Environ Monit Assess (2012) 184:6211–6228
DOI 10.1007/s10661-011-2414-y

Karst aquifers on small islands—the island of Olib, Croatia

Tatjana Vlahović · Boris Munda

Received: 25 October 2010 / Accepted: 14 October 2011 / Published online: 3 November 2011

Abstract Water supply is a major problem in the Adriatic islands, especially during the summer tourism season, and represents a limiting factor to the islands' further economic development. Much attention has been given to water supply solutions, primarily in terms of attempting to use the existing island water. Unfortunately, few islands have favourable hydrological conditions to accumulate significant quantities of surface water or groundwater. In the period from 2001 to 2004, investigations were conducted on many islands to define their own freshwater or partially brackish water resources since desalinisation technology could resolve a significant part of the water supply demand on small and distant islands. Due to the specificity and complexity of research in karst areas, the study was conducted in phases and included the geological and hydrogeological reconnaissance of the island, aimed at locating possible areas on the island where the necessary quantities of groundwater of adequate quality could be captured; a detailed hydrogeological mapping of the specified areas, geophysical investigation and test drilling; and, over several days, test pumping of the most promising borehole. One of the islands investigated was the island of Olib. The conducted surveys indicated that it is possible to pump about 3.5 L/s of groundwater from the karst aquifer of the island of Olib, which fully complies with the sanitary quality of drinking water.

Keywords Groundwater · Hydrogeological research · Island of Olib · Water supply

T. Vlahović (✉)
Croatian Natural History Museum,
Demetrova 1,
Zagreb, Croatia
e-mail: tatjana.vlahovic@hpm.hr

B. Munda
Geoaqua d.o.o,
Hanamanova 16a,
Zagreb, Croatia

Introduction

Most Adriatic islands in Croatia are built predominantly of karstic carbonate rock with the surface hydrographical network poorly developed. In such terrains, due to increasing karstification, major water quantities infiltrate and flow underground. The freshwater systems on the islands are also limited due to the wide, open influence zone of the sea, which causes large freshwater quantities to flow diffusely into the sea. At present, only three Adriatic islands meet their water supply needs exclusively from their own sources (Cres, Lošinj and Vis). All the others, particularly smaller and more distant ones, have either partial water supply from own sources (surface lakes, spring and groundwater captured through wells and galleries), with the remaining necessary quantities transported by submarine pipelines from the mainland, or their total drinking water demand must be transported from the mainland by water tankers. In the period from 2001 to 2004, investigations were carried out on a dozen small and distant islands as part of a study on potential solutions for water supply by using the islands' own freshwater resources or by desalination of slightly brackish groundwater (Starc et al. 1997). Due to the unique, complex nature of karst and attempts to find the most feasible solutions to water supply, investigations were carried out in three phases. The first phase included the identification of promising areas on the islands that could enable abstraction of groundwater quantities of adequate quality, the second included detailed hydrogeological investigations of the identified areas, geophysical investigations and investigation drilling, and the third comprised several days' investigation pumping the most promising boreholes.

One of the islands included in the investigations was the island of Olib, which belongs to the Zadar archipelago (Fig. 1). The island has a surface area of 25.63 km^2, measures 9.3 km in length and up to 6.3 km in width, narrowing down to 1.4 km in its central part. It stretches in the meridional direction north−south, is built of carbonate deposits, mostly limestone with some dolomite, and belongs to the Dinaric karst belt (Fig. 1). All permanent inhabitants live in the only settlement, Olib, located close to the sea on the southwest part of the island. The population is 147 according to the 2001 census, increasing up to 2,000 in the tourist season. There are over 100 private water tanks and a public water tank near the church which is presently used only as technical water for sanitary use (Magdalenić 1991). Groundwater is abstracted from numerous privately owned shallow boreholes (over 20) and three excavated wells (KZ-1, KZ-2, KZ-3) located in the settlement (Fig. 2a, b). These boreholes are drilled mechanically, with a hammer (no core removal), mostly to a depth of 1–2 m below sea level. Borehole discharge is about 0.2 L/s. The salinity of water from the boreholes also generally decreases inland, whilst

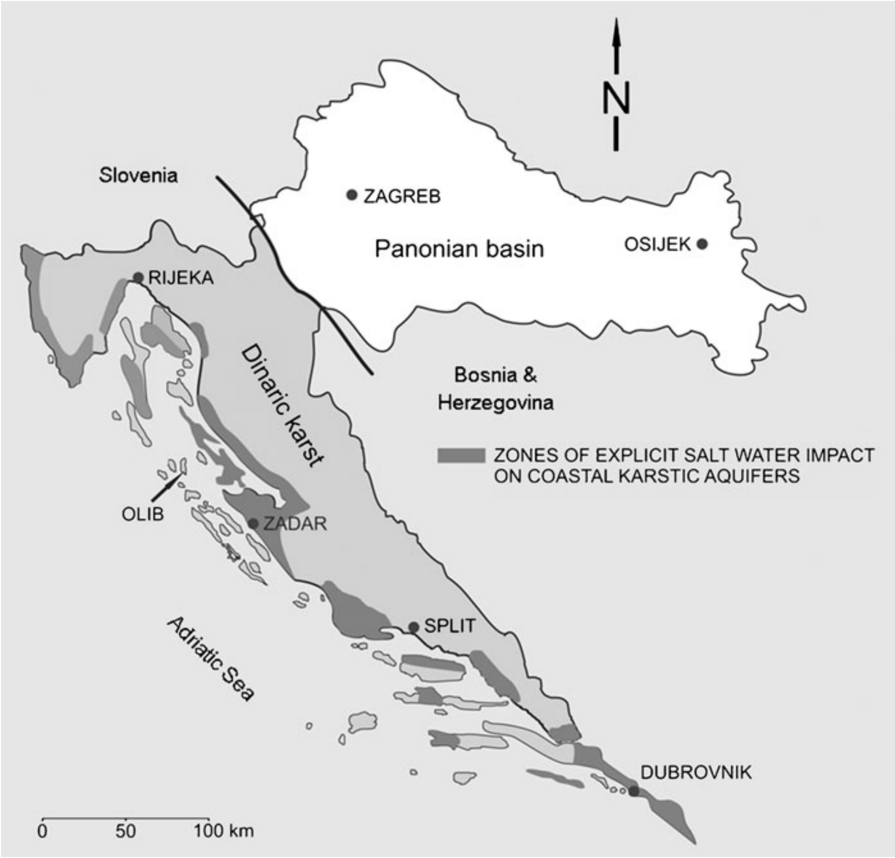


Fig. 1 Geographical location of the island Olib, Croatia, in the Dinaric karst belt

in boreholes at the highest levels, water salinity in July is <200 mg/L chloride (Munda and Vlahović 2006). Public excavated wells are located in the settlement, 80 to 500 m from the sea, with chloride concentrations in well water decreasing proportionate to the distance from the sea (Munda and Vlahović 2006). Well KZ-1 is 4.5 m deep, with a diameter of 1.8 m and a 0.5-m water head above sea level. The water chloride content is about 400 mg/L, indicating the influence of seawater, which increases proportionally to drawdown. The chloride concentration of water in well KZ-2 is about 360 mg/L chloride. Well KZ-3 is 12 m deep, with a diameter of 1.4 m. The chloride content, with a low yield of about 2–3 m^3/day, is within the limits permitted for drinking water, i.e. <200 mg/L chloride.

As these wells do not satisfy demand, a study to identify additional water quantities was initiated. The minimum necessary groundwater quantity (fresh or brackish water) in the dry period is 3 L/s, which would satisfy the needs of both the domestic and the tourist population in the tourism season.

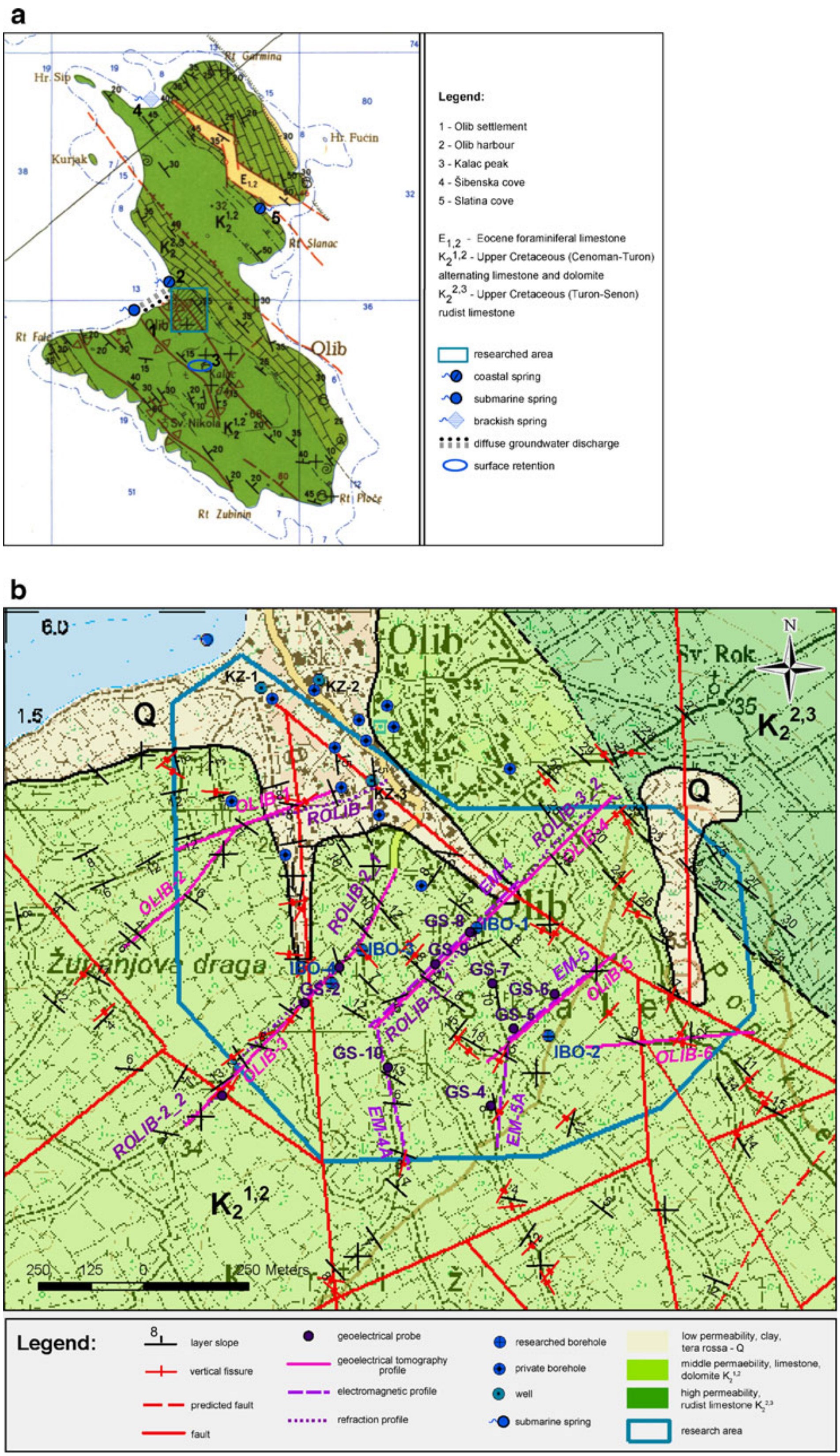
Carbonates, in particular those of the karstified coastal areas and islands, are characterised by complex hydrogeological relations. They have been investigated and described, though the methodologies vary. Some authors emphasize geochemistry (Capaccioni et al. 2005; Vlahović and Bačani 2005; Buljan et al. 2006; Kallioras et al. 2006; Terzić et al. 2007a), some geophysics (Šumanovac et al. 2003; Šumanovac 2005; Terzić et al. 2007b), whereas others calculate water balance (Jones and Banner 2003; Terzić 2004; Bačani et al. 2006; Kim et al. 2006; Petalas and Lambrakis 2006; Prieto et al. 2006). It should be noted that contrary to the research conducted in the alluvial (Pannonian) part of Croatia, in markedly karstic terrains, such as the Dinaric karst belt, for which modelling is difficult, such investigations have been very rare.

