GEOL. CROAT.	46/2	291 - 306	5 Figs.			ZAGREB 1993

Hydrogeology of the Hinterland of Šibenik and Trogir, Croatia

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Key words: Karst hydrogeology, Karst springs, Karst catchment areas

Ključne riječi: hidrogeologija krša, krški izvori, krška slijevna područja

Abstract

Intense karstification of carbonate rocks in the study area is the reason why the surface streams disappear and why sea water penetrates deeply into the coastal area. Locally occurring impermeable rocks have the function either of true or of hanging hydrogeological barriers. It has been discovered that the hanging barriers produce complex hydrogeological conditions, especially near major karst springs. The consequences of insufficient knowledge of these conditions are the reason why only a part of the existing drinking water resources are used nowadays (despite heavy demand) in such areas, and why the protected areas are disproportionally large if compared with the use of drinking water. Groundwater tracing, performed recently, considerably revised earlier opinions on the catchment areas of the most important springs of the area: the Jaruga, Torak and Pantan springs. These springs drain an area in excess of 1000 km^2. The discharge of these springs can be increased by constructing several surface reservoirs and by a controlled recharge of the karst underground with that water. Field conditions are not suitable for underground water storage.

Sažetak

Snažan razvoj okršavanja karbonatnih stijena na istraživanom terenu uzrok je nestanku površinske mreže tokova, a u priobalju je omogućio prodor morske vode duboko u kopno. Lokalno zastupljene nepropusne stijene su potpune ili viseće hidrogeološke barijere. Ustanovljeno je da viseće barijere dovode do zamršenih hidrogeoloških odnosa, posebno u blizini velikih krških izvora. Posljedica nedovoljne proučenosti tih odnosa je da se danas koristi samo dio tamošnjih pitkih voda, kao i nesrazmjerno veliko zaštitno područje u odnosu na iskorištenost pitkih voda. Izvedeno trasiranje podzemnih voda znatno je promijenilo ranije poglede na slijevove najznačajnijih izvora, Jaruge, Torka i Pantana, na kojima istječu podzemne vode iz terena površine preko 1000 km^2. Izdašnost navedenih izvora može se povećati i posredno, izvedbom nekoliko površinskih akumulacija i kontroliranim ispuštanjem voda u krško podzemlje. Za ostvarenje podzemnih akumulacija ne postoje povoljni uvjeti.

1. INTRODUCTION

There remains insufficient knowledge of water divides in the karst of Croatia. Heavy tectonic deformation of the rocks brought about complex hydrogeological conditions in areas composed of low permeability or impermeable strata. The hydrogeological conditions were studied using the most recent geological data on the catchment areas and of the surrounding areas of the most important springs. The feasibility of increasing the water supply was also considered. This also involved studying the implications of the existing deep sea water intrusion into the land. The adjacent regions, Ravni Kotari-Bukovica and the town of Split Commune, have already been studied in a similar way (FRITZ, 1978, 1981).

2. GEOGRAPHIC FEATURES

The discussed area is situated in the central region of the Croatian coast, between the towns of Šibenik and Split (Fig. 1). The northwestern part of the area is part of the North Dalmatian plateau through which the river Čikola cut a canyon. Upstream of the canyon this river flows through the Petrovo Polje which extends to its spring. There is a 12 km tributary called the Vrba creek which enters the river very close to the Čikola river spring.

The area northeast of the Petrovo Polje and the Vrba valley belongs to the slopes of Mt. Svilaja while the extensive Zagora (the Zagora of Šibenik, Trogir and South Split) lies to the southwest. The Zagora extends almost to the coast, particularly near the town of Trogir. The relief of the Zagora is sharply developed. Among several ridges, stretching in the Dinaric direction and reaching heights of 400-700 m above sea level, there are several small valleys and minor karst poljes at altitudes rarely below 200 m above sea level (the Primorski Dolac and Sitno Gornje) and mostly between 300-400 m above sea level. It is the most typical karst relief in which arable land is scarce. The vegetation is scant and three types may be distinguished: stony ground with copses, isolated groves of oak or hornbeam, and arable land.

Rainfall is almost the only precipitation, varying from 900 mm a year at the coast to 1400 mm a year toward the hinterland. Of this, two-thirds falls between September and March, and as a result there is a water shortage in the summer and early autumn, particularly in the Zagora.

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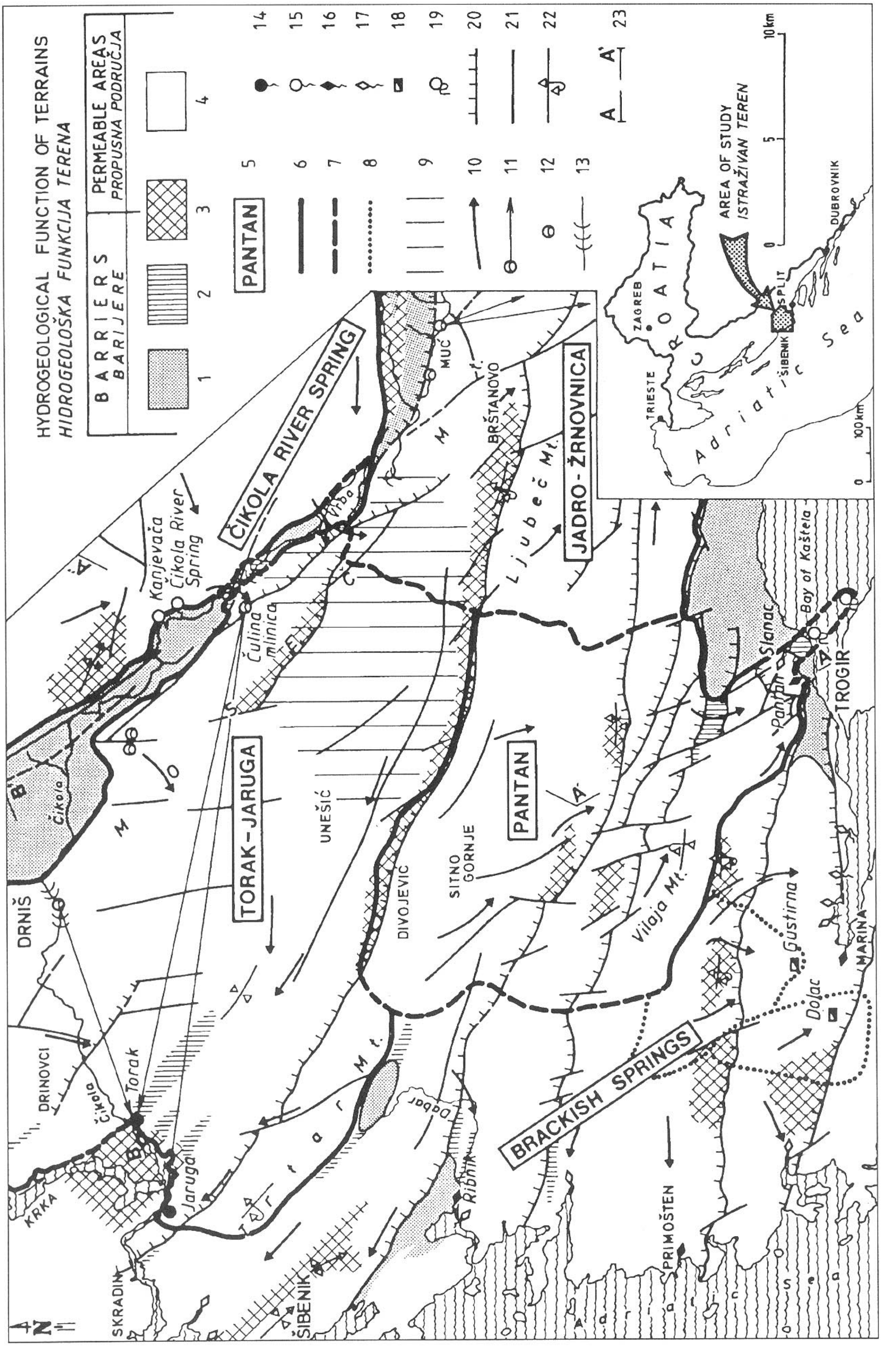
HYDROGEOLOGICAL FUNCTION OF TERRAINS
HIDROGEOLOŠKA FUNKCIJA TERENA
BARRIERS
BARIJERE
PERMEABLE AREAS
PROPUSNA PODRUČJA
PANTAN
ČIKOLA RIVER SPRING
TORAK-JARUGA
PANTAN
JADRO-ŽRNOVNICA
BRACKISH SPRINGS
AREA OF STUDY
ISTRAŽIVAN TEREN
CROATIA
ZAGREB
TRIESTE
SPLIT
ŠIBENIK
DUBROVNIK
Adriatic Sea
DRNIŠ
DRINOVCI
Torak
Jaruga
KRKA
SKRADIN
ŠIBENIK
PRIMOŠTEN
Ribnik
Dabar
Trtar Mt.
UNEŠIĆ
DIVOJEVIĆ
SITNO GORNJE
Vilaja Mt.
Gustirna
Dolac
MARINA
TROGIR
Pantan
Slanac
Bay of Kaštela
Ljubeč Mt.
BRŠTANOVO
MUČ
Vrba
Čulina mlinica
Kanjevača
Čikola River Spring
Čikola
10km
100km

3. LITHOSTRATIGRAPHY, HYDROGEOLOGICAL PROPERTIES OF ROCKS AND FUNCTION OF TERRAIN

The coastal area and the Zagora are composed of Upper Cretaceous and Palaeogene sedimentary rocks, while the northeast part of the region is formed from Permian, Triassic, Jurassic and Lower Cretaceous deposits. Quaternary deposits are not relevant to the present study.

