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Drought impacts on karstic spring annual water potential. Application on Almyros (Crete) brackish spring

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ABSTRACT

Frequent and intense drought episodes threaten the water balance of the fragile water systems in the coastal areas of the Mediterranean. Coastal brackish karstic springs offer a challenging solution for increasing water availability in case of temporary or permanent water shortages for alleviating the impacts of droughts and aridity in these areas. The paper discusses the impacts of droughts on the fresh water potential of the karstic spring of Almyros (Heraklion-Crete). Both time series of water quantity and quality of the spring are studied using a gross annual water balance model for the spring. Drought years are represented by the (Reconnaissance Drought Index)-RDI of the nearby meteorological station of Heraklion. Statisfactory correlation between RDI and water characteristics of the spring are derived. Finally, trends in the fresh water annual volumes time series are identified.

Keywords: Drought impacts; Reconnaissance drought index; Brackish water; Water quality; Karstic springs; Climate change; Almyros brackish spring

1. Introduction

Many Mediterranean coastal areas suffer from water shortages caused by increased demand for water and by frequent and intense drought episodes. To face these water scarcity problems proactive planning incorporates measures for lowering the water demand, improving the performance, and utilizing new sources of water (mainly brackish or reclaimed). In this context the existing high water potential of brackish karstic springs seem to offer a challenging opportunity for the Mediterranean coastal areas to face water scarcity problems.

According to reports of international organizations the Mediterranean basin will be substantially affected by the anticipated climatic changes such as increase on air temperatures, decrease of precipitation and sea level rise. By the year 2050, the surface temperature is expected to increase by 2.5°C and the precipitation will decrease by 10.5% in the region of Middle East and North Africa (MENA) according to Al-Jamal [1]. Moreover, population growth rate in these countries has an average of about 2.5% [2]. These changes threaten the water balance in the water systems of these areas which already suffer from water shortages. Additionally, during the last few decades existing freshwater sources have become increasingly limited in many regions of the world, particularly in MENA [3].

Having said this, it is challenging to find ways for exploiting the water potential of coastal karstic springs although in most of the cases they discharge brackish water.

A special category of coastal karstic springs are the springs with brackish water during most days of the year and good with quality water for only some days of the year. The present study concentrates on this category of coastal karstic springs by analyzing the water discharge and water quality of an important such spring, the Almyros spring in the outskirts of Heraklion-Crete.

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The development of Almyros semi-brackish spring is of great socioeconomic significance for the island of Crete, an island with great irrigation and drinking water demands and with expanding touristic activities.

Heraklion is a city of nearly 200 000 inhabitants and its north coastal areas are considered probably as the most touristic area of Greece. As result a rather permanent water shortage is exacerbated during the summer months when the water demand is becoming double. Needless to say that the situation is even more critical during the drought years in which water availability is even lower.

The paper aims at estimating the drought impacts on the annual water potential of Almyros spring. Both quantity and quality time series are analysed in an attempt to find correlation between drought characteristics and water characteristics of the spring. Also an attempt is made to identify trends in both of the above characteristics.

2. Description of Almyros karstic spring

The Almyros karstic spring is situated in the central north part of Crete island at an elevation of +3 m above sea level, 8 km west from the centre of Heraklion city, and 1 km from the sea (Fig.1). This spring is the only identified outlet of a karst system that has developed in two different limestone formations. It flows out at the contact point between the marly sediments and the limestones. Discharge rates range from 4 $m^3\ s^{-1}$ in the summer to 70–80 $m^3\ s^{-1}$ in the winter, following heavy rainfalls on the Psiloritis Mountain (Fig.1); whereas the average annual volume of water discharged at the Almyros spring is $250 \times 10^6\ m^3$ [4]. The electric conductivity value varies between 331 μS cm^{-1} (during floods) and 18430 μS cm^{-1} (when the flow is low) as a result of the mixing of the seawater with freshwater [5]. The origin of Almyros spring water salinity could not be attributed to the dissolution of evaporite rocks because there is no evidence of the presence of any evaporite rocks in Almyros catchment area. Most geologists, following Breznik [6] assume that spring water is becoming brackish at the point where the karstic conduit which comes from the sea meets the fresh water conduit. Recent studies have shown that the seawater enters the karst conduit at a depth of around 500 m below sea level, while 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 [5,7].

