Environ Geol (2008) 54:197–211
DOI 10.1007/s00254-007-0808-5

ORIGINAL ARTICLE

Optimization of water resources management using SWOT analysis: the case of Zakynthos Island, Ionian Sea, Greece

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Received: 14 April 2006 / Accepted: 9 May 2007 / Published online: 31 May 2007

Abstract Zakynthos, an island of 408 km^2 in the Ionian Sea, is completely dependent on its groundwater resources for fulfilling the demands of the water supplies. The use of groundwater resources has become particularly intensive during the last decades because of the intense urbanization, the tourist development and the irrigated land expansion that took place. The main aquifers are developed in limestones (karstic), sandstones of neogene deposits (confined) and alluvial deposits (phreatic). This paper focuses on the assessment of their hydrogeological characteristics and the groundwater quality. For this investigation, groundwater level measurements, drilling data, pumping tests and chemical analyses of groundwater samples were used. The average annual consumption that is abstracted from the aquifer systems, is 4.9×10^6 m^3 year^{-1}. The exploitable groundwater reserves were estimated to be 3.3×10^6 m^3 year^{-1}. In the last decades, the total abstractions exceed the natural recharge, due to the tourist development; therefore the aquifer systems are not used safely. The results of chemical analyses showed a deterioration of the groundwater quality. According to the analyses the shallow alluvial aquifer and the confined aquifer are polluted by nitrates at concentrations in excess of 25 mg L^{-1}. High sulphate concentrations might be related to the dissolution of gypsum. Seawater intrusion phenomena are recorded in coastal parts of aquifer systems. The increased Cl^- concentrations in karstic aquifer indicate signs of overexploitation. Strengths, weaknesses, opportunities and threats (SWOT) analysis was applied in order to evaluate the SWOT of the groundwater resources. Moreover, some recommendations are made to assist the rational management that aim at improving the sustainability of the groundwater resources of Zakynthos Island.

Keywords Greece · Zakynthos Island · Aquifers · Groundwater quality · SWOT analysis · Water resources management

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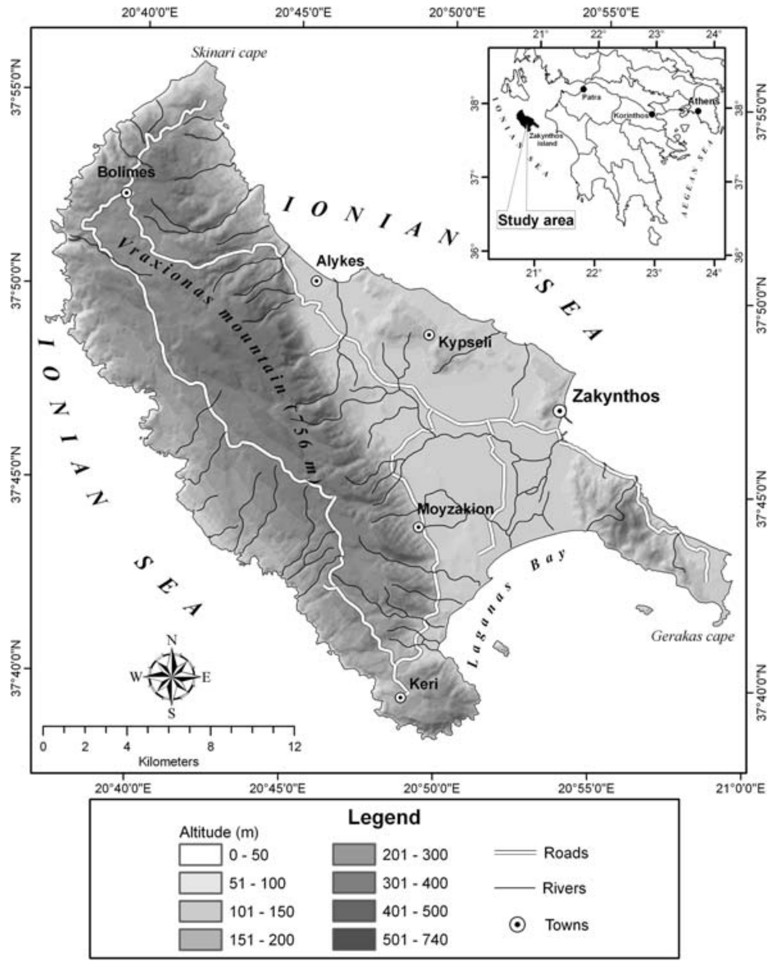
Introduction

Zakynthos Island is located in the south of the Ionian Sea, close to western Greece's coastline, covering an area of 408 km^2. It has ~12,000 inhabitants and it is worth mentioning that between 1981 and 2001, the population of the island has nearly doubled. In Fig. 1 the study area is presented.

The island is characterized by increasing demands for water, especially during the last decades, due to its development. Groundwater is the primary source used to meet both domestic and agricultural needs. On an annual basis, 4.9×10^6 m^3 of groundwater are extracted, with a maximum daily rate of 21,000 m^3 during the summer months. Consequently, stress is put on the groundwater resources. As a result, problems such as salinization, quality deterioration, decline of groundwater level and increasing pollution risks appeared. All these problems are directly related to the intensive exploitation in combination with the lack of rational management (Voudouris et al. 2006). Sources of groundwater pollution are the seawater intrusion due to

Fig. 1 Topographic map of the study area



overexploitation of coastal aquifers, the fertilizers from agricultural activities and the disposal of untreated waste in torrents or in old water pumping wells. Furthermore, municipal sewage-treatment systems do not exist, apart from those in Zakynthos city. Surface water quality deterioration is also apparent and is mainly attributed to the uncontrollable discharge of untreated olive oil mill effluent. It is pointed out that groundwater from the aquifer systems of the island is not suitable for human consumption.

The development of great pressures on the water resources and the existence of sensitive ecosystems (Laganas bay and the island forests) have led to the emergence of local authorities and non-governmental organizations in protecting the natural environment.

Previous studies Institute of Geological and Mineral Researches (IGME 1986) have recognized the importance of the karstic aquifer and provided drilling and groundwater level data. In this study, the results of a hydrogeological study, including development of aquifers, hydraulic parameters and groundwater quality are presented. The purpose of this paper is to propose a policy for creating an integrated management for the groundwater resources of Zakynthos Island. For this reason, strengths, weaknesses, opportunities and threats (SWOT) analysis was applied in order to optimize the measures for sustainable groundwater.

Data collection and analysis

The following data were used for this investigation:

- Hydrometeorologic from Zakynthos station, located in the airport area at 8 m a.s.l. for the period 1970–1997. To calculate rainfall–altitude relationship, data from another five neighbouring rain gauges stations were used (Diamantopoulou 1999a).
- Zakynthos is covered by a geological map at a scale of 1:50,000; this map was surveyed by the IGME in 1980. Drilling investigations began in the late 1970. These data collected by IGME, including geological and hydrogeological information (depth and type of geological formations and aquifer), are reviewed in this study.
- Static water level measurements during non-pumping periods, between May and September 1995–1997 were used. Piezometric maps have been drawn using the kriging method. The Surfer Version 8 programme has been used for this purpose.

- Pumping test data to calculate the hydraulic parameters were provided by IGME. Constant rate pumping tests were used to determine Transmissivity (T) and Storage coefficient (S), applying Theis and Jacob methods. Specific capacity (Q/s) is defined as the ratio of discharge (Q) to drawdown (s) at the pumping borehole for a given time (Jalludin and Razack 2004).
- Field measurements of hydraulic conductivity of the vadose zone were made using the constant-head method.
- The exploitable dynamic groundwater reserve (Q_{ed}) is calculated, using the following formula: $Q_{ed} = A \cdot S_y \cdot l_d$, where A = effective area for groundwater recharge, S_y = specific yield, l_d = average water level decline in dry period. The exploitable dynamic groundwater represents the long-term average annual recharge under conditions of maximum groundwater use (Naik and Awasthi 2003).
- Groundwater quality data, based on chemical analyses during the period 1995–1997 (see groundwater quality).
- SWOT analysis was applied in order to optimize the sustainable groundwater resources management.