The oldest rocks in this and neighbouring regions are of Permian age (P) (ŠUŠNJARA et al., 1992). These together with Lower Triassic rocks (T_1) provide the basement for Pliocene (Pl_3) and Quaternary (Q) deposits in the Petrovo Polje. The Permain and Lower Triassic are represented by siltites, sandstones, pelitic sediments and gypsum. The Permian and Lower Triassic clastic rocks occurring at the spring area of the Vrba creek and westward, toward the village of Muć, are represented by sandstones, siltites, well-bedded marly limestones and marls. As a unit, they are impermeable. These, together with Pliocene marly deposits, act as hydrogeological barriers which facilitate the development of a network of surface streams (Figs. 1, 2).

In the Zagora, the terrain is composed of a thick complex of permeable carbonate rocks of Upper Cretaceous age ($K_2^{1,2}$, K_2^3) composed of limestones, dolomites and calcareous breccias deformed into a series of inclined folds. The low permeability dolomites, when occurring in the core of anticlines, act as relative barriers to groundwater flow. Palaeogene Liburnian and foraminiferal limestones ($E_{1,2}$) belong also to this permeable complex.

In the North Dalmatian plateau, the superior part of the Middle Eocene (${}^2E_2$) is composed of calcareous breccias and conglomerates, limestones and thin-bedded marly limestones. The breccias, conglomerates and limestones are considerably karstified and are therefore classified as permeable rocks. The marly limestones have low permeability and act as local hydrogeological barriers, as observed between the Torak and Jaruga springs.

In the area of Kaštela and the Bay of Morinj, foraminiferal limestones are directly overlain by a complex of younger impermeable rocks, Middle Eocene clastics (${}^1E_2$). These deposits are permeable only in parts close to the land surface, resulting in the appearance of minor intermittent and permanent springs. The flysch, as a whole unit, is impermeable and it forms a hydrogeological barrier for neighbouring karst groundwater.

The relationship between permeable and impermeable rocks within the study area is clearly indicated in Figs. 1, 2 and 3. The Zagora is composed almost entirely of permeable carbonate rocks, as illustrated in Fig.2.

4. TECTONIC BASIS OF HYDROGEOLOGICAL CONDITIONS

The area considered by this paper belongs to the Adriatic megastructural unit (HERAK, 1986, 1991) composed of Cretaceous and Palaeogene sedimentary rocks. Orogenic activity has resulted in intensive folding and faulting. There are various types of folds, mainly of the Dynaric trend, while inclined folds of southwestern vergence prevail. Thrusts are the most frequently observed faults along the folded structures. Longitudinal faults are cut by several diagonal and transversal faults, of which only the basic ones are indicated in Fig.1. Thrust tectonics have resulted in imbricated structures and the removal of parts of folds, e.g. in anticlines the southern (south western) limbs are frequently partly or totally missing.

The hydrogeological functions of the terrain are shown in Figs. 1 and 3. They were determined on the basis of lithological composition and structural position of sedimentary rocks of the study area. Where the core of an anticline is composed of dolomites or thin-bedded limestones, the structure has the function of a relative and, exceptionally, full barrier to groundwater flow in neighbouring calcareous rocks. When evaluating this function, one should also understand the consequences of the fault tectonics on earlier anticlinal forms.

The same problems occur when evaluating the hydrogeological function of low permeability and impermeable rocks in the near hinterland of the Jaruga and Torak springs, as well as that of impermeable Eocene flysch deposits in the coastal area. In the areas where flysch deposits are not very thick, these strata form a partial (hanging) hydrogeological barrier under which karst groundwater flows (Fig. 3).

The most outstanding anticlinal structure with dolomites in the core is observed in the central part of Zagora, between the villages of Divojević and Brštanovo, along a 30-km-stretch. The dolomites do not appear at the land surface along the entire strike, and the whole anticlinal structure is not entirely preserved. In spite of this the structure is a relative barrier that divides the catchment area of the Pantan spring from that of the Jaruga and Torak springs. This is probably the result of a considerable depth to groundwater flow. The relative

Fig. 1. Hydrogeological map: 1 - Full barrier; 2 - Partial (hanging) barrier; 3 - Relative barrier, mainly underground; 4 - Permeable areas; 5 - Name of hydrogeological catchment area; 6 - Water divide, proved; 7 - Zonal water divide, uncertain; 8 - Local water divide; 9 - Possible shifts of water divide, particularly during rainy seasons; 10 - Assumed direction of groundwater flow; 11 - Underground connection ponor-spring, proved; 12 - Ponor (swallow hole); 13 - Zone of ponors; 14 - Major karst spring; 15 - Spring; 16 - Major brackish spring; 17 - Brackish spring; 18 - Intake of groundwater; 19 - Submarine spring, intermittent; 20 - Major reverse fault, overthrust; 21 - Major fault; 22 - Axis of overturned or inclined anticline; 23 - Hydrogeological cross section line.

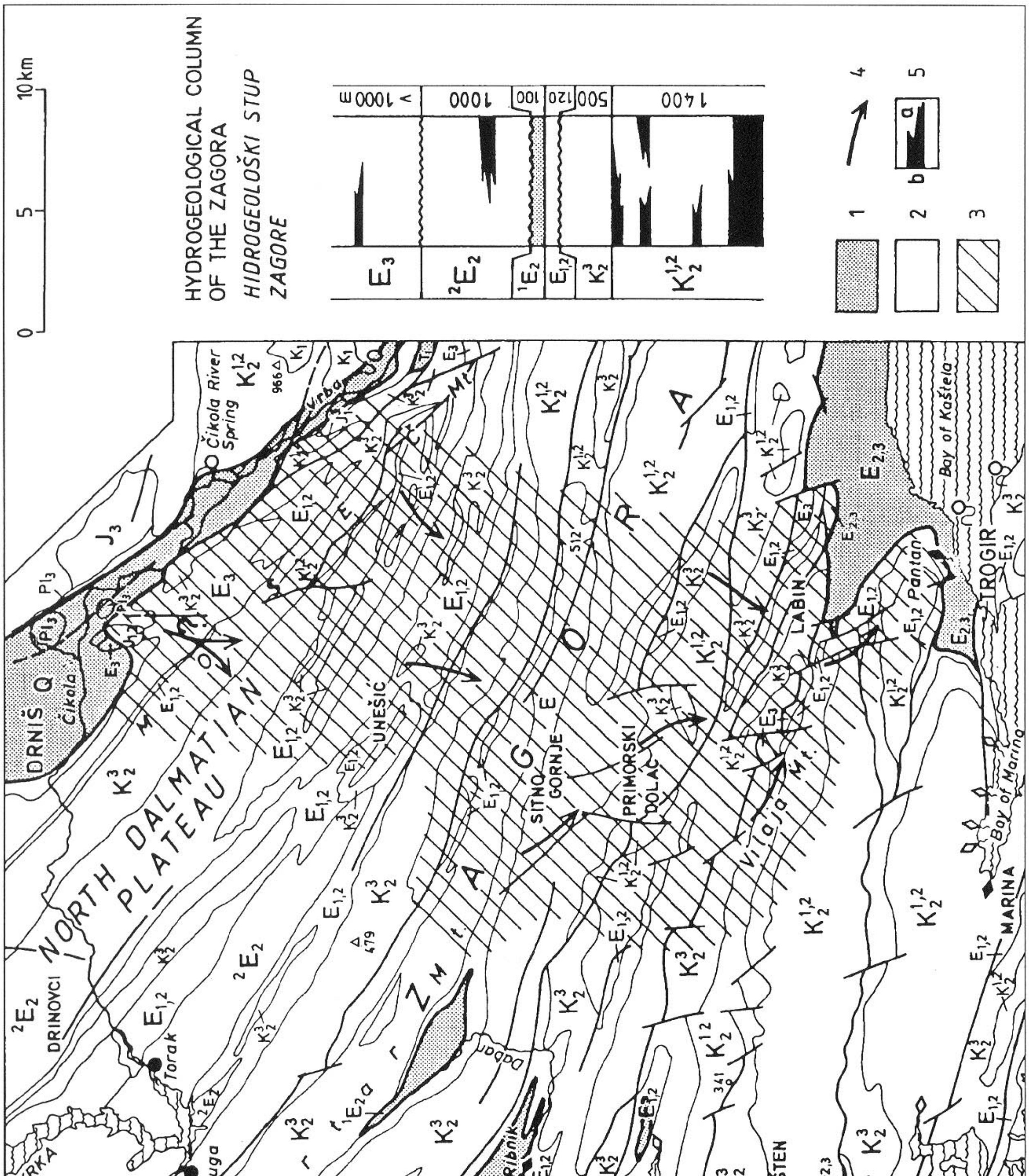

Fig. 2. Lithostratigraphy of the area around the Pantan spring: 1 - Impermeable rocks: marls, calcareous marls (Pl_3, $^1E_2$, $E_{2,3}$), clastic and carbonate rocks (T_1); 2 - Permeable rocks: calcareous conglomerates and breccias, lenses of marls land clays (E_3); calcareous breccias, conglomerates, limestones ($^2E_2$); foraminiferal limestones ($E_{1,2}$); rudist limestones (K_2^3); limestones, dolomites, ocasionally thin-bedded limestones ($K_2^{1,2}$); limestones with interbeds of dolomites (K_1); dolomites with lenses of limestones (J_3); limestones (J_2); limestones and dolomites (J_1); 3 - catchment area of the Pantan spring, earlier assumption, after KOMATINA (1967), FRITZ (1970) and FRITZ et al. (1984); 4 - Direction of groundwater flow, assumed according to the previous idea about the catchment area extension; 5 - Hydrogeological column of the Zagora area: a - very permeable carbonate rocks, b - low permeability carbonate rocks.