On the island of Olib, the investigation included both a geological and hydrogeological survey of the island and a detailed geological and hydrogeological mapping of different perspectives of the area to the south of the settlement of Olib. Sites for geophysical investigation were determined based on an analysis of the resulting maps, whilst sites for investigation boreholes were determined based on the correlation of the results of the mapping and geophysical investigation. Test pumping of the boreholes was then carried out and the physicochemical properties of groundwater measured.

Study area—geology and hydrogeology

The island of Olib is a part of the Dinaric karst belt which is characterized by deep, irregular karstification and is strongly influenced by tectonics, compression, reverse faults and folding. The geological composition of the island is dominated by Upper Cretaceous carbonate sediments and, to a lesser degree, Paleogene carbonate deposits and Quaternary clastic deposits (Mamužić et al. 1970; Mamužić and Sokač 1973) (Fig. 2a). Cretaceous sediments comprised alternating limestone and dolomite, dolomitic limestone and dolomite of Cenoman–Turon age ($K_2^{1,2}$), and Turon–Senon rudist limestone ($K_2^{2,3}$). Paleogene deposits are almost entirely built of Eocene foraminiferal limestone ($E_{1,2}$), specifically miliolid, alveoli and nummulite limestone. According to geotectonic zoning (Mamužić and Sokač 1973), Olib belongs to the Zadar archipelago tectonic unit. In this structural unit, vertical to slightly sloped folds stretching in the northwest–southeast direction are characteristic. The folds are interrupted by faults of the same stretching direction, and both are further crisscrossed by transverse and diagonal faults. The majority of the island is built of the Upper Cretaceous anticline located in the south and southwest part of the island. The anticline ridge is built of Cenoman–Turon alternating limestone and dolomite with flanks of Turon–Senon rudist limestone. The layers are generally slightly sloped, from 5° to 35°, with the steeper ones quite rare. The anticline is interrupted by a series of vertical and subvertical faults, of which the faults of the northwest–southeast and north–south stretching directions are the most pronounced. From the southeast, through a reverse fault, the anticline structure is overhung by the southwest, interrupted by a flank of the Cretaceous–Paleogene syncline. The syncline is built of Cenoman–Turon limestone and dolomite, and Turon–Senon rudist limestone transgressively covered by Eocene foramniferal limestone.

Hydrogeological relations are characterised by geological composition and morphological features. They are a consequence of lithostratigraphic and structural–tectonic conditions. Such terrain characteristics strongly influence hydrological conditions. In


a
Legend:
1 - Olib settlement
2 - Olib harbour
3 - Kalac peak
4 - Šibenska cove
5 - Slatina cove
E1,2 - Eocene foraminiferal limestone
K2 1,2 - Upper Cretaceous (Cenoman-Turon) alternating limestone and dolomite
K2 2,3 - Upper Cretaceous (Turon-Senon) rudist limestone
researched area
coastal spring
submarine spring
brackish spring
diffuse groundwater discharge
surface retention
Hr. Sip
Rt Garmina
Hr. Fucin
Kurjak
Rt Slanac
Olib
Rt Fale
Sv. Nikola
Rt Ploče
Rt Zubinin
b
Olib
Sv. Rok
Q
K2 2,3
K2 1,2
Žuranjove draga
KZ-1
KZ-2
KZ-3
OLIB-1
ROLIB-1
OLIB-2
ROLIB-2_1
ROLIB-2_2
OLIB-3
ROLIB-3_1
ROLIB-3_2
OLIB-4
OLIB-5
OLIB-6
EM-4
EM-4A
EM-5
EM-5A
IBO-1
IBO-2
IBO-3
IBO-4
GS-2
GS-4
GS-5
GS-6
GS-7
GS-8
GS-9
GS-10
250 125 0 250 Meters
Legend:
layer slope
vertical fissure
predicted fault
fault
geoelectrical probe
geoelectrical tomography profile
electromagnetic profile
refraction profile
researched borehole
private borehole
well
submarine spring
low permeability, clay, tera rossa - Q
middle permaebility, limestone, dolomite K2 1,2
high permeability, rudist limestone K2 2,3
research area

◀ **Fig. 2** **a** Geological map of the island Olib with coastal, submarine and brackish springs, surface retention and diffuse groundwater discharge. **b** Hydrogeological map of the investigation area with the position of pumping sites and geophysical profiles

combination with climatic conditions, this plays a key role in the formation and dynamics of karst and, in particular, island aquifers.

Carbonate rocks of fissure–cavernous porosity and varying permeability were identified based on the lithological composition, genesis and structure; the intensity and depth of karstification; and the level of fissure backfilling, i.e. their interconnections on the island. In terms of their porosity, carbonate deposits are divided into highly permeable and medium to highly permeable deposits (Fig. 2b). Highly permeable deposits include well-karstified Turon–Senon rudist limestone ($K_2^{2,3}$) and Eocene foraminiferous limestone ($E_{1,2}$). Structural elements (strata sloping towards the sea), fissure systems and openness of rudist limestone towards the sea indicate an unfavourable structural position of these deposits with regard to groundwater abstraction. As medium to highly permeable deposits, alternating limestone and dolomite deposits ($K_2^{1,2}$) were identified. Dolomite, or dolomitised limestone, is less present than limestone. Limestones are karstified, and their karstification level (Tišljar 2001) does not significantly decrease even in the case of limestone undergoing the dolomitisation process. The thin interlayer of pure dolomite is very rare and has no significant role in the determination of the hydrogeological characteristics of the lithologic member. However, the dolomitisation process of this lithologic member has significantly influenced its determination as medium to highly permeable deposits.

Due to the described geological composition, the island does not have a surface hydrographic network with permanent water flows. Precipitation drains almost exclusively through the underground, and surface water flows appear only after extremely heavy rains. After losing a portion of rainwater to evapotranspiration, the remainder is mostly infiltrated into the underground and lost via dispersal on the coast. The direction of groundwater flow is determined by the structure spreading in the northwest–southeast direction and a strong fault system of the same direction, along which a depression descends in terraces towards the sea. This depression represents the most fertile part of the terrain, spreading through the central part of the settlement Olib. From the Kalac peak in the island's central part, infiltrated rainwater flows underground towards the sea. A portion of the cove which serves as the Olib harbour contains coastal springs and submarine springs and is also the location of the occurrence of wider diffuse groundwater discharges. Submarine springs also occur in the Slatina cove and the Olib harbour, and their locations can be seen during calm seas. In the north of the island, in Šibenska cove, 7 m off the coast and 20 m off its cape, the only brackish spring appears, with a yield of 0.1 L/s (Ivičić and Biondić 1998). Its discharge decreases in the recession period, becoming only a small well in the summer months. Surface retention of rainwater is very rare and related to the locally pronounced limestone dolomitisation processes. In such places, surface fens form and are used as livestock drinking holes (Fig. 2a).

Materials and methods

Research methods

In 2001/2002, the first phase of the investigation was carried out on the island. This included a geological and hydrogeological survey and focused on the identification of promising areas for further investigations. An area southeast of the settlement Olib was identified in this phase. In 2003, surveys resumed in the identified area, i.e. detailed geological and hydrogeological mapping, geophysical investigation and investigation drilling. The analysis of results obtained by detailed mapping (structural–tectonic characteristics, strata sloping towards the sea, openness of fissure systems towards the north coast of the island) helped determine the locations of geophysical investigations (Fig. 2b) comprising electrical sounding (AB/2=300 m, ten probes), electrical resistivity tomography (in the length of 3 km, six profiles), seismic refraction (in the length of 2 km, three profiles) and geoelectrical magnetometry (in the length of 1.5 km, two profiles). These methods significantly contribute to the determination of structural and lithological relationships and the geometry of the aquifer (Šumanovac 2006), especially in the karstic terrains where the basic goal is to map a narrow fracture and fault zones and potential underground objects (Šumanovac and Weisser 2001; Engelsfeld et al. 2008). The data of 2D electrical tomography were processed and interpreted according to the method of Loke and Barker (1995, 1996), whilst refraction data were processed using the generalized reciprocal method (Palmer 1981). The geophysical survey locations of boreholes were determined according to several features:

(a) Results of the detailed geological and hydrogeological surveys
(b) Analysis and correlation of results of the geophysical investigation
(c) Purpose of the survey (for public water supply)
(d) Need to remove the location from potential polluters (settlement Olib has no constructed sewerage network)
(e) Seawater influence on the quality of abstracted groundwater reduced to the minimum

Investigation drilling was carried out from 15th July to 15th August 2003; four boreholes were drilled (IBO-1, IBO-2, IBO-3 and IBO-4) to a total depth of 203.7 m (Fig. 2b). The boreholes were drilled with continual core removal. Determination of the core and determination of the rock quality designation was obtained by the correlation of available carotage diagrams and the drilled core. Following the installation of a piezometer, short-term test pumping was carried out in a very dry period.