Climate

Two main geomorphologic domains occur on Zakynthos (Fig. 1): (1) Vraxionas mountain in the western part with the maximum altitude 756 m above mean sea level and (2) plateau in the eastern part. The total crop area is 134 km^2 and in a part of 4 km^2, irrigated agriculture is practiced National Statistical Service of Greece (NSSG 2001). The land is mainly used for the cultivation of vineyards, olives, citrus fruits and seasonal vegetables.

The island has Mediterranean type climate with wet winters and hot, dry summers. The hydrological year is considered to last from September to the end of August of the next year. The annual precipitation at the airport station, 8 m above sea level for the period 1970–1997 range between 337 and 1,243 mm; the mean value (m) is 826 mm and the standard deviation (s) 240. The coefficient of variation (s/m) is 0.29, showing wide dispersion of annual rainfall. An increasing number of droughts (e.g. 1977, 1989 and 1992–1993) have occurred during the last decades (Diamantopoulou 1999a).

Based on data from five rain gauges stations during the period 1970–1997 it is concluded that, the precipitation (P) is strongly correlated with the altitude (H) by the relation $P = 1.33H + 817 (R^2 = 0.89)$ (Diamantopoulou 1999a). The greatest annual rainfall values occur in the western part of the island (Vraxionas mountain) and a decrease is recorded Eastward.

Thus, the calculated mean annual rainfall rate in island is 1,050 mm corresponding to 428×10^6 m^3 year^{-1}. The rainfall occurs mainly from late October to May (85% of annual rainfall) and the peak season is from December to November. June and July are the months of the lowest rainfall of the island.

The average annual temperature is 16.8°C; January is the coldest month and July is the hottest one. The coefficient of the actual evapotranspiration, which is estimated with the Thornthwaite method, ranges from 62% in the coastal areas to 46% in the mountainous areas of the annual rainfall. Thus, the actual evapotranspiration is estimated to be around 247×10^6 m^3 year^{-1} or 57.7% of the annual rainfall.

Using the Thornthwaite method, the remaining amount of water is allocated to natural recharge (infiltration) and surface runoff. Thus, the natural recharge and runoff was estimated to be 181×10^6 m^3 year^{-1}. Out of this amount, a volume of water of 149×10^6 m^3 year^{-1} infiltrates in the limestones and then it is mainly discharged, through submarine springs, in the Ionian Sea.

The island is drained by small torrents. The flow in these torrents persists during the wet period, after heavy storms. The total surface potential was estimated to be 25×10^6 m^3 year^{-1} (Diamantopoulou 1999a). Based on future global warming scenarios, a sea level rise in Mediterranean Sea will be an additional threat to the water supply and the quality, with major economic impacts to the island (Kent et al. 2002).

Geological setting

From a geological point of view, Zakynthos belongs to the Paxos (Pre-Apulian) zone apart from the east part of the island, which belongs to the frontal part of the Ionian zone (Aubouin and Dercourt 1962; Underhill 1989). The Ionian zone is considered to be overthrusted to the Paxos zone. The Paxos zone consists of an east-dipping Upper Cretaceous to Plio-Quaternary sedimentary succession. The main part of the Paxos zone in the island, which consists of Upper Cretaceous limestones that are overlain by Eocene limestones (Kati 1999). Limestones cover about 50% of the total area of the island (Vraxionas mountain). Further to the East, a narrow Oligocene zone overlies on the Eocene deposits and consists of marly limestones and marls. The remaining part is covered by Miocene and Pliocene. In the lower Miocene beds, occur gypsum deposits. The Pliocene sequence contains two units: (a) a lower of marls and marly sandstones, and (b) an upper of sandstones deposits with intercalated marls (Kypseli unit).

The Ionian zone deposits consist of Triassic gypsum and evaporites, which are strongly affected by diapirism and black limestones that overlay the gypsum beds. The approximate trace of the Ionian trust is based on the western limit of Triassic evaporate outcrop. The remaining part of the Ionian zone is covered by Pliocene sediments (marls and sandstones). Diapiric intrusion has caused the development of folds, faults, dips and unconformities in the cover sediments (Underhill 1988). Exposed diapirs are dominated by gypsum. Boreholes data, obtained by British Petroleum record that over 1,500 m of halite occurs in the subsurface (B.P. Co Ltd 1971).

The Quaternary deposits include Pleistocene and Holocene deposits, which are developed in the eastern part of the island and consist of alternating beds of gravels, sands, clays and silty clays. The Pleistocene deposits cover the hills (100–200 m a.s.l) and the alluvial deposits the lowlands, with an average thickness of 5–10 m. A simplified geologic map of the island and a geological section are shown in Fig. 2.

A well-defined, SW–NE trending pericline exists in the West, which is dissected by E–W trending, high-angle, dip-slip extensional faults (Underhill 1989). Contractional structures characterize many areas in the Cretaceous outcrop and also include the development of numerous NW-SE oriented reverse faults.

Hydrogeological setting

Aquifer systems

Three main aquifer systems are encountered in the island: (1) the karstic aquifer of carbonate formation, (2) the confined aquifer, which is developed in neogene deposits, named Kypseli unit and (3) the shallow unconfined alluvial aquifer. In Table 1 the hydrogeological and hydraulic properties of the aforementioned aquifers, are shown.

Karstic aquifer

The carbonate rocks of the Paxos zone comprise the karstic aquifer, which has a high permeability, associated with karstification and secondary fracture porosity (Mandilaras et al. 2006). The percentage of rainfall, which infiltrates through the carbonate rocks has been estimated to be around 50% of the annual precipitation (Diamantopoulou 1999a).

The yield of boreholes, ranges from 20 to 80 $m^3\ h^{-1}$ and the average Transmissivity is $1.7 \times 10^{-2}\ m^2\ s^{-1}$ (Table 1). The Transmissivity (T) correlates well with the specific capacity (Q/s) and the best fit line is (Fig. 3): $T = 0.209(Q/s)^{0.78}(R^2 = 0.76)$. In the eastern part the karstic aquifer system is in contact with the fine grained Miocene deposits and in the western part, groundwater is discharged through submarine springs in the Ionian Sea. Groundwater flow is controlled by the pattern of the existing fracture system. The lower active karstic is located at depths ranging from 10 to 100 m, below sea level, as deduced from drilling data (IGME 1986). During the last decades, this aquifer is exploited by 35 deep boreholes.

The groundwater table was at depth 2–5.5 m above mean sea level. Due to intensive exploitation during the prolonged dry periods, the water level declined. Hydrographs of selected boreholes, are presented in Fig. 4. The hydrographs except from the various water level fluctuations, they also show the decline of the water level during those dry periods. Assuming an average decline of 3.5 m the exploitable groundwater reserves were estimated to be $2.1 \times 10^6\ m^3\ year^{-1}$ (Diamantopoulou 1999a).

According to the European classification (Calaforra et al. 2004) the karstic aquifer system of Zakynthos Island is low to medium permeability, free or semi-confined conditions with some intrusion problems and moderate exploitation.

Confined aquifer of neogene deposits

This aquifer is developed in the sandstones of neogene (Pliocene) deposits (Kypseli unit), forming a multiple aquifer system with an average thickness of 50 m. As a result of their origin, the deposits are characterized by a high degree of heterogeneity and anisotropy.

The average Transmissivity (T) and Storage coefficient (S) values are $T = 2.4 \times 10^{-3}\ m^2\ s^{-1}$ and $S = 3.8 \times 10^{-3}$, respectively, as deduced from the conducted pumping test analyses (Diamantopoulou 1999b). The best fit equation that correlates Transmissivity and specific capacity is (Fig. 3): $T = 3.02(Q/s)^{1.086}(R^2 = 0.92)$. This equation can be used to calculate the Transmissivity in boreholes, where specific capacity data are available.