Obtaining water of appropriate quality for human consumption and irrigation purposes from Almyros spring is a difficult problem and needs interdisciplinary scientific cooperation [8]. The quality and quantity of Almyros brackish water should be carefully studied in order to assess future water potential. Tsakiris et al. [9] employed two fuzzy set methodologies for assessing the water potential of karstic saline springs and applied

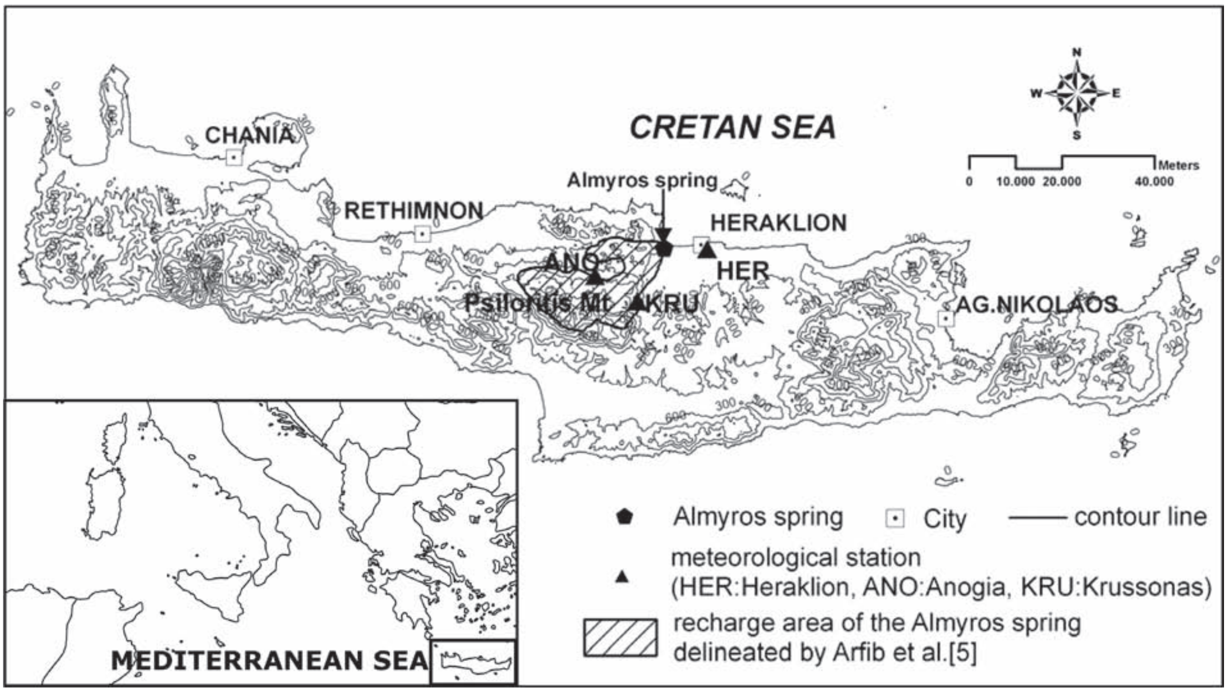

Fig. 1. Location of Almyros spring in the general map of Crete island.

these methods to the case of Almyros spring. These methods have been applied for assessing the quantity of water from the Almyros spring which is suitable for drinking or irrigation purposes. According to Tsakiris et al. [9] the min intersection rule is more suitable for the estimation of the water potential for drinking purposes, while the multicriteria filtering method proved to be a flexible method for categorizing annual water quantities into quality classes with respect to irrigation quality criteria and EU directives on water quality.

Climate change is expected to have far-reaching impacts for catchment basins, precipitation patterns, evapotranspiration, discharge rates, water levels and residence times [10,11]. Many researchers [10,12,13] suggest that change in climate variables might alter the water quality and affect availability of water resources. 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 global climate changes [14]. Moreover, the Almyros karst system can be considered as a filter system and output signals such as changes of Almyros spring discharge can be compared with input signals such as rainfall.

