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On the Appearance of a Brackish Spring 30 m Above Sea Level Near Trogir (Southern Croatia)

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Key words: Brackish springs, Sea water intrusion, Coastal karst phenomena, Karst hydrogeology, Trogir, Croatia

Ključne riječi: bočati izvori, intruzija morske vode, priobalni krški fenomeni, hidrogeologija krša, Trogir, Hrvatska

Abstract

The intermittent karst spring Slanac east of the town of Trogir is unique karst phenomenon by its appearance at an altitude of 30 m bove sea level. This is a consequence of the areal hydrogeology and he development of karstification and karst groundwater flow paths rom the most recent glaciation to the present. There are at least three actors controlling the discharge of brackish water at such altitudes luring the highest groundwater tides: (a) a considerably greater permeability of calcareous rocks lying below the present sea level in omparison to the permeability of the upper parts, (b) the presence of lmost pure sea water upstream of a hanging hydrogeological barrier t the spring site at the end of a dry season, (c) ever higher hydraulic esistance to groundwater flow below the hanging hydrogeological arrier due to ever longer siphonal flows and their gradual colmataion.

Sažetak

Povremeni bočati izvor Slanac istočno od Trogira svojom pojavom na nadmorskoj visini od 30 m jedinstveni je krški fenomen. Nastao je kao posljedica hidrogeološke građe šireg područja i razvoja okršavanja i putova tečenja krških podzemnih voda od posljednje oledbe do danas. Najmanje su tri čimbenika presudna da pri najvećim vodnim valovima dolazi do izbijanja bočate vode na tako velikoj nadmorskoj visini: a) osjetno veća propusnost vapnenačkih stijena na dubinama nižim od današnje razine mora u odnosu na propusnost viših dijelova; b) prisutnost praktično čiste morske vode krajem sušnog razdoblja uzvodno od viseće hidrogeološke barijere, gdje se izvor nalazi; c) s vremenom nastali sve veći otpori tečenju podzemnih voda ispod viseće hidrogeološke barijere do vrulja uslijed sve dužih sifonskih tokova, kao posljedica recentnog uzdizanja razine mora i, vjerojatno, njihove postupne kolmatacije.

1. GENERAL DATA

The intermittent brackish spring Slanac is part of the pring zone of a large hydrogeological drainage area approximately 270 km^2), within which the only perma-ent water point is the brackish spring Pantan east of rogir. During the dry season, in addition to the Pantan pring, the groundwater of this drainage area also flows ut from two submarine springs in the Bay of Kaštela, vhile the Slanac spring is active only during the highest tages (Fig. 1). The appearance of the Slanac spring at o high altitude can be explained only if the hydrogeoogical conditions of the whole group of springs and heir genesis are considered.

The hydrogeology of the spring area has not been xplored in detail prior to the work of FRITZ et al. 1991[1]), although various explorations for the use of resh groundwater have been carried out in this area luring the last twenty years. Most exploration was nappropriate and confined to exploratory drilling. This esulted in the fact that proper attention was not taken f the appearance of the brackish spring Slanac at an ltitude of 30 m above sea level.

A relatively small number of data about water points within this group spring are known.

The Pantan spring emerges at an altitude of 2.7 m as an ascending spring from a local depression (lake) 13 m (BRITVIĆ, 1965[2]) or 12 m deep (BAGARIĆ, 1990[3]). The water springs out along a 40 m fracture running along the axis of the lake bed (which is 9-10 m below sea level). The spring (lake) occurs on the boundary between a complex of permeable calcareous rocks and impermeable flysch deposits. It is very difficult to measure the total rate of discharge, and therefore impossible to define the relationship curve between the rate of discharge and the spring water level (BONACCI et al., 1991). Furthermore, the effect of sea tides on the rate of discharge and spring water salinity have never been observed. The available data are as follows:

Britvić's year-long monitoring (BRITVIĆ, 1965[2]) showed that the chloride content varied between 10,600

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nstitute of Geology, Sachsova 2, P.O. Box 268, 41000 Zagreb, Croatia.

