Geologia Croatica	59/2	139–147	5 Figs.	2 Tabs.		ZAGREB 2006

The Effect of the Seawater Intrusion on the Robinzon Coastal Spring

Renato **BULJAN**[1], Tamara **MARKOVIĆ**[1] and Zoran **PEH**[2]

Key words: Salt-water/freshwater relationship, Coastal aquifer, Karst, Croatia.

Abstract

The Robinzon Spring, located 70 m from the seacoast, is a freshwater, perennial spring with a yield ranging from the maximum 2 m^3/s to the minimum 0.165 m^3/s. The spring occurs at the contact between permeable carbonate rocks and impermeable flysch deposits. This contact is deeply weathered, eroded and submerged below sea level. Such conditions emphasize the delicate relationship between the fresh- and seawater. The objective of the study was to shed more light on the hydrogeological setting of the spring's underground recharge area by means of borehole measurements and preexisting knowledge about the dynamics of the fresh- and seawater acquired from similar cases. The spring's underground area is divided into three zones: (i) zone of good water circulation (rockfall material and fractured dolomite), (ii) zone of poor water circulation (massive dolomites), and (iii) zone of 'trapped' water (contact between the dolomite and flysch deposits).

1. INTRODUCTION

The Robinzon Spring in the Duboka Ljuta valley near Dubrovnik (Fig. 1) is one of the important karst springs within the Dubrovnik area, which is captured for the water supply of the town of Cavtat and its surroundings. The spring is located on the regional tectonic contact where carbonate sediments are thrust over clastic flysch deposits, and where this structure is cut by a dextral tear fault known as the Slivnički Fault. The spring consists of several dispersed springs of similar yields which well upwards forming a small pond 10 m wide at an altitude of 0.7 m. This pond empties to the sea via a 50 m long channel. The spring discharge is variable, depending on hydrological conditions. Usually, during dry periods of the year (mostly during summer), the amount of fresh water feeding the spring is reduced. As a result, the balance between the fresh- and seawater is disturbed, causing seawater to intrude into the aquifer. Geologically, this condition is predisposed by the deeply weathered and eroded contact between the permeable and impermeable rocks in the zone around the spring's location. Water losses through the 16.6 km long hydrotechnical tunnel of the Dubrovnik power plant near the spring (which connects the accumulation of Trebinje with the Dubrovnik power plant) used to increase the spring's capacity during the droughts. However, repair works in the hydrotechnical tunnel (Fig. 2) in 1998, prevented further losses causing the spring to return to its natural condition. The main goal of this study was to find out more information about the underground strata of the spring area using borehole measurement data, and preexisting knowledge of the dynamics of fresh- and seawater inputs during the summer period when great amounts of fresh water are required.

2. METHODS

Data concerning the tectonic/structural setting, main flow directions in the karst aquifer and depth of the eroded contact between permeable and impermeable rocks were compiled from aerial photographs of the study area and by hydrogeological mapping of the area around the spring (Fig. 2). Geophysical data can also contribute to the direct characterization of data by providing multi-dimensional and high resolution subsurface measurements in a minimally invasive manner (HUBBARD & RUBIN, 2000). Thus shallow reflective seismics were used to detect the contact line between the permeable and impermeable rocks, and to determine the thickness of the rockfall and spring deposits within the spring zone. Seismic results were used to determine locations for the four research boreholes surrounding the spring. These were located perpendicularly to the spring zone and aligned to the cross-section A–B in order to measure permeability. Borehole R–1 was located in the zone of the deepest contact between dolomites and flysch, R–2 was located west of the pumping station, while boreholes R–3 and R–4 were situated on the rims of the spring zone. The area between the boreholes was investigated by geophysical seismic tomographic measurements (ANDRIĆ, 2001[3]). A pumping test was

---

[1] Croatian Geological Survey, Department of Hydrogeology and Engineering Geology, Sachsova 2, HR-10000 Zagreb, Croatia; e-mail: tamara.markovic@hgi-cgs.hr

[2] Croatian Geological Survey, Department of Mineral Resources, Sachsova 2, HR-10000 Zagreb, Croatia.

[3] ANDRIĆ, M. (2001): Robinzon–Duboka Ljuta, seizmička tomografska mjerenja [*Robinzon–Duboka Ljuta tomographic measurements* – in Croatian].– Unpublished report, Archive of the Civil Engineering Institute of Croatia, Zagreb, 30 p.

