GEOLOGIJA *31, 32*, 555–576 (1988/89), Ljubljana

UDK 556.334.34.36.551.44(495) = 20

Development of the brackish karstic spring Almyros in Greece

Sanacija zaslanjenega kraškega izvira Almyros v Grčiji

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Abstract

In karstic massifs of anisotropic permeability groundwater circulates practically, only through zones of high permeability called veins. Coastal springs are contaminated by sea-water either at the mouth of a submarine spring or inside the karstic massif in a branching of veins. The methods to desalinate brackish karstic spring are:

- isolation of the karstic aquifer from sea-water intrusion by a dam at the spring or by a grout-curtain that seals the lower vein with sea-water;
- interception of fresh-water by boreholes, wells or drainage galleries within the karstic massif, inland of the sea-water influence;
- rise of the spring level by a dam. In that case, fresh-water accumulates in the karstic massif and prevents the intrusion of sea-water.

There are already numerous cases of successful development of brackish springs. A more detailed analysis discusses the development possibilities of the important brackish spring Almyros with a mean discharge of 7 m^3/s on Crete island in Greece.

Kratka vsebina

Podzemna voda se pretaka v kraških masivih neenakomerne prepustnosti v pomembnih količinah samo skozi močno prepustne cone, imenovane žile. Obmorski izviri se zaslanijo ali v ustju podmorskega izvira ali v razcepu žil znotraj kraškega masiva. Zaslanjene izvire lahko saniramo na naslednje načine:

- z izolacijo kraškega masiva od morske vode s pregrado pri izviru ali z injekcijsko zaveso, ki zatesni spodnjo žilo z morsko vodo;
- z zajetjem sladke vode z vrtinami, vodnjaki ali drenažnimi rovi v notranjosti kraškega masiva izven vpliva morske vode;
- z dvigom gladine izvira s pregrado. V tem primeru se sladka voda akumulira v kraškem masivu in prepreči vdor morske vode.

Imamo že mnogo primerov uspešne sanacije zaslanjenih kraških izvirov. Bolj podrobno razpravljamo o možnosti sanacije pomembnega zaslanjenega izvira Almyros s srednjim pretokom 7 m^3/s na otoku Kreti v Grčiji.

Contamination in the branching of veins

Karst aquifers of anisotropic permeability are characterized by zones both of very low and of high permeability. Groundwater circulates practically only through zones of high permeability, called veins. The term "vein" does not determine its shape which can be a solution canal, a cave, a fractured or cavernous zone, etc. The vein in which fresh-water circulates is a primary vein. The place where the primary vein branches (Fig. 1) into the lower vein connected with the sea and into the upper vein leading to the spring is called a branching of veins (or vein-branching). Lower veins were formed by fresh-water when their carbonatic rocks massif was above sea level during previous geological periods. Later the elevation of the sea level increased in relation to the massif with veins either due to the tectonic subsidence of the massif

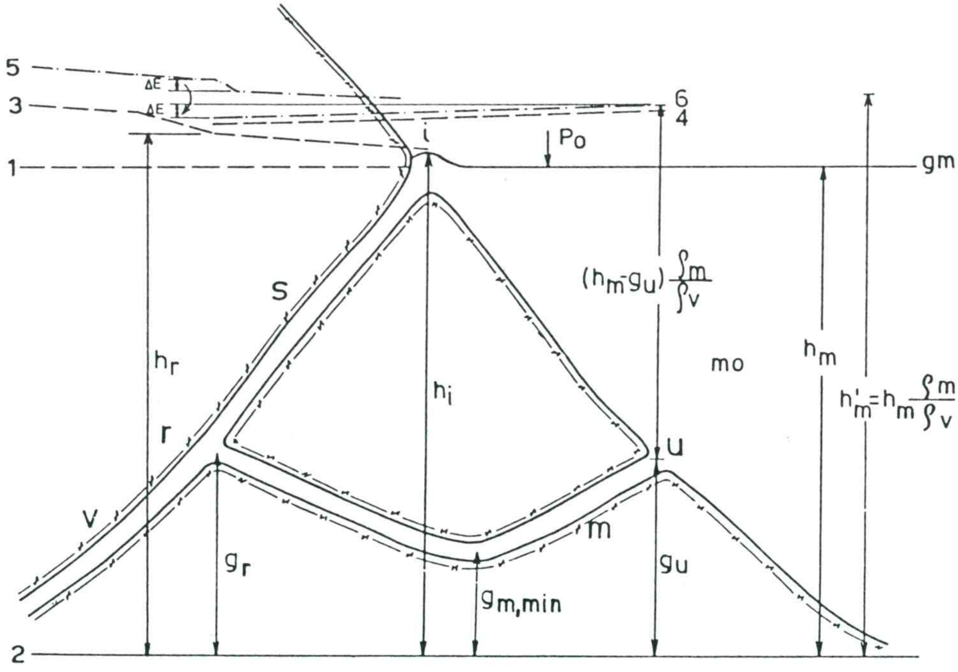


Fig. 1. Scheme of karstic veins of a brackish spring (after Breznik 1973)

mo – Sea; *gm* – Sea level; *i* – Brackish spring; *v* – Primary vein with fresh-water; *m* – Lower vein with sea-water; *s* – Upper vein with brackish water; *r* – Vein-branching; *u* – Mouth of lower vein; *m, min* – Lowest point of lower vein; *h* and *g* – Height above reference level; *1* – Mean sea level; *2* – Reference level; *3* – Piezometric head line of the primary and upper veins; *4* – Piezometric head line of the lower vein; *5* – Energy head line of the primary and upper veins; *6* – Energy head line of the lower vein; *3* to *6* – All the heads expressed through the head of fresh water

Sl. 1. Položaj kraških »žil« zaslanjenega izvira (po Breznik 1973)

mo – morje; *gm* – gladina morja; *i* – zaslanjen izvir; *v* – dovodna žila s sladko vodo; *m* – spodnja žila z morsko vodo; *s* – zgornja žila s somornico; *r* – razcep žil; *u* – ustje spodnje žile; *m, min* – najgloblji del spodnje žile; *h* in *g* – višina nad primerjalno ravnino; *1* – srednja morska gladina; *2* – primerjalna ravnina; *3* – piezometrična višina dovodne in zgornje žile; *4* – piezometrična višina spodnje žile; *5* – energetska višina dovodne in zgornje žile; *6* – energetska višina spodnje žile; *3* do *6* – višine so podane s stebrom sladke vode

(Tertiary to Holocene periods), or due to the rise (Holocene) of the sea level (Herak, 1975, 1977).

The mechanism of contamination inside the karstic massif was explained by Gjurašin (1943), Kuščer (1950) and Breznik (1973). This type of contamination of coastal springs is the most frequent one along the limestone coasts of Yugoslavia and Greece, and there are some such springs along the coasts of France, Italy, Turkey, Syria, Lebanon and other countries.

Supposed disposition of karstic aquifers

The Almyros spring on the Crete island in Greece is a typical brackish spring contamined in the branching of veins inside a karstic massif of anisotropic permeability (Burdon & Papakis, 1964; Kuščer I. & Kuščer D., 1962; Plataki, 1968).

