Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.800253

52 (2014) 2494–2501
March

Taylor & Francis
Taylor & Francis Group

Karstic spring water quality: the effect of groundwater abstraction from the recharge area

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Received 12 November 2012; Accepted 4 April 2013

ABSTRACT

Karstic systems are complex hydrogeological systems which are difficult to study due to their complicated function mechanism. This mechanism is even more complex in coastal karstic springs due to sea water intrusion into the system. Modelling of water quality of such coastal karstic springs is a real challenge, which requires an interdisciplinary effort based on hydrodynamic monitoring and accurate characterization of geology and hydrogeology of the system. The paper examines the impact of simultaneous groundwater abstraction from the recharge area of a karstic spring (upstream of the spring) on the water quantity and quality of the spring. The case study examined is Almyros brackish karstic spring in Heraklion, Crete. Based on standard statistical tests of the water quantity and quality indicators time series before and after the initiation of simultaneous groundwater abstraction from the recharge area of the spring, it was concluded that water quality of the spring deteriorates (represented by Cl^- concentration) and the quantity decreases for the summer period. However, no statistically significant influence on both quantity and quality was detected during the winter period months.

Keywords: Karstic springs; Brackish water; Water quality; Groundwater abstraction; Reconnaissance Drought Index; Almyros (Crete) spring

1. Introduction

Coastal karstic aquifer systems are very important sources of freshwater in many regions of the world. These systems have complex and unique features: (a) they constitute important fresh groundwater resources; (b) they are very heterogeneous having tectonic discontinuities and complicated geological structure; and (c) their water varies considerably during the hydrological year in terms of quality (chloride concentration, conductivity, etc.) and quantity (groundwater levels, discharge, etc.) [1–7].

Furthermore, the seawater intrusion in coastal karstic aquifer systems results in the degradation of the water quality of karstic springs. It is therefore very important to examine the water quality of springs and the causes of its salinization. Coincidentally coastal karstic springs exist in some parts of the world which have very limited water resources [1]. Improving the quality of the spring water is particularly important for providing good quality water for use by local communities particularly under conditions of water

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scarcity and climate change; while the climate change issue offers opportunities to many countries for applying corrections to poorly managed water systems [2].

Although many interdisciplinary research efforts have been made worldwide for the understanding of the functional mechanisms within various karstic water systems that control the impacts of groundwater abstraction from the upstream areas, it is not yet fully understood [3–9]. In order to better understand the karstic systems, advanced qualitative and quantitative modelling can be applied. The modelling of the coastal karstic aquifer systems should also be supported by the detailed detection of the geometry of the karstic conduits; while the calibration and the testing of the models should be assisted by systematic continuous measurements taken *in situ* through the use of a monitoring system. In order to study any influence of groundwater abstraction from the recharge area of the spring water quantity, quality parameters time series of all these parameters together with climate indices are required. The most common methodology for determining impacts and pressures is the Driver-Pressure-State-Impact-Response (DPSIR) approach which is adopted by the Directive 2000/60/EC. According to the DPSIR, there is a chain of causal links starting with "drivers" (causes) through "pressures" (e.g. contaminants) to "states" (e.g. chemical and biological) and "impacts" on ecosystems (function and structure) and eventually leading to "responses" (policy) [10,11]. The DPSIR approach has been widely applied in various countries [10–13]. In this paper, in order to assess the impact of groundwater abstraction from the recharge area of the spring on karstic spring water quality and discharge, we applied a conventional statistical methodology based on the null hypothesis test.

In short, the objective of this paper is to assess the impact of groundwater abstraction on karstic spring water quality and discharge; the case study examined is the Almyros karstic spring in Heraklion (Crete), in which groundwater pumping from the recharge area upstream to the coastal spring is implemented from 1988 onwards.