Although many research efforts have been made [4,5,6,7,8,9,15] the Almyros spring system is not yet fully understood. The main causes of uncertainties in defining the behaviour of Almyros spring are

(i) the undefined karst hydrological basin which is not corresponding exactly to the topographic catchment;
(ii) the partially unknown spring function mechanism;
(iii) the unknown underground network parameters such as the number of karst conduits as well as their dimensions depth and position;
(iv) the unknown interaction between circulation of groundwater in karst and water drilled from the boreholes above the spring;
(v) the lack of daily water quality data (e.g. Cl concentration) which is necessary for calculating precisely the freshwater/spring water mixing ratio

3. Data and methods

3.1. Available data

This study uses all systematically collected data concerning hydrometeorological and water quality data over the period 1975–2000. Monthly precipitation and average air temperature data were available at three stations which are within and near to the catchment.

Average monthly spring discharge and chloride concentration (one measurement per month) were also available for the same period. Fig. 2 shows the monthly time series of spring discharge and water volume precipitated on the recharge area. Fig. 3 represents graphically the monthly time series of chloride concentration. Unfortunately for any water balance simulation the recharge area of the spring was not rationally determined so far. Many researchers [5,7] consider the catchment area being 300 km^2, others 500 km^2 [15], whereas the Region of Crete [16] determined the area as 530 km^2. Although there is still ambiguity in the determination of the recharge area this study adopted the latter fig. which can be more realistically explaining the annual water volumes recorded at the spring.

3.2. Drought representation with the reconnaissance drought index

Drought is a natural phenomenon characterized by significant decrease of water availability over a large area and during a significant period of time [17]. Drought

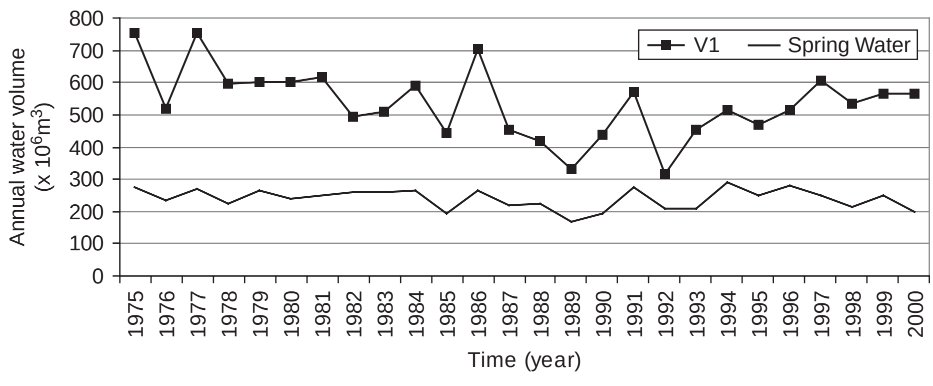

Fig. 2. Annual water volume precipitated on the Almyros recharge area (V1) and annual water volume discharged from the Almyros spring.