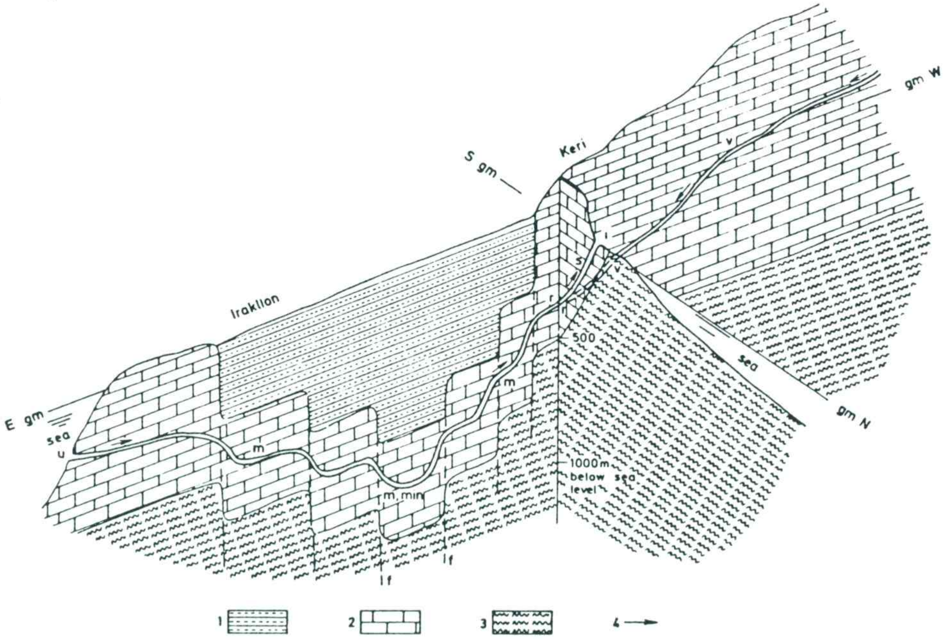


Fig. 2. Schematic block diagram of veins in the karstic massif of the Almyros spring (after Breznik 1978)
1 – Neogene deposits (sand, clay, organic limestone); *2* – Tripolitza series deposits (limestone mostly); *3* – Metamorphic schists (quartzite, phyllite, chlorite, marble); *4* – Direction of flow in veins during dry period; *i* – Almyros spring; *v* – Primary vein; *r* – Branching of veins; *s* – Upper vein; *m* – Lower vein; *m, min* – Lowest point of lower vein; *u* – Mouth of lower vein; *gm* – Sea level; *f* – Fault

Sl. 2. Shematičen blok diagram žil v kraškem masivu izvira Almyros (po Breznik 1978)
1 – neogenski sedimenti (pesek, glina, organski apnenec); *2* – sedimenti serije Tripolitza (pretežno apnenec); *3* – metamorfni skrilavci (kvarcitni filit, klorit, marmor); *4* – smer pretoka v žilah v sušnem obdobju; *i* – izvir Almyros; *v* – dovodna žila; *r* – razcep žil; *s* – zgornja žila; *m* – spodnja žila; *m, min* – najnižji del spodnje žile; *u* – ustje spodnje žile; *gm* gladina morja; *f* – prelom

The probable disposition of the lower karstic aquifer is explained in Fig. 2. The lower main karstic aquifer which drains the Psiloritis massif is a deep, confined aquifer contaminated by sea-water in several 500 to 1000 meter deep vein-branchings (mixing points). There are some vein-branchings of different depths at a supposed distance of 2 to 5 km from the spring.

The upper secondary karstic aquifer which drains the NE part of the Psiloritis massif (Keri plateau) is a semi-unconfined aquifer. The main outflow of both aquifers is the Almyros spring. The circulation between veins of the two aquifers is probably weak, except in the spring area.

The very deep position of the primary and lower veins is explained by a gradual subsidence of the eastern part of the Psiloritis massif (Papadopoulos & Scanvic, 1968) and by the existence of a Mesozoic limestone stratum below the Neogene deposits of the Iraklion graben (Fig. 2). In former geologic periods the lower vein of the lower aquifer was the primary vein and the main outflow into the sea probably to the NE of Iraklion. During the Pleistocene period, with an 80 meter lower sea level, the direct outflow into the sea in the area of the Almyros spring was blocked by a belt of metamorphic schists of Roghdia. The present upper vein and the spring were formed or reactivated afterwards. The present upper vein has namely a better hydraulic gradient in comparison with the present lower vein which is supposedly over 20 km long. Such a long vein is not an exception. For instance the famous sea-water mills with a maximum inflow of 1.7 m^3/s of sea-water on the western shore of the Kefallinia island feed the lower vein of the Sami Springs with a discharge of 10 m^3/s of brackish water situated on the eastern shore at a distance of 15 km.

Observations of Almyros spring

Measurements of discharge, salinity and elevation of water level of brackish springs are the most important observations necessary to determine their mechanism.

Discharge versus salinity relation

The salinity starts and stops suddenly in correlation with the spring discharge in the spring Blaž in Yugoslavia. The Almyros spring, however, has a gradual increase of the salinity during the decrease of its discharge.

The discharge-salinity relations of the Almyros spring (Fig. 3) cleary show that the salinity of the spring depends mainly on discharge and only sligtly on spring level. In natural conditions, losses of head due to friction in the upper vein predominantly influence the important piezometric surface of fresh-water in the branching of veins. The discharge of about 12–13 m^3/s is the critical discharge that regulates the inflow of sea-water at a spring level of 3 metres above M.S.L.

Summer test 1977 with rise of spring level

A dam was constructed downstream of the Almyros pool and the level of the spring artificialy raised with the aim to reduce its salinity. There was not any rain during the test. The observation data are presented in Table 1.

The influence of the rise in spring level was either small – 5 percent decrease in discharge and salinity – or nil as the measurement accuracy was about 10 percent. Percolation of water below the dam and springs on the downstream slope of the dam were observed.

Consequenty we recommended (Breznik, 1977, 1978) a reconstruction of the dam spillway and a similar test to be performed in winter when the discharge is greater.

Winter test 1987 with rise of spring level

The stability of the dam was increased with relief wells and the spillway reconstructed. The level of the spring was raised to 10 metres above M.S.L. Discharge and salinity were observed. The former and new results are presented in Fig. 3. The salinity is reduced below 50 mg Cl/1 one or two days after the discharge rose over about 12–13 m^3/s. The brackish water, namely has to be washed out of the underground storage after the inflow of sea-water has been blocked. Intrusion of sea-water, perceptible by a rise in salinity over 100 mg Cl/l started when the discharge was reduced either below 12.5 m^3/s (29 March 1987) or below 9.2 m^3/s (14 May 1987). A discharge of about 10–11 m^3/s was a critical discharge which regulated the sea water inflow at the spring level of 10 metres above M.S.L. during the 1987 test.

Boreholes between the spring and the sea

From 1968 to 1971 many boreholes were drilled between the spring and the sea with the aim to find the area with sea-water intrusion into the karstic massif, and to explore the geology of the area. The deepest boreholes reached below 400 m. The limestone massif was found to be underlain by metamorphic schists at a depth of about 300 metres below the spring. The schists crop out between torrent Keri and the sea. Limestone strata extend in the depth for about 0.5 km from the spring towards the sea where they are cut of by a fault. The level and the salinity at different depths were measured. Sea-water was not detected and the highest salinity of water in boreholes was only one half of the Almyros spring salinity (United Nations, 1968, 1971, 1972).