The aquifer of Kypseli unit in the northeastern part of the island, has a high water potential. Groundwater recharge of the aquifer, mainly takes place by direct infiltration during rainfall. In the eastern part of the island, the aquifer is in direct hydraulic communication with the sea, contributing to seawater intrusion during the dry periods, when the abstractions exceed the natural recharge of the aquifer. Using the constant-head method, the hydraulic conductivity of the vadose zone was estimated to be $1.5 \times 10^{-6}\ m\ s^{-1}$ and it contributes to the protection of the groundwater from pollution sources.

Figure 5 shows the piezometric map, which was constructed from interpolated field measurements, in September 1997. The direction of groundwater flow, is generally from South to North-East at an hydraulic gradient of 2–7%, as measured from the compiled piezometric maps. Piezometric lines, up to 600 m from the coast, were negative at a

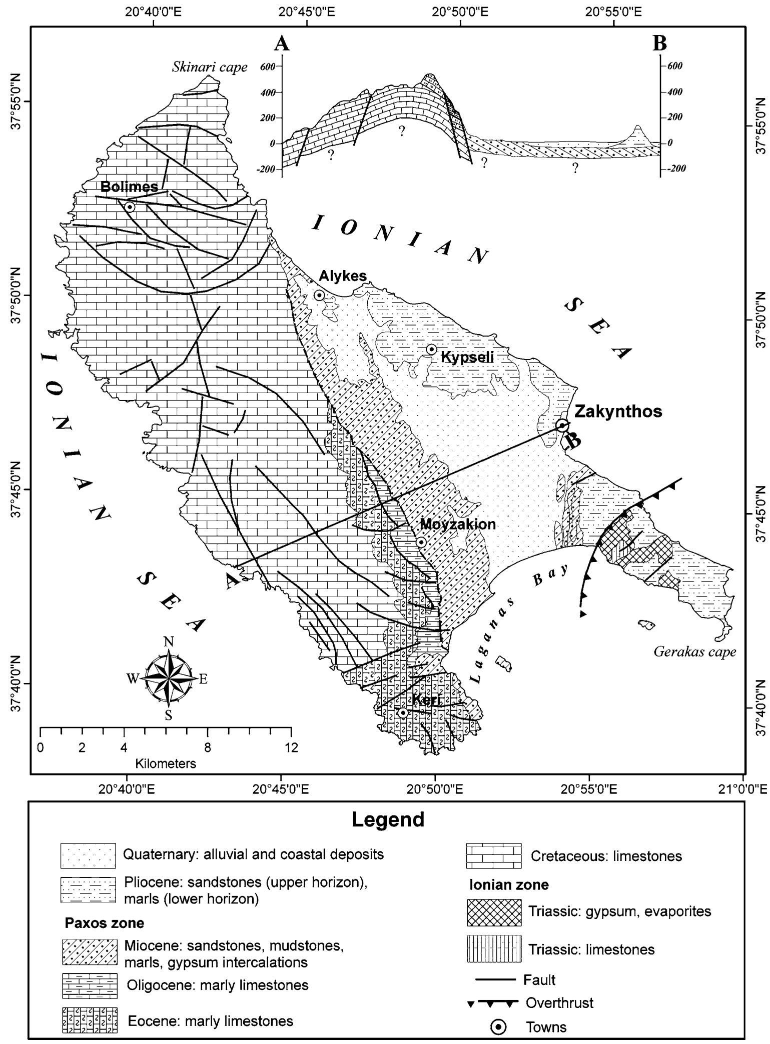


Fig. 2 Geological map (*above*) and geological section (*below*) of Zakynthos Island (adapted from IGME 1980, with changes)

depth of 5 m below the sea level. The decline of the average level during the dry period from May to October, is 5.5 m. Thus, the exploitable groundwater reserves were estimated to be 0.3×10^6 m^3 year^{-1}.

Phreatic alluvial aquifer

Alluvial aquifer, is developed in Quaternary deposits in the central eastern part of the island. These deposits, reach a maximum thickness of 10 m. The alluvial aquifer is unconfined (phreatic) and is characterized by medium potential.

The occurrence of fine-grained materials in the Miocene deposits developed between karstic and alluvial aquifer, suggests that the lateral inflows from the karstic aquifer are negligible (Diamantopoulou 1999a). The hydraulic parameters of the aquifer vary widely, due to the lithological variability of the deposits. The hydraulic conductivity (k) ranges from 6×10^{-5} m s^{-1} to 3.2×10^{-3} m s^{-1} (Table 1). Groundwater flow nearly follows the surface drainage pattern. Overexploitation has caused a decline of groundwater levels and changes in the direction and the velocity of groundwater flow. The general groundwater flow direction in alluvial aquifer, is South-East oriented (Fig. 6).

The water table elevation is highest in April and lowest in October. The average levels that rise in the wet period, which is from October to April, range from 2 to 4 m. The mean hydraulic gradient of alluvial aquifer, ranges from 10 to 15‰ in the inland to 1–5‰ close to the coast. Comparing the groundwater level map (Fig. 7) of the September 1980 period (IGME 1986, unpublished data) with the map of September 1997 period (Fig. 6), an extension of the depression cone towards inland can be observed. Furthermore, there is no identifiable difference in groundwater flow direction. The exploitable groundwater reserves were estimated to be 0.9×10^6 m^3 year^{-1}.

Land use and water uses in Zakynthos

The total crops area is 166.64 km^2 including the fallow land 24.2 km^2 in 2001 (Table 2). The areas of major land

Table 1 Hydrogeological characteristics of the aquifers in Zakynthos Island

Aquifer	Geological formations	Hydraulic characteristics
Karstic aquifer	Karsticified limestones	d_{av} = 100 m, A = 18 km^2
		P_{ef} = 4%
		$k = 6 \times 10^{-4}$ m s^{-1}
		$T = 1.7 \times 10^{-2}$ m^2 s^{-1}
		$C_{sp} = 3.6 \times 10^{-2}$ m^3 s^{-1} m^{-1}
		$Q_{ed} = 2.110^6$ m^3 year^{-1}
Confined aquifer	Pliocene deposits sandstones with marls and clays	d_{av} = 50 m, A = 15 km^2
		$k = 2.8 \times 10^{-4}$ m s^{-1}
		$T = 2.4 \times 10^{-3}$ m^2 s^{-1}
		$C_{sp} = 1.3 \times 10^{-3}$ m^3 s^{-1} m^{-1}
		$S = 3.8 \times 10^{-3}$
		$Q_{ed} = 0.3 \times 10^6$ m^3 year^{-1}
Phreatic aquifer	Alluvial deposits	d_{av} = 6–10 m, A = 59 km^2
		$P_{ef} = 10^{-2}$
		$k = 6 \times 10^{-5}$ m s^{-1} – 3.2×10^{-3} m s^{-1}
		$T = 1.6 \times 10^{-2}$ m^2 s^{-1}
		$Q_{ed} = 0.9 \times 10^6$ m^3 year^{-1}

d_{av} average thickness (m), A effective area (km^2), T transmissivity (m^2 s^{-1}), k hydraulic conductivity (m s^{-1}), *Pef* effective porosity, *Csp* specific capacity (m^2 s^{-1} m^{-1}), S storativity, Q_{ed} exploitable dynamic groundwater reserves (m^3 year^{-1})

use classes are shown in Fig. 8, based on Corine Land Cover data (Bossard et al. 2000).

