Journal of Hydrology (2007) **343**, 29–42

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

An assessment of hydrogeological parameters on the karstic island of Dugi Otok, Croatia

Josip Terzić [a],*, Franjo Šumanovac [b], Renato Buljan [a]

[a] *Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia*
[b] *Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia*

Received 14 August 2006; received in revised form 1 June 2007; accepted 14 June 2007

KEYWORDS
Island;
Karst hydrology;
Pumping tests;
Geophysical surveys;
Salt-water intrusion;
Hydraulic conductivity

Summary Extensive explorations have been performed in the northern part of the island of Dugi Otok in the Adriatic Sea (Croatia) with the purpose of extraction of fresh and/or brackish water. The island is predominantly composed of karstified carbonate rocks of the Cretaceous age. The explorations included geological and hydrogeological mapping of the area, geophysical surveys (by means of the geoelectric tomography method, electrical resistivity sounding, and surface seismic refraction), exploratory core drilling, hydrochemical *in situ* and laboratory explorations, and the pumping test with the calculation of rock mass parameters. Based on the obtained results, it was concluded that it is possible to exploit the groundwater with a pumping quantity of 5 l/s without intrusion of salt water into the fresh-water lens. Choosing a pumping regime based on the parameters of the aquifer (rock mass hydraulic conductivity order of magnitude 10^{-4}–10^{-6} m/s), and knowing the parameters of the well, as well as the tidal efficiency, should reduce the possibility of intrusion to the minimum. Because of the systematic quality of the performed explorations and obtained results, the island of Dugi Otok can serve as a typical example for such kinds of exploration works on other karstic islands. Hydrogeological composition behaves partly according to Ghyben–Herzberg's law, but because of the nature of the karstic hydrogeological system, such a statement needs to be accepted approximately because of the highly complicated relationships.

Introduction

Dugi Otok (114.44 km^2) is the seventh largest of the Adriatic islands (Starc et al., 1997) and belongs to the group of northern Dalmatian islands. It is situated in the middle of the Adriatic Sea (Fig. 1). In the investigated area, the main limitation is that the island is only 2 km wide. The morphology is typically karstic. There is a field, or karst polje, covered by Quaternary layers in the northern part. There is a ridge (elevation 159 m) toward the south, composed of weathered karst limestone. Geological structures are

* Corresponding author. Tel.: +385 16160814; fax: +385 16144713.
E-mail address: terzic@hgi-cgs.hr (J. Terzić).

0022-1694/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2007.06.008

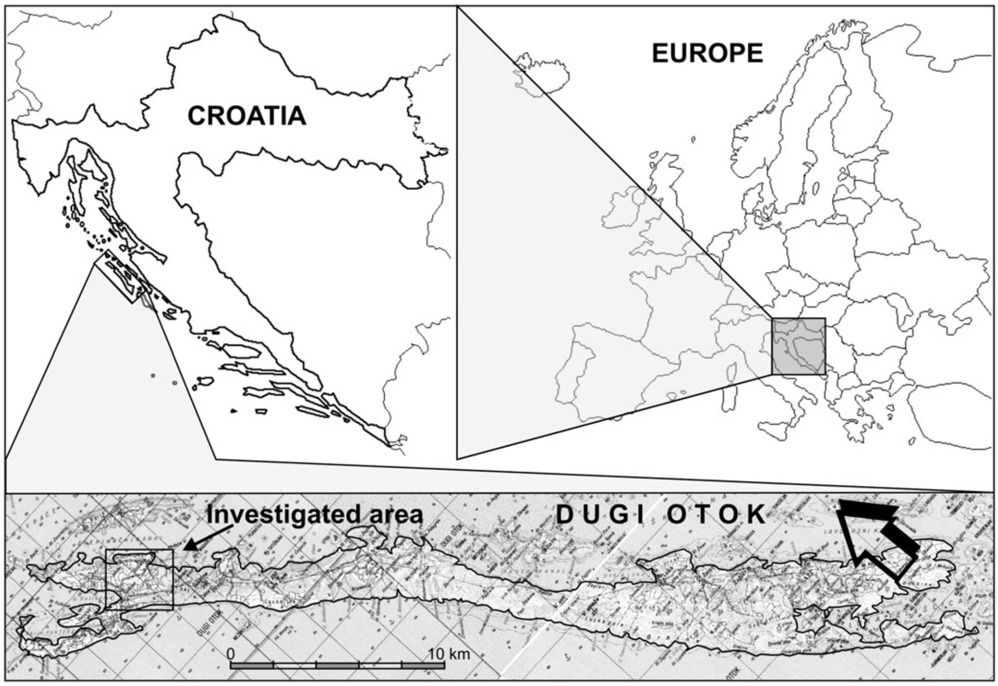

Figure 1 Location of the investigated terrain on the island of Dugi Otok in Croatia.

compressed and the rocks are reverse faulted. The strike of the geological structures is NW—SE. This direction is typical for this part of the karst terrain and it is often called ''dinaric'' after the typical location of the dinaric karst — the Dinara Mountain. Dinaric karst is characterized by very deep and irregular karstification strongly influenced by tectonics, compression, reverse faults, and overthrusting structures. The structures are additionally neotectonically disturbed, because of the change in stress direction from approximately NE—SW to N—S. The dinaric karst is a well-known ''*locus typicus*'' and many internationally accepted terms in karst hydrogeology originate from the dinaric karst area.

In a system whose size and type correspond to those of the Božava area (Fig. 2) on Dugi Otok (where neither concentrated springing nor the presence of channel flows have been observed), hydraulic parameters have been calculated based on pumping test data. Such a calculation is appropriate to local scale of investigation. Improved parameterization of an aquifer, however, leads to a better understanding of the hydrogeological system (Sauter, 1992; White, 2002; Terzić, 2004a,b; Urumović, 2000, 2003). Here, consideration is primarily given to hydraulic conductivity, tidal efficiency, and transmissivity as parameters of the aquifer. Estimation of certain well parameters, the turbulent and laminar flow ratios, and hydrochemical and geophysical parameters corroborate the discussion and conclusions.

The hydrogeology of carbonate and specially karstified islands is very complicated, as described on different terrains throughout the world (De Breuck, 1991; Jones and Banner, 2003; Vacher and Quinn, 2004; Schneider and Kruse, 2006). Basic features shared by all karst terrains include a heterogeneous environment, sensitiveness to pollution, hard to model, and influenced by seawater. Karst terrains in Croatia are distinct, because they are mountainous terrains in which, because of structural compression, reverse faulting, and considerable karstification depths, there is a prevalence of preferential flow zones and deep syphon flows

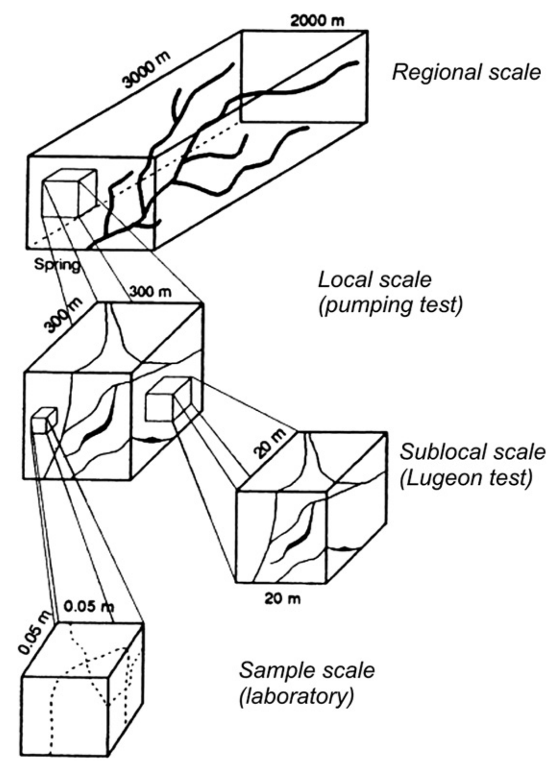

Figure 2 Research scale and suggested methods for determination of hydraulic parameters in karstified systems (Sauter, 1992).

of groundwater. The main differences between Dinaric karst and Pleistocene coral reef karst described elsewhere are in porosity, infiltration, and the significance of tectonics. Coral reef limestones have a primary and secondary porosity averaging 45%, and recharge 20% of yearly precipitation (Jones et al., 2000; Jones, 2002; Jones and Banner, 2003). The Dinaric karst terrain in Croatia is mostly built of Cretaceous and Paleogene carbonates. The karst from previous karstification phases is either eroded or infilled and has practically no hydrogeological significance. Tectonic fault and fracture zones form preferential flow directions. There is practically no primary porosity. Average secondary porosity is only 3—5%. Deep underground siphons in the preferential flow paths drain groundwater from the mainland karst, but on the islands these paths have been submerged by the Quaternary sea-level rise after glaciations (Šegota, 1982; Pirazzoli, 2005) of about 100 m. Of greatest hydrogeological importance are the Quaternary karstifications, epikarst zones, and fracture zones. In such terrain, with only a little vegetation and almost no soil cover, infiltration is fairly high. Because there is no relevant data, it is reasonable to presume an average infiltration of about 40% of total rainfall. Average annual precipitation is 900 mm year^{-1} (Terzić, 2006). In the Božava area, the infiltration cannot be considered as diffuse outside the polje. It can be described as discrete, although there are no ponors. It occurs through open fractures, and is scattered all over the terrain. Such circumstances lead to a relatively short mean residence time of groundwater in the karst underground. The results of isotope studies made for the nearby Kvarner region indicated a mean residence time between 5 and 10 years (Hertelendi et al., 1995), which is in accordance with the mean residence time in coral reef islands (Jones et al., 2000).