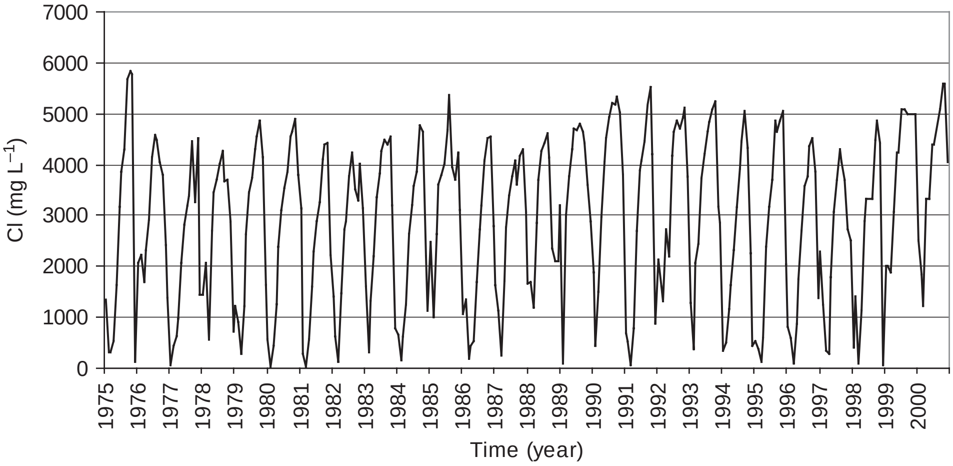

Fig. 3. Chloride concentration in Almyros springwater versus time (monthly measurements).

intensity is conventionally assessed by drought indices. Numerous drought indices have been proposed mainly based on the area of application and the purpose of the analysis required. Analytical reviews on the subject give detailed descriptions of most drought indices whereas specific software (e.g. DrinC) has been written for their calculation [13,18,19,20].

The Reconnaissance Drought Index (RDI) is based on the ratio between two aggregated quantities of precipitation and potential evapotranspiration. The first expression of the RDI for a certain time period, indicated by a certain month (k) during a certain year is calculated by the following equation:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j}. \tag{1}$$

In which P_j and PET_j are the precipitation and potential evapotranspiration, respectively, of the jth month of the hydrological year. The hydrological year for the Mediterranean region starts in October, hence for October $k = 1$. The above equation may be calculated for any period of the year. For the estimation of PET the Hargreaves formula was used since Hargreaves method [21] requires only measured temperature data which can be found in most regions of the world. Heraklion meteorological station was used for the calculation of RDI. This station has reliable long series of data of both rainfall and temperature. Unfortunately, Anogia and Krussonas stations (Fig.1), have only rainfall data and could not be used for the RDI calculation.

For real world applications if α_k is calculated as a general indicator of meteorological drought it is advisable to use periods of 3,6,9 and 12 months. In case 12-month period is selected the result could be directly compared with the Aridity Index produced for the area under study. If α_{12} for a certain year is lower than Aridity Index then the area is suffering from drought during this year.

Two more expressions of the index are used:

The normalised RDI (RDI_n), is computed using the following equation:

$$\mathrm{RDI_n(k)}\,\frac{a_k}{\bar{a}} - 1, \tag{2}$$

where $\bar{a}$ is the mean of a_k for all the years of available data.

Finally the standardised RDI (RDI_{st}) is computed following a similar procedure to the one that is used for the calculation of SPI:

$$\mathrm{RDI_{st}(k)} = \frac{y_k - \bar{y}_k}{\hat{\sigma}_k}. \tag{3}$$

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

For the purpose of this study the 6-month and the 12-month RDI was used for both the initial and standardized form using the meteorological data of the station of Heraklion. In Fig. 4, the results of RDI_{st} are presented for 6 and 12 month respectively.

3.3. *Freshwater-seawater ratio calculation*

The ratio of mixing between fresh and seawater may be estimated by chloride mass balance approach for a certain period of time, which is based on the premise

