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Investigations of the brackish karst springs on the Croatian Adriatic Sea coast

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Abstract The Croatian Adriatic Sea coast is a highly and deeply karstified area. Thus its coastal aquifers are open to seawater intrusion. There are many coastal karst springs, and the vast majority of them are brackish year round, or during periods of low summer discharges. Increasing development of these areas threatens to cause a shortage of fresh water. Consequently, there is an increased need for developing water reserves in the coastal aquifers and understanding the mechanism of seawater intrusion. This paper gives an overview of eight selected coastal brackish karst springs along the Croatian Adriatic Sea coast. An explanation of their functioning, an overview of measures taken for the prevention of seawater intrusion in some of them, and the practical success of those measures is given.

Key words coastal karst; brackish karst springs; seawater intrusion; Croatia

INTRODUCTION

Watersheds of the karst springs along the Croatian Adriatic Sea coast are situated in the Dinaric carbonate karst massif. The whole area is significantly open to seawater intrusion deep into the coastal aquifers. The development of karst processes in these areas and their hydrogeological consequences have been significantly influenced by changes of the erosion baseline throughout geological history. About 20 000 years ago the sea level was approx. 100 m below the present level. In such conditions many permanently or temporarily brackish springs have emerged on the Croatian coast.

The major characteristic of these springs is the variable concentration of chlorides during the year with an unfavourable distribution with respect to water supply needs. The increased intrusion of seawater during the warm and droughty summer periods is the result of a concomitant lower groundwater level in the coastal aquifers.

A substantial prerequisite for spring protection is knowledge of the mechanism of seawater intrusion. The dynamic of freshwater and seawater mixing is significantly different for each karst spring. Therefore, extensive investigations of each spring have to be made, resulting in varying decisions regarding appropriate spring protection. Generally, there are three possible ways of protecting brackish karst springs (Bonacci & Roje-Bonacci, 1997; Breznik, 1998): (a) the construction of a grout curtain; (b) the artificial raising of the spring water level; and (c) the interception from a karst aquifer further from the seawater intrusion zone.

The intrusion of seawater into coastal karst aquifers is present along the entire Mediterranean coastline and other coastal karst areas in the world. Many hydrologists, hydrogeologists and other experts have been involved in the solution of this problem and numerous investigations, analyses, mathematical models and attempts regarding their development have been made (Lambrakis *et al.*, 2000; Maramathas *et al.*, 2003; Arfib & de Marsily, 2004; Blavoux *et al.*, 2004; Pulido-Bosch *et al.*, 2005; Guhl *et al.*, 2006).

This paper gives an overview of eight brackish karst springs or spring zones on the Croatian coast, their basic hydrogeological characteristics and information about their seawater intrusion processes, and planned and performed measures for their protection.

OVERVIEW OF EIGHT CROATIAN COASTAL BRACKISH KARST SPRINGS

Hydrogeological characteristics

Almost half of the Croatian territory is made of carbonate rocks, which belong to the Dinaric karst (Herak *et al.*, 1969). The hydrogeological map given in Fig. 1 shows the domination of carbonate rocks in the coastal area with small patches of true and relative barriers. These conditions constitute a favourable prerequisite for brackish spring formation and seawater intrusion deep into the coastal aquifers. The Croatian Adriatic Sea coast is characterised by a large number of permanent or periodical brackish and submarine springs. Brackish springs appear at sea level, below and above sea level, and even 20 m above sea level. The locations of the eight brackish, coastal, and karst springs analysed in this paper are indicated in Fig. 1 .

