GEOL. CROAT.	50/2	279 - 288	10 Figs.			ZAGREB 1997

Hydrogeological Exploration of the Rječina River Spring in the Dinaric Karst

Božidar **BIONDIĆ**, Franjo **DUKARIĆ**, Mladen **KUHTA** and Ranko **BIONDIĆ**

Key words: Hydrogeological exploration, Dinaric karst, Karst spring, Karst aquifer, Overthrusted structures, Deep retention spaces, New intake structure, Access gallery, Monitoring of the karst aquifer.

Abstract

The Rječina spring is one of the major springs in the Dinaric Karst. It appears at the contact between permeable carbonate and impermeable clastic rocks, with a discharge of up to 120 m^3/s but it dries up during the dry summer seasons. The spring occurs close to the town of Rijeka, 325 m above sea level and offers an outstanding opportunity to cover gravitationally the public water demand of a town of about 200,000 inhabitants, and the touristic needs of the whole region. This hydrogeological research project is a part of efforts to solve the problems of water deficiency during the dry summer seasons up to a maximum of three months. It was necessary to enter the parts of a karst aquifer that are active even in time of any outflow from the Rječina spring by complex geological, hydrogeological and geophysical exploration accompanied with deep exploratory boreholes. During earlier exploration, it was determined that there are no active inflows in the immediate hinterland of the spring and that it is necessary to discover the inflows from other karst structures, that behave as retentions of karst springs in the zones of permanent discharge. The presence of multiple overthrusted structures in the zone around the spring site suggest the existence of deep zones of water retention, which may be reached by an access gallery from the Rječina canyon. This work represents a substantial change in the exploration methodology for Dinaric Karst aquifers, because it directs the researchers toward deep, unknown retention spaces which contain large reserves of high-quality groundwater outside urban areas.

1. INTRODUCTION

The Rječina spring is the largest karst spring in the northern Adriatic area, but it is inactive during the summer dry seasons for up to three months a year. This is a great problem for the water supply to the town of Rijeka (Fig. 1), because all groundwater extraction sites in the coastal area have to be activated during these periods. This is a risk to high water quality and a considerable cost as the water has to reach 540 m above sea level. The Rječina spring, occurring at 325 m above sea level would be an economically and technically very favourable gravitational water supply for the largest part of the town. Moreover, the Rječina spring water is of extremely high quality with the potential of remaining so for future generations, as the spring catchment area in the mountains of Gorski Kotar is protected to a water reserve level.

The Rječina spring occurs a substantial distance North of the closest urban center of the Rijeka area (Fig. 2). It has only recently been of interest as part of the urban water supply as previous demand was covered by supply from coastal springs. This was also influenced by the temporary dryness of the spring during summer dry seasons, when the demand for potable water reaches a maximum. The hydro-power potential of the spring initiated the first studies after World War II. Poljak and Crnolatac directed their exploration toward estimation of the possibilities of water storage in the predominant flysch deposits of the Rječina river valley without much consideration of the karst catchment areas. ŠIKIĆ & PLENIČAR (1975), the authors of the Basic Geological Map 1:100,000 Sheet Ilirska Bistrica, provided a base for the exploration of the karst areas, as this map comprises the carbonate massif of a part of Gorski Kotar and Slovenski Snežnik Mt. which drain towards the Rječina spring and other karst springs within the Rijeka region.

The first hydrogeological bases of the carbonate hinterland of the Rječina spring were made by Biondić and Vulić in 1969. For the first time the Rječina spring catchment area was defined and combined with a very detailed hydrogeological description. This was, also, the first hydrogeological definition of a karst catchment area in the Dinarides. Within this exploration, Božičević performed a speleological exploration, including detailed research of the Rupa ponor in the Grobničko Polje. The Rječina spring was also of interest to researchers of karst morphology and it was first explored by Italian diver-speleologists in 1928. They reached a depth of 15 m, followed by Croatian diver-speleologists in 1971 (to 34 m), 36 m in 1984 and 50 m in 1996. During the most

This paper was presented at the scientific meeting dedicated to the 80th anniversary of the life of Professor Milan Herak, held on March 5th, 1997 in Zagreb

---

Institute of Geology, Sachsova 2, P.O. Box 268, HR-10000 Zagreb, Croatia.

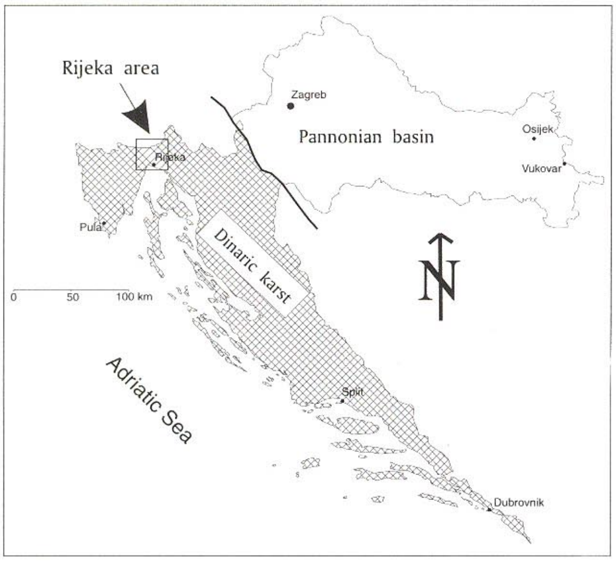

Fig. 1 The Dinaric karst region in Croatia showing the position of the study area.

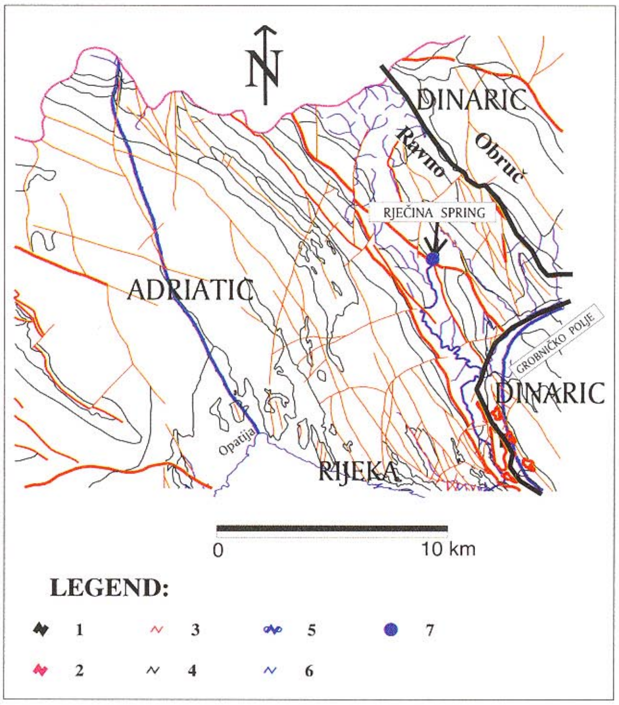

Fig. 2 A tectonic sketch of the study area. Legend: 1) boundary between the Adriatic and Dinaric units; 2) main reverse fault; 3) faults; 4) geological boundary; 5) watershed; 6) rivers; 7) Rječina spring.