2. Case study

The Almyros karstic spring is located in the north part of the island of Crete, 1 km inland from the coast and 8 km west from the centre of Heraklion city (Fig. 1). The recharge area of Almyros spring is composed of the group of two units [4,14–16]: (a) the autochthonous permeable unit of Plattenkalk (geological bedrock) comprises limestones (not seen on Fig. 2); and (b) the

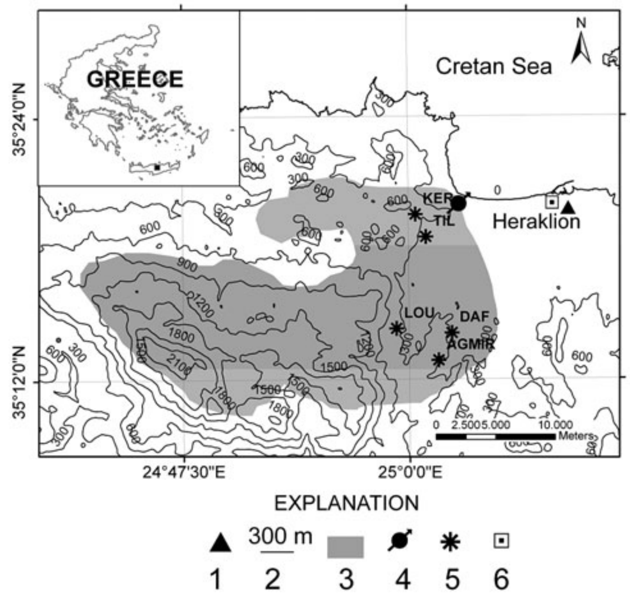

Fig. 1. General map of Crete Island showing the location of Almyros spring, the location of meteorological station, the locations of the five fields of groundwater abstraction boreholes and the recharge area of the spring. (1: Meteorological station, 2: contour line, 3: recharge area of Almyros spring, 4: Almyros spring, 5: field of groundwater abstraction boreholes, 6: city).

Tripolis unit comprises mainly karstified limestones and calcareous dolomites (Figs. 2 and 3). Locally, the two limestone units might be separated by the intercalation of Metamorphic Schists (Phyllites, Quartzites, Marbles) or Flysch which constitute an impermeable layer; while Neogene deposits dominate the eastern part of the study area. A large north–south fault plays a significant role in the function mechanism of the

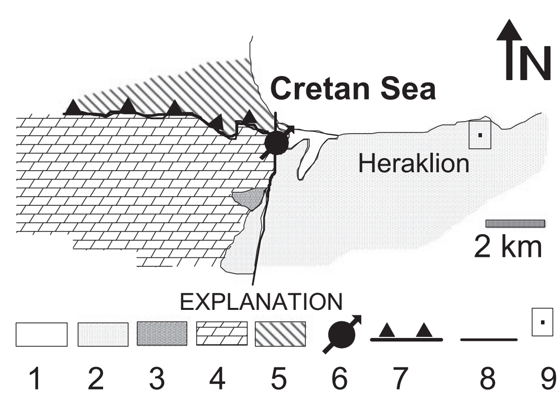

Fig. 2. Geological map of the study area showing the location of Almyros spring (modified from [15]) (1: Alluvium, 2: Neogene deposits, 3: Flysch, 4: Limestones of Tripolis unit, 5: Metamorphic Schists, 6: Almyros spring, 7: Thrust contact, 8: Normal fault, 9: City).

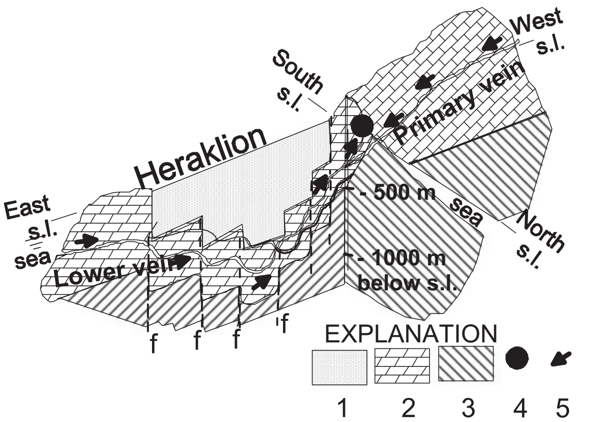

Fig. 3. Schematic block diagram of conduits in the karstic massif of the Almyros spring (not to scale—modified from [4]) (1: Neogene deposits, 2: Limestones of Tripolis unit, 3: Metamorphic Schists, 4: Almyros spring, 5: direction of flow in conduits during dry period, s.l.: sea level, f: fault).

Almyros spring (Fig. 2). The altitude of Almyros spring is + 3 m a.s.l. and the spring is the only identified outlet of a complex recharge area composed of several aquifer units. The spring flows out at the contact point between the limestones of Tripolis unit and the Neogene deposits (Figs. 2 and 3). Recent studies have shown that the distance from the Almyros spring to the marine intrusion is estimated to be between 2.5 and 10 km, depending on the dimensions of the conduits; while the seawater enters the karst conduit at a depth of about 500 m b.s.l. [14,17].

