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# A new approach for the development and management of brackish karst springs

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**Abstract** A new approach to the method of artificial upraising of the water outlet point, for management and development of brackish karst springs, uses the MODKARST model. Brackish karst springs simulation can be used to estimate the necessary upraising of the spring elevation, so that sea-water intrusion is blocked. The consequent freshwater loss to the sea, due to this upraising, can also be estimated. The method has been applied to the periodically brackish karst Almiros spring at Heraklion of Crete, Greece. The spring simulation showed that the sea-water intrusion could be prevented through an artificial upraising of the water-outlet point, realized by the construction of a dam. The exact upraising has been estimated. Freshwater loss to the sea because of this upraising has also been estimated. The model could also be used as a tool for the management of the spring. For example, it was used to assess management options for the spring during the depletion period of the year 1994. The best scenario for the development of the spring during this period has been estimated.

**Résumé** Une nouvelle approche de la méthode de relevage des eaux à l'exutoire, pour la gestion et le développement des sources karstiques saumâtres, utilise le modèle MODKARST. La simulation des sources karstiques saumâtres peut être utilisée pour estimer l'élévation nécessaire de la source, de telle manière à bloquer l'intrusion de l'eau de mer. La perte d'eau douce vers la mer peut également être estimée. La méthode a été appliquée au karst de la source d'Almiros, à Heraklion en Crète, Grèce. La simulation de la source montre que l'intrusion marine peut être évitée en construisant un barrage créant une remontée artificielle du niveau de l'eau

à l'exutoire. La remontée exacte a été calculée. La perte d'eau douce vers la mer a également été estimée. Le modèle peut également être utilisé comme outil pour la gestion de la source. Par exemple, il aurait été inutile de dresser un plan de gestion de la source durant l'année sèche 1994. Le meilleur scénario pour le développement de la source durant cette période a été estimé.

**Resumen** Se propone un nuevo enfoque alternativo al método de ascenso artificial del punto efluente, para la gestión y desarrollo de manantiales kársticos salados basado, en el modelo MODKARST. La simulación de manantiales kársticos salados puede usarse para estimar el ascenso necesario de la elevación del manantial de modo que la intrusión de agua marina sea bloqueada. También puede estimarse la pérdida consecuente de agua dulce al mar debido a este ascenso. El método se ha aplicado al manantial kárstico Almiros, con agua salada periódica, en Heraclion, Creta, Grecia. La simulación del manantial mostró que la intrusión de agua marina podía prevenirse a través de un ascenso artificial del punto de efluencia lo cual se lograría mediante la construcción de una presa. Se ha estimado el ascenso exacto. También se ha estimado la pérdida de agua dulce hacia el mar ocasionada por este ascenso. El modelo también podría usarse como una herramienta para el manejo del manantial. Por ejemplo, se utilizó para apoyar la gestión del manantial durante la época de escasez en el año 1994. Se ha estimado el mejor escenario para el desarrollo del manantial durante este periodo.

**Keywords** Karst · Salinization · Salt-water/fresh-water relations · Groundwater development · Groundwater management

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## Introduction

It is not easy to get fresh water from a brackish karst spring. This problem is sometimes solved by the construction of development bores or tunnels but it is difficult to locate the line which separates the brackish area from the area upstream where drilling would produce fresh water. Thus, during the first stages, the development must proceed by trial and error. On the other hand, it is very difficult to determine the amount of water that could be