Piezometric boreholes

Several new boreholes were drilled in the karstic massif behind the Almyros spring. Levels of karstic groundwater and salinity were observed in these boreholes and in the old ones. The results are presented in the following Table 2.

In most of the boreholes the levels were measured on the 11. 02. and 6. 10. 1983 and the salinity on the 17. 02. and 21. 10. 1983.

Mehanism of groundwater flow

Mechanism of contamination

An about 40 meter high column of sea-water exerts due to its higher density the same hydrostatic pressure as an about 41 meter high column of fresh water. That is known as the Ghyben-Herzberg law.

In coastal aquifers in sand and gravel of isotropic permeability the surface of equal fresh and sea water pressures is called interface or zone of mixing. This zone is about 2 m thick and can be detected in every borehole in the coastal area (Cooper, 1959).

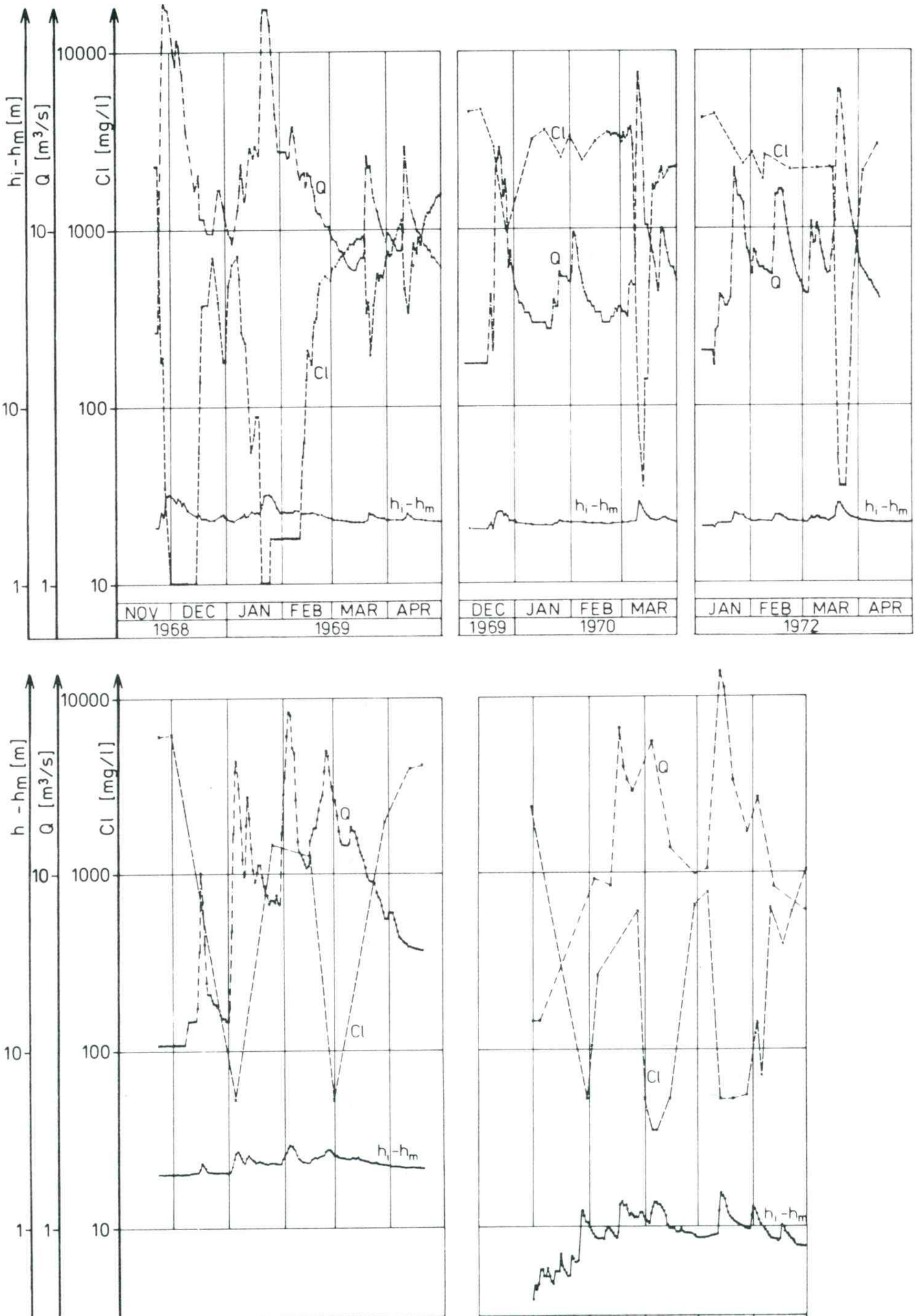
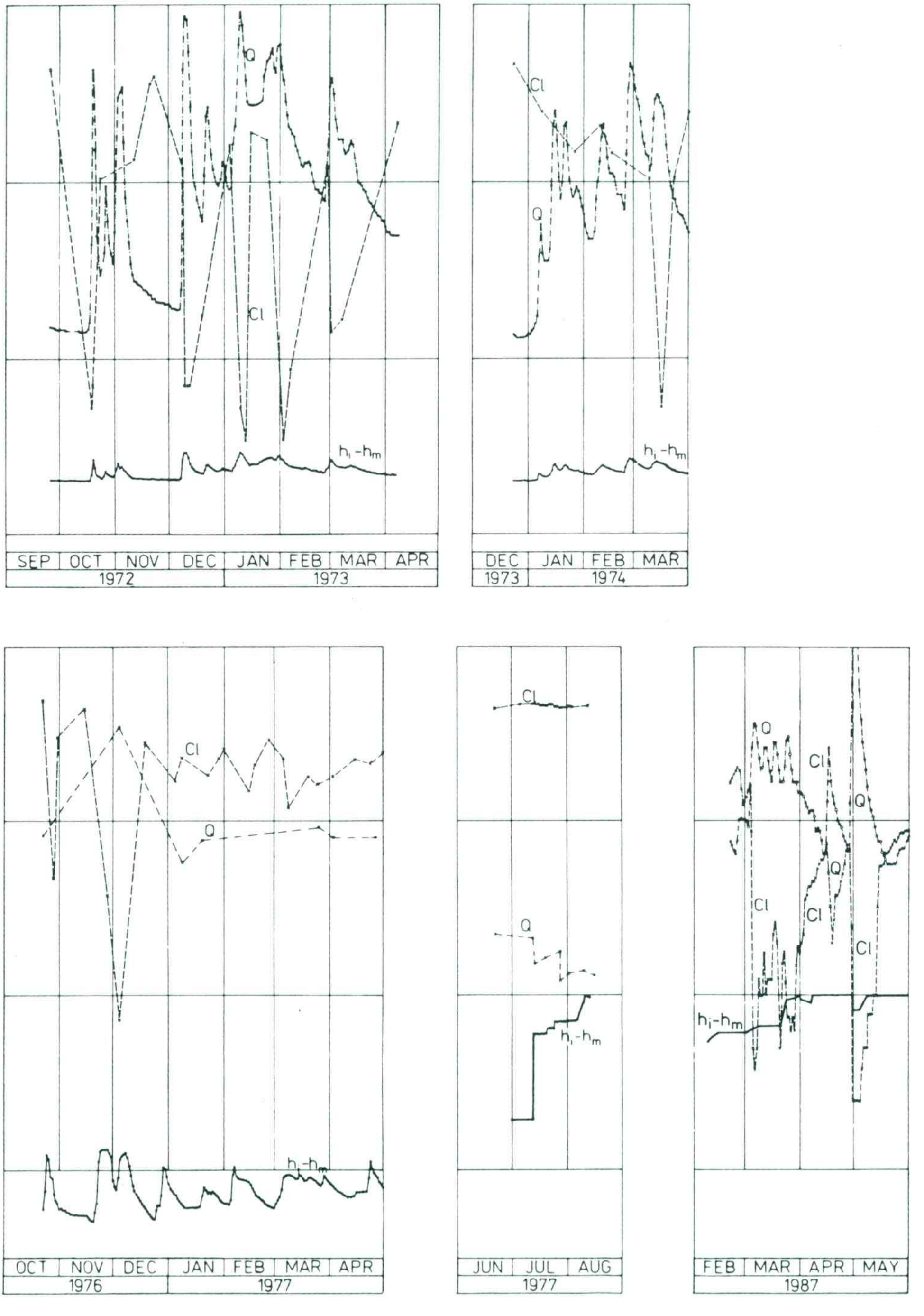