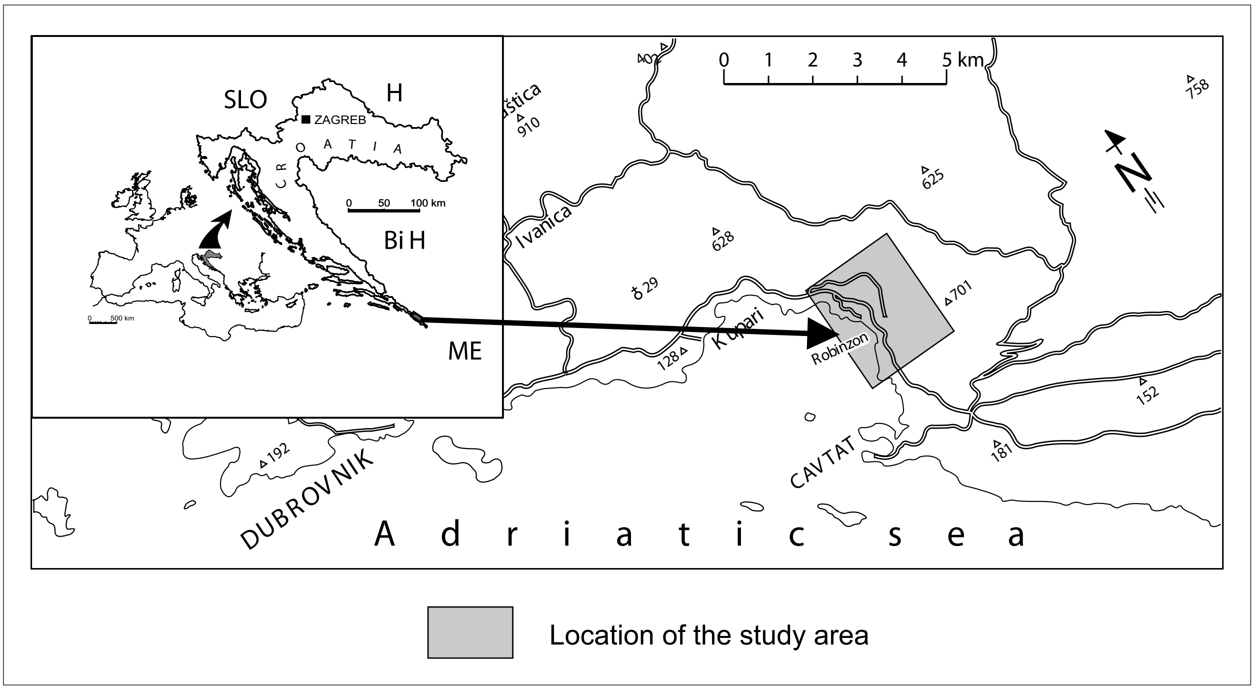

Fig. 1 Location map of the Robinzon Spring.

also performed with station pumps working for 7.5 hours with the capacity of 260 l/s. During the pumping test electroconductivity (EC), temperature (T) and water level were measured every 5 m down the boreholes and in the pond. Data describing the lithology and tectonic setting of the wider area of the spring were taken from the Basic Geological Map, sheet Dubrovnik (MARKOVIĆ, 1966, 1971). However, data explaining the natural conditions of the Robinzon Spring before the power plant had been built were drawn out from the cadastral sheet of the Duboka Ljuta–Robinzon Spring (PERGER, 1960[4]). Chemical analyses of the spring water were collected from the Department of Public Health of Splitsko–Dalmatinska County, and the INA Department of Fluid Analysis and Ecology. These were used to determine the water type and influence of the sea on the spring water composition.

3. MORPHOLOGICAL CHARACTERISTICS AND GEOLOGICAL SETTING

The Robinzon Spring is located in the coastal region of southern Dalmatia, approximately 2 km north of the town of Cavtat. In the steep hinterland of the spring there is a coastal range of hills typically reaching elevations in excess of 400 m above the sea level. The hinterland is a carbonate plateau composed of carbonate rocks and studded with numerous ponors. The climate is typically Mediterranean with mild, rainy autumns and winters, and dry, hot summers. The air temperatures seldom drop below 8°C during the winter, while the highest values rarely exceed 30°C during the summer. Mean annual precipitation is approximately 1900 mm.

The catchment area of the Robinzon Spring is formed of Triassic, Jurassic and Cretaceous carbonate sedimentary rocks, Eocene flysch deposits, and various types of Quaternary sediments (Fig. 2). The Upper Triassic dolomites, occasionally alternating with dolomitic limestone, prevail in the hinterland, reaching a thickness of approximately 300 m. The Mesozoic carbonate rock formation is completed with Jurassic and Cretaceous limestones succeeding the Upper Triassic dolomites in normal sequence. Flysch deposits, extended along the coastline, play a crucial role in forming the Robinzon Spring as these separate the permeable, freshwater saturated carbonate rocks from the sea. Rare Quaternary deposits can occur both in the sinkholes (terra rossa) and on the steep part of the seaward side of the coastal range, forming the rockfalls. Anthropogenic deposits can be also found within the spring area. These were formed during the construction of a tunnel and several underground rooms for the nearby power plant. Geological structures in the surveyed area extend mostly NNW–SSE, or NW–SE. The dip of the layers and fault planes suggest the predominant direction of movement of the thrusted subsurface structures (PRELOGOVIĆ et al., 1994[5]; BULJAN & PRELOGOVIĆ, 1997; BULJAN, 1999). The hinterland of the Robinzon Spring is traversed by a major thrust moving the regional Dinaricum structural unit over the Epiadriaticum unit (HER-

---

[4] PERGER, V. (1960): Kartoteka izvora, Duboka Ljuta – izvorište Robinzon [*Data about Duboka Ljuta – the Robinzon Spring* – in Croatian].– Unpublished report, Archive of the Hrvatska elektroprivreda, Dubrovnik, 80 p.

[5] PRELOGOVIĆ, E., BULJAN, R. & FRITZ, F. (1994): HE Ombla, strukturna istraživanja [*Ombla Power Plant, Structural investigations* – in Croatian].– Unpublished report, Archive of the Croatian Geological Survey, Zagreb, 86 p.