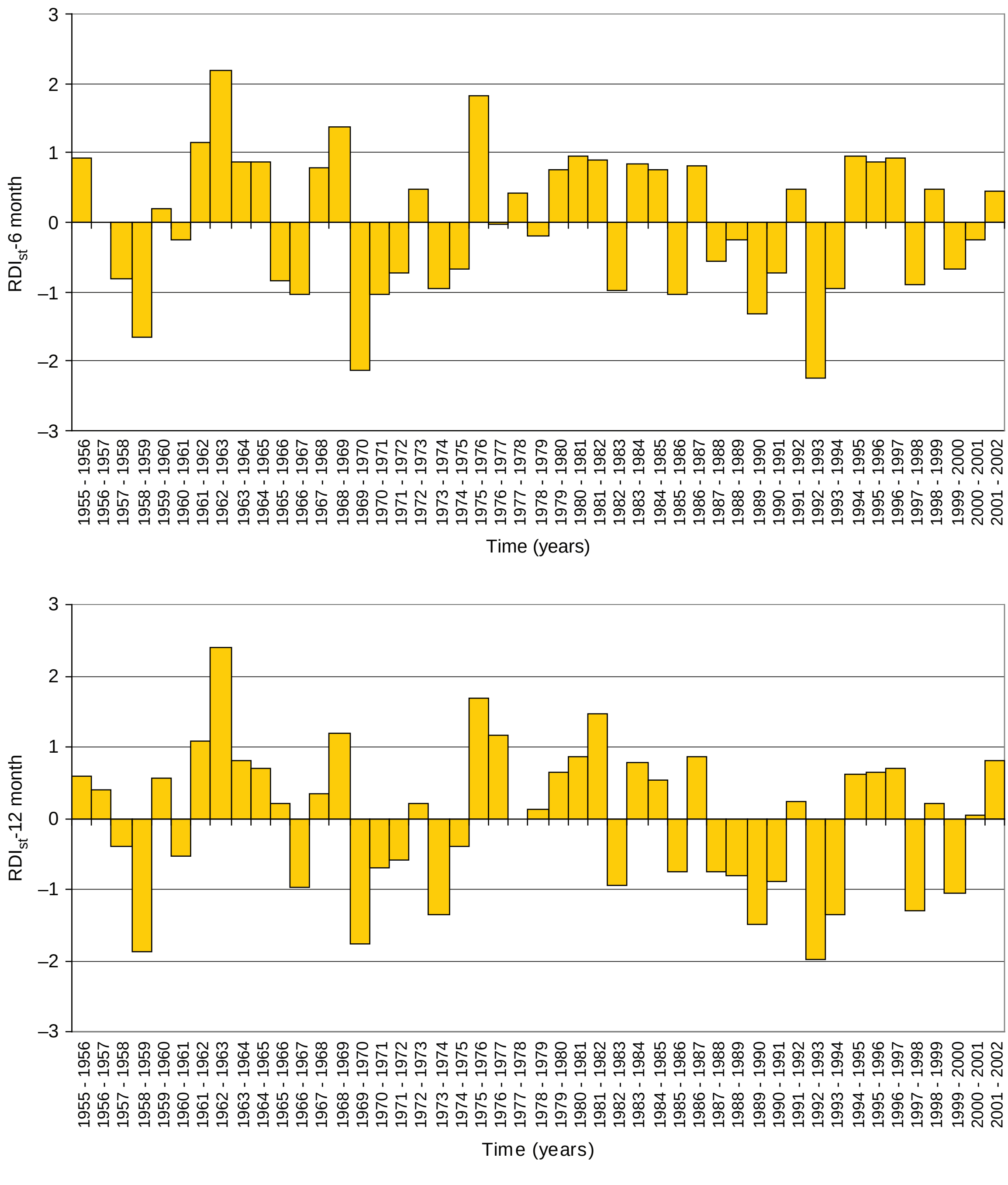

Fig. 4. RDI_{st} values for 1955–2002 for 6 and 12 month periods (Heraklion-Crete).

that chloride (Cl^-) behaves as a conservative tracer, as follows:

$$C_{Cl\,spring} \times V_{spring} = C_{Cl\,sea} \times V_{sea} + C_{Cl\,fresh} \times V_{fresh} \quad (4)$$

or

$$C_{Cl\,spring} \times Q_{spring} = C_{Cl\,sea} \times Q_{sea} + C_{Cl\,fresh} \times Q_{fresh.} \quad (5)$$

In which $Q_{spring} = Q_{sea} + Q_{fresh}$ (6)

Here C_{Cl} is the concentration of Cl^- (mg L^{-1}), V is the annual volume of water, Q is the discharge, and subscripts $_{spring,\ sea}$ and $_{fresh}$ indicate the conservation mixture, the seawater and the fresh water, respectively. The annual water volume (V) is estimated by aggregating daily spring discharges (Q).

In order to reach practical results the $C_{Cl\,sea}$ is taken equal to 19000 mg L^{-1} and $C_{Cl\,fresh}$ is taken equal to 10 mg L^{-1} [22,23]. The Almyros springwater measured chloride concentration ranges from 26 mg L^{-1} (during floods) to

5851 mg L^{-1} (when the flow is low) as a result of the mixing of freshwater of the karstic reservoirs with the seawater [16].