recent study in 1996 a lower channel was discovered at depth (KUHTA, 1998). Groundwater was twice pumped out from the spring cave system during the dry summer seasons of 1969 and 1973. Vast cave spaces were opened and speleologically explored by BOŽIČEVIĆ (1973, 1974). Under natural conditions, these cave spaces had been filled with remnant water even in the summer dry periods. In the upper part of the cave system, a 20-m-long gallery was constructed to facilitate entry to the cave even during high water stages.

Since 1971, the Rječina spring has formed an increasing part of the hydrogeological research projects of the entire catchment area of springs discharging in the town of Rijeka. During these explorations, numerous detailed mappings and groundwater tracings were made in the carbonate hinterland of these springs, which helped to define the catchment area. To maximise the use of the Rječina spring, a considerable possibility would be to build a surface dam submerging the spring. Recent study showed that the immediate area around the spring does not contain significant amounts of water, but the spring can be submerged without problems, i.e. without water losses toward the downstream parts of the catchment area. The basic conclusion was that the close spring hinterland occurs intermittently out of the influence of deep underground retentions which control the spring discharge during the summer dry seasons. Therefore, new explorations should be directed toward those geologic structures which are potentially active aquifers during the summer dry seasons.

2. GEOLOGICAL REVIEW

Generally, the base for the hydrogeological exploration of karst areas is a good knowledge of the geological structure, but it is of a special importance for the Rječina river spring where all the complexity of the structural composition of the Dinarides is fully displayed (HERAK, 1986, 1991). The lithostratigraphy and tectonics define the geometry of karst aquifers into which the hydro-dynamics elements can be included.

Within the Rječina spring area, the aquifer is composed of Cretaceous and Palaeogene carbonate rocks, while the Palaeogene flysch deposits form a barrier to groundwater flow. In this study, the most important influence were certain lithostratigraphic changes within the carbonate mass, and the structural position of various lithostratigraphic units (BIONDIĆ, 1988).

The Lower Cretaceous limestones and calcareous breccias (K_1), the oldest rocks in this area, form an anticline which can be traced from the Rječina river hinterland, to the north-western edge of the Grobničko Polje. The calcareous breccias are overlain by dolomitized breccias ($K_{1,2}$), up to 150 m thick, formed by late-diagenetic dolomitization of tectonised transitional deposits between the Lower and Upper Cretaceous. The dolomitized breccias are overlain by an Upper Cretaceous ($K_2^{1,2}$) unit, 500 m thick, in which dolomites and limestones alternate. Dolomites prevail in the hinterland of the Rječina spring, and gradually pass into a pure Upper Cretaceous calcareous complex of rudist limestones ($K_2^{2,3}$), up to 350 m thick. At the transition to Palaeogene deposits, the sedimentary environment substantially changed. Continental sedimentation began over a marked karst relief, with occasional lagoonal and brackish lake sediments as for example in the hinterland of the spring, where the Palaeogene began with Liburnian deposits. Following a marine transgression over the area typical marine foraminiferal limestones

($E_{1,2}$), up to 200 m thick, were deposited. Toward the river Zala valley, a gradual transition toward clastic sedimentation above the foraminiferal limestones can be observed. This began with 30-50 m thick transitional clastic deposits ($^1E_{2,3}$) and continued with flysch deposits ($^2E_{2,3}$), the thickness of which might reach about 600 m (based on their thickness in the Istrian flysch basin). The Eocene-Oligocene calcareous breccias (Jelar deposits) have not been observed within the explored area. The Quaternary sediments are very important for the understanding of events when the actual surface and underground hydrosystem was formed. The occurrence of Pliocene-Pleistocene lacustrine sediments at the north-western edge of the Grobničko Polje indicate the existence of a palaeodepression before the Quaternary. These lacustrine sediments (gravel and conglomerates), and fluvioglacial fans toward the surrounding mountainous area are the results of heavy glacial activity in the catchment area. The remnants of river terraces (sandy-clayey sediments with cobbles) also have a significant role as they show the arrangement of surface streams in their genetic sequence during the Quaternary. Deluvial and outwash deposits on steep slopes of the Rječina river canyon reflect recent erosional processes and do not affect the hydrogeological interpretations.

Interpreting the geological structure, it is necessary to consider not only the local conditions but also the regional ones, as the hydrodynamics is related most closely to the regional tectonics. For the study area, as well as for the whole of the Dinarides, it is important to define the relationship of the macrostructural units. According to HERAK (1986, 1991), in the Rijeka region this means the relationship between the Dinaric and Adriatic units. Their mutual relationship is significant for the formation of groundwater and its flow toward the Adriatic coastal area. According to our exploration, the boundary between these two macrostructural units stretches along the thrust contact of the Obruč structural unit. This is a continuation of a fault contact extending from Ilirska Bistrica, in Slovenia, over the Ravno area, to the north-western edge of the Grobničko Polje. The Grobničko polje was formed at the intersection of numerous large perpendicular faults. They caused the south-westward transposition of Dinaric structure and the covering of Adriatic structures to the Vinodol flysch valley (Fig. 2). According to this interpretation, the carbonate massif of the Rječina spring hinterland belongs to the Adriatic megastructural unit, which is characterised by folded structures and numerous imbricate-thrust structures and, at the carbonate massif border, large occurrences of Palaeogene flysch deposits. This is also confirmed by normal lithostratigraphic transitions from areas of carbonate sedimentation to clastic ones in the area of Zale and Ravno to the north of the study area.