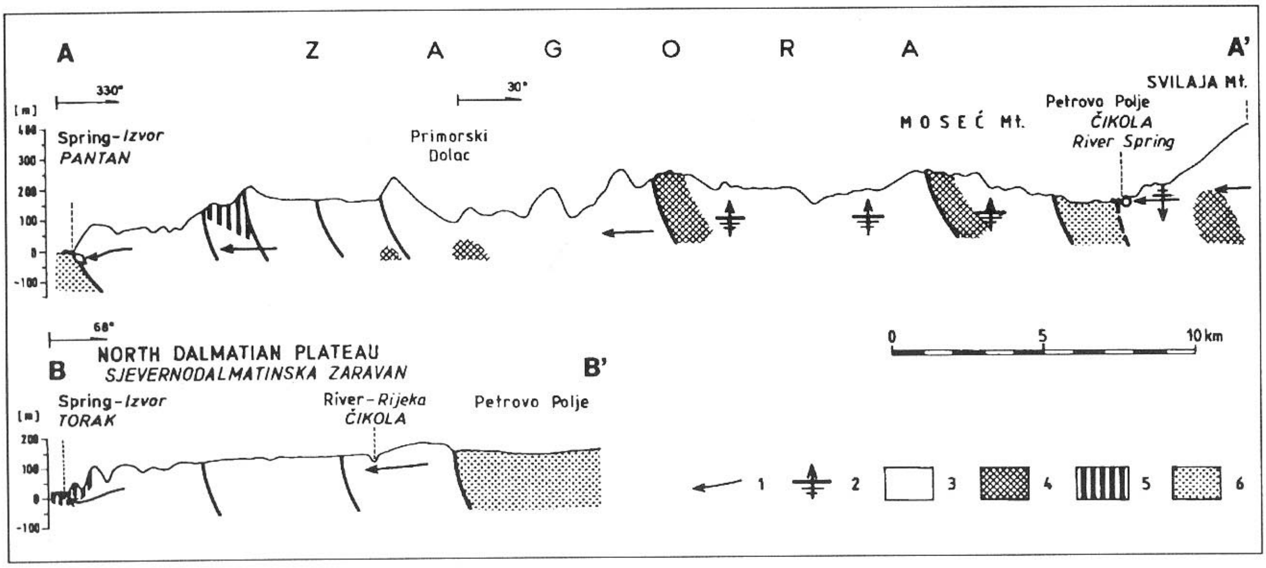

Fig. 3. Hydrogeological cross sections. Groundwater flow direction in relation to the strike of folds: 1 - perpendicular or diagonal, 2 - longitudinal; 3 - Permeable areas; Hydrogeological barriers; 4 - relative, mainly underground, 5 - hanging, 6 - full barrier.

barriers, if deep enough, become increasingly similar to complete barriers.

The Eocene flysch deposits east of Trogir, although having a large extension, do not act as a complete barrier within the whole area. This may be explained by the fact that, due to an intensive faulting and thrusting, these deposits are reduced in thickness and function as a hanging barrier which retards fresh groundwater flowing toward the Pantan and Slanac springs during the rainy seasons, while a some groundwater flows under the barrier toward the Arbanija (Divulje) and Slatina submarine springs in the Bay of Kaštela. With decreasing activity of these submarine springs after a rainy season, the sea water intrusion increases.

5. KARSTIFICATION AND GEOMORPHOLOGICAL CHARACTERISTICS

The area of study belongs mostly to the "orogenic accumulated karst" (HERAK, 1977). Intensive karstification of carbonate rocks accured from the Middle Eocene until the recent. In the Dalmatian Zagora, the highest degree of karstification occured during the Quaternary (FRITZ, 1981). This resulted in a total disappearance of surface streams and an "accumulation of underground morphologic phenomena" (BAHUN, 1973) as well as in a remarkable lowering of groundwater levels. The present dry valleys, e.g. the Labinska Draga, north of Trogir, are relatively recent remnants of previous surface streams.

A large number of ridges and valleys trend parallel to the strike of deposits and basic dislocations. The land-forms are usually controlled by the lithology of an area, by the position of rocks in geological structures and by the deformation of these rocks. However, it is not valid for the North Dalmatian plateau (the lower Čikola river area), where the rocks are planed equally without reflection of their lithologic composition, position and deformations. The karst plateaus are phenomena of complex genesis, which is not fully understood (e.g. BAHUN, 1990).

There are not long-lasting floods of depressions nor longer active ponors in the area of study. Intermittent ponors are situated in the vicinity of impermeable rocks between Drniš and Muć, while the only permanent ponor is the Čulina Mlinica (Čulina Water-mill, Fig.1). Due to deep karstification, there are no springs of large discharge rates in the Zagora. Most of them dry up in the dry season. However, speleological phenomena have been abundantly developed. A great number of them are deeper than 100 m. Out of the explored speleological phenomena, extremely important information was discovered in the Ogradica jama (pronounced yahmah, karst shaft): the groundwater level was always below the bottom of the jama, which is at 91 m above sea level.

The above mentioned data evidently indicate the existence of groundwater flows in the Zagora and the coastal area.

It is already well known that the genesis of water phenomena occurring near to the coast, particularly if submarine springs are involved, is closely related to changes of sea water level. By studying in detail this relationship in neighbouring areas (FRITZ 1978, 1984, 1991), the development of present coastal water phenomena can be linked to the recent karstification that has lasted since the Würm glacial stage. The formation of springs along river valleys, e.g. the Jaruga and Torak springs, has happened within the time interval ranging from the last phase of valley formation, to date (BAHUN & FRITZ, 1987; FRITZ, 1991).

The fresh/sea water contact is particularly intricate. Sporadic increases in water salinity in the intake galleries Dolac and Gustirna prove a deep sea water intrusion into the land. In the lowest part of the catchment area of the Pantan spring, water emerges from the Pantan spring and from the mentioned submarine springs in the Bay of Kaštela during rainy seasons. When the groundwater level is high, water also flows out from the brackish spring Slanac. This brackish spring is situated approximately 30 m above sea level which is a rare accurence. The Mutual connections and sea water influence on these springs will be the topic of another paper.

6. CHARACTERISTICS OF SIGNIFICANT SPRINGS AND GALLERIES

Within the Zagora, all the available water occurs underground and emerges through only three springs. Two of these, the Torak and Jaruga, are situated in the valleys of the Krka and Čikola rivers, while the third one, the Pantan, is at the coast of the Bay of Kaštela.

Northeast of the Zagora, i.e. northeast of the Drniš-Muć line, from the Svilaja mountain (which is composed of permeable rocks), groundwater emerges from the Čikola river spring and from the springs of Kanjevača (Fig. 1).

The groundwater, held in permeable rocks of the area lying between the Zagora and the coast, flows out from a number of brackish springs appearing along the southeastern bank of the Krka river estuary and the coast between the towns of Šibenik and Trogir. During the dry season, only several springs discharge individually more than 10 l/s of brackish water. Some fresh groundwater derived from the catchment area of the coastal brackish springs is withdrawn from two underground galleries, the Gustirna and Dolac, and used for public water supply. Similar conditions for the use of potable groundwater also exist in the hinterland of the Ribnik spring.

6.1. THE JARUGA SPRING

The name of the spring, Jaruga, refers to a narrow belt of land lying between the southeastern bank of the Krka river, downstream of the Skradinski Buk (the waterfall of Skradin), and a steep valley side. Within this belt, along a 200 m line, water springs from the carbonate hinterland and flows toward the Krka river, partly on the land surface, but mainly through Quaternary deposits. Most of the water of this dispersed spring is abstracted at four sites and used for the water-supply of Šibenik and at one site for the water-supply of Lozovac (Fig. 4, signs I to V). Downstream, springs occurring along the Krka river, together with the 300-m-distant intake structure of the Copić Vrilo (Copić Spring), should be considered as constituent parts of the dispersed spring Jaruga. The minimal discharge rate of the Copić Vrilo is about 30 l/s and this water is conveyed into a well from where it is pumped into the Šibenik waterworks. There are no other springs further downstream along the southeastern bank of Krka.

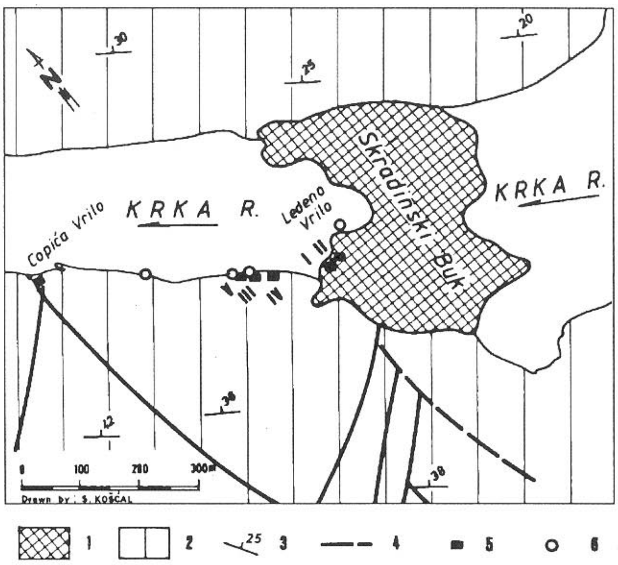

Fig. 4. The Jaruga dispersed spring: 1 - Travertine; 2 - Limestones; 3 - Strike and dip of beds; 4 - Fault; 5 - Intake of water; 6 - Permanent spring.

The intake structures I and II are situated at two springs in travertine, directly below a dry part of a steep cliff of the Skradinski Buk. Both springs are rising. The minimal water level at the intake structure is 1.62 m above sea level. Water freely flows from both intake structures by gravitation, into a pumping well. The rate of discharge from intake structure I ranges between 50 and 150 l/s and from II between 105 and 800 l/s.