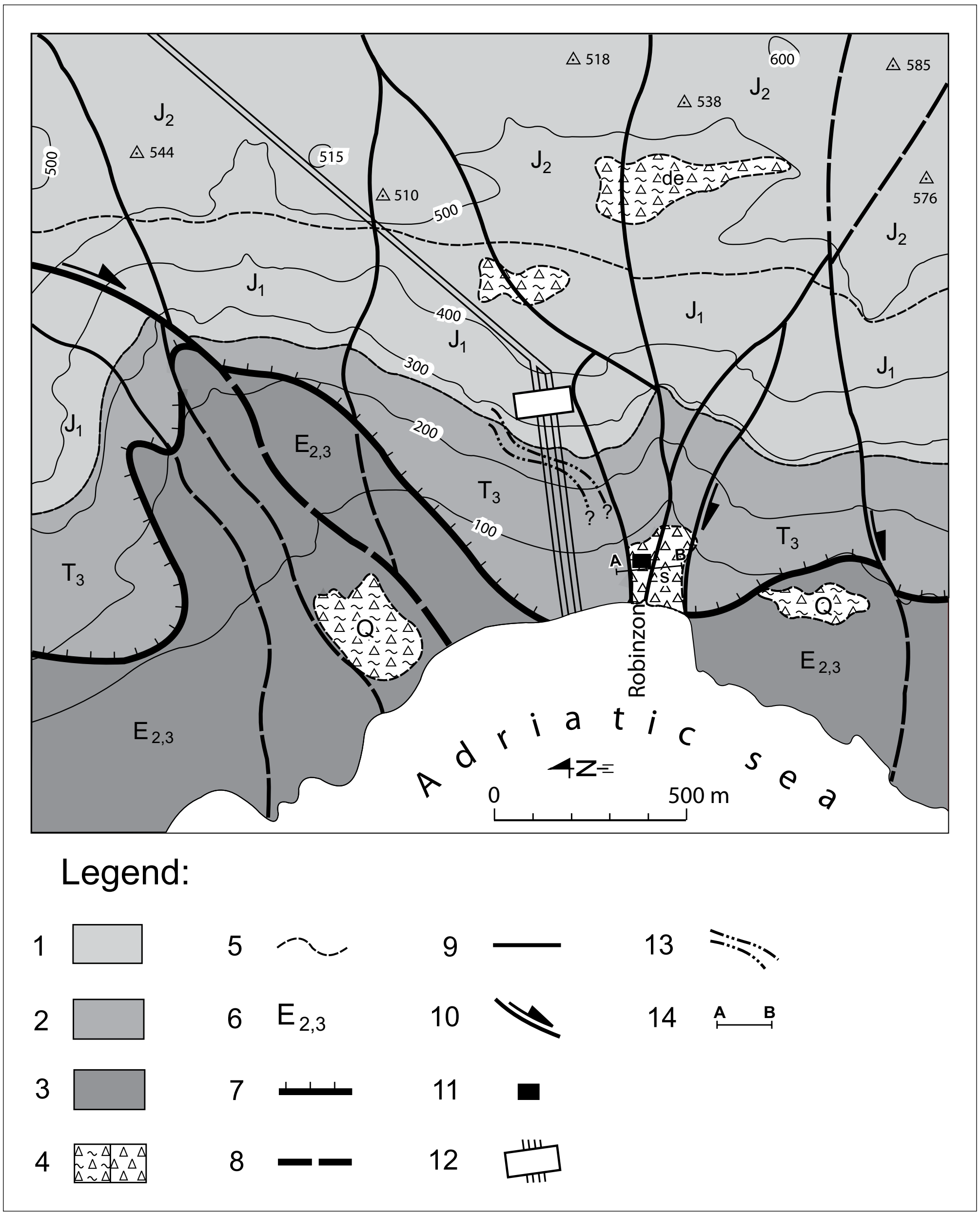

Fig. 2 Simplified hydrogeological map of the study area. Legend: 1 – permeable carbonate rocks; 2 – poorly permeable carbonate rocks; 3 – impermeable clastic rocks; 4 – permeable clastic rocks; 5 – geological boundary; 6 – chronostratigraphic unit; 7 – thrust fault; 8 – the Slivnički fault; 9 – normal fault; 10 – tear faults; 11 – the Robinzon Spring; 12 – the Dubrovnik power plant; 13 – caves; 14 – hydrogeological cross-section.

AK, 1977, 1986, 1991). The dip of the plane of tectonic transport is approximately 30°, while the estimated horizontal movement is over 10 km (MARKOVIĆ, 1971). Carbonate deposits strike NE–SW with moderate (20–50°) northwest dip, revealing a monocline placed behind the steep front of the thrust. Major joint and fault systems in the surveyed area strike 105–295° and 25–205°. The hinterland is a heavily faulted terrain traversed by sub-vertical tear faults with predominantly strike-slip (horizontal) movements. Fault planes are bent along the strike direction with varying strike and dip of the bent segments. The most important fault zone in the area is the zone of the Slivnički Fault (measured parameters: R136/72/62), with reverse dextral movement (Fig. 2). This zone divides the major Dinaricum structural unit into two structural blocks, which are further broken by smaller transverse faults into local tectonic structures. In its upper part, the zone of the Slivnički Fault represents a linear divide between the Robinzon and Ombla catchments (MILANOVIĆ, 1977).

Generally, the thrust is cut almost perpendicularly by a number of transverse faults of different size and importance, which occurred as a result of the long horizontal movement during the faulting and thrusting of the carbonate rocks over the younger flysch deposits. Some segments of the thrust are also reduced and eroded along the contact due to the strike slip of individual blocks. Faults with planes dipping R10/74 and R87/82 are dominant in the immediate vicinity of the Robinzon Spring (Fig. 2). The area between the spring and its hinterland is tectonically destroyed and partially eroded. It is dominated by the steeply-dipping faults: R194/84, R310/78/150 (normal dextral), and R280/80, R352/76/50 (reverse dextral). A number of smaller faults of secondary importance also occur in the vicin-