The investigations described here were initiated in 2000. Their aim was to supply part of the island with water by means of fresh water or desalinated brackish water. Because of the considerable distance of the island from the mainland, no water supply by underwater pipelines is planned at present. As the island is relatively narrow (2 km), it seemed unlikely to expect extraction of all the fresh water in its karstic underground reservoir to occur at one place. By geological and hydrogeological understanding of the terrain, the promising areas have been identified. In these areas, detailed hydrogeological mapping, geophysical surveys, exploratory core drilling, piezometer construction, *in situ* and laboratory hydrochemical analyses, and pumping tests have been performed. At the end of these investigations, it was concluded that it was possible to pump a quantity of about 5 l/s of groundwater without desalination, and a larger quantity of water with a determined grade of desalination. In addition, numerous data were obtained, the detailed scientific analysis of which leads to a relatively high level of understanding of the hydrogeological functioning of the northern part of the island of Dugi Otok.

Six exploratory boreholes were drilled with different results. In two of them, it was possible to collect the karst groundwater, which makes the whole project successful in practical terms, because there is enough water to assure water supply to the islanders, as well as for all economic activities, amongst which tourism is the most important. Exploitation of the groundwater for water supply began in the summer of 2006.

Geological setting

Three units of differing water permeability were separated by mapping the terrain (Fig. 3). Two of them were built of carbonate rocks: dolomites ($K_{1,2}$) and limestones ($K_2^{1,2}$ and $K_1^{3,4}$); the third was a Quaternary mixture of clay, silt, and rock fragments filling the morphological karst polje depression. The structure was characterized by reverse faulting and predominantly dextral shear faults. The dolomites were situated between two reverse faults, and, because of decreased karstification, they act as a barrier and lessen considerably the influence of the sea on groundwater from the SW direction. The karst polje has a similar function on the NE part of the investigated terrain, because in the area around the karst polje, there is a limestone rock mass, and, although weathered and karstified, it is filled with fine-grained material and has considerably lower permeability. The thickness of the Quaternary deposits in the polje is up to 12 m. The boreholes are placed in the area around the polje and toward the main reverse fault. This part of the terrain is composed of karstified limestone rocks and is protected on both sides from the direct incursion of the sea, which means that the spatial arrangement of the geological units contributes considerably to the formation of the aquifer.

Two local sites were chosen for groundwater capture by the boreholes. The first one was the area of the karst polje with its immediate surroundings, and the second one was the area between the two described barriers. It was found out that the karst polje was a place of very low permeability, and although there was no considerable increase in salinity, there was no possibility of extracting significant quantities of water by boreholes. The karstified limestone area toward the SW of the field proved to be a more convenient hydrogeological terrain.

Geophysical surveys

General

The Dugi Otok karst areas are a very difficult environment for geophysical and any other exploration, mainly, because of high surface inhomogeneities and uneven lithological boundaries. The karst phenomena, such as crevices, bays, and depressions filled with terra rossa, are characterized by low resistivities and seismic velocities, but also by very strong lateral variations, relative to the compact carbonate rocks characterized by high resistivities and high seismic velocities. This situation generates a very high level of geophysical noise. For these reasons, geophysical exploration should include a variety of methods.

The main goal of the geophysical investigation was to uncover fault and fracture zones, which are usually the main aquifers in karst areas, as well as the lithological setting. Three geophysical methods were applied: electrical sounding, surface electrical tomography, and seismic refraction. Šumanovac et al. (2003) established the geophysical investigation procedure, which was very successful and has been used in many studies of small Croatian islands.

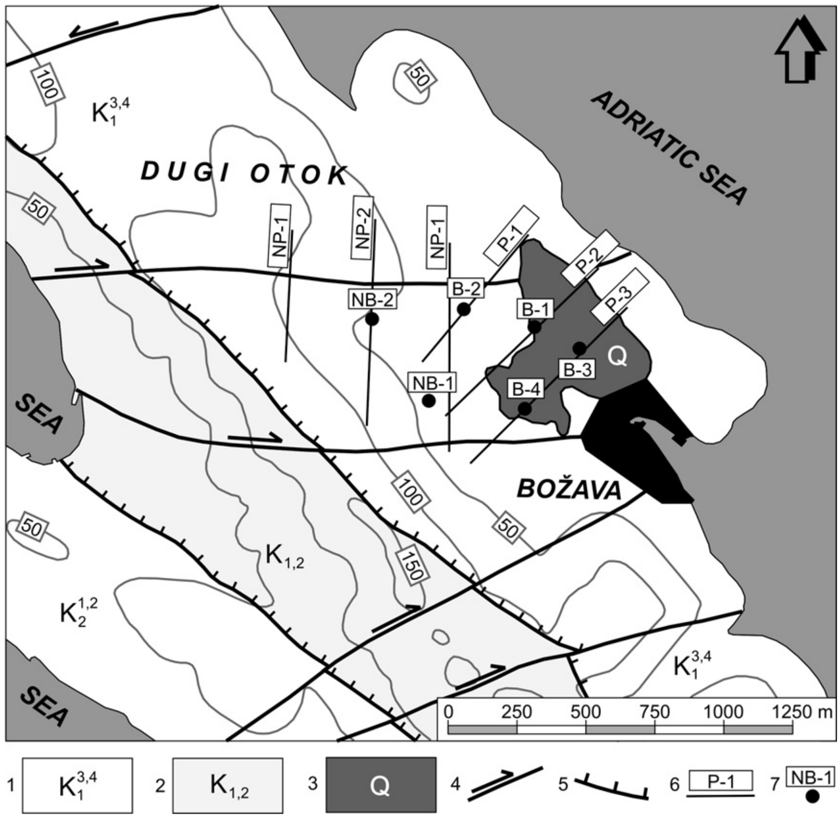

Figure 3 Schematic hydrogeological map of the investigated part of the island of Dugi Otok with geophysical profile and borehole locations. 1-permeable karstified limestone; 2-dolomites, lower permeability; 3-quaternary deposits, karst polje; 4-horizontal fault; 5-reverse fault; 6-geophysical profile; 7-borehole.

Seismic reflection methods were not used, because experience has shown that this technique seldom gives satisfactory results in karst areas, especially for shallow targets. Only weak reflections can be expected in carbonate rocks, due to uneven reflectors and high levels of noise as the refraction energy is dominantly registered. (High-resolution seismic reflection can give better results for targets of deeper than 100 m, where poor resolution of electrical methods can be expected. At these depths, contacts between compact and fractured carbonates, between carbonates and flysh layers, and the position of fracture and fault zones can be mapped with satisfactory precision (Šumanovac and Weisser, 2001).)

Several electrical soundings revealed the general lithological setting at the targeted zone, and enabled the definition of the optimum arrangement of 2D electrical tomography profiles. Seismic refraction profiles were then run on the parts of the electrical profiles, where lower resistivities pointed to fractured zones, for the purpose of precise definition of narrow fractured zones.

Data acquisition and processing

A Schlumberger array was applied for electrical sounding measurements with maximal half-distances of 600 m depending on the target depth. Two-dimensional electrical tomography measurements were carried out using the Wenner array with a unit electrode spacing of 10 m; so that 60—80 electrodes were used, depending on the profile length. Target depths for inverse resistivity models were 50—70 m. The measured data (resistivity pseudosections) were processed using a 2D inverse modeling software applying the Loke and Barker inversion method (Loke and Barker, 1996).