The electric conductivity of the Almyros spring water exhibits a high seasonal variability. The electric conductivity value of the Almyros spring water varies up to 331 $\mu S\,cm^{-1}$ (during the winter months) and up to 18,430 $\mu S\,cm^{-1}$ (during the summer months) as a result of the mixing of the seawater with freshwater [7,17].

In order to supply water to the city of Heraklion (nearly 200,000 inhabitants) and its touristic area which is considered as the most touristic area in Greece, about 40 boreholes located in five fields have been drilled since 1988. These fields of boreholes are located in the eastern part of the Almyros spring recharge area (TIL: Tilisos; KER: Keri; AGMIR: Agios Mironas; LOU: Loutraki; and DAF: Dafnes) (Fig. 1). The average annual groundwater quantity which is abstracted from the five fields of boreholes of the recharge area of Almyros spring is estimated as $11.8 \times 10^6\,m^3$ according to the data provided by the Heraklion Water Supply Utility Company (DEYAH) (Fig. 4); whereas Arfib et al. [14] reported that almost all boreholes reach an aquifer whose level suggests a direct link with the Almyros spring.

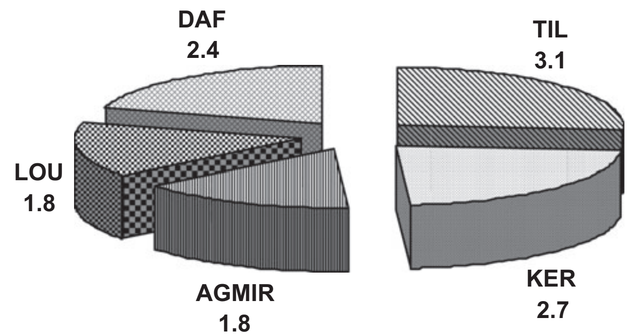

Fig. 4. Fields of groundwater abstraction boreholes located within the recharge area of Almyros spring and the average annual volumes of abstracted water ($\times 10^6\,m^3$).

Maramathas et al. [18] concluded that elevating of the spring water outlet improves the water quality and the time intervals with good quality water become longer. The first study that proposes the analysis of discharge-salinity lag to estimate the distance from the zone of fresh water–sea water mixing to the spring was conducted by Arfib et al. [14]. The analysis of geological, hydrochemical and hydrological data in the Almyros recharge area yielded the following conclusions [14]: (a) the volume of the karst conduit between the mixing zone and the Almyros spring was found to be constant throughout the year and approximately 770,000 m^3; and (b) the distance between the spring and the mixing zone within the conduit is estimated to be between 2,500 and 8,000 m. Tsakiris et al. [6] employed two fuzzy set of methodologies to assess the water yield potential of karstic saline springs and applied these methodologies to the Almyros spring (Heraklion-Crete). They could estimate the drinking water yield potential using the minimum intersection rule of fuzzy set methodology. Alexakis and Tsakiris [7] studied both time series of water quantity and quality variations of the spring discharge, using a gross annual water balance model for the Almyros spring. The status of each year (with respect to drought) was represented by the drought index Reconnaissance Drought Index (RDI) of the nearby meteorological station at Heraklion. Satisfactory correlation between RDI and water characteristics of the Almyros spring was obtained. In the study, a gross annual water balance model was used to describe the behaviour of Almyros karstic spring. An attempt was made to correlate the annual water potential with the climatic conditions in the area. In this context, the annual freshwater volumes were correlated with the RDI of 6 and 12 month periods, successfully. Alexakis and Tsakiris [7] concluded that climate change and the consequent increase in sea level are most likely to accelerate the seawater intrusion in Almyros coastal karstic aquifer which will be caused by the reduction of the freshwater hydraulic head. There are signs that drought conditions and low freshwater hydraulic head will affect also Almyros spring water quality. The reduction of freshwater head in association with reduced rainfall has as a result lower water table and therefore more increase of seawater intrusion.

3. Measurements and conditions

This study uses all systematically collected monthly data concerning hydrological (spring discharge), meteorological and water quality data (chloride concentration) over the period 1975–2000. The hydrological and water quality data have been provided by the Region of Crete.

