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EXPERIMENTS WITH A MODEL OF A BRACKISH KARST SPRING

SUMMARY

A model of a brackish karst spring connected with the sea by a karst channel is described. The outlet of this type of spring is often above sea level, the hydrostatic pressure, however, below sea level.

Since definite model parameters cannot be derived, the observations in the field are only qualitatively comparable with the results of the model.

A drying up of a brackish water spring can be simulated in the model. The fresh water from the mountains then flows in the karst channels directly into the sea. On the basis of these results, damming up of brackish karst springs to improve the water quality appears to hold little promise of success.

1. INTRODUCTION

Within the framework of scientific cooperation with the Institute of Geology and Mineral Exploration, Athens, in the field of groundwater technology, detailed hydrogeological and geophysical investigations were carried out on karst aquifers on Crete in the areas of Agios Nikolaos and Iraklion (Fielitz [1], Vierhuff [4], Vogelsang [5]). These two areas are characterized by springs of brackish water up to 4 m above sea level. The salt content of the spring water depends on the time of year.

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Tests with a model of a karst spring that produces brackish water were induced by the failure of an attempt (verbal information) to dam up the Almyros Spring at Iraklion so that the spring water would also be usable in the summer when flow is at a minimum.

The evaluation of chemical analyses of the water from 121 karst springs in the Peloponnes (Trippler et al. [3]) demonstrates that contaminated karst springs at sea level are not rare. The water of 22 springs was found to be contaminated by sea water.

2. THE MODEL OF A BRACKISH-WATER KARST SPRING

2.1. Theoretical Basis

The model is based on the paper of I. Kuscer & D. Kuscer [2]. The authors assume that a brackish-water karst spring flows at sea level only because of the differences in the specific gravity between fresh, brackish, and sea water. (Other authors with the same idea are mentioned in this citation).

Figure 1 shows a karst channel in an idealized form. F indicates fresh water, B brackish water, S salt water (sea water).

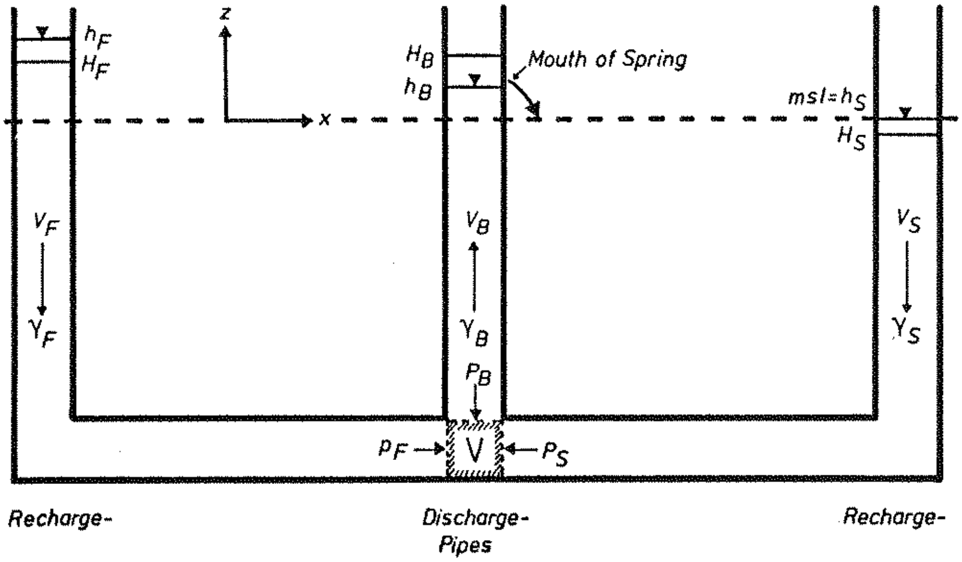

Fig. 1 – Schematic representation of a karst spring that produces brackish water.

The fact that the fresh water and sea water karst channels are separate until they meet in a chamber in which mixing occurs is important to the model. This chamber is connected with the surface by at least a third karst channel, so that water can flow from a spring.