Refraction P-wave data were acquired using a 12-channel unit on profiles with geophone distances of 5 m, for a spread length of 55 m. The seismic source was a sledgehammer striking a steel plate placed on the surface at seven shots per spread. A seismic refraction analysis system was used to complete the data processing and interpretation, which is based on the generalized reciprocal method (Palmer, 1981).

Geophysical results and discussion

The general resistivity model, obtained through electrical soundings and electrical tomographic measurements, comprises of three zones. The lowest resistivity can be found in the shallow surface zone and is produced by the clayey deposits and carbonate fragments with clay. The highest resistivities can be found below them, corresponding to varying mixes of compact limestone and carbonate rocks. At depths of 40—50 m, resistivities drop in all the profiles, and in certain profile sections very low resistivities are found. These are probably caused by the influence of seawater or brackish water, except in the Božava field where they are caused by saturated clay (with fresh or slightly brackish water); because these deposits are located below the apparent sea level.

Sharp lateral changes and low resistivity zones are clearly visible in the middle part of the profile P-2, and also at the ends of the profile NP-1 (Fig. 4). These changes are interpreted as fractured fissure zones, where water may be located. The interpreted refraction profile running along the tomographic profile P-2 is shown in Fig. 5. Three main zones have been interpreted: the soil in the polje, the weathered epikarst zone (P-wave velocities 1520—2631 m/s), and a basal refractor (3370—5064 m/s). The refractor depth ranges 2—14 m. The high velocity and depth variations in the weathered zone are characteristic of karstic terrain. The lowest seismic velocities in the basal refractor point to moderately disintegrated rocks. Narrow fractured zones were interpreted on the basis of the effects of time—distance graphs and velocity changes. Most of them are concentrated between 340 and 480 m which coincide with the zone of dramatic lateral resistivity changes. The interpreted fracture zones, which coincide with the zones of the lowest resistivities, were singled out for exploratory drilling. Similar zones were recognized near the ends of the profile NP-1, at positions 170 and 580 m. The first exploratory borehole B-1 is located in the profile of P-2, and NB-1 in the profile NP-1 (Figs. 3 and 4). Inside the boreholes, fractured limestones with partly clay-filled holes were found, and even fresh water was discovered. Other exploratory boreholes were also drilled in the low resistivity zones confirming geophysical interpretations. It can be concluded that the geophysical exploration was a basis for the positive results of hydrogeological exploration carried out under the very difficult conditions of the karst island terrains.

Boreholes and pumping tests

Exploratory boreholes

Six exploratory boreholes were drilled (Table 1; Fig. 3). Two boreholes (B-3 and B-4) did not penetrate the fractured rock mass, so the other four: B-1, B-2, NB-1, and NB-2 were used for further processing. For the pumping test in the final exploratory phase, boreholes B-1 and NB-1 were used.

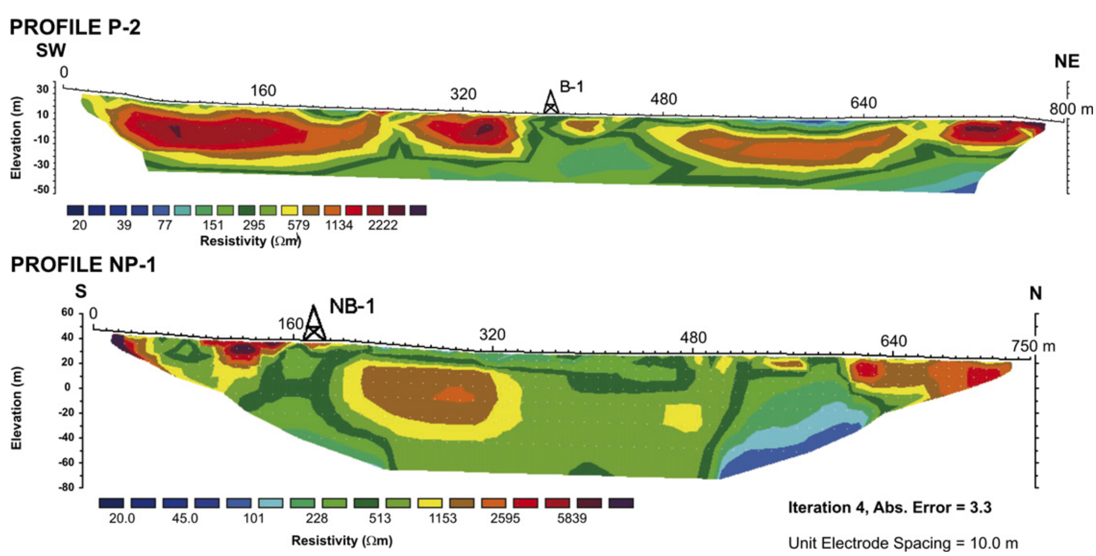

Figure 4 Results of 2D inversion of the P-2 and NP-1 resistivity profiles in the hinterland of the Božava field. Fig. 3 shows the profile locations. Robust inversion is applied on the NP-1 profile, which is intended for cases of very high resistivity contrasts.

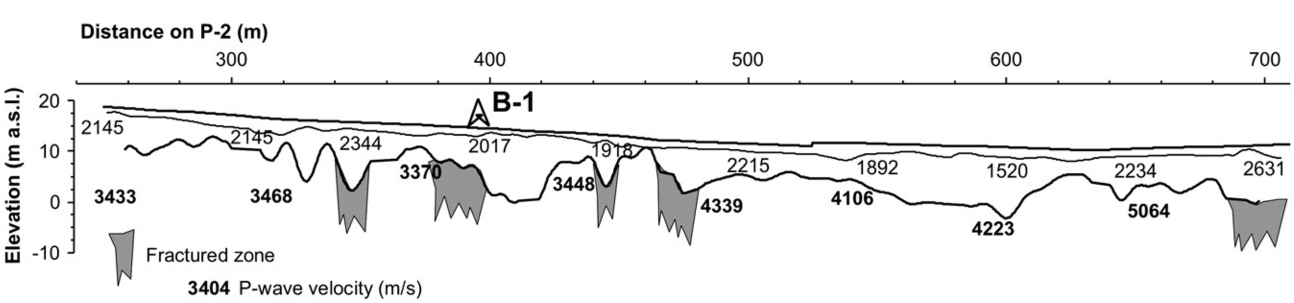

Figure 5 Interpreted seismic refraction P-wave data along the P-2 profile (location shown in Fig. 3). The inferred zones of fracturing were confirmed at several sites by exploratory drilling. The central part of the survey coincides with a strong low resistivity zone in Fig. 4.

Table 1 Exploratory boreholes in the Božava area

Borehole	*H* (m a.s.l.)	Depth (m)	Screen depth (m a.s.l.)	GWL (m a.s.l.)	Distance from the coast (m)	*Q* (l/s)	*K* (m/s)	*T* (m^2/s)	Cl (mg/l)	% Sea in sample
B-1	13.44	56	−3.56 to −38.56	0.30	506	0.74	0.0000085	0.00026	118	0.59
B-2	23.53	56	−2.97 to −29.97	0.29	807	1.00	0.0000104	0.00034	2400	12
B-3	10.00	31	No casing	–	350	–	–	–	–	–
B-4	18.93	56	−1.07 to −36.07	–	385	–	–	–	–	–
NB-1	41.26	75	−0.74 to −32.74	0.94	734	4.00	0.00016	0.0052	460	2.3
NB-2	45.91	76	0.91 to −29.09	1.54	759	0.1	–	–	282	1.41

Basic data and parameters. Locations shown in Fig. 3.

Borehole B-2 is characterized by considerable discharge (at least 1 l/s), but it is under the distinct influence of sea intrusion and the water is too salty. Borehole NB-2 has very low discharge. During the pumping test, which lasted for 10 d with several breaks, boreholes B-1 and NB-1 were pumped; B-1 with a continuous pumping quantity of 0.74 l/s and NB-1 after the step-drawdown test, the continuous pumping quantity was about 3.5 l/s. On NB-1, the step-drawdown test was performed with three pumping rates, to obtain the well parameters and to discover the share of the laminar and turbulent flow. During the pumping of the two boreholes, the levels in the other two boreholes were observed (B-2 and NB-2) every 2 h, as well as the level of the sea. There were no mutual influences observed between the boreholes, but the influence of the tide was considerable, only on observed wells.

Step-drawdown test on the NB-1 borehole

A step-drawdown test, designed for investigating wells with turbulent flow (Jacob, 1946), was performed in borehole NB-1 (Fig. 6) at three pumping rates (1.7, 2.3, and 3.3 l/s). Each quantity was pumped for 6 h, after which the rebound of the water level was measured. The well parameters (1) were defined by

- the linear loss parameter (*B*), also called the formation loss parameter; this describes the losses in the aquifer;
- the nonlinear (usually square) loss parameter (*C*); this describes the turbulent losses on the well edge, that is, the well in contact with the aquifer, which depends primarily on the well design (Driscoll, 1995).