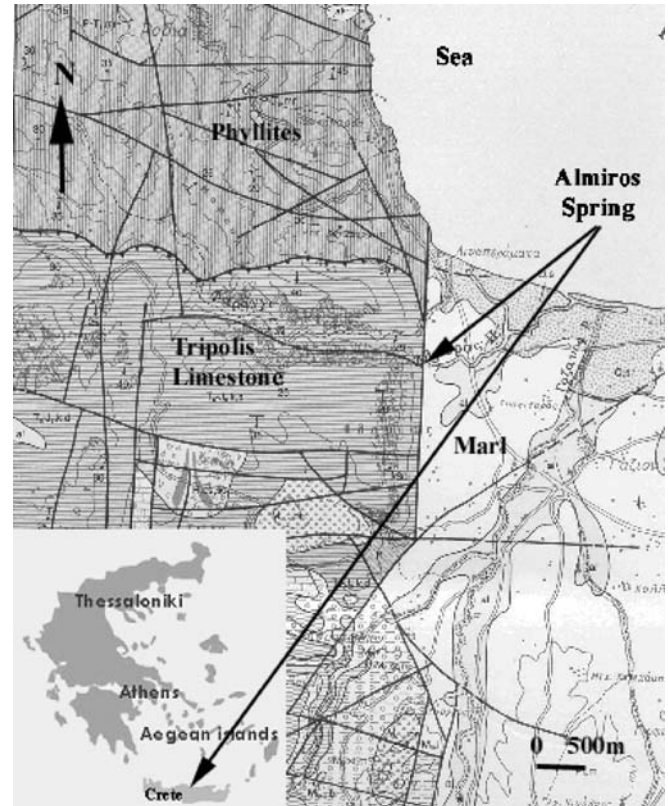
**Table 1** Equations, variables and parameters of the model (modified from Maramathas et al. 2003b)

<p><b>Equations</b></p> $sS_1 \frac{dH}{dt} + Q_2 - \gamma \dot{P} S_1 = 0$ $sS_1 H \frac{dH}{dt} + \frac{Q_1^3}{2gS_2^2} - H\gamma \dot{P} S_1 + L \left[ \frac{Q_1}{sS_1} \right]^2 Q_1 = 0$ $\frac{Q_3^2}{2gS_3^2} + \frac{p_3}{\rho_\theta g} - H_\theta = 0$ $p_3 = \rho_w g (H_\theta + h + \frac{S}{\pi} H) - L_\alpha Q_2^2$ <p><b>Model input information</b></p> <p>Rainfall rate <math>\dot{P}</math> (L/T)</p> <p><b>Model output information</b></p> <p>Spring discharge:</p> $Q = Q_1 + Q_2$ <p>Chloride concentration of the spring water:</p> $\frac{\rho_\theta C_\theta Q_2 + \rho_w C_w Q_1}{\rho_\theta Q_2 + \rho_w Q_1}$	<p><b>Variables</b></p> <p><math>Q_1</math> Karst system discharge (<math>L^3/T</math>)  <math>Q_2</math> Sea water discharge (<math>L^3/T</math>)  <math>H</math> Water level above discharge point (L)  <math>p_3</math> Pressure at the intersection between the Sea water tube and the freshwater tube (<math>MLT^{-2}</math>)</p> <p><b>Calibration Parameters</b></p> <p><math>s</math> Coefficient of storage  <math>S_1</math> Recharge area (<math>L^2</math>)  <math>\gamma</math> Infiltration coefficient  <math>S_2</math> Outflow-tube cross section of the karst-system reservoir (<math>L^2</math>)  <math>L</math> Energy loss coefficient (<math>L^{-1}T^{-2}</math>)  <math>S_3</math> Outflow-tube cross section of the sea water reservoir (<math>L^2</math>)  <math>H_\theta</math> Depth of the intersection between the sea water tube and the freshwater tube (L)  <math>\pi</math> Specific yield  <math>L_\alpha</math> Pressure loss coefficient of the sea-tube outlet region (<math>ML^{-1}</math>)</p> <p><b>Measured Parameters</b></p> <p><math>g</math> Gravity (<math>LT^{-2}</math>)  <math>\rho_\theta</math> Sea water density (<math>ML^{-3}</math>)  <math>\rho_w</math> Freshwater density (<math>ML^{-3}</math>)  <math>h</math> Spring elevation (L)  <math>C_w</math> Chloride concentration, fresh water  <math>C_\theta</math> Chloride concentration, sea water</p> <p><b>FOOTNOTE</b></p> <p>L: Length  T: Time  M: Mass</p>
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taken from the reservoir every year without sea-water intrusion going further inland. Besides, it is difficult to locate the water through the construction of a bore in such karst areas, since it moves following a network of conduits.