The assumptions used for the calculation of the freshwater/seawater ratio due to he lack of daily data of water quality are: (i) the spring water volume (V_{spring}) is the sum of seawater volume (V_{sea}) and freshwater volume (V_{fresh}), (ii) the only significant source of chloride is the seawater, and (iii) only one sample per month was analysed for measuring chloride concentration.

The ratio of spring water to fresh water can be calculated as follows:

$$\frac{Q_{spring}}{Q_{fresh}} = \frac{C_{Clsea} - C_{Clfresh}}{C_{Clsea} - C_{Clspring}}. \tag{7}$$

Considering that the Cl_{sea} and Cl_{fresh} are known, and Cl_{spring} is the measured value, then the ratios $\frac{Q_{spring}}{Q_{fresh}}$, $\frac{Q_{spring}}{Q_{sea}}$, $\frac{V_{spring}}{V_{fresh}}$ and $\frac{V_{spring}}{V_{sea}}$ can be readily calculated.

3.4. Gross annual water balance model

From previous studies it may be concluded that Almyros spring hydraulic system mechanism is very complicated when short time scale is used [5,7]. On the opposite if the time scale is annual and provided that some sound simplifying assumptions are adopted, the water balance mechanism can considerably simplified. Such a simple conceptual water balance tree is the one presented in Fig. 5 representing the water flow from the recharge area to the outlet of the Almyros spring.

The gross conceptual model presented in Fig. 5 is based on the mass conservation principle applied on annual basis.

In Fig. 5, V_1 is Volume of water that precipitates on the catchment area, P is annual precipitation, A is the catchment area, d is deep percolation coefficient (e.g. 0.50) and λ is the fraction of percolated water which contributes to the spring discharge.

Although the presented simple annual conceptual model is easy to understand and compute, it incorporates parameters which are estimated with significant uncertainty. These parameters include the recharge area of the spring A, the deep percolation coefficient d, and the fraction λ of percolated water which contributes to the discharge of the spring. Also other uncertainties in the estimation of fresh water volumes reaching the spring are due to the single measurement per month of chloride concentration of the spring water.

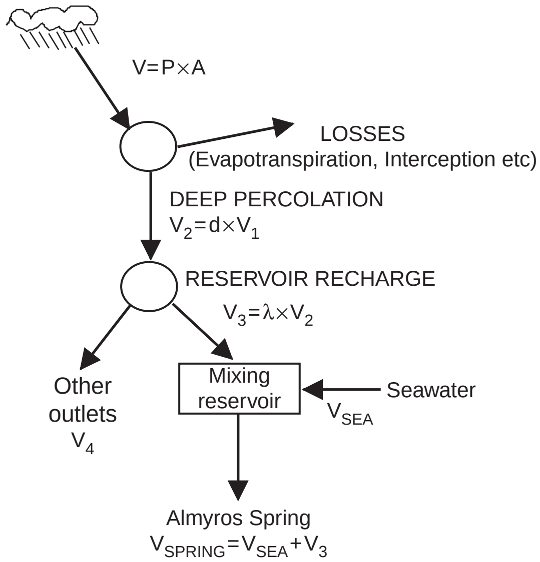

Fig. 5. Reconnaissance schematization of the gross conceptual model of Almyros karstic spring.

3.5. Identify trends of major determinants

A great deal of attention lately was focused on trend detection analysis of hydrologic and water quality data, especially in connection with the anticipated changes in global climate [24,25]. For the available data of the study area, trend analyses using ordinary linear regression versus time is not appropriate because the required assumption of normally distributed residuals is often violated [24, 26]. According to McCuen [25] the Mann–Kendall test [27,28] is designed to detect a monotonically augmentative or diminishing trend in the data rather than an episodic or abrupt event. The Mann-Kendall trend test is a non-parametric test which does not require assumptions of normality of populations. According to Gilbert [29] the Man–Kendall test compares the relative magnitudes of sample data rather than the data values themselves. The Almyros spring dataset was categorized into four sub-datasets: (a) monthly, (b) annually, (c) wet period and (d) dry period. Based on the Mediterranean climate type the hydrological year consists of a wet and a dry period; the wet period lasts from October through March and the dry period from April to September. The DOS executable program code "Kendall.exe" for computing the Mann–Kendall test written by Helsel et al. [30] has been applied in this study for identifying statistically significant trends.