3.1. Spring water quality and quantity parameters

The assessment of water quality is based on the following assumptions and limitations on the availability of data: (a) chloride concentration (Cl^-) is the recorded water quality parameter for the period 1975–2000; (b) the source of chloride is the seawater; (c) the mean of three to four chloride concentration measurements was used as the representative value of the corresponding month; (d) the mean of three to four measurements per month of the spring discharge represented the discharge of the month; and (e) the summer period is represented by the August figures (discharge and Cl^- concentration) and winter period by January figures.

Regarding the quantity, the monthly spring water volume is estimated by aggregating mean daily spring discharges. The spring discharge of Almyros (January and August) and the chloride concentration of the spring water (January-August) for the period 1975–2000 are shown in Figs. 5 and 6, respectively.

As can be seen from Fig. 5, the discharge of the spring is significantly lower during August compared to January. However, a much higher variability of January discharge is observed compared with the discharge of August which seems rather constant. The opposite occurs with water quality represented by chloride concentration (Fig. 6). The values of Cl^- concentration are higher in August compared with the values of January. However, the variability of Cl^- (although lower than January) is still high for August. Finally, in general, for January lower values of Cl^- concentration represent higher discharges. Table 1 presents the main statistical parameters for discharges and Cl^- concentration from the data of Figs. 5 and 6.

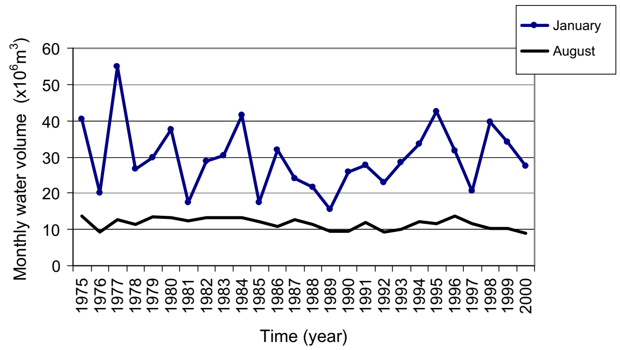

Fig. 5. Monthly water volumes from the spring for January and August, respectively, during the period 1975–2000.

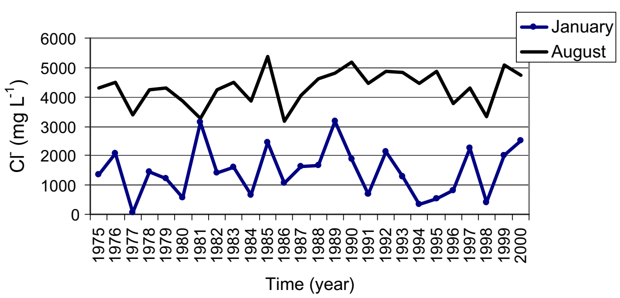

Fig. 6. Mean chloride concentration of the Almyros spring water during the period 1975–2000 for January and August, respectively.

3.2. Climatic variables

In order to assess the climate influence on water quality, the most important climatic variables were monitored for the period 1975–2000 for which quality data were available. The most crucial issue in this context is to investigate whether, during the period 1975–2000, the climatic factors exhibited a significant change mainly for the two periods examined 1975–1987 and 1988–2000.

4. Methodology

The analysis followed in this paper considers two distinct periods with data on the discharge and the water quality of the spring: namely the pre-development (no abstraction from the recharge area) 1975–1987, and after-development (annual abstraction from the recharge area) 1988–2000. In each of these periods, the magnitudes studied are the mean discharges of the spring and the chloride concentration in January (winter) and August (summer), respectively.

More analytically, the chloride concentration dataset of Almyros spring was divided into four sub-datasets: (a) January chloride mean values for the period

Table 1
Statistical parameters for spring discharge and Cl^- concentration data of spring water

	Monthly volume ($\times 10^6$ m^3)		Cl^- concentration (mg L^{-1})	
	January	August	January	August
Arithmetic mean	29.74	11.61	1478.10	4324.00
Standard deviation	9.19	1.51	846.90	597.00
Coefficient of variation	0.31	0.13	0.57	0.14

pre-1988; (b) January chloride mean values for the period post-1988; (c) August chloride mean values for the period pre-1988; and (d) August chloride mean values for the period post-1988.