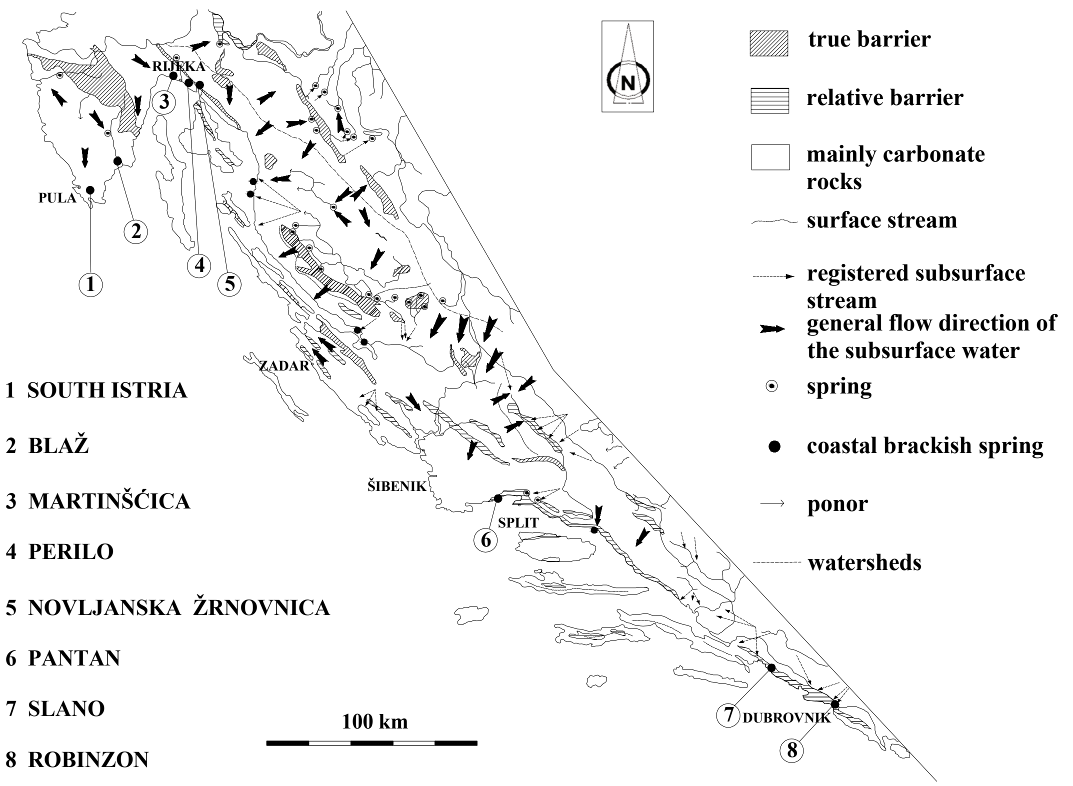

Fig. 1 Hydrogeological map of the Croatian Adriatic Sea coast with indicated positions of brackish karst springs analysed herein (Herak *et al.*, 1969).

South Istria spring zone

The southern Istrian peninsula is formed of a series of carbonate deposits. Limestone is dominant, with the occasional appearance of dolomite layers, lenses, breccias and marls (Fig. 2). The hydrogeology of this karst region can be described as an open coastal zone with a series of small coastal springs with discharges up to 24 L/s. Several wells with a total capacity of 200 L/s have been drilled into the coastal karst aquifers for the water supply of the town of Pula. Many of these wells are situated adjacent to the coast where the groundwater level does not exceed 3 m a.s.l. (Bonacci & Roje-Bonacci, 2000). Intensive exploitation causes the lowering of the groundwater level in dry periods, which results in seawater intrusion into the aquifers, exploitation wells and coastal karst springs. The problem is intensified by many private and uncontrolled wells, which use water for irrigation.

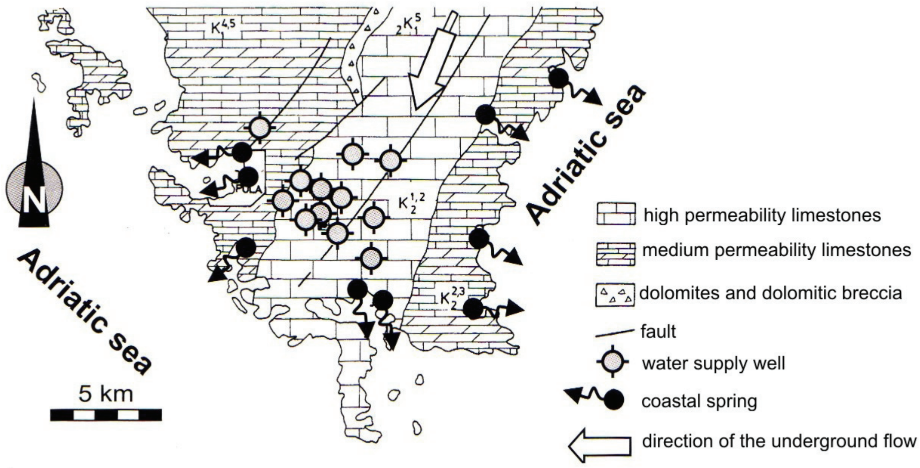

Fig. 2 Hydrogeological map of the Southern Istrian spring zone (COST Action 621, 2004).