The Ledeno Vrilo (Cold Spring), the third spring at the travertine barrier, is inundated by the Krka river. Its rate of discharge is considerable but not known. The intake structures III, IV and V have the form of drainage ditches or wells in Quaternary deposits that consist of large calcareous blocks and debris, as well as of clay and travertine silt. The minimal and maximal groundwater levels at the intake structures III and IV are approximately equal and range between 1.24 and 1.68 m above sea level. These levels are somewhat lower at intake structure V where they range between 1.35 and 1.54 m above sea level. A wall was constructed between the intake structures and the Krka river, from the structure furthest upstream to structure V. All the water of this dispersed spring is not extracted by these intake structures. This is proven by the existence of the Ledeno Vrilo and several more, mainly inundated springs occurring along the mentioned wall. By the beginning of 1989, the continuation of a long dry period from 1988 , resulted in a fall in the total yield of the intake structures, to about 350 l/s. Detailed exploration of the part of the dispersed spring occurring within travertine deposits (begun at this time), has unfortunately ceased though it promised good results, particularly taking into account the rising direction of groundwater flow.

The minimal rate of discharge of this dispersed spring is not known, neither is the regimen of water springing during the whole hydrological year.

6.2. THE TORAK SPRING

This spring is situated on the southeastern bank of the extreme upstream end of a lakeland formed by the Čikola river near the Skradinski Buk. The altitude is about 50 m above sea level. The spring is of a circular shape having a diameter of about 180 m. The lake is 47 m deep. Water springs from the lake bed at about 3 m above sea level. This is the same altitude at which the Jaruga spring occurs. At the land surface, the spring is surrounded by Eocene marly deposits, but the spring receives water from shallow-underlying Cretaceous deposits.

The discharge rates of the spring have not been measured. In documents describing the construction of an intake structure at that spring, the estimated discharge rate is 1000 l/s. There is no doubt that a considerably larger amount of water is discharged during rainy seasons. Last year, by the end of a very dry period a sink of water was recorded from the part of the mentioned lakeland situated upstream from the Skradinski Buk into the spring lake. This indicates that, probably, the Torak spring is a sporadic estavelle, which is not surprising as both the Torak and Jaruga springs had a mutual erosional base during their development, before the deposition of travertine of the Skradinski Buk. It was the valley of the Krka and Čikola rivers at that time. Thus, a hydraulic connection between these two springs could be preserved in the hinterland until the present. However, the distance at which this connection occurs from the springs remains open.

It was discovered by tracing, performed by the end of a dry season, that the whole river Čikola that sinks downstream from the town of Drniš flows out at the Torak spring. This points to the conclusion that, groundwater flows toward the Jaruga group of springs only from the northeastern part of catchment area. Therefore, very polluted water from the river Čikola canyon deteriorates only the quality of the Torak spring water. It would be interesting to measure by tracing where the water sinking in those ponors during mean and high water stages flows out. This question is of particular interest where the protection of the Jaruga spring water is concerned.

6.3. THE PANTAN SPRING

This highly discharging brackish spring is the only permanent spring in the lower part of a large catchment area of the same name. During high-water stages, groundwater flows out from the submarine springs Arbanija and Slatina as well as, exceptionally, from the brackish Slanac spring. Therefore, all these water phenomena make a combined complex spring zone (Fig. 1).

The Pantan spring is an ascending spring occurring in Eocene flysch deposits at the boundary between a complex of Upper Cretaceous and foraminiferal limestones and the flysch deposits themselves. It is situated in a depression, in a lake 13 m deep (BRITVIĆ[1]). The water level is 2.7 m above sea level. Water springs from the lake bed along a 40 m fissure, i.e. about 10 m below sea level.

It is difficult to measure the total amount of water flowing out from the spring, thus, it is not possible to plot an accurate diagram showing the dependence of spring rate on spring water level (BONACCI et al., 1991). The data about discharge rates varies considerably. Moreover, the influence of sea tides on the rate of discharge and water salinity has never been defined. KOMATINA[2] offers the highest rate of discharge, up to 12,000 l/s with a chloride content varying between 500-10,000 mg/l. On the basis of one year's observations BRITVIĆ[1] states that the chloride content ranged between 160 and 10,600 mg/l, while a mean summer rate of discharge was 250 l/s. MIJATOVIĆ[3] indicated an amount of 400 to 500 l/s of fresh water when estimates were made of the potential exploitable discharge rate of this spring. BAGARIĆ (1973) and BAGARIĆ[4] measured 760 l/s of brackish water (465 l/s of fresh water) and concluded that, in the summer of a very dry year, in 1973, if the spring water level had risen to 4.5 m above sea level (if a dam had been constructed or so) the spring would have discharged slightly above 200 l/s of fresh water.

The intermittent brackish spring Slanac erupts at the edge of the Kaštelansko Polje, at a contact zone between calcareous rocks and flysch. It is about 1200 m from the coast. With the increase of discharge rate, the spring site "shifts" approximately ten metres into the area of limestones, where it reaches its highest altitude: 30 m above sea level. The spring is active only during extremely high water stages. BRITVIĆ[1] cites that the spring was active between April 6-28, 1964 when its water was about three times more saline than the Pantan spring water at the same time. A rate of discharge as high as 0.7 m^3/s was mentioned. KOMATINA[2] cites 850 mg/l of chlorides in spring water on April 10, 1958. According to our observations during the hydrological year of 1986/87, the spring was active between January 15-19, 1987 and also between February 20-29, 1987. The spring water was considerably more saline in January (ranging between 3,610-5,680 mg/l of chlorides, with a peak of 17,960 mg/l reached the first day) than in February (between 1,060-1,350 mg/l of chlorides).

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[4] BAGARIĆ, I. (1990): Izvještaj o analizi postojeće dokumentacije, izvršenim dopunskim istražnim radovima i izradi programa istražno kaptažnih radova za desalinizaciju voda izvora Pantan.- Report, Civil Engineering Inst. of Croatia, Zagreb.

The submarine springs of the Bay of Kaštela have the form of submerged ponikvas (dolines, sinkholes). The Arbanija submarine spring is at the depth of about 35 m and the Slatina at about 32 m below sea level. Alfirević observed the activity of these submarine springs from September 14, 1963 to August 16, 1964, stating that these springs were active between December 18, 1963 and April 16, 1964 (ALFIREVIĆ, 1966). MIJATOVIĆ[5] provides data on the flow of sea water into the Arbanija submarine spring, estimating the rate to be about 200 l/s, and results of a water flow tracing that had been performed in september 1971 when 20 kg of sodium fluorescein gradually disappeared into the submarine spring. The tracer was not found in the Pantan spring water indicating that this water phenomenon should be considered as a submarine estavelle.

6.4. THE RIVER ČIKOLA SPRING

The spring of the river Čikola is active on average for six months of the year. The adjacent springs Velika Kanjevača and Mala Kanjevača are even shorter in activity springing only during the highest water stages in the hinterland. Together these springs, when active provide the largest volume of the river Čikola water. The regimen of the Čikola river spring is a characteristic example of specific conditions of karst springs where the drying up of springs is common (Fig. 5).

Between October 1, 1980 and October 31, 1982, the Čikola river spring was active for 14 months. During this period, it dried up six times, of which the longest dry period occurred between mid-May and mid-December 1981 and between mid-May and mid-October 1982. During the spring activity, the rate of discharge always exceeded 4 m^3/s. It surpassed 6 m^3/s during two months and the maximum rate recorded was 8.7 m^3/s. The maximum rate of discharge of the springs Velika Kanjevača and Mala Kanjevača combined was 3.2 m^3/s during this period.

When active the spring water level was approximately 280 m above sea level. After drying up, the water table gradually descends at the spring site, as observed in a cave from where the spring outflows. The maximum recorded drawdown was 13 m. In 1986-1987, four production wells 2 m apart were drilled from the land surface and they tapped the spring cave. The aim was to add these to the supply of the water-system for the town of Drniš. Each well was provided with a pump of 50 l/s capacity. On the basis of data of several pump tests ŠARIN (1991) estimated that an accurate safe yield from the spring site to be 111 l/s during the dry season while considerably larger quantities of water might probably be extracted.

6.5. DRAINAGE GALLERIES

In order to avoid a negative effect of sea water on fresh groundwater, three drainage galleries for drinking water supply were constructed in the hinterland of major brackish springs.

The intake structure **Gustirna** (or Rimski Bunar, Roman Well) is situated 2.5 km upstream in the hinterland of brackish springs in the Bay of Marina. It consists of a vertical shaft 82.1 m deep, the western gallery is 230 m long at 2.5 to 2.7 m above sea level. The construction design permits the extraction of 60 l/s during dry season. With such a rate of abstraction, the chloride content should not exceed 250 mg/l. However, the chloride content has occasionally surpassed the permitted concentration.

The intake structure **Dolac** (or Svinca) is 3 km from thewestern end of the Bay of Marina. Its vertical shaft is 34 m deep, its western gallery 70 m long and lies at 1.3 m above sea level, while the eastern gallery is 410 m long and lies at 1.9 m above sea level. About 20 l/s of fresh water was extracted during a pump test but the test has to be repeated because a possible recirculation of the pumped water was not taken into consideration.

The intake structure **Plano** is about 2 km from the Bay of Kaštela and 1.6 km to the north of the Pantan spring. It is composed of a vertical shaft and a horizontal gallery at 2.0 m above sea level. The gallery has been extended several times and now is 67 m long. A 100 m horizontal borehole was made from the gallery in an attempt to find water-bearing caverns or fissures. The construction work was stopped because only 1-2 l/s of fresh water was pumped during a dry season and such an amount is considered insufficient, i.e. negative, if the ground-water extraction potential of that area is taken in account.