Parameter *B* directly depends on aquifer transmissivity and storage, as well as on the pumping time and the well radius. If the flow toward the well is laminar, the pumping quantity and the drawdown are linearly related. When turbulent flow appears, the relationship is more complex and calculation of both parameters *B* and *C* is necessary to express and distinguish the two kinds of flow. Parameter *C* which denotes the turbulent losses is attributed to the ''inefficiency'' of the well (Jacob, 1946). However, it has

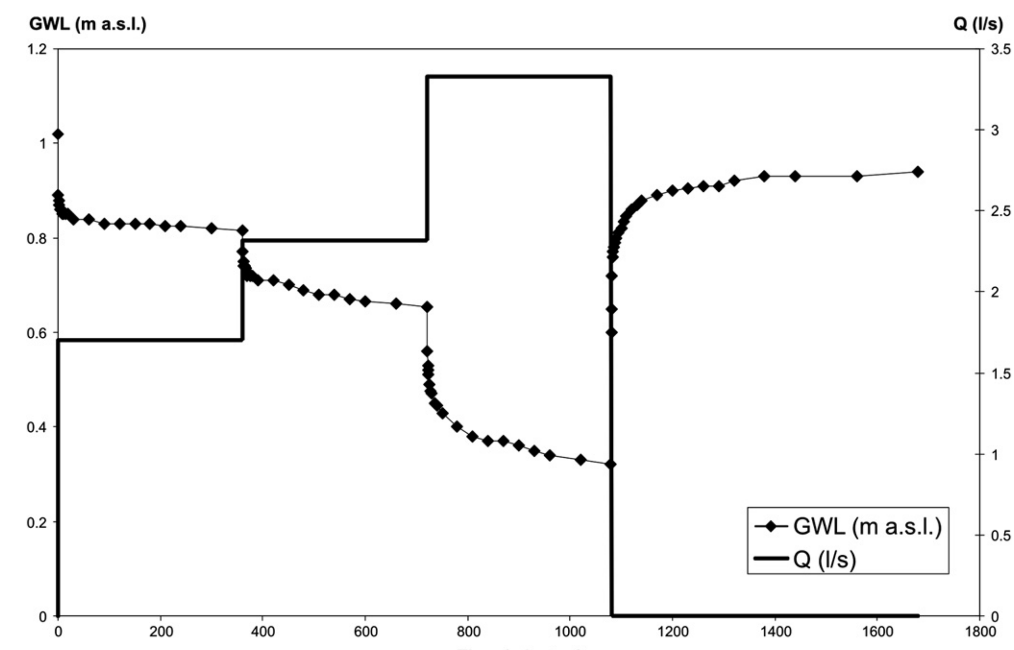

Figure 6 Step-drawdown test in borehole NB-1 (location shown in Fig. 3). Change in groundwater level for three pumping rates (6 h each) and groundwater level recovery.

often been proved in practice that parameter B can partly describe the laminar losses in the well and around it, and parameter C can partly refer to turbulent losses in the aquifer, especially in karst terrains.

The total drawdown of water level after the first pumping quantity was 0.205 m, after the second pumping quantity it was 0.365 m, and after the third it was 0.7 m (Fig. 6). After 10 h of measuring the recovery of the water level, the level came back to 8 cm below the starting level.

The total drawdown of water level in the well is expressed by

$$s = BQ + CQ^2 \tag{1}$$

where, s denotes the drawdown (m), B denotes the parameter of the linear losses (s/m^2), C is the parameter of the nonlinear losses (s^2/m^5), and Q is the pumping quantity (m^3/s).

To calculate B and C parameters, it is necessary to solve a system of equations. Each pumping rate and its drawdown represent an equation. Values for B and C in the step-drawdown Eq. (1) were determined from a graph, where (ds/dQ) is plotted against the equivalent discharge (ratio of square and linear difference between two steps of pumping rates). The linear fit obtained contains the B and C value (Driscoll, 1995; Jalludin and Razack, 2004). The calculation for the borehole NB-1 gives: $B = 22.21$ s/m^2 and $C = 54944$ s^2/m^5. The equation, $s = BQ + CQ^2$, changes to $s = 22.21Q + 54944Q^2$ for NB-1. On the basis of these parameters, it is possible to calculate the functional relation of drawdown (s) and the pumping rate (Q). Observed values fit the calculated drawdown curve (Fig. 6).

In borehole NB-1, the nonlinear losses C are much greater than the linear formation losses B. This means that if the streaming in the aquifer is predominantly laminar, considerable turbulent flows appear on contact between the well design and the aquifer. However, because streaming occurs in the karstified rock mass, a part of the turbulences is attributed to the flow in the karst aquifer. On the basis of the step-drawdown test data (Fig. 7), the relation of the laminar to total losses L_p (Driscoll, 1995) has been calculated, which is expressed as a percentage:

$$L_p = \frac{BQ}{BQ + CQ^2} \cdot 100 \tag{2}$$

It is noticeable (Fig. 7) that the high share of turbulent flow in the well NB-1 grows considerably with the increase in the pumping quantity.

Pumping test

According to the statements of numerous authors, the parametric description of hydraulic conductivity is appropriate to a certain degree in karstified rock mass (Ford and Williams, 1989; Urumović, 2000, 2003; Motyka, 1998; White, 2002; Terzić, 2004a). The measured value will depend on the scale of observation. For a local scale, as shown in Fig. 2, a pumping test samples the zone within the fictive radius of the pumped well's influence.

The pumping of borehole B-1 was done at a pumping rate of 0.74 l/s, and NB-1 at a rate of 3.5 l/s (Fig. 7). Both boreholes were pumped for 10 d almost continuously. Disruptions and changes in the pumping rate were caused by technical problems.

In the cases considered, the most suitable method was that of well hydraulic parameter calculation with the successive series of stationary states (3). During the pumping quantity ''Q'', the radial flow of the groundwater toward the well appears and the parameters are determined as

$$s^* = \frac{Q}{2\pi T} \ln \frac{R_0}{r_z} \tag{3}$$

where, s^* is the equivalent drawdown, Q is the pumping rate, T is the transmissivity, R_0 is the fictive radius of the well influence, and r_z is the effective radius of the well.

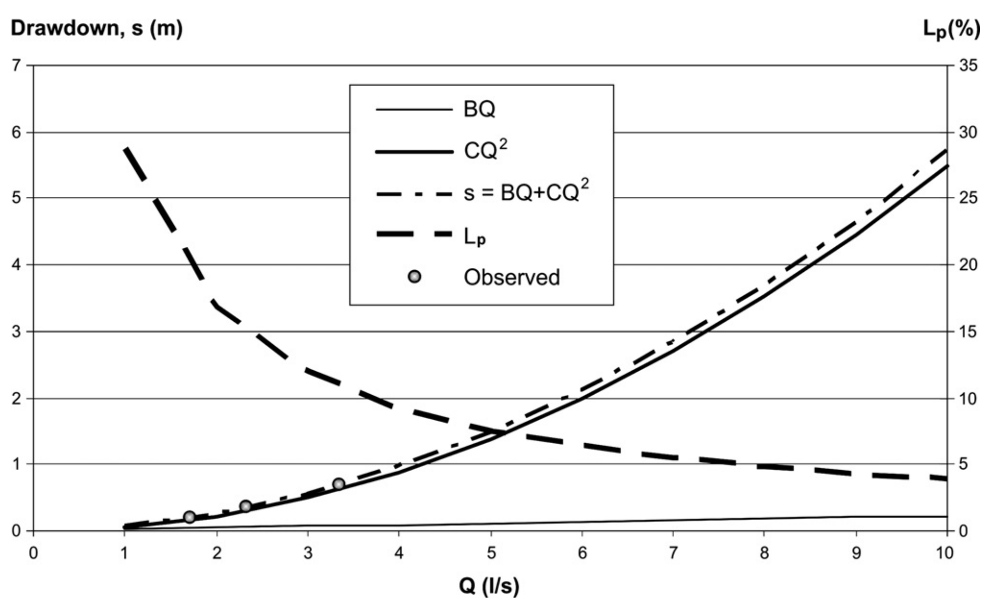

Figure 7 Diagram showing best-fit drawdown/pumping rate function ($s = f(Q)$), with the curves of laminar (BQ) and turbulent (CQ^2) losses for 6 h pumping of the well NB-1. L_p = percentage of laminar to total losses. Open circles show observed data.