The following conventions have been adopted [31]:

(i) Statistical significance is inferred when the "Confidence in Trend" (1-p) value of the Mann–Kendall test is more than 95%.

(ii) The Mann–Kendall Statistic (S) measures the trend in the data. Positive values (S>0) indicate an increase in the time series over time, whereas negative values (S<0) indicate a decrease in the time series. The strength of the trend is proportional to the magnitude of the S value (large magnitudes indicate a strong trend).

4. Results and discussion

Using the above methods and data some important results were obtained concerning the behaviour of the Almyros spring, the existing trends of the fresh water potential as well as the trends of the climatic factors of the region.

A simple procedure for testing the validity of the proposed gross annual water balance model was used by comparing the annual fresh water volumes at the spring estimated by the model with the annual fresh water volumes estimated by the chloride mass balance approach. The results were presented in the graph of Fig. 6 by plotting the above two quantities on the two axes with a 1:1 gradient line ($y = x$). From this graph it can be deduced that the model with the average values d = 0.50 and λ = 0.80 performs satisfactorily for estimating the annual fresh water potential (Fig. 6). The statistical significance of the 1:1 slope of the regression line was tested using the t-statistic. At the significance level of 1 – a = 0.95, the null hypothesis (slope statistically different than 1:1) was rejected.

From the historical record of the precipitation and total potential evapotranspiration at 6-month and 12 month basis the standardized RDI from the meteorological station of Heraklion was calculated. Therefore based on the above calculations the annual fresh water potential (annual volume of fresh water at the spring) was correlated with RDI_{st6} and RDI_{st12}, respectively.

An attempt to correlate the annual fresh water potential with the climatic factors of the area was also made. For this purpose annual fresh water volumes were plotted against the drought index RDI_{st} for the 6- and 12-month periods which correspond to the wet period and the entire hydrology year. The simple linear regression model which was applied gives satisfactory results for all the above determinants as can be seen in Fig. 7. From these graphs it can be deduced that better correlation is achieved for the drought index calculated for the 6-month period. This is a logical outcome since the high discharges of the spring occur during the period October to March for each hydrological year.

Based on RDI data of the period 1975–2000, significant decreasing trend of RDI_{st12} has been estimated; while there is no significant trend for the RDI_{st6} (**Table 2**).

The Mann–Kendall statistics for identifying trends in the water volumes, chloride concentrations and drought indices are outlined in Tables 1 and 2.

According to monthly hydrologic data of the period 1975–2000, significant decreasing trends of freshwater and springwater volumes have been estimated and there is no significant trend for the seawater volume discharged by the Almyros spring. Moreover, according to monthly water quality data a positive significant trend is observed in chloride content of the springwater. Annual,

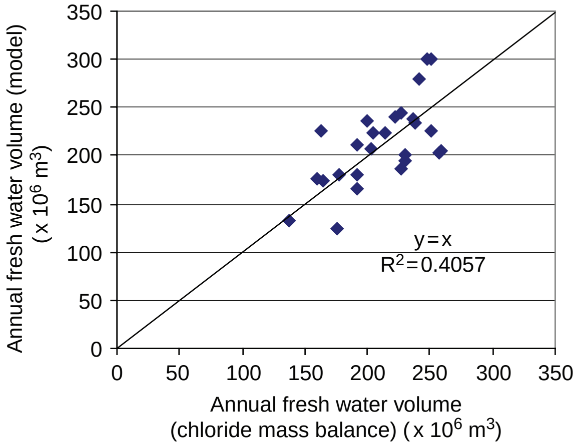

Fig. 6. Annual fresh water volumes calculated by the model versus the ones estimated by the chloride mass balance approach.