The local tectonic structures of the Rječina spring area best reflect the regional relationships. On the cliff above the spring, many thrusts occur within the carbonate complex, and also throughout the carbonate massif over the flysch deposits, as well as intense rotative faulting which caused mutual movements of parts of the overthrusts and the formation of structural blocks. The highest thrusted structure is placed east of the spring, on a plateau above the canyon. This structure has a very important function in further hydrogeological deliberations within this project. In this "top" thrusted structure, the carbonate rocks are folded and of a very variable composition: from very permeable limestones to poorly permeable dolomites. From a hydrogeological aspect, a crushed anticline of Dinaric strike having very permeable Lower Cretaceous limestones in its core is of special interest. This anticline lies parallel to the Rječina river valley (canyon). In the Grobničko Polje area, this anticline is entirely opened on one side forming the main seasonal groundwater discharge zone during the rainy seasons. From the Grobničko Polje toward the Rječina spring hinterland, the anticline plunges slightly, and the very permeable limestones have progressively thicker cover of low permeability dolomites and dolomitic breccias. To the east of this anticline, a synclinal form opens, and its margin is obscured by the Dinaric Obruč overthrust. The whole structure of the Rječina spring hinterland sinks toward the north-west, hence, progressively younger deposits are recorded in this direction, toward Ravno and Mlaka, where there is a gradual transition of carbonate rocks into impermeable flysch that forms northwestern boundary of the structure.

Geomorphological phenomena, as in all karst areas of the Dinarides, are a direct result of the lithological characteristics, geological structure, hydrogeological properties of rocks and the changes in hydrological and meteorological conditions, particularly during the Quaternary epoch. The relief forming processess must be considered dynamically, through time, because the present state is only a momentary reflex of the interaction of endogenous and exogenous processes. The material traces in the shape of morphological phenomena and younger sediments (river valleys, river terraces, underground phenomena etc.) enable at least a partial reconstruction of the geomorphological development of a terrain and, importantly provide insight into the genesis of the actual hydrogeological relationships and groundwater dynamics.

Sedimentary outcrops indicate that the Grobničko Polje depression was already formed by the Pliocene, when numerous karst poljes in the Dinarides were lakes. The Grobničko Polje is possibly the starting point of the development of karst processes for the whole catchment of all springs in the Rijeka region (BIONDIĆ et al., 1998). Present relief formation is associated with the Pleistocene and the alternation of glacial and interglacial stages. Intense glacial activity is obvious from the discovery of glacial sediments in the mountainous area of Platak and Snježnik. The interglacial stages brought increased amounts of water resulting in increased erosion and fluvioglacial sedimentation. In the area of Grobničko Polje and higher located Gomanca Polje, glacial lakes were formed. These had a controlling function in the development of underground karst morphology and karst aquifers during the Quaternary.

A study of Quaternary sediments shows that all surface streams were directed toward the Grobničko Polje. The bed of the intermittent stream Zala still down cuts from the Ravno area to the Grobničko Polje. The case of the Rječina spring and the development of the lenght of this river canyon is especially interesting. The river spring and canyon are geologically very young features. The discovery of terrace sediments on a carbonate ridge in the spring hinterland (about 220 m above the present spring site) are indicators of surface streams in the hinterland prior to the existence of the large karst spring at the high rock foot. The terrace sediments also confirm that all surface streams, including the Rječina river, flowed toward the Grobničko Polje.

Through the development of karst processes, water from the surface progressively was descending into the carbonate underground and the deep canyon was being deepened in the area composed of flysch rocks. The discoveries of fossil springs high in the cliff above the present spring confirm the gradual canyon opening and the water removal into a deeper karst underground. This erosional process is ongoing, as confirmed by discovery of two cave conduits at the Rječina spring (BOŽIČEVIĆ, 1974). One of these is overflowing and the other ascending, which will result during future canyon development, further deepening and water springing at another, somewhat lower level.

The Rječina stream, during its first development phase, flowed into the Grobničko Polje. The runoff from the Grobničko polje to the present Bay of Kvarner, which was not submerged in that time (ŠEGOTA, 1968), was effected only through the karst underground. The main water communication was directed toward the Zvir spring in Rijeka. The erosional bed of this spring is much deeper than the bed of the Rječina river. This is now the main drainage direction of a large karst catchment area of springs in the town of Rijeka.

The deep Rječina river canyon dominates the morphology of the study area. It has been mostly formed in flysch sediments, while massive carbonates occure above and surrounding the hinterland of the spring. The plateau is characterised by elongated valleys and structures directed toward the Grobničko Polje. An expressive morphological step is formed by the Obruč overthrust, that is also a boundary of the Adriatic and Dinaric macrostructural units.

Numerous speleological phenomena have been recorded in the study area. The largest phenomen are the cave system of the Rječina river spring, extending horizontally over more than 200 m, and the Rupa ponor in the Grobničko Polje, which is part of the main zone of ponors toward the coastal springs.

3. HYDROGEOLOGICAL REVIEW

The general hydrogeological situation of the whole catchment area depends on the tectonics and the significant lithological variation of this area. The lithological characteristics directly affect the hydrogeological properties of these rocks, while their vertical and lateral changes influence the spatial arrangement of potential aquifers.

Within the carbonate complex, in the area of the Rječina spring, two groups of rocks of different hydrogeological characteristics may be distinguished. While the limestones represent a very permeable medium and generally the main groundwater collectors, the dolomites are much less permeable and very often form barriers to groundwater flow, within very permeable limestones or they direct this flows along the bounding structures. The flysch sediments are generally impermeable and they, depending on their structural position, also form barriers to groundwater flow in karst areas. The Rječina spring appears at the tectonic contact between very permeable karstified limestones and the Eocene flysch. However, groundwater flow is recorded below impermeable flysch sediments at some other sites. The Quaternary deposits, depending on their lithological characteristics, are of variable permeability; however, they have no major significance in this area due to their relatively small thickness.

It would be too simple to assume that very permeable limestones are always also active aquifers. This depends both on the position of the rock units and the geological structure of the terrain, and those explains the complexity involved in the hydrogeological exploration of karst terrains, especially in the high zones of karst catchment areas. Considerable changes in the conditions of groundwater dynamics of the study area have to be connected with the latest vertical and rotary movements of the tectonic forms that were originally tangentional (overthrusted geologic structures). All larger spring sites in this catchment area are associated with the latest tectonic movements. This refers to the Rječina spring, to the intermittent springs at the northwestern edge of the Grobničko Polje and to the permanent coastal group of springs as Zvir and Martinščica. Even the flysch zone, stretching almost continuously from the Bay of Trieste to the town of Novi Vinodolski, does not function as a hydrogeological barrier along its full length. This is caused by its variable depth due to the latest tectonism and erosional processes. The result is that groundwater flows through the Upper Cretaceous and Eocene highly permeable karstified limestones beneath the flysch. A similar case is the underground flow from the ponors in the Grobničko Polje to the coastal springs Zvir and Martinščica.

