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Ognjen Bonacci, Ivana Željković & Amira Galić

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ORIGINAL ARTICLE

Karst rivers' particularity: an example from Dinaric karst (Croatia/Bosnia and Herzegovina)

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Abstract The very complex system of sinking, losing and underground transboundary Karst rivers, lakes and aquifers in the central part of the deep and bare Dinaric karst in Croatia and Bosnia and Herzegovina is analysed. The groundwater and surface water are hydraulically connected through numerous karst forms which facilitate the exchange of water between the surface and subsurface. A complex underground conduit system is an inherent characteristic karst system analysed. Groundwater and surface water exchange with both adjacent and distant aquifers through underground routes or inflows from surface streams and artificial reservoirs. Because of a complex surface and underground karst features, which strongly influenced its hydrological and hydrogeological regime, the main open stream flow, with a longitude of about 106 km, undergoes eight name changes. In this paper, it is noted as "the eight-name river". In fact, it represents one river with losing, sinking and underground stream sections. Different surface and underground karst forms play crucial roles in the way the water flowing over the surface and on the underground sections of its catchment. The analysed area is full of varied and often spectacular surface landforms, including for example the Blue and Red Lakes and the Kravice Waterfall. The analyses made in the paper show the existence of a decreasing trend of mean annual discharges on the eight-name river, which can cause numerous problems in the regional water resource management of this transboundary river and catchment.

Keywords Karst hydrology · Karst river · Polje · Dinaric karst

O. Bonacci · I. Željković (✉)
Faculty of Civil Engineering, Architecture and Geodesy, Split University, Matice hrvatske 15, 21000 Split, Croatia
e-mail: ivana.zeljkovic@gradst.hr

A. Galić
Faculty of Civil Engineering, Mostar University, Matice hrvatske bb, 88000 Mostar, Bosnia and Herzegovina

Introduction

The rivers are the bloodstreams of landscapes and catchments. This is especially true in complex karst regions. The case which is discussed in this paper represents a very special example of the evolution of karst hydrography and of the behaviour of karst hydrology caused by interplay with extremely complex karst geomorphology. The study area (Fig. 1) is located in Bosnia and Herzegovina and Croatia between 43°05′ and 43°60′N, and 17°00′ and 17°60′E. Generally, each karst catchment is unique, but in the case of the analysed catchment it is especially true. This is the result of a deep and extremely strong regional karstification which causes the development of extreme surface karst forms as well as a complex underground conduit system.

The main open stream, with a longitude of about 106 km from spring to mouth in the Neretva River, undergoes eight name changes. Owing to this reason, the river will be noted in this paper as "the eight-name river". Both the beginning and end of this river catchment are in Bosnia and Herzegovina, but it also partly flows through Croatia. Its catchment is roughly estimated to be $1{,}100 \pm 200$ km^2.

The determination of the catchment boundaries and the catchment area in karst represents an extremely complex and sometimes unsolvable task. The differences between the topographic and hydrologic catchments in karst terrain

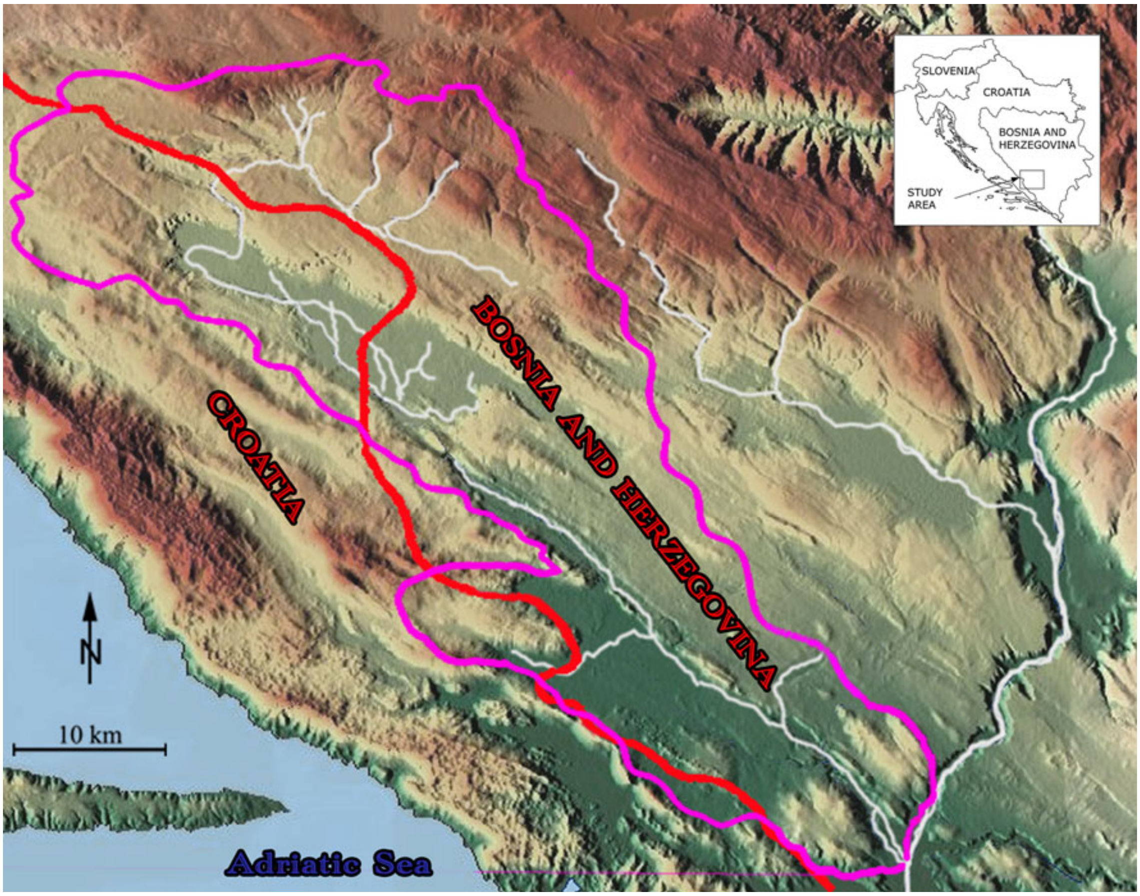


Fig. 1 The study area location maps

are as a rule, so large than data about the topographic catchment are useless in hydrological and hydrogeological analyses (Bonacci 1999, 2007; Bonacci et al. 2006; Bonacci and Andrić 2008). In general, the position of the karst catchment boundaries depends upon the rapidly fluctuating groundwater levels, especially during periods of abrupt groundwater rise (Bonacci 1987, 1995, 2001). Due to this reason catchment area in karst can change very fast. In situations of high groundwater level, the redistribution of catchment areas is caused by overflow from one to the other catchment. In the study area, there is the great variability of surface and underground karst geomorphological features (mostly unknown), as well as the interplay of pervious and impervious layers within the deep karst massif. This creates a lot of possibilities for contact between two or more karst aquifers and karst springs.

A catchment in karst represents a complex water transport system in which the heterogeneity of the surface and underground karst forms, serving for flow circulation and storage, makes discovering and quantifying the water flowing through them difficult. Numerous and extremely different surface and underground karst forms makes possible unexpected connections of water flows in the karst medium space which changes over time. Rapid changes in the surface and underground flow paths over time are caused by different natural or anthropogenic causes (Čalić 2011; Bonacci 2004a; Beach et al. 2008; Podobnikar et al. 2009).

An additional problem connected to the study area is that during the last century there were many large projects (the construction of tunnels and hydroelectric power plants, the development of irrigation systems, massive karst groundwater pumping, fish farming, urbanisation, etc.) initiated and implemented by the countries which shared karst catchments and aquifers. The consequences of these projects, as well as new ones which are in the design phase, have changed and will change the regional hydrological, hydrogeological and ecological phenomena.