If brackish water flows from this spring, the following inequality equation is valid for the pressure of the water where it flows into and out of the chamber where mixing takes place:

$$p_F > p_B < p_S \tag{1}$$

If the coordinate system in Fig. 1 is taken as a basis, the individual pressures at the inlets can be described as a product of the water columns and the specific gravity:

$$\begin{aligned} p_S &= -\gamma_S (z - H_S) \\ p_B &= -\gamma_B (z - H_B) \\ p_F &= -\gamma_F (z - H_F) \end{aligned} \tag{2}$$

The following equation is valid for the case of static equilibrium between the brackish and sea water levels:

$$\gamma_B (z - H_B) = \gamma_S (z - H_S),$$

from which the following equation can be derived:

$$H_B = H_S (\gamma_S/\gamma_B) + z (\gamma_B - \gamma_S)/\gamma_B) \tag{3}$$

Both in the field and in the model, $H_S \neq 0$ and is always below sea level, since pressure losses occur because of the flow of the salt water.

The results of the tests with the model can be compared only if H_B and H_F are calculated and then related to H_S. However, H_S is not determined in the model. Therefore, H_S is set equal to 0.

This means that H_S is assumed to be identical with sea level.

This assumption yields the following simplified equation:

$$H_{B,F} = z (\gamma_{B,F} - \gamma_S)/\gamma_{B,F} \tag{4}$$

Brackish water can flow from the spring only if p_F is approximately equal to p_S. Whether this relation is maintained depends on the flow of fresh water from the mountains, which, although it is subject to seasonal fluctuation, can be regarded as constant over long periods. This makes it necessary to assume that a unconfined water table exists in the karst on the mountain side of the spring. The fresh water, some of which infiltrates at high altitudes, must have lost most of its potential energy by the time it has reached the karst water level. If these conditions are fulfilled, the system regulates itself.

The calculation of the pressure H is also necessary for comparison with the measured data h. The pressure h_B is identical with the height of the outlet of the brackish-water spring. According to the inequality (1), the brackish-water spring can only function if h_B is less than H_B.

The pressure of the fresh water flow h_F (mountain side) is the sum of the equilibrium pressure H_F (calculated according to Eq. 4) and a variable, dynamic partial pressure necessary to overcome the friction of flow.

The values of h_F and h_B are measureable in the model; under natural conditions h_F is in general unknown. Only if the unconfined water table is encountered in a well on the mountain side of the spring can h_F be measured. A knowledge of the depth of the chamber in which mixing occurs is of practical consequence, since this makes it possible to calculate H_B. Only if H_B is known can it be determined how high the spring outlet must be dammed (e.g. at the Almyros Spring at Iraklion) in order to obtain fresh water from the spring.

Using Equation 4, only a minimum depth of the chamber where the mixing takes place can be given if h_B is to be approximately equal to H_B.

2.2. Description of the Model

The tests with the model were carried out with two different mixing chambers of 30 L and 3 mL, respectively. The 30-L container was made of plexiglass so that the mixing processes could be made visible by adding various dyes to the water.

The connection with the spring, as well as to the fresh-water and salt-water reservoirs, was effected via comparatively rigid plastic tubing (inner diameter approximately 10 mm).

Using a flow gauge and a finely adjustable valve, the desired quantity of fresh water was filled into length of plastic tubing serving as reservoir. An «unconfined karst water table» with a head h_F was thus established. The flow gauge measuring the rate of flow of fresh water into the mixing chamber could measure a maximum of 1.5 L/min; if this was exceeded, the fresh-water flow rate was determined from the specific gravity of the brackish water and the discharge rate of the spring.

The sea water basin had a surface area of about 2.3 m^2, so that h_S was kept approximately constant for the duration of the test.

The spring was also made of plastic tubing and was equipped with a overflow outlet.

The sea water was represented by a NaCl solution with a specific gravity of about 1.028 p/cm^3. The conductivity of the brackish spring water was continuously measured and used to determine approximately the specific gravity of the brackish water.

A theodolite was used to read the water heads h_F, h_B, and h_S from a measuring rod.

2.3. Performance of the Tests

The discharge rates of the model spring were between 0.5 and 2.5 L/min during tests. With the smaller mixing volume, equilibrium was reached within a few minutes, while by the larger mixing volume 30-90 min were required.