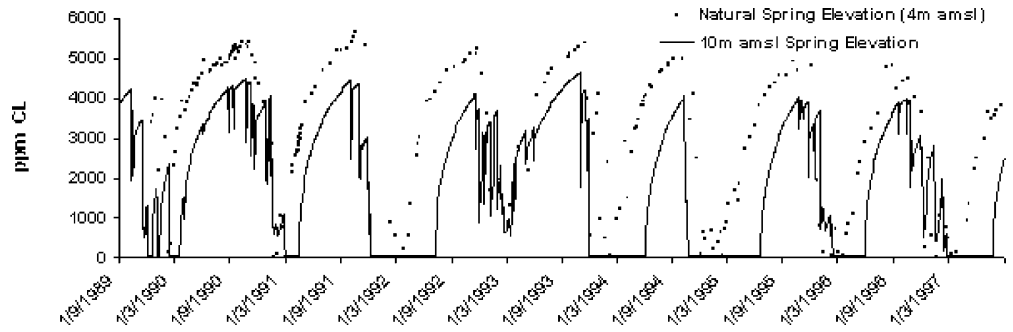
In some cases, with the construction of a dam in front of it, it is possible for sea-water intrusion to be blocked by the artificial upraising of the water-outlet point of the spring. In this way, the freshwater level in the spring reservoir will rise and the corresponding increase in pressure will prevent sea-water intrusion (Maramathas et al. 2003a; Breznic 1973). This is an old but not very popular method due to two difficult to solve problems: firstly, the determination of the sufficient upraising; and secondly, the estimation of the freshwater loss to the sea (discharge to the sea). Tubes, microtubes and conduits that previously brought sea water to the spring reservoir, will bring fresh water to the sea after the spring upraising as a consequence of the increase in freshwater pressure.

This article presents a new method of solving the above-mentioned problems. The method is based on the MODKARST deterministic model, which simulates the brackish karst springs hydrograph (discharge vs. time) and chemograph (chloride variation in the spring water vs. time). It incorporates mass and energy balances in a system of reservoirs that approximates the karst system and the sea (Maramathas et al. 2001, 2003b). The equations, the variables and the parameters of the model are presented in Table 1. The same model could also be