[1] FRITZ, F., RENIĆ, A. & BULJAN, R. (1991): Izvor Pantan kod Trogira, Hidrogeološka osnova za eksploataciju pitkih podzemnih voda.- Unpubl. tech. report, Institute of Geology, Zagreb.

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

[3] BAGARIĆ, I. (1990): Izvještaj o analizi postojeće dokumentacije, izvršenim dopunskim istražnim radovima i izradi programa istražno kaptažnih radova za desalinizaciju vode izvora Pantan.- Unpubl. tech. report, Institute of Civil Engineering, Zagreb.

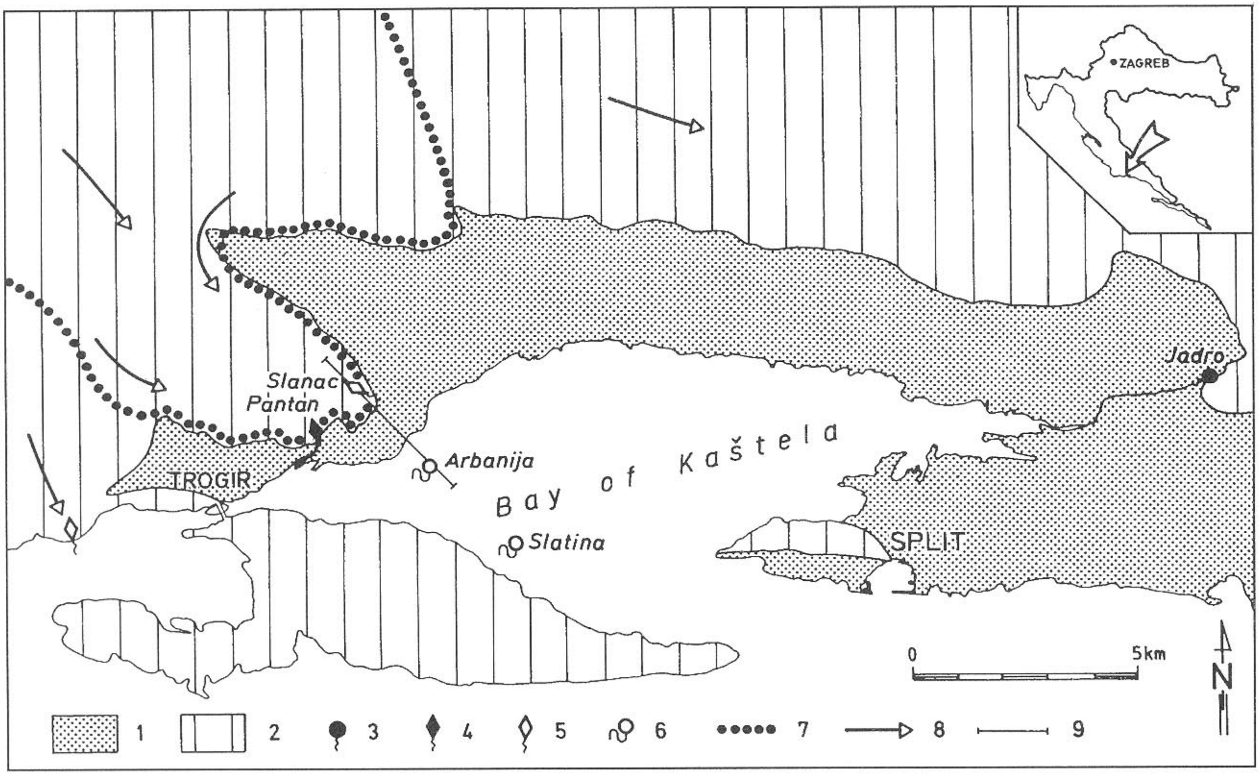

Fig. 1. Hydrogeological map of a wide area around the Slanac spring. Legend: 1 - Impermeable rocks; 2 - Permeable calcareous rocks; 3 - Karst spring; 4 - Permanent brackish spring; 5 - Intermittent brackish spring; 6 - Submarine spring; 7 - Approximate boundary of the Pantan spring drainage area; 8 - Assumed groundwater flow direction; 9 - Position of schematic hydrogeological cross section (shown in Fig. 3).