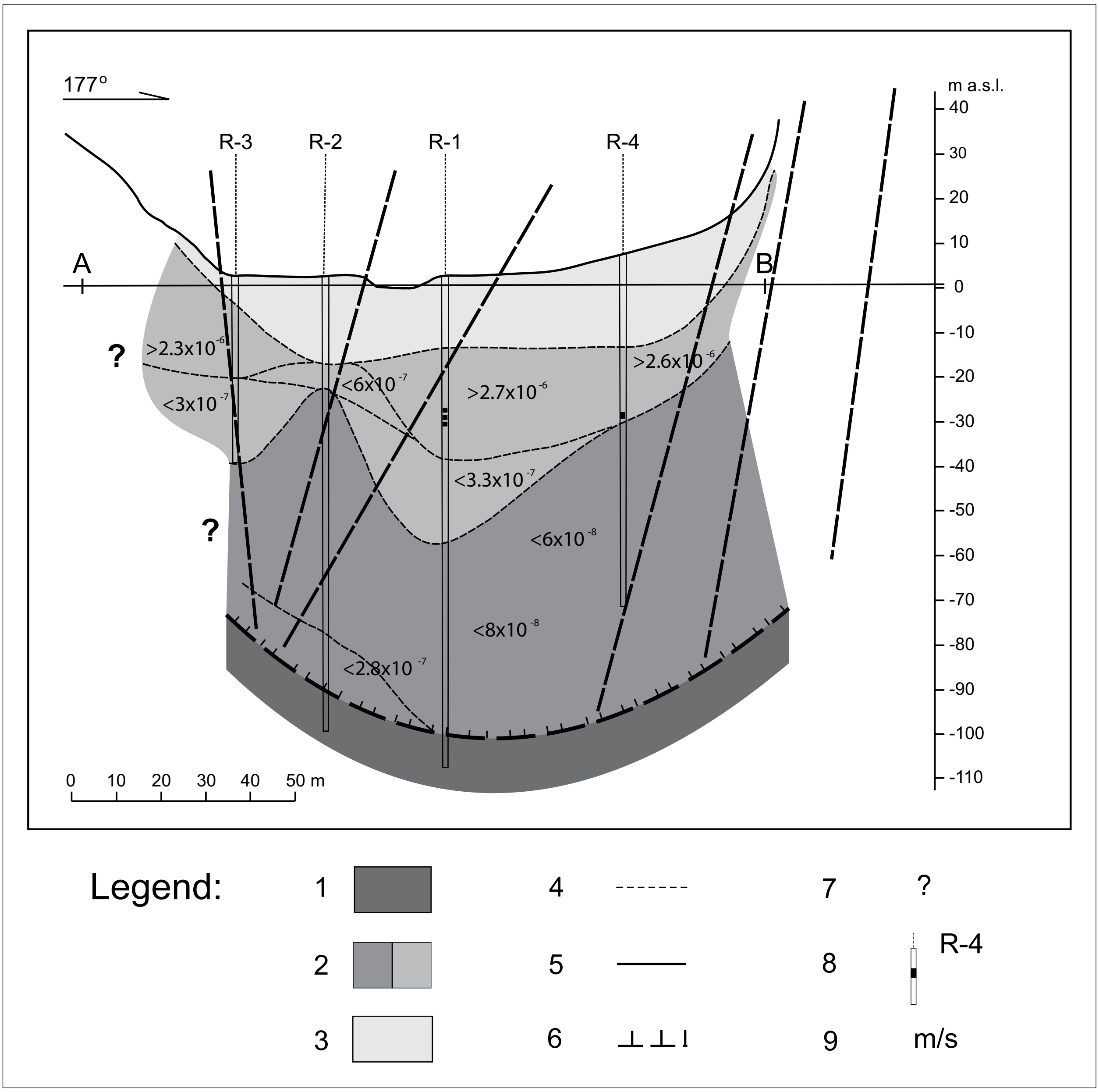

Fig. 3 The hydrogeological cross-section of the Robinzon Spring area. Legend: 1 – flysch; 2 – dolomite cataclastic breccia; 3 – Quaternary deposits; 4 – boundary of the different water permeability; 5 – fault; 6 – thrust; 7 – undefined area; 8 – borehole with caverns; 9 – permeability in m/s.

ity of the spring. The immediate proximity of the spring location is characterized by a narrow zone of rockfall material formed at the foothill of the steep thrust fault scarp (Fig. 2). The thickness of the rockfall material is up to 20 m in places.

4. HYDROGEOLOGICAL FEATURES

A number of issues relevant to the interpretation of hydrogeological relationships in this study must be fully understood prior to assessing the effects of seawater intrusion on the coastal spring. These include: (a) the hydrogeological characteristics of the rocks; (b) tectonic setting; (c) size and hypsometric position of the geological structures; (d) terrain morphology; (e) local and regional patterns of precipitation; (f) anthropogenic impacts; (g) main groundwater flow directions from the hinterland to the spring; (h) the spring type; (i) nature of the contact between permeable and impermeable rocks and, finally, (j) analysis of the balance between fresh- and seawater in time and space.

The hydrogeological characteristics of the various carbonate rocks in the study area were deduced from their lithological composition, amount of tectonic deformation on the surface, and detailed hydrogeological mapping of the Robinzon Spring area. Sedimentary rocks were classified into three groups: highly permeable rocks, poorly permeable rocks and impermeable rocks (Figs. 2 and 3). Carbonate rocks, such as, for example, Jurassic karstified limestone, belong to the first group. The preferred groundwater flow paths (conduit flow) were formed in the carbonate rock complex due to secondary porosity (fissure dissolution), which is typical for karst terrains. This type of porosity together with considerable tectonic fragmentation and karstification is crucial for the high permeability of carbonate rocks in the hinterland of the Robinzon Spring. Quaternary sediments such as the rockfall material, spring- and anthropogenic deposits are also highly permeable. Tectonically fractured dolomites and limestone belong to the transition group of poorly permeable rocks, while the Eocene flysch series represents the group of impermeable sedimentary rocks. The latter is composed of marls and clayey marls occasionally interbedded with thin layers of limestone, limestone breccia, sandstone and silt.

The hydrogeological characteristics of the sedimentary rocks in the particular geological setting of the Robinzon Spring area were used to determine their hydrogeological function. The narrow coastal zone of the clastic flysch strata extends 'streamwise' (into the sea) beyond the catchment area of the Robinzon Spring (Fig. 2), but owing to its uniform regional extension and considerable thickness it plays a crucial role in the formation of the catchment. This zone separates the sedimentary complex with good reservoir and permeability characteristics from the sea, which is the ultimate recipient of the waters from the coastal hinterland. The absence of submarine springs in this part of the Dubrovnik coastal area is caused by the hydrogeological barrier of flysch strata obstructing the groundwater flow to the sea. Dispersed groundwater discharge from the karstified spring hinterland is blocked by the continuous impermeable flysch zone. Thus, the total outflow is concentrated on a small number of springs because the groundwater can only reach the sea by flowing over the hydrogeological barrier.