The specific forms of geological genesis, orogenesis and the genesis of climate that took place during the long history of the region, which is analysed in this paper, have resulted in the extremely high diversity of geomorphological, hydrogeological, hydrological and ecological karst phenomena (Redžić et al. 2011). In fact, the eight-name river represents a system of losing, sinking and underground stream sections. Despite the abundant precipitation, many sections of the analysed stream are losing, and one short section is an underground river. Underground flow was presupposed by tracing test on river Vrljika through *ponor* Šainovci (*ponor*—natural surface opening with surface stream flowing partially or completely underground) from where water reappears again in Tihaljina spring (Petrik 1960). More than 100 temporary and permanent karst springs emerge along the longer axes of a dozen of *poljes* (*polje*—large, flat-floored depressions within karst limestone) existing throughout the study area. Owing to the extremely complex surface and underground karst features, numerous geological, hydrogeological and hydrological investigations proved insufficient to define the catchment boundaries or the directions of groundwater flow in the different hydrological situations.

The objective of this paper is to present to karst international scientific community the extremely complex hydrological–hydrogeological karst system on the eight-name river and catchment.

Geology

The study area (Fig. 2) is a part of the Outer or karstic Dinaric Alps (Herak 1986), which is a subunit of the Dinaric Alps. The structural relationships inside it are complex and are characterised by very deep and irregular karstification and strongly influenced by tectonics, compression, reverse faults and overthrusting structures. The main structural–tectonic features of the terrain structures are predominantly in the Dinaric direction. The axis of wrinkles and chief faults are of Dinaric spreading (NW–SW).

There are four main tectonic structures units spread through observed area: Imotski, Zavelim, Svitav-Ljubuški and Stolac-Čitluk. The border between Imotski and Zavelim unit is system of deep faults created during tectonic movement when Permo-Triassic gypsum rock extruded near the village of Sobač. The Svitav-Ljubuški and Stolac-Čitluk are divided by limestones drawn over Eocene flysch. Eocene flysch is in form of overturned syncline which is tucked under Čapljina-Ljubuški anticline.

During the main orogenic phases, the Mesozoic deposits were intensively folded and tectonically fractured. Intensive tectonics in this area caused the presence of folding, flexure stretching, faulting and imbricate structures. Faults are often a reverse character with older stratigraphic rock pulled over younger rock. They have been tectonically lifted to the surface and consist of gypsum layers also containing gravel, sandstone and marls. The strike of the major structures and deformations is Dinaric. Faults tending N–S are also common (Slišković 1994).

The study area is composed of sedimentary rocks of the Permo-Triassic, Triassic, Upper Jurassic, Lower and Upper Cretaceous, Palaeogene, Neogene and Quaternary ages (Slišković 1994).

The Triassic strata (mainly dolomites) form partial barriers for water circulation within the study area. The broader region has been exposed to repeated tectonic movements. Owing to this reason, there are many hydrogeologically important features as for example: anticlines, synclines, longitudinal and transversal faults.

Limestone, dolomites (of Jurassic age) and their combinations are the dominant lithological units that lie beneath the Lower and Upper Cretaceous periods from about 70 to 145 million years ago. They lie in the north-western parts of terrain where they normally lie beneath limestone of the Lower Cretaceous. The Cretaceous deposits, composed of stratified to massive limestone with rare dolomites; occupy the largest amount of space in the basin.

The whole area is tectonically very disturbed, which is the result of wrinkling processes in its Mesozoic and Tertiary layers. Tectonic activity in this area occurred during the Upper Jurassic and Lower Cretaceous periods, in the transitional period between the Upper Cretaceous and the Tertiary (when basic tectonic units were formed) and during the Upper Eocene (maximum). During the Tertiary and Quaternary periods, structures which formed in the Upper Eocene finally acquired their present form. It should be stressed that dolomites do not considerably obstruct groundwater circulation (Slišković and Ivičić 2000; 2002).

Most of the small mountain lakes have been formed by glacial processes. Predominantly carbonate in composition, limestone and dolomites alternate vertically and horizontally with the occasional appearance of breccias and marl intercalations. It is assumed that the thickness of the carbonate rocks exceeds 3,000 m in some places.

The Quaternary deposits extend throughout karst poljes, as well as along the open streamflows. Older Quaternary deposits are represented by glacial moraine material in the northern part of the terrain and by lacustrine clay in the Imotsko Polje (the largest polje in the analysed catchment) and also by gravel-sand and clay materials which have a considerable thickness over 100 m. Younger Quaternary deposits are mostly alluvial by origin with sandy and gravel composition. Alluvial deposits along the Imotsko Polje have the greatest thickness.

The lithology and thickness of the Quaternary deposits are various, which causes their diverse hydrogeological functioning in different part of poljes. The most of these deposits influence groundwater flow as hanging barriers. Hanging barriers can be found in Rakitno, Roško, Posuško, Imotsko and Ljubuško-Vitinsko polje (Fig. 2).