and 160 mg/l and the average summer rate of discharge was 250 l/s of fresh water. MIJATOVIĆ (1974[4]) measured a discharge rate of 1.0 m^3/s of brackish water on 16/8/1973. He used this volume to evaluate the amount of exploitable water (0.4 to 0.5 m^3/s). BAGARIĆ (1973) measured 760 l/s of water in September 1973 (465 l/s of fresh water), and later concluded (BAGARIĆ, 1990) that during 1973, which was a dry year, somewhat more than 200 l/s of fresh water would have flown out if the spring water level had been elevated to 4.50 m above sea level.

The intermittent brackish spring Slanac is situated in the extreme western part of the Kaštelansko Polje at the contact zone between calcareous rocks and flysch deposits (Figs. 1, 2 and 3). The spring is active only during the highest groundwater stages. BRITVIĆ (1965[2]) wrote that the spring was active from 6 to 28/4/1964 (with a discharge rate of 0.7 m^3/s) and its water was about three times more saline than the Pantan spring water. KOMATINA (1967[5]) stated that the chloride content was 850 mg/l on 10/4/1958. According to 1986/87 field observations used for the Basic Hydrogeological Map of Croatia (undertaken by the Institute of Geology in Zagreb) the spring was active from 15 to 19/1/1987 and from 20 to 29/2/1987. During the earlier period, the chloride content was higher (averaging 3,910-5,680 mg/l, with an anomalous high of 17,960 mg/l) than during the second period (1,060 and 1,350 mg/l). Unfortunately, the rate of discharge was not observed. There are estimates that the maximum discharge rate exceeds 1 m^3/s.

There is no doubt that groundwater of the Pantan spring catchment area also emerge from two intermittent submarine springs, the Arbanija and Slatina, occurring in the western part of the Bay of Kaštela (Fig. 1). The Arbanija is located approximately 800 m from the settlement of Divulje on the mainland while the Slatina is equally distant from the settlement of Slatina on Čiovo island (BREZNIK, 1973). Data on the depth of these submarine springs vary, those given by ALFIREVIĆ (1966) being the most quoted. He stated that water flowed out from a ponikva-like (like a doline or sinking hole) depression at a depth of 32 m (Arbanija) and 35 m (Slatina). BREZNIK (1973) stated the same depth for the Arbanija but 39 m for the Slatina. Both authors concordantly cited the bed of the Bay of Kaštela around the submarine springs was about 15 m below sea level and that it was relatively flat.

ALFIREVIĆ (1966) observed the submarine spring activity once a month and stated that they were active

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[4] MIJATOVIĆ, B. (1974): Ispitivanje korelacije između nivoa vode na izvoru Pantan i piezometarskog nivoa u istražnoj bušotini Pa-1.- Unpubl. tech. report, Geozavod, Belgrade.

[5] KOMATINA, M. (1967): Hidrogeološke odlike terena Dalmacije, Zapadne Bosne i Hercegovine.- Unpubl. study report, Geozavod, Belgrade.

[6] MIJATOVIĆ, B. (1972): Dopunski istražni radovi u području izvora Pantan, Projekt vodozahvata.- Unpubl. tech. programme, Geozavod, Belgrade.