The Rječina spring is an intermittent karst spring reaching a maximum discharge rate of 120 m^3/s (annual average about 8 m^3/s). It is a part of the intermittent discharge zone from the catchment area of the Rijeka town springs (BIONDIĆ, 1988; BIONDIĆ et al., 1995) that

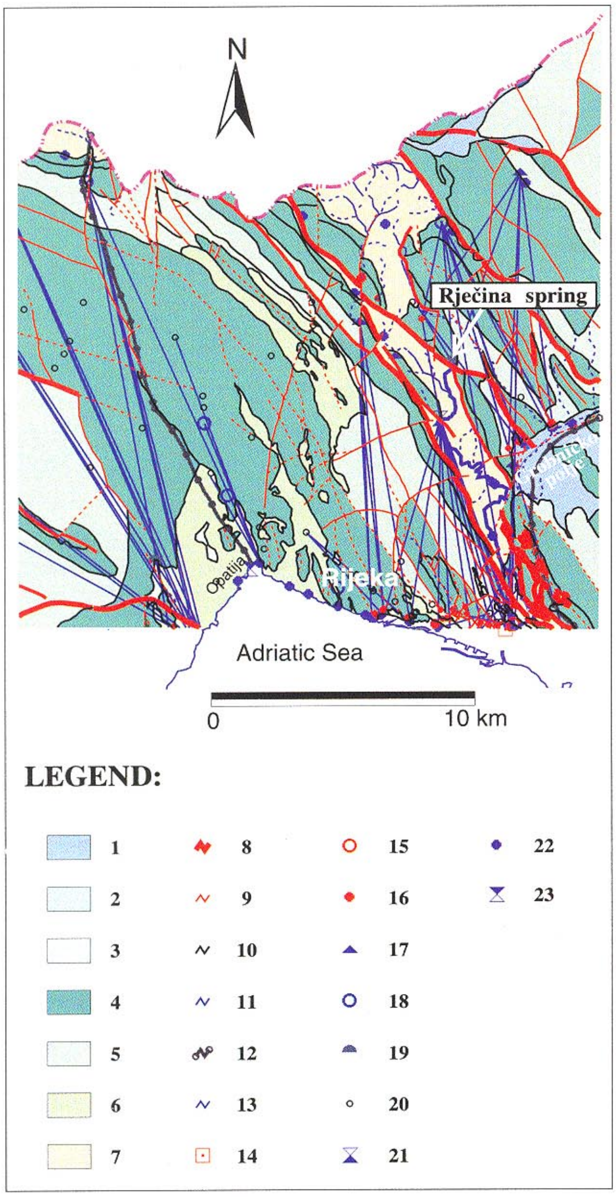

Fig. 3 The regional hydrogeological map. Legend: 1) Quaternary layers of variable permeability, relatively small thickness; 2) Quaternary layers of low permeability, relatively small thickness; 3) highly permeable alluvial deposits; 4) highly permeable carbonate rocks; 5) medium permeable carbonate rocks; 6) low permeable carbonate rocks; 7) impermeable clastic rocks; 8) main reverse fault; 9) fault; 10) geological boundary; 11) groundwater flow direction tested by tracing; 12) watershed; 13) river; 14) intake structure; 15) dug well; 16) drilled well; 17) hole with water; 18) ponor; 19) cave; 20) hole; 21) estavelle; 22) spring; 23) submarine spring.

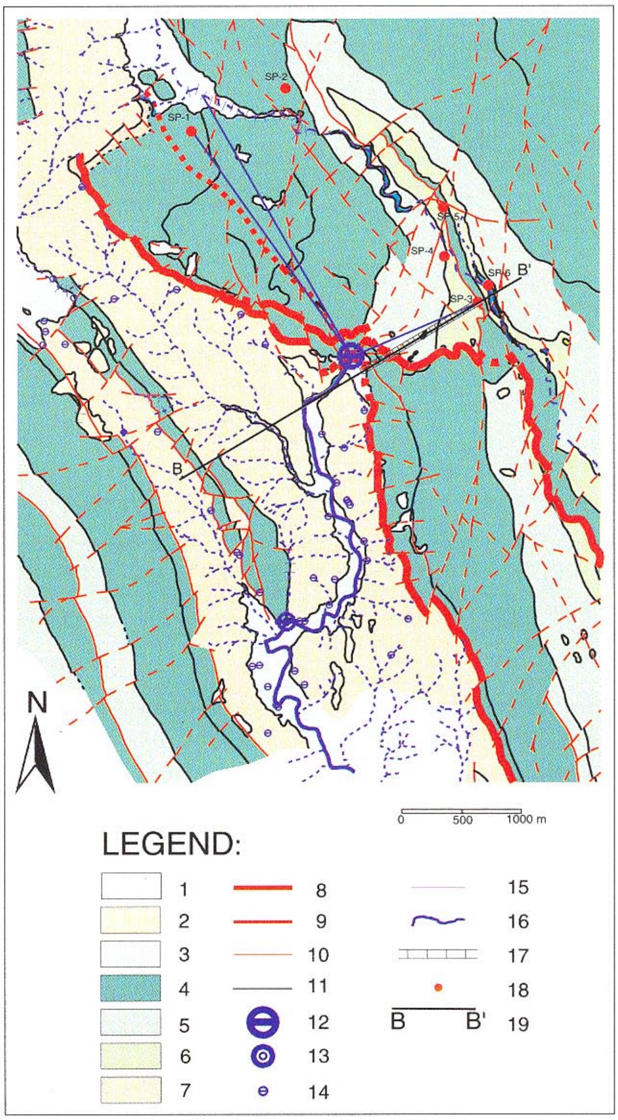

Fig. 4 A detail hydrogeological map of the study area. Legend: 1) highly permeable debris; 2) low permeable debris; 3) highly permeable alluvial deposits; 4) highly permeable carbonate rocks; 5) medium permeable carbonate rocks; 6) low permeable carbonate rocks; 7) impermeable clastic rocks; 8) main reverse fault; 9) reverse fault; 10) fault; 11) geological boundary; 12) Rječina spring; 13) estavelle; 14) small spring; 15) groundwater flow direction tested by tracing; 16) river; 17) proposed gallery; 18) exploration borehole; 19) cross section B-B'.