Physicochemical parameters (conductivity, temperature, salinity and total dissolved substances) were measured by depth in natural conditions and after several hours of pumping. These parameters were measured using a LF 197 conductometer and 325 TetraCon probe from WTW (Germany).

To determine available groundwater quantities, test pumping of the borehole was performed over several days in the following dry period by application of the step method (three pumping rates and groundwater level recovery after the end of pumping; Jacob 1946). The maximal pumping rate was $Q_{\max}$=3.5 L/s. Drawdown in the nearby boreholes IBO-1 and IBO-4 was continuously monitored. A plastic pipe was installed in the Olib harbour in an area protected from waves to monitor sea level using contact electrical echo sounder SEBA Hydrometrie (Germany). Measurements were initially taken every 2 h, and later during the test pumping every 4 h.

Additionally, three physicochemical parameters of groundwater (electrical conductivity, total dissolved substances and temperature) were measured by depth in IBO-1, IBO-3 and IBO-4 prior to, during and at the end of the test pumping. Measurements by depth prior to pumping were performed to gain insight into the static state, undisturbed by pumping, i.e. to determine the boundary of fresh/brackish water and seawater mixing, whilst measurements at the end of pumping were done to determine changes in groundwater salinity following test pumping. During pumping, measurements were intended to show the relation between the quantity and quality of pumped water and the required limit quantity of NaCl that would enable the inclusion of a borehole into public water supply following processing of raw groundwater in a desalinisation plant. Additionally, detailed physicochemical and microbiological groundwater analyses were carried out at the beginning and end of pumping.

Results

The locations for boreholes IBO-1 and IBO-4 were determined based on an analysis of the results of geoelectric tomography and seismic refraction results and of borehole IBO-2 on the results of geoelectric tomography and geoelectric sounding as the obtained results displayed solid fractures of carbonate rock mass, low quantities of clayish component and low sea impact on groundwater. The location for IBO-3 was predominantly based on the results of geological and hydrogeological mapping. An interpretation of the geophysical investigation is provided in Table 1; the determined anomalies in the electomagnetic investigation partially complete the knowledge on zones of intensified (amplified) conductivity that can be attributed to the layers of higher fragmentation or clayishness. The geoelectrical tomography profile with inserted locations of boreholes IBO-3 and IBO-4 is shown in Fig. 3.

The determination of the drilled cores established that all observation boreholes were made in limestone of Cenoman–Turon age ($K_2^{1,2}$), which are slightly dolomitised in places. The limestone is highly karstified, in part very fragmented, and the fissures are open or partially closed by the crystallisation of calcite and clay. At the location of IBO-1, the caving

Table 1 Interpretation of geophysical investigation

Resistivity (Ωm)	Predicted lithological determination
<100	Carbonate rock mass with fissures filled with salt water or highly salinated water
100–450	Carbonate rock mass with brackish or freshwater, almost in the form of hovering lenses
450–1,600	Carbonate rock mass with small dimension fissures, with or without backfill, possibly partly filled with water
<1,600	Carbonate rock mass with increased fissures and smaller cavities, filled with air and partly weathering products. In the surface area, fissures and cavities are backfilled with clay and debris that significantly reduces resistivity (resistance lower than 1600 Ωm)

in during drilling indicates the cavernous porosity of the limestone. The lithological profile of borehole IBO-3 is shown in Fig. 4. A detailed overview of the investigation drilling is provided in Table 2.

In the test pumping in summer 2003, IBO-1 did not give satisfactory results as the pumping quantities dropped from 0.66 to 0.16 L/s in 10 min, so pumping was discontinued. The measured physicochemical parameters indicated almost fresh water, with the electrical conductivity at the base of the well measuring about 2,500 μS/cm (Fig. 5). The results also showed the groundwater inflows to IBO-2 and IBO-4 to be minimal; thus, these boreholes were assessed negatively and test pumping was discontinued. The results of the measurement of electrical conductivity and other physicochemical parameters by depth in IBO-2 indicated a border of fresh (brackish) and salt water between 63 and 64 m (Fig. 5). The highest levels of electrical conductivity were recorded in IBO-4 (Fig. 5); therefore, further testing in this well was discontinued.

Test drilling in IBO-3 showed very good results. Pumping in two quantities (0.74 and 1.33 L/s) with slight drawdowns (0.24 and 0.43 m, respectively) indicated the possibility of obtaining larger groundwater quantities for water supply. After 7 h of test pumping and measurements of salinity and electrical conductivity, it was determined that in extremely dry periods, this borehole can provide 1.5 L/s or possibly larger groundwater quantities, with salinity of 0.6 or about 200 mg/L chloride and measured electrical conductivity of about 1,500 μS/cm (Fig. 6). Other measured physicochemical parameters—salinity, TDS and temperature—are shown in Figs. 7, 8 and 9.

Test pumping of the IBO-3was carried out by the step method at three different rates—0.96, 2.10 and 3.20 L/s—in the period from 8 to 22 April 2004. The test pumping data of the most promising IBO-3 borehole are shown graphically in a linear scale which depicts the reduced levels of groundwater as a function of time, depending on the pumped quantity (Fig. 10).

Prior to the start of pumping, the values of electrical conductivity by depth were nearly identical (1,268 μS/cm at 32.0 m and 1,299 μS/cm at 42.0 m), whilst the groundwater interval along the entire length was in the form of freshwater or a very slightly brackish column (Fig. 11). In the course of pumping at rate Q=0.96 L/s, the maximum drawdown of Δs= 0.53 m was measured. The impact of sea level oscillations on drawdown was minimal during pumping. During pumping, the electric conductivity initially showed a mild increase (from 1,280 to 1,315 μS/cm), followed by stabilisation. During pumping at the quantity of Q=2.10 L/s, a maximum drawdown of Δs=1.51 m was registered, and no significant impact of sea level oscillations on drawdown was observed. During pumping, the electrical conductivity showed a continuous but very mild increase (from 1,319 to

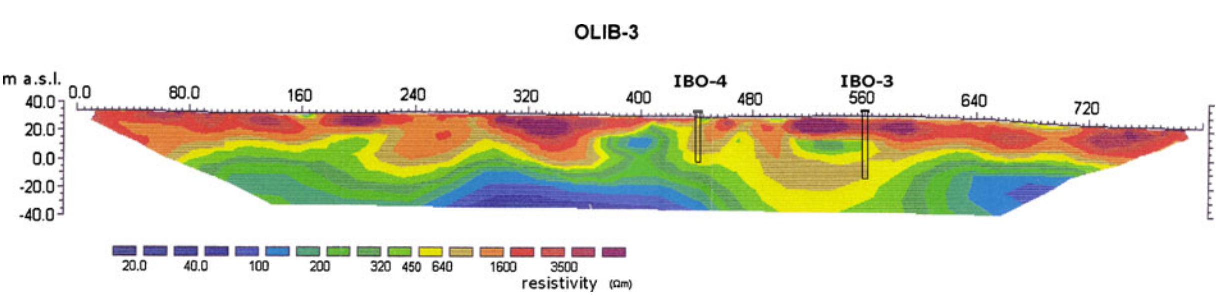


Fig. 3 Geoelectrical resistivity tomography profile—Olib 3 ERT transect (one of six conducted transects)