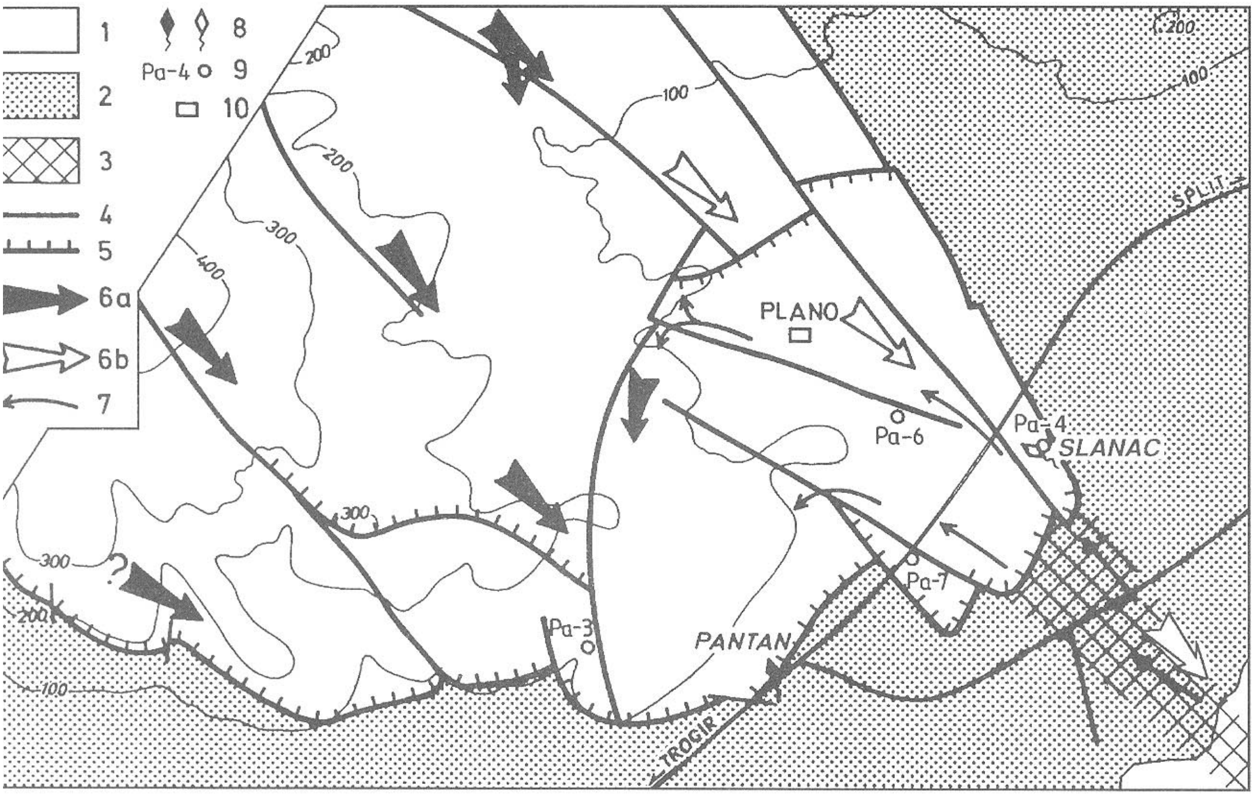

Fig. 2. Hydrogeological map of the sea-fresh water contact area. Legend: 1 - Permeable calcareous rocks; 2 - Impermeable rocks, (complete) hydrogeological barrier; 3 - Impermeable rocks, hanging hydrogeological barrier; 4 - Major fault; 5 - Major reverse fault, overthrust; 6 - Assumed fresh groundwater flow direction: a - During the whole year; b - During rainy season; 7 - Assumed direction of sea water penetration during dry season; 8 - Brackish spring; 9 - Exploratory borehole, observation well; 10 - Exploratory gallery (tunnel).

during the wet season of 1963/64, i.e. from December 1963 to April 1964. MIJATOVIĆ (1972⁶) mentioned that about 200 l/s of sea water sank into the submarine springs and 20 kg of sodium fluorescein gradually disappeared into the Arbanija in September 1971, thus concluding that this submarine spring was a submarine estavelle.