This method was chosen because of its simplicity. A more precise analysis is made impossible by the natural karst conditions. The well is observed as a cylinder and the water streams perpendicular to the surface of the cylinder. In the case of the karstified rock mass, the parameters of the aquifer should be observed as approximate values, within an order of magnitude, primarily, because of the considerable presence of turbulent flow in the aquifer (Figs. 7 and 8). The sizes R_0 (the fictive radius of the well influence) and r_z (effective well radius) need to be supposed. A radius of drilling of 0.06 m can be accepted for r_z and for R_0 it is justified to take 100 m in such conditions. The impact of errors in the assumed R_0/r_z ratio is limited, because it appears within the logarithm in (3). It is also necessary to assume a thickness of the aquifer, but it has been proved justified to accept the hypothesis that hydraulic conductivity on the Adriatic karstic islands decreases with depth, and at a determined depth of some tens of meters under the current sea level, a relatively impermeable underlayer can be supposed (Terzić, 2004a). Although such an impermeable base is formed by a filling of the caves and joints, it is also probable that the rock mass is less and less karstified in the deeper layers, especially outside the zones of the preferential flows. Graphic presentations of the hydraulic conductivity division with the pumping time (Fig. 8), as well as similar experiences on some other Adriatic islands, show that this supposition is justified (Terzić, 2004a,b). The hydraulic conductivity of the rock mass (Table 1) in the area of the exploratory borehole B-1 is within values that will not significantly depart from the value 10^{-6} m/s, and in the surrounding of the exploratory borehole NB-1 within the order of magnitude of 10^{-4} m/s.

Tidal efficiency in the fresh-water lens

No hydraulic connection was noticed between the separate exploratory boreholes, and that is in accordance with the presumed fictive radius of well influence. However, during the pumping of boreholes B-1 and NB-1, oscillation of the water levels was observed in boreholes B-2 and NB-2 (Fig. 9). Sea level oscillations were also observed at a reference point on the sea coast (Fig. 9).

The tidal efficiencies or the ratios of the amplitude of inland water level fluctuations to sea level oscillations (Ferris et al., 1962; Urumović, 2003) are shown in Table 2. The delay in the borehole level oscillations relative to the changes in the sea level is roughly equal at both boreholes (B-2 and NB-2) and is about 3 h and 40 min (Table 2 and Fig. 9). There is a direct relation between tidal (or barometric) efficiency and the coefficient of storage, and therefore with transmissivity as well (Ferris et al., 1962; Urumović, 2003). However, these relations are derived from artesian aquifers, so implementation in the discussed case study with an unconfined karst aquifer would not be appropriate.

In the pumped wells, no tidal efficiency was noticed because one of them is in the polje, where there is likely to be no seawater underneath. The other one is far from the coast in an area where the fresh-water lens is in contact with the slightly brackish water of the transition zone. The tidal efficiency was restrained, because of the pumping itself. If the observation had been continuous, by data loggers, and with barometric compensations, there would be some tidal efficiency observed as well. That value is presumably too small to influence appreciably the pumping test and interpretation. For real expression of tidal efficiency, it needs to be observed in the steady state.

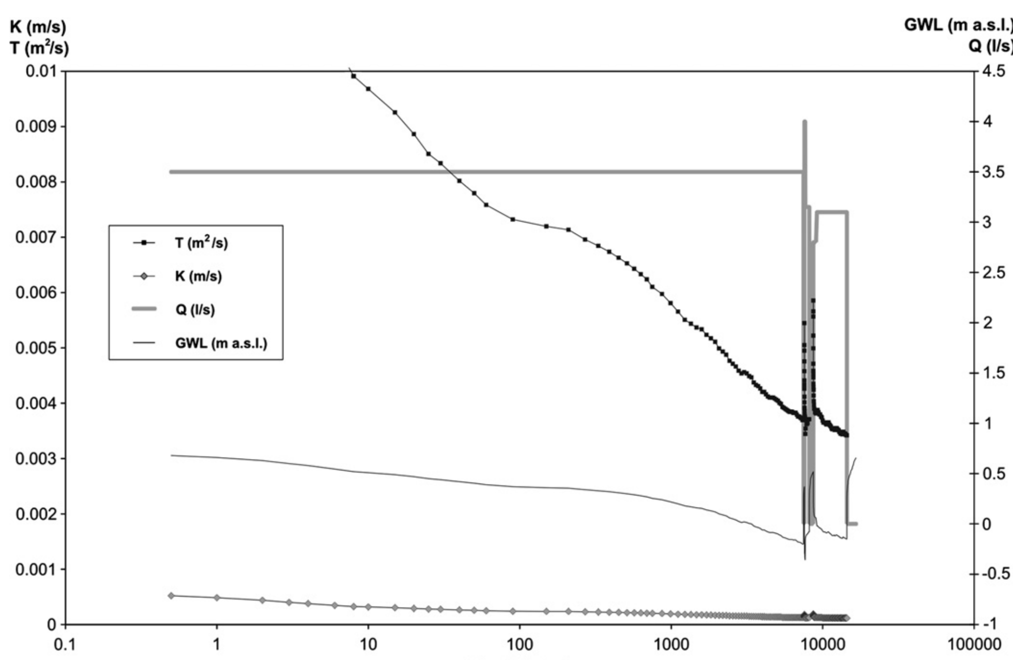

Figure 8 Continuous pumping test of borehole NB-1 with max. 3.5 l/s. The diagram shows pumping rates (raw data, all disruptions, and changes in pumping rate are shown), groundwater level, and inferred transmissivity, and hydraulic conductivity.

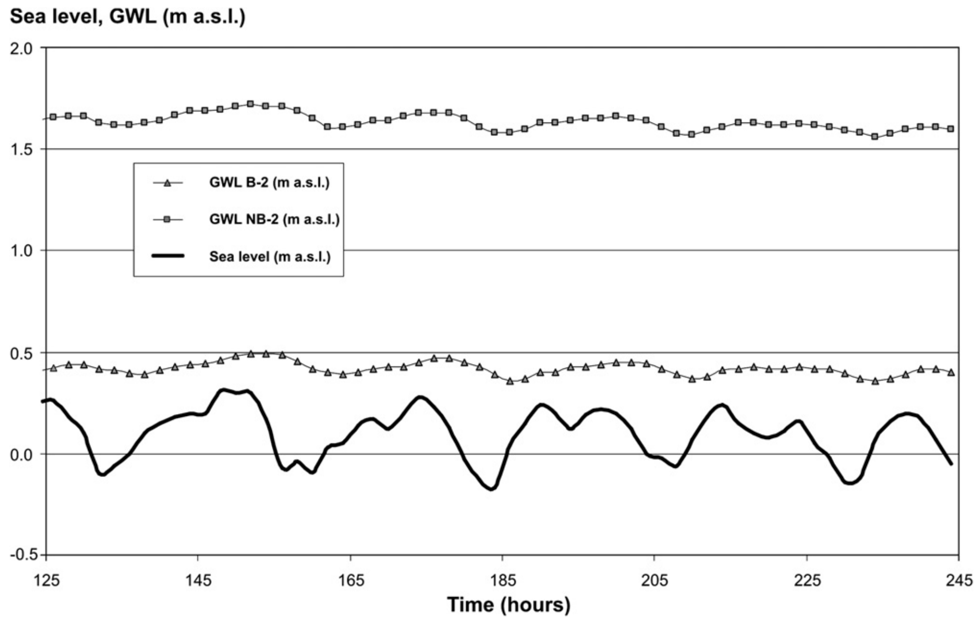

Figure 9 The oscillation ranges of the sea level and the groundwater level in observed boreholes B-2 and NB-2. Locations shown in Fig. 3.

Table 2 Oscillation of the sea level and levels in the observation boreholes B-2 and NB-2 caused by tidal fluctuation

	Maximal level (m)	Minimal level (m)	Oscillation range (m)	Tidal efficiency, TE (—)	Average time delay (hh:mm)
SEA	0.31	−0.17	0.48	—	—
B-2	0.49	0.26	0.23	0.479	03:40
NB-2	1.72	1.56	0.16	0.333	03:40

Tidal efficiency amplitude and time delay are shown.