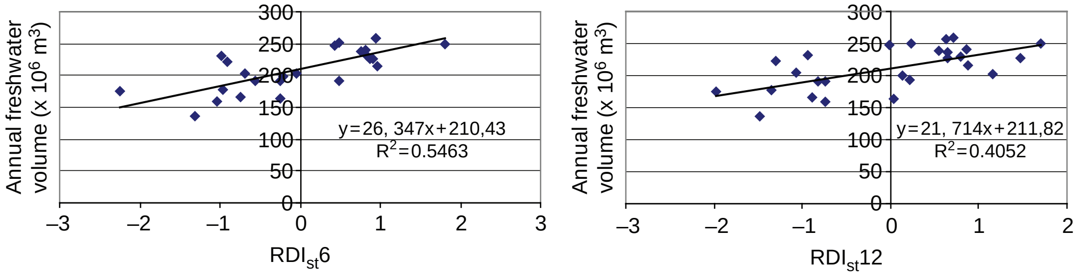

Fig.7. Annual fresh water volume vs RDI_{st} for the first semester and the entire hydrological year.

Table 1
Mann–Kendall trend results of the Almyros brackish spring dataset.

Dataset	Number of values	Mann–Kendall Statistic (S)	p	Confidence in Trend ($1-p$)	Trend (level of significance %)
Fresh water (monthly)	312	−4373	0.0176	0.9824	Decreasing (98.24%)
Spring water (monthly)	312	−4200	0.0226	0.9774	Decreasing (97.74.%)
Sea water (monthly)	312	1741	0.3447	0.6553	No significant trend
Cl spring water content (monthly)	312	4836	0.0086	0.9914	Increasing (99.14%)
Fresh water (annual)	26	−49	0.2898	0.7102	No significant trend
Spring water (annual)	26	−50	0.2797	0.7203	No significant trend
Sea water (annual)	26	33	0.4786	0.5214	No significant trend
Fresh water (wet period)	26	−50	0.2798	0.7202	No significant trend
Spring water (wet period)	26	−50	0.2800	0.7200	No significant trend
Sea water (wet period)	26	22	0.6397	0.3603	No significant trend
Fresh water (dry period)	26	−57	0.2166	0.7834	No significant trend
Spring water (dry period)	26	−52	0.2597	0.7403	No significant trend
Sea water (dry period)	26	19	0.6886	0.3114	No significant trend

Table 2
Mann–Kendall trend results of the RDI_{st} for the period 1975–2000 for 6 and 12 month (Heraklion-Crete).

Dataset	Number of values	Mann–Kendall Statistic (S)	P	Confidence in Trend ($1-p$)	Trend (level of significance %)
RDI_{st} (6 month)	26	−55	0.2337	0.7663	No significant trend
RDI_{st} (12 month)	26	−111	0.0027	0.9973	Decreasing (99.73%)

wet period and dry period datasets did not reveal statistically significant trends for fresh water, spring water and seawater volume (Table 1).

5. Concluding remarks

In this study a gross annual water balance model was used to describe the behaviour of Almyros karstic spring in Heraklion Crete. An attempt was made for correlating the annual water potential with the climatic conditions in the area. In this context the annual fresh water volumes were correlated with the Reconnaissance Drought Index of 6- and 12-month periods, successfully.

The Mann–Kendall test detected trends for the measured quantity determinants (annual water volume of fresh water and spring water) and the measured chloride concentration (quality parameter). The measurements were conducted on a monthly basis and cover only the period 1975–2000.

The major conclusions derived for the quantity and quality parameters are

- the annual fresh water and spring water volume time series exhibit significantly decreasing trends;
- the springwater chloride content time series exhibits a significantly increasing trend.

Climate change is most likely to accelerate the seawater intrusion in Almyros coastal karstic aquifer which will be caused by reduced freshwater hydraulic head. There are signs that drought conditions and low freshwater hydraulic head will affect also Almyros spring water quality. The problem could be more serious if increased water abstraction will be practiced in areas of higher altitude affecting the spring.

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