The land is used mainly for the cultivation of crops on arable land (32.25 km^2), olive trees (65.14 km^2), vineyards

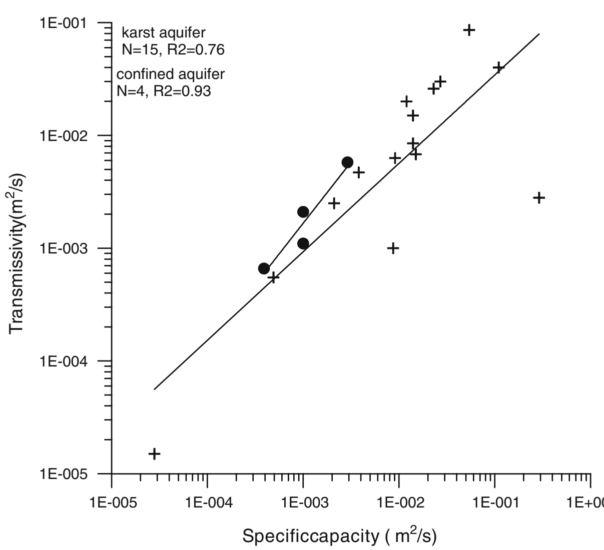


Fig. 3 Transmissivity (m^2 s^{-1}) versus specific capacity (m^2 s^{-1}) in the karstic (*crosses*) and confined aquifer (*circles*). *Solid line*: best fit line

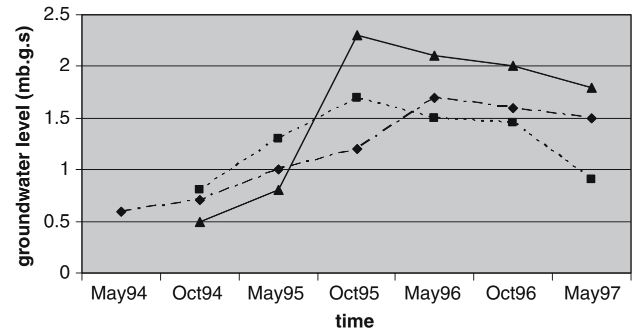


Fig. 4 Hydrograph of groundwater table fluctuations (m from the ground surface) in the karstic aquifer

(31.84 km^2), citrus fruits (9.18 km^2) and garden area (4.05 km^2). The total irrigated area is 5.25 km^2, according to the Ministry of Agriculture and NSSG (NSSG 2001). The percentage of the irrigation area has increased between 1971 and 2001 from 2 to 3.2%. Chemical fertilizers are used for the cultivated crops in the island. In terms of nitrogen (N), an amount of 30–100 kg ha^{-1} year^{-1} is recommended, depending on the type of cultivation.

Water resources in Zakynthos Island is characterized by high water requirements for agricultural and tourism during the dry period (April–late October) when water availability is low. The groundwater is abstracted for domestic and irrigation purposes. Based on data from the NSSG, the permanent population of the island is 12,000 (NSSG 2001). According to the local authorities during the summertime, the island's population increases by 1,000%, because of the high rates of tourism. The tourism industry requires big quantities of water supply, with peak consumption during the dry period.

Based on the records of the Municipal Water Company, the average wintertime and summertime daily consumption per person is 160 and 240 L, respectively. Hence, the total consumption for domestic use, including the tourism industry requirements is: $Q_{dom} = 2.8 \times 10^6$ m^3 year^{-1}.

The groundwater abstracted, is used to cover irrigation needs of some 5.25×10^6 m^2 of the island. Based on data from the Ministry of Agriculture, the average annual crop water requirements are 0.35×10^6 m^3 km^{-2}. Hence, the total abstraction for irrigation use is:

$$Q_{irr} = 5.25\,\text{km}^2 \times 0.35 \times 10^6\,\text{m}^3\,\text{km}^{-2} = 1.8 \times 10^6\,\text{m}^3\,\text{year}^{-1}.$$

Irrigation period begins at May and finishes at September and apparently coincides with the maximum of domestic water consumption due to tourism. It should be mentioned that, during the dry years the abstraction rate for agriculture purposes is higher, because of the prolonged irrigation period and the increased needs for water. Apart from these aforementioned amounts, pumping for industrial needs

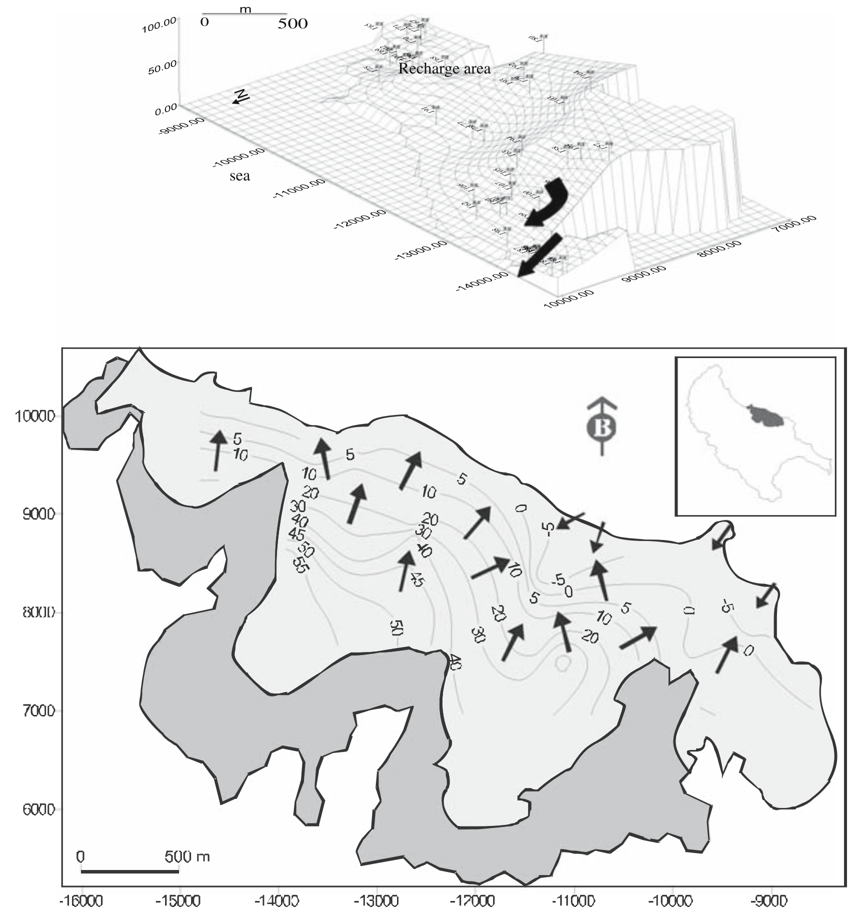


Fig. 5 3-dimensional map of the Kypseli unit confined aquifer with the boreholes location marked (*above*) and piezometric map (metres amsl) for September 1997 (*below*)

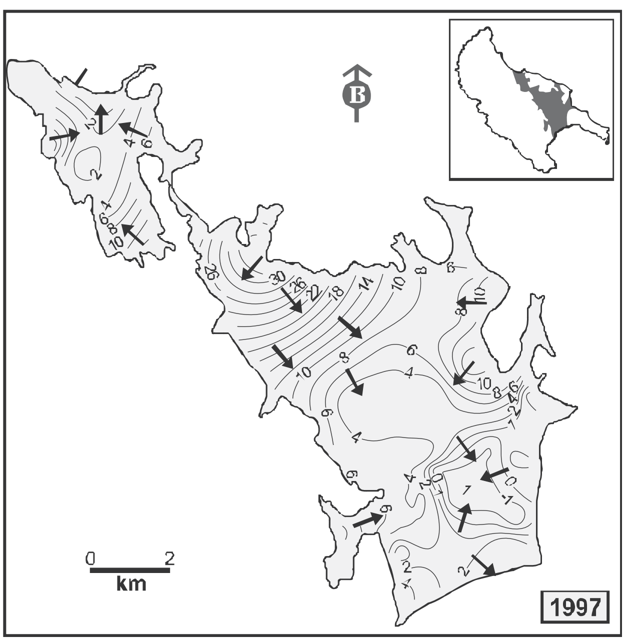


Fig. 6 Contours lines (metres amsl) in alluvial aquifer (September 1997)