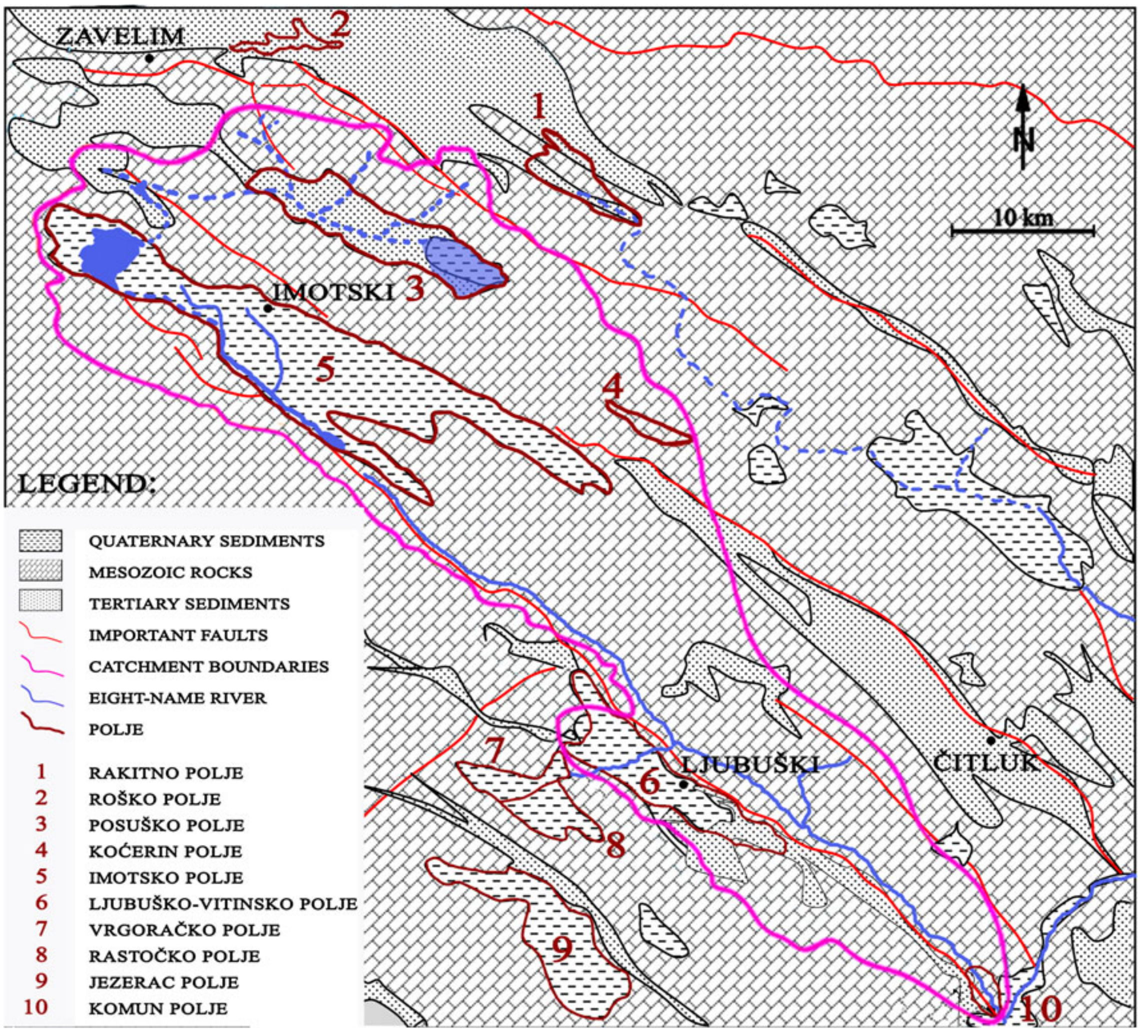


Fig. 2 Simplified geological map of the study area indicating the main karst poljes

Geomorphology and hydrography

Karst landforms are the result of a number of independent driving forces operating on a block of carbonate rocks (White 1988). Various factors and processes influence the evolution of karst forms (Čalić 2011) for example: (1) topography, (2) lithology, (3) tectonic setting, (4) active tectonics, (5) climate-dependent hydrological processes, (6) environment-dependent karst solution dynamics, (7) geomorphological processes, (8) anthropogenic influences. Among geomorphological processes the most important are (1) weathering, (2) slope, (3) fluvial processes, and (4) glacial processes. The surface and underground karst landscape can evolve over time due to small scale diffusive processes, large scale river erosion and karst denudation during high and low water (Kaufmann 2009). The karst system components formed during a previous phase may become relict, or it may become incorporated into the new structure, developing by adjusting itself to the new setting (Klimchouk 1998).

Any karst forms can more or less influence water circulation and thus influence the development of landscape hydrography (Goldscheider 2005; Goepert et al. 2011). Hydrography can be defined as the geographical description of water bodies. In the analysed area, there are many peculiar surface karst landforms, ranging in size from very small (micro-rills) to extremely large (wide karst poljes and very deep collapsed *dolines*-elongated recess on Earth's crust that is always open in the direction of the river runoff). At the same time, this area is very rich with underground geomorphological forms hidden below the surface like Blue and Red Lake (Fig. 3), as the most knowledgeable, Begića ponor which has underground flow to Imotsko-Bekijsko polje, but it is not well observed, ponor Šainovac—natural passage from river Matica to Tihaljina, Ravlića cave, Majića ponor, Mala and Velika Studenčica cave (near Ljubuški) and many others. The main obstacle for water circulation determination, sustainable water management, and especially the explanation of interplay

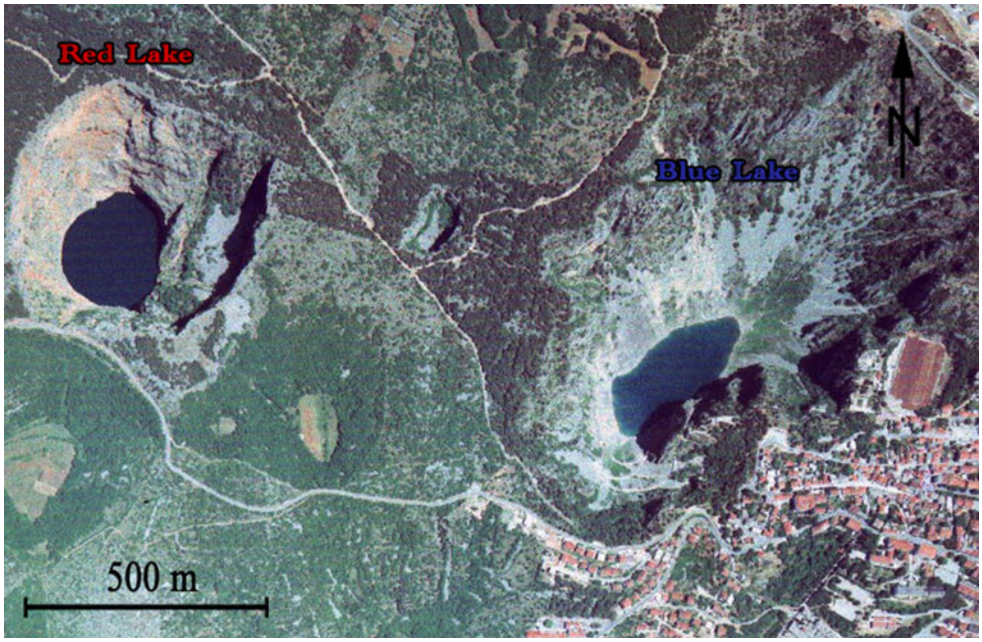


Fig. 3 Photography of the Blue and Red Lakes (Taken by V.Čosić)

between geomorphology and hydrology is the limited availability of information about existing underground forms.

Larger karst poljes recorded on study area (Fig. 2) represent what are perhaps the most important karst forms controlling water circulation as well as the hydrologic–hydrogeologic behavior of this system. They exhibit complex karst features, such as permanent and temporary springs and rivers, losing and sinking rivers, swallow-holes and estavelles. Milanović (1995; 2004a, b, c) considers that reverse faults of a regional extent have frequently played a key role in their genesis, and that they are tectonically controlled along tectonic boundaries.

In the area, there are in all four basic types of poljes (Bonacci 1987, 2004b): (1) closed; (2) upstream open; (3) downstream open; (4) upstream and downstream open. In closed and upstream open poljes only underground drainage exists. In downstream and upstream and downstream open poljes both underground drainage and surface drainage are present. Closed poljes prevail in the area.

From the hydrologic–hydrogeologic perspective, a polje is to be considered part of a wider system. It cannot be treated as an independent system, but only as a subsystem in the process of surface and groundwater flow through the karst massif. The poljes are regularly flooded during the cold and wet periods of the year. Flood zone area is variable and depends on the amount of rainfall and the hydrological cycle. Flooding of the poljes in the Dinaric karst in natural conditions lasts on average from 3 to 7 months per year, mostly between October and April, but there are cases when flooding can persist for up to 10 months. Poljes may be flooded when: (1) the groundwater level rises above their bottoms; (2) inflow exceeds the maximum capacity of the outflow structures (ponors or swallow-holes) and (3) both occur simultaneously.

The karst poljes in the study area lie between mountains. They spread in a NW–SE direction. The bottom of the higher polje is situated at an altitude of 900 m a.s.l., while the bottom of the lover polje is at 30 m a.s.l. The Imotsko Polje, with length of 32.4 km and an area of 95 km^2, is the largest in the analysed catchment.

Two exceptional karst phenomena from the study area are displayed in Fig. 3, the Red and Blue Lakes near the town of Imotski, Croatia. Bögli (1980) and Williams (2004) describe the Red Lake as the deepest known case of a collapse doline containing a permanent lake. Less than 1,000 m from the Red Lake is the Blue Lake, which dries up every 4 years on average (Bonacci 2006; Bonacci and Roje-Bonacci 2008; Palandačić et al. 2012). The water level in the Red Lake fluctuates from 230.80 to 274.45 m a.s.l. The fluctuation of the water level in the Blue Lake is from about 241 (bottom—in this case the lake is dry) to 342 m a.s.l. The water level fluctuations in both lakes follow the groundwater level oscillations in the surrounded aquifers (Bonacci and Roje-Bonacci 2008).