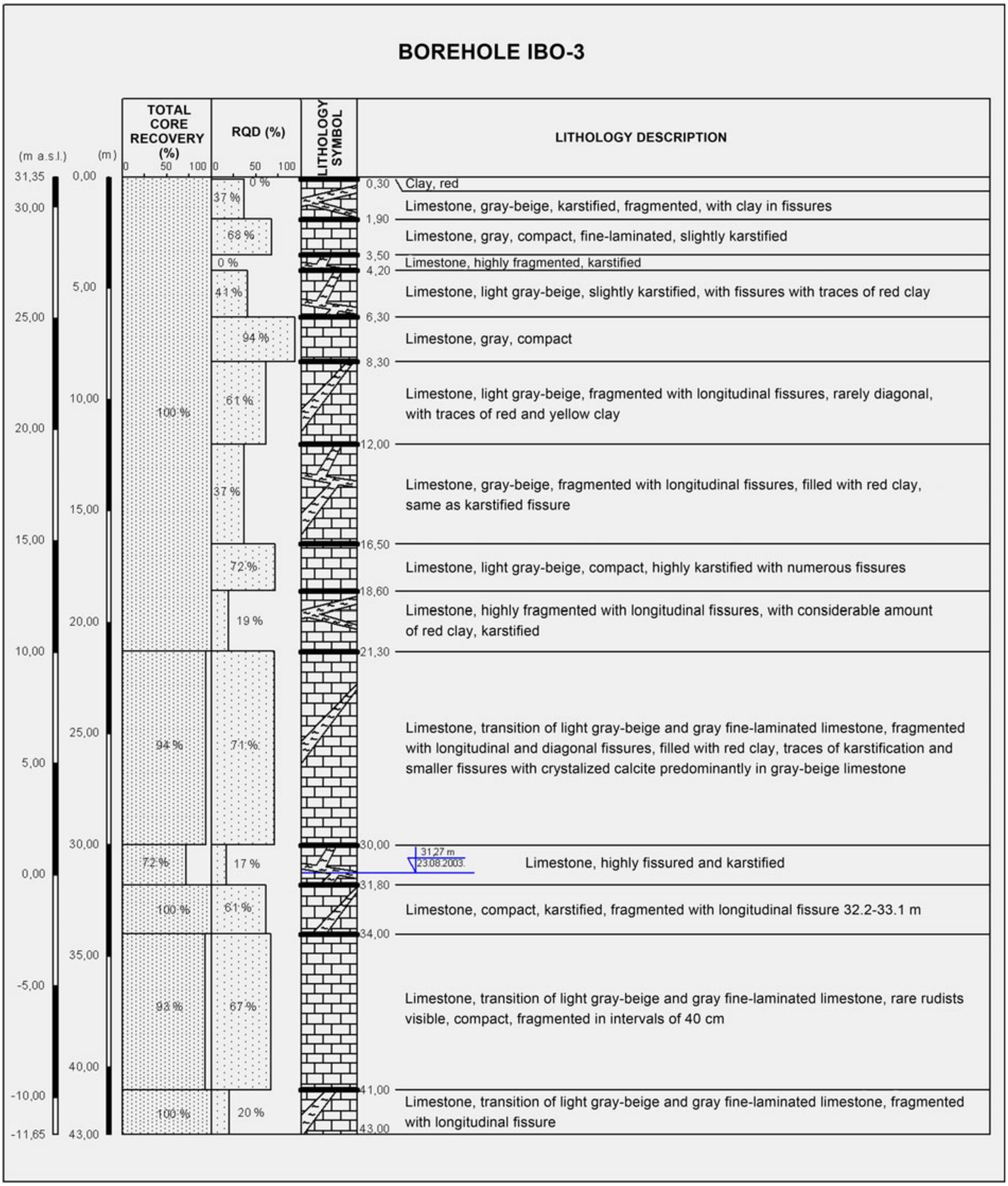


Fig. 4 Lithological profile of borehole IBO-3

1,339 μS/cm). During pumping at quantity Q= 3.20 L/s, a maximum drawdown of Δs=3.29 m was registered, and no impact of sea level oscillations on drawdown was observed. However, it is possible that the measured oscillations are partially consequential to the opening of fault systems within the aquifer. The values of electric conductivity during pumping, measured at 6-h intervals, showed a continuous but

Table 2 Overview of performed investigation drilling

	IBO-1	IBO-2	IBO-3	IBO-4
Geodetic measurement	y=4,914,252.365 x=5,483,124.456 z=36.495 terr. level	y=4,913,991.134 x=5,483,239.585 z=47.722 terr. level	y=4,914,198.895 x=5,482,849.635 z=31.345 terr. level	y=4,914,116.171 x=5,482,777.757 z=31.258 terr. level
Start of drilling	17 July 2003	23 July 2003	02 August 2003	11 August 2003
End of construction	22 July 2003	01 August 2003	06 August 2003	13 August 2003
Initial drilling profile, ∅ = 146 mm	0.00 m	0.00 m	0.00 m	0.00 m
End drilling profile, ∅ = 116 mm	60.20 m	65.00 m	43.00 m	35.50 m
Installation of PVC pipe, ∅ = 114 mm	+0.20 to −56.00 m (56.20 m)	+0.30 to −65.00 m (65.30 m)	+0.30 to −43.00 m (43.30 m)	+0.30 to −35.00 m (35.30 m)
Desilter of PVC pipe, ∅ = 114 mm	−56.00 to −51.00 m (5.00 m)	−65.00 to −63.50 m (1.50 m)	−43.00 to −42.00 m (1.00 m)	−35.00 to −34.00 m (1.00 m)
Slotted filter PVC pipe, ∅ = 114 mm	−51.00 to −36.00 m (15.00 m)	−63.50 to −48.50 m (15.00 m)	−42.00 to −33.00 m (9.00 m)	−34.00 to −26.00 m (8.00 m)
Full PVC pipe, ∅ = 114 mm	−36.00 to +0.20 m (36.20 m)	−48.50 to +0.30 m (48.80 m)	−33.00 to +0.30 m (33.30 m)	−26.00 to +0.30 m (26.30 m)
Borehole development by air lift (h)	32	8	0	0
Test pumping	1 h (0.66 and 1.10 L/s)	10 min—no water	12 h (0.74 and 1.33 L/s)	10 min—no water
Measurement of salinity and electrical conductivity per depth	From 37.0 to 55.0 m	From 48.0 to 65.0 m	From 32.0 to 42.5 m	From 32.0 to 35.5 m
Groundwater level	0.325 m a.s.l. 23 August 2003 at 19:45	0.852 m a.s.l. 29 August 2003 at 17:00	0.075 m a.s.l. 23 August 2003 at 19:30	0.798 m a.s.l. 23 August 2003 at 19:15

a very slight increase of about 10 μS/cm. Even at the maximum pumping rate, the borehole mostly recharges from shallower intervals saturated by freshwater. By the end of pumping, no stabilisation of electrical conductivity was achieved. At the end of the test pumping, the electrical conductivity measured per borehole depth increased (2,010 μS/cm, Fig. 11).

Based on the pumping test conducted at borehole IBO-3, the $Q - s/Q$ diagram was done where, according to Jacob (1950), the drawdown equation was defined:

$$s = 320Q + 213333Q^2.$$

In the equation, s is the measured drawdown (in metres) and Q the pumping rate (cubic metres per second). If we assume that the optimum drawdown at the borehole is 7 m, according to the graphical solution from the $Q{-}s$ diagram (Fig. 12), at borehole IBO-3, higher quantities of the groundwater can be abstracted than was proven by the test pumping, so the pumping rate could be up to 5 L/s. The relevant results obtained during test pumping are shown in Table 3.

In the IBO-3 borehole, the distribution of groundwater temperature per depth shows temperature stability from the surface to the bottom of the borehole. Groundwater temperature was 14.9°C, with the exception of the temperature measured in the first metre of groundwater of 15.1°C due to warming from the increased summer air temperatures. The measurements of electrical conductivity by depth prior to the start of pumping and at the end of pumping were also conducted in IBO-1 and IBO-4 (Fig. 13). The electrical conductivity by depth in IBO-1 indicated equalisation, i.e. a very mild increase between 37.0 and 52.0 m, ranging from 982 to 1,007 μS/cm. From 52.0 to 55.8 m, the electrical conductivity markedly increased to 3050 μS/cm. At the end of test pumping, the measurements registered the same values measured by depth up to 46.0 m. From 46.0 m to the bottom, the electrical conductivity increased in relation to the pre-pumping measurements.

In the IBO-1 borehole, the temperature distribution of groundwater by depth is uniform, with a mild increase towards the borehole bottom. At the surface, groundwater temperature was slightly higher at 15.3°C, whereas the temperature stabilises below, ranging from

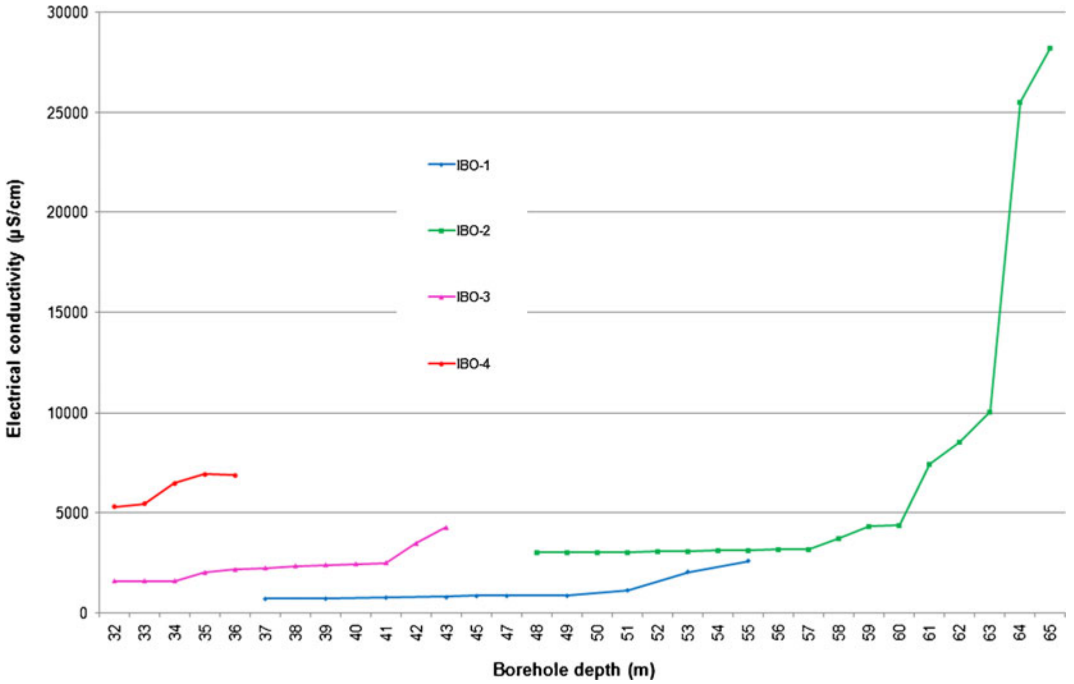


Fig. 5 Electrical conductivity of water along the depth of the boreholes (in 2003)

15.0°C to 15.1°C. In the final metres above the bottom of the borehole, a very slight temperature increase (15.2°C) was observed.