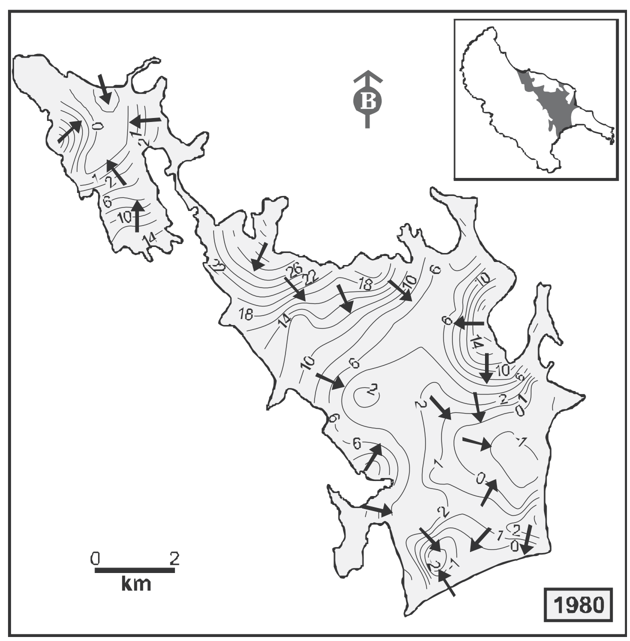


Fig. 7 Contours lines (metres amsl) in alluvial aquifer for September 1980 (IGME 1980)

Table 2 Total crops and irrigated areas in km^2

Year	Total crops	Total irrigated area
1971	143.48	2.94
1981	135.12	No data
1991	82.70	4.92
2001	166.64	5.25

Data from NSSG (2001)

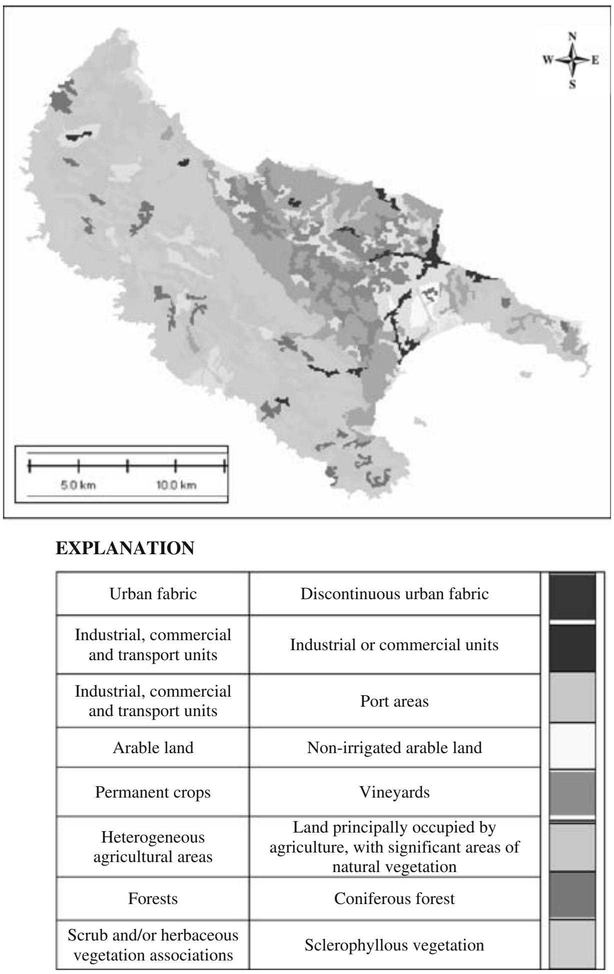


Fig. 8 The major land use classes in Zakynthos Island (Corine Land Cover data)

(mainly for olive extraction plants and livestock) was estimated to be 0.3×10^6 m^3 $year^{-1}$.

From the above-mentioned estimates, the average annual consumption in Zakynthos Island, is $Q_{con} = 4.9 \times 10^6$ m^3 $year^{-1}$ when the exploitable groundwater reserves were estimated to be 3.3×10^6 m^3 $year^{-1}$. Apparently, the delicate balance has been already disturbed affecting negatively the quantity, as well as the quality of the available groundwater recourses.

Groundwater quality

A large number of groundwater samples were obtained from production boreholes and wells as follows: 31 in September 1995, 15 in May 1996, 18 in September 1996, 111 in May 1997 and 95 in September 1997. All the samples were analysed for major ions, nitrites, ammonia and SiO_2. Electrical conductivity (EC), temperature (°C) and pH were also measured in situ. After filtration and preservation with acidification (HCl), the water samples from alluvial and confined aquifer were analysed by atomic absorption to determine the heavy metals concentration: Fe, Mn, Zn, Cu, Pb, Ni, Co and Cd.

The results of chemical analyses were tested by ion balance. The calculated errors are <5%, are not systematic, and are distributed between positive and negative values. Table 3 shows the mean values and ranges of the chemical parameters for the three aquifers.

The majority of the analysed samples show pH values >7, indicating a slightly alkaline type. The average temperature ranges from 18.4 to 19.4°C. EC varies between 307 and 6,430 μS cm^{-1} and indicates high values in those areas, where exploitation has been recorded and where the groundwater level is below the sea level. As it is illustrated in Fig. 9, there is a strong relationship between Total Dissolved Salts (TDS) concentrations and EC values ($R^2 = 0.92$) in all samples. The groundwater quality characteristics of each aquifer are presented below.

Karstic aquifer

The average value of EC (Table 3) ranges from 576 to 4,920 μS cm^{-1} and exhibits significant local variation. The higher value 4,920 μS cm^{-1} is equivalent to ~11% of the conductivity of seawater. In most of the samples, Total Hardness (TH) exceeds the value of 300 mg L^{-1} in $CaCO_3$, and also the groundwater is classified as very hard. Mean nitrate concentration is low, reaching 3.2 mg L^{-1}.

Mean chloride concentration in the groundwater ranges between 15 and 1,495 mg L^{-1}. Prolonged drought periods, which lead to increased groundwater pumping, cause groundwater level decline as well as a deficient groundwater balance in the karstic aquifer, which results in the triggering of the seawater intrusion. High chloride concentrations have been recorded towards the end of drought seasons. Seawater intrusion extends up to 4.5 km from North-Western shore and 2.5 km from the South-Eastern shore. The seawater intrusion has been probably favoured by some preferential paths, along the faults zones.

Table 3 Statistical summary of chemical parameters (mg L^{-1}) of groundwater samples

Parameters	Karstic aquifer		Confined aquifer		Phreatic aquifer	
	Range	Mean/SD	Range	Mean/SD	Range	Mean/SD
PH	6.65–8.36	7.33/0.34	6.40–7.63	6.89/0.24	6.06–8.53	7.27/0.39
EC (μS cm^{-1})	576–4,920	1,941/1,055	385–1,634	1,102/248	307–6,430	1,793/956
TH (mg L^{-1} $CaCO_3$)	188–594	3,777/107	120–210	185/11.5	150–240	194/16.1
T (°C)	17–21	18.4/0.98	13–21	18.5/1.15	15/22	19.4/1.6
Ca^{2+}	69.6–180	105.5/30.4	40.8–226.7	153.2/41.1	16.8–518	180/89.4
Mg^{2+}	1.0–91.1	27.2/11.9	1–75.8	18.1/14.3	2.9–434	80.6/77.8
Na^{+}	5.6–744	199.2–/120.4	13.0–274	51.8/37.7	11.6–2,067	242.7/275.8
K^{+}	0.4–33.2	8.5/6.7	0.5–20.8	2.71/3.9	0.4–112.2	10.1/15.1
HCO_3^{-}	112.2–461.2	246.2/72.3	85.4–502.6	348.6/71.6	87.8–827	400.9/140.1
Cl^{-}	15–1,495	391.8/222.4	17–200	77.4/33	18/1,790	466/302
SO_4^{2-}	0.1–235	74.9/52.8	0.8–500	154.5/76.4	3–1,800	401/357
NO_3^{-}	0–36.3	3.2/5.7	0–52.8	17.6/13.3	0.6–56.9	11.1/15.4
NO_2^{-}	0–0.2	0.02/0.04	0–7.7	0.18/0.09	0–9.1	0.34/1.22
NH_4^{+}	0–0.3	0.06/0.09	0–3.92	0.73/0.1	0–3.87	0.9/0.92
PO_4^{3-}	0–1.12	0.14/0.24	0–2.0	0.21/0.35	0.03–2.21	0.4/0.41
Fe	0–0.4	0.03/0.07	0–1.87	0.1/0.2	0–3.9	0.1/0.41
Mn	0–0.3	0.07/0.09	0–8.8	0.51/1.2–3	0–17.5	1.3/3.1
SiO_2	0–23.2	4.4/3.5	0.2–18.4	6.9/5.3	0.4–16.5	4.03/3.7
Zn (μg L^{-1})			7–753	105.2/89	7.5–776	74/101
Cu (μg L^{-1})			0–43	7.7/15	0–212	18.5/22
Pb (μg L^{-1})			0–4	2.3/0.1	1–16	3.2/0.4
Ni (μg L^{-1})			0–7	1.1/2.8		
Cd (μg L^{-1})			0–0.17	0.03/0.01	0–0.545	0.18/0.004
Co (μg L^{-1})			0–0.7	0.08/0.001	0–5.4	0.3/0.7