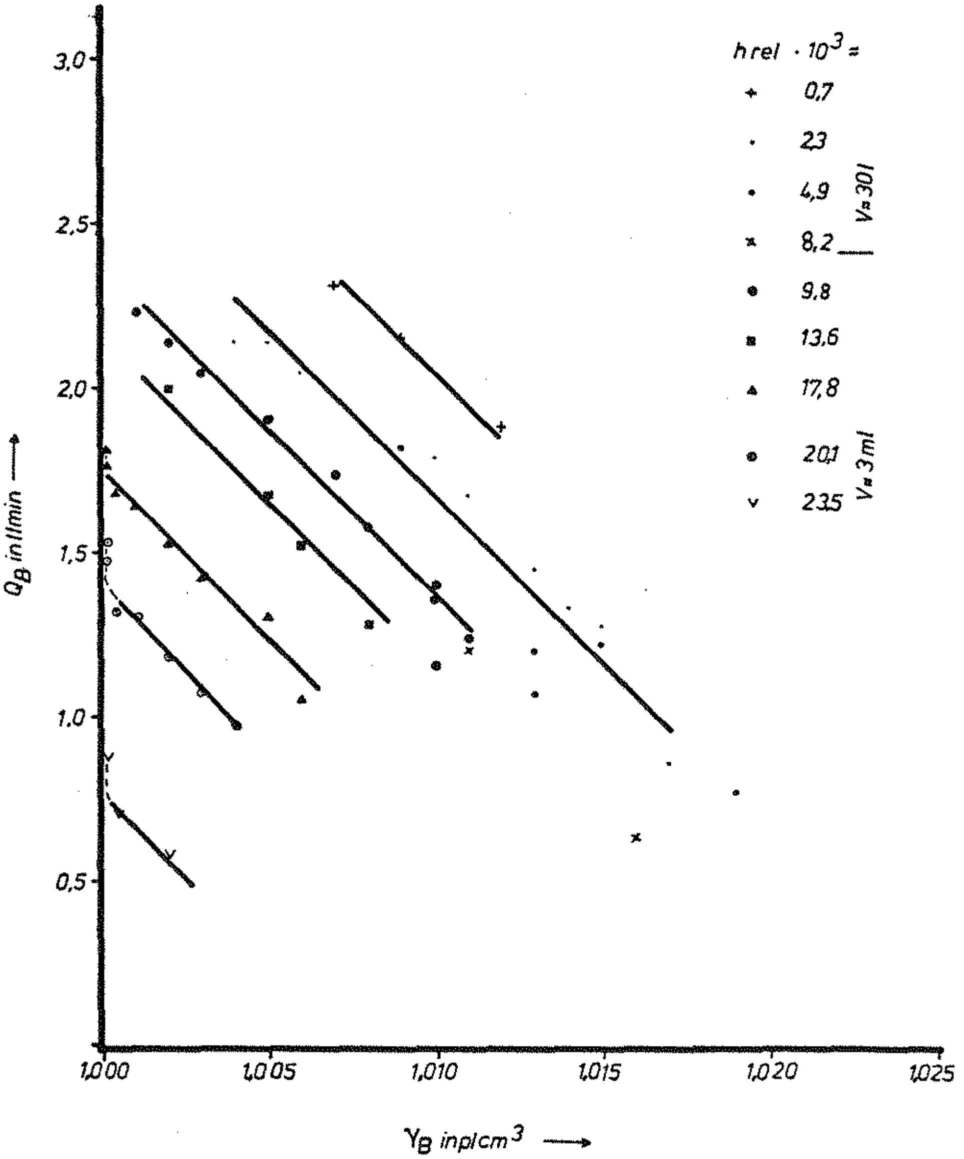

Fig. 2 - The yield of a spring as a function of the specific gravity of the spring water.

The conductivity of the discharging brackish water was continuously monitored during an experiment. An experiment was considered to be finished when the conducitivity remained constant over a sufficiently long period of time.

The experiments were carried out from summer to late fall, 1982. Thus, the temperature of the water in the model varied considerably. The specific gravities of the spring water in the model determined by conductivities are therefore surely somewhat incorrect, but this source of error was unavoidable with the design of the model.

3. TEST RESULTS

Table 1 shows the results of the tests using different model parameters, e.g. the relative elevation of the spring ($h_{rel} = h_{B/z}$), variable input of fresh water and the variable z.