7. HYDROGEOLOGICAL CONDITIONS IN CATCHMENT AREAS

The carbonate composition of the Zagora, with all its features of a typical karst terrain, hinders the subdivision of catchment areas of the most significant karst springs in central Dalmatia, i.e. the catchment areas of the springs Jaruga and Torak in the Krka river valley near the Skradinski Buk, the spring Pantan near the town of Trogir and the spring Jadro near the town of Split. During dry seasons, water of the Zagora of Šibenik, Trogir and Split flows out from these springs.

Heavy precipitation that falls on impermeable rocks in the upper parts of the catchment areas of the rivers Čikola and Dabra (the latter is southeast of Šibenik) from sporadic torrents allowing a large amount of precipitation to flow superficially into the river Krka or

[5] MIJATOVIĆ, B. (1972): Kompleksna hidrogeološka istraživanja u području izvora Pantan, Slanac i Kaštelanskih vrulja. Projekat dopunskih istražnih radova i ispitivanja.- Arch. OVP, Split.

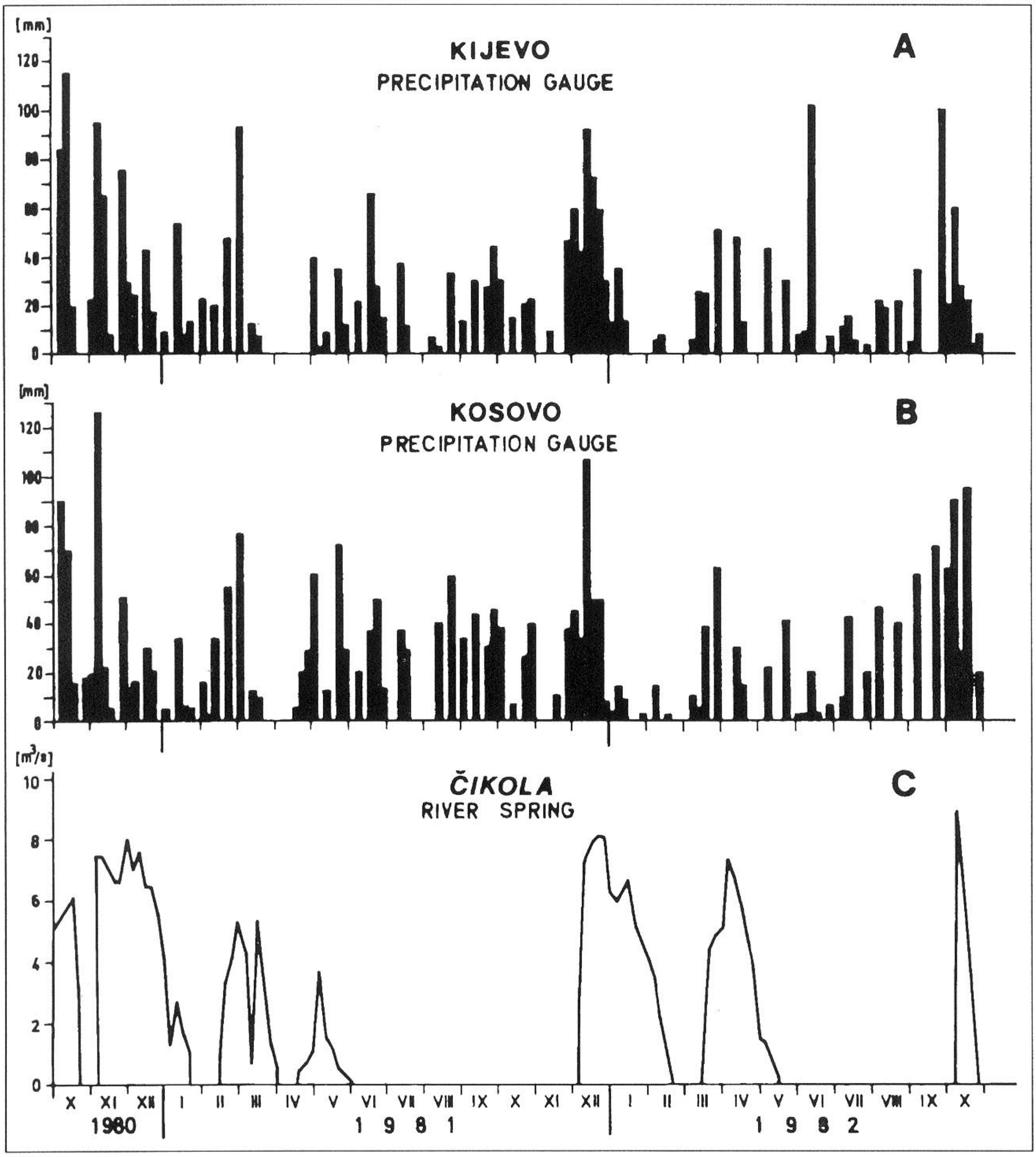

Fig. 5. Hydrograph of the Čikola river spring (C) and simultaneous rainfall histrograms at the nearest gauges (A, B).

into the Bay of Morinj. When these surface streams in the Zagora dry up (as happens during the entire dry season), all the water from the area of study discharges through the above mentioned springs.

Problems in the determination of karst catchment areas have already been described in detail (FRITZ, 1978). The basic characteristic is that the catchment area is not bordered by topographic (relief) divides, as in surface drainage areas, but by underground divides. The Dalmatian Zagora is a "locus typicus" for this characteristic. The catchment area bordered in this way, shall be called a hydrogeological catchment. In order to determine a hydrogeological catchment area as accurately as possible, it is necessary first of all to determine the hydrogeological function of the terrain. This function depends mostly on the lithology of that terrain and on the structural position of low permeability strata. It is also necessary to have, as much as possible, accurate data about groundwater tracing, which are needed especially where the catchment area divides pass over areas of a uniform calcareous composition, as in most parts of the Zagora.

The hydrogeological map (Fig. 1) shows the hydrogeological functions of the study area. They refer to an impermeable area and three categories of hydrogeological barriers. The criteria for the determination of each barrier are the same as those applied in adjacent areas, e.g. the Ravni Kotari and in the hinterland of the town of Split (FRITZ, 1978, 1981).

7.1. CATCHMENT AREA OF THE PANTAN SPRING

Most data relate to the catchment area of the Pantan spring. For a long time, it was thought that this area was approximately 533 km^2 (KOMATINA[2]), or 542 km^2 (FRITZ[6]). These figures were based on the assumption that the catchment area in the Zagora extends to impermeable rocks in the Petrovo Polje and in the Vrba creek valley. This opinion (Fig. 2) remained until recently (e.g. FRITZ et al.[7]).

However, the assumption was proven false after groundwater tracing performed in 1990. By the end of the dry season of that year, 100 kg of uranine was poured into the Čulina Mlinica ponor (swallow hole), situated within permeable rocks south of the Vrba creek mount in the river Čikola (Fig. 1), into which some 5 l/s of water flowed during this time. The results of the tracing showed that all the groundwater of that area flowed westward at an apparent velocity of 0.8 cm/s toward the Torak spring and 0.7 cm/s toward the Jaruga spring. This leads to the conclusion that dolomites in the core of the anticlinal structure near the village of Divojević acts as a hydrogeological barrier (although the anticline is considerably degraded in some places). This means that the Pantan spring catchment area extends only to that anticline by the end of dry seasons, while the area north of the anticline belongs to the catchment area of the Torak and Jaruga springs. It would be worthwhile undertake tracing from this ponor during high water stages to verify the function of the barrier under other hydrological conditions.

The question of the precise location of the eastern and western boundaries of the Pantan spring catchment area remains open because both boundaries occur within permeable rocks of similar lithology and geological structure.

According to all the studies data, the catchment area of the Pantan spring is estimated to cover approximately 266 km^2 (Fig. 1). BONACCI et al. (1991) came to a similar conclusion by calculating the runoff coefficient from data from 9 months of monitoring of the fresh water discharge from the Pantan spring as shown below:

Catchment area (km^2)	160	180	200	220	240
Runoff coefficient	0.81	0.72	0.65	0.59	0.54

The authors emphasize that the above mentioned results should be considered as preliminary ones but, nevertheless, they think that these results should not be neglected.

The catchment area of the Pantan spring, most probably, only extends to the hydrogeological barrier at Divojević even during high water stages, although the deeper that barrier is the better it fulfils its function.

7.2. CATCHMENT AREAS OF THE TORAK AND JARUGA SPRINGS AND PART OF THE RIVER ČIKOLA SPRING

The catchment area of the Torak and Jaruga springs, is one of the most interesting ones in the karst of Croatia with respect to its hydrogeological function, but it has not been studied in great detail. This catchment area extends farther to the north of the study area. It comprises, probably, the entire southeastern flank of the river Krka, including the Promina Mt., up to the divide of the Miljacka spring catchment area, as assumed by FRITZ & PAVIČIĆ (1987).

Certain problems concerning part of the catchment area of the Torak and Jaruga springs, i.e. east of the river Čikola, are also considered here. From the groundwater tracing from the Čulina Mlinica ponor, it has been found that the catchment area extends far to the east during dry seasons, up to the divide of the catchment area of the Jadro and Žrnovnica springs. A more precise location for this eastern divide will be difficult to determine even in the future, because of a uniform calcareous lithology and a lack of ponors suitable for tracing.