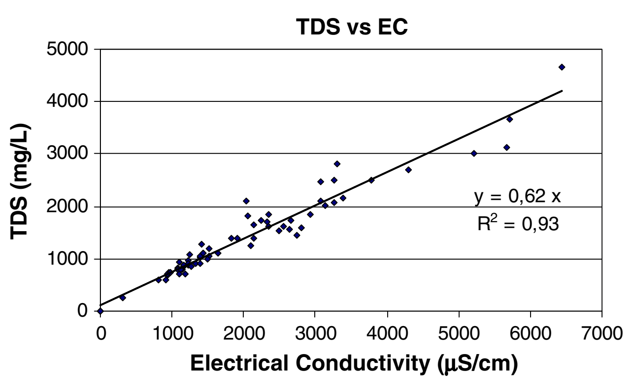


Fig. 9 Relationship between TDS concentrations (mg L^{-1}) and EC (μS cm^{-1}) values in all samples

Calcium and bicarbonate are the predominant ions in fresh waters near the recharge zones and Ca–HCO_3 type is the main type of groundwater from the karstic aquifer. A Na–HCO_3 to Na–Cl type of water (Fig. 10) denotes excessive mixing, ion exchange processes and saline water intrusion (Appelo and Postma 1996).

Confined aquifer of neogene deposits

According to Table 3, the confined aquifer of neogene deposits contains fresh to mixing water. The EC values range between 385 and 1,634 μS cm^{-1}. Furthermore, groundwater contains Ca^{2+} (41–226 mg L^{-1}), Mg^{2+} (1–76 mg L^{-1}), Na^{+} (13–274 mg L^{-1}), K^{+} (0.5–20.8 mg L^{-1}), HCO_3^{-} (85–502 mg L^{-1}) and NO_3^{-} (0–52 mg L^{-1}).

The Cl^{-} concentration, as determined by the titration method, ranges from 17 to 200 mg L^{-1} and the mean value is 77 mg L^{-1}. It is worth mentioning, that the Cl^{-} concentration was higher near the end of dry season (October). Sulphate (SO_4^{2-}) concentration ranges from 1 to 500 mg L^{-1}. High SO_4^{2-} concentrations could be attributed to gypsum dissolution. Sulphate reduction is also a typical reaction in some areas (Martinez and Bocanegra 2002):

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^{-}.$$

The occurrence of H_2S in some areas, e.g. Mouzakion, indicates that sulphate reduction takes place, causing an increase of HCO_3^{-}. The predominant groundwater

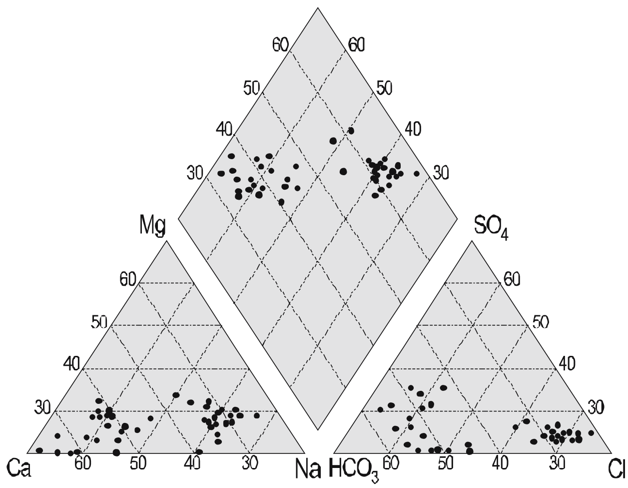


Fig. 10 Piper diagram of groundwater samples from karstic aquifer

hydrochemical type, as illustrated by the Piper diagram in Fig. 11 is: Ca–HCO_3 and Ca–HCO_3–SO_4.

Phreatic alluvial aquifer

The unconfined (phreatic) aquifer is developed within the alluvial deposits. It can be concluded from Table 3 that the aquifer contains low groundwater quality. Indicative of the extent of groundwater deterioration, is the fact that the aquifer is not suitable for supplying water for potable use, not even for irrigation. The EC ranges from 307 to 6,430 μS cm^{-1}; high values of EC along the coastline are attributed to seawater intrusion. The highest value (6,430 μS cm^{-1}) during the period 1995–1997, is equivalent to about 14% of the EC of seawater.

Nitrate concentration ranges from 1 to 57 mg L^{-1}. High nitrate concentrations are attributed to several reasons, most important of which are the irrational application of fertilization and irrigation doses and also the use of septic tanks in conjunction with the disposal of untreated domestic effluent into abandoned wells (Voudouris et al. 2004a). This means that through the nitrification processes with the presence of oxygen, ammonium is transformed from N-fertilizer into nitrates.

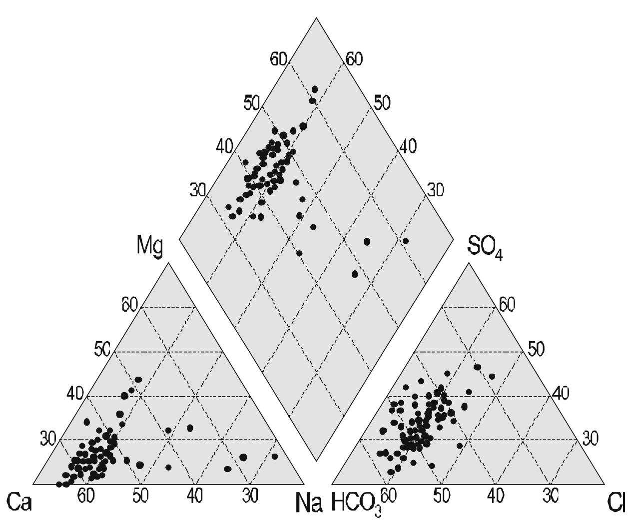


Fig. 11 Piper diagram of groundwater samples from confined aquifer

The Cl^- concentration ranges from 8 to 1,790 mg L^{-1}; the mean value is 466 mg L^{-1}. High chloride values have been recorded in the coastal area (Laganas Bay) due to seawater intrusion. The highest Cl^- concentration value 1,790 mg L^{-1} was recorded on September 1997 (not corresponding to the same sample of highest value of EC) is 10.5% of the chloride concentration of seawater. Prolonged dry periods in combination with the overexploitation of the aquifer, produce a lowering in the groundwater level and trigger the salinization process (Lambrakis et al. 1997).

Sulphate (SO_4^{2-}) concentration ranges from 3 to 1,800 mg L^{-1}. High sulphate concentrations can be associated with the dissolution of gypsum. Figure 12 illustrates the distribution map of chloride and sulphate in alluvial aquifer for September 1997.

The classification of groundwater types is illustrated in Fig. 13, by the Piper diagram. Four general groundwater groups have been identified: (1) Ca–HCO_3, (2) Ca, Mg–HCO_3–SO_4, (3) Na–HCO_3, Cl and (4) Na–Cl. The first two types represent fresh water, the third type characterizes water from the transition zone and the fourth type represents a typical brackish water in which the ions Na^+ and Cl^- predominate (Voudouris et al. 2004b).

Due to the overall increase of nitrate and chloride in groundwater, the waters from alluvial aquifer exceed the quality standards for the drinking water.