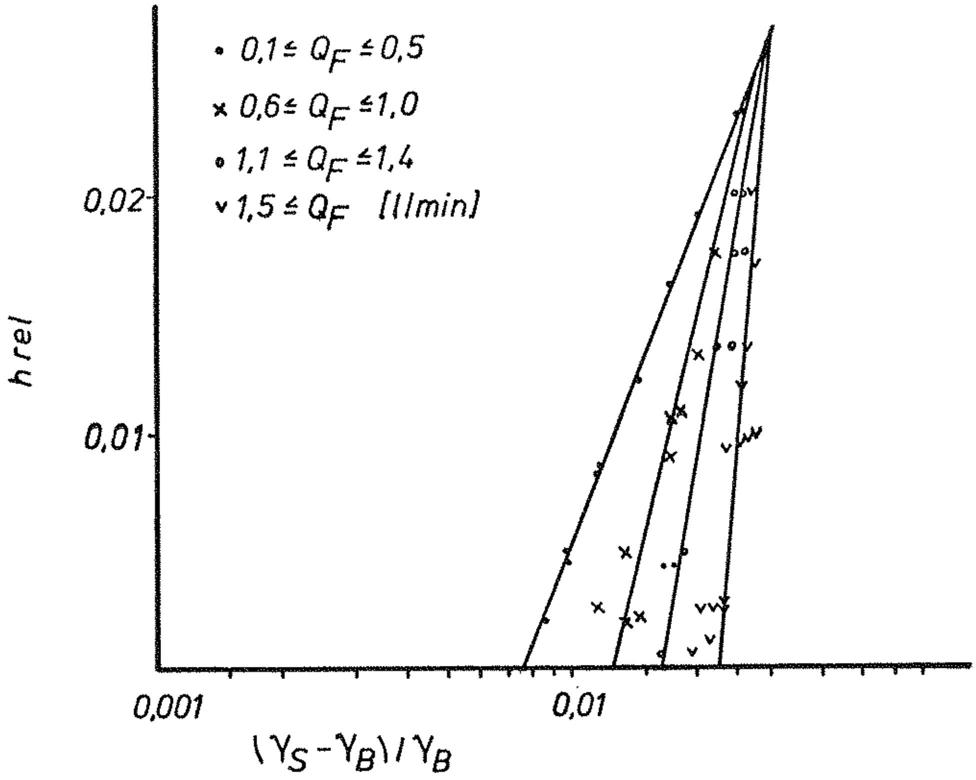

Fig. 3 - The relative elevation of the spring as a function of the specific gravity of the sea and brackish water.

TABLE 1 – Data from a model of a brackish-water karst spring (using a ca.-30-L mixing chamber)

Nr.	z	F (fresh water)			B (brackish water)						Q	
		h	H	h-H	h	hrel	H	h-H	B	S	B	F
	mm		mm				mm		p/cm**3		L/min	
						(−3)			1.0...			
1	8389	216	226	−10	17	2.0	73	−56	18	27	.86	.31
2	8389	218	228	−10	17	2.0	85	−68	17	27	.97	.41
3	8389	222	229	−7	18	2.1	100	−82	15	27	1.18	.51
4	8388	226	230	−4	19	2.3	104	−85	15	27	1.28	.62
5	8390	231	230	−1	17	2.0	113	−96	14	28	1.33	.70
6	8390	236	232	5	18	2.1	122	−104	13	28	1.45	.80
7	8389	250	232	18	20	2.4	136	−116	11	28	1.58	.96
8	8390	259	235	24	19	2.3	142	−123	11	28	1.67	1.21
9	8389	274	234	40	20	2.4	152	−132	10	28	1.79	1.38
10	8389	322	333	89	21	2.5	180	−159	06	28	2.05	1.61
11	8390	344	232	112	21	2.5	187	−166	05	28	2.14	1.76
12	8389	365	231	134	22	2.6	194	−172	04	28	2.14	1.83
13	8391	381	231	150	20	2.4	200	−180	04	28	2.28	1.95
14	8388	236	337	−1	41	4.9	123	−82	13	28	1.20	.64
15	8388	283	233	50	42	5.0	156	−114	09	28	1.82	1.24
16	8388	226	236	−10	38	4.5	85	−47	18	28	.77	.28
17	8388	232	236	−4	68	8.1	98	−30	16	28	.63	.27
18	8388	249	236	13	70	8.3	142	−72	11	28	1.20	.73
19	8388	334	242	92	100	11.9	213	−113	03	29	1.94	1.74
20	8388	274	244	30	5	.6	146	−141	12	29	1.88	1.20
21	8388	308	244	64	6	.7	169	−163	09	29	2.14	1.58
22	8388	343	244	99	7	.8	188	−181	07	29	2.31	1.88
23	8388	264	238	26	130	15.5	174	−44	08	29	.88	.75
24	8388	242	240	2	42	5.0	110	−68	15	29	1.22	.71
25a	8388	233	240	−7	41	4.9	116	−75	15	29	1.07	.61
25b	7918	....	227	7	....	5.2	110	−69	....	....	....	....
26	8390	205	231	−26	−21	−2.5	57	−78	21	28	1.00	.32
27	8389	227	233	−6	42	5.0	83	−41	18	28	.82	.32
28	8390	233	232	1	72	8.6	100	−28	16	28	.71	.32
29	8390	238	232	6	102	12.2	123	−21	13	28	.57	.32
30	8390	238	231	7	136	16.2	148	−12	10	28	.49	.32
31	8390	220	231	−11	161	19.2	168	−7	07	28		.21
32	8390	225	231	−6	161	19.2	169	−8	07	28		.24
33	8390	228	231	−3	161	19.2	169	−8	07	28		.27
34	8390	230	231	−1	161	19.2	170	−9	07	28		.31
35	8390	235	231	4	161	19.2	171	−10	07	28		.37
36	8390	238	231	7	161	19.2	171	−10	07	28		.41
37	8390	241	231	10	161	19.2	171	−10	07	28		.44
38	8390	243	231	12	161	19.2	171	−10	07	28		.48
39	8390	246	231	15	161	19.2	171	−10	07	28		.51
					The spring dries up.							
40	8390	95	231	−136	30	3.6	171	−141	07	28		.51
41	8392	88	231	−143	21	2.5	171	−150	07	28		.51