Fig. 3. Salinity in dependence of discharge and pool level elevation in the Almyros spring
Cl – salinity; *Q* – discharge; $(h_i$-$h_m)$ – elevation of spring pool surface



Sl. 3. Slanost v odvisnosti od pretoka in višine gladine jezerca izvira Almyros
Cl – slanost; *Q* – pretok; $(h_i - h_m)$ – višina gladine jezerca izvira

Table 1. Observations during summer test 1977

Tabela 1. Meritve med poletnim poizkusom 1977

Date	Spring level m above M.S.L.	Discharge m^3/s	Salinity mg Cl/1
21.6.1977		4.72*	4366
5.7.1977			4544
12.7.1977	1.97	4.62*	4686
12.7.1977	5.96	4.62*	4688
15.7.1977	5.96		4692
18.7.1977	5.97		4615
20.7.1977	8.06		4611
21.7.1977	8.10		4635
24.7.1977	8.89		4601
27.7.1977	8.89	4.23*	4541
27.7.1977	8.89	3.54**	
30.7.1977	8.89		4516
1.8.1977	8.93	3.69**	4473
4.8.1977	8.93		4491
12.8.1977	9.87	3.59**	4526
15.8.1977			

Remark: * discharge measured at the spring
** discharge measured at DEI and sea canals

In coastal karstic aquifers of anisotropic permeability such an interface does not exist because there the main quantity of water flows through fissure or canal veins. A discontinuous plane of equal fresh and seawater pressures in veins is called the equilibrium plane (Breznik, 1973). The difference between an interface and an equilibrium plane is like the difference between the phreatic surface of an unconfined aquifer and the piezometric surface of a confined karstic aquifer. The first exists in the whole mass of gravel and could be detected in every borehole. The second exists in veins only and in boreholes which have penetrated into the karstic veins.

The position of the equilibrium plane determines the mixing process of fresh and sea water in the vein-branchings. In the spring-autumn period the piezometric surface of fresh-water in the primary vein is low and the equilibrium plane crosses the vein-braching what enables the sea-water to intrude into the karstic aquifer. The energy for such a flow pattern is furnished by fresh-water flowing through the vein-branching.

Spring-Autumn Period in Almyros spring

In that period the Almyros is contaminated by sea water. The contamination occurs in those vein-branchings where sea water has an equal pressure than the fresh water. The head and energy lines explain the relevant flow conditions. Some vein-branchings at different depths produce the gradual salination of the spring.

Table 2. Water level and salinity in boreholes (Breznik, 1984 a)

Tabela 2. Gladina in slanost vode v vrtinah (Breznik, 1984 a)

Borehole	Distance from Almyros Spring km	Depth of bottom below M.S.L. m	Groundwater Level above M.S.L. In Winter m	Groundwater Level above M.S.L. In Autumn m	Salinity mg Cl/1 In Winter m	Salinity mg Cl/1 In Autumn m
I1(ALD 3) (Faragi Gonies)	8.6		45.8			
T1 -"-	7.7		44.6	42.6	57	43
Argiri Tylissos	4.0		22-30	14-16		
T2	3.4	10	31.1	28.4		35
G5(ALD 1)*	3.0		42.6	41.9	57	43
G6(AGR 1)	3.0		28.0	22.6	71	78
G3(G1 3/68)	1.0	15	7.3	3.4	99	113
G4(FAO 9)	0.5		8.9	5.6	681	780
G2(FAO 6)	0.3	126	2.9	1.4	1106	3332

* perhaps blocked

Winter period in Almyros spring

In the winter period the piezometric surface of fresh-water is high and the corresponding equilibrium plane in a low position. The Almyros spring discharges fresh-water.

The lowest point of the lower vein – in limestone somewhere below the impervious Neogene deposits of the Iraklion-Festos graben – is certainly deeper than the vein-branching. A high pressure of sea-water in a lower vein of such a shape prevents losses of fresh-water out of submarine springs during the fresh-water flow of the Almyros spring in winter. Submarine springs were never observed in the Iraklion sea, although they could be easily detected by their wheels, i.e. characteristic surface surges. Evidently they do not exists in this area.

Possibilities of Development

Methods of Development

The methods to desalinate brackish karstic springs are:

- isolation of the karstic aquifer from sea-water intrusion by a dam at the spring or by a grout-curtain that seals the lower vein;
- interception of fresh-water by boreholes, wells or drainage galleries within the karstic massif, inland of the sea-water influence;
- rise of the spring level by a dam. In that case, fresh-water accumulates in the karstic massif. The fresh-water piezometric surface is raised to a higher level and the equilibrium plane is pushed down so that sea-water intrusion is blocked also during dry periods.

There are already numerous cases of successful development of brackish springs (Biondić & Vulić, 1974; Fritz & Pavlin, 1978). The important Bačvice springs in Yugoslavia were developed by grout-curtains that have blocked their lower veins and isolated the aquifer from sea-water intrusion. Two regional drinking water supply systems were constructed with desalinated water of this springs. The Žrnovica spring in Yugoslavia was developed by means of a grout-curtain and by the rise of the spring level. The period of fresh-water flow was extended by a short grout-curtain in the area of the Tabačina spring (Pavlin, 1982).

The Dobrica, Dobra and Golubinka springs in Yugoslavia and Brojnica spring in Italy were isolated by small diaphragm walls from seawater influence. The Kiveri springs in Greece were developed by isolation of the spring area from the sea by a dam and by the rise of the spring level (Pavlin & Biondić, 1971; Ständer, 1971; Pavlin, 1973, 1982; Pavlin & Fritz, 1978; Breznik, 1973).