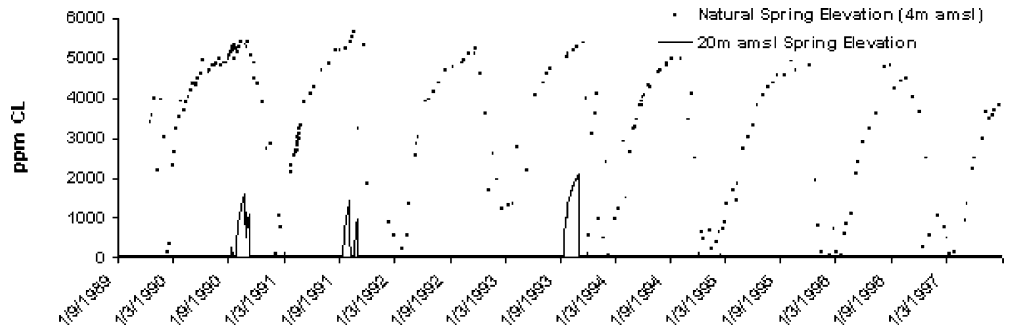


**Fig. 1** Map of the area of the Almiros spring in the Greek island of Crete

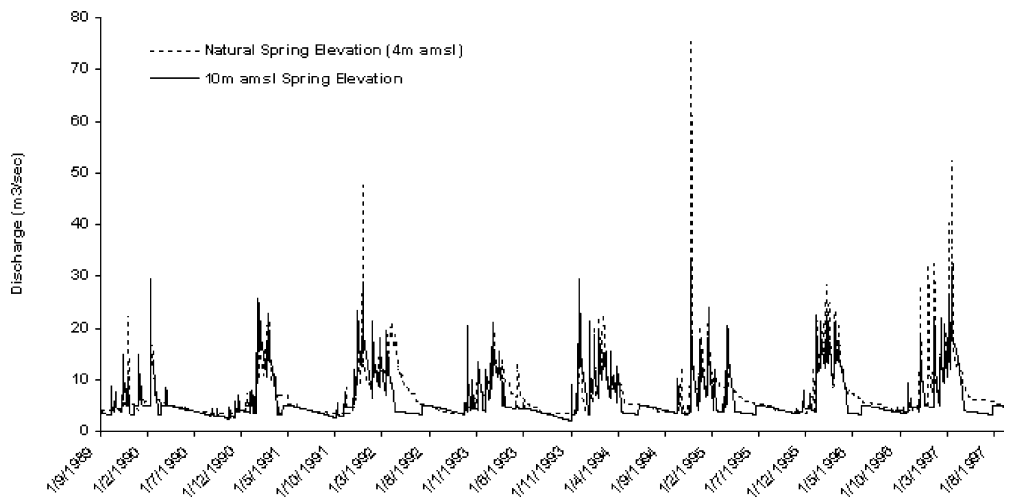
**Fig. 2** Measured chloride concentration vs. time at the observed spring elevation point (4 m a.m.s.l.) compared with the simulated chloride concentration at an elevation of 10 m



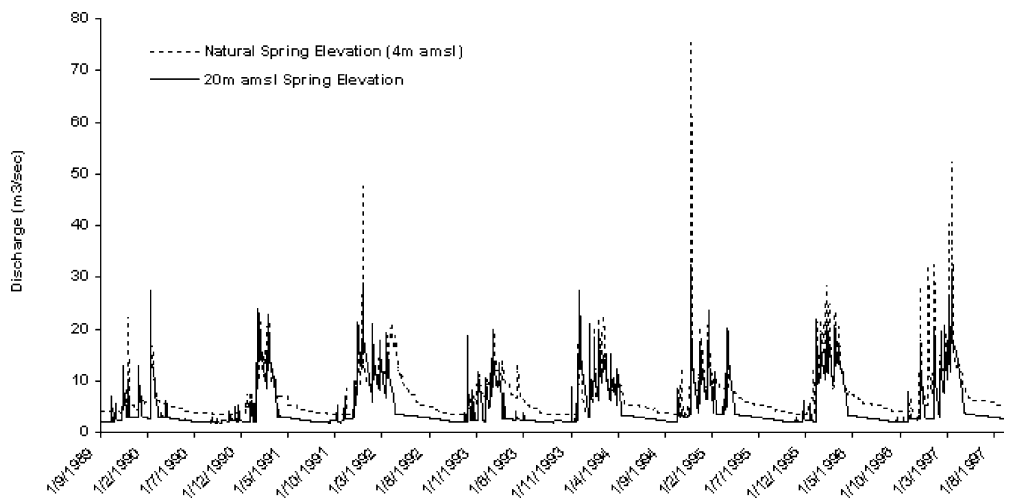
**Fig. 3** Measured chloride concentration vs. time at the observed spring elevation point (4 m a.m.s.l.) compared with the simulated chloride concentration at an elevation of 20 m. (Maramathas et al. 2003a, modified)