Segue: Table 1

Nr.	z	F (fresh water)			B (brackish water)						Q		
	mm	h	H mm	h-H	h	hrel	H mm	h-H	B p/cm**3	S	B L/min	F	
						(−3)			1.0...				
42	1776	50	48	2	18	10.1	28	−10	11	27			
43	1729	52	47	5	36	20.8	46	−10	04	27			
44	1732	51	46	4	31	17.9	38	−7	05	27			
45	7763	260	226	34	83	10.7	143	−60	11	29	1.24	.79	?
46	7761	260	226	34	85	11.0	143	−58	10	29	1.16	.75	?
47	7761	265	226	39	73	9.4	147	−74	10	29	1.36	.90	
48	7761	275	226	49	73	9.4	151	−78	10	29	1.40	.94	
49	7759	289	226	63	75	9.7	163	−88	08	29	1.58	1.15	
50	7760	311	226	85	76	9.8	174	−98	07	29	1.74	1.35	
51	7763	329	226	103	72	9.3	184	−112	05	29	1.90	1.56	
52	7762	362	226	136	74	9.5	200	−126	03	29	2.05	1.72	
53	7762	382	226	156	75	9.7	210	−135	02	29	2.14	2.00	
54	7761	403	226	177	76	9.8	216	−140	01	29	2.23	2.14	
55	7762	274	226	48	103	13.3	165	−62	08	29	1.28	.94	
56	7761	299	226	73	106	13.7	181	−75	06	29	1.52	1.22	
57	7761	324	226	98	106	13.7	194	−88	04	29	1.67	1.44	
58	7762	358	226	132	105	13.5	208	−103	02	29	1.99	1.84	
					The spring dries up.								
59	7761	270	226	44	137	17.6	177	−40	06	29	1.05	.83	
60	7763	285	226	59	136	17.5	189	−53	05	29	1.30	1.09	
61	7762	304	226	78	137	17.7	201	−64	03	29	1.43	1.28	
62	7762	314	226	88	137	17.7	208	−71	02	29	1.54	1.42	
63	7762	330	226	104	138	17.8	216	−78	01	29	1.65	1.58	
64	7762	343	226	117	139	17.9	223	−84	004	29	1.68	1.66	
65	7762	356	226	130	139	17.9	226	−87	001	29	1.76	1.76	
66	7762	373	226	147	139	17.9	226	−87	001	29	1.81	1.81	
					The spring dries up.								
67	7764	251	226	25	126		226	−100					
68	7769	268	218	50	154	19.8	187	−33	04	28	.98	.84	
69	7768	275	218	57	155	20.0	194	−39	03	28	1.08	.97	
70	7768	286	218	68	156	20.1	201	−45	02	28	1.19	1.10	
71	7768	298	218	80	156	20.1	210	−54	01	28	1.30	1.26	
72	7768	309	218	91	157	20.2	215	−58	004	28	1.32	1.30	
73	7768	329	218	111	157	20.2	217	−60	001	28	1.48	1.48	
74	7768	337	218	119	157	20.2	217	−60	001	28	1.53	1.53	
					The spring dries up.								
75	7768	212	218	−6	110		218	−108			1.53	1.53	
76	7764	224	217	7	181	23.3	196	−15	03	28			
77	7764	231	217	14	182	23.4	205	−23	02	28	.56	.53	
78	7763	245	217	28	183	23.6	215	−32	004	28	.70	.69	
79	7763	257	217	40	183	23.6	217	−34	001	28	.87	.87	
					The spring dries up.								
80	7764	113	217	−104	62		217	−155	001	28	.87	.87	

Tests 1 - 44 were carried out using the 30-L mixing chamber. The addition of dyes to the water made it possible to see the mixing processes in the plexiglass chamber. Photographs were taken of some of the experiments. Tests 45 - 80 were carried out using the 3-mL mixing chamber.