The measured values of electrical conductivity per depth in IBO-4 show a continuous though a very slight increase between 32.0 m (2,320 μS/cm) and

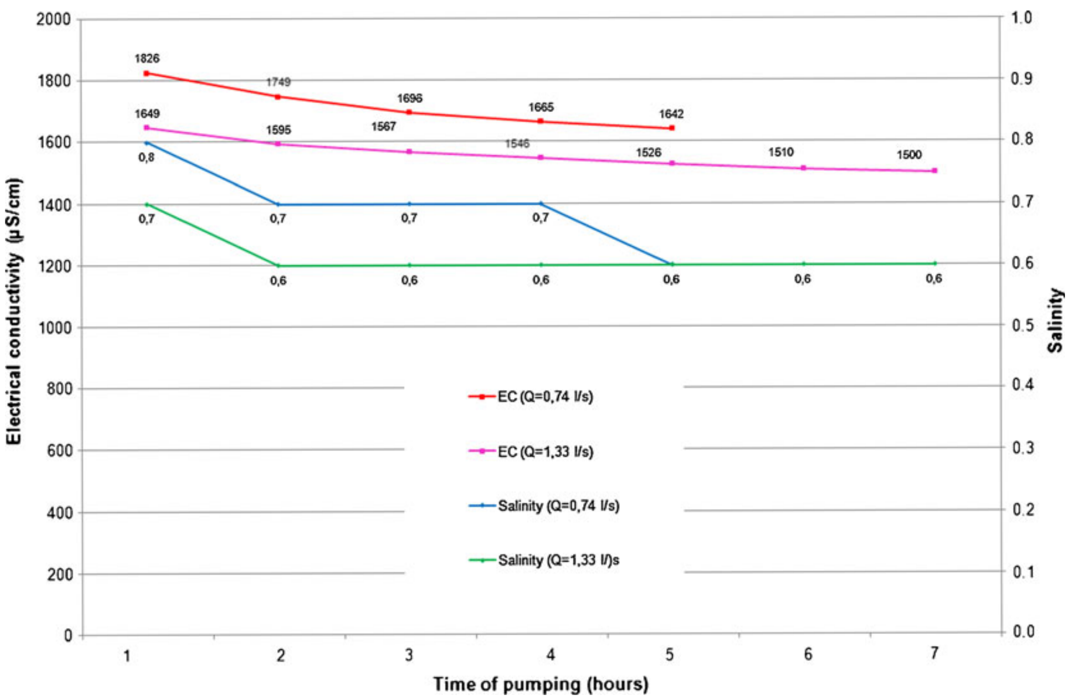


Fig. 6 Electrical conductivity and salinity of the water during the pumping test in summer 2003

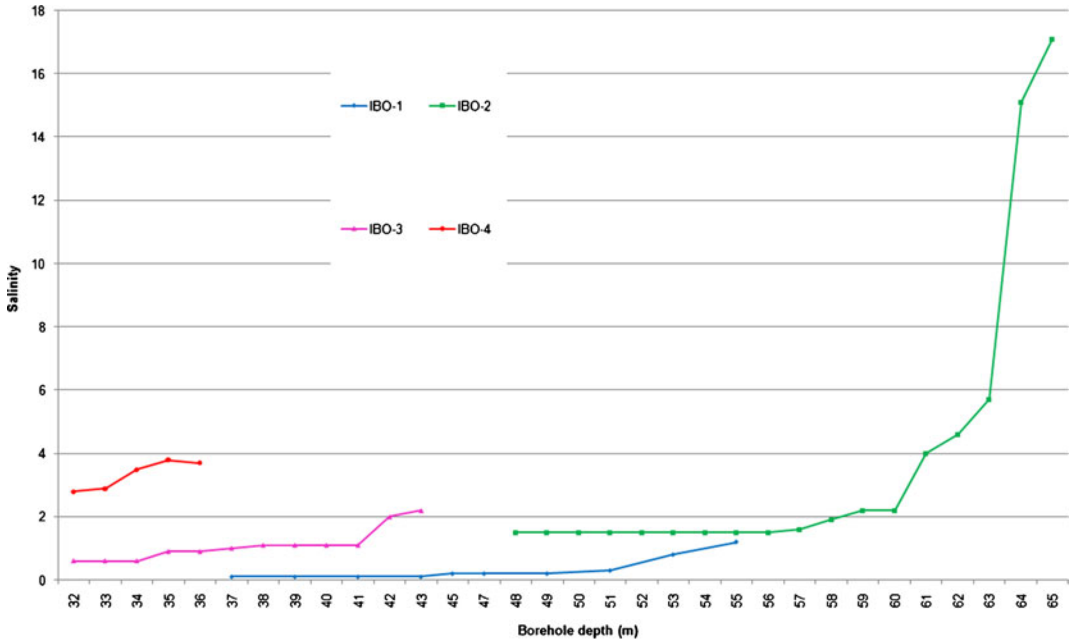


Fig. 7 Salinity of water along the depth of the boreholes (in summer 2003)

34.0 m (2,430 μS/cm). Below 34.0 m, the values of electrical conductivity register a somewhat sharper increase. At 35.0 m, the measured value was 3,090 μS/cm. After pumping, the measured electrical values were nearly identical, with the exception of the values measured at the borehole bottom where the measured value of electrical conductivity was lower (2,790 μS/cm) than prior to the test pumping. The

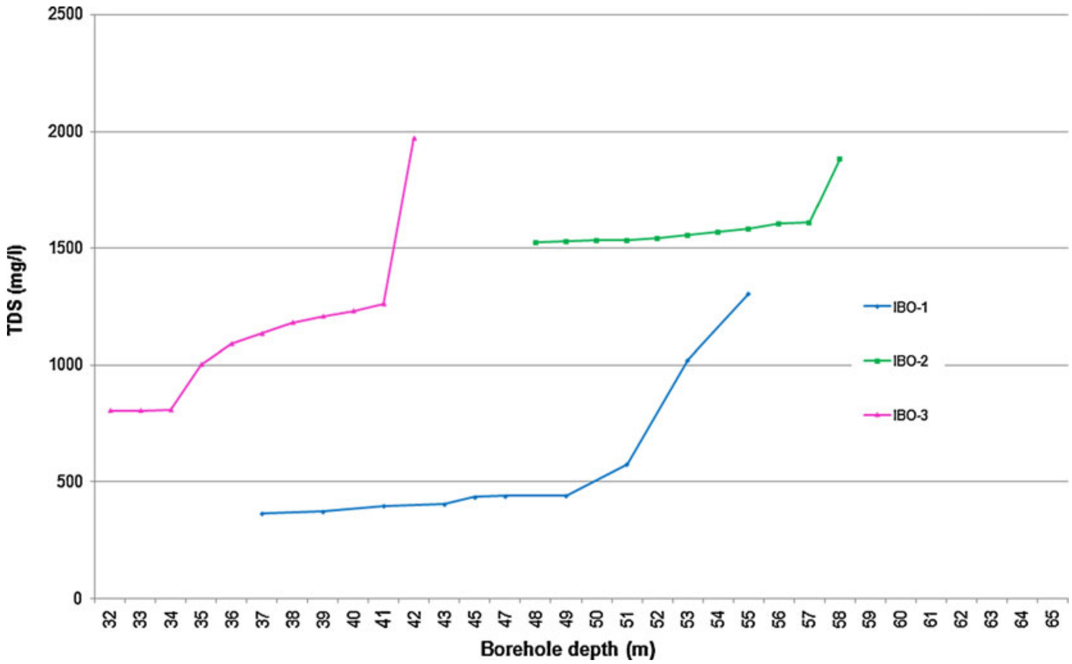


Fig. 8 TDS of water along the depth of the boreholes (in summer 2003)—the values in borehole IBO-4 are missing because they exceeded the limits of the measuring instrument (over 2,000 mg/L)

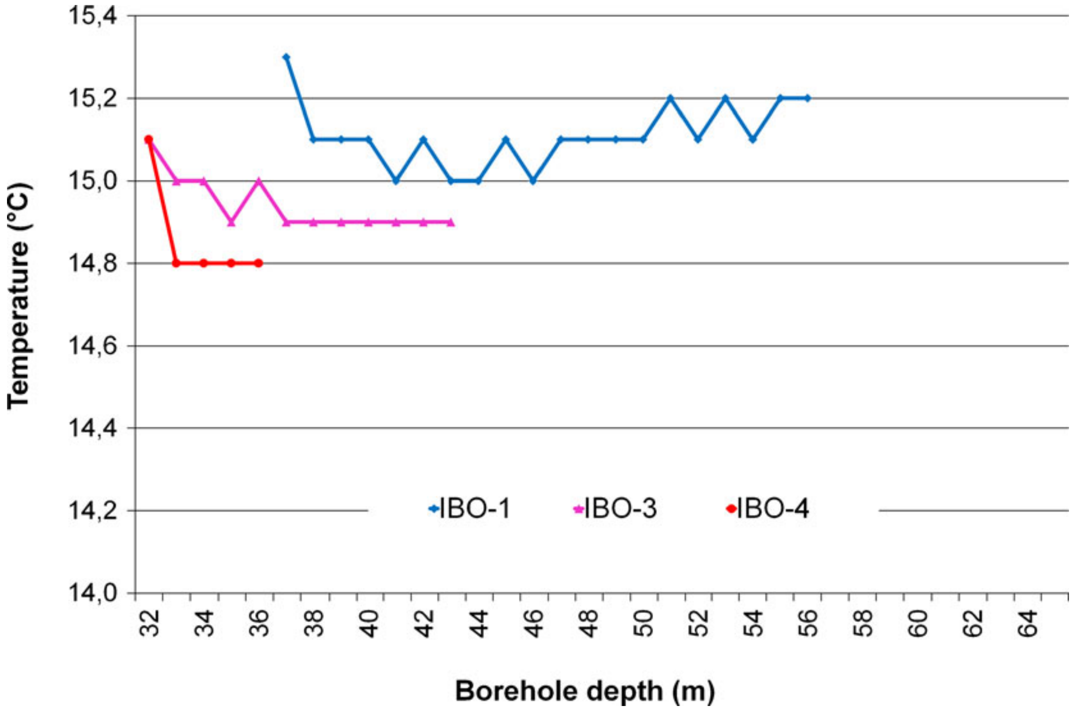


Fig. 9 Temperature of water along the depth of the boreholes (in summer 2003)