The criteria used for the data-set categorization were the following:

- the period starting in 1988 was the groundwater abstraction began in the recharge area of the spring at a higher altitude
- January characterizes the winter period and August characterizes the summer period in relation to the quantity/quality data. Based on the Mediterranean climate type, the hydrological year consists of a winter period which lasts from October to March and a summer period which lasts from April to September

For the available data for the study area, the conventional statistical hypotheses were performed for detecting possible changes in the data-sets of the two periods analysed. Since the analysis is based on a small length of the data series ($n < 30$), the student-t statistical test is among the most appropriate hypothesis-testing techniques [24,25]. The acceptance or rejection of the null hypothesis (H_o) is the result of these tests. In this paper, the student *t*-test was applied for the comparison of the two discharge mean values, two chloride mean values for the periods 1975–1987 and 1988–2000, respectively.

In parallel, the climatic conditions in the two periods 1975–1987 and 1988–2000 were analysed for detecting any significant changes which could be blamed for the changes in discharge and water quality.

Conventionally, the climatic changes are detected through the examination of each climatic variable separately. In this paper, an innovative approach was adopted. That is to study the two major climatic determinants namely the precipitation and the potential evapotranspiration (PET) together by a composite index, the RDI.

Analytical reviews of RDI and detailed description of the index are presented by various researchers [19–23]. Although the RDI was intended for characterizing drought severity, it is also a very reliable index for investigating climate changes since it is based on both precipitation and PET. As known, the latter determinant is dependent heavily among others on temperature which is also a sensitive variable of the climate [19]. Therefore, RDI is applied in this study in order to detect possible changes in the climate characteristics of the two periods (1975–1987 and 1988–2000). Obviously, the assessment of the impact of groundwater abstraction on the recharge area on the water balance and water quality of the spring is valid, provided that no climatic influence on these determinants is detected.

The RDI is based on the ratio between two aggregated quantities of precipitation and PET. The initial value of the RDI for a certain period of time of *k*-months duration from the beginning of the hydrological year is calculated by the following equation [21,22]:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} \mathrm{PET}_j} \tag{1}$$

in which P_j and PET_j are the precipitation and PET of the *j*th month of the hydrological year, respectively. The hydrological year for the Mediterranean region starts in October, hence for October $k = 1$. Eq. (1) may be calculated for any period of the year.

The expression of the index which is used in this study is the Standardized RDI (RDI_{st}) which is computed by the following equation [21,22]:

$$\mathrm{RDI}_{st}(k) = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k} \tag{2}$$

in which y_k is the $\ln\alpha_k$, $\bar{y}_k$ is its arithmetic mean and $\hat{\sigma}_k$ is its standard deviation.

RDI_{st} is a very reliable index representing the climatic conditions of an area for a selected period since it represents the major determinants of water balance, precipitation and evapotranspiration.

If RDI_{st} is positive, the period can be considered as wet. If RDI_{st} is negative, the period is characterized as

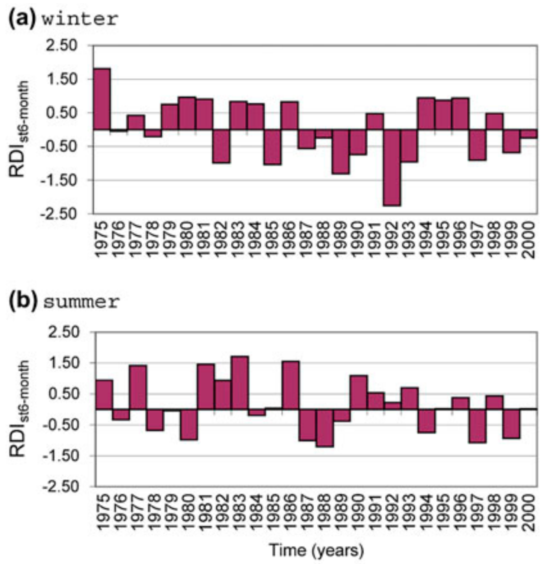

Fig. 7. RDI_{st} values for 1975–2000 for 6 month periods: (a) winter (October to March) and (b) summer (April to September).

dry. Also, if RDI_{st} is near zero, the situation is characterized as normal for the area.

It should be considered here that reliable results regarding the characterization of a period may be derived for a period of duration at least three months up to an entire year.