Yield is plotted in Fig. 2 versus specific gravity. It can be seen that different straight lines are obtained for different relative levels of the spring (h_{rel}). The test series with the two mixing chambers complement each other.

The general trend of the test series demonstrates that the smaller the difference between the relative pressure heads of the spring and sea level, the higher the yield, assuming the specific gravity of the brackish water remains constant.

In Figure 3, h_{rel} is plotted as a logarithmic function of the specific gravities. It can be seen that the slopes of the straight lines vary with the quantity of the freshwater input. Accordingly, the model spring may be brackish up to a relative elevation equal to $h_{rel} \approx 27 \times 10^{-3}$. At this value, $\gamma_B = 1$, regardless of yield; the spring water must then be fresh water.

In Table 1, the values in column h-H under «fresh water» and «spring water» should be noted. (See Fig. 1 for the definition of h and H). If the theoretically possible water level (H) is subtracted from the measured one (h), the hydrostatic pressure is obtained in mm water head in order to determine whether the measured water level h is below (–) or above (+) «sea level». It will be noticed that the hydrostatic pressure at the level of the spring outlet is below sea level in all of the tests.

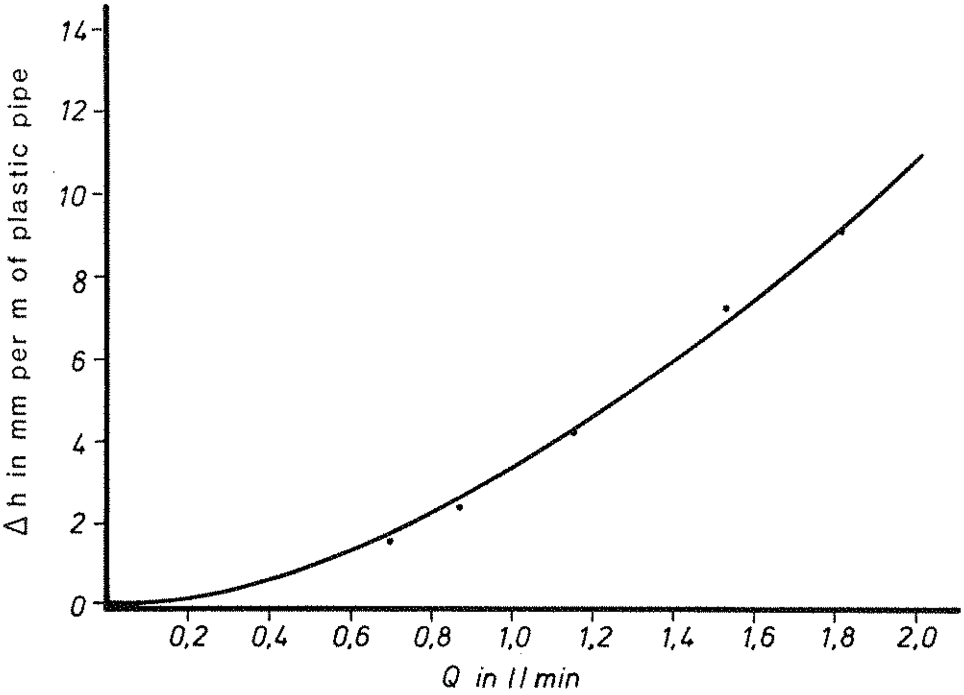

Fig. 4 - Flow resistance in the input tubing of the model.

In order to overcome the frictional resistance in the plastic tubing, the height h of the fresh water input must be above «sea level». This frictional resistance is a function of the flow rate of the water. Figure 4 shows the frictional resistance per unit length of the tubing.