comprises a wide mountainous area in Gorski Kotar and a part of the Slovenski Snežnik Mt. The permanent springs of this catchment area are: Zvir, extraction site Zvir II, pumping site Martinščica and coastal springs in the town of Rijeka. This is the most productive catchment area in the northern Adriatic region and the main potable water supply for the town of Rijeka, and a major part of the Bay of Rijeka (approximately 3 m^3/s during the dry summer seasons). The Rječina spring occurs high in the catchment area (325.21 m above sea level) and has the function of an overflow for medium and high groundwater, for which the natural underground flow is directed toward the Grobničko Polje and the permanent coastal springs (Fig. 3). The springs at the north-western edge of the Grobničko Polje are also intermittent, but they are active for a much shorter period than the Rječina spring, hence, water only flows out from those springs during the high stages. During dry seasons, the Grobničko Polje springs are without water, but the water flows through the deep karst underground towards the permanent coastal springs. This flow is monitored in several observation boreholes and has been confirmed by numerous water tracing tests (BIONDIĆ et al., 1979). The immediate hinterland of the

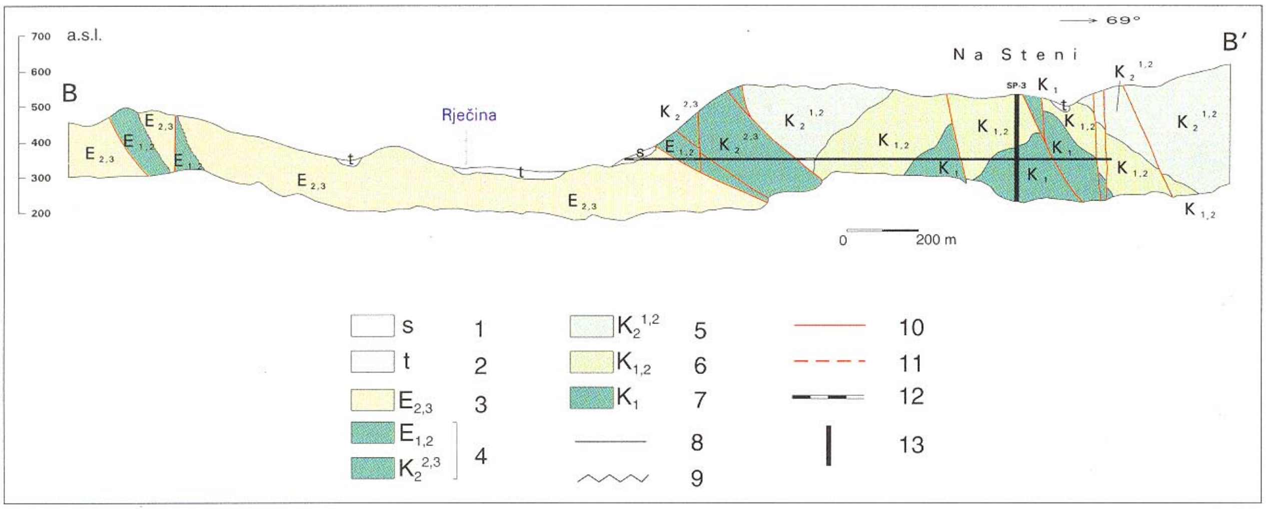

Fig. 5 Cross-section through the active karst aquifer with the proposed intake gallery. Legend: 1) intergranular porosity, high permeability; 2) intergranular porosity, high to variable permeability; 3) impermeable clastic rocks; 4) high permeable carbonate rocks; 5) medium permeable carbonate rocks; 6) low permeable carbonate rocks; 7) high permeable carbonate rocks; 8) geological boundary; 9) erosional boundary; 10) fault; 11) presumed fault; 12) proposed gallery; 13) borehole SP-3.

Rječina spring also lacks an active groundwater circulation, although its cavernous conduits are filled with delayed groundwater.

The described water dynamics in the catchment area of the Rijeka town springs has been defined by numerous groundwater tracing tests. For the high parts of this area, to which the Rječina spring belongs, the tracing of a small ponor at Trstenik village in the mountainous part of the catchment area is particularly interesting. It was performed at the beginning of a summer dry season, when the flow from the Rječina spring began to decline and the intermittent springs on the north-western edge of the Grobničko Polje were dry, while about 1.5 m^3/s flowed out from the permanent coastal spring Zvir. The observation boreholes at the north-western edge of the Grobničko Polje and the permanent coastal springs of this catchment area were monitored. The appearance of the tracer in the boreholes and permanent springs confirmed groundwater connection between the mountainous area of high precipitation (more than 3,000 mm per year) and the zones of intermittent and permanent springing. Similar results were also produced by the tracing of ponors in Mlaka situated adjacent to the intermittent springing zone.

For the Rječina spring, what happens in the zone of intermittent springs is the most important. This zone belongs structurally to the Adriatic edge. It is a folded area of Dinaric strike, where each fold thrusts over the other, as is clearly visible on the cliff above the Rječina spring. In these folds, limestones and dolomites alternate. A combination of the folded masses of different hydrogeological characteristics, combined with a north-westwards sinking of the whole structure under the impermeable flysch deposits, forms a basis for the formation and flow of surface and groundwater. The whole carbonate mass, at its north-western side, is bordered with impermeable flysch (Fig. 4) and, at its south-eastern side in the Grobničko Polje, cut by a strong perpendicular fault. Along this fault, the main drainage direction is formed toward the permanent springs of the catchment area (BIONDIĆ et al., 1995).

The challenge for hydrogeological exploration was to determine whether it would be possible to extract deep groundwater during the dry summer seasons, when the Rječina spring is inactive. Such action has not previously occurred in the Dinaric karst terrains. Alternatively, one intermittent spring must be transformed into a permanent one in order to provide a permanent urban water supply from a high, unurbanised zone within the same catchment area. Taking into account the absence of active groundwater inflows in the immediate vicinity of the spring during the dry summer seasons, the exploration had to be directed to other structural forms which, even during dry seasons, keep an active connection with the main recharge areas in the mountainous part of the catchment area. The tangentional structural forms offered such a possible solution.