The presence of tidal responses in coastal and island aquifers and fresh-water lenses is very important in practical application–in planning the water pumping regime. For example, an interruption of pumping at higher salinity saves energy at the desalinating plant. According to the theoretical suppositions (Ghyben—Herzberg's law), because of the difference in density of the salt and the fresh water, for each meter above sea level there is about 40 m of fresh water under sea level. In a real dynamic system, it is not so, because a relatively broad transition zone of water mixing, with a gradual transition from salt to fresh water, appears because of the underground flow and the chemical mixing of fresh and sea water. Theoretically, if the water levels were lowered to below sea level during pumping, a conical rising of salt water and a salinity increase in the well would appear. But this is not always so in practice, because of groundwater dynamics and the factors of time. So, there exist coastal and island pumping sites at which the water levels fall periodically below sea level for a determined time without an excessive increase in salinity. Observing all the data of B-1 (a drawdown of about 9 m below sea level, no changes in electrolytic conductivity, no influence of tide), it is justifiable to suppose that in the local surficial aquifer under the karst polje, there is no salt water under the fresh and the brackish water. A similar phenomenon has been noticed in numerous other Adriatic karst islands (Terzić, 2004a,b), because of the considerably lower permeability of the rock mass whose discontinuities and cavities are filled with clay and silt.

Hydrochemical data

In situ electrolytic groundwater conductivities (CND) were measured as a function of depth within each borehole before and after test pumping (Fig. 10).

Data differ from borehole to borehole but the differences in chemistry before and after pumping are not significant. At boreholes B-2 and NB-2 which were not pumped, there were no significant changes. Small aberrations presumably reflect changes caused by the dynamics of the tide and by natural groundwater streaming rather than by the pumping in boreholes B-1 and NB-1. At all boreholes except borehole B-2, there was a determined increase in CND value at a depth of 26—28 m below sea level. Although the water above that depth is slightly brackish, it is possible to consider 26—28 m the top of a zone of considerable mixing of fresh and salt water. At borehole B-1, there were no changes, whereas at borehole NB-1, there were significant differences. The CND value from 13.00 to 29.00 m below sea level increased after pumping by 0.3—1.1 mS/cm, whereas, beneath that depth, CND considerably decreased. It is most plausible to explain this by the stratification of water in the borehole: before pumping, there was a concentration of very salty water at the bottom, whereas the water

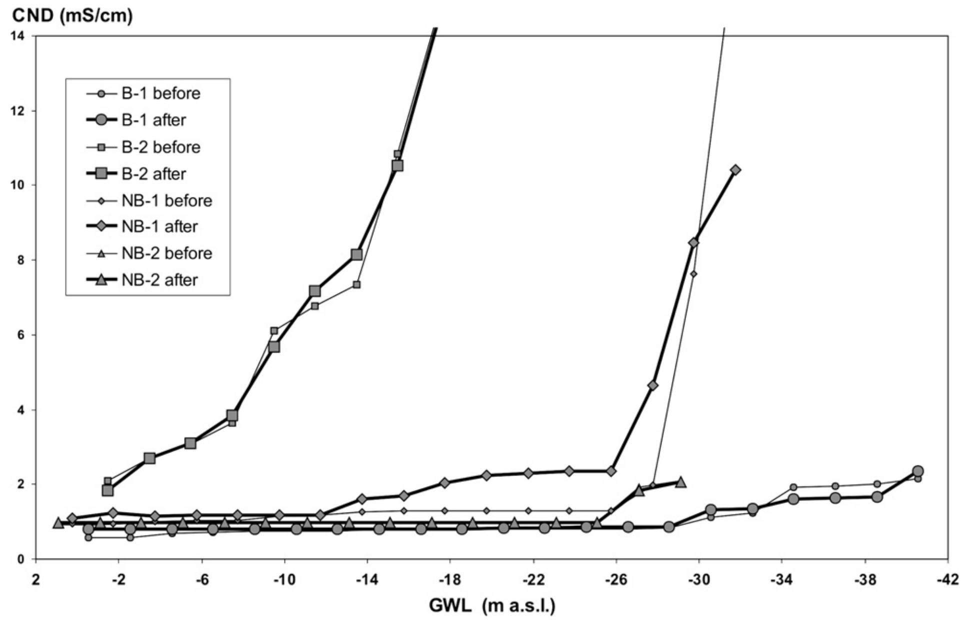

Figure 10 *In situ* measurements of the groundwater electrolytic conductivity in four boreholes before and after the pumping test. Boreholes B-1 and NB-1 were pumped, B-2 and NB-2 were only observed. Locations shown in Fig. 3.

above it was not too salty. As the water was mixed, because of the radial streaming toward the well for 10 d, there was no possibility for it to stratify in the well a day after pumping.

The CND values of the pumped water were measured during pumping (Fig. 11). The line of linear trend for each borehole was added to the CND values (Fig. 11). The linear trend of the salinity increase in borehole B-1 during pumping is inconsiderable and can be neglected. In borehole NB-1, there is an increase and there are no signs of slowing down. In borehole NB-1, the values increased from 1.38 to 1.82 mS/cm after 10 d of pumping. In spite of the increase, these end values are not excessive. During the pumping standstill for a duration of about 10 h, the quality of water improved in the sense of a decrease of CND, which was a good indicator (Fig. 11, 136—145 h). If a continuous increase in the same trend was accepted, the CND would increase to 10 mS/cm after 4807 h of continuous pumping (200 d), and to 20 mS/cm after 10362 h (432 d). Of course, such values serve only as a warning that these trends require monitoring during exploitation. On the other hand, the pumping was at the time of a hydrological minimum, which means that the

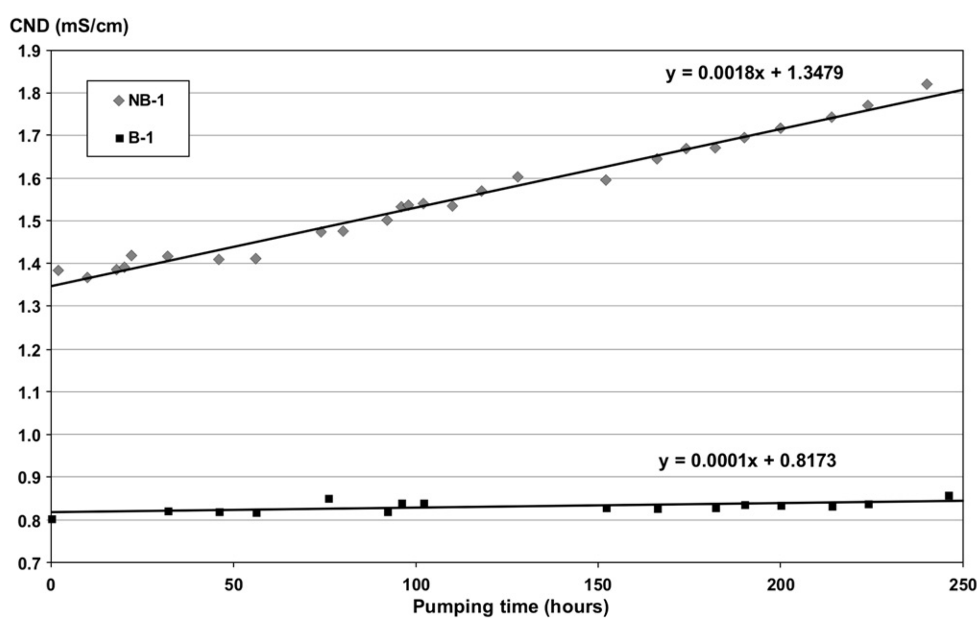

Figure 11 *In situ* electrolytic conductivity of the groundwater pumped from boreholes B-1 and NB-1 during the pumping experiment.

initial rains would moderate or overturn such trends. It will only be possible to obtain the more meaningful data during long-term exploitation. On the other hand, the notably large number of days necessary for the aquifer to become excessively salty allows the possibility of initiating exploitation, because the trend at the extreme hydrological minimum does not correspond to the trend throughout the entire hydrological year or over periods of several years. Aside from that, a correctly planned pumping regime could potentially reduce each salinity increase to negligible values.