Blaž Spring

Blaž Spring is the main spring in a karst spring zone, consisting of about 20 permanent and temporary springs situated along the coast of the Raša Bay in a line 500 m long (Fig. 3). This represents the contact zone between carbonate rocks and impermeable flysch layers. The average spring discharge outflow is about 1.6 m^3/s and the maximum discharge is 2.6 m^3/s (Bonacci & Roje-Bonacci, 1997). Due to the intrusion of seawater and high chloride concentration during the summer period, water from it cannot be used for water supply. Seawater intrusion occurs every year during hot and droughty summer periods. Figure 3 shows the positions of 20 boreholes drilled in the spring vicinity for the purpose of analysing the relationship between freshwater and seawater in the aquifer. Seawater penetrates the aquifer directly through the karst conduit connected to the Adriatic Sea. Seawater intrusion into the Blaž Spring could possibly be prevented by blocking the karst conduit through which the main quantity of seawater intrudes into the spring.

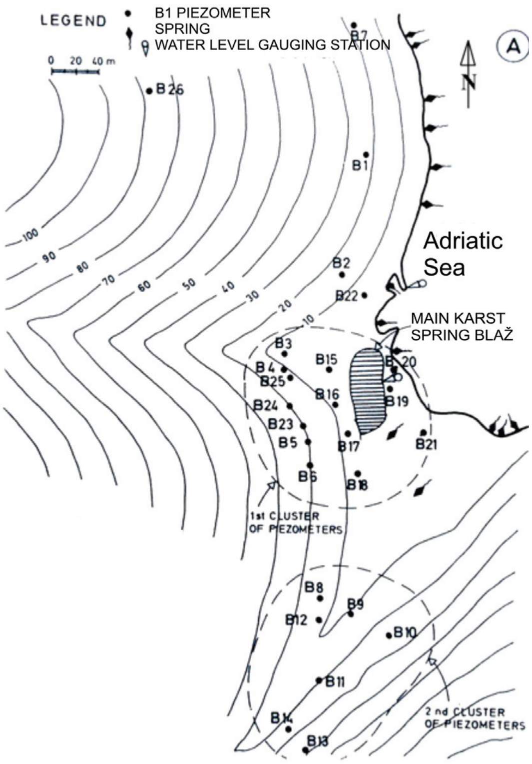

Fig. 3 Blaž Spring location (Bonacci & Roje-Bonacci, 1997).

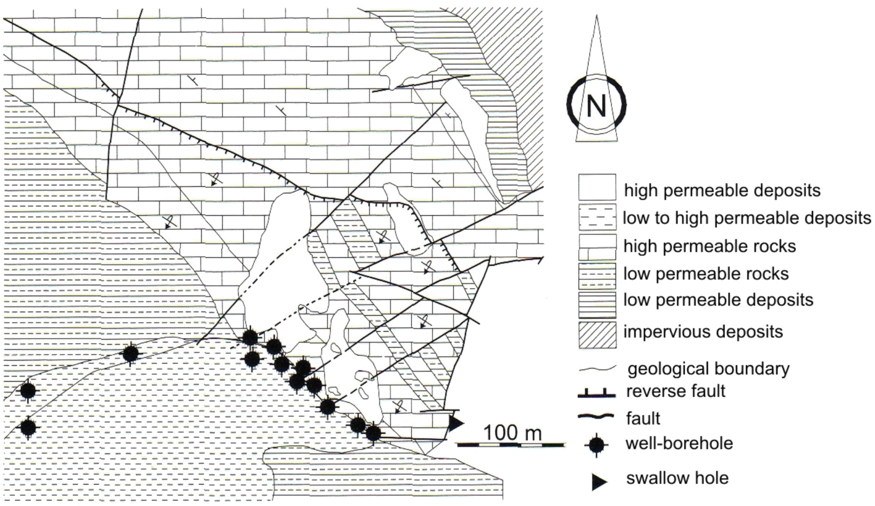

Fig. 4 Hydrogeological map of the Martinšćica Spring zone (COST Action 621, 2004).

Martinšćica Spring

The Martinšćica Spring is one of the springs exploited for the water supply of the city of Rijeka, with a maximum discharge of 400 L/s. The water supply system consists of several wells shown in Fig. 4. However, the wells are not in operation due to increased salinity during the summer dry periods. Piezometers drilled farther in the karst massif showed that the boundary between freshwater and seawater depends on local geological conditions and changes in the groundwater level during the time of operation. As the local dolomite layers are nearly impermeable, brackish water from deeper layers could not have any influence on freshwater flowing through the layer of limestone inside dolomites. This hydrogeological condition gives the possibility of successful spring exploitation, but under the condition of controlling the dynamic reserves of freshwater.