2. HYDROGEOLOGICAL CONDITIONS OF THE AREA OF SPRINGS AND SUBMARINE SPRINGS

The downstream (southern) part of the drainage area of the springs Pantan and Slanac and submarine springs Arbanija and Slatina is composed of Upper Cretaceous and Paleogene limestones, calcareous breccias and some dolomites. The springs and submarine springs occur at the boundary between the limestones and Eocene flysch deposits (Fig. 1). The springs are at the upstream part of the flysch, and the submarine springs at its downstream part.

As a consequence of intensive tectonics, the carbonate rocks of the drainage area are considerably deformed, karstified and most permeability is secondary. Therefore, there are neither permanent nor ntermittent surface streams and all the atmospheric vater quickly sinks (FRITZ et al., 1993). The Eocene lysch deposits, as a unit, are impermeable and function as hydrogeological barriers for karst groundwater. Since the coast of the Bay of Kaštela is composed of impermeable rocks of the Eocene flysch, groundwater must flow under these rocks toward the submarine springs (Fig. 1). This suggests that these impermeable rocks do not extend deep enough to be entire barriers, thus they behave as "hanging" (partial) hydrogeological barriers (Figs. 2 and 3). However, elsewhere, the flysch deposits reach much greater depths and form complete hydrogeological barriers. This has resulted in a considerable concentration of groundwater flow toward the hanging barrier, i.e. towards the area of the present submarine springs. The Slanac spring occurs above that flow, at the upstream side of the hanging barrier.

Detailed geological study of the extreme downstream part of the drainage area allowed local structural blocks to be delineated (Fig. 2). The blocks are the lowest in relation to the impermeable flysch deposits and, within them, there exist conditions for groundwater flow from the mainland towards the submarine springs and optimal conditions for sea water intrusion into the mainland as revealed by boreholes Pa-4, Pa-6 and Pa-7. A schematic map showing groundwater flow through the study area during low and high stages is shown in Fig. 3.

The development of karstification, morphogenesis and the age of this group of springs have been partly described (FRITZ, 1992). It must be emphasised that the palaeo-depression of the Bay of Kaštela, in the area