Being a total hydrogeological barrier in the Dubrovnik coastal area, the flysch strata extend from the Slano settlement in the west to Kotor Bay (Montenegro) in the east, a distance of approximately 70 km. Only a few permanent and high-yield springs occur on the geological boundary with permeable carbonate rocks. The springs are characterized by the highest yields when situated at the lowest altitude where the flysch barrier is most deeply eroded. The portions of the Adriatic coast where the flysch hydrogeological barrier is nonexistent (for example, the shores in the foothills of Velebit Mt. in the Northern Adriatic) are completely devoid of permanent springs, or springs of significant capacity because the subsurface waters from the coastal hinterland flow to the sea through the carbonate rocks in quite a diffuse manner.

The highly permeable limestone of Jurassic age is a predominant rock type but often interbedded with lenses, thin beds and zones of poorly karstified dolomites. Due to their poor permeability the local dolomites are very important in directing groundwater flow into the permeable limestone sections of the carbonate rock complex. Similarly, the Slivnički fault zone acts as a significant hydrogeological factor because all the waters drained from the area are transmitted as concentrated flow through the very permeable fault zone to the hydrogeological barrier. The tectonic boundary between the carbonate rocks and clastic flysch sequence is considerably above sea level (230 m, Fig. 2). The Robinzon Spring is a natural outlet, discharging water collected from the hinterland along the fault zone, because the erosion process strongly affected the carbonate rock sequence at the site. Other significant surface springs or submarine springs cannot be found along the coastline. PERGER (1960[4]) mentioned a few submarine springs but those have been subsequently buried and no longer exist. The fact is that a conduit water-flow only appears at the Robinzon Spring because the flysch zone hinders the dispersive water flow from the hinterland. This confirms by borehole determined hydrogeological function of the flysch sequence as a total barrier. Dolomite rocks occurring at the thrust front, crushed by the dextral transcurrent faults, came into contact with flysch clastics and thus eliminated their primary role as a hydrogeological barrier. However, this is not observed in the spring zone where the highly permeable Quaternary sediments occur.

According to PERGER (1960[4]), the Robinzon Spring has a natural yield varying between $Q_{min} = 20$ l/s (August 6, 1957) and $Q_{max} = 20.5$ m^3/s (January 4, 1954). During tunnelling works for the Dubrovnik power plant, the cave system had been hit by drilling, which affected the maximum and minimum discharges on the spring outlet. The hydrogeological study of the Metković–Dubrovnik–Konavle area (BOJANIĆ & IVIČIĆ, 1984[6]) contains new information about the minimum $Q_{min} = 165$ l/s (September 19, 1964) and maximum yield $Q_{max} = 2$ m^3/s (December 12, 1981). During the repair works at the power plant and the tunnel locations during May 2000, when the tunnel was drained for restoration for a period of 21 days, the loss of 240 l/s of water from the tunnel were found to feed the Robinzon Spring (PAVIŠA, 2000[7]).

5. RESULTS AND DISCUSSION

Four shallow boreholes with maximum depth of approximately 100 m below the surface, were planned in the Robinzon Spring area, in the impermeable flysch

---

[6] BOJANIĆ, L. & IVIČIĆ, D. (1984): Hidrogeološka studija područja Metković–Dubrovnik–Konavle [*Hydrogeological study of the Metković–Dubrovnik–Konavle area* – in Croatian].– Unpublished report, Archive of the Croatian Geological Survey, Zagreb, IGI.186/84, 180 p.

[7] PAVIŠA, T. (2000): Analiza vode iz dovodnog tunela HE Dubrovnik [*Water analysis from the tunnel HE Dubrovnik* – in Croatian].– Unpublished report, Archive of the Hrvatska elektroprivreda, Dubrovnik, 30 p.

W	A	GW	DOL	FL	D
R-1	5.38	4.38	17.60	103.60	111.00
R-2	2.41	1.40	19.80	89.91	100.00
R-3	2.52	1.42	7.20	-	42.40
R-4	9.44	8.15	22.80	-	90.00

Table 1 General data on the drilling experiment at the Robinzon Spring locality. Explanation: W – borehole; A – altitude (m); GW – relative depth of the groundwater level (m); DOL – relative depth of the overlying permeable dolomite rock (m); FL – relative depth to the underlying impermeable flysch rocks (m); D – relative depth of the drilled borehole (m).

formation (according to the geophysical data). However, only two reached the expected depth (boreholes R–1 and R–2), while the remaining two were terminated early (R–3 due to the failure of the drilling experiment). Material drilled down to the impermeable flysch layer consisted of carbonate rocks: surface rockfall material (roughly to 20 m depth), followed by crushed dolomite rock, in places filled with limestone matrix, down to 111 and 100 m from the surface, respectively. Data from the drilling experiment are summarized in Table 1.

The hydrogeological cross section through the Robinzon Spring area was compiled from various sources: geologic map data (lithology), core data from drilling intervals, tomographic measurements (ANDRIĆ, 2001[3]), and results of permeability measurements (Fig. 3). The upper part of the cross section (light grey) is composed of fragments and pebbles of the dolomite rockfall material mixed with a clay–silt matrix, representing the highly permeable zone. Effective measurement of rock permeability to be carried out at pressures of 0.5 and 1 MPa was impossible due to the significant loss of water, estimated at about 30–80 l/s, using Darcy's Law for flow in a confined aquifer. Permeability of the dolomites underlying the surface rockfall material exceeds 3x10^{-7} m/s. Essentially, this zone is divided into the upper part where permeability is very high, ranging from 2.3 to 2.7x10^{-6} m/s, and the lower part where permeability is around 3x10^{-7} m/s, excluding the area around borehole R–2 where permeability is 6x10^{-7} m/s (Fig. 3). This is the cavernous zone, channeling the groundwater flow from the carbonate hinterland to the sea. Also, the tomography measurements detected the fractured zones at a distance of 5 m from borehole R–1 towards borehole R–2 at relative depths between -48 and -52 m. The permeability measured in this zone is 3x10^{-7} m/s, indicating the possibility of groundwater circulation. Also, the temperature measured in borehole R–1 (Fig. 3) is constant at 13.8°C. The measured data indicate a highly permeable zone between boreholes R–1 and R–2 down to the relative depth of -60 m. However, this zone becomes shallower in the direction of borehole R–2 (relative depth of -25 m,) and then deeper again toward borehole R–3 (relative depth of -42.4 m). The middle-grey coloured area in the cross section