Detailed hydrogeological mapping of the spring area highlighted a manifold overthrusting of carbonate rocks of different hydrogeological characteristics (limestones and dolomites) at the eastern side of canyon, and the very spring zone. This suggested the possibility of the existence of active aquifers even when the Rječina spring is inactive. The hydrogeological map (Fig. 4) and the cross-section (Fig. 5) show three such overthrusts with paraclases inclined mainly north-eastwards. The first overthrust is composed of very permeable limestones lying over the flysch barrier and directly passes the spring site. The second overthrust is visible high on the slope, above the spring, and this overthrust above inspired the search for an active aquifer. It is part of a folded structure that extends south-eastwards to the Grobničko Polje where is the huge intermittent discharge zone, reaching the rate of up to 15 m^3/s in rainy seasons. The core of the folded structure is composed of Lower Cretaceous highly permeable calcareous breccias and limestones. These rocks, being covered by younger poorly permeable dolomitized breccias, could be a good medium for the formation of "captive" aquifers. The third overthrust which covers the aforementioned thrust fold and its very permeable limestone zone is too high to be in the zone of active groundwater circulation.

Detailed hydrogeological mapping was followed by geophysical exploration using double gradient mapping and resistivity sounding. The sounding reached depths sufficient to enable hydrogeological interpretation to below the Rječina spring level. By interpreting the measured geoelectrical data, three sites of well-marked minimums (maximal differences in the rock resistivity for two deep hold) were discovered along the core of the fold structure. The results of the hydrogeological mapping and geophysical exploration were used to prepare the forecast cross-section which were a basis for defining of the locations and depths of exploratory boreholes.

The exploratory-observation boreholes were located along the core of the fold structure that follows the Rječina river valley to the north-western edge of the Grobničko Polje. One of the boreholes (SP-3) provided data allowing full description of the hydrogeological characteristics of the active karst aquifer (Figs. 4 & 6). Down to a depth of 145 m below surface, this borehole was drilled through practically impermeable Lower Cretaceous dolomitic breccias, with a constant return of drilling water. However, when the borehole reached highly permeable crushed calcareous breccias at the depth of 145 m, an abrupt loss of drilling water occured combined with a simultaneous subartisian rise of groundwater level high above the contact between the impermeable and permeable rocks. The borehole ended at a depth of 300 m in the highly permeable Lower Cretaceous calcareous complex. It may be concluded that the highly permeable Lower Cretaceous calcareous breccias and limestones form an active karst semiconfined aquifer, even during the summer dry seasons.

Significant results were obtained from the monitoring of groundwater levels in the region surrounding the Rječina spring, and at the north-western edge of the Grobničko Polje, and have been compared with the rates of discharge from the Rječina spring (Fig. 7). Data from the observation boreholes arround the Rječina spring and those at the north-western edge of the Grobničko Polje support the theory of full aquifer activity even during a total cessation of activity from the Rječina spring.

To define the aquifer dynamics, good results were obtained by measuring groundwater temperature along the aquifer depth in different hydraulic conditions (Fig. 8). The borehole SP-3 showed a constant decrease of water temperature downwards approaching the temperature of the Rječina spring water (7.5°C) and this also means the approach to the depth from where water flows toward the spring. This is also an indicator of an active aquifer, open toward deep structures, that is also possible geologically. A different situation exists in the observation well at the north-western edge of the Grobničko Polje where the lower temperature values were

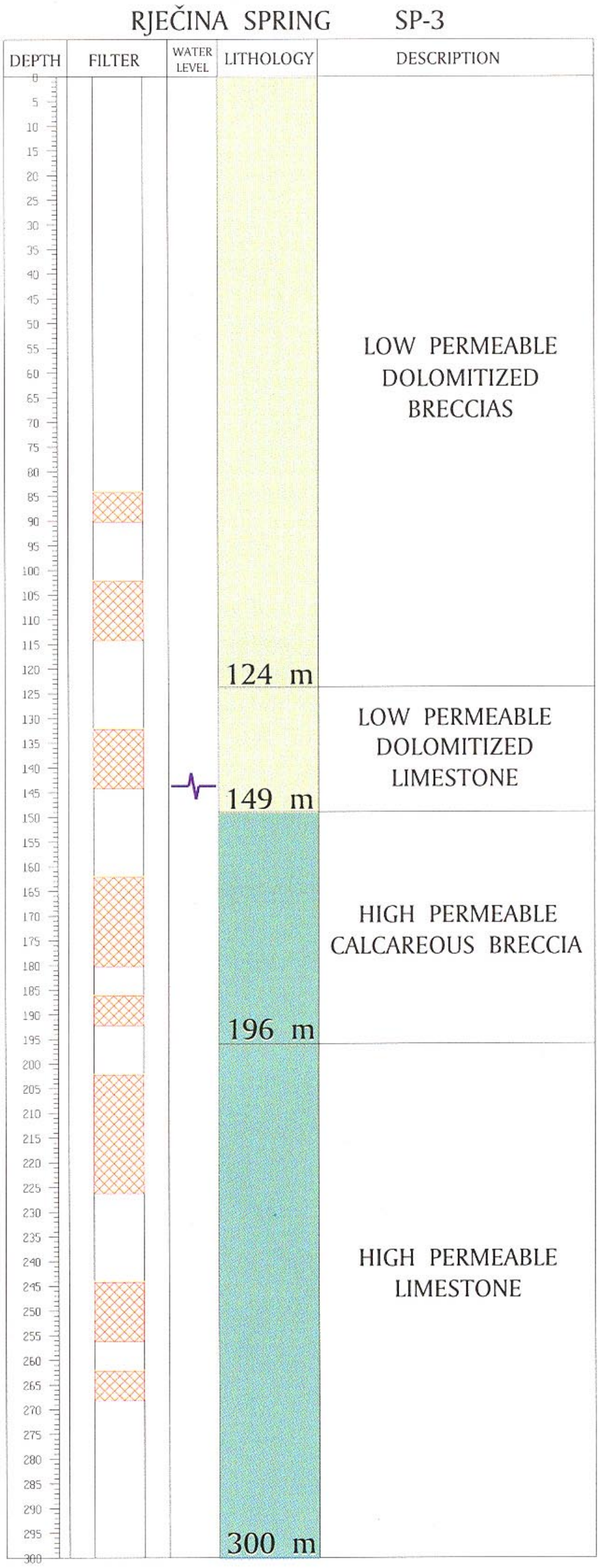

Fig. 6 Exploratory borehole SP-3.