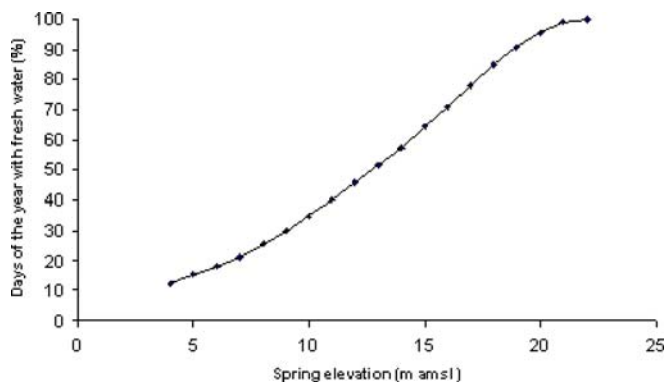


**Fig. 4** Measured discharge vs. time at the observed spring elevation point (4 m a.m.s.l.), compared with the simulated discharge at an elevation of 10 m



**Fig. 5** Measured discharge vs. time at the observed spring elevation point (4 m a.m.s.l.) compared with the simulated discharge at an elevation of 20 m. (Maramathas et al. 2003a, modified)





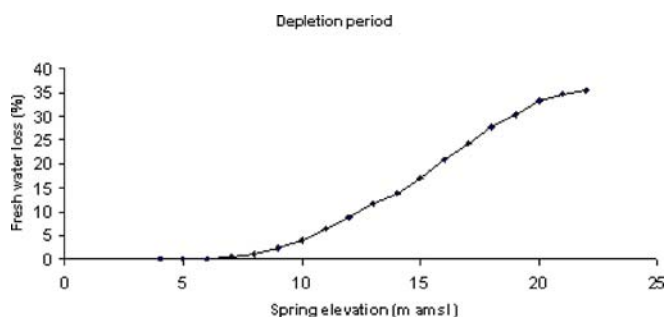
**Fig. 6** Days during the year (%) with fresh water vs. spring elevation (simulated). (Maramathas et al. 2003a, modified)

used for the management of these springs. As an application, the case of the periodically brackish karst spring of Almiros at Heraklion Crete, Greece has been studied.

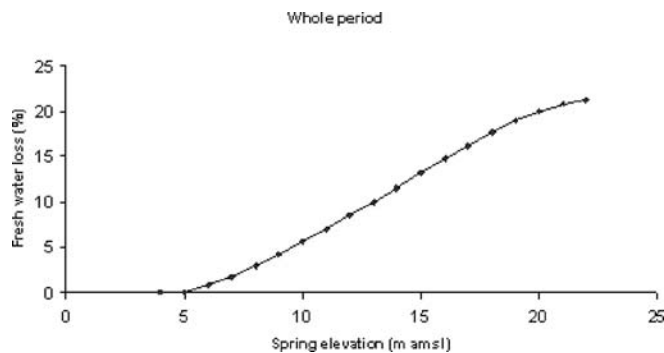
### Almiros spring at Heraklion, Crete and its development

The Almiros spring is located 10 km west of the city of Heraklion, at an elevation of about 4 m above mean sea level (a.m.s.l.) and at a distance of 1 km from the sea. It is a periodically brackish karst spring. Its discharge fluctuates between 4 m<sup>3</sup>/s in the summer and 70–80 m<sup>3</sup>/s in the winter following heavy rainfall on the Psiloritis Mountain. The annual water spring discharge approaches 250×10<sup>6</sup> m<sup>3</sup>. At low discharge, the spring water is brackish due to sea water entering the spring's reservoir. Karstified Mesozoic limestone of the Ionios and Tripolis formations form the hydrogeological basin of the spring (Fig. 1; Fitrolakis 1980; Vidakis 1983). Low rainfall during summer months and resulting low freshwater pressure in the reservoir, in constant contact with the sea, cause the spring water to become brackish in the summer.