The regimen of the Čikola river spring (Fig. 5), particularly during very high rates of flow in the active phase, together with the behaviour of the groundwater level in the spring cave during periods when the spring is dry (ŠARIN[8, 9] and ŠARIN, 1991), point to the conclusion of a considerable underground outflow. The possible drainage site of the catchment area may occur east of the Čulina Mlinica ponor. At this point, a gorge occurs in the Vrba creek valley and, according to the most recent data, also a break in a zone of permeable rocks, where the Vrba creek dries up by the end of dry seasons. During heavy droughts, the Vrba creek dries up upstream of the area composed of impermeable rocks (see Fig. 1), thus, the water from this catchment area is probably subterranously drained into the neighbouring catchment areas at this site.

It is now known that groundwater flows from the area of the Čulina Mlinica ponor toward the Torak and Jaruga springs during the dry season, and therefore, the

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6 FRITZ, F. (1970): Geološka građa i hidrogeološki odnosi sabirnog područja izvora Pantan.- Report, Inst. of Geol., Zagreb

7 FRITZ, F., PAVIČIĆ, A. & RENIĆ, A. (1984): Hidrogeološka studija područja Trogir-Šibenik-Drniš-Knin.- Report, Arch. No. 248/84, Inst. of Geol., Zagreb.

8 ŠARIN, A. (1984): Tehnički izvještaj o pokusnom crpljenju izvora Čikole u 1983.god.- Report, Inst. of Geol., Arch. No. 51/84, Zagreb.

9 ŠARIN, A. (1988): Tehnički izvještaj pokusnog crpljenja bunarskog zahvata izvora Čikole u 1988. godini.- Report, Inst. of Geol., Arch. No. 145/88, Zagreb.

water that comes from the Čikola river catchment area must also flow in this direction. It remains questionable to which catchment area the water that sinks from the Čikola river between the impermeable rocks of the Vrba creek valley and the impermeable complex of rocks near the village of Muć belongs. This water probably belongs to the catchment area of the Jadro and Žrnovnica springs, especially during high water stages.

If the underground discharge from the Čikola river catchment area is required to be decreased, it could be done by the construction of a grout curtain at the above two segments of the Vrba creek valley. Such a construction would increase the groundwater withdrawal capacity at the actual pumping site of the Čikola river spring, as well as at potential pumping sites in the hinterland of the Velika Kanjevača and Mala Kanjevača springs. However, this should be thoroughly studied in order to determine whether and to what degree such curtains would affect the Torak, Jaruga and Jadro springs.

7.3. CATCHMENT AREA OF BRACKISH SPRINGS

The remaining karst springs occurring near the sea are within the influence of sea water. Of the many brackish springs, there are only approximately ten springs which offer realistic possibilities for the establishment of fresh water pumping sites in the hinterland. Most of them occur in the Bay of Marina. It is necessary to mention that two water-supply drainage galleries have already been constructed in the hinterland of these springs, the Gustirna (Rimski Bunar) and the Dolac (Svinca).

The catchment area of the Gustirna drainage gallery amounts to about 38 km^2. From this intake structure, about 60 l/s of fresh water (chloride content not surpassing 200 mg/l) is pumped in the dry season of a hydrologically average year. In extremely dry years, the pumping of such amounts of water results in an increase in the chloride content.

The catchment area of the Dolac drainage gallery comprises a part of the catchment area of coastal brackish springs amounting to about 23 km^2. A pumping test showed a safe yield of about 20 l/s of fresh water in the dry season. Part of the groundwater not taken by this gallery flows toward the brackish coastal spring Mandrača in the village of Marina. The rate of discharge of this spring varies considerably under the influence of sea tides. At low water stages, during a high tide, one may observe sea water flowing into the land at the spring site.

Between the village of Maina and the town of Trogir, there are a number of springs, of which the permanent ones are shown in Fig. 1.

Most of brackish coastal springs are dispersed springs, i.e. they are groups of springs occurring very close together in rows several tens of metres long. Within such groups, the number of individual spring sites increases during the wet season. It is practically impossible to estimate the rate of total discharge of a dispersed spring. Instead, only the rates of discharge of the "main" individual springs (i.e. of main constituents of these dispersed springs) are estimated. These main springs usually flow out from fractures that stand out by their size or shape. In the dry season, one can frequently see only a mixing of sea and fresh water in the main springs. If we add to these facts the effect of sea tides on the rate of discharge of brackish coastal springs, one may imagine how inaccurate data are about the amount of water, especially fresh water, flowing out from these coastal springs.

Concerning the water-supply aspects, two more sites are interesting in the area of study: the hinterland of springs at Primošten and of springs in the Bay of Morinj. In the hinterland of Primošten, exploratory boreholes located on the basis of previous hydrogeological exploration showed an increase of groundwater salinity during pumping tests. The hinterland of springs in the Bay of Morinj, of which Ribnik has the highest yield, is probably under a lesser sea water influence than the hinterland of Primošten. In addition a short depth to groundwater makes the conditions for rational groundwater extraction favourable.

7.4. DEPTH TO GROUNDWATER IN THE ZAGORA

On the basis of speleological investigations in the hinterland of the town of Split BOŽIČEVIĆ & FRITZ[10] estimated the depth to groundwater in the Zagora of Split and Trogir. In doing that estimation the altitude of erosion bases in the Zagora of Split was also taken into consideration, that is to say, that the Jadro spring is at about 30 m above sea level and that the Žrnovnica spring occurring more to the east appears at about 80 m above sea level. In the Zagora of Trogir, until the beginning of Holocene (about 9000 years ago), the erosion base was the site where the submarine springs of the Bay of Kaštela flow out today, i.e. some 32 to 35 m below the present sea level. The lowest levels of explored caves occurring in the lowest depressions of the Zagora of Split do not reach groundwater in the dry seasons. Traces of high groundwater stages were noticed in a jama (karst shaft) at 167 m above sea level. This jama occurs in the area of the assumed water divide between the catchment areas of the Pantan and Jadro springs. We do not know how deep groundwater levels lower during dry seasons. We may only make assumptions. Taking into account the altitude of groundwater levels at the boundaries of the Pantan and Jadro spring catchment areas (120-140 m above sea level) one may conclude that the groundwater level is

[10] BOŽIČEVIĆ, S. & FRITZ, F. (1978): Općina Split. Hidrogeološka studija, Speleološka istraživanja.- Report, Inst. of Geol., Zagreb.

130 to 150 m deep below ground level, even in the lowest depressions of the Zagora of Split. However, in the catchment area of the Pantan spring, due to a lower erosion base, groundwater should occur at lower altitudes. This assumption is in accordance with the results of the speleological investigations.

In the upper part of the Pantan spring catchment area, within a depression situated near the village of Sitno Donje, there is a jama without any trace of groundwater at even high water stages, and its bottom is 91 m above sea level. Since the lowest depressions of the Zagora of Trogir occurring at the villages of Sitno Donje and Primorski Dolac are at altitudes somewhat below 200 m, the depth to groundwater is probably 130 to 140 m in these lowest areas during dry seasons. Under the other depressions in the Zagora, groundwater is considerably deeper.

8. CONCLUSIONS

The hinterland of the towns of Šibenik and Trogir is composed predominantly of carbonate rocks: limestones, calcareous breccias and conglomerates, and dolomites. These strata form karst aquifers, with the exception of the dolomites and thin-bedded limestones which form relative hydrogeological barriers when occurring in the core of anticlines. The degree of impermeability of these barriers increases with depth. Basically, impermeable flysch-like rocks of Eocene age (coastal area), as well as of Permian, Lower Triassic and Neogene age (the Drniš-Muć section), are mainly full barriers and only at some places partial (hanging) barriers. The basic hydrogeology of the area is shown in two cross sections (Fig. 3).

Intense deformation of these carbonate rocks resulted in heavy karstification of the study area. The fault tectonics often reduced folds and this has intensely affected the hydrogeological conditions of this area. A consequence of the intense karstification is the disappearance of surface streams (only the Čikola river and Dabar creek have remained) as well as great infiltration of precipitation underground and a deep intrusion of sea water into the land.

The water table is more than 130 m below the lowest depressions in the Zagora during dry seasons. Groundwater is more than 200 m deep in most other depressions. Almost all groundwater discharges through several major karst springs: the Torak, Jaruga, Pantan and Jadro. The Jadro receives water from the extreme eastern parts of the Zagora. A monotonous carbonate composition of the Zagora pases enormous difficulties to the detailed delineation of water divides between the catchment areas of these springs without new groundwater tracing. This also indicates the priorities for further exploration.

Karst groundwater formed in the coastal area and, only exceptionally, in marginal parts of the Zagora, flows out from most of the intermittent and permanent coastal brackish springs.

These springs are of low discharge, the rate is over 10 l/s only at several of them. Some fresh groundwater is taken from the catchment areas of these springs by the drainage galleries Gustirna and Dolac and used for public water supply. The salinity of water extracted from the galleries increases during extremely dry years. Favourable conditions for further extraction of fresh groundwater within the catchment area of coastal brackish springs exists only in the hinterland of the Bay of Morinj.

The other springs appear mainly within flysch-like rocks, but their discharges are negligible in the dry season, when only a few of them discharge at about 1 l/s.

The problem of groundwater divides within the Zagora was substantially clarified after groundwater tracing from the Čulina Mlinica ponor. It lead to the conclusion that the anticline occurring between the villages of Divojević and Brštanovo has the function of a hydrogeological barrier during low groundwater stages. This barrier divides the catchment areas of the Pantan spring and that of the Torak and Jaruga springs and it has been quite a new revelation (Fig. 2).

The presence of hanging hydrogeological barriers results in extremely complex underground hydraulic conditions in karst terrains. Within the area of Study, they occur in two sites: in the Vrba creek valley and in the areas of the Torak, Jaruga and Pantan springs.