Fresh-water of the springs Gustirna, Opačica, Bakar, Kovča-Zaton, Stari grad, Korita, Jelsa, Dubrava, Zvir and others in Yugoslavia was intercepted in galleries or shafts. Alike the success was achieved with many deep boreholes in Greece and Italy (Tadolini & Zanframundo, 1988) at distances of 5 to 10 km from the sea. It has been possible to intercept only about 20 % of the discharge of the correspondent springs (Fritz, 1978, 1979; Mijatović, 1976, 1986, Breznik 1973).

Development of the Almyros Irakliou Spring

Extensive geological and geophysical investigations as well as drilling of deep boreholes in 1968 to 1971 in the area between the spring and the sea have failed to detect the lower vein. Now we are sure that it is not there. The lower vein is presumably very long and at a great depth at an unknown position, and probably connected with the sea to the NE of Iraklion. As its precise location is not known, it is impossible to **isolate** the spring by grouting (Breznik, 1958, 1962, 1976, 1978).

Otherwise, it is possible to **intercept** the fresh-water in the area of the Gonies gorge or in the Tylissos area by deep boreholes connected by a drainage gallery. The technical and economic disadvantage of the interception method are the very great number of boreholes wanted to intercept every important karstic vein, and that is still aggravated by the high ground elevation. In the Gonies gorge about 450 meter deep tube-wells with an about 320 meter pumping head and in the Tylissos area about 300 meter deep tube-wells with an about 200 meter pumping head would be needed.

Observations of the natural conditions indicate that the Almyros spring offers favourable possibilities for development by means of a **rise in spring level.** The most important observation results to consider are:

- Discharge – spring level – salinity relation

  During winter the spring delivers fresh-water at a discharge of about 12–13 m^3/s and level of 3 m above M.S.L. During smaller discharges and lower levels the spring water is brackish.
- Flood discharge and loss of water

  As submarine springs have never been observed in the sea of Iraklion (Breznik, 1984 b), there are no losses of water through the lower vein, even during the flood periods with discharges of about 50 m^3/s and a very high piezometric head of fresh-water in vein-branching and lower vein.

- Discharge – raised spring level – salinity relation
  During the 1977 summer test the level was raised to 10 m above M.S.L., and with a discharge of about 4 m^3/s the decrease in discharge and salinity of 4500 mg Cl/l were either very small – about 5 % – or possibly nil.
- During the 1987 winter test the level was raised to 10 m above M.S.L., and with a discharge of about 10–11 $^3/s$ the spring delivered fresh water.

The explanation of these results is as follows:
The piezometric head in the vein-brancing regulates the position of the equilibrium plane and of the inflow of sea-water into the spring.

- During winter the karstic massif is filled with water, so the piezometric surface rises. The fresh-water head and pressure at the vein-branching and in the lower vein are high enough to block the inflow of sea-water. The equilibrium plane is below the vein-branching and sea-water cannot infiltrate into the vein at discharges above 12–13 m^3/s (Fig. 4).
- During flood discharges the head and pressure at the vein-branching are higher due to very high losses of head in the upper vein. The equilibrium plane is lowered

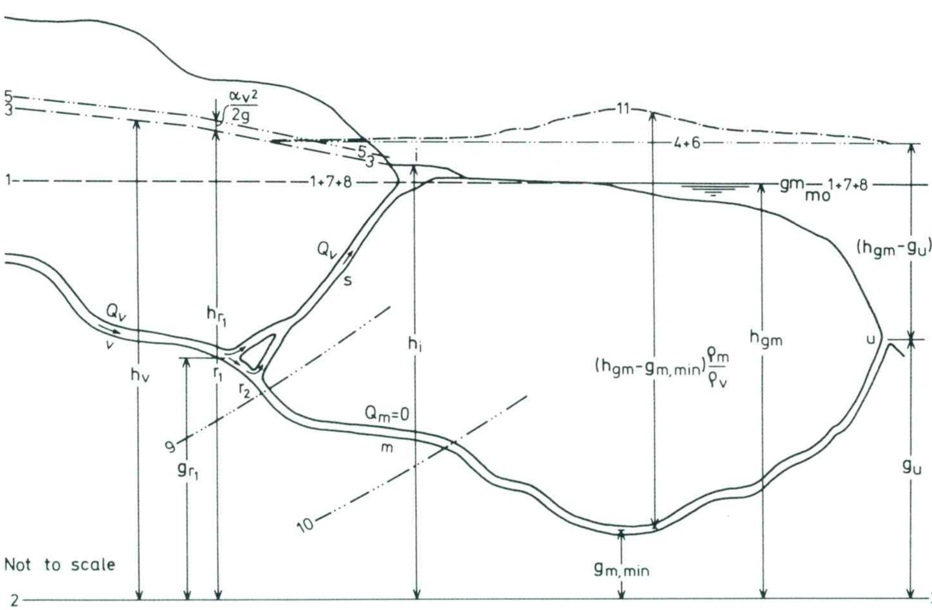


Fig. 4. Flow directions in the lower aquifer of the Psiloritis-Iraklion region in the winter period during fresh-water flow of Almyros spring (after Breznik, 1984 a). See legend of Fig. 1
7 – Piezometric head line of the lower vein; *8* – Energy head line of the lower vein; 7–8 all the head expressed through the head of sea-water; *9* – Equilibrium plane in winter period; *10* – Equilibrium plane during winter flood discharge; *11* – Pressure line of the lower vein expressed through the head of fresh-water

Sl. 4. Smeri pretoka v spodnjem vodonosniku področja Psiloritis-Iraklion pozimi med sladkovodnim izlivom izvira Almyros (po Breznik, 1984 a). Glej legendo slike 1
7 – Piezometrična višina spodnje žile podana s stebrom morske vode; *8* – Energetska višina spodnje žile podana s stebrom morske vode; *9* – Ravnotežna ploskev v obdobju zime; *10* – Ravnotežna ploskev v obdobju zimskih poplavnih pretokov; *11* – Tlačna črta spodnje žile podana s stebrom sladke vode

and interesects the lower vein at a lower elevation. But not all the lower vein is above equilibrium plane, as this would induce losses of fresh-water through the lower vein. There is no flow of either fresh- or sea-water through the lower vein (Fig. 4).

- From spring to autumn, the karstic massif is drained, the spring level lowered and the fresh-water head at the vein-branching subsides as losses of head in the upper vein are smaller due to smaller discharges. The ascending equilibrium plane crosses the vein-branching and with discharges below 12–13 m^3/s some sea water infiltrates into the upper vein (Fig. 5). In the case of more vein-branchings sea water infiltrates first throught the lower ones.
- During the 1977 test the fresh-water head and pressure at the vein-branching were equal to the sea-water head and pressure, expressed through the head of fresh-water, so sea water countinued infiltrating into the upper vein. This indicates that the fresh-water head and pressure at the vein-branching were at that time smaller than during the winter when the discharge had amounted to 12–13 m^3/s and the spring water was fresh. The artificial rise in spring level in 1977 did not counterbalance the difference in head losses between the discharges of 4 m^3/s and 12–13 m^3/s. The artificial rise in spring level was too small. Evidently, during the summer a higher artificial rise in spring level is needed.