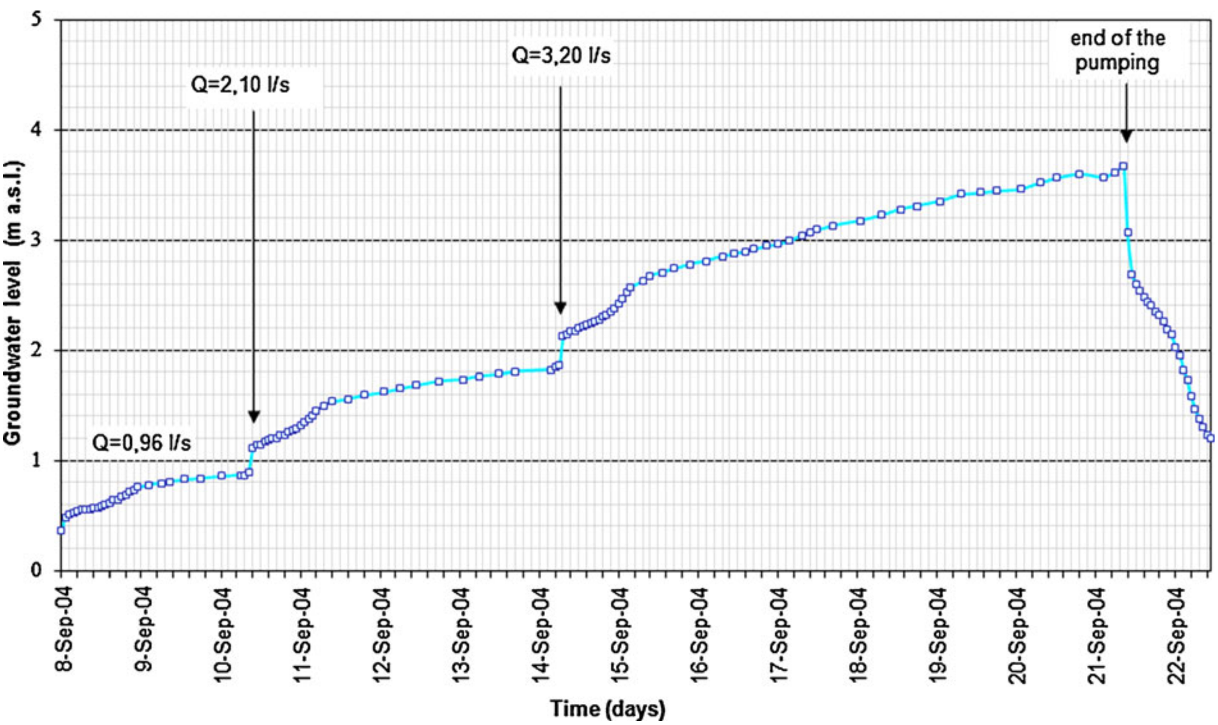


Fig. 10 Step-drawdown test in the borehole IBO-3. The *left side of the curve* corresponds to the pumping period, whilst the *right side* corresponds to the period of recharge of the groundwater levels after the end of pumping

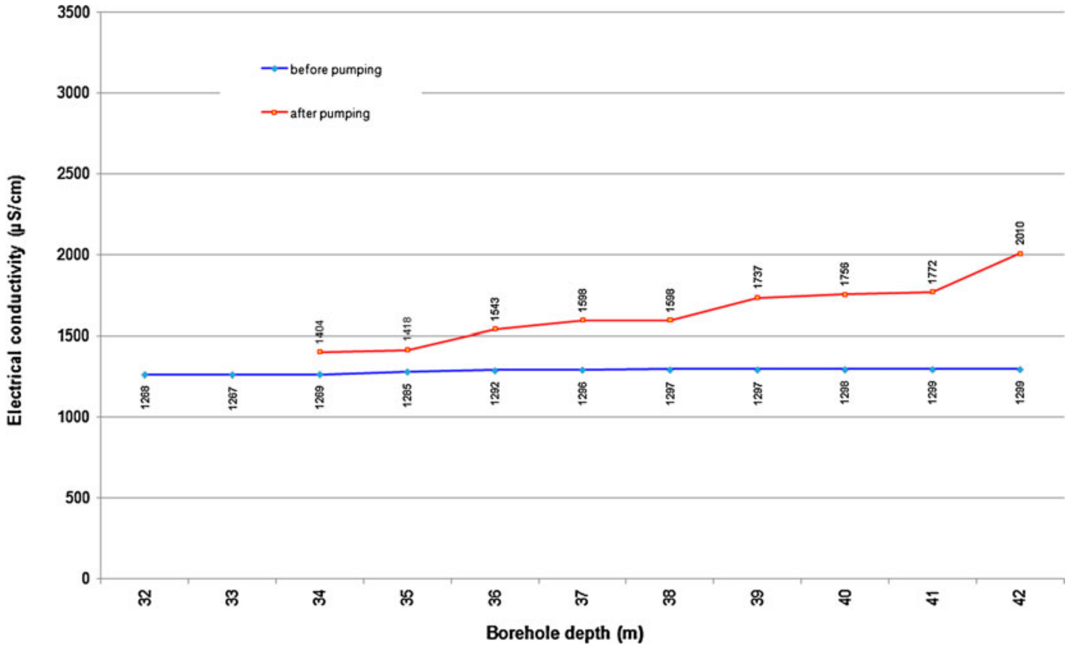


Fig. 11 Electrical conductivity of water along the depth of the borehole IBO-3

measurement results proved the presence of a hydraulic connection of groundwater in IBO-4 and IBO-3.

In the IBO-4 borehole, the temperature distribution of groundwater by depth is uniform. The temperature is constant, at 14.8°C, with the exception of groundwater exposed to air temperature which is slightly higher and equals 15.1°C. During test pumping of IBO-3, groundwater oscillation levels in the observation boreholes IBO-1 and IBO-4 and the sea level oscillations, i.e. tide levels, were monitored (Fig. 14). The oscillations of groundwater levels in the observation boreholes range from 6 cm in IBO-1 to about

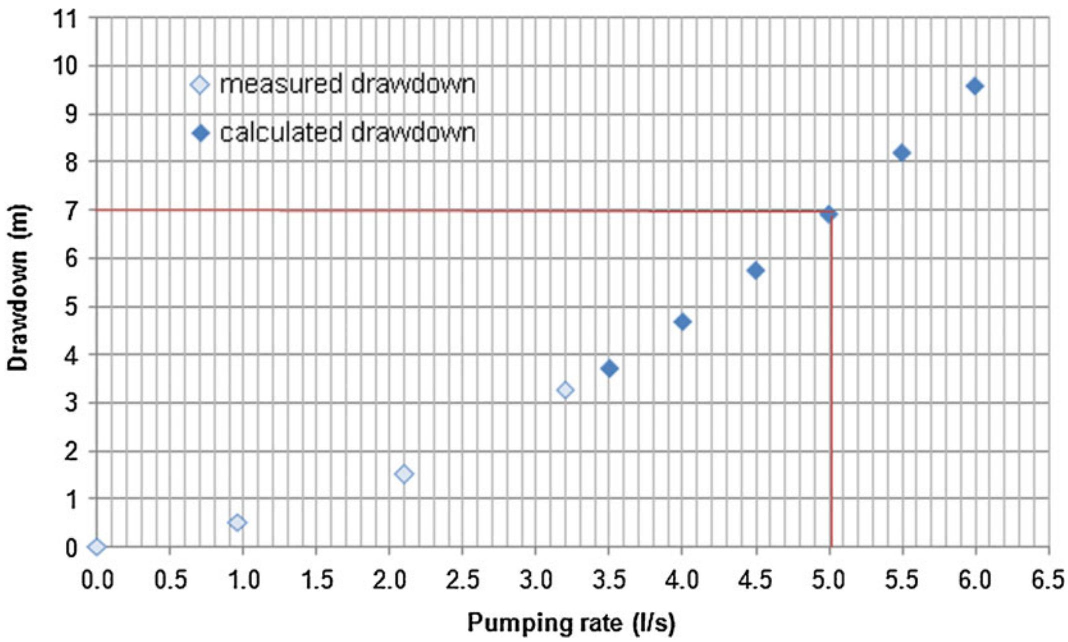


Fig. 12 Dependence of the groundwater level drawdown in the borehole IBO-3 to the pumping rate, the $Q - s$ diagram, $s = f(Q)$

Table 3 Relevant results obtained during investigation pumping

	Pumping rates, Q (L/s)	Pumping time, t (h)	Static GWL (m a.s.l.)	Dynamic GWL (m a.s.l.)	Max. drawdown (m)	30-h recovery (m a.s.l.)	Suction depth (m)	EC—at the beginning (μS/cm)	EC—at the end (μS/cm)
IBO-3	0.96	72	0.25	−0.35	0.53		41.40	1.280	1.306
IBO-3	2.10	96	0.25	−1.26	1.51		41.40	1.306	1.339
IBO-3	3.20	168	0.25	−3.04	3.29		41.40	1.339	1.404
IBO-3			0.25			−1.2			

40 cm in IBO-4. The seawater influence on the groundwater levels in the observation boreholes was not significant, particularly in IBO-1. With regard to the locations of the observation boreholes, a certain influence of seawater on the pumped borehole cannot be ruled out; however, the groundwater level oscillations within are masked by the dominant impact of test pumping.

Detailed physicochemical and microbiological analyses at the beginning and at the end confirmed that the quality of abstracted groundwater from IBO-3 fully complied with the requirements stipulated by the ordinance on the sanitary quality of drinking water. All physicochemical indicators in the water were below the maximum permitted concentrations for drinking water both before and after pumping, whilst microbiological contamination was not registered (Table 4). Additionally, chloride content in the water was 161 mg/L before pumping and only 23.8 mg/L after the 14-day pumping.