For the purpose of this study, the six-month RDI_{st} for the winter (October–March) and summer period (April–September) was used in standardized form using the meteorological data of the station of Heraklion-Crete which is quite close to the spring (in fact the spring is in a suburb of the city of Heraklion). In Fig. 6, the results of RDI_{st6} are presented for two six-month periods (a.winter, b.summer). In Fig. 7, it can be noticed that RDI_{st6} is calculated for two different six-month periods one starting in October and one starting in April. It should be stressed that RDI was calculated based on monthly values of precipitation and PET of the nearby meteorological station of Heraklion. For the calculation of PET values, the Hargreaves method was applied.

5. Results and discussion

5.1. Determining the effect of groundwater abstraction

The null hypothesis, H_o: discharge $\text{mean}_{\text{pre-1988}} = \text{discharge mean}_{\text{post-1988}}$ (it means that there is no influence of water abstraction in the Almyros spring discharge) against the alternative hypothesis, H_1: discharge $\text{mean}_{\text{pre-1988}}$ – discharge $\text{mean}_{\text{post-1988}} > 0$ (it means that there is a negative influence of the simultaneous water abstraction on the spring discharge), has been examined with the student-*t* one tailed statistical test (Table 2). The subscripts $_{\text{pre-1988}}$ and $_{\text{post-1988}}$ indicate the study period 1975–1987 and 1988–2000, respectively.

All the tests were performed at a significance level $a = 0.05$ with degree of freedom $n = 24$ $(n = 13 + 13 - 2 = 24)$.

The symbols used are:

s_p^2: pooled variance, $Sx_{\text{pre-1988}}\text{-}x_{\text{post-1988}}$: estimator of the standard error of the differences between the two population means of pre-1998 and post-1998, n: degrees of freedom,

$|t_n|$: critical t value for n degrees of freedom and

$|t_{th}|$: critical (theoretical) value corresponding to the given degree of freedom n).

At a significance level $a = 0.05$ for the discharge of the spring, the null hypothesis was accepted for the January values whereas it was rejected for the August values. This result shows that the influence of groundwater abstraction to the decrease of spring water discharge in the summer is statistically significant after the year 1988, which is the starting period of the groundwater pumping from the recharge area.

In relation to the spring water quality, the null hypothesis, H_o: chloride $\text{mean}_{\text{pre-1988}} = \text{chloride mean}_{\text{post-1988}}$ (that is no influence of simultaneous water abstraction in the spring water quality) against the alternative hypothesis, H_1: chloride $\text{mean}_{\text{pre-1988}}$ – chloride $\text{mean}_{\text{post-1988}} < 0$ (which means that there is a deterioration of the water quality of the spring due to the abstraction of water from the discharge area), was examined with the student-*t*, one tail, statistical test (Table 2). At a significance level $a = 0.05$, the null hypothesis was accepted for the January values; whereas the null hypothesis was rejected for the August values. This result shows that the contribution of groundwater abstraction to the degradation of spring water quality is statistically significant during summer after the year 1988.

5.2. Determining the influence of climate

Climate change is expected to have significant impacts for the catchment basins, precipitation patterns, evapotranspiration, discharge rates, water levels and residence times [26,27]. Many researchers suggest that change in climatic variables might alter the water quality and affect availability of water resources [7,26,28–32]. First-hand information about climate change could be gathered by spring discharges, as springs are the first to be affected. The springs particularly in carbonate aquifers are highly sensitive to climatic changes [33]. Based on these opinions, it

Table 2
The results of the statistical test for the discharge and chloride concentration of Almyros spring water at significance level $a = 0.05$

Data-set	Number of mean values	s_p^2	$Sx_{pre\text{-}1988}\text{-}x_{post\text{-}1988}$	n	$\lvert t_n \rvert$	$\lvert t_{th} \rvert$ (one tail)
Discharge (January)	26	87	4	24	$\lvert 0.610 \rvert$	$\lvert 1.711 \rvert$
Discharge (August)	26	2	1	24	$\lvert 3.080 \rvert$	$\lvert 1.711 \rvert$
Chloride (January)	26	745,499	339	24	$\lvert -0.230 \rvert$	$\lvert 1.711 \rvert$
Chloride (August)	26	308,272	218	24	$\lvert -2.210 \rvert$	$\lvert 1.711 \rvert$

Table 3
Results of student-t statistical test applied for the RDI_{st6} values of the Almyros spring recharge area