Water from the Red Lake upper zone is connected by karst conduit(s) to a few permanent and temporary karst springs in the Imotsko Polje (Bojanić et al. 1981). A speleodiving expedition (Garašić 2001) definitely confirmed the existence of an active underground river that crosses the Red Lake along its bottom, at an altitude of less than 6 m bellow the Adriatic Sea level. Petrik (1960) supposed

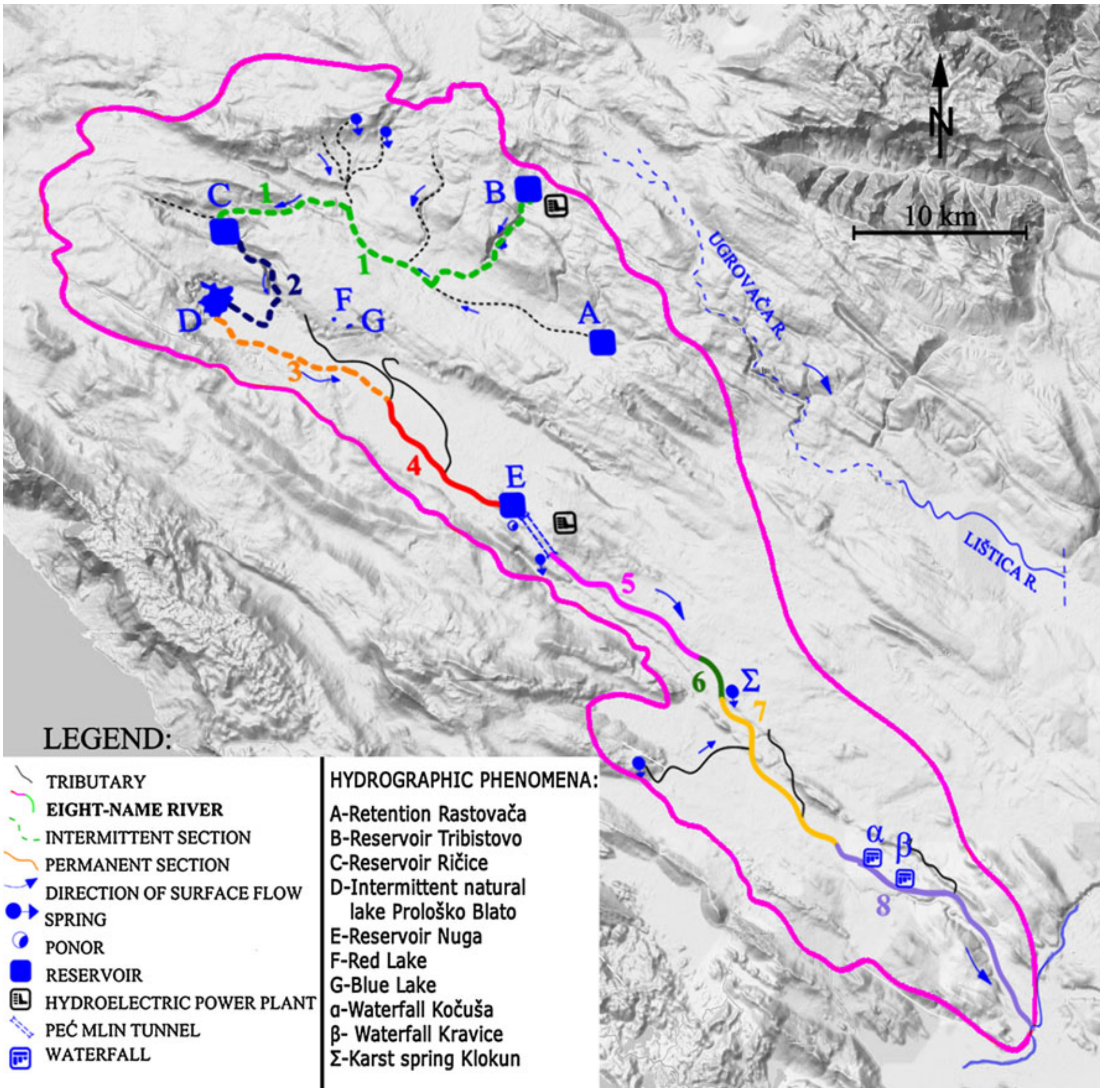


Fig. 4 Map indicating the main hydrographic phenomena in the study area with the names of the rivers: *1* Ričina, *2* Suvaja, *3* Sija, *4* Vrljika, *5* Tihaljina, *6* Sita, *7* Mlade and *8* Trebižat

that the mouth of this ˝underground˝ river is in the Adriatic Sea *vruljas* (about 35 m b.s.l.) at areal distance of about 23 km (*vrulja*—spring below the sea surface). This connection as well as the deep position of the karst underground river and vruljas possibly can be explained by the effect of the Messinian salinity crises (MSC) on the analysed karst landscape. Mocochain et al. (2009) explained the river dynamics of the Lower Ardèche River (France) as the consequence of the MSC.

Hydrographic features that have been assessed as important for understanding this complex karst system are evident in Fig. 4. There are endless natural (different kinds of ponors, permanent and temporary karst springs, permanent and temporary lakes, mountain lakes and all underground karst features) and in the last decades more and more artificial (tunnels, reservoirs, irrigation canals, hydroelectric power plants, water pumping systems, etc.) features and objects.

Generally, rivers are key links in the connectivity of different landscape elements. As rivers flow across the landscape, they usually increase in size, merging with other rivers. The network of rivers thus formed is a drainage system and is often dendritic (tree-like), but may adopt other patterns depending on the regional topography, local karst features and underlying geology (Knighton 1998). In karst terrains, the local topography plays an especially important role in river system development.

The connections between different parts of karst systems and the position of the karst catchment boundaries depend upon the rapidly fluctuating groundwater levels (Bonacci