Perilo Spring

Perilo Spring is also one of the coastal karst springs whose water is used for the water supply of the city of Rijeka. A pumping facility has been placed in its karst aquifer farther inland (Fig. 5). Its pumping capacity in the dry summer periods is 240 L/s. In those periods the intrusion of seawater into the spring can occur, being caused by overexploitation and low groundwater levels. The small width of the permeable limestone placed within impermeable flysch layers gives the possibility of grout curtain construction. However, controlled water pumping connected with the continuous monitoring of the groundwater level has resulted in not taking any invasive measures.

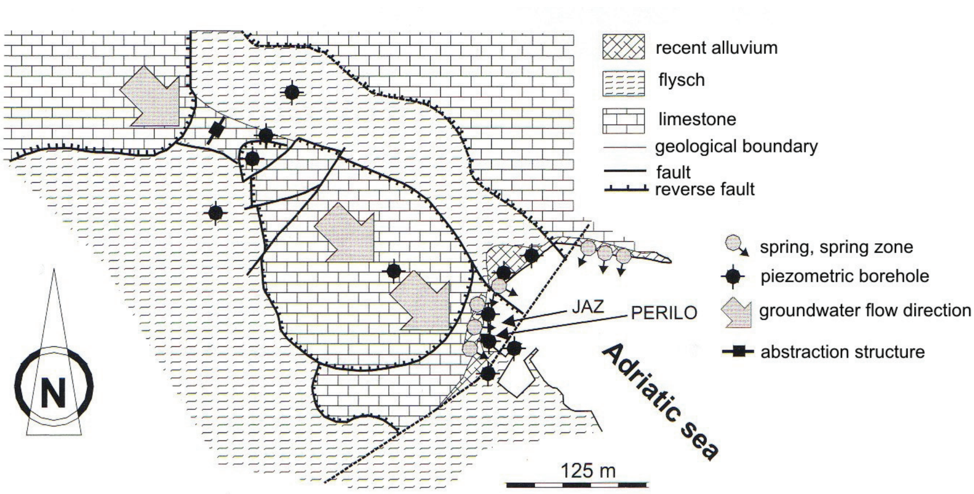

Fig. 5 Hydrogeological map of the Perilo Spring zone (COST Action 621, 2004).

Novljanska Žrnovnica Spring zone

The Novljanska Žrnovnica Spring zone is situated along the northern part of the Croatian Adriatic Sea coast. Its water is used for water supply of the tourist area of the Novljansko-Crkvenička Riviera. Its catchment is mainly underlain by Lower Cretaceous high permeability limestone (Fig. 6). Limestone breccias cross the area and function as a hydrogeological barrier. The dynamic of groundwater circulation and its interaction with seawater is complex, which under natural conditions causes the periodical intrusion of seawater. In order to decrease seawater intrusion, a grout curtain

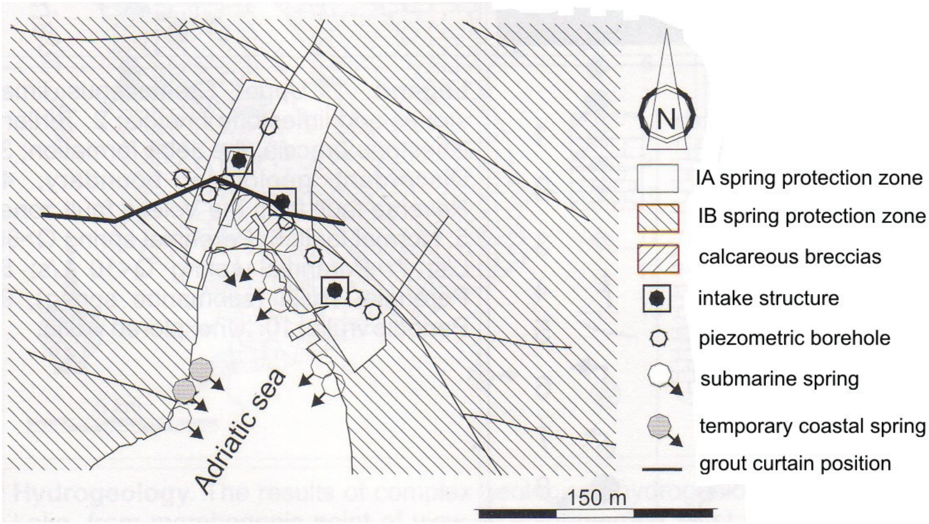

Fig. 6 Hydrogeological map of the Novljanska Žrnovnica spring zone (COST Action 621, 2004).

has been constructed (Biondić *et al.*, 2005). Its purpose is to prevent contact between seawater and freshwater in the shallow zone. Monitoring the results carried out in deep boreholes has revealed that the mixing zone between fresh and seawater is at a depth of 90 to 110 m below sea level. This indicates that the efficiency of the grout curtain is not absolute, and the intrusion of seawater into the aquifer still occurs in extremely dry years.