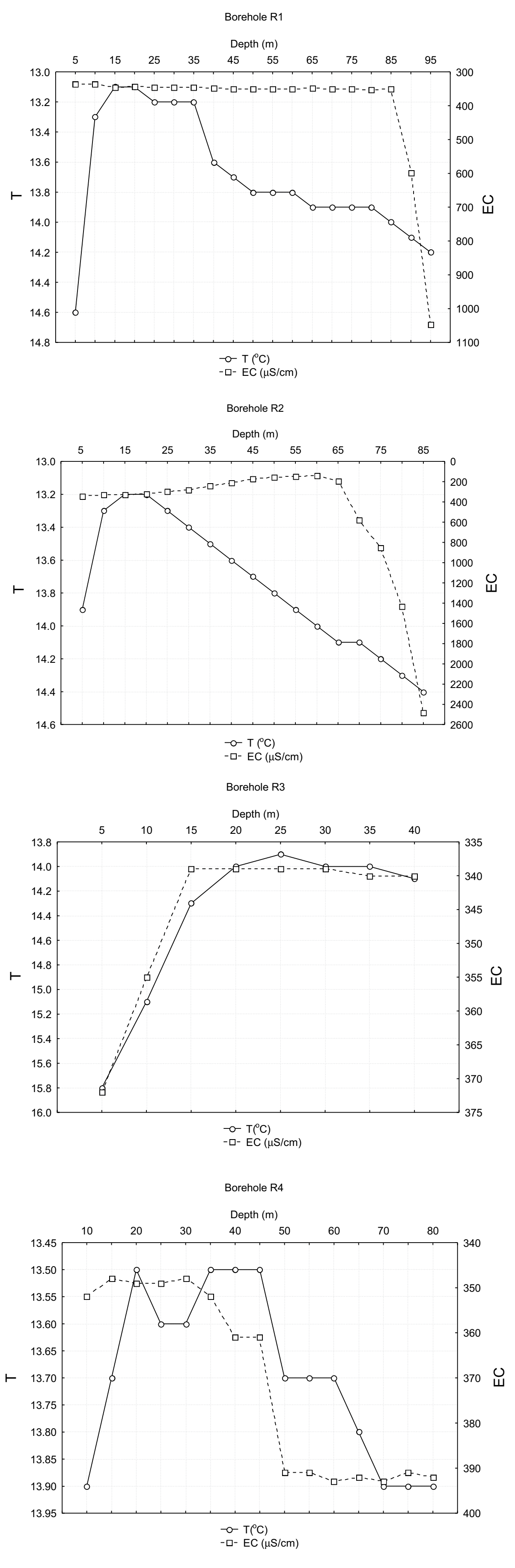

Fig. 4 Variations of the EC and T with the depth during the pumping test.

Date	pH	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	Ca (mmol/l)	Mg (mmol/l)	Cl^- (mmol/l)	SO_4^{2-} (mmol/l)	SO_4^{2-}/Cl^-	Mg/Ca
01/93	7.76	66	8.8	178	20	10.5	1.647	0.362	0.564	0.109	0.194	0.220
04/94	7.71	58	8.8	174	16	7.5	1.447	0.362	0.451	0.078	0.173	0.250
06/95	7.81	57	14	188	18	7.5	1.422	0.576	0.508	0.078	0.154	0.405
03/96	7.75	60	11	186	20	8.3	1.497	0.453	0.564	0.086	0.153	0.302
06/96	7.63	59	5.6	175	8.5	16.3	1.472	0.230	0.240	0.170	0.708	0.157

Table 2 Results of the Robinzon Spring water analysis (courtesy of the Department of Public Health of the County Splitsko–Dalmatinska and INA Department of Fluid Analysis and Ecology).

represents the zone of the dolomite rocks where measured permeability is reduced to $2.73x10^{-7}$ m/s, except for the interval between -80 to -85 m (relative depth) in borehole R–2, where permeability is increased to $6x10^{-7}$ m/s (Fig. 3). This zone is apparently devoid of caverns. However, tomographic measurements in borehole R–4 disclosed the fractured zone at the relative depth of -57.5 m (velocity of P waves 4000–4600 m/s). At this depth only the fractured rocks filled with clay have been drilled, the lowest permeability of which was measured at $2x10^{-8}$ m/s (Fig. 3). The deepest part of the hydrogeological cross-section is represented by impermeable flysch deposits (dark grey) reached by drilling only in the two boreholes closest to the spring (Table 1), so that the boundary between the carbonate and flysch deposits was only drawn approximately. Thus the depth to the underlying impermeable flysch deposits farther from the spring in the E–W direction remains unknown as does the storage capacity of the carbonate block lying north of the spring area.