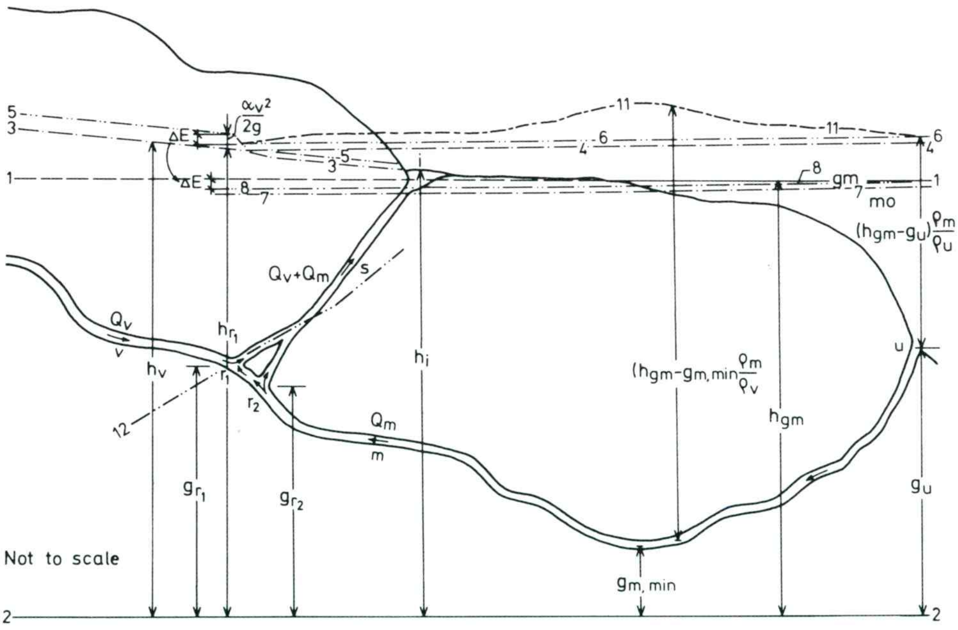


Fig. 5. Flow direction in the lower aquifer of the Psiloritis-Iraklion region in the spring-autumn period during brackish water flow of Almyros spring (after Breznik, 1984 b). See legend of Figs. 1 and 4

12 – Equilibrium plane in the spring-autumn period

Sl. 5. Smeri pretoka v spodnjem vodonosniku področja Psiloritis-Iraklion od spomladi do jeseni med zaslanjenim pretokom izvira Almyros (po Breznik, 1984 b). Glej legendo sl. 1 in 4

12 – Ravnotežna ploskev v obdobju pomlad-jesen

– During the 1987 winter test the spring level was raised to 10 m above M.S.L. and the spring delivered fresh water at discharges of about 10–11 m^3/s. This indicates a clear influence of the level rise on the spings salinity.

Supposition on the Necessary Artificial Rise in Sping Level

The unknown value is the piezometric head of fresh-water in the vein-branching $(h_r - h_m)$ during the fresh-water flow of the spring. It is the sum of the spring elevation $(h_i - h_m)$ and of losses of head yQ^2 in the upper vein reduced for the velocity head $\alpha v_r^2/2g$ in the vein-branching.

$$(h_r - h_m) = (h_i - h_m) + yQ^2 - \frac{\alpha v_r^2}{2g}$$

The direction of flow, largely determined by the orientation of the veins, may influence the mixing process during high discharges but cannot be accounted for with certainty. This influence is very small in the spring-autumn period as the velocity of flow is small due to small discharges.

The elevation of the spring can be measured. Losses of head depend on length, cross section and roughness of the upper vein and the square of discharge. On that last quantity also depends the velocity head. The natural condition of the vein does not change.

Thus, the changes in loss of head and velocity head can be expressed as functions of discharge:

$$\Delta h_{n-1} : \Delta h_n : \Delta h_{n+1} = Q_{n-1}^2 : Q_n^2 : Q_{n+1}^2 \text{ and}$$

$$\frac{\alpha v_{n-1}^2}{2g} : \frac{\alpha v_n^2}{2g} : \frac{\alpha v_{n+1}^2}{2g} = Q_{n-1}^2 : Q_n^2 : Q_{n+1}^2$$

where

Δh – loss of head m

$\frac{\alpha v^2}{2g}$ – head of velocity m

g – acceleration of gravity m/s^2
v – velocity of flow m/s
Q – discharge m^3/s

The thus derived ratios of loss of head for characteristic discharges are given in the following Table 3.

The ratios between the losses of head and the discharge clearly indicate the predominance of the influence of discharge on the fresh-water head and pressure in the vein-branching.

The characteristics of the upper vein that determine the losses of head in vein-branching can be calculated if the discharge at which the fresh-water flow starts is measured at two different spring levels.

Table 3. Ratios between losses of head as function of discharges

Tabela 3. Razmerje med tlačnimi izgubami in pretokom

Period	Discharge Qn m^3/s	Qn^2	Ratio between losses of head $(Qn/Qmin)^2$
Winter - flood	50	2500.0	454.5
Winter - fresh water	12.5	156.3	28.4
Spring - brackish water	11	121	22.0
Autumn - minimum	4	16	2.9
Autumn - minimum of fresh water (Qmin)	2.35	5.5	1.0

During the winter test 1987 the spring level was 10 m. The discharge increased very quickly and considering the volume of underground storage it is difficult to assess the critical discharge at which the fresh-water flow initiated. It was easier to evaluate the discharge at which fresh-water (salinity below 50 m Cl/l) began to become slightly salty (100–200 mg Cl/l).

This discharge was 10 to 11 m^3/s during the winter test 1987 and 12 to 13 m^3/s during the years 1971–1977 when the spring level was 3 m above M.S.L.

$h_r - h_m = (h_{i.1} - h_m) + yQ_1^2$

$h_r - h_m = (h_{i.2} - h_m) + yQ_2^2$ (Breznik 1978)

$h_i - h_m$ – spring level m above M. S. L.

$h_r - h_m$ — piezometric head in vein-branching during the fresh-water flow of the spring m above M. S. L.

y – hydraulic characteristics of upper vein

Q – discharge

For $Q_1 = 12.5\,m^3/s$, $(h_{i.1} - h_m) = 3\,m$, $Q_2 = 10.5\,m^3/s$ and $(h_{i.2} - h_m) = 10\,m$ is $y = 0.1522$ and $h_r - h_m = 26.78\,m$

For measurement data of the piezometric levels in boreholes in the karstic marssif behind the Almyros spring see Table 2. The boreholes I1 (ALD 3), T1 and G5 (ALD 1) with winter levels of 45.8, 44.6 and 42.6 m above M.S.L. are too far inland. The boreholes G3/68 and G4 (FAO 9) with winter levels of 7.3 and 8.9 m are apparently in the secondary upper karstic aquifer and the borehole G2 (FAO 6) with a winter level of 2.9 m in the outflow area of both aquifers.

However, the boreholes Argiry-Tylissos, T2 and G6 (AGR 1) with winter levels of 22–30 m, 31.1 m and 28.0 above M.S.L., all situated in the Tylissos-Koubedes area, could give an indication on the winter levels either in the area of the vein-braching, or in an area more inland of that area, or in an area drained by the upper aquifer.