Many attempts have been made to improve the quality of the spring water with limited success (Breznic 1990). Twenty-five years ago, a small dam with a height



**Fig. 7** Calculated freshwater loss (%) vs. spring elevation (depletion period is May to October only). (Maramathas et al. 2003a, modified)



**Fig. 8** Calculated freshwater loss (%) vs. spring elevation (whole period, i.e. year-round). (Maramathas et al. 2003a, modified)

of 6 m was constructed on the downgradient side of the spring to prevent sea-water intrusion, but its height was not sufficient to stop this from happening. During this experiment of raising the elevation of the water outlet from its natural level (4 m a.m.s.l.) to 10 m a.m.s.l., the quality of the spring water was improved by about 10%. As an alternative approach, many bores have been drilled upstream of the spring without finding substantial quantities of water, as the water in the karst reservoir follows a network of conduits, making it difficult to locate.

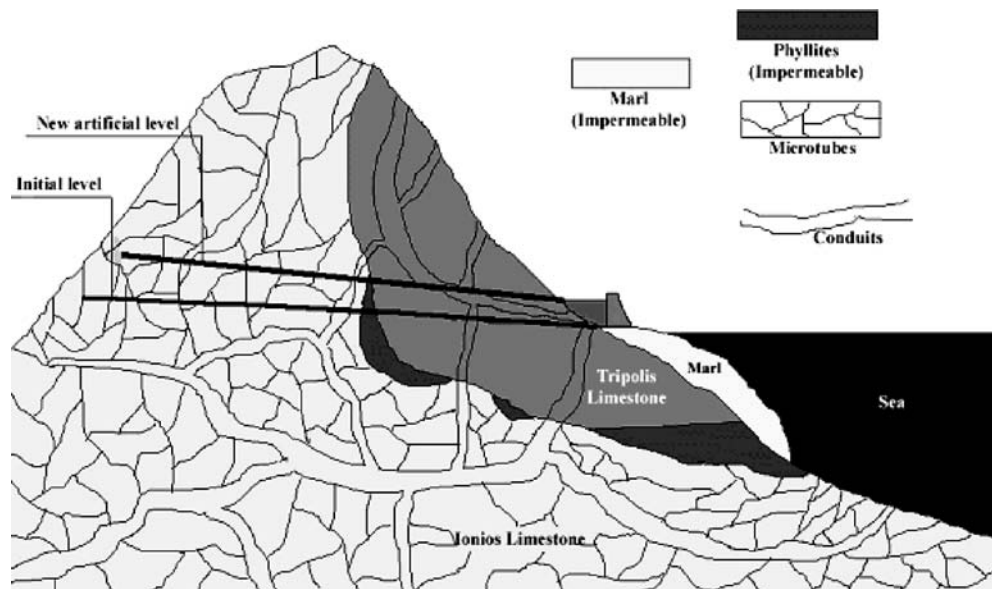
### Model results for scenarios of spring outlet elevation

The MODKARST model has been used for the Almiros spring simulation. The model fitting has been done with the least squares method. According to this method, an optimization program was tasked with estimating the

**Table 2** Spring freshwater loss at different elevations of the water outlet point as a percentage of the fresh water that the spring gives at its natural elevation

Elevation (m a.m.s.l.)	Loss during whole period (year-round) (%)	Loss during depletion period (%)
4	0.00	0.00
5	0.03	0.00
6	0.81	0.00
7	1.70	0.50
8	2.96	1.02
9	4.24	2.32
10	5.55	4.06
11	6.99	6.39
12	8.53	8.93
13	9.98	11.63
14	11.50	13.91
15	13.15	17.05
16	14.68	20.83
17	16.21	24.26
18	17.68	27.75
19	18.97	30.38
20	19.96	33.22
21	20.74	34.75
22	21.23	35.33

**Fig. 9** Sketch of a dam in front of the Almiros spring. Location of tubes and conduits are schematic



parameter values so that the following mathematical expression (Eq. 1) would reach its smallest possible value:

$$\sum_{t=1}^D [(Q_{M_t} - Q_{F_t})^2] + \sum_{t=1}^D [(C_{M_t} - C_{F_t})^2] \quad (1)$$

Where  $Q_{M_t}$ ,  $C_{M_t}$  are the model-calculated values for the discharge and chloride concentration,  $Q_{F_t}$ ,  $C_{F_t}$  are the field measurements respectively, and  $D$  is the time period for the optimization (number of days). After finding significant fit, the model was used to investigate the problem of spring development and management.