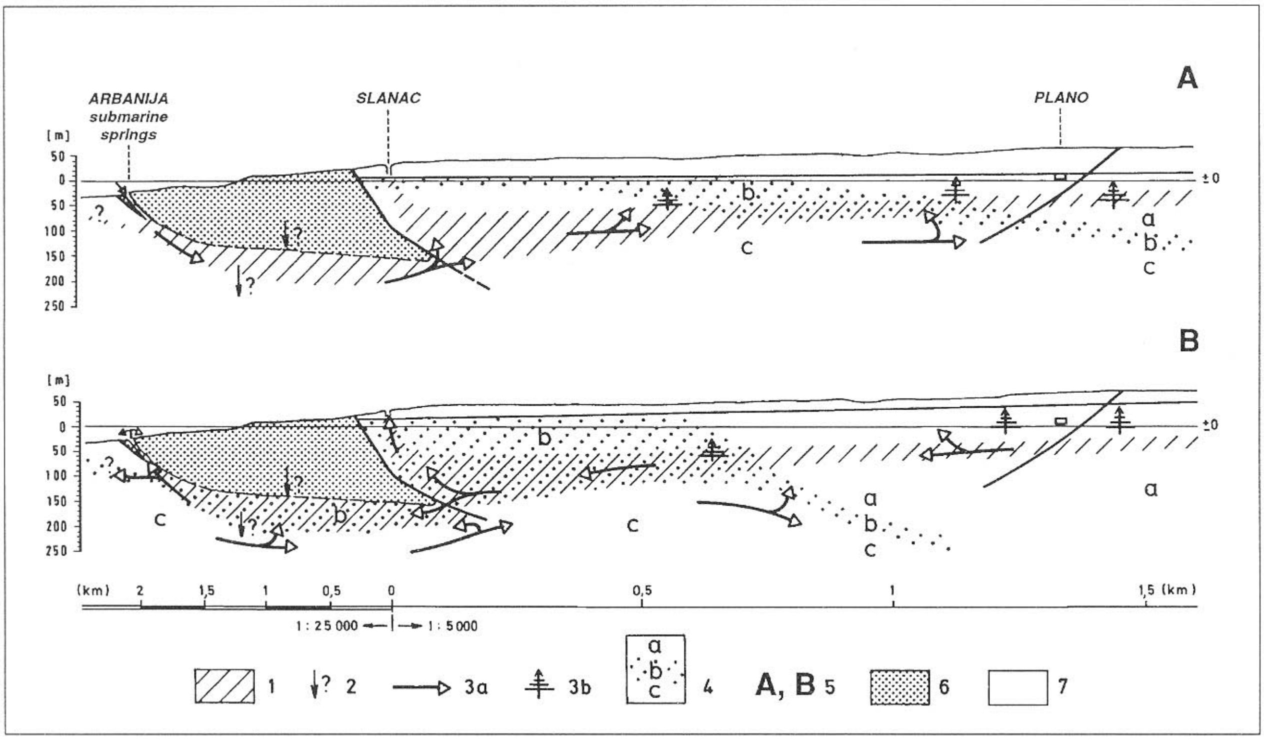

Fig. 3. Schematic hydrogeological cross sections: submarine springs - Slanac spring - exploratory gallery Plano. Legend: 1 - Zone of highest permeability in limestones; 2 - Unknown, greater depth; 3 - Groundwater flow directions: a - Parallel to cross section line; b - Diagonal to perpendicular to cross section line (toward the Pantan spring); 4 - Stratification of groundwater: a - Fresh water; b - Brackish water; c - Sea water; 5A - Dry season; 5B - Rainy season; 6 - Impermeable rocks; 7 - Permeable calcareous rocks.

of the submarine springs Arbanija and Slatina, was for a long time the erosion basis for karst groundwater of the present drainage area of the Pantan spring. For this reason, the basic network of karst groundwater in the downstream part of the drainage area occurs below the present sea level. This is also confirmed by the morphology of the Pantan spring and by facts established during exploration for groundwater (e.g. the low permeability of rocks at the intake gallery of Plano, 2 m above sea level - Figs. 2 and 3). Groundwater started to flow out on the land itself only after the submersion of palaeo-karst springs in the Bay of Kaštela palaeodepression at the beginning of the Holocene and after a further sea level rise. This occurs at the lowest altitude of the boundary between calcareous rocks and the Eocene flysch, at the site of the present Pantan spring.

With the sea level rise during the Holocene (i.e. with a rising erosion base for karst groundwater in the coastal area), and the appearance of the Pantan spring, decreasing amounts of water flowed towards the submarine springs and they have become only sporadically active. The periods of activity have gradually been decreased. Simultaneously, water flow at the Pantan spring has progressively increased. The intermittent spring Slanac appeared as a result of the last rise of sea-level and mainland groundwater levels and of the described development of the basic groundwater flow network towards the submarine springs. It must be emphasised that the higher altitude intermittent spring Slanac always discharges brackish water containing much more sea water than the adjacent lower altitude permanent spring Pantan. The altitude difference between these two springs is 27 m. It may be added that the occurrence of karst brackish springs above sea level is not a rare phenomenon. However, such springs occurring at more than 10 m above sea level are rare. BREZNIK (1973) mentioned two such springs: the Anavaoloussa spring near Peranea in Greece, at about +12 m, and lake Kournos on Crete, at +17 m.

3. THE HYDROGEOLOGICAL BASIS FOR THE APPEARANCE OF THE SLANAC SPRING

Hydrogeological conditions are shown in section in Fig. 3. The submarine spring Arbanija, the Slanac spring and the intake gallery Plano that are shown schematically in the cross section (Fig. 3). The line of the cross section is shown in Fig. 1.