We can surmise therefore that the needed autumn elevation of spring level should be from 20 to 30 m above M.S.L. This elevation has to be determined by new tests in the rise of the spring level.

Rockfill dam

The construction of an appropriate rockfill dam might be confronted with serious problems. The requested height (20 to 30 m) of the dam is not exactly known in advance because it depends on the rise of the spring level achievable by the dam. That requests a dam and a spillway that can be constructed in stages. A concrete face rockfill dam would be an appropriate solution.

Makropolos (1985/86) concluded that there is a 90-percent probability for a 0.21–0.24 g horizontal acceleration earthquake at Knossos near Iraklion in the next 50–100 years. We have to expect a bigger earthquake at the Almyros rockfill dam site due to the presence of the main fault and sandy materials below the dam.

Fine to medium sand saturated with water is not a good foundation ground in seismic areas as the overturning of a structure in the 1961 Niigata earthquake in Japan and the collapse of the San Fernando dam in the 1971 earthquake in USA have demonstrated. Very gentle slope of dam faces will be required.

The stability of the present dam was endangered by springs on the downstream face in the 1977 test and improvement measures were undertaken afterwards. Construction of a deeper diaphragm wall and other measures will be necessary in order to obtain the Lane's ratio (length of flow: head of water) of 5–8 needed for the hydraulic stability of sand layers against underground erosion. Construction of the present diaphragm wall was difficult already because of blocks of older rocks in sand layers. A semicircular dam is needed as the space around the spring is limited and the rocky abutments are short.

Underground dam

An underground dam similar to many constructed below surface dams and in embankments of reservoirs in karstic areas of Yugoslavia and Spain offer the advantage of a step by step construction and of a smaller financial risk.

The first stage is the installation of 2000 mm steel pipes into the lower and upper springs with the assistance of divers and a crane on the surface. The pipes are fixed and sealed with concrete plugs and grouting by pumping the concrete and the grout from the surface. An outlet valve and a gate or 2 valves with driving mechanism on the pool shore and on the road are installed later. Piezometric boreholes are needed too. The first test of raising the piezometric surface in the rock massif by partial closure of the valve and the gate could be made in summer or autumn during small discharges of the spring. There is a fair chance to achieve a desalinisation of the spring, because the rise in piezometric level can be only small due to permeability and a too small stability of the rock above the upper spring. That could be sufficiently increases by prestressed anchors, however. The main task of these constructions will be implemented in the second stage (Fig. 6).

The second stage consists in the drilling of boreholes and interception wells and excavation of a collecting gallery. The wells have to be drilled either out of the collecting gallery by a technique used in mining (e. g. diameter 350 mm, depth 400 m, Bleiberg mine, Austria, works performed by Geološki zavod Ljubljana) or from the surface by the normal drilling technique and by 30 m deeper wells. The aim is to open new ways for underground circulation. A test of closing the lower and upper springs by the valves installed in the first stage and observation of the piezometric surface should show the flow capacity of the new water passage. Afterwards, a second test in raising the piezometric surface in the rock massif can be performed also in spring period. A cupola-shaped concrete plug in the access tunnels would make such a test possible. During a to high spring discharge the plugs could be blasted because a to high water pressure inside the rock massif could be dangerous. The concrete plug in a spring at Fatničko polje in Yugoslavia had to be blasted after the piezometric head in the rock massif rose over 100 m and endangered a village and a road. There are better chances to succeed in this test than in the first stage because the rise can be done in spring period also.

The third stage entails closure of canals of the lower and upper springs with concrete plugs cast by pumping concrete from the surface. The underground dam is constructed by sealing the main canals by a grout-curtain of cement-bentonite-sand grout (Borelli & Pavlin, 1965, Pavlin 1970, 1982) and by sealing the cavities either by pumping cement mortar or by constructing prepact concrete through 15 mm

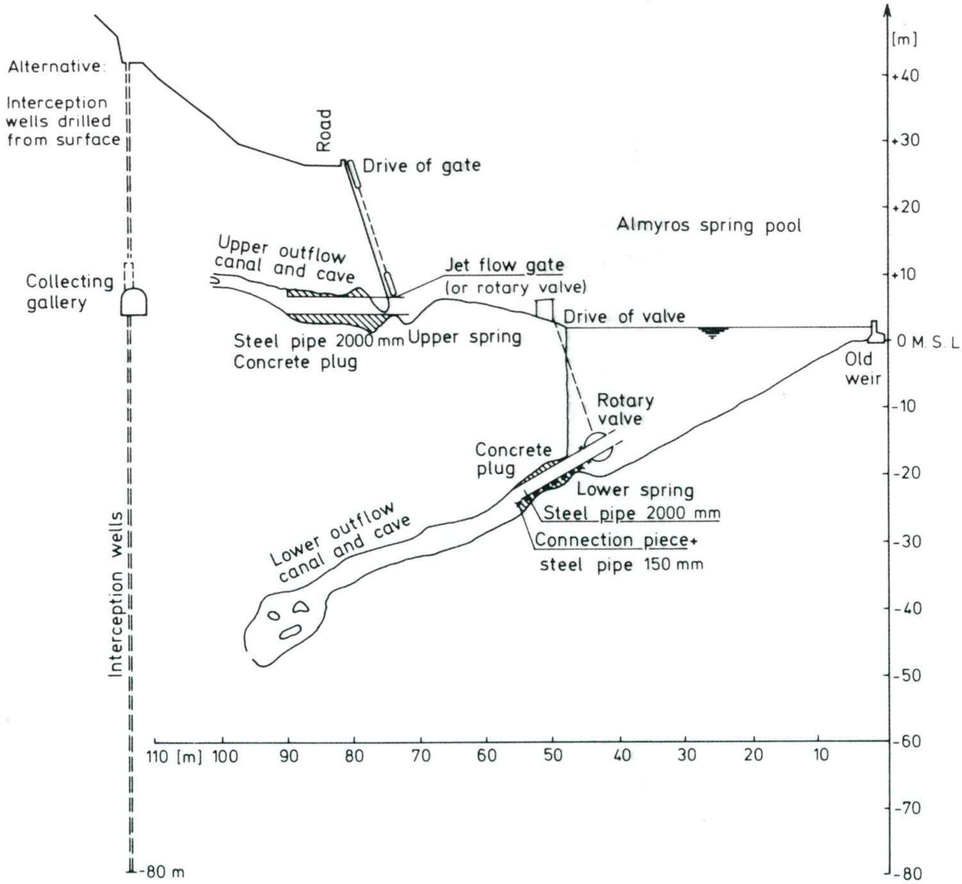


Fig. 6. Cross-section of Almyros springs with structures needed for the first and second stages of explorations

Sl. 6. Prerez izvirov Almyros z objekti potrebnimi za prvo in drugo fazo raziskav boreholes – a technique used at Nikšič dams in Yugoslavia (B r e z n i k , 1979, 1985) or by pumping concrete through 300 mm boreholes – a technique used at Keban dam in Turkey (Ö z b e k 1975).