The parameters such as temperature (T) and electroconductivity (EC) were computed vs. the depth diagrams constructed for all four boreholes at fixed time. Such a diagram (T, EC vs. depth – Fig. 4) shows the decrease of temperature down to a depth of -35 m in the case of the borehole R–1, which indicates the existence of groundwater flow (TRAVI et al., 1995; FALKOWSKA & PIEKAREK-JANKOWSKA, 1999). At greater depths, between -35 and -80 m, the temperature slightly increases, while in the deepest part of the boreholes, from -80 to -95 m, the increase of temperature with depth becomes linear indicating that the groundwater flow is nonexistent in this zone – a phenomenon called the bottle effect. Furthermore, the EC value also increases in this interval, which is caused by mixing of the zones of fresh- and saltwater (WEAVER et al., 1995; MAS-PLA et al., 1999; LAND et al., 2004) in the borehole as in the contact zone between permeable dolomite and impermeable flysch rocks. For borehole R–2 the same diagram (T, EC vs. depth – Fig. 4) shows the decrease of temperature down to the depth of -20 m, which again indicates the existence of groundwater flow. Deeper down the borehole, between -20 and -65 m, the temperature slightly increases at first but in the deepest part, below -65m, the temperature and EC again increase linearly with depth as in the case of R–1. Mixing of fresh- and salt-water is thereby confirmed in boreholes R–1 and R–2. In the case of the boreholes R–3 and R–4 located farther from the spring with respect to R–1 and R–2 (along the cross section A–B) the conditions are analogous to the first pair of boreholes, and can be interpreted in the same way.

The water level was measured both in the boreholes and at the water gauge near the spring. Drawdown data were similar from boreholes R–1, R–2 and R–4, ranging between 0.10 and 0.11 m. A lowering of the water at the water gauge was slightly higher (0.13 m), due to its greater proximity to the spring. To increase the drawdown values, long-term pumping with higher capacity is required.

Natural waters acquire their chemical characteristics both by dissolution and by chemical reactions with solids, liquids and gases with which they come into contact during the various phases of the hydrological cycle (STUMM & MORGAN, 1995). Seawater intrusion into highly developed karst aquifers is a serious problem in many places along the coastal lines. It occurs where seawater is drawn into an aquifer with the decline in the hydraulic head causing the contamination of the coastal springs and boreholes (HEM, 1985). Chloride, which is the major anion in seawater, moves through aquifers at nearly the same rate as the intruding water. Increasing chloride concentrations may be the first indication of seawater intrusion into the area devoid of other possible sources of saline contamination. Again, magnesium and sulfate are present in seawater in much higher concentrations. A high Mg/Ca molar ratio may sometimes be indicative of seawater intrusion. Many authors used the Mg/Ca and SO_4^{2-}/Cl^- ratios as tracers for determination of seawater intrusion (e.g. VENGOSH et al., 2002; LEBOEUF et al., 2003). A wide range of SO_4^{2-}/Cl^- ratios (0.02–0.23) is detected in groundwater in relation to seawater values (= 0.05; VENGOSH et al., 2002). Sulphate and chloride concentrations vary from 7.5 to 16.3 mg/l, and 8.5 to 20 mg/l, respectively, ruling out a major influence of sea water on the spring (aquifer) (Table 2). According to the chemical composition (Piper diagram, Fig. 5) the water from the Robinzon Spring belongs to the Ca–HCO_3 hydrochemical type. This is the primary water type which is principally derived from dissolu-

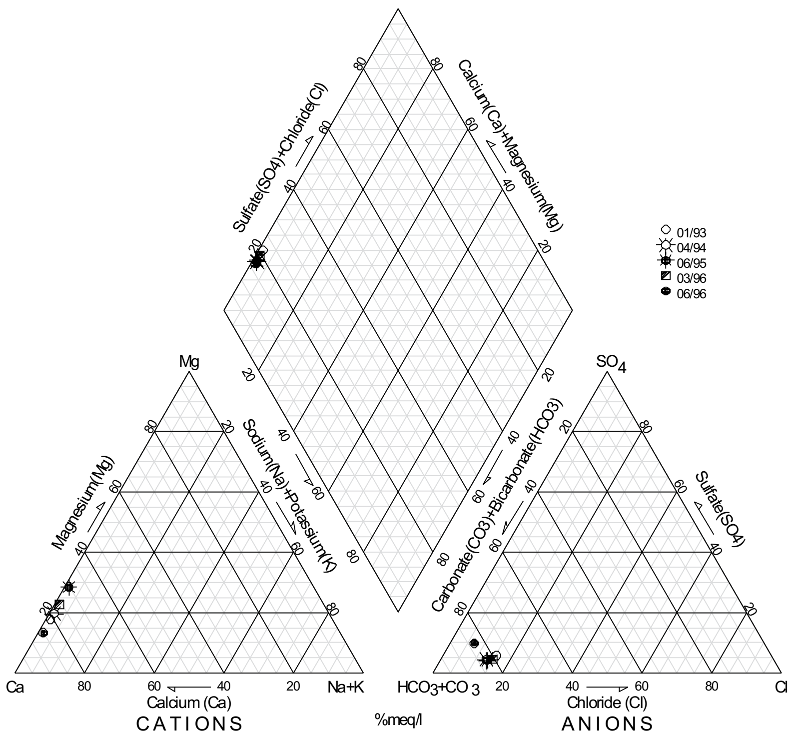

Fig. 5 Piper diagram of Robinzon Spring water; samples taken in January 1993, April 1994, June 1995, March and June 1996.

tion of carbonate minerals (calcite and dolomite) that compose the aquifer. Also, the Mg/Ca ratio is very low, which is typical for freshwater flowing through the carbonate (limestone) aquifer. The chemical composition of the spring water shows that the spring is not greatly influenced by seawater and the flowing water from the Robinzon Spring is fresh water.