Discussion

In most karstic Adriatic islands which are predominantly built of carbonates, water supply represents a

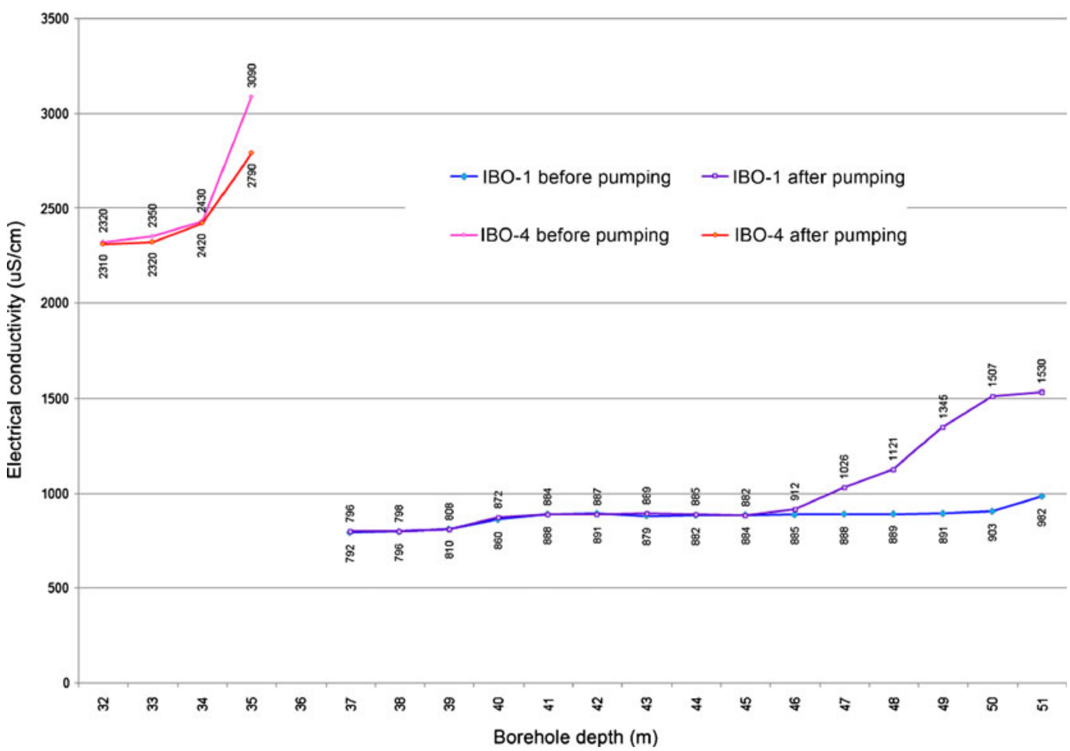


Fig. 13 Measurements of electrical conductivity by depth prior to the start of pumping and at the end of pumping of boreholes IBO-1 and IBO-4

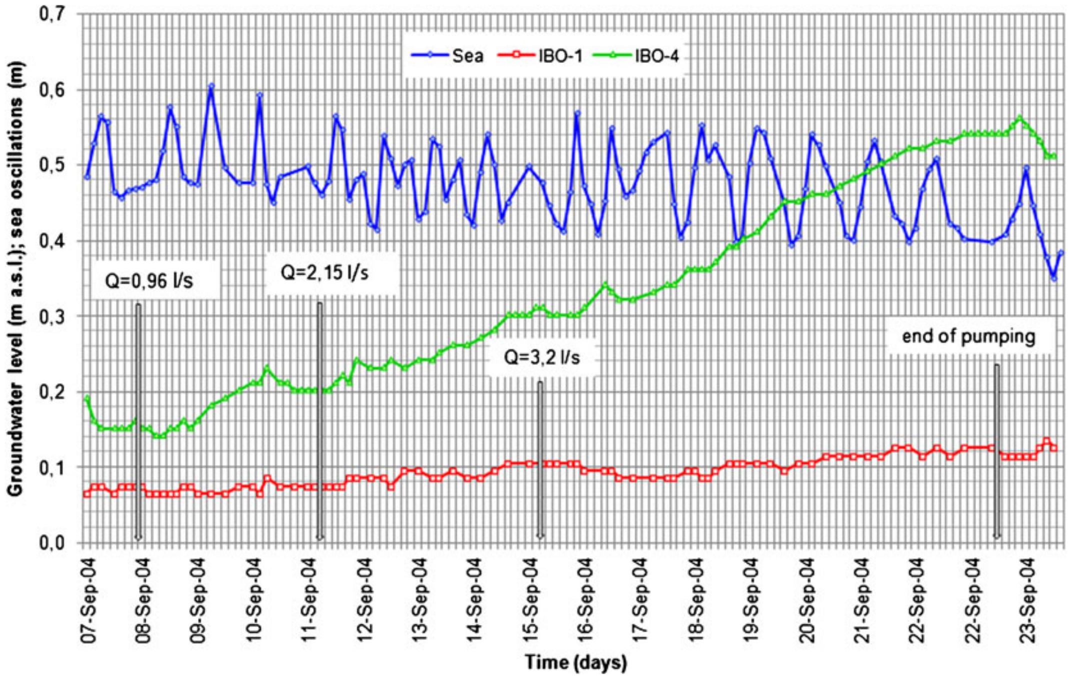


Fig. 14 Electrical conductivity of water per depth of boreholes IBO-1 and IBO-4 (in summer 2004). Groundwater levels in the observation boreholes and sea level oscillations, i.e. tide levels, during the pumping of borehole IBO-3

great obstacle to socioeconomic development and prosperity (Magdalenić 1991; Terzić 2004; Bačani et al 2006; Terzić et al. 2007b; Stevanović 2010). Water shortages and significant reductions are most pronounced during the summer season when interruptions in water supply commonly occur (Stevanović 2010). Therefore, using present island water resources as one of the possible solutions has nowadays gained much attention. Unfortunately, only a few islands, especially those small and distant ones, have hydrogeological conditions to accumulate sufficient surface freshwater or groundwater quantities which are satisfactory in terms of quality and quantity to be engaged in public use. The conducted research at the island Olib displayed that even at small and distant islands, sufficient quantities of groundwater can be pumped to be satisfactory for public use.

Based on the results of the geological, hydrogeological and geophysical investigations, four boreholes were drilled on which further investigation was conducted. The obtained results of the geophysical investigation helped determine the physical distribution of the fault systems that predispose groundwater flow, seawater impact on its salinity and approximate backfilling of fissure systems by the clayish component. Although the results of the geophysical investigation were promising, research drilling results did not confirm the assumptions derived by geophysical investigation. The location of the IBO-3 borehole displayed the best results for water supply, even though it was assigned the least perspective by the results of the geophysical investigation.

The results of the test pumping in the IBO-1 borehole were not satisfactory, even though several parameters such as equipment passing during drilling, cavernous porosity, core determination and the relatively fast recovery indicated a promising location. As groundwater inflow was too low and fissures were backfilled with clay, accessing borehole by airlift was not allowed, and therefore the test pumping was discontinued. Additionally, the obtained results such as minimal groundwater inflows in boreholes IBO-2 and IBO-4 and the highest levels of electrical conductivity in IBO-4 showed that further testing in both boreholes needs to be discontinued.

Test drilling at the last borehole, IBO-3, and the measured water quantities, salinity and electrical conductivity displayed an opportunity to include IBO-3 borehole into the public water supply on the island Olib. In this, the most perspective location, the

Table 4 Analytical data (physicochemical and microbiological) for the groundwater from borehole IBO-3

Components	Beginning of pumping	End of pumping
EC (μs/cm)	1,314	1,428
TDS (mg/L)	672	719
HCO_3^- (mg/L)	494.1	493.4
Alkalinity (mg $CaCO_3$/L)	405	
SiO_2 (mg/L)	4.995	3.13
NH_4^+ (mgN/L)	0.02	<0.03
NO_3^- (mgN/L)	0.1	0.3
Cl^- (mg/L)	161	23.8
Pb^{2+} (μg/L)	<0.5	<0.5
Cd^{2+} (μg/L)	0.108	<0.1
Hg^{2+} (μg/L)	<0.01	<0.01
Zn^{2+} (μg/L)	17.27	<5
Total Fe (μg/L)	4.49	<1
Total Cr (μg/L)	<0.4	<5
Mn^{2+} (μg/L)	<0.4	1.8
Na^+ (μg/L)	37485.0	60100
K^+ (μg/L)	1286.2	1090
Phenols (mg/L)	<0.001	<0.0005
SO_4^{2-} (mg/L)	26.6	3.7
PO_4^{2-} (mg/L)	0.003	<10
Total hardness (°dH)	26.32	515.2
Carbonate hardness (°dH)	22.68	384
Calcium hardness (°dH)	22.14	222.2
Magnesium hardness (°dH)	4.18	48.2
Total oils and fats (μg/L)	Under detection limits	28.3
Mineral oils (μg/L)	Under detection limits	–
Use of KMO_4 (mg O_2/L)	0.8	0.67
Anionic detergents (mg/L)	<0.001	0.0256
No. of aerobic bacteria (1 mL/22°C)	10	12
No. of aerobic bacteria (1 mL/37°C)	7	7
Total coliforms (100 mL)	0	0
Faecal coliforms (100 mL)	0	0
Sulfido-reductive clostridia (20 mL)	Not isolated	0
Pseudomonas aeruginosa (100 mL)	Not isolated	0

electric conductivity during pumping showed a mild increase followed by stabilisation, which can be attributed to a dominant recharge from the surface interval of the relatively fresh water column. These indicators display a stronger impact of pumping rates on drawdown than the impacts of tide levels. Whilst observing the tidal effect on groundwater and seawater flow in the coastal aquifer on Jeju Island, Kim et al. (2006) concluded that water-level variation is more sensitive to tidal fluctuations near the coast and more dependent on rainfall towards inland. During pumping at the quantity Q=2.10 L/s with a maximum drawdown of Δs=1.51 m, the electrical conductivity showed once again a continuous and mild increase, indicating that recharge at this pumping rate still occurs with a significant inflow of freshwater from the surface. At the end of the test pumping, the electrical conductivity per borehole depth increased up to 2,010 μS/cm and indicated potential of a satisfactory water quality in long-term pumping of IBO-3 for public water supply.