In the outer part of access tunnels steel pipes of 2000 mm have to be fixed and sealed by concrete plugs. The valve and the gate installed in the first stage into the springs have to be dismantled and fixed on steel pipes at the outflow of access tunnels (Fig. 7). By partial closing of the valve and of the gate the piezometric surface will be gradually raised to 20 or 30 m. Desalination of the spring has to succeed also in autumn during the lowest discharges. The stages from one to three are still exploratory, and a final positive result is not assured in advance.

The forth stage is to be implemented only if a complete desalination has been achieved in the third stage. The construction works will include the extension and

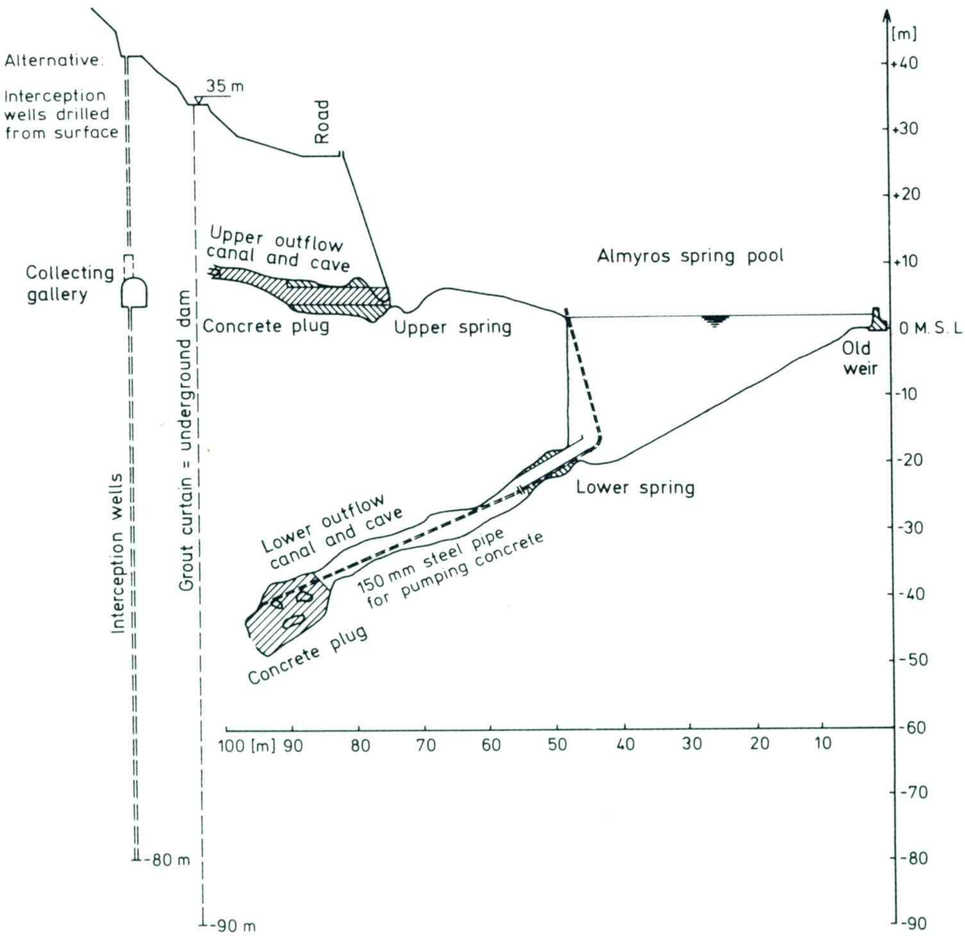


Fig. 7. Cross-section of Almyros springs with structures needed for the third stage of explorations

Sl. 7. Prerez izvirov Almyros z objekti potrebnimi za tretjo fazo raziskav condensing of the grout-curtain, completion of the bottom outlets, construction of a shaft with spillway, chute and skijump, of the water supply tunnel, of the pipeline with control valve and of the monitoring and driving devices. A small hydropower station could be installed, too.

It cannot be known in advance how many interception wells will have to be drilled, but the underground canals area is not wide. The proposed underground dam is very small in comparison with the already constructed grout-curtains of Yugoslav dams in karstic areas (Breznik, 1979, 1983, 1985, 1988, 1989; Pavlin, 1961, 1970). Underground dams are safe in special conditions, e. g. wars, terroristic attacks or earthquakes.

Evaluation of development success

With the plan of raising the spring level the two following circumstances are to be taken into consideration as possibilities of an unsuccessful development.

Escape of fresh-water through the lower vein

Due to the increased spring level fresh-water could escape through a lower vein that rises from the vein-branching toward the sea (Breznik 1973). The equilibrium plane in such a case is below the lower vein. If a lower vein is falling from the vein-branching, the equilibrium plane might cross the lower vein and fresh-water would not be lost. It seems that the Almyros spring indeed has a falling lower vein, as no losses of fresh-water into the sea have been observed also during the flood periods (Fig. 2).

Losses of fresh-water around the dam or into the upper karstic aquifer

In such cases the spring level could not be raised to the needed elevation in the spring pool and not high enough in the vein-branching, and so the spring water would remain brackish during the lowest discharges. We estimate that there is a possibility of such water losses. In the spring and perhaps also in the summer month the losses would be less than the fresh-water discharge, and the levels in the spring and vein-branching could be raised to the necessary elevation; the spring water would be fresh. Yet in the autumn period the levels in the spring and vein-branching might decline and admit the instrusion of seawater.

During the summer test in 1977 with a spring-level elevation of 10 m above M.S.L. the losses around the dam were small, and only an about 5-percent decrease in spring discharge was estimated. The rise of water level in boreholes around the spring was small, too. This indicates small losses of water outside the main spring during the 1977 rise of spring level. On the base of these observationes we estimate that the losses into the upper karstic aquifer will not deplete too much the spring fresh-water flow. The losses around the dam can be blocked by a larger grouting screen.

We have to allow for a 20-percent risk of failure in the autumn period. But also in such a case of small probability the water would persist fresh during the winter, spring and early summer periods and could be used for irrigation or stored in a reservoir in the Neogene area for use in late summer and autumn.

In any case we have to expect some losses of fresh-water into the upper karstic aquifer or around the dam. The dam alone cannot capture the whole fresh-water flow of the spring. Yet the lost water will be probably fresh and could be captured by wells, by the existing dam and smaller dams.

The Almyros spring offers very good natural conditions and technical possibilities for a successful desalination but the progress of explorations has been surprisingly slow. We estimate the distrust in the proposed rise-in spring-level with underground dam method being the main reason.

Rehabilitation of the natural scenery

The Almyros spring was a natural beauty with its depth, size, shape, flora, quantity of water and a historical monument with old mills.

A surface dam would destroy all this forever. An underground dam offers all the possibilities to restore the previous natural scenery and the old mills. This and a museum explaining the mechanism of the sea-water intrusion, of many exploration campaigns, of the engineering works performed and of the mechanism of an unique desalination achieved could made Almyros spring world famous and a touristic attraction similar to the Kefallinia island sea-water mills.

In the case of a development failure a rockfill would remain as a „monument“ of an unsuccessfull development. On the other hand all the structures of the underground dam development method would not be visible.

Author's rights

Acknowledgements

Thanks are due to the Government of Greece and to many