual discharges of Lika

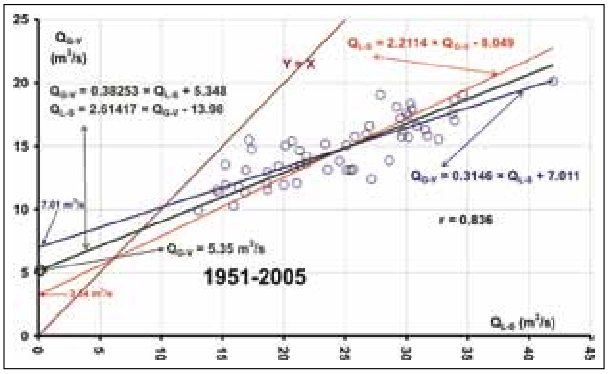

Fig. 11: Mean annual discharges of Gacka at Vivoze Q_{G-V} versus Lika at Sklope Q_{L-S} for the period of 1951-2005 with linear regression lines and the linear correlation coefficient.

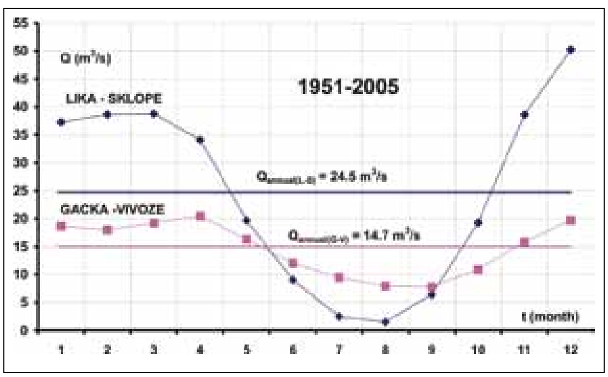

Fig. 12: Annual time series of average monthly discharges for Lika at Sklope Q_{L-S} and Gacka at Vivoze Q_{L-S} stations during the period of 1951-2005.

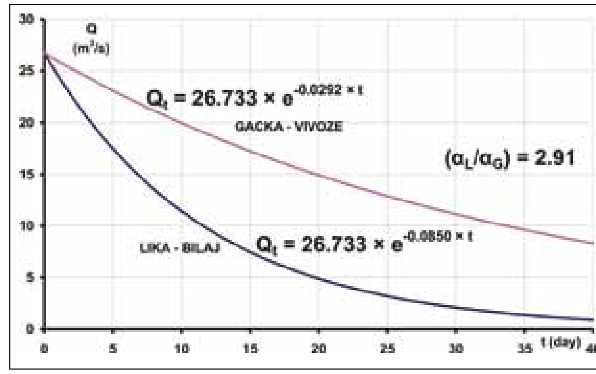

Fig. 13: Master depletion curves for Lika at Bilaj and Gacka at Vivoze.

at Sklope Q_{L-S} and average annual rainfall on the Lika River catchment P_L for the period of 1951-2005. Annual rainfalls on the catchments are calculated using the arithmetic average method. In both analysed cases linear correlation coefficients are high (r = 0.856 for the Gacka at Vivoze and r = 0.885 for the Lika at Sklope). The regression line for the Lika River at Sklope crosses the abscissa at the point P_L = 608 mm, which means that an annual rainfall equal to or smaller than that value could not cause any runoff on the catchment under consideration (Bonacci 2001). For the Gacka at Vivoze the regression line crosses the abscissa at the point P_G = -19 mm. From the hydrological point of view this is unacceptable and can be explained by fact that the Gacka River is feed with water from another source. The logical assessment is that water from the Lika River feeds some of the springs of the Gacka River. This hypothesis will be supported in the following part of the paper by some pure hydrological evidence.

Figure 11 provides a graphical presentation of the dependence between mean annual discharges on the Gacka River at Vivoze and the Lika River at Sklope. The expressions are given in Figure 10. The high value of the coefficient of linear correlation r = 0.836 is proof that similarities exist in the hydrological regimes of two neighbouring karst rivers. This fact is not surprising but the fact which needs additional explanation is that the mean regression line crosses the ordinate at the point Q_{G-V} = 5.35 m³/s. It varies from 3.64 m³/s to 7.01 m³/s for two regression lines $Q_{L-S}=f(Q_{G-V})$ and $Q_{G-V}=f(Q_{L-S})$ respectively (Figure 11). From the hydrological point of view this is very unusual behaviour for two neighbouring catchments. It is expected that the regression line for two neighbouring rivers with similar geological and climatological conditions passes through a co-ordinate point of departure or close to it due to unavoidable random mistakes in the definition of mean annual discharges. A possible and logical explanation is that the Lika River feeds the Gacka River with an average annual discharge of about 5.35 m³/s. This value is different during each year and depends on the hydrological situation. Very probably it varies from 3.64 m³/s to 7.01 m³/s. It is very probably higher during the wet years than during the dry ones.