Pantan Spring

The Brackish karst spring Pantan is situated in Kaštela Bay in the vicinity of the town of Trogir. Its catchment area is underlain by highly permeable limestone rocks. The spring exit is situated at the contact between limestone and flysch layers at an altitude of 2 m a.s.l. The winter discharge is up to 10 m^3/s and in dry periods declines to 1.3–2 m^3/s. Chloride concentration varies between 50 and 10 000 mg/L. During the wet winter months salinity is low, while in the dry summer months it is very high. Close to the Pantan Spring lies the temporary Slanac karst spring, as well as the two submarine springs of Arbanija and Slatina (Bonacci *et al.*, 1995). The Slanac Spring exit is situated at an elevation of 20 m a.s.l. Numerous investigations there have resulted in hypotheses regarding a seawater intrusion mechanism (Mijatović, 1984; Fritz, 1994; Bonacci, 1995). There are many different concepts for the protection of the Pantan Spring, but, because the mechanism of seawater intrusion has yet to be completely explained, spring protection measures have never been undertaken.

Slano Spring

Drinking water for the town of Slano is pumped from two wells which belong to the Slano karst spring aquifer (Fig. 8). The concentration of chlorides in the Slano spring water increases during the dry summer period. Seawater intrusion also appears after

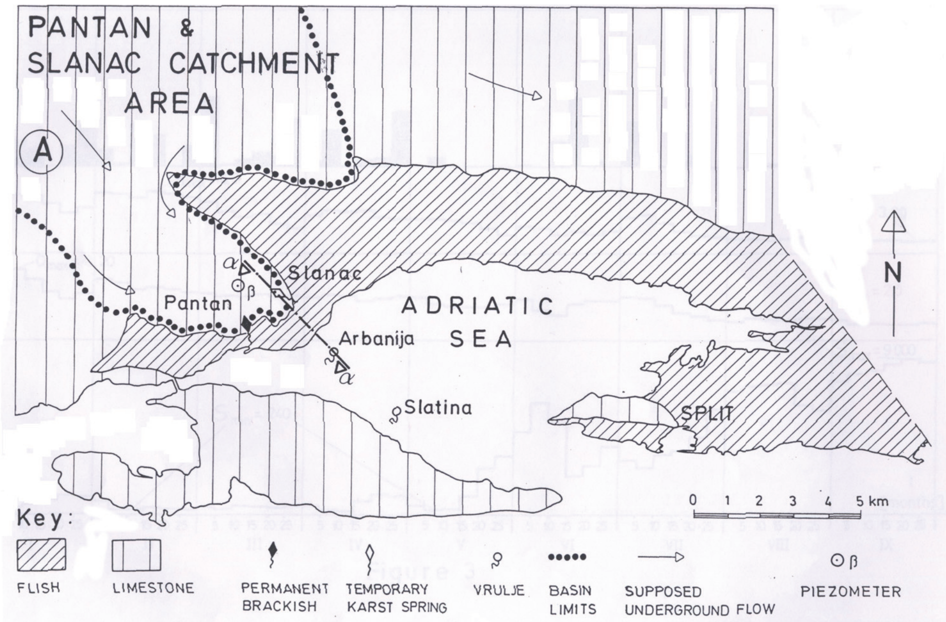

Fig. 7 Hydrogeological map of a wide area around the Pantan spring (Bonacci *et al.,* 1995).

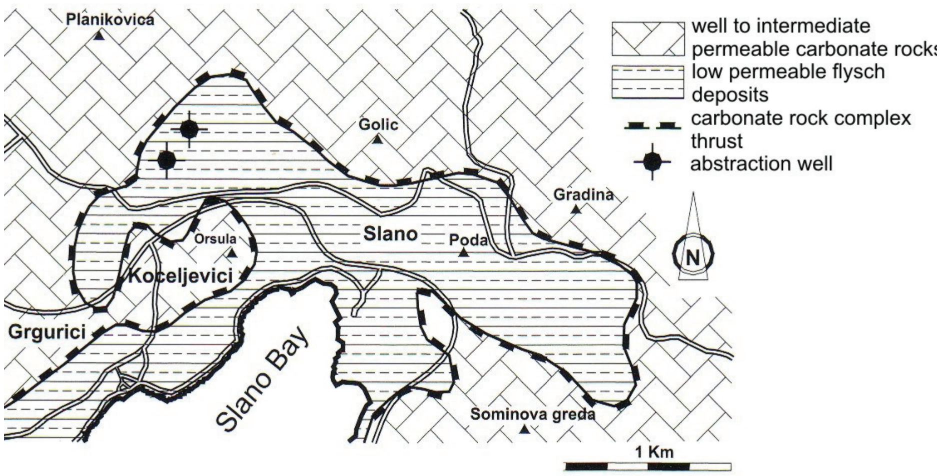

Fig. 8 Hydrogeological map of Slano Spring (COST Action 621, 2004).