On the basis of the laboratory water analyses taken after pumping (Table 3), a Piper's diagram was made (Fig. 12). Regarding the cations, both samples clearly belong to the calcium part of the diagram. The situation with anions is more complex and the samples are closer to mixed waters without the prevailing anion. Water from borehole B-1, after the pumping test, belongs to the calcium-carbonate facies, while water from the borehole NB-1 is closer to the calcium-chloride facies. This is the consequence of the fresh water mixing with the salt water underneath the fresh-water lens, and the influence of the sea (of the chlorides) is higher in samples from borehole NB-1. To express quantitatively the share of sea water in percentages, the relatively simple method of calculation called ''conservative mixing'' (Appelo and Postma, 1994) was used. The percentage share of sea water in these samples is 0.59% for B-1 and 2.29% for NB-1 (Table 1). These indicators show the presence of sea water beneath the whole island except under the karst polje. The low share of sea water in the sam-

Table 3 Physical parameters and basic ion composition on samples from B-1 and NB-1 boreholes taken at the end of the pumping test

Parameter	Turbidity (NTU unit)	pH (—)	Use of $KMnO_4$ (mg O_2/l)	Ammonia (mg N/l)	Chlorides (mg Cl/l)	Nitrates (mg N/l)	Nitrites (mg N/l)	CND (lab) (mS/cm)
B-1	0.5	6.9	0.4	0.02	118	6.9	0.019	1.026
NB-1	0.2	6.5	1.4	0.02	460	0.3	0.001	2.24
	CND (in situ) (mS/cm)	Alkalinity (mg $CaCO_3$/l)	Potassium (mg K/l)	Sodium (mg Na/l)	Calcium (mg Ca/l)	Magnesium (mg Mg/l)	Sulphate (mg SO_4/l)	Hydrogen-carbonate (mg HCO_3/l)
B-1	0.858	325	0.21	18.81	148.2	31.3	28.99	396.5
NB-1	1.821	475	1.52	24.12	380.4	69.8	44.2	580

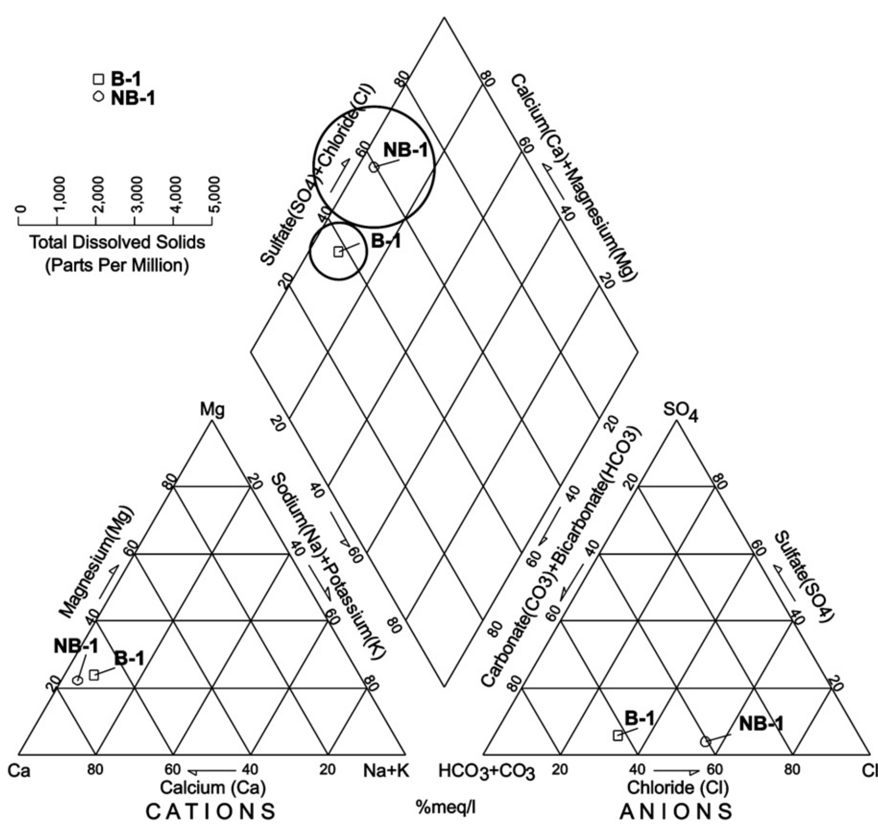

Figure 12 Presentation of the hydrogeochemical data by Piper-diagram. Samples are taken from boreholes B-1 and NB-1 at the end of the pumping test.

ple from borehole B-1 is the consequence of sea water spray brought by wind, which is subsequently carried underground by rainfall infiltration. The experience from other Adriatic islands (Terzić, 2006) indicates that a small proportion (up to 5) mg/l of chlorides could be in the rainwater itself. All over the terrain, winds could blow a spatter of seawater. Outside certain local extremes on wind-exposed slopes, this can raise chloride concentrations up to 30–40 mg/l. All values higher than these are a consequence of underground mixing. Groundwater in B-1 and especially NB-1 borehole is in the upper part of the transition zone (460 mg/l Cl), and that is proved by the pumping test (salinity increase, Fig. 10). These are different circumstances from those indicated in the case studies of coral reef islands (Jones et al., 2000).

Concluding discussion

Installation of two wells in the Božava area is the result of extensive explorations which were systematically performed over several years. Because of the application of the methods presented, it has been possible to identify optimal sites for water supply wells in such a sensitive karst system and complex hydrogeological circumstances.

Although the area of Božava is composed of a karstified rock mass, the calculation of the hydraulic parameters from local pumping tests is justified if the results are regarded as approximate by an order of magnitude. The results of the pumping tests, both continuous and by step, can be explained in the context of the local geology. The hydraulic conductivity from 10^{-4} to 10^{-6} m/s corresponds to the karstified limestone rock mass which was mapped on the island (Fig. 3). Lower water permeability in the area of the karst polje is the result of the filling of the joint apertures and cavities with clastic fine-grained material of the field. The rock mass around borehole NB-1 shows higher water permeability (hydraulic conductivity of 10^{-4} m/s), and the suitable location of the borehole in the central part of the island between the two relative barriers – dolomites on the SW and the karst polje on the NE, allows for less salty water.

The step-drawdown test on the same borehole points out clearly the prevalence of the turbulent flow (Fig. 7). Part of these turbulent flows is attributed to the well design, but a part belongs most probably to the streaming in the fractured and karstified rock mass. Besides the calculation of the hydraulic parameters, the pumping tests have pointed to the fact that the water-bearing rock mass is less and less permeable in the deeper parts, which was shown in some recent studies of similar terrains (Terzić, 2004a,b). On the local scale of study (Fig. 2), it appears justifiable to presume a relatively impermeable underlayer at the determined depth.

The observation of tidal efficiency points to the fact that fresh-water lens is hydrogeologically linked to sea water with a gradual changeover from almost completely fresh water to completely salt water (a transition or mixing zone). Parts of the fresh water/salt water mixing zone were imaged by, *in situ* hydrochemical measurements. A zone of considerable mixing of fresh and salt water lies at a depth of about 27 m below sea level and it is noticed as a ''hydrochemical discontinuity'', that is a relatively quick jump in salinity increase (Fig. 10). Although, there are only a few boreholes, the fresh-water lens is partially mapped in 2D by electrical tomography (Fig. 4). This lens is actually the underground transition zone between the fresh and brackish water, while the seawater forms a wedge toward the middle of the island. This wedge intrudes deep into the island through fracture and fault zones. So the fresh-water lens is very heterogeneous, discontinuous, and difficult to model. Under the polje, there is most probably no seawater. These circumstances call for a certain precaution during long-term extraction.

After 10 d of pumping at wells NB-1 and B-1, the water was not excessively salty and could be used for drinking practically without desalination. The trend of increase in salinity during pumping (Fig. 11) is a warning that it is necessary to observe every change and to accommodate the pumping regime to hydrological circumstances. The percentage share of sea in the water samples after pumping is relatively low (Table 1). Given the fact that the pumping was performed in October 2004, after almost 6 months without any precipitation on the study site, the trend of increase in salinity is expected to represent an extreme case and does not represent too great a limitation. On the other hand, this conclusion applies only to the specific pumping rate that was used (below 4 l/s). Higher pumping rates could cause a significant increase in seawater intrusion, and that can only be estimated by a pumping test with higher rates. By the step-drawdown test, only the approximate drawdown for higher pumping quantities was calculated, and not the quality deterioration. Fortunately, current water demand on the island is much below the used rates.

In karstic terrains, geophysical data can be very important (Šumanovac and Weisser, 2001). It is on the basis of these data that the exploratory boreholes in this study were located. The basic data regarding lithological and tectonic relationships were acquired through 2-D electrical tomography. Small zones of lower resistivities were confirmed as sites of rock fracture. These sites were further mapped using seismic refraction. In the area of Božava, the interpreted resistivities seem to be strongly influenced by groundwater salinity. In the areas where the influence of sea water is dominant, resistivities are lower than 200 Ω m. In the zone of brackish and fresh water, they range from 200 to 1000 Ω m. The dry and compact rock mass shows higher resistivity. The zones of low resistivity extend in some areas upward to the ground surface, especially in areas where low resistivities are associated with saturated clastic sediment (clay and silt) or fractured fault zones. From the hydrogeological point of view, low resistivity zones are promising, as they point to fractured carbonates with water. But unfortunately, fractures may be filled with clay, which also decreases the measured resistivities. This means that one cannot distinguish permeable faults with water from impermeable clayey faults on the basis of a determined low-resistivity zone. One of the six boreholes (Table 1) did not hit a fracture zone at all (NB-2). Two more were ''negative'' although they were in fracture zones: these zones were impermeable, filled with fine-grained material and clay which gave a wrong geophysical signal (B-3, B-4). One borehole was negative because the groundwater was too salty (B-2), and two were positive and these two are the ones mostly discussed in the article (B-1, NB-1).