Heavy metals

Based on the results of the chemical analyses (Table 3), the heavy metal contents in the confined aquifer are in low concentrations. Iron (Fe) concentration is high in some places due to the oxidation of sulphide minerals (Stamatis et al. 2001). The mean manganese (Mn) concentration is 0.07, 0.51 and 1.3 in karstic, confined and alluvial aquifer, respectively.

High concentrations (>0.1 μg L^{-1}) of zinc (Zn) are recorded in alluvial aquifer, mainly in the central part due to the erosion process and the leaching of salts. High concentrations of copper (Cu) can be associated to Cu-fertilizer use (Diamantopoulou 1999a).

The majority of samples show Ni and Co concentrations below detection limits. According to Mandia (1993), the trace elements Cu, Mn, Ni and Cd have been detected in the leachate solutions of gypsum and/or anhydrite-bearing evaporites.

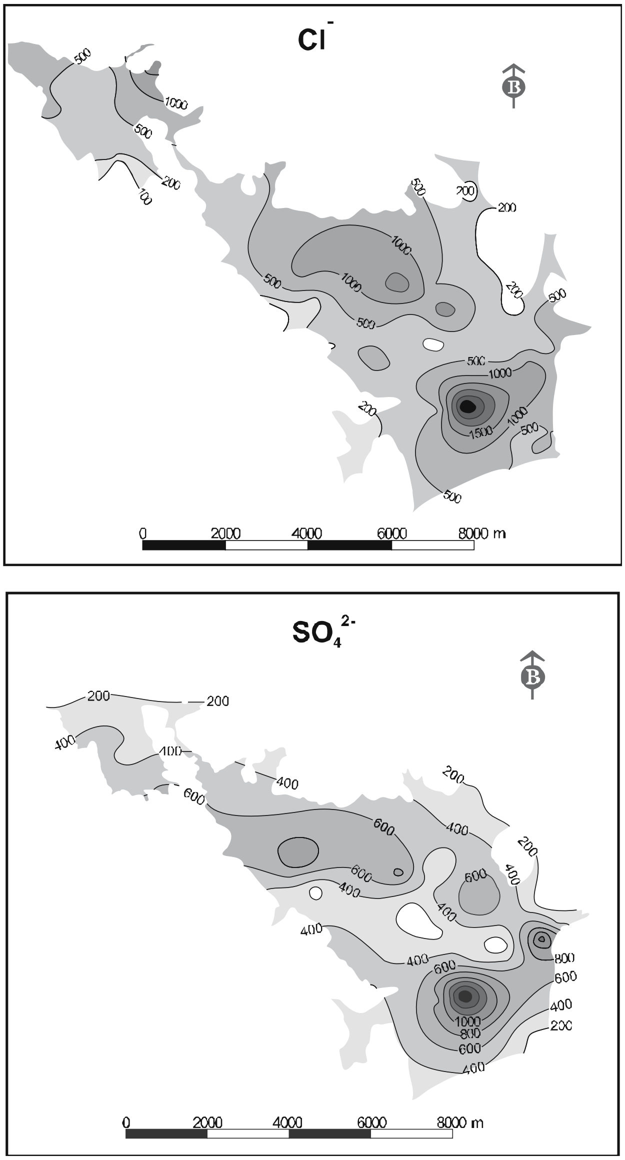


Fig. 12 Distribution maps of Cl^- and SO_4^{2-} (mg L^{-1}) in alluvial aquifer (September 1997)

SWOT analysis

Strengths, weaknesses, opportunities and threats analysis is a useful tool for the planning development and decision-making and has widely been applied to environmental planning and water resource management (AHRD 2001; Baser 2001; ELARD 2004). The acronym SWOT corresponds to the initial of the included parameters: SWOT.

Strengths and weaknesses are factors of the system (internal issues), while opportunities and threats are factors of the external environment (external issues). In other words, a SWOT analysis helps find the best match between environmental trends (opportunities and threats) and internal capabilities and facilitate a strategic approach to

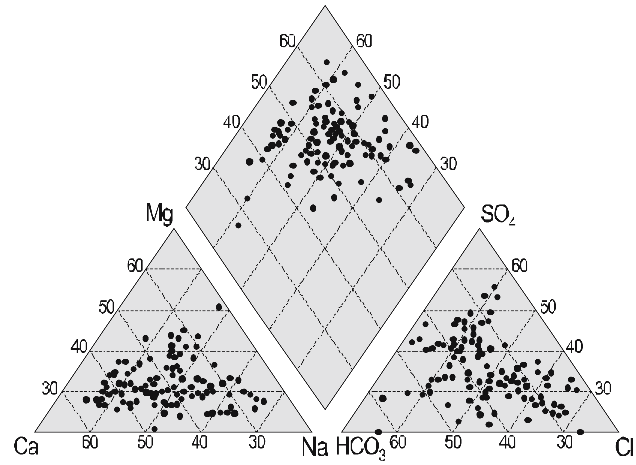


Fig. 13 Piper diagram of groundwater samples from phreatic alluvial aquifer

administration (Richards 2001). Concerning the application of SWOT analysis, it is necessary to minimize or avoid both weaknesses and threats. Weaknesses should be converted them into strengths (Danca 2000). Likewise, threats should be converted into opportunities. In addition, strengths and opportunities should be matched to optimize the water resources of the island.

The basic dimensions of the analysis, are shown in Fig. 14. Briefly, the process of the application of the method includes the following steps (Hill and Westbrook 1997):

- Recording of the present situation in the research area.
- Examination of the possible acts for the facing of the problems that were detected.
- Analysis of the opportunities and the threats that come from external environment.
- Analysis of the strengths and the weaknesses of the system and finally.
- Categorising of the proposed actions.

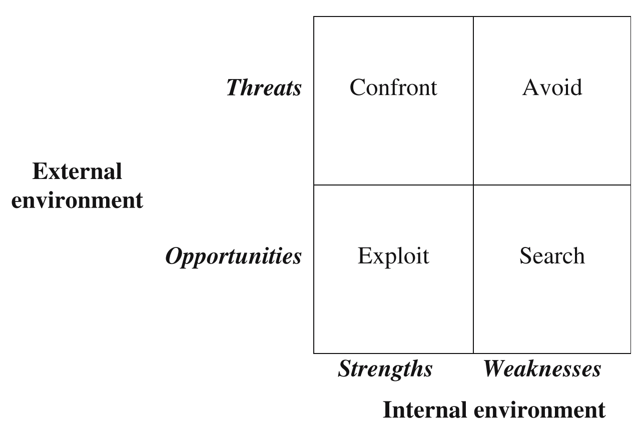


Fig. 14 Basic dimensions of the SWOT analysis (Richards 2001)

In this study, the SWOT analysis is applied as a technique for the sustainable groundwater management in order to conserve groundwater and protect its quality. According to the methodology (European Commission 1999), it is necessary to analyse the strengths and the weaknesses that influence the aquifer systems of the island. Furthermore, the opportunities and the threats must be analysed in order to facilitate the sustainable development of the water resources.

The SWOT analysis has been based on the detailed examination of the existing conditions of water resources on the island. The stresses on groundwater resources are: urbanization, population growth, tourism and agricultural development, climatic changes, environmental needs and lack of rational management. The effects of the aforementioned stresses on groundwater are the increased water demand, the depletion of the aquifers and the groundwater quality deterioration.

Table 4 shows the framework of SWOT analysis in groundwater resources, including the elements of the internal environment (strengths and weaknesses) that are detected in the island. The strengths are the availability of the surface water during the wet period and treated wastewater that can be exploited. Desalination of seawater and brackish water is one of the ways of meeting water demands. Recently, considerable attention has been given to the use of renewable energy (solar and wind) as sources for desalination. Renewable energy coupled to desalination offers a promising prospect for covering the needs of water in island. Furthermore, the existence of recent hydrogeological studies is an advantage for the rational water resource management, as it can provide new data and contribute to the planning of better strategies in order to achieve water sustainability.