Figure 12 represents an annual time series of average monthly discharges for Lika at Sklope Q_{L-S} and Gacka at Vivoze Q_{G-V} stations during the period of 1951-2006. The annual hydrologic regime of the Gacka at Vivoze is uniform while on the Lika at Sklope it is extremely variable. It can be seen that in hot parts of the year (from July to September) the mean monthly discharges at the Gacka are significantly higher than at the Lika, which can be explained by the fact that water from the Lika riverbed, as its aquifer, feeds some of the Gacka karst springs. This conclusion can be supported by the facts that the minimum mean monthly discharges in the period of 1951-2005 on the Lika River at Sklope are higher than at the Gacka River at Vivoze only in December, and that maximum mean monthly discharges on the Gacka River at Vivoze in the same period are higher in July and August than on the Lika River at Sklope.

Figure 13 represents master depletion curves for Lika at Bilaj and Gacka at Vivoze. Their equations are given in Figure 13. Based on them the values of retention times t_L (for the Lika River at Bilaj) and t_G (for the Gacka River at Vivoze) are defined as:

$$t_L = 1/\alpha_L = 1/0.0850 = 11.8 \text{ days} \quad (2)$$

$$t_G = 1/\alpha_G = 1/0.0292 = 34.2 \text{ days} \quad (3)$$

Retention time at Lika is 2.9 times lower than at Gacka. It can be explained in that the karst aquifer of the Gacka River is much more abundant that the Lika's aquifer.

WATER TEMPERATURE

Water temperature represents one of the most important physical characteristics of rivers and springs. This is especially true for karst rivers and springs (Bonacci 1987). Water temperature integrates underground and surface environmental influences and can be a useful parameter for the examination of sources, residence times and interchanges of stream and spring water within an environment (Bonacci *et al.* 2008). Water temperature is a relatively simple and inexpensive variable to monitor. The monitoring of water temperature in Croatia is based on a once-daily measurement at about 7 h 30 min am.

At a Lika-Bilaj gauging station (Figure 2) the minimum, mean and maximum measured water temperatures in the period of 1964-1991 were: 0.6°C; 9.3°C; 21.4°C. During the period of 1964-2005 the Gacka River at the Čovići gauging station had the following characteristic water temperatures: 6.4°C; 9.1°C; 11.6°C. The difference in water temperature regime of the two neighbouring rivers is extremely high.

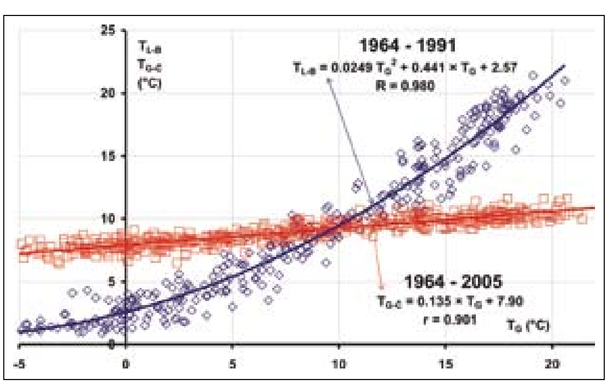

Fig. 14: Relationships between mean monthly water temperatures of Gacka at Čovići $Q_{G-Č}$ and mean monthly air temperatures measured at the Gospić meteorological station T_G for the period of 1964-2005 and mean monthly water temperatures of Lika at Bilaj Q_{L-B} and mean monthly air temperatures measured at the Gospić meteorological station T_G for the period of 1964-1991.