A critical state occurs in the model when the pressure p_F starts to rise above the pressure p_S of the sea-water input. In the model this is achieved by putting the outlet h_B at a comparatively high level at the beginning of the test and stepwise increasing the input of freshwater. When this is done, the salt water changes its direction of flow several times, moving a few centimeters to and from in the input tubing. This instable state changes abruptly into a stable movement of the water in the direction of the sea-water basin. The brackish-water spring runs dry. A new spring comes into existence below sea level. This new stable state can be changed in this arrangement of the model only by reducing the hydraulic potential of the entire system until the salt water flows again into the mixing chamber. Observations of changes in flow direction at spring outlets below sea level have been described by Kuscer & Kuscer [2].

Figure 5 shows the behavior of h_F with respect to time. The variations in pressure from 1422 h to 1428 h represent fluctuations in the system which occur shortly before the new stable state is attained. (This test is not shown in Table 1).

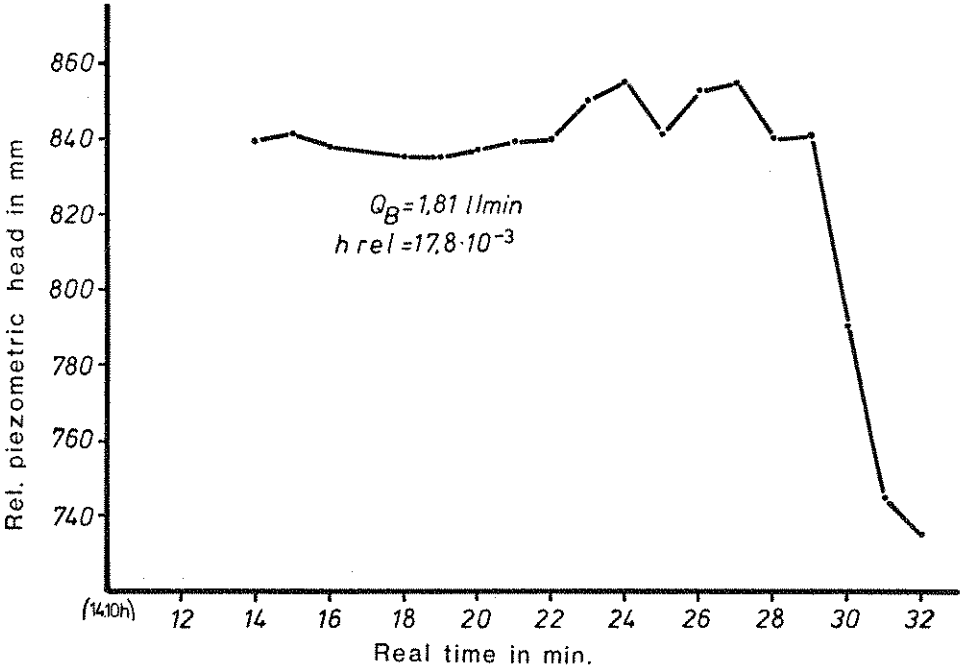

Fig. 5 – h_F shortly before and during the drying up of the spring.

Figure 6 shows the conductivity of the outflowing brackish water plotted against time for tests 45 - 54 (see Table 1). In principle, the conductivity of the «spring water» fluctuates around an average value every time the model is newly arranged. But generally, the amplitude of the fluctuations increase with decreasing average value. The time between maxima is three to four minutes and are comparable to that shown in Figure 5.

The reasons for the comparatively strong variations in specific gravity in tests 53 and 54 are still unclear and cannot be explained by a «salt-water bubble» in the fresh-water flow, since at the given flow velocities such a bubble would leave the system after about 20 seconds.

These observations could be explained as follows:

If the average specific gravity of the brackish water is comparatively high, the equilibrium between the pressures p_F and p_S is not affected by minor changes in specific gravity. But if the average specific gravity of the brackish water decreases, small irregular fluctuations in the specific gravity disturb this