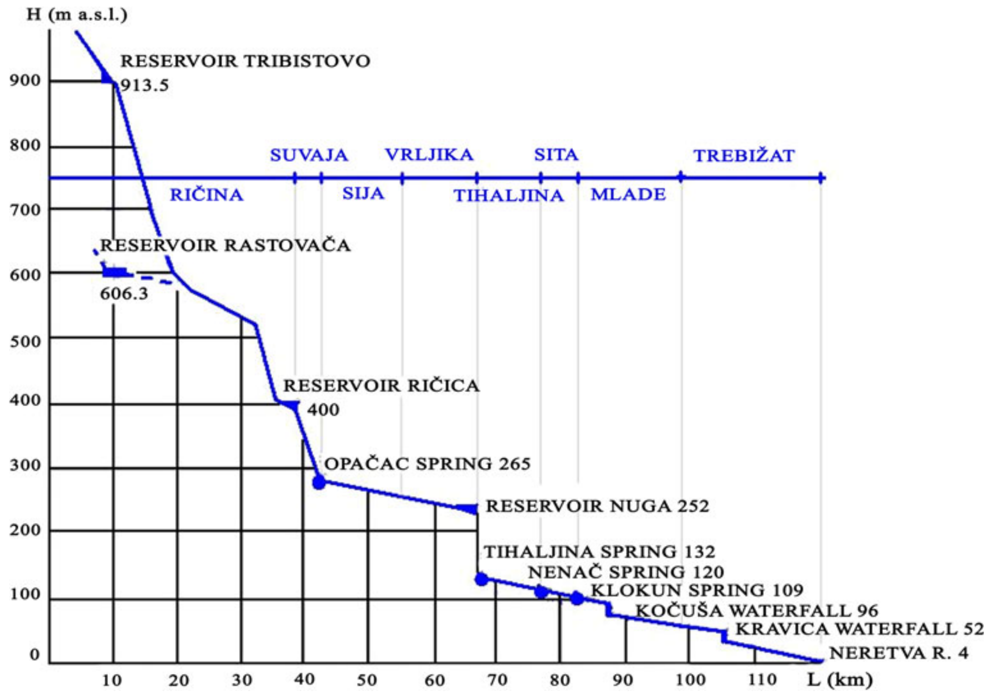


Fig. 5 Longitudinal cross-section through the eight-name river

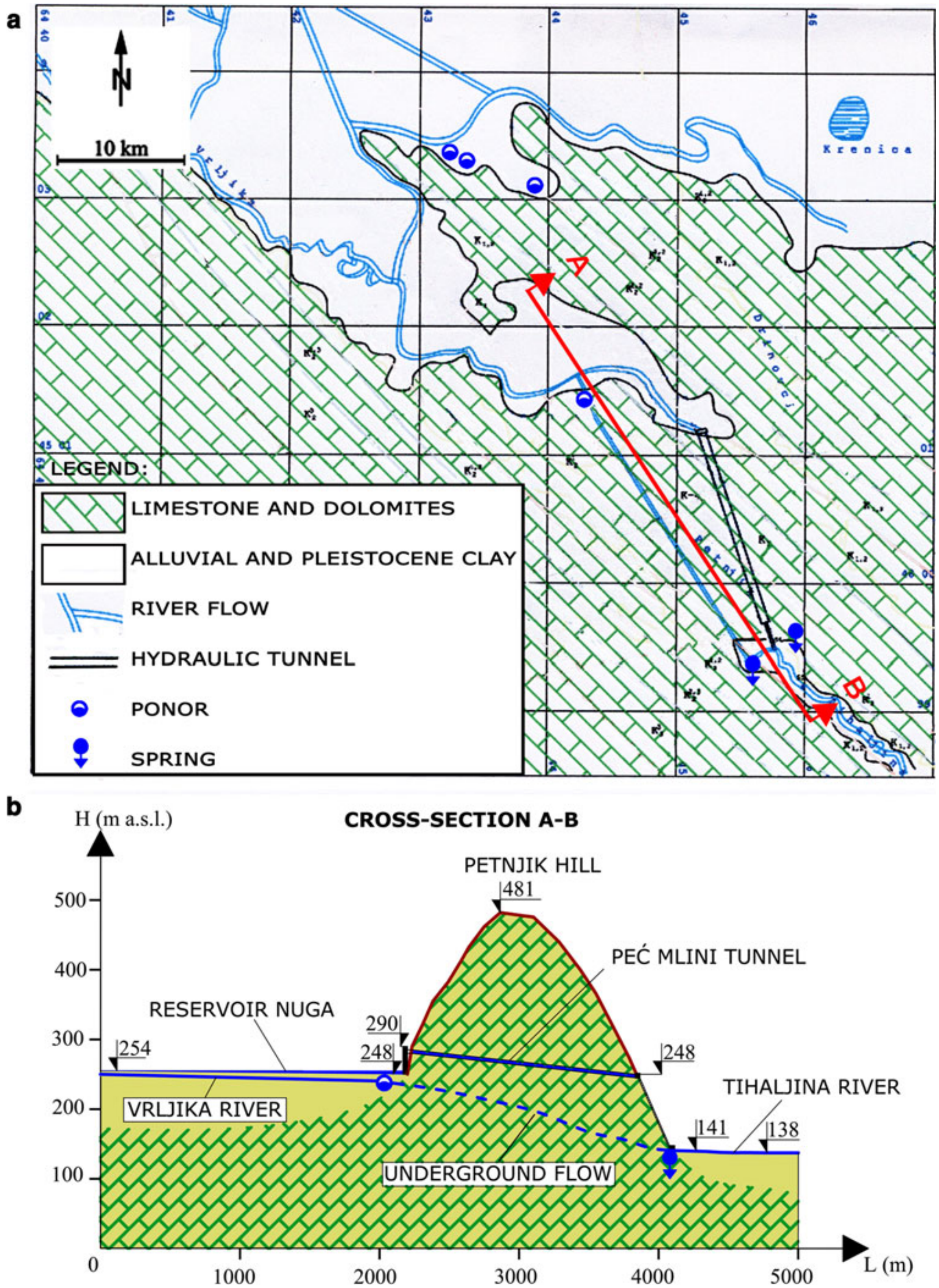
1995). When the groundwater level is extremely high, underground karst conduits, which have been inactive till that point, become functional, causing the redistribution of catchment areas, that is, the overflow from one to another catchment. Water circulation depends on the link between the land surface and underground features which change very fast in time and space due to the peculiar characteristics of the karst network, its vertical zonation, the organisation of permeability, the hierarchisation from the superficial swallow holes to the springs, the river development in time and space, the evolutionary changes in a three-dimensional pattern, anthropogenic influences, etc. All these factors have influenced one another, variously in different hydrogeological situations. The large and fast variability found in karst water circulation cannot be observed properly by typical, simple and inexpensive methods of field measurement, which is one of the main reasons why this karst system has not been investigated well enough.

From Fig. 4, it can be seen that the upper parts of the eight-name river as well as most of the other streams in the analysed region, are losing, sinking or underground. In karst terrains groundwater and surface water constitute a single dynamic system. Owing to this reason, one of the almost unavoidable characteristics of open streams, creeks and rivers in karst regions is that they either have partial water loss along their course or they completely sink into the underground. Sinking, losing and underground streamflows are more typical, significant and relatively frequent karst phenomena than it is reflected in their treatment in the karst literature. A synonym for a sinking and losing stream is an influent stream and such streams have an integral function in karst hydrology and hydrogeology (Bonacci 2010a; Wohl and Beckman 2012). Longitudinal cross-section through the eight-name river is well developed and non-uniform morphology of its bottom can be clearly seen in Fig. 5.

The location Peć Mlini, were the eight-name river as the Vrljika River sinks underground and after about 1,500 m it reappears in karst springs as the Tihaljina River, is shown in Fig. 6a (situation) and b (cross-section). Tihaljina spring is located on the foothills of Humac hill and is passing through partial barrier layered with massive limestones and dolomites, highly permeable and karstified (Slišković 1994). The hydroelectric power plant Peć Mlini is constructed in 2004 at this location.

Ponors or swallow-holes represent discontinuities in the karst massif through which the water sinks underground (Bonacci 2004c). In this way, they play a crucial role not only from the hydrologic–hydrogeologic standpoint, but also because of their ecological and environmental roles. In the study area, ponors are usually situated close to the terminus of the poljes. Milanović (2001) gives the following classification of ponors from a morphological viewpoint: (1) large pits and caves, (2) large fissures and caverns, (3) a system of narrow fissures and (4) alluvial ponors. It should be stressed that all underground phenomena (vertical caves also known as *jamas*, karst conduits, caves and even bedding planes) and some surface forms (dolines) can take on the function of ponors. Jamas most frequently function as ponors and present a pathway for the fast and direct contact of the surface water with the karst underground.

Fig. 6 Situation (**a**) and longitudinal cross-section (**b**) through the Peć Mlini location



Of the important geomorphological and hydrological forms, the Kravice and Kočuša waterfalls are to be mentioned. The locations of two waterfalls (Kravice and Kočuša) on the eight-name river are designated in Figs. 4 and 5. Figure 7 shows two photographs of the highest waterfall (Kravice) on the Trebižat River (Galić et al. 2008). Figure 8a represents the situation during high water, and Fig. 8b during low water. Discharges over the Kravice Waterfall vary over a large range from about 1 to more than 200 m^3/s. The mean annual discharge is about 31 m^3/s. Both waterfalls are formed on tufa barriers. Ford and Williams (2007) defined tufa as a grainy deposition accreting to algal filaments, plant stems and roots at springs, along river banks, in cave entrances, etc. In other sections of the analysed river, there are few locations where tufa is deposited.