Figure 14 represents the relationships between mean monthly water temperatures of Gacka at Čovići $Q_{G-Č}$ and the mean monthly air temperatures measured at the Gospić meteorological station T_G for the period of 1964-2005 and the mean monthly water temperatures of Lika at Bilaj Q_{L-B} and the mean monthly air temperatures measured at the Gospić meteorological station T_G for the period of 1964-1991. In both cases the coefficients of linear and nonlinear correlations between water temperature and air temperature at the Gospić meteorological station are high (r = 0.901 for Gacka at Čovići, and R = 0.980 for Lika at Bilaj). Figure 15 shows the annual time series of average monthly water temperatures for Lika at Bilaj and Gacka at Čovići stations and the average air temperatures at Gospić meteorological station T_G during the period of 1964-1991.

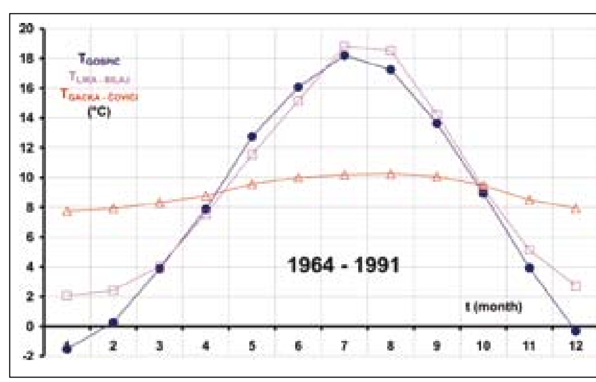

Fig. 15: Annual time series of average monthly water temperatures for Lika at Bilaj and Gacka at Čovići stations and average air temperatures at the Gospić meteorological station during the period of 1964-1991.

From all the previously given analyses it is obvious that resident time in karst underground of water discharging from the Gacka karst springs is long, much longer, than in the case of the Lika River.

CONCLUSIONS

All the previously mentioned analyses lead to the conclusions that the hydrological behaviour of two analysed rivers Lika and Gacka is unusual and unexpected, even for the deep and well-developed Dinaric karst terrain in which their catchments were developed. The Lika River has a completely torrential and intermittent hydrological regime. It dries up very often, during the last twenty years practically every year, while the Gacka River has a very well regulated hydrological regime and never dries up. It is very probable that their topographic catchments do not correspond to their hydrological catchments.

In accordance with the previous analyses the most probable explanation for the unusual hydrological behaviour of the two neighbouring karst rivers is that water from the Lika River and catchment recharges some karst springs of the Gacka River. This assessment could be supported by the fact that the altitude of the Lika River channel is higher than the exits of all the karst springs of the Gacka River. In Figure 16 (a) there is provided a situation and cross section A-A (Figure 16 b) between these two rivers with designated supposed groundwater flow in the direction from the Lika River to the Gacka River springs. Figure 17 provides a simple schematic conceptual presentation of how the water from the Lika and Gacka Rivers are interconnected. Until now geologists and hydrogeologists did not consider this hypothesis. The crucial task of further analyses is to find the section of the Lika River open stream course as well as part of its karst aquifer from which water reappears at some of the Gacka River springs. At the same time which of the ten main Gacka karst springs are fed by the water from the Lika River should be discovered.

A possible argument for the existence of the above-mentioned underground connection is given in the paper of Bojić's *et al.* (2007). They measured the isotopic composition of the following three Gacka River springs: Tonkovića, Majerovo and Pećina (Figure 4). They concluded that the analysed springs have fairly different stable (^{18}O) isotope values although they are located at approximately the same altitude, which indicates that their recharge areas lie at different altitudes.

Next proofs that water from the Lika River feeds some of the Gacka River karst springs should be find using hydrogeological methods and approaches. The investigation explained in this paper has pointed to the necessity of performing further detailed and karst-specific measurements and analyses. In order to protect extremely valuable groundwater and surface water resources of the Gacka River it is of the paramount importance to discover groundwater connections between two analysed rivers using tracing methods as well as isotopic and geochemical analyses (Pavičić 2001; Pavičić *et al.* 2003; Horvatinčić *et al.* 2007).