the first intensive precipitation event in autumn. This phenomenon can be explained by the influence of turbulence in the mixing zone between seawater and freshwater. After a relatively short period of time, the situation stabilises, and the concentration of chlorides rapidly decreases. The applied solution is controlled water pumping synchronised with the groundwater level conditions.

Robinzon Spring

The Robinzon Spring is situated on the southern part of the Adriatic Sea coast near the town of Dubrovnik. The spring exit is 70 m from the coast. The maximum and

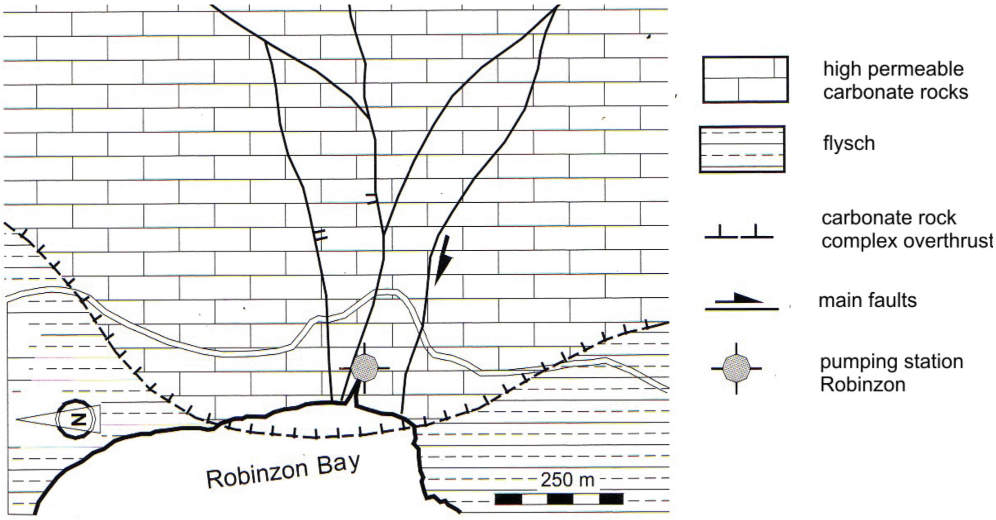

Fig. 9 Hydrogeological map of Robinzon Spring (COST Action 621, 2004).

minimum discharges are about 2 m^3/s and 165 L/s, respectively. The Robinzon Spring emerges on a tectonic contact between very permeable carbonate layers and impermeable flysch layers. Water discharging from the spring is influenced by the seawater, especially during the dry summer periods. The proposed idea was to abstract freshwater from the karst aquifer further from the seawater intrusion zone. For this purpose, the conductivity was measured in boreholes drilled in the aquifer farther inland. As the result of numerous investigations, the construction of a grout curtain was proposed, but so far this solution has yet to be implemented.

DISCUSSION

The overview of the eight Croatian coastal brackish karst springs given in this paper has shown that they often emerge in the contact zone between limestone and flysch layers. Their aquifers are situated in the karst massif, which is mainly composed of limestone with the occasional appearance of dolomite and flysch layers and lenses, dolomite breccias, and marls. Morphological, hydrogeological and geological conditions cause an unstable equilibrium between fresh and seawater during different hydrological situations. This is the main reason that each of these springs has different and very specific conditions of seawater intrusion into their aquifers. For some springs a probable direct connection exists between the sea and the spring exit through unknown karst conduits (Blaž, Pantan). Along the Croatian Adriatic Sea coast, karst spring zones, consisting of many closely distributed and functioned springs, are a normal occurrence. Most of them have a relatively small outflow discharge, whereas only one of them has substantially greater discharge.

The basic characteristics of the eight karst springs described above are shown in Table 1. There are: (a) constantly brackish springs; (b) periodically brackish springs during dry, summer periods; and (c) springs which are brackish only in situations occurring during extremely dry years. Only the last mentioned group of karst springs,

Table 1 Characteristics of coastal brackish karst springs and zones explained in this paper.