It should be noted that throughout the study area, fracture zones were mapped at the surface. The geophysical methods provide significant help by delineating these zones in the subsurface, as well as establishing the overall salinity patterns of the groundwater.

The hydrogeological functioning of portions of the karst island system has been sufficiently well determined to lead to the extraction of groundwater (5 l/s). This quantity is adequate for the needs of the local inhabitants for the moment. The foundations have been set for further study, for a possible increase of the pumping quantities and for water protection. The adjustment of the pumping regime will determine the effectiveness of the water supply. The possibility of collecting additional quantities of water remains open, when it becomes necessary, especially in the event of building the equipment for desalination. Knowledge of the magnitude and the time delay of tidal efficiency may contribute to an optimized pumping regime. Pumping at higher levels (as a consequence of high sea tide) may increase the salinity of the pumped water. If the brackish water is pumped for desalination, knowledge of the effect of the tide could lead to energy savings of the desalinator.

The exploration project in the area of Božava, because of its systematic approach and the results obtained, can serve as a typical example for exploration on all such karstic islands, as well as on all other terrains with similar hydrogeological circumstances. The description of aquifer parameters even in karst conditions is justified to a certain extent. The main issue regarding this is that a researcher needs to be aware of scale (Fig. 2) and to choose the methodology accordingly. The presented case study is recognized as being of the ''local scale''. On a larger scale, the regional one, this kind of parametric description is doubtful, because most of the groundwater may be drained through conduits and siphons. On a smaller scale, the sub-local, this methodology is also justified, although hydraulic parameters could be more precise if Lugeon's water pressure test was done (Cha et al., 2006). The parameters estimated in the Božava area by: (1) the pumping test, (2) geophysical surveys, and (3) hydrochemical analysis increase the level of understanding of the complex environment. A similar methodology could be applied on every karstic coastal aquifer, because of the systematic research which yielded positive results (in a practical sense). Of course, natural conditions, inherent differences, and particularities must be taken into consideration when planning a research, as well as many other practical reasons.

Acknowledgements

The authors are grateful to the research investors ''Croatian waters''. Also, they extend their gratitude to all the colleagues who have taken part in designing in the Božava area on Dugi Otok and the numerous data used from their reports. They are arranged alphabetically as follows: Brajković, Z., Capar, A., Graovac, G., Ivanović, S., Ivičić, D., Jeić, D., Kamenarić, M., Kapelj, S., Marković, T., Munda, B., Panežić, D. and Pekaš, Ž. Partially, the research performed was carried out in the framework of the research projects of the Croatian Ministry of Education, Science and Sports: ''Basic hydrogeological map of Croatia'' and ''Geophysical explorations of aquifer systems, environment and energy resources''.

References

Appelo, C.A.J., Postma, D., 1994. Geochemistry Groundwater and Pollution. AA Balkema, Rotterdam, Brookfield, ISBN 90-5410-105-9, 536p.

Cha, S., Lee, J., Lee, D., Amantini, E., Lee, K., 2006. Engineering characterization of hydraulic properties in a pilot rock cavern for underground LNG storage. Engineering Geology 84, 229—243. doi:10.1016/j.enggeo.2006.02.001.

De Breuck, W. (Ed.), 1991. Hydrogeology of Salt Water Intrusion. A Selection of SWIM Papers. International Association of Hydrogeologists. ISBN 3-922705-92-8. Verlag Heinz Heise GmbH & Co KG. Hannover, Germany, 422p.

Driscoll, F.G., 1995. Groundwater and Wells. Johnson screens, St. Paul, Minnesota, ISBN 0-9616456-0-1, 1089p.

Ferris, J.G., Knowles, D.B., Brown, R.H., Stallman, R.W. 1962. Theory of Aquifer Tests. Groundwater hydraulics. US Geological Survey water-supply paper 1536-E. 174p.

Ford, D., Williams, P., 1989. Karst geomorphology and Hydrology. Chapman & Hall, London, 601p..

Hertelendi, E., Svingor, E., Rank, D., Futo, I. 1995. Isotope investigation of Lake Vrana and springs in the Kvarner Area. In: First Croatian geological congress, Opatija 18—21.10.1995; Proceedings, Zagreb, vol. 1, pp. 89—94.

Jacob, C.E., 1946. Drawdown test to determine effective radius of artesian well. Translational, American Society Civil Engineers 112, 1047—1070.

Jalludin, M., Razack, M., 2004. Assessment of hydraulic properties of sedimentary and volcanic aquifer systems under arid conditions in the Republic of Djibouti (Horn of Africa). Hydrogeology Journal 12, 159—170. doi:10.1007/s10040-003-0312-2.

Jones, I.C. 2002. Geochemical evolution of groundwater in the Pleistocene limestone aquifer of Barbados. PhD dissertation. The University of Texas at Austin, Austin, TX, 273 p.

Jones, I.C., Banner, J.L., 2003. Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico and Guam. Journal of Hydrology 278, 131—143.

Jones, I.C., Banner, J.L., Humphrey, J.D., 2000. Estimating recharge in a tropical karst aquifer. Water Resource Research 36 (5), 1289—1299.

Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudo-sections by a quasi-Newton method. Geophysical Prospecting 44, 131—152.

Motyka, J., 1998. A conceptual model of hydraulic networks in carbonate rocks, illustrated by examples from Poland. Hydrogeology Journal 6 (4), 469—482.

Palmer, D., 1981. An introduction to the generalized reciprocal method of seismic refraction interpretation. Geophysics 46, 1508—1518.

Pirazzoli, P.A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. Quaternary Science Reviews 24, 1989—2001.

Sauter, M., 1992. Quantification and forecasting of regional groundwater flow and transport in a karst aquifer (Gallusquelle, Malm, SW Germany). Tubinger Geowissenschaftliche Arbeiten, Part C (13), 151.

Schneider, J.C., Kruse, S.E., 2006. Assessing selected natural and anthropogenic impacts on freshwater lens morphology on small barrier islands: Dog Island and St. George Island, Florida, USA. Hydrogeology journal 14 (1—2), 131—145.

Šegota, T., 1982. The sea level and vertical movements of the Adriatic Sea bottom since Ris-Würm glaciations till today. Geol. vjesnik Zagreb 35, 93—109 (in Croatian).

Starc, N., Kaštelan-Macan, M., Ćurlin, S. (Ed.). 1997. National program of islands development — the Republic Croatia, Ministry of development, Zagreb. ISBN 953 96810-5-7 (in Croatian), 228p.

Šumanovac, F., Weisser, M., 2001. Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. Journal of Applied Geophysics 47, 13—28.

Šumanovac, F., Pekaš, Ž., Vlahović, T. 2003. Water exploration on small Croatian islands by electrical tomography and refraction seismics. In: Proceedings of the 9th Meeting of Environmental and Engineering Geophysics, O-069, Prague.

Terzić, J., 2004a. Hydrogeological relations on karstic islands — the island of Vis case study. Rudarsko-geološko-naftni zbornik (The Mining-Geological-Petroleum Engineering Bulletin) 16, 47—58 (in Croatian).

Terzić, J. 2004b. Similarities and differences in hydrogeological relations on karstified Adriatic islands in Croatia — case study on Islands of Vis, Premuda, Silba, Ilovik and Molat. 32nd International geological congress, Florence, Italy.

Terzić, J. 2006. Hydrogeology of the Adriatic Karstic Islands. Ph.D. Dissertation. Faculty of mining, geology and petroleum engineering, University of Zagreb, Croatia, 220p (in Croatian).

Urumović, K. 2000. Circumstances of sea water intrusion in karstic aquifer of the Pula wells. In: 2nd Croatian geological congress, Cavtat — Dubrovnik, Proceedings, Zagreb. pp. 815—820 (in Croatian).

Urumović, K. 2003. Physical basics of groundwater dynamics. University of Zagreb, Faculty of mining, geology and petroleum engineering, Zagreb. ISBN 953-6923-01-7. 318p (in Croatian).

Vacher, H.L., Quinn, T.M. (Eds.), 2004. Geology and Hydrogeology of Carbonate Islands, Elsevier, Netherlands, ISBN 0-444-51644-1.

White, W.B., 2002. Karst hydrology: recent developments and open questionsEngineering Geology, 65. Elsevier Science.