Climate, hydrology and hydrogeology

Locations of meteorological and hydrological gauging stations and the results of dye tracing tests in study area are shown in Fig. 8.

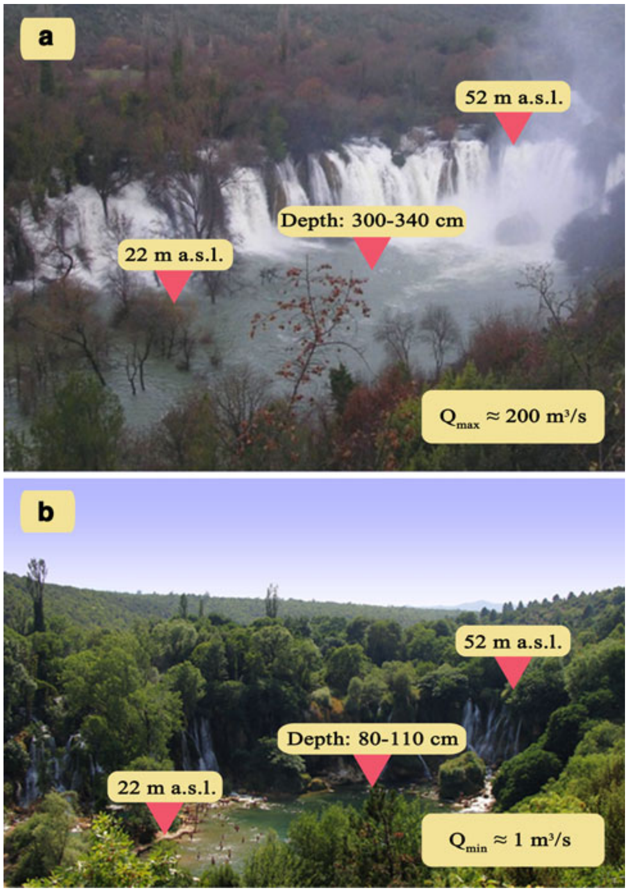


Fig. 7 Photographs of the Kravice Waterfall during high (**a**) and low (**b**) water (taken by Galić A.)

The study area is located at the periphery of the Mediterranean climate belt, with a strong influence of continental climate. It is located only 10–30 km from the Adriatic Sea, but it is separated from the sea by the Biokovo Mountain chain, which has a maximum altitude of 1,762 m a.s.l. The average annual air temperature in the area varies from less than 8 °C (northern higher part) to 14 °C (southern lower part) with a minimum daily temperature in January below −10 °C, and a maximum daily temperature in July and August above 35 °C. Climate change and/or variability in the analysed region have been determined. It seems that a warming up started in the period between 1987 and 1992, mostly in 1988. Differences of average mean annual air temperatures before and after the warming up are about 0.8 °C (Bonacci 2010b).

The annual rainfall ranges from 750 to 2,350 mm with an average of about 1,500 mm. The maximum rainfall occurs in October and November, and the minimum in July and August. Decreasing trends of annual precipitations were noted at many rain gauging stations in the study area during the period of 1950–2010.

Karst aquifer(s) is (are) very thick (hundreds of meters) and contain endless cracks, fractures, joints, bedding plains and conduits serving as groundwater pathways. The variability across time and space makes the determination of water circulation in the study area extremely sensitive and complex. Because of extreme groundwater oscillations, different hydrological and hydrogeological connections are active depending on the season. The great variability of surface and underground karst forms, as well as the interplay of pervious and impervious layers in the analysed karst massif, create practically endless possibilities of contact between two or more karst surface areas and aquifers which can belong to and feed different permanent and temporary karst springs as well as different river sections.

Rimmer and Salinger (2006) established that the water surfacing from karst springs may not actually depend on the surface area of the catchment, but rather that it is a function of the total subsurface area contributing to groundwater flow. A series of point-to-point tracer tests can be used to establish a regional network of underground flow routes analogous to the network of a surface river system (Worthington and Smart 2003).

Only a few fluorescein dye tracing tests were made in the study area. Their results are shown in Fig. 8. It can be seen that there are connections between ponors which are beyond the supposed catchment boundary and there are springs which belongs to the eight-name river catchment. Palandačić et al. (2012) use the population structure of the endemic fish species *Delminichthys adspersus* as the natural tracer to confirm known underground water connections between ponors and springs as well as to suggest new connections in the study area. They propose a holistic approach of karst area studies, combining hydrology with biology.

The largest permanent karst spring in the analysed catchment is Klokun located 80 m from the riverbed of the Tihaljina River (Figs. 4, 5). This is a typical abundant ascending or vauclusian karst spring. Discharges vary from 3.5 to more than 20 m^3/s with an average discharge of about 7.5 m^3/s.

Table 1 provides a few characteristics of nine discharge gauging stations on the eight-name river. Table 2 provides the characteristic (minimum, average and maximum) discharges at all of these gauging stations.

Table 3 provides the mean annual discharges in the available subperiod till 1987, and in the subperiod 1988–2007 measured at the following four gauging stations in the upper part of the eight-name river: (1) Jovića most at Ričina; (2) Proložac at Suvaja; (3) Šumet and Sija and (4) Kamen most at Vrljika. A strong drop in the mean annual discharges has been noted at all of them. A possible explanation of such a strong drop in mean annual discharges can be found in the development of artificial reservoirs in the upper part of the analysed catchment, in uncontrolled groundwater pumping and in inferior regional