Spring	Capacity (L/s)	Abstraction	Seawater intrusion characteristics	Proposed measures	Successfulness of measure	Classification according to the COST Action 621 (2004).			
						Permeability	Structure	Seawater intrusion	Exploitation
South Istria	200	Wells in hinterland	Due to overexploitation in dry periods	Controlled exploitation	Successful	High	Free-unconfined	Moderate-high and variable-seasonal	High
Blaž	1600–2600	Not used for water supply	Every year in dry periods	Grout curtain	Not constructed	High	Free-unconfined	Variable-seasonal	Under-exploited
Martinšćica	400	Wells	Due to overexploitation in dry periods	Controlled exploitation	Successful	High	Free-unconfined	Variable-seasonal	Moderate
Perilo	240	Abstraction structure in hinterland	Due to overexploitation in dry periods	Grout curtain/controlled exploitation	Not constructed/ successful	High	Free-unconfined	Variable-seasonal	Moderate to high
Novljanska Žrnovnica	400	Spring interception with pumping	Seawater intrusion in extremely dry years	Grout curtain/controlled exploitation	Partly successful/ successful	High	Free-unconfined	No intrusion	Moderate
Pantan	1300–10 000	Not used for water supply	Seawater intrusion in dry periods	(1) interception in hinterland; (2) grout curtain (3) spring level rising	No measures applied	High	Free-unconfined	Variable-seasonal	Under-exploited
Slano	6	Two exploitation wells	Overexploitation in dry periods and first high freshwater wave	Controlled exploitation	Partly successful	High	Free-unconfined	Variable-seasonal	Moderate
Robinzon	165–2000	Spring interception with pumping	Seawater intrusion in dry periods	Grout curtain	Not constructed	High	Free-unconfined	Variable-seasonal	Moderate

which are brackish only rarely, can be used for a relatively reliable water supply. However, these springs should be constantly monitored and analysed with the aim of increasing the reliability of their water supply. In the four last columns of Table 1 the classification according to the COST Action 621 (2004) of the eight Croatian karst springs is given.

It should be noted that completely successful protective measures of seawater intrusion into karst spring coastal aquifers and karst springs have not been obtained for any of the presented examples. This means that the mechanism of seawater intrusion has not been completely explained. In some cases there are, to a certain extent, clear hydrogeological conditions which lead to the possibility of an efficient invasive measure, such as the construction of a grout curtain (Blaž, Perilo, Novljanska Žrnovnica, Robinzon). A partly successful grout curtain has been constructed only in the case of the Novljanska Žrnovnica Spring zone, where, in combination with strictly and continuously controlled water pumping, it presents successful spring protection. No other grout curtains have yet been built at any of the other springs.

The most efficient measure for freshwater pumping is the abstraction of water in the karst massif away from the zone of contamination (South Istria, Martinšćica, Perilo and Slano). In this case, water abstraction must be carefully controlled to maintain the equilibrium between freshwater and seawater. One substantial prerequisite is a detailed knowledge of the hydrogeological and hydraulic characteristics which govern the seawater intrusion. In the case of abstracting water from aquifers, the main problem is overexploitation. Agricultural development, which is planned to be intensified, also presents potential dangers. In the case of coastal aquifer overexploitation, the contact zone between sea and freshwater will be moved deeper into the karst massif, resulting in new karst groundwater pollution.

CONCLUSION

Croatia belongs to the group of countries with a large proportion of coastal karst aquifer exploitation. However, seawater intrusion makes large quantities of this water unsuitable for water supply, especially during the hot summer season. For the further development of these coastal areas, it is very important to protect their springs and aquifers from seawater intrusion.

In recent practice many of the karst springs which are potentially useful for water supply were investigated. By monitoring and studying hydrological, hydrogeological, geological and morphological relationships using different parameters (discharge, salinity in the spring and in piezometers, groundwater and spring water levels, dimensions of conduits, geological layers and their characteristics, etc.), detailed hypotheses of the seawater intrusion mechanisms were developed.

Generally, the problem of karst spring protection from seawater intrusion is very complex, invasive technical measures are very expensive, and at the same time their success is uncertain. A very common solution is water abstraction from the karst aquifer with controlled interception, i.e. controlling the unstable equilibrium of fresh groundwater and seawater. It should be noted that the construction of grout curtains in Croatian coastal karst areas is usually avoided. It is a very expensive technical measure in the karst environment, and at the same time its efficiency is problematic. An additional complication is the fact that, in many cases, where the seawater intrusion occurs in very deep layers, the grout curtain must be deeper than 100 m.