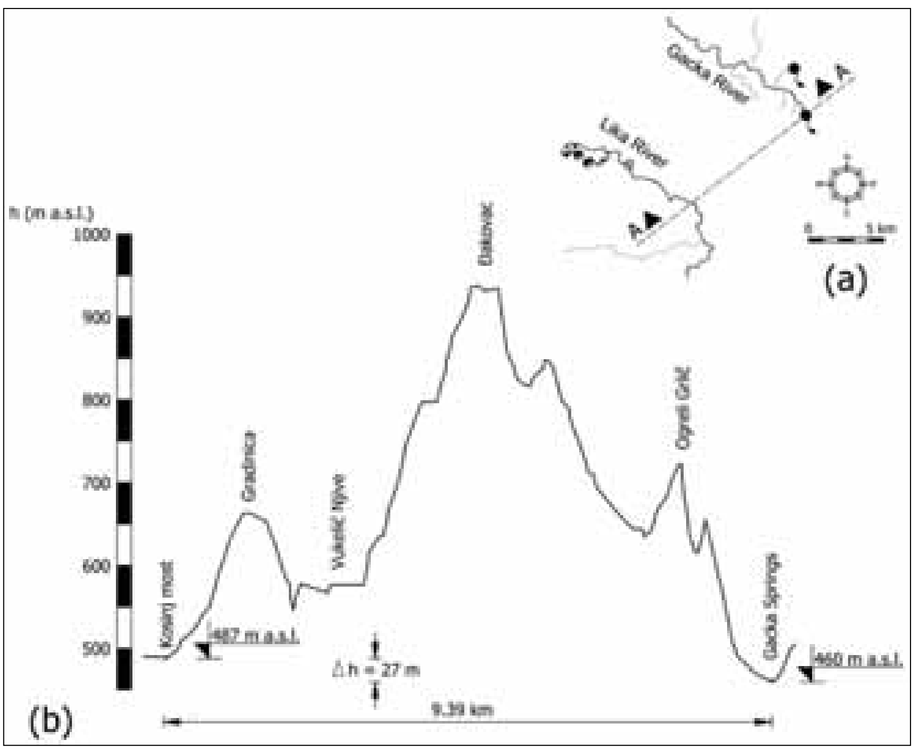

Fig. 16: Map indicating (a) part of the Lika and Gacka Rivers catchment and (b) cross-section A-A between these two rivers with designated supposed groundwater flow in the direction from the Lika River to the Gacka River,

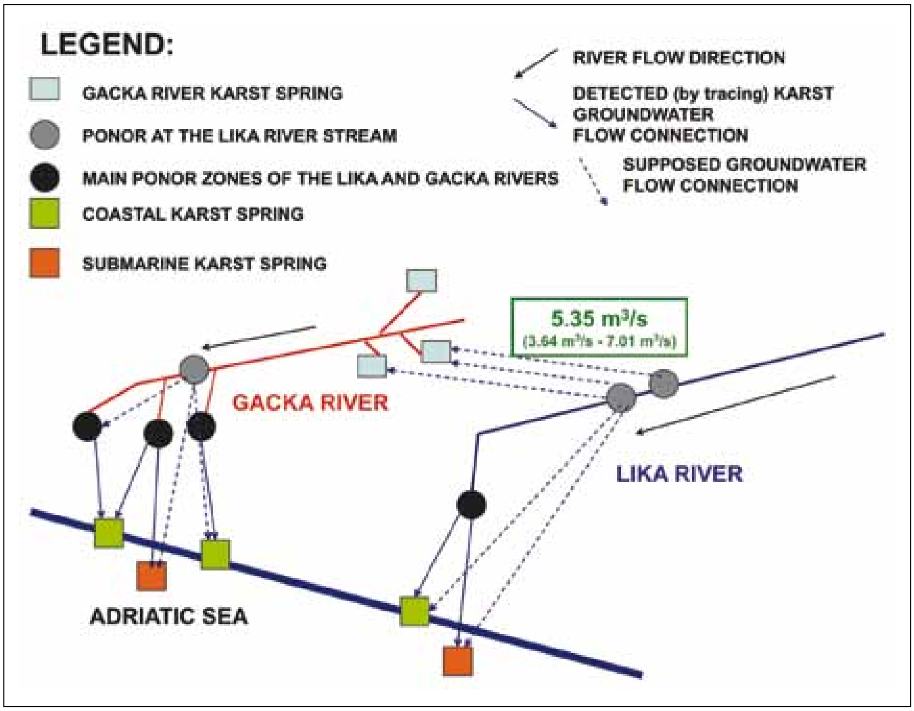

Fig. 17: Schematic conceptual presentation of the karst groundwater connection between Lika and Gacka Rivers.

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