In the study area, only part of the fresh water potential is currently abstracted. On the other hand, protection areas arround the springs, in which a set of requested prohibitions has to be obeyed, are rather large. This is caused by (1) a great depth to groundwater in the Zagora, (2) a deep sea water intrusion into the coastal area and (3) complex hydrogeological conditions within the areas of the Pantan, Torak, Jaruga spring and of the river Čikola. An area amounting to about 1200 km^2 is protected while only 600 l/s of drinking water is extracted during the dry season. An additional amount of about 120 l/s of potable water can be extracted from the Pantan spring while, there is no doubt, a large amount of water has not yet been withdrawn from the Jaruga spring. A dilemma remains: to solve the drinking water demand of an area by using and treating the Krka river water or by looking after groundwater in the Jaruga spring area.

Tracing of the river Čikola water in a zone of ponors downstream of the town of Drniš during a low water stage, determined that all the water flows subterraneously into the Torak spring. This water is heavily polluted, causing the deterioration of the Torak spring water quality.

During mean and high water periods, large portions of surface and groundwater run off is unused. The feasibility of creating groundwater storage has not yet been studied. However, a surface water storage in the river Čikola canyon is being studied. The reservoir should be used for an electric plant. The assumed water loss from this reservoir would increase the discharge rates of the Torak and Jaruga springs (FRITZ, 1991). If this water storage is not constructed, a similar effect on these springs could be achieved by constructing small reservoirs on impermeable rocks occurring in the Petrovo Polje and in the Vrba creek valley and by channelling the stored water into the adjacent ponors.

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Hidrogeologija zaleđa Šibenika i Trogira

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U građi zaleđa Šibenika i Trogira (Zagora) prevladavaju karbonatne naslage gornje krede i paleogena, zastupljene vapnencima, vapnenačkim konglomeratima i brečama, te nešto manje dolomitima. Naslage su intenzivno borane, a rasjedna tektonika znatno je reducirala pojedine dijelove borâ. Posljedica snažnog okršavanja karbonatnih stijena u promatranom prostoru je nestanak mreže površinskih tokova, brza infiltracija oborinskih voda u podzemlje i prodor morske vode duboko u priobalno krško podzemlje. Navedene karbonatne stijene su vodonosnici krških podzemnih voda, osim u slučajevima, kada naslage dolomita ili pločastih vapnenaca tvore jezgre antiklinala. Takve strukture su relativne hidrogeološke barijere. Stupanj njihove nepropusnosti raste s porastom dubine.

U priobalnom području Trogira flišne stijene eocena u cjelini su nepropusne, isto kao i naslage permske, donjotrijaske i neogenske starosti na potezu Drniš - Muć. One su uglavnom potpune i samo lokalno nepotpune (viseće) hidrogeološke barijere (sl. 3).

Gotovo sva podzemna voda iz Zagore istječe na pet izdašnih krških izvora po kojima su nazvani slijevovi. To su Torak i Jaruga sa zajedničkim slijevom, zatim Pantan i s krajnjeg istočnog dijela Zagore izvor Jadro i Žrnovnica. Iz područja Svilaje podzemne vode izviru na izvorima Čikole i Kanjevače (sl. 1).

Karbonatna građa Zagore sa svim značajkama tipičnog krškog terena, uveliko otežava razgraničavanje slijevova Torak - Jaruga, Pantan i Jadro - Žrnovnica. Pojedini slijev nije omeđen topografskim razvodnicama, kao kod orografskog slijeva, već podzemnim. Tako omeđen slijev nazivat ćemo hidrogeološki slijev.

Slijev Torak - Jaruga je po svojoj hidrogeološkoj problematici jedan od najzanimljivijih u našem kršu, ali do sada nije detaljnije proučavan. Proteže se i sjevernije od obrađivanog terena (FRITZ & PAVIČIĆ, 1987). Ovdje se opisuje problematika dijela porječja istočno od rijeke Čikole. Trasiranjem podzemnih voda iz ponora Čulina mlinica u sušnom razdoblju ustanovljeno je, da slijev doseže daleko na istok. Ondje graniči sa slijevom Jadro - Žrnovnica. Detaljniji položaj te istočne granice bit će i u buduće teško odrediti zbog jednolične vapnenačke građe terena, a nema ni pogodnih ponora za trasiranje. Slijev izvora Čikole prazni se i podzemno na što upućuje tamošnji režim istjecanja vode (sl. 5). Povoljni hidrogeološki odnosi za podzemno istjecanje voda iz slijeva su u području istočnije od ponora Čulina mlinica, gdje u dolini Vrbe postoje, po novijim podacima, dva prekida zone nepropusnih stijena u kojima su okršeni vapnenci i gdje pri kraju sušnog razdoblja presušuje tok potoka Vrba. Kako u sušnom razdoblju iz područja Čuline mlinice podzemne vode otječu prema izvorima Torak i Jaruga, to s njima otječe i dio voda slijeva Čikole iz nizvodnog prekida zone nepropusnih stijena. Kojem slijevu pripadaju ponorne vode potoka Vrbe iz uzvodnog prekida, odnosno podzemne vode koje tuda otječu iz slijeva izvora Čikole, zasada je nepoznato. Vjerojatno, posebno u vrijeme velikih voda, bar dio otječe u slijev Jadro - Žrnovnica, a dio u slijev Torak-Jaruga. Ukoliko bismo željeli smanjiti podzemno istjecanje iz slijeva Čikole i povećati izdašnost crpilišta na njezinu izvoru i na potencijalnim crpilištima Velika i Mala Kanjevača, to bi se moglo riješiti izvedbom injekcijskih zavjesa na spomenuta dva poteza uzduž doline Vrbe. Treba razmotriti kako će se to odraziti na izvorima Torak, Jaruga i Jadro.

O slijevu Pantana dugo je vladalo mišljenje da se prostire sve do Petrova polja i doline Vrbe (sl. 2). Spomenutim trasiranjem podzemnih voda iz ponora Čulina mlinica spoznalo se da je antiklinala Brštanovo - Divojević hidrogeološka barijera, pa u sušnom razdoblju slijev Pantana doseže samo do te antiklinale, a da teren na sjeveru pripada slijevu Torak-Jaruga. Ocjenjujemo da je i u vrijeme velikih voda spomenuta antiklinala hidrogeološka barijera, što bi trebalo provjeriti trasiranjem na istom ponoru.

Iz propusnih terena između Zagore i mora (i iznimno iz rubnih dijelova Zagore) podzemne vode istječu na niz priobalnih bočatih izvora uz lijevu stranu estuara rijeke Krke i uz obalu od Šibenika do Trogira. U sušnom razdoblju na svega nekoliko od tih priobalnih izvora istječe više od 10 l/s bočate vode. Dio slatkih voda iz slijeva bočatih izvora, zahvaćen je za potrebe vodoopskrbe drenažnim galerijama Gustirna i Dolac. Slični uvjeti za zahvat pitkih voda postoje još samo u zaleđu izvora Ribnik. Dubina do podzemne vode u Zagori je na temelju speleoloških istraživanja i ispod najnižih depresija u sušnom razdoblju preko 130 m, a ispod većine ostalih depresija je preko 200 m.

Izvor Jaruga se nalazi uz lijevu obalu Krke nizvodno od Skradinskog buka. Glavnina voda ovog izvorišta danas je zahvaćena s četiri vodozahvata za šibenski i jednim zahvatom za lozovački vodovod (sl. 4, oznake I do V). Sastavnim dijelom izvorišta Jaruga treba smatrati i nizvodne izvore uz Krku, zaključno s oko 300 m udaljenom kaptažom Copića vrila. Dalje nizvodno uz lijevu obalu Krke nema više izvora. Kaptaže I i II izvedene su na dva izvora u sedri neposredno ispod suhog dijela Skradinskog buka. Oba su uzlaznog tipa. Iz obje kaptaže voda gravitacijski otječe u crpni zdenac. Izdašnost kaptaže I je od 50 do 150 l/s, a kaptaže II od 105 do 800 l/s. Kaptaže III, IV i V izvedene su u obliku drenažnih jaraka, odnosno zdenaca u kvartarnom nanosu. Između crpilišta i rijeke Krke izgrađen je zid od najuzvodnije kaptaže, pa do V kaptaže. Njima nisu zahvaćene sve vode izvorišta. Dokaz je tome Ledeno vrilo (izvor u podnožju sedrene barijere potopljen vodama Krke), kao i više uglavnom potopljenih izvora uz spomenuti zid. Ukupna izdašnost kaptaža provjeravana je samo pokusnim crpljenjem izvan sušnog razdoblja. Preračunato, najmanja je izdašnost ocijenjena s oko 500 l/s. Početkom 1989. godine, u nastavku dugog sušnog razdoblja iz 1988. godine, izdašnost crpnih objekata smanjila se iznimno na oko 350 l/s. Režim istjecanja voda tijekom hidrološke godine nije praćen.

Izvor Torak se nalazi na oko 50 m n.m. na lijevom kraju ujezerenja Krke uzvodno od Skradinskog buka. Mjesto izvora je jezero kružnog oblika promjera 180 m, duboko 47 m. Iz dna jezera na oko 3 m n.m. istječe voda, a to je praktično ista nadmorska visina kao i izvorišta Jaruga. Izdašnost izvora nije nikad mjerena. U dokumentaciji vodovoda podatak je od 1000 l/s. Nema sumnje, da u kišnom razdoblju istječe i znatno više vode iz jezera. Međutim, zadnjih godina krajem jako sušnih razdoblja registrirano je uviranje vode Krke u jezero izvora, pa u slučaju ako je količina uviranja veća od istovremene crpne količine, Torak funkcionira kao povremeni ponor i ima obilježje estavele. Izvori Torak i Jaruga imali su u vrijeme prije taloženja sedre Skradinskog buka zajedničku erozijsku bazu (dolina rijeka Krke i Čikole). Vjerojatno je očuvana ranija dobra hidraulička povezanost u zaleđu ovih izvora, ali je pitanje na kojoj je udaljenosti od izvora. Krajem sušnog razdoblja, ustanovljeno je trasiranjem da sav tok Čikole, koji ponire nizvodno od Drniša, izvire na Toraku. Jako onečišćene vode Čikole tada utječu samo na kvalitetu voda Toraka. Zaključujemo, da je u to vrijeme dotok vode k izvorištu Jaruga samo iz sjeveroistočnog dijela slijeva. Bilo bi interesantno ustanoviti trasiranjem utjecaj istih ponora na otjecanje u vrijeme srednjih i visokih voda, osobito s gledišta zaštite izvora Jaruge. Ostaje otvorenim pitanje utjecaja voda Toraka na vode izvora Jaruga, ukoliko Torak funkcionira i kao ponor.