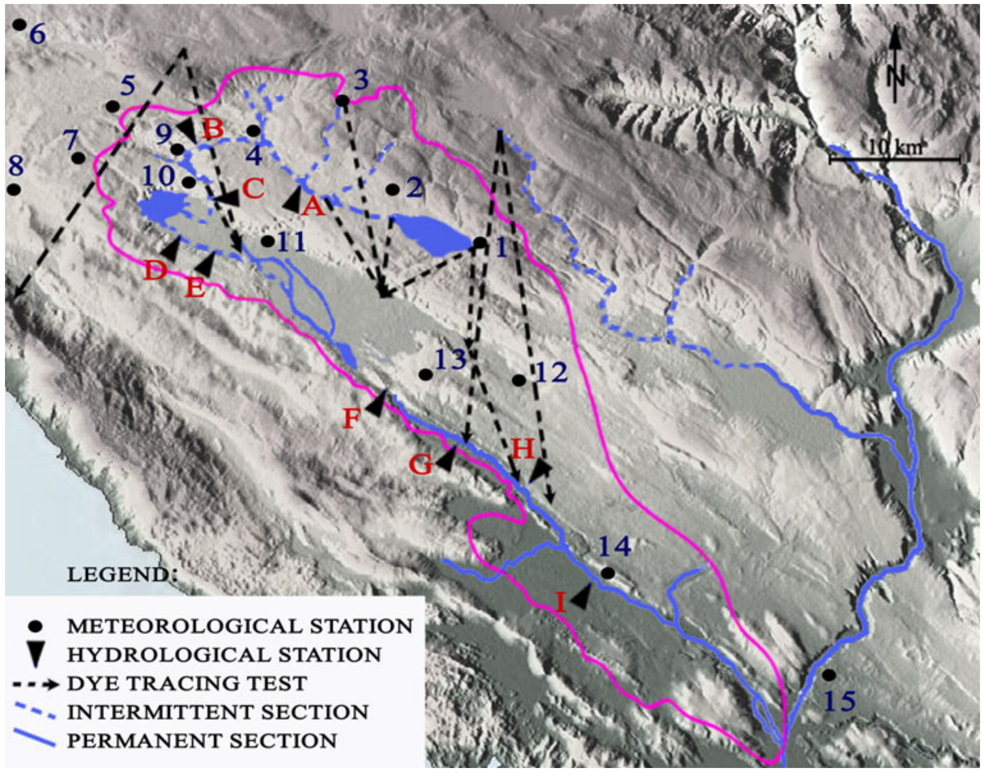


Fig. 8 Map of the eight-name river catchment indicating meteorological and hydrological gauging stations and results of dye tracing tests (1-Bročanac, 610 m a.s.l.; 2-Posušje, 651 m a.s.l.; 3-Tribistovo, 930 m a.s.l.; 4-Vir, 570 m a.s.l.; 5-Vinice, 725 m a.s.l.; 6-Aržano, 645 m a.s.l.; 7-Studenci, 604 m a.s.l.; 8-Lovreč, 526 m a.s.l.; 9-Ričice, 571 m a.s.l.; 10-Brana Ričice, 402 m a.s.l.; 11-Imotski, 435 m a.s.l.; 12-Grude, 290 m a.s.l.; 13-Drinovci, 280 m a.s.l.; 14-Ljubuški, 98 m a.s.l.; 15-Čapljina, 5 m a.s.l.; A-Jovića most at Ričina; B-Ričice at Ričina; C-Proložac at Suvaja; D-Šumet at Sija; E-Kamen most at Vrljika; F-Peć Mlini at Tihaljina; G-Tihaljina at Tihaljina; H- Klobuk at Mlade; I-Humac at Trebižat)

Table 1 Main characteristics of nine discharge gauging stations on the eight-name river

No.	Station name	River section	Altitude (m a.s.l.)	Available period
1	Jovića most	Ričina	582	1979–2007
2	Ričice	Ričina	415	1989–2007
3	Proložac	Suvaja	284	1955–2007
4	Šumet	Sija	271	1961–2007
5	Kamen most	Vrljika	260	1962–2007
6	Peć Mlini	Tihaljina	135	1967–2001
7	Tihaljina	Tihaljina	125	1963–1989
8	Klobuk	Mlade	106	1965–2001 (1992)
9	Humac	Trebižat	65	1946–2001 (1980; 1982–1994)

Missing data are given in brackets

water management as well as in climate changes and/or variability. Similar behaviour of mean annual discharges has been noticed in the downstream section of the eight-name river, but there are not enough accurate data to formulate a reliable conclusion.

Conclusions

The analysed case is a good example of the strong interplay as well as the extreme complexity of karst surface and underground features and karst hydrology–hydrogeology. The main obstacle is that the shortage of groundwater level data does not allow for the formulation of definite conclusions about the functioning of this complex system. The full characterisation of the complex conduit organisation as an inherent characteristic of the karst aquifer is the only way to find accurate karst springs and rivers catchments and to protect their water resources (Perrin and Luetscher 2008; Pardo-Iguzquiza et al. 2011). The variability, in time and space, of the karst aquifer as well as the conduit parameters make this process extremely sensible and complex. In the complex procedure of catchment determinations as well as the explanation of water circulation in the analysed region, it is of paramount importance to take into account the local and regional geomorphological and other processes and parameters which can influence the hydrodynamic and mass transfer and storage of water into karst aquifers. In addition, spatial distribution of recharge in karstified terrains represents a complex issue in which

Table 2 Characteristic (minimum, average and maximum) discharges determined at the nine discharge gauging stations on the eight-name river

No.	Station name	River section	Q_{min} (m^3/s)	Q_{av} (m^3/s)	Q_{max} (m^3/s)
1	Jovića most	Ričina	Dry	0.13	76
2	Ričice	Ričina	Dry	0.25	77
3	Proložac	Suvaja	Dry	0.66	182
4	Šumet	Sija	Dry	1.3	47
5	Kamen most	Vrljika	0.8	8.5	80
6	Peč Mlini	Tihaljina	0.1	11	70
7	Tihaljina	Tihaljina	0.1	16.5	128
8	Klobuk	Mlade	2.3	25	214
9	Humac	Trebižat	0.9	31	209

Table 3 Mean annual discharges till 1987 and in the period 1988–2007 measured at four gauging stations in the upper part of the eight-name river

Station name and river section	Subperiod	Q_{av} (m^3/s)
Jovića most at Ričina	1979–1987	0.258
	1988–2007	0.073
Proložac at Suvaja	1955–1987	1.018
	1988–2007	0.056
Šumet at Sija	1961–1987	1.95
	1988–2007	0.439
Kamen most at Vrljika	1962–1987	9.94
	1988–2007	6.72

application of conventional methods does not produce satisfactory results in these terrains (Radulović et al. 2012).

Accurate answers for many questions concerning the interplay between karst features and hydrology in the analysed catchment cannot be obtained using the available information. The lack of reliable data is evident. Of 20 known stations, which were observed in and around the observed area, only 8 of them are still working and 7 of them have more 20 years of significant collectable data (mostly monthly precipitation data, 5 of them with daily precipitation data but only from the 1990s). In addition, the stations are not evenly distributed so they can approximately cover only 40 % of the NW area of the catchment, if the World Meteorological Organization (WMO) recommendations are considered for minimum densities of meteorological stations in mountain areas (WMO 2008).

The dense network, including the continuous and automatic monitoring of many climatologic, hydrologic and hydrogeologic parameters, has to be established to collect more accurate data, which will then make it possible to explain such an extremely complex karst system.

The analyses made in the paper show the existence of a decreasing trend of mean annual discharges on the eight-name river, which can cause many troubles for the regional water resource management of this transboundary river and catchment.

The analysed river at its catchment is divided between two countries Croatia and Bosnia and Herzegovina. New irrigation projects, a shortage of water caused by climate changes or climate variability, flood management, the production of hydropower, etc. could cause serious problems in water resources management between the neighbouring countries. To achieve the sustainable development of this vulnerable and valuable karst area, a better understanding of the deep and long-lasting mutual relationship between human activities and natural processes is of crucial importance. The inevitable prerequisite lies in a better understanding of regional karst hydrological and hydrogeological regimes. A holistic and interdisciplinary use of geomorphological and hydrological–hydrogeological approaches, methods and concepts should help to achieve this goal. Special attention should be paid to the fact that the decreasing trend of discharges in last twentieth period has been established. Decreasing of river flow can be explained by natural as well as anthropogenic influences. Annual rainfall regime shows decreasing trend, while mean annual air temperature shows increasing trend (Bonacci et al. 2012). At the same time, uncontrolled quantity of groundwater and surface water is used for intensive agricultural production.

This can be a trigger for starting a divergence between different users. Potential conflict between water users is real, especially during dry and hot summers when the water demands are very high and the available water is very low. The greatest problem is that in both states detailed plans of future water demands as well as water availability (especially not well investigated groundwater resources) are not constructed nor developed. The fact that the analysed catchment lays in two states represents obstacle in process of negotiation.