The $Q-s$ diagram at borehole IBO-3 assumed the limit pumping rates for IBO-3, but did not define the groundwater quantities in the case of increased abstraction, which may be a limiting parameter in plans to include the borehole in the island's water supply system (Ford and Williams 1989; Motyka 1998; Urumović 2000, 2003; Terzić 2004). Considering that the temperature, electrical conductivity and total dissolved substances curves showed no anomalies, we can conclude that the freshwater and seawater mixing boundary in the stationary state is located beneath the final depth of borehole IBO-3. Temperature distribution of groundwater by depth is uniform, with the surface groundwater temperature slightly higher due to the influence of air temperature and above the bottom of the borehole slightly higher due to the impact of seawater temperature.

By a very mild increase between 37.0 and 52.0 m, the electrical conductivity by depth in the IBO-1 borehole indicated equalisation. In depths from 52.0 to 55.8 m, the electrical conductivity markedly increased up to 3.050 μS/cm, indicating a considerable influence of seawater due to the vicinity of saltwater mixing. The boundary of freshwater and seawater mixing was raised by nearly 6.0 m in comparison with the start of pumping. These measurements confirmed the hydraulic connection, i.e. impact of pumping of IBO-3 on IBO-1. The difference in the measured values of electrical conductivity per depth with regard to boreholes IBO-1 and IBO-3 is likely due to more open fissure systems in the higher intervals of the borehole, thus resulting in the dominance of freshwater inflow over water mixed with seawater. According to Ng et al. (1992), open fissure systems and joints developed under tectonic stress and karst development associated with sea level fluctuations are the two most important causes of porosity and permeability in the aquifers on Grand Cayman.

Measurements of the groundwater level in the observation boreholes IBO-1 and IBO-4 confirmed the hydraulic connection of groundwater with the pumped boreholes, although this was weakly pronounced (Ferris et al. 1962; Urumović 2003). Oscillations of groundwater levels of 6 cm in IBO-1 to approx. 40 cm in IBO-4 are due to the distances between the observation boreholes and the pumped boreholes (280 m in IBO-1 and 110 m in IBO-4), rock permeability and the change in structural–tectonic conditions at the locations of the observation boreholes. In addition, temperature distribution by depth displayed that there are no groundwater inflows with different physicochemical characteristics, i.e. that the aquifer at the location of the borehole IBO-4 is poorly permeable.

Therefore, in terms of quantity and quality, groundwater resources from IBO-3 are so far the only ones that completely fulfill conditions for public use as these completely meet the requirements assigned by the Croatian Ordinance on the sanitary quality of drinking water (Official Gazette, 182/2004). It was proven that no processing of raw water is required prior to its inclusion into the Olib water supply system. In the case of including borehole IBO-3 into the public water supply in the future, it is necessary to develop a groundwater exploitation programme and abstraction monitoring for maintaining the quantity and quality of raw groundwater necessary for water supply as well as measures for protection of the recharge area of the abstracted aquifer.

Conclusions

The conducted test pumping of borehole IBO-3, including measurements of the electrical conductivity of water per depth and during pumping in the summer of 2004, indicates a promising location and consequentially a possible inclusion of the borehole with the capacity of 3.2 L/s into the public water supply of the island Olib. The groundwater quality determined on the basis of the physicochemical and microbiological analyses and additional measurements of chloride contents and electrical conductivity per depth at the start and at the end of the pumping fully complies with the provisions of the Croatian Regulation on the Sanitary Quality of Drinking Water. The water does not need processing prior to its inclusion into the public water supply. At the pumping end, the chloride concentration in water was only 23.8 mg Cl^- per litre. In the case of the exploitation of borehole IBO-3, drilled observation boreholes IBO-1, IBO-2 and IBO-4 should be used as the observation boreholes for monitoring oscillations in groundwater levels and quantities. If there is a need for larger groundwater quantities for water supply, analysis of the measured and calculated drawdown and pumping rates, the drawdown vs. pumping rates graph, determined that in terms of the borehole yield, it is possible to abstract the quantity of about 5 L/s, with the expected optimal drawdown of about $\Delta s=7$ m. A drawdown by the abstraction of 3.2 L/s ($\Delta s=3.29$ m), the height of the relatively fresh water column and measurements of electrical conductivity along the depth after pumping and before increasing pumping rate show that it is necessary to conduct a test pumping with the proposed quantity and to monitor groundwater quality. Additionally, a possibility of providing accessory groundwater quantities through further hydrogeological investigations on the island Olib is advisable.

References

Bačani, A., Vlahović, T., & Perković, D. (2006). Yield assessment for Blato well field, island of Korčula. *Mining-Geological-Petroleum Bulletin, 18*, 1–13.

Buljan, R., Marković, T., & Zelenika, M. (2006). Aquifer of the western part of the Prgovo polje on the island Lastovo. *Mining-Geological-Petroleum Bulletin, 18*, 15–27.

Capaccioni, B., Didero, M., Paletta, C., & Didero, l. (2005). Saline intrusion and refreshening in a multilayer coastal aquifer in the Catania Plain (Sicily, Southern Italy): Dynamics of degradation processes according to the hydrochemical characteristics of groundwaters. *Journal of Hydrology, 307*, 1–16.

Engelsfeld, T., Šumanovac, F., & Pavin, N. (2008). Investigation of underground cavities in a two-layer model using the refraction seismic method. *Near Surface Geophysics, 6*, 221–231.

Ferris, J. G., Knowles, D. B., Brown, R. H. & Stallman, R. W. (1962). Theory of aquifer tests. Groundwater hydraulics (pp. 1–174). US Geological Survey Water-Supply Paper 1536-E.

Ford, D., & Williams, P. (1989). *Karst geomorphology and hydrology* (pp. 1–601). London: Chapman & Hall.

Ivičić, D. & Biondić, B. (1998). Dalmatian islands—Natural conditions, state and potentials of water supply (pp. 119–

135). Croatian Hydrological Society—Round table “Water on Croatian islands”, Proceedings, Hvar.

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

Jacob, C. E. (1950). Flow of groundwater. In H. Rouse (Ed.), *Engineering hydraulics* (pp. 321–386). New York: Wiley.

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.

Kallioras, A., Pliakis, F., & Diamantis, I. (2006). Conceptual model of a coastal system in northern Greece and assessment of saline vulnerability due to seawater intrusion conditions. *Environmental Geology, 51*, 349–361.

Kim, K., Seong, H., Kim, T., Park, K., Woo, N., Park, Y., et al. (2006). Tidal effects on variations of fresh–saltwater interface and groundwater flow in a multilayered coastal aquifer on a volcanic island (Jeju Island, Korea). *Journal of Hydrology, 330*, 525–542.

Loke, M. H., & Barker, R. D. (1995). Least-squares deconvolution of apparent resistivity pseudo-sections. *Geophysics, 60*, 1682–1690.

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.

Magdalenić, A. (1991). Hydrogeology and water supply of Adriatic islands. *Marine Proceedings Rijeka, 29*, 461–474.

Mamužić, P. & Sokač, B. (1973). Basic geological map in the scale of 1:100,000, Silba and Molat sheets. Croatian Geological Survey, Zagreb.

Mamužić, P., Sokač, B. & Velić, I. (1970). Basic geological map in the scale of 1:100000, sheet Silba. Croatian Geological Survey, Zagreb.

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

Munda, B., & Vlahović, T. (2006). Water-supply solving possiblities on the Olib island. *Croatian Waters, 14*(55), 155–287.

Ng, K.-C., Jones, B., & Beswick, R. (1992). Hydrogeology of Grand Cayman, British West Indies: A karstic dolostone aquifer. *Journal of Hydrology, 134*, 273–295.

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

Petalas, C., & Lambrakis, N. (2006). Simulation of intense salinization phenomena in coastal aquifers—The case of the coastal aquifers of Thrace. *Journal of Hydrology, 324*, 51–64.

Prieto, C., Kotronarou, A., & Destouni, G. (2006). The influence of temporal hydrological randomness on seawater intrusion in coastal aquifers. *Journal of Hydrology, 330*, 285–300.

Starc, N., Kaštelan-Macan, M., Ćurlin, S. (Eds.) (1997). National program of islands development—The Republic Croatia (pp. 1–228). Ministry of Development, Zagreb.

Stevanović, Z. (2010). Case study: Intake of the Bolje Sestre karst spring for the regional water supply of the Montenegro coastal area. In N. Krešić & Z. Stevanović (Eds.), *Groundwater hydrology of springs—Engineering, theory, management, and sustainability* (pp. 457–478). Oxford: Butterworth-Heinemann.

Šumanovac, F. (2005). Geophysical water exploration on the Korčula Island (Croatia). *Proceedings of the67th EAGE Conference and Exhibition*, Madrid, G002.

Šumanovac, F. (2006). Mapping of thin sandy aquifers by using high resolution reflection seismics and 2-D electrical tomography. *Journal of Applied Geophysics, 58*, 144–157.

Šumanovac, F., & Weisser, M. (2001). Evoluation 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. *Proceedings of the 9th Meeting of Environmental and Engineering Geophysics*, Czech Association of Applied Geophysicists, O-069, Prague.

Terzić, J. (2004). Hydrogeological relations on karstified islands—The Islands of Vis case study. *Mining-Geological-Petroleum Bulletin, 16*, 47–58.

Terzić, J., Marković, T., & Pekaš, Ž. (2007a). Influence of sea-water intrusion and agricultural production on the Blato Aquifer, Island of Korčula, Croatia. *Environmental Geology, 54*, 719–729.

Terzić, J., Šumanovac, F., & Buljan, R. (2007b). An assessment of hydrogeological parameters on the karstic Island of Dugi Otok, Croatia. *Journal of Hydrology, 343*, 29–42.

Tišljar, J. (2001). *Sedimetology of carbonates and evaporites* (pp. 1–375). Zagreb: Croatian Geological Survey.

Urumović, K. (2000). Circumstances of sea water intrusion in karstic aquifer of the Pula wells (pp. 815–820). *Proceedings of the 2nd Croatian Geological Congress*, Cavtat-Dubrovnik.

Urumović, K. (2003). *Physical basics of groundwater dynamics* (pp. 1–318). Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb.

Vlahović, T. & Bačani, A. (2005). Groundwater resources of Blatsko polje, Island of Korčula (pp. 251–252). *Proceedings of the 3rd Croatian Geological Congress*, Opatija.