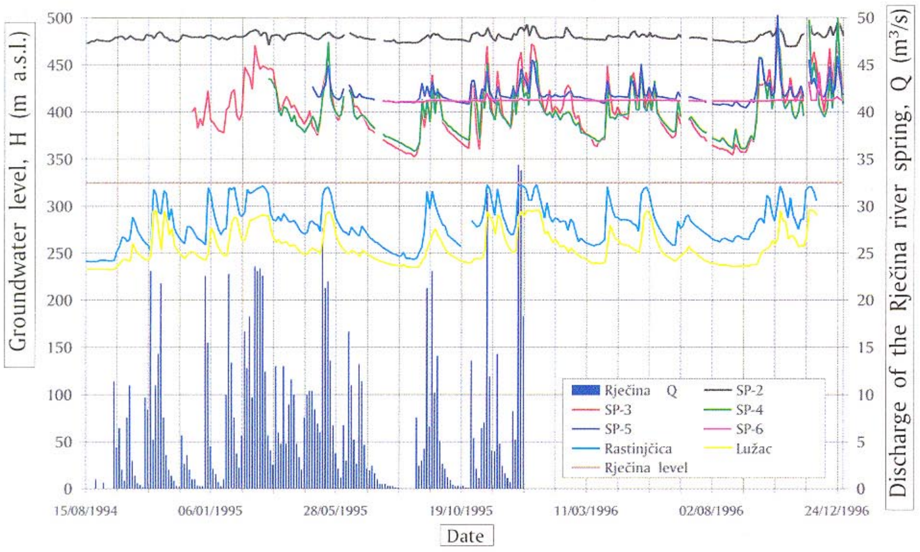

Fig. 7 Diagram of the observed groundwater levels and Rječina spring capacity.

recorded in the shallow parts of aquifer (Fig. 9), which is the normal situation in spring zones. The electrical conductivity measurement under various hydraulic conditions showed a constant exchange of water in the deep karst underground (Fig. 10).

Groundwater flow tracings from the observation borehole SP-3 determined the connection of the explored karst aquifer with groundwater at the NW edge of the Grobničko Polje, and also with the Rječina spring, where the traser appeared. This shows a lateral openness of the aquifer toward the Grobničko Polje, and also toward the Rječina spring.

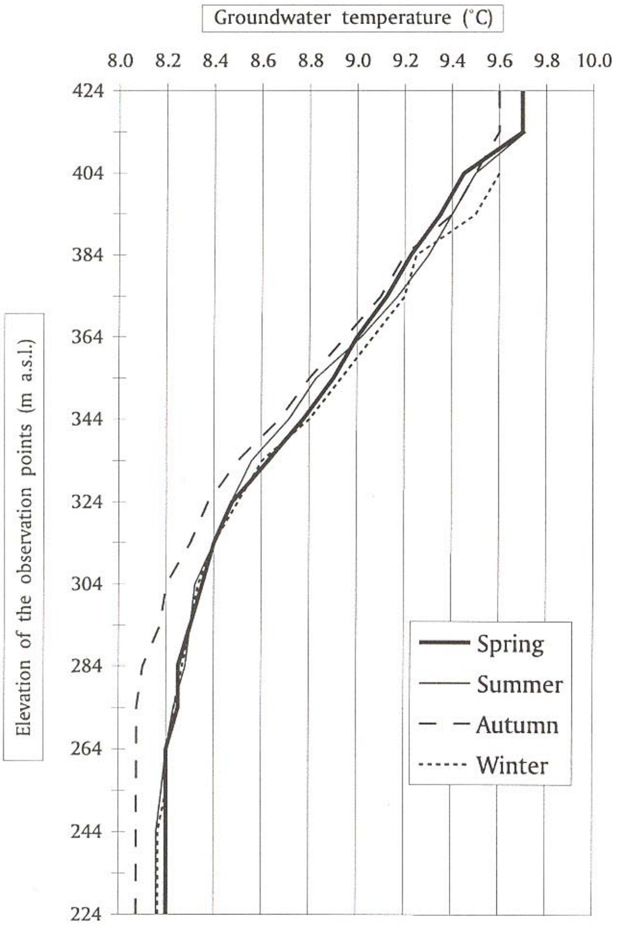

Fig. 8 Diagram of the groundwater temperature variations in the borehole SP-3.

4. CONCLUSION

The Rječina river spring, due to its position and water quality, is an outstandingly suitable source for the water supply of Rijeka. It enables a gravitational inflow of high-quality water into the whole water-supply area. However, the cessation of activity for up to three months in the dry summers is a problem as during these dry periods the entire urban water supply has to be converted to the permanent coastal springs. This considerably increase production cost and creates problems in the protecting of spring water quality (BIONDIĆ & GOATTI, 1986).

Detailed hydrogeological mapping, geophysical exploration, exploratory boreholes, groundwater flow tracing and detailed measurements of hydrodynamic and geohydrochemical parameters identified karst aquifers which are active during Rječina spring inactivity. They indicated that the best aquifer conditions exist in a folded structure in the second overthrust above the Rječina spring. This structure is composed of Lower Cretaceous calcareous breccias and limestones. The measurements in the borehole SP-3 show a high water-level amplitude between 352 and 475 m above sea level, water temperature lowering with depth, a considerable exchange of groundwater under different hydrological conditions and connection with a zone of springs at the north-western edge of the Grobničko Polje. This was a good indicator of the aquifer activity and justifies elaboration of the first phase of the project for water extraction and further aquifer exploration.

It has been proposed that the explored karst aquifer can be tapped by a gallery from the Rječina river cany-

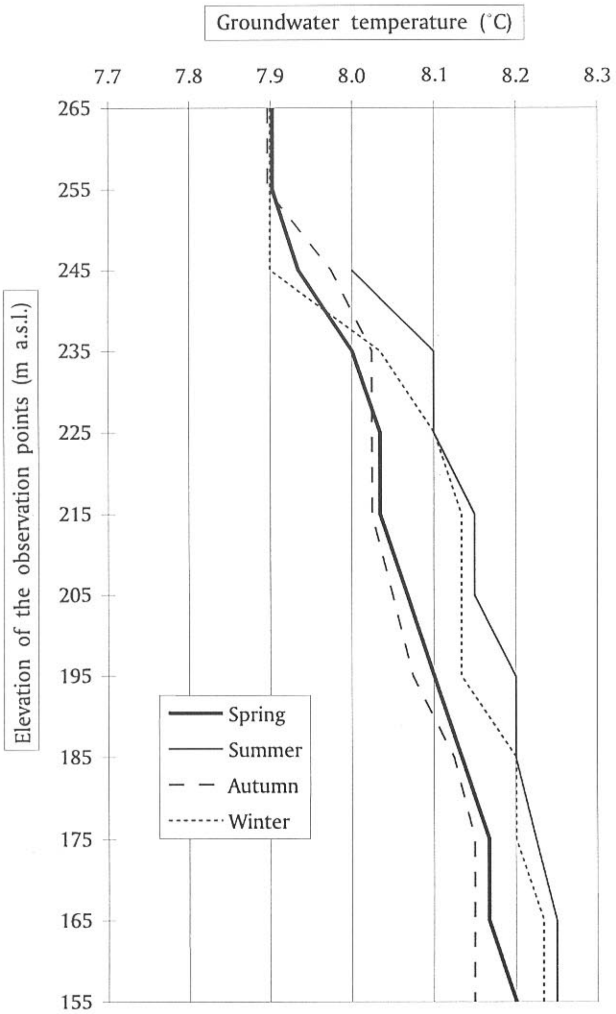

Fig. 9 Diagram of the groundwater temperature variations in the spring zone of Grobničko polje.