Izvor Pantan ima bočatu vodu, a nalazi se nedaleko Trogira. Jedini je nepresušni vodni objekt u nizvodnom dijelu ovećeg hidrogeološkog slijeva. U vrijeme velikih voda podzemne vode iz tog slijeva istječu još na vruljama Arbanija (Divulje) i Slatina, a samo izuzetno na izvoru Slanac. Navedeni vodni objekti čine stoga jedno izvorište. Pantan je uzlazni izvor na rasjednom dodiru između foraminiferskih vapnenaca i fliša. Nalazi se u jezeru dubine oko 13 m s razinom vode na 2,7 m n.m. Voda izvire na dnu jezera. Budući da je vrlo teško mjeriti izdašnost izvora podaci znatno variraju. Osim toga nikada nije analiziran utjecaj morskih mijena na izdašnost izvora i salinitet vode. Najveću izdašnost od 12.000 l/s navodi KOMATINA[1]. BRITVIĆ[2] je odredio sadržaj klorida između 160 i 10.600 mg/l i ljetnu prosječnu izdašnost od 250 l/s slatke vode. MIJATOVIĆ[3] je izmjerio 16.8.1973. godine protok od 1000 l/s bočate vode od čega je 400 do 500 l/s slatke vode. BAGARIĆ (1973) i BAGARIĆ[4] je izmjerio u rujnu 1973. godine 760 l/s (465 l/s slatke vode), pa zaključuje da bi te sušne 1973. godine istjecalo u slučaju uspora vode (na mjestu izvora do +4,50 m) nešto preko 200 l/s slatke vode.

Povremeni izvor Slanac s bočatom vodom nalazi se u kontaktnoj zoni vapnenaca i fliša na nadmorskoj visini od oko 30 m. Udaljen je 1200 m od mora. Izvor je aktivan samo u vrijeme ekstremno velikih voda. BRITVIĆ[2] navodi aktivnost od 6. do 28.04.1964. godine, i izdašnost od 700 l/s kada je voda sadržavala tri puta više klorida nego istodobno na izvoru Pantan. KOMATINA[1] navodi da je 10.4.1958. godine sadržaj klorida bio 850 mg/l. Po našim opažanjima hidrološke 1986-87. godine izvor je bio aktivan od 15-19.01.1987. godine i od 20. do 28.02.1987. godine. U vrijeme prve aktivnosti salinitet je bio između 5.679 i 3.407 mg/l klorida (prvi dan čak 17.962 mg/l), a u vrijeme druge aktivnosti između 1.064 i 1.348 mg/l klorida.

Vrulje u Kaštelanskom zaljevu imaju oblik potopljenih ponikava. Arbanija je na dubini oko 35 m, a Slatina na oko 32 m ispod razine mora. Njihovu je aktivnost motrio u razdoblju od 14.09.1963. godine do 16.08.1964. godine jedanput mjesečno ALFIREVIĆ (1966). Vrulje su sigurno bile aktivne od 18.12.1963. godine do 16.04.1964. godine, a nisu bile aktivne 20.11.1963. godine, odnosno 18.05.1964. godine. MIJATOVIĆ[5] navodi podatak o uviranju morske vode u vrulji Arbanija (ocijenjeno 200 l/s), i o trasiranju s 20 kg natrijevog fluoresceina (rujan 1971. godine), koji se postupno izgubio u vrulji, ali tijekom motrenja nije ustanovljen u vodama Pantana. Po tim podacima ova vodna pojava je podmorska estavela.

Izvor Čikole aktivan je prosječno šest mjeseci godišnje. U to vrijeme s obližnjim krškim izvorima Velika i Mala Kanjevača, koji su još kraće aktivni i izviru samo kod najviših vodostaja uzaleđu, daje glavninu voda rijeci Čikoli. Režim istjecanja na izvoru je karakterističan primjer specifičnih uvjeta izviranja vode u kršu, gdje presušivanje izvora nije rijetkost (sl. 5). U vrijeme aktivnosti izvora Čikole razina vode je na oko 280 m n.m., a u vrijeme kad izvor nije aktivan razina se vode ustali na oko 267 m n.m. Temeljem podataka crpljenja, ŠARIN (1991) ocjenjuje sigurnu izdašnost u

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[1] KOMATINA, M. (1967): Hidrogeološke odlike delova terena Dalmacije, zapadne Bosne i Hercegovine.- Izvješće, Geozavod, Beograd.

[2] BRITVIĆ, V. (1965): Izvještaj o hidrogeološkom kartiranju na području Pantana Trogir.- Izvješće, Geotehnika, Zagreb.

[3] MIJATOVIĆ, B. (1976): Kompleksna hidrogeološka istraživanja u području Pantana. Rezultati dopunskih istražnih radova i ispitivanja.- Projekt vodozahvata. Arhiv OVP, Split.

[4] BAGARIĆ, I. (1990): Izvještaj o analizi postojeće dokumentacije, izvršenim dopunskim istražnim radovima i izradi programa istražno kaptažnih radova za desalinizaciju voda izvora Pantan.- Izvješće, IGH, Zagreb.

[5] MIJATOVIĆ, B. (1972): Kompleksna hidrogeološka istraživanja u području izvora Pantan, Slanac i Kaštelanskih vrulja. Projekat dopunskih istražnih radova i ispitivanja.- Arhiv OVP, Split.

sušnom razdoblju od 111 l/s, s prognozom mogućnosti crpljenja i većih količina. Vode izvora Čikole zahvaćene su za vodovod Drniša.

Kaptaža Gustirna (Rimski bunar) nalazi se 2,5 km u zaleđu izvora bočatih voda u Marinskom zaljevu. Sastoji se iz vertikalnog okna dubine 82,11 m, zapadne galerije dužine 18 m (na +1,50 m n.m.) i istočne dužine 230 m (na +2,50 do 2,70 m n.m.). Projektnom dokumentacijom dopušteno je u sušnom razdoblju korištenje 60 l/s, a da sadržaj klorida ne prijeđe 250 mg/l. Tijekom eksploatacije slanost vode narasla je povremeno iznad dopuštene granice. **Kaptaža Dolac** (Svinca) udaljena je 3 km od zapadnog kraja Marinskog zaljeva. Sastoji se iz vertikalnog okna dubine 34 m, zapadne galerije dužine 70 m (na +1,30 m n.m.) i istočne dužine 410 m (na +1,90 m n.m.). Pokusnim crpljenjem ustanovljena je izdašnost od oko 20 l/s pitke vode. Crpljenje treba ponoviti zbog mogućeg povrata vode pri provedenom crpljenju. **Kaptaža Plano** udaljena je oko 2,0 km od obale Kaštelanskog zaljeva, odnosno 1600 m sjeverno od izvora Pantan. Sastoji se od vertikalnog okna i galerije na +2,00 m n.m. koja je u više navrata produživana do ukupno 67 m dužine. Iz galerije je izvedena i horizontalna bušotina dužine 100 m radi otkrivanja vodoprovodnih šupljina. Radovi su prekinuti, jer je u sušnom razdoblju dotok vode u galeriju svega 1-2 l/s.

Navedeni podaci upućuju da se u šibenskom i trogirskom zaleđu vodoopskrba može rješavati samo pod izrazito nepovoljnim uvjetima i to zbog velike dubine vodâ u Zagori, dubokog prodora morske vode u priobalje i zbog zamršenih hidrogeoloških odnosa u području velikih izvora Pantan, Torak, Jaruga i Čikola. U sušnom razdoblju koristi se ukupno oko 600 l/s pitke vode. To je nesrazmjerno malo u odnosu na površine slijevova od oko 1200 km^2, koje treba štititi od onečišćenja (zaštitna područja crpilišta Torak, Jaruga i izvora Čikole prostiru se i izvan prikazanog terena). Ocjenjuje se da se u zaleđu Pantana može privesti eksploataciji daljnih oko 120 l/s pitke vode. Nesumnjivo je da znatne količine vode nisu zahvaćene na izvorištu Jaruga, te ostaje dilema treba li nedostatak vode u tom području rješavati kondicioniranjem voda rijeka Krke, ili treba potrebne količine tražiti u izvorištu Jaruga. Velike količine podzemnih i površinskih voda nekontrolirano otječu u vrijeme srednjih i velikih voda. Zasada nisu spoznate povoljne varijante ostvarenja podzemnih akumulacija. Istražuje se mogućnost ostvarenja površinske akumulacije u kanjonu Čikole za potrebe hidroenergetike. Planirani gubici vode iz ove akumulacije povećali bi izdašnost izvora Torak i Jaruga (FRITZ, 1991). Ukoliko se takva akumulacija ne ostvari, sličan učinak može se postići izvedbom malih akumulacija unutar nepropusnih stijena u Petrovu polju i dolini Vrbe i kontroliranim ispuštanjem vodâ iz akumulacija u ponore uzduž južnog ruba Petrova polja.

Manuscript received October 12, 1992.
Revised manuscript accepted July 02, 1993.