The thickness of flysch deposits lying between the Slanac spring and the Arbanija submarine spring, i.e. the hanging hydrogeological barrier thickness, is not known. Some siphonal conduits, used by groundwater flowing towards the submarine springs in the Bay of Kaštela, and which were formed during the most recent karstification phase, are also used also by sea water. Sea water intrusion has gradually increased because of the decrease in submarine spring activity and a simultaneous increase of the discharge rate of the Pantan spring. The anticipated minimum thickness of the flysch deposits (hanging hydrogeological barrier) is shown in Fig. 3 and is a factor controlling the thickness of maximum karstification and the permeability of limestones both under and upstream of the hanging barrier. It also controls the depth of the sea water - fresh water contact in the area between the springs and submarine springs and also upstream, toward the gallery at Plano. The assumed groundwater and sea water flow directions within the realm of the group of springs are shown in Fig. 2.

The appearance of the Slanac spring is associated with the groundwater flow during rainy seasons or, more precisely, only with the flow after the heaviest precipitation. In order to explain the formation of this spring 30 m above sea level, which during its short sporadic activity discharges only brackish water, it is necessary to remember that the highest permeability of the limestones occurs below sea level in the spring group area.

The maximum extent of sea water intrusion is shown in Figs. 2 and 3 (cross section A). Minimum sea water inflow occurs during high groundwater stages and, when it is limited to the local structural blocks in the Slanac-Plano area (Fig. 3, cross section B).

Deep sea water inflow was preciously discovered by geophysical exploration carried out in the first phase of groundwater exploration (SAJKOVIĆ, 1970[7]). The geoelectric survey indicated a distinct zone of low electrical resistivities which coincided perfectly with local structural blocks in the Slanac-Plano area. A low resistivity zone was recorded up to somewhat more than 2 km upstream of the Slanac spring.

During later exploration, some interesting data was recorded on sea water intrusion during the dry seasons. At a very low rate of extraction (approximately 10 l/min) and without any previous pumping, a rise in chloride content was noticed; from 80 to 2,060 mg/l in the borehole Pa-6 and from 2,340 to 2,980 mg/l in the borehole Pa-3. A rise of chlorides content with depth was also noticed: from 80 to 1,970 mg/l to 35 m in the borehole Pa-4 and from 220 to 3,360 mg/l to 90 m in the borehole Pa-7. It is necessary to mention that, on the basis of data from the boreholes Pa-4 and Pa-7, a groundwater slope was observed from the Slanac spring to the Pantan spring. The fall amounted to about 9 m. At the same time, the groundwater level at the Pantan spring was only 3 m lower than at the gallery Plano (MIJATOVIĆ, 1981[8]).

The ascending (siphonal) groundwater flows toward each member of the considered spring group, which suggest deep groundwater flow. The Pantan spring site is not connected with major faults that are apparent at the surface (Fig. 2). This suggests some other cause of the spring genesis; it is most probably related to an overthrust contact between permeable and impermeable rocks at shallow depth. Local structural blocks have a significant role in the concentration and development of groundwater conduits; especially their recent movements. We may expect that the central parts of local structural blocks penetrate most deeply into impermeable flysch deposits, and as a result, groundwater conduits may be concentrated in these blocks. If the contact (overthrust) zone of permeable and impermeable rocks is very deep, the groundwater conduits could be developed first of all in boundary zones of local structural blocks. This problem is particularly interesting where the extraction of fresh groundwater, drained by the Pantan spring, is concerned.

It is now possible to conclude that sea water only penetrates into the land through local structural blocks between the boreholes Pa-7 and Pa-4 (Fig. 2). The schematic cross sections in Fig. 3 show a model of groundwater salinization through that area during two extreme stages, in a critically dry season and in a very rainy season.