One of the model parameters is the elevation of the spring's water outlet point and, consequently, the model can simulate the springs for different spring elevations. This model feature has been applied to the Almiros spring for the years from 1989 to 1997 and the results are presented in Figs. 2, 3, 4, 5, 6, 7, 8 and in Table 2. The model predicted chloride variation vs. time for 10 and 20-m (a.m.s.l.) spring elevations, shown in Figs. 2 and 3 respectively, compared with the measured chloride concentrations at the observed elevation (4 m a.m.s.l.). It was noted that spring water quality improved as the elevation of the water outlet point increased. Shown in Figs. 4 and 5, the model predicted discharge vs. time for 10 and 20-m (a.m.s.l.) spring elevations respectively, compared to the measured discharge at the observed elevation (4 m a.m.s.l.). From these figures, it can be seen that part of the water is lost as the elevation of the spring increases. This part can be calculated from the model through the comparison between the simulated hydrographs at the various predicted spring elevations and the hydrographs of observed elevation. In Fig. 6, the simulated percentage of the days throughout the year with fresh water vs. the spring elevation (for the hydrologic years 1989–1997) are presented. From this illustration, it is evident that the periods during which the spring gives fresh water are

lengthened as the spring elevation increases, and the spring gives fresh water 100% of the year when the elevation reaches 22 m a.m.s.l. Finally, the model-calculated freshwater loss vs. spring elevation for the depletion period and the entire period are presented in Figs. 7 and 8 respectively, and in Table 2. The depletion period, which lasts from around May to October in Greece, is the dry period of the year with no recharge.

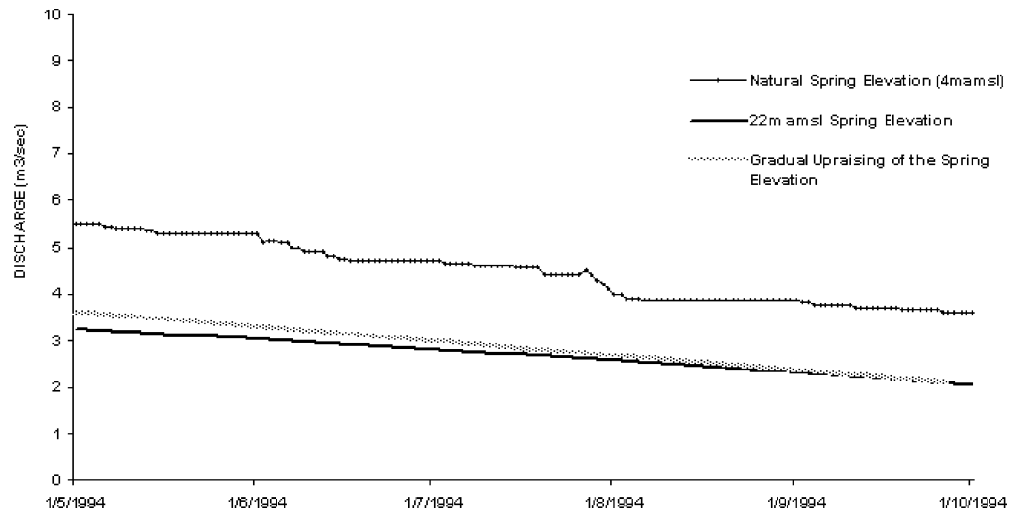
Taking everything mentioned above into consideration, it can be concluded that with an upraising of the water outlet point of the spring, the quality of its water improves and the freshwater periods during the year become longer, while with an upraising of this point up to the elevation of 22 m a.m.s.l., sea-water intrusion is totally blocked. The artificial upraising of the water outlet point of the spring could be realized through the construction of a dam (Fig. 9) in front of the spring.