The weaknesses are the increased water demand during summertime for agricultural and tourism when the water availability is low, the lack of adequate monitoring data (groundwater levels, quality data, discharge of springs, torrents, etc.), the lack of surface water protection measures, the insufficient knowledge of water-saving practices in agriculture, the inadequate water pricing and the lack of economic incentives for efficient water use. Furthermore, Table 4 includes the elements of the external environment (opportunities and threats). The opportunities conclude situations, e.g. EU financial assistance, EU Framework Directive (2000/60/EC), Nitrate Directive (91/676/EC) and experiences on integrated management of coastal aquifers from other islands.

The importance of integrated water resources management is emphasized in the recent EU water framework directive (2000/60/EC). The Directive 2000/60/EC provides new legislation and opportunities for the sustainable management of water resources. A major objective is to reach a good quantitative and chemical status of groundwater within 15 years from the entry into force of the Directive (2000/60). The directive requires the establishment of monitoring programmes covering groundwater quantitative status, chemical status and the assessment of significant, long-term pollutant trends resulting from human activity by 22 December 2006 at the latest.

In response to this Directive, Greek authorities have taken suitable initiatives to harmonize Greek water policy (Law 3199/2003). In order to achieve an effective implementation of the Directive in Greece, seven water districts are proposed, based on hydrogeological and hydrological criteria considering the current administrative structure of the country (Mimikou 2002). The first water district includes Peloponnesus and Zakynthos Island. It is pointed out that, Greece is among the last countries in relation to the implementation of the Directive and is quite behind schedule compared to other European countries (Mimikou 2005).

The threats are situations that might cause problems, e.g. climatic changes (sea level rise and enlargement of seawater intrusion), tourist competition pressures with other islands, which lead to high standards of water quality, proliferation of golf courses and continued increase in water demand, and finally the lack of effective administration on national basis (non-coordination among institutes–universities–ministries and others end users, centralization, lack of special regulations and laws, lack of dissemination of information).

The evaluation of the aforementioned elements of SWOT analysis may give decision makers and water resource managers new insights into choosing the appropriate strategies for sustainable groundwater management of the island.

Conclusions-recommendations for a groundwater management strategy

Zakynthos Island is solely dependent on groundwater resources for its water supply. The main aquifers of the island are the karstic aquifer in carbonate rocks, the confined, which is developed in neogene deposits, and the unconfined alluvial aquifer. The pressures on groundwater resources are: urbanization, population growth, tourism and agricultural development, climatic changes, environmental needs and lack of rational management.

The average annual consumption in Zakynthos Island, abstracted from all the aquifer systems is $Q_{con} = 4.9 \times 10^6$ m^3 year^{-1}. The exploitable groundwater reserves were estimated to be 3.3×10^6 m^3 year^{-1}. Results demonstrate that the management of the aquifer systems is really un-

Table 4 SWOT analysis for groundwater resources in Zakynthos Island

Strengths
Availability of treated wastewater for irrigation use
Availability of surface water (torrents and springs) during the wet period
Existence of recent hydrogeological studies
Presence of Municipal Water Company of Zakynthos that manages the drinking water use
Limited industrial activities
Possibility of construction of desalination plant
Weaknesses
Increased water requirements for agricultural and tourism during the dry period (April–late October) when the water availability is low
Lack of adequate monitoring data (groundwater levels, quality data, discharge of springs and torrents and land uses changes)
Lack of surface water protection measures
Insufficient knowledge of water-saving practices in agriculture
Inadequate water pricing and lack of economic incentives for efficient water use and less polluting practices
Lack of know-how of decision-makers
Opportunities
Making productive of European financial assistance in water resource management activities/projects
EU Water Framework Directive (2000/60/EC) to ensure good chemical status for groundwater
Nitrate Directive (91/676/EC) which requires member states to take measures to reduce agricultural nitrate
Experiences in integrated management of coastal aquifer systems from other areas
Threats
Climatic changes (prolonged dry periods, sea level rise and enlargement of seawater intrusion)
Touristic competition pressures with other islands, which lead to high standards of water quality, proliferation of golf courses and continued increase in water demand
General problems in national administration (centralization, lack of special regulations and laws, non-coordination among institutes–universities–ministries and others end users, lack of dissemination of information, etc.)

safe. The aquifer system has shown signs of depletion, seawater intrusion and quality contamination. The intensive exploitation has caused a drawdown of the water table; the largest depressions have been recorded in Southeastern part of the island.

Sea water intrusion extends up to 4.5 km from the Northwestern shore and 2.5 km from the Southwestern shore in karstic aquifer. Seawater intrusion phenomena are also recorded in the Southeastern part of the island (Laganas bay), where the phreatic alluvial aquifer is developed.

High sulphate concentrations might be attributed to dissolution of gypsum. Given that the island is dominated by urbanization as well as rural land uses, high nitrate concentrations can be attributed to: (1) the use of fertilizers and (2) infiltration of municipal wastewater into groundwater from septic tanks.

Chemical analyses from groundwater, indicate that the water type in the recharge areas is a Ca–HCO_3 type, whereas the Na–Cl type is observed in coastal areas that are affected by sea water intrusion. Na–HCO_3 type characterizes mixing water from the transition zone between fresh- and sea-water.

Groundwater samples from alluvial and confined aquifer are enriched in Zn and Pb. The concentrations of Cd in the groundwater of confined aquifer are low, with few exceptions and in the phreatic aquifer are higher due to urban activities. The majority of the samples show concentrations of Ni and Co below detection limits.

Strengths, weaknesses, opportunities and threats analysis was applied in order to evaluate the SWOT of the groundwater resources. Based on SWOT analysis results, the following recommendations are proposed in order to restore the negative water balance, to provide adequate water and to improve the water quality in Zakynthos Island:

- Reduction of groundwater abstraction should be applied in the areas that are affected by seawater intrusion.
- Utilization of the treated wastewater for irrigation purposes in order to decrease the groundwater abstraction. The use of reclaimed or recycled waste water for various non-potable uses has proved to be the most reliable of sources, like in most Mediterranean countries (Chartzoulakis et al. 2001). In Zakynthos, it is estimated that, more than 4,000 m^3 day^{-1} in wet period

and 8,000 m^3 day^{-1} in dry period of secondary treated waste water effluent is produced.

- Water-saving techniques such as spray irrigation and drip irrigation should be applied in order to decrease the groundwater quantities used for agriculture. Training courses should be organized in order to educate people in using methods to optimize water use.
- Planning of surface water protection measures, such as banning of the olive oil mills and domestic effluent disposal in torrents, as well as construction of proper landfills, which are environmentally compatible.
- Construction of small interception dams in the main torrents of the hilly region, aiming at the retardation of wintertime torrential flows and the increasing of the groundwater recharge. In addition, these dams would improve the water supplies for the agriculture requirements.
- Construction of desalination plant to supply the tourist demand during the summertime when the fresh water availability is low, in order to decrease the abstracted groundwater from coastal aquifers and to reduce the risk of marine intrusion.

The low price of water, results in people not saving water; thus, effective measures must be taken to prevent the unconsiderable use of water, e.g. incentives for efficient water use. An interesting dimension to the problem would be to introduce an 'ecotax' for the tourists and the visitors to the island (Kent et al. 2002).

The present water resource management scheme is centralized and is characterized by the lack of special laws and regulations. Therefore, a more decentralized administration system of water supply, under the Municipal Water Company of Zakynthos, should be set up. As a member state of the EU, the Directive 2000/60/EC sets the framework and objectives for sustainable management of water resources in Greece. Initiatives have been taken by Greek authorities in order to harmonize Greek water polity (Law 3199/2003) and the Directive is in process of implementation.

Finally, a systematic monitoring of both groundwater level and quality should be applied in a sufficient number of boreholes, in order to avoid seawater intrusion phenomena on a large scale. The solution of the water supply problem for the island could be made on the frame of rational management of water resources, but will require high expenditures.

Acknowledgements The authors would like to thank Diana Sotiropoulou, MSc Environmental Technology, Imperial College of London for her help in correcting the manuscript and Andreas Antonakos, MSc Applied Geology, University of Patras for his assistance in designing the maps. The authors greatly appreciate the careful revisions of the anonymous referees.

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