6. CONCLUSIONS

Geological, structural and hydrogeological settings highlighted in this study have facilitated differentiation of the karst underground terrain of the Robinzon Spring area into three hydrogeological zones. The first is characterized by good water circulation (rockfall material, fractured and cavernous dolomite), the underlying second zone is of a poor water circulation (dolomites), while the third, deepest, zone "traps" the water (contact between dolomite and flysch). The increased values of EC were detected only at the bottom of the third zone in boreholes R–1 and R–2, where the tectonic boundary of highly permeable dolomites with underlying impermeable flysch strata was reached by drilling. Such an increase definitely indicates seawater intrusion into the spring zone. The relationship between the sea and fresh water was not disturbed during the pumping test carried out under conditions of high or moderate discharges at the spring outlet. However, the vital question of what would happen if pumping was carried out during the dry period when the inflow of fresh water was small remains unanswered. To provide reliable answers it is necessary to complete the pumping test and to measure the various parameters (T, EC, major anions and cations) from the water samples from the Robinzon Spring, and from the neighbouring boreholes R–1 and R–2 during both the rainy and dry seasons of the year. The results would pave the way for understanding whether the deeper parts of the aquifer represent an isolated hydrological system (siphon without circulation), or are they connected with other parts (underground flows). They would also provide answer regarding possible contamination of the drinking water by saline water at the pumping station as a result of seawater intrusion.

Acknowledgements

The authors wish to express their gratitude to Department of Public Health of the County Splitsko–Dalmatinska and INA Department of Fluid Analysis and Ecology that provided water chemistry data. We also wish to acknowledge the help of Mr. Tomo PAVIŠA.

7. REFERENCES

BULJAN, R. (1999): Značenje strukturnog modela u razradi zahvata i zaštite podzemnih voda izvorišta područja Ombla kraj Dubrovnika [*The significance of the structure model in the groundwater capture and protection of the Ombla spring area near Dubrovnik* – in Croatian].– Unpubl. PhD Thesis, University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, 176 p.

BULJAN, R. & PRELOGOVIĆ, E. (1997): The significance of structural and geological relationship assessment in the construction of the Ombla underground Hydroelectric Power Plant.– RGN Zbornik, 9, 17–22, Zagreb.

FALKOWSKA, L. & PIENKAREK-JANKOWSKA, H. (1999): Submarine seepage of fresh groundwater: disturbance in hydrological and chemical structure of the water column in the Gdansk basin.– ICES J. of Marine Science, 56/1, 153–160.

HEM, J.D. (1985): Study and interpretation of the chemical characteristics of natural water.– U.S.G.S. Water Supply Paper 2254, 263 p.

HERAK, M. (1977): Tektonogenetski pristup klasifikaciji krških terena [*Tectogenetic approach to determine karst terrains* – in Croatian].– Krš Jugoslavije, 9/4, 65–80, Zagreb.

HERAK, M. (1986): A new concept of the geotectonics of the Dinarides.– Acta Geologica, 16, 1–42, Zagreb.

HERAK, M. (1991): Dinaridi – mobilistički osvrt na genezu i strukturu (Dinarides – Mobilistic view of the genesis and structure).– Acta geologica, 21/2, 35–117, Zagreb.

HUBBARD, S.S. & RUBIN, Y. (2000): Hydrogeological parameter estimation using geophysical data: a review of selected techniques.– J. of Cont. Hydrology, 45/1–2, 3–34.

LAND, M., REICHARD, E.G., CRAWFORD, S.M., EVERETT, R.R., NEWHOUSE, M.W. & WILLIAMS, C.F. (2004): Groundwater quality of coastal aquifer systems in the West Coast Basin.– Los Angeles County, California, 1999–2002. U.S.G.S. and U.S. Dep. of the Interior. Sci. Report 2004–5067, 40 p.

LEBOEUF, P.P., BOSCH, P.A., CALVACHE, M.L., VALLEJOS, A. & ANDREU, J.M. (2003): Strontium, SO_4^{2-}/Cl^- and Mg^{2+}/Ca^{2+} ratios as tracers for the evolution of seawater into coastal aquifers: the example of Castell de Ferro aquifer (SE Spain).– C.R. Geoscience, 335, 1039–1048.

MARKOVIĆ, B. (1966): Osnovna geološka karta SFRJ 1:100.000. List Dubrovnik K34–49 (Basic Geological Map of SFRJ. Dubrovnik. Sheet).– Zavod za geol. i geofiz. istraživanja Beograd (1963–1965), Savezni geološki zavod Beograd.

MARKOVIĆ, B. (1971): Osnovna geološka karta SFRJ 1:100.000. Tumač za list Dubrovnik K34–49 (Basic Geological Map of SFRJ. Geology of Dubrovnik. Sheet).– Zavod za geol. i geofiz. istraživanja (1966), Savezni geološki zavod Beograd, 43 p.

MAS-PLA, J., BACH, J., VIFLAS, E., TRILLA, J. & ESTRALRICH, J. (1999): Salinization processes in a coastal aquifer system (Alt Emporda, NE Spain).– Physics and Chemistry of the Earth. Part B: Hydrology. Oceans and Atmosphere, 24/4, 337–341.

MILANOVIĆ, P. (1977): Hidrogeologija karsne izdani Ombla [*Hydrogeology of the Ombla Spring* – in Croatian].– Geološki glasnik, Sarajevo, 35–48.

STUMM, W. & MORGAN, J.J. (1995): Aquatic chemistry. Chemical Equlibria and Rates in Natural Waters.– John Wiley & Sons. INC. New York – Chichester – Brisbane – Toronto – Singapore, 1022 p.

TRAVI, Y., PIZARD, P. & BETTON, M. (1995): Temperatures and thermal gradients in the Senegalese Maastrichtian aquifer: simulated test on their effect on flow discharge.– J. Hydrology, 167/1–4, 99–119.

VENGOSH, A., GILL, J., DAVISSON, M.L. & HUDSON, G.B. (2002): A multi-isotope (B, Sr, O, H and C) and age dating (^3H–^3He and ^{14}C) study of groundwater from Salinas Valley, California: Hydrochemistry, dynamics and contamination processes.– W.R. Resources, 38, 352–363.

WEAVER, T.R., FRAPE, S.K. & CHERRY, J.A. (1995): Recent cross-formational fluid flow and mixing in the shallow Michigan basin.– Geol. Soc. of America Bulletin, 107/6, 697–707.

Manuscript received September 10, 2006.

Revised manuscript accepted November 24, 2006.