A universal solution for the coastal karst spring protection of seawater intrusion does not exist. The hydrological and hydrogeological functioning of each spring is unique. The efficient exploitation and protection of coastal karst aquifers open to seawater intrusion is a complex task, which needs a high level of knowledge about aquifer functioning, as well as of the unstable equilibrium of freshwater and seawater. This overview of eight karst springs along the Croatian Adriatic Sea coast shows that the most applied measure is controlled interception farther inland from the spring. This does not mean it is always the best solution. Better knowledge of the springs' functioning would result in better solutions for their protection. Improved coastal karst aquifer management-based on more complex knowledge of freshwater and salt water dynamics in vulnerable parts of these aquifers, should result in increases in the available quantities of drinking water.

REFERENCES

Arfib, B. & de Marsily, G. (2004) Modelling the salinity of an inland coastal brackish karstic spring with a conduit-matrix model. *Water Resour. Res.* **40**, W11506, doi:10.1029/2004WR003147.

Blavoux, B., Gilli, E. & Rousset, C. (2004) Watershed and origin of the salinity of the karstic submarine spring Port-Miou. *C. R. Geoscience* **336**, 523–533.

Biondić, B., Biondić, R. & Kapelj, S. (2005) The sea water influence on karstic aquifers in Croatia. In: *Ground Water Management of Coastal Karstic Aquifers.* Final report, COST Action 621 (ed. by L. Tulipano), 303–311. Office for Official Publications of the European Communities, Luxemburg.

Bonacci, O. (1995) Brackish karst spring Pantan. *Acta Carsologica* **XXIV**, 97–107.

Bonacci, O. & Roje-Bonacci, T. (1997) Sea water intrusion in coastal karst springs: example of the Blaž Spring. *Hydrol. Sci. J.* **42**(1), 89–100.

Bonacci, O. & Roje-Bonacci, T. (2000) Heterogeneity of hydrological and hydrogeological parameters in karst: examples from Dinaric karst. *Hydrol. Processes* **14**(14), 2423–2438.

Bonacci, O., Fritz F. & Denić, V. (1995) Hydrogeology of Slanac spring, Croatia. *Hydrogeol. J.* **3**(3), 31–40.

Breznik, M. (1998) *Storage Reservoirs and Deep Wells in Karst Regions.* A. A. Balkema, Rotterdam, The Netherlands.

COST Action 621 (2004) *The Main Coastal Karstic Aquifers of Southern Europe: A Contribution by Members of the COST-621 Action "Groundwater Management of Coastal Karstic Aquifers"* (ed. by J. M. Calaforra) (EUR 20911), Office for Official Publications of the European Communities, Luxemburg.

Fritz, F. (1994) On the appearance of a brackish spring 30 m above sea level near Trogir (southern Croatia). *Geologia Croatica* **47**(2), 215–220.

Guhl, F., Pulido-Bosch, A., Pulido-Leboeuf, P., Gisbert, J., Sanchez-Martos, F. & Vallejos, A. (2006) Geometry and dynamics of the freshwater–seawater interface in a coastal aquifer in southeastern Spain. *Hydrol. Sci. J.* **51**(3), 543–555.

Herak, M., Bahun, S. & Magdalenić, A. (1969) Pozitivni i negativni utjecaji na razvoj krša u Hrvatskoj. *Krš Jugoslavije* **6**, 45–71 (in Croatian).

Lambrakis, N., Andreou, A. S., Polydoropoulos, P. & Georgopoulos, E. (2000) Nonlinear analysis and forecasting of a brackish karstic spring. *Water Resour. Res.* **36**(4), 875–884.

Maramathas, A., Maroulis, Z. & Marinos-Kouris, D. (2003) Brackish karstic springs model: application to Almyros spring in Crete. *Ground Water* **41**(5), 608–619.

Mijatović, B. F. (1984) Problems of sea water intrusion into aquifers of the coastal Dinaric Karst. In: *Hydrogeology of the Dinaric Karst* (ed. by G. Castany, E. Groba Castany, E. Groba & E. Romijn), 115–142. International Contributions to Hydrogeology, AIH 4, Hannover, Germany.

Pulido-Bosch, A., Vallejos, A., Pulido-Leboeuf, P., Molina, L. & Calaforra, J. M. (2005) Some considerations about karst coastal aquifers, on the example of two Andalusian cases. In: *Ground Water Management of Coastal Karstic Aquifers.* Final report. COST Action 621 (ed. by L. Tulipano), 271–281. Office for Official Publications of the European Communities, Luxemburg.