The freshwater loss caused by upraising to the elevation of 22 m a.m.s.l., is in the order of 21% for the whole hydrologic period (year-round), and 35% for the depletion period. However, if totally fresh water is not necessarily required from the spring and higher chloride concentrations can be tolerated, modifications

**Table 3** Gradual upraising plan of the spring elevation for the depletion period of the year 1994

Spring elevation (m a.m.s.l.)		Spring elevation (m a.m.s.l.)	
01 May	7.5	11 July	13.5
07 May	8	18 July	14
12 May	8.5	25 July	14.5
18 May	9	01 Aug.	15
23 May	9.5	09 Aug.	15.5
29 May	10	17 Aug.	16
04 June	10.5	24 Aug.	16.5
10 June	11	01 Sept.	17
16 June	11.5	09 Sept.	17.5
22 June	12	18 Sept.	18
28 June	12.5	27 Sept.	18.5
05 July	13		

**Fig. 10** Hydrographs for the observed spring elevation point (4 m a.m.s.l.) in 1994, for the simulated 22-m spring elevation point and for the simulated gradual upraising of the spring elevation point



are possible and the water loss can be lowered. With the MODKARST model, the appropriate spring elevation can be estimated so that the water quality and the implied water loss have the desired values.

### Two management scenarios for the spring

As an application, the MODKARST model was used for the management of the spring during the depletion period of the year 1994. Two scenarios were examined. The first scenario was the artificial upraising of the water outlet point to the elevation of 22 m a.m.s.l. where sea-water intrusion is totally blocked. The second scenario was the gradual artificial upraising of the water outlet point so that sea-water intrusion is blocked and freshwater loss is kept to a minimum. The model estimated a plan for a gradual upraising of the spring elevation (presented in Table 3). In order to attain this, the model was used repeatedly, incrementally increasing the spring level and yielding a model prediction for the number of days that the spring should give freshwater. In Fig. 10, the real hydrograph at the real elevation (4 m) and the simulated hydrographs for the 22 m-spring elevation, and for the gradual upraising of the spring elevation according the estimated plan, are presented. As it can be seen, the freshwater loss decreases with the gradual upraising of the spring elevation (second scenario). In Table 4, the model calculations for freshwater loss for the two scenarios, and the difference between them, are reported. The gradual rise of spring outlet could be realized through a computer-controlled water gate at the bottom of the dam.

**Table 4** Spring freshwater loss ( $m^3$ ) for the depletion period of the year 1994

22 m a.m.s.l. spring elevation	Gradual upraising	Difference
20,204,734	17,235,438	2,969,295

### Conclusions

A suitable development method for some brackish karst springs is the artificial upraising of the water outlet point. This method is applicable if the necessary rise of the water outlet point and the resulting freshwater loss to the sea can be reliably estimated. The MODKARST model can estimate the necessary spring upraising and calculate the freshwater loss to the sea.

The Almiros spring simulation showed that the upraising of its water outlet point, through the construction of a small dam, could prevent sea-water intrusion into the spring reservoir. In this case, the dam would need to be constructed to the elevation of 22 m a.m.s.l. At this elevation, sea-water intrusion will be totally blocked. Freshwater loss caused by this upraising will be about 35% during the spring depletion period (May to October, where no recharge takes place) and 21% during the whole hydrologic period. After application of the model presented for the Almiros spring, it has been concluded that with a gradual upraising of the water outlet point according to a plan derived from a series of MODKARST simulations, the loss of freshwater decreases.

### Recommendations for the development of the spring

A small dam must be constructed to the elevation of at least 22 m a.m.s.l. in front of the spring's water outlet point. A network of rain gauges must be installed in representative points across the recharge area. Rainfall data can then be used as input in the simulation of the spring, based on the MODKARST model. The model will calculate the water level behind the dam necessary to ensure that the quality of the spring water will meet the desired quality. A computer-controlled water gate at the bottom of the dam could be used to keep the water behind the dam at the desired level.

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