The hydraulic mechanism of brackish springs was basically explained by GJURAŠIN (1943) and KUŠČER (1950), and mostly complemented by BREZNIK (1973, 1976). In accordance with the effect of the different specific weight of sea and fresh water (Ghyben-Herzberg ratio), the sea-fresh water contact should lie very deep in the Slanac (and Pantan) spring area, at more than 1000 m below sea level. Such an occurrence seems unlikely. A concentrated flow of fresh groundwater in the hinterland of the hanging hydrogeological barrier could have a hydrodynamic effect resulting in the appearance of the brackish spring Slanac at such a high altitude. The hydrogeological conditions resulting in salinization of the Slanac spring may be explained as follows:

During the dry season, sea water penetrates into the land through the submarine spring Arbanija and fills almost all openings and fissures in probably the highest permeability zone in the limestones (Fig. 3A - "dry season"), as confirmed by tracing. At this time, all the fresh groundwater flows toward the Pantan spring (Fig. 2). The submarine spring activity begins only after abundant autumn rains, while the Slanac spring begins to discharge only after the highest groundwater levels. During the first day of activity of the Slanac spring, almost pure sea water flows out (18,000 mg/l of chloride). On the second day of spring activity, the chloride content falls sharply to several thousands mg/l and later stabilizes at about 1,000 mg/l. The lift of brackish water to the elevation of 30 m above sea level must be caused mainly by the higher permeability of rocks lying below the present sea level in comparison with the permeability of rocks occurring near or above sea level. This should be also caused by the position of privileged hydraulic connections between the spring Slanac (situ-

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[7] SAJKOVIĆ, J. (1970): Izvještaj o električnim ispitivanjima na Pantanu kod Trogira.- Unpubl. tech. report, Geozavod, Belgrade.

[8] MIJATOVIĆ, B. (1981): Izvještaj o vodoistražnim radovima na području Pantana kod Trogira od 1975-1981.- Unpubl. tech. report, Geozavod, Belgrade.

ated at the intersection of the youngest transversal faults) and deep permeable parts of the terrain.

The hydrogeological explanation of the formation of the brackish spring Slanac so high above sea level may be even more complicated than that described above, particularly if the hydraulics of some parts of the scheme are considered. This questions the validity of proposals for the desalinationof the Pantan spring, particularly those of BAGARIĆ (1973, 1990[3]) and BREZNIK (1976) which proposed construction of a low dam at the spring itself to maintain high spring water levels. This idea was only based on certain classic hypotheses of the sea - fresh water relationship.

4. CONCLUSION

The intermittent brackish spring Slanac is a member of a group spring draining a rather large karst area. The groundwater of this drainage area flows out permanently only from the major karst spring Pantan and intermittently, at the Slanac spring and also from two submarine springs in the Bay of Kaštela (Fig. 1). The Slanac spring is situated upstream of a hanging hydrogeological barrier, above the groundwater flow paths toward the submarine springs (Fig. 2). It is active only when all the flowing groundwater cannot pass to the submarine springs. It happens only at the highest groundwater stages and not every year.

The groundwater conduits toward the submarine springs are also basic conduits of sea water intrusion which occur when the submarine springs are not active, in the dry season. In the close hinterland of the hanging hydrogeological barrier, where the Slanac spring is situated, the network of recent karst groundwater conduits reaches, probably, depths in excess of 100 m (Fig. 3).

Sea water inflow into the submarine spring Arbanija has been observed during a dry season. This indicates that the submarine spring is an estavelle which facilitates sea water penetration into the land. A volume of almost pure sea water is retained in the close hinterland of the hanging barrier untill the beginning of activity of the Slanac spring. After 24 hours of such activity, the chloride content of the spring water sharply decreases to approximately 1,000 mg/l.

There are at least three factors which enable a brackish water discharge at the elevation of 30 m above sea level. Firstly, the permeability of rocks lying below the present sea level is considerably higher than that of overlying rocks. Secondly, a large amount of sea water in the land upstream of the hanging hydrogeological barrier before the rainy season. Thirdly, an ever increasing resistance to the flow of groundwater under the hanging barrier toward the submarine springs caused by ever larger siphonal conduits and their gradual colmatation.

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