References

Beach T, Luzzadder-Beach S, Dunning N, Cook D (2008) Human and natural impacts on fluvial karst depressions of the Maya lowlands. Geomorphology 101:308–331

Bögli A (1980) Karst hydrology and physical speleology. Springer, Berlin

Bojanić L, Ivičić D, Batić V (1981) Hidrogeologija Imotskog polja s osvrtom na značaj u regionalnom smislu [Hydrogeology of Imotski Polje with review on regional significance]. Geološki Vjesnik 34: 127–135

Bonacci O (1987) Karst hydrology with special references to the dinaric karst. Springer, Berlin

Bonacci O (1995) Ground water behaviour in karst: example of the Ombla Spring (Croatia). J Hydrol 165(1–4):113–134

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

Bonacci O (2001) Analysis of the maximum discharge of karst springs. Hydrogeol J 9(4):328–338

Bonacci O (2004a) Hazards caused by natural and anthropogenic changes of catchment area in karst. Nat Hazards Earth Syst Sci 4(5/6):655–661

Bonacci O (2004b) Poljes. In: Gunn J (ed) Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, pp 599–600

Bonacci O (2004c) Ponors. In: Gunn J (ed) Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, pp 600–601

Bonacci O (2006) Crveno i Modro jezero kod Imotskog [Red and Blue Lakes near Imotski]. Hrvatske Vode 14(54):45–54 (Croatian)

Bonacci O (2007) Analysis of long-term (1878–2004) mean annual discharges of the karst spring Fontaine de Vaucluse (France). Acta Carsologica 36(1):151–156

Bonacci O (2010a) Sinking, losing and underground karst streamflows. In: Bonacci O (ed) Proceedings of international interdisciplinary scientific conference "sustainability of the karst environment—dinaric karst and other karst regions". IHP-VII series on groundwater no. 2, Paris, pp 9–16

Bonacci O (2010b) Analiza nizova srednjih godišnjih temperature zraka u Hrvatskoj [Analysis of mean annual air temperature series in Croatia]. Građevinar 62(9):781–791 (Croatian)

Bonacci O, Andrić I (2008) Sinking karst rivers hydrology: case of the Lika and Gacka (Croatia). Acta Carsologica 37(2–3):185–196

Bonacci O, Roje-Bonacci T (2008) Water losses from the Ričice reservoir built in the Dinaric karst. Eng Geol 99(3–4):121–127

Bonacci O, Jukić D, Ljubenkov I (2006) Definition of catchment area in karst: case of the rivers Krčić and Krka, Croatia. Hydrol Sci J 51(4):682–699

Bonacci O, Ljubenkov I, Knezić S (2012) The water on a small karst island: the island of Korčula (Croatia) as an example. Environ Earth Sci 66(5):1345–1357

Čalić J (2011) Karstic uvala revisited: toward a redefinition of the term. Geomorphology 134(1–2):32–42

Ford D, Williams P (2007) Karst hydrogeology and geomorphology. Wiley, Chichester

Galić A, Prskalo M, Glamuzina G, Marinčić J (2008) Kompleksna analiza značajki područja vodopada Kravice na rijeci Trebižat [Complex analyzes of regional characteristics of the waterfall Kravice on the Trebižat River]. Rudarsko Geološki Glasnik 12:89–108 (Bosnian)

Garašić M (2001) New speleohydrogeological research of Crveno Jezero (Red Lake) near Imotski in Dinaric karst area (Croatia, Europe): International speleodiving expedition 'Crveno jezero 98'. 13th International Congress of Speleology, Speleo Brazil, 2001

Goepert N, Goldscheider N, Scholz H (2011) Karst geomorphology of carbonatic conglomerates in the Folded Molasse zone of the Northern Alps (Austria/Germany). Geomorphology 130(3–4): 289–298

Goldscheider N (2005) Fold structure and underground drainage pattern in the alpine karst system Hochifen-Gottesacker. Ecologae Geologicae Helvetiae 98:1–17

Herak M (1986) A new concept of geotectonics of the dinarides. Acta Geologica 16:1–42

Kaufmann G (2009) Modelling karst geomorphology on different time scales. Geomorphology 106:62–77

Klimchouk A (1998) The typology of gypsum karst according to its geological and geomorphological evolution. Int J Speleol 25(3–4):49–60

Knighton D (1998) Fluvial forms and processes. Hodder Arnold, London

Milanović P (1995) Prirodni uslovi i tehnicke mogucnosti formiranja podzemnih akumulacija u karstu [Natural conditions and technical possibilities of underground reservoirs formation in karst areas]. Vodoprivreda, 27(153–155): 47–60

Milanović P (2001) Karst hydrogeology. Water Resources Publications, Littleton

Milanović P (2004a) Izgradnja hidrotehnickih objekata u karstu - rizik kao neizbezna komponenta uspesnosti [Induced subsidences hazard as consequence of dams, reservoirs and tunnels construction in karst]. Vodoprivreda 36(209–210): 239–251

Milanović P (2004b) Water resources engineering in karst. CRC Press, Boca Raton

Milanović P (2004c) Dinaride poljes. In: Gunn J (ed) Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, pp 291–293

Mocochain L, Audra P, Clauzon G, Bellier O, Bigot J-Y, Parize O, Monteil P (2009) The effect of river dynamics induced by the Messinian Salinity Crises on karst landscape and caves: example of the Lower Ardèche river (mid Rhône valley). Geomorphology 106:46–61

Palandačić A, Bonacci O, Snoj A (2012) Molecular data as a possible tool for tracing groundwater flow in karst environment: example of Delminichthys adspersus in Dinaric karst system. Ecohydrology 5(6):791–797. doi:10.1002/eco.269

Pardo-Iguzquiza E, Durán-Valsero JJ, Rodríguez-Galiano V (2011) Morphometric analysis of three-dimensional networks of karst conduits. Geomorphology 132(1–2):17–28

Perrin J, Luetscher M (2008) Inference of the structure of karst conduits using quantitative tracer tests and geological information: example of the Swiss Jura. Hydrogeol J 16(5):951–967

Petrik M (1960) Hidrografska mjerenja u okolici Imotskog [Hydrographic measurements in the Imotski area]. Ljetopis JAZU 64:266–286 (Croatian)

Podobnikar T, Schöner M, Jansa J, Pfeifer N (2009) Spatial analysis of anthropogenic impact on karst geomorphology (Slovenia). Environ Geol 58(2):257–268

Radulović M, Stevanović Z, Radulović M (2012) A new approach in assessing recharge of highly karstified terrains—Montenegro case studies. Environ Earth Sci 65(8):2221–2230

Redžić S, Barudanović S, Trakić S, Kulijer D (2011) Vascular plant biodiversity richness and endo-relictness of karst mountains Prenj, Čvrsnica and Čebulja in Bosnia and Herzegovina (W. Balkan). Acta Carsologica 40(3):527–555

Rimmer A, Salinger Y (2006) Modelling precipitation-streamflow processes in karts basin: the case of the Jordan River sources. Israel J Hydrol 331:524–542

Slišković I (1994) On the hydrogeological conditions of Western Herzegovina (Bosnia and Herzegovina) and possibilities for new groundwater extractions. Geologia Croatica 47(2):221–231

Slišković I, Ivičić D (2000) Hidrogeologija Imotskog polja [Imotski Polje hydrogeology]. Rudarsko-Geološki Glasnik 4:59–67

Slišković I, Ivičić D (2002) Hidrogeologija sliva Imotskog polja i rijeke Tihaljine [Imotski Polje and Tihaljina River hydrogeology]. Rudarsko-Geološki Glasnik 5:117–127

White WB (1988) Geomorphology and hydrogeology of karst terrains. Oxford University Press, Oxford

Williams P (2004) Dolines. In: Gunn J (ed) Encyclopedia of caves and karst science. Fitzroy Dearborn, New York, pp 304–310

WMO (2008) Guide to hydrological practices volume I: hydrology—from measurement to hydrological information, Publication WMO-No. 168, 6th edn. Geneva, pp I.2–24

Wohl E and Beckman ND (2012) Leaky rivers: implication of the loss of longitudinal fluvial disconnectivity in headwater streams. Geomorphology. doi:10.1016/j.geomorph

Worthington SRH, Smart CC (2003) Empirical equations for determining tracer mass for sink to spring tracer testing in karst. In: Beck BF (ed) Sinkholes and the engineering and environmental impacts of karst. American Society of Civil Engineers, Reston, pp 287–289