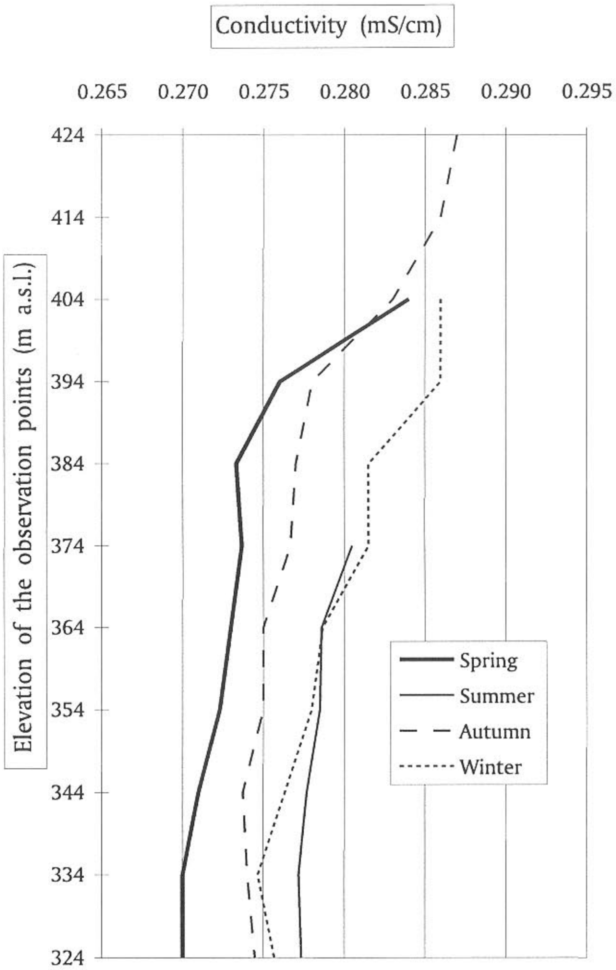

Fig. 10 Diagram of the groundwater conductivity variations in the borehole SP-3.

on, so that the active part of the aquifer is interested, but above the recorded minimal groundwater levels. Global experience support that such "water mining" is not to be recommended. Such an intake construction might cause permanent harm to the aquifer, negatively affecting the zone of permanent coastal springs. An underground entrance into the aquifer above the levels of minimal water stages does not mean the avoidance of problems associated with high water stages. In any case a gravitational drainage of water from such constructions would have to be insured. On the basis of all these and earlier explorations, a 1200 m-long gallery at an elevation of 355 m above sea level can be proposed (Figs. 4 & 5). This would enter the massif from the Rječina river canyon above the level of the Rječina spring, but needs to be further defined. Past experiences has proved that any water construction in such heterogeneous karst underground requires constant reinterpretation and design right up until the final construction and test pumping.

The final aquifer geometry, water dynamics and possible volumes of water extraction must be defined by additional hydrogeological, geophysical and geochemical exploration, and by the drilling and monitoring of observation boreholes, as well as by test pumping of production wells.

5. REFERENCES

BIONDIĆ, B. (1988): Tapping and protection of groundwater in the Adriatic karst region related to the new conception of structures of Dinarides.- Proceedings of the 21st IAH Congress, 187-193, Quilin, China.

BIONDIĆ, B., GOATTI, V. & VULIĆ, Ž. (1979): Hydrogeological investigation of watershed Rječina spring, Grobničko polje, Zvir and Martinšćica.- Proceedings of the 1st Intern. Symp. About Groundwater - UNDP, 61-69, Zagreb.

BIONDIĆ, B. & GOATTI, V. (1986): Protection of groundwater in karst area of Croatian littoral.- Proceedings of 19th IAH Congress, 112-120, Karlove Vary.

BIONDIĆ, B., ŠARIN, A., HERTELENDI, E., DUKARIĆ, F., HINIĆ, V., HRVOJIĆ, E., GOATTI, V., IVIČIĆ, D., KAPELJ, S., KOROLIJA, B., SINGER, D., BIONDIĆ, R. & MESIĆ, S. (1995): National report for Croatia.- Final report of EU COST 65 Project "Hydrogeological aspects of groundwater protection in karstic area", 65-87, Bruxelles.

BIONDIĆ, B., BIONDIĆ, R. & DUKARIĆ, F. (1998): Protection of karst aquifers in the Dinarides in Croatia.- Environmental Geology, 34/4, 309-319.

BOŽIČEVIĆ, S. (1973): Contribution to the hydrogeology of the Rječina spring.- Geol. vjesnik, 25, 277-283.

BOŽIČEVIĆ, S. (1974): Morphology of the Rječina spring water channels.- Geol. vjesnik, 27, 273-281, Zagreb.

HERAK, M. (1986): A new concept of geotectonics of Dinarides.- Acta geol., 16/1, 1-42, Zagreb.

HERAK, M. (1991): Dinaridi. Mobilistički osvrt na genezu i strukturu (Dinarides. Mobilistic view of the genesis and structures).- Acta geol., 21/2, 35-117, Zagreb.

KUHTA, M. (1998): Speleo diving explorations of the Rječina spring.- Speleolog, 44/45, in print, Zagreb.

ŠEGOTA, T. (1968): Sea level changes in holocen and younger würm.- Geographical bulletin, 30, 15-39, Zagreb.

ŠIKIĆ, D. & PLENIČAR, M. (1975): Osnovna geološka karta SFRJ 1:100.000. Tumač za list Ilirska Bistrica L33-89 (Geology of Ilirska Bistrica sheet).- Institut za geol. istr., Zagreb & Geol. zavod Ljubljana (1967), Sav. geol. zavod Beograd, 50 p.

Manuscript received April 14, 1997.
Revised manuscript accepted November 10, 1997.