Data-set	Number of mean values	s_p^2	$Sx_{pre\text{-}1988}\text{-}x_{post\text{-}1988}$	n	$\lvert t_n \rvert$	$\lvert t_{th} \rvert$ (two tail)
$RDI_{st6\ Apr–Sept}$	26	0.77	0.34	24	$\lvert 1.290 \rvert$	$\lvert 2.064 \rvert$
$RDI_{st6\ Oct–March}$	26	0.84	0.36	24	$\lvert 1.720 \rvert$	$\lvert 2.064 \rvert$

would be interesting to investigate the influence on the observed consequences for the periods before and after 1987 when the simultaneous groundwater abstraction started. For this purpose, a composite climatic index, the RDI, was used as explained earlier in this paper. The RDI_{st6} values for the Almyros recharge area were divided into four sub-data-sets according to the benchmark year on which the groundwater abstraction started and the periods April to September and October to March: (a) $RDI_{st6\ Apr–Sept}$ values from 1975 to 1987; (b) $RDI_{st6\ Apr–Sept}$ values from 1988 to 2000; (c) $RDI_{st6\ Oct\text{-}March}$ values from 1975 to 1987; and (d) $RDI_{st6\ Oct\text{-}March}$ values from 1988 to 2000.

The null hypothesis, H_o: RDI_{st6} values $_{pre\text{-}1988} = RDI_{st6}$ values $_{post\text{-}1988}$ (which means that there is no statistically significant difference between the RDI_{st6} values during the periods 1975–1987 and 1988–2000) against the alternative hypothesis, H_1: RDI_{st6} values $_{pre\text{-}1988} \neq RDI_{st6}$ values $_{post\text{-}1988}$ (which means that there is a statistically significant difference between the RDI_{st6} values during the periods 1975–1987 and 1988–2000), was examined using the student-t, two tail statistical test (Table 3).

The tests were performed at a significance level $a = 0.05$. At this significance level, the null hypothesis was accepted for all $RDI_{st\ 6}$ values.

This result shows that RDI_{st} (for both January and August) remains practically the same for both periods 1975–1987 and 1988–2000. Therefore, one can support the finding of Table 2 that the deterioration of water quality of the spring (at least during the summer) is caused mainly by the groundwater abstraction which was initiated during 1988.

The influence of this water abstraction (in the two periods examined) is estimated as an increase by 11% of the mean Cl^- concentration in the summer period of the year associated with a decrease of mean discharge by more than 12% for the same period.

It goes without saying that having reached these indications, what could be the best practices of groundwater abstraction in the future? It is logical to conclude that for the estimation of the volume of water abstraction which can cause the least impacts, a comprehensive model of the spring mechanism is required. At this stage, it could be said that the groundwater abstraction could be decreased, be realized only in wet and normal years, or be realized only in winter time. These practices seem to result in mitigation of impacts on the spring water quantity and quality.

6. Conclusions

In this study, an attempt was made to assess the impact of simultaneous groundwater abstraction from the recharge area of a karstic spring to the spring water quantity and quality. Using the karstic spring of Almyros (Heraklion-Crete) as the case study, it was indicated that even a relatively small quantity of groundwater abstracted annually from the recharge area of the spring has a significant impact on the water quantity and quality of the spring at least during the summer period.

This is attributed to the fact that karstic systems exhibit very fragile behaviour. If a small change in one input determinant of the water balance occurs, this might cause amplified consequences in the discharge and the water quality of the karstic spring.

This impact was statistically detected during the summer season in which the recharge is low and the chloride concentrations are high.

Considering the climatic conditions of the two periods examined before and after the initiation of annual groundwater abstraction from the recharge area, no significant change was detected using a composite climatic index (RDI) incorporating both precipitation and PET. Therefore, the detected changes in the summer from the spring could be attributed to the abstraction of groundwater from the recharge area. This strong indication needs to be reaffirmed when more lengthy set of data will be available.

To mitigate the impact of simultaneous water abstraction on the quantity and quality of the spring water, three options are foreseen:

(a) to abstract water only during the winter period;
(b) to decrease the abstraction rate; and
(c) to abstract water only in wet or normal years.

The impacts on the water quantity and quality for any other simultaneous groundwater abstraction scenario may be derived after a detailed and comprehensive modelling of the karstic system mechanism.

Acknowledgement

The authors wish to thank Dr M. Kritsotakis, Region of Crete, for kindly providing valuable data for this study.

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