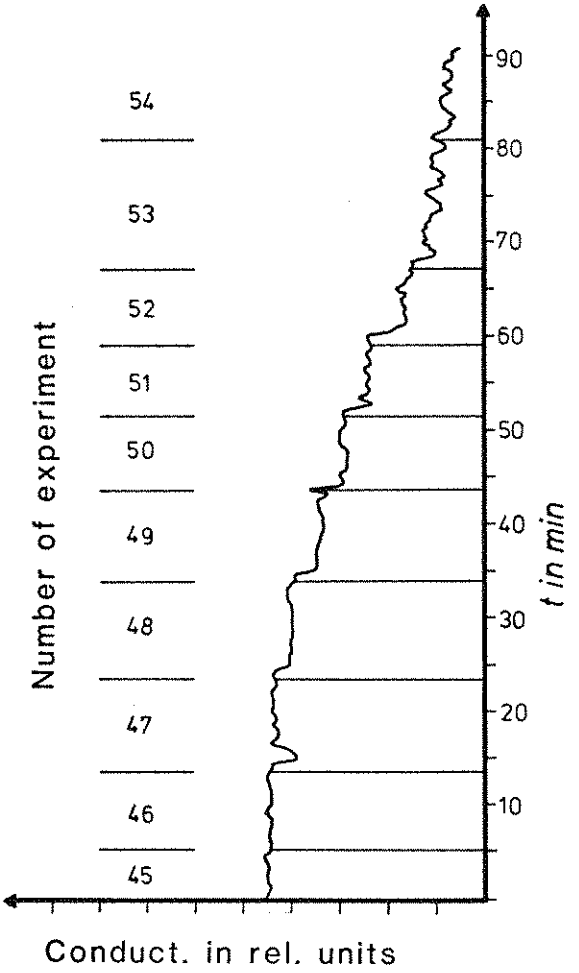

Fig. 6 - The conductivity of the brackish spring water in tests 45 - 54 (using the 3-mL mixing chamber).

equilibrium, building on itself. After reaching a maximum, the pressure and specific gravity oscillate with almost constant frequency around an average value. This may be explained in the following way: Assume that the pressure p_F is increased for a short period of time. This hinders the entrance of the salt water into the mixing chamber, since p_S is constant. Because the water flowing to the spring now contains less salt, the weight of the brackish-water colums decreases, causing a decrease in p_F. This can be seen as an intermediate minimum in Figure 5. The pressure head of the sea water, p_S, which has remained constant, is now large enough for salt water to enter the mixing chamber. This increases the weight of the brackish-water column, forcing an increase in p_F. This in turn reduces the brackishness of the spring water. Depending on the construction of the model, an oscillation of the measured parameters of the model is observed.

The frequency of this oscillation is theoretically a function of the surface area of the unconfined karst water table.

Table 2 shows the pressure heads before and after the drying up of the spring. The direction of flow of the water is marked by arrows.

TABLE 2 - Comparison of the pressure heads before and after the drying up of the spring (tests 39 & 41) (arrows indicate the direction of the water flow).

	h_F	h_B	h_S
before	8636 ------------>	8611	<------------ 8625
afterwards	8480	8472	8453
	----------------	----------------	--->

4. ASSESSMENT OF THE TESTS WITH THE MODEL OF A BRACKISH-WATER KARST SPRING

It is difficult to compare the results of the tests with the model with the natural behaviour of a brackish-water spring since no definite relationship between the natural state and the model can be established via comparison parameters (calibration of the model). The parameter «yield» is shown in Figures 2 and 3, for example. Although this value and its variation with time is characteristic for a spring, it depends on the roughness of the channel walls, which is difficult to determine and may itself depend on the yield. Therefore, the yield of a spring cannot be used for comparison.

According to equation 4, brackish-water springs which have a connection with the sea can occur at very different elevations. The depth of mixing, z, can be estimated from the data of the spring only relatively inaccurately as a minimum value, assuming the elevation h_B of the outlet is set equal to the unknown equilibrium height H_B.

Table 1 shows the values obtained in series of 5 tests in which the model spring dried up and the freshwater discharged into the «sea». Such events can most probably be observed at the beginning of the rainy season, when the supply of freshwater in the karst increases. It is conceivable that after a further increase in the freshwater supply, the pressure in the karst system would become high enough that the spring would produce freshwater. This probably happens with the Almyros Spring at Iraklion during the winter.

It would of interest to take more detailed measurements of the transition from brackish-water to fresh water in a spring.

The question of how a dried-up spring becomes a brackish-water spring again could not be answered with the model. To answer this question, the shape of the karst channels is possibly of decisive importance, for example, double connection with the sea and variable diameter of the karst channel so that the salt water could also possibly form layers beneath the freshwater.

In the model tests, the «spring» was caused to dry up by increasing the freshwater input by increasing p_F until it was greater than p_S. This can also be achieved by keeping the freshwater input constant and placing the mouth of the spring h_B higher and higher. This can be compared with the damming up of the Almyros Spring at Iraklion. According to the results obtained using the model, however, there is the danger that the spring will dry up if the spring is dammed up even higher than it has. Any further construction is then questionable. Therefore, it is recommended that tests be carried out with a model of the spring before damming the spring any higher. These tests should be aimed especially at a simulation of the behaviour of the spring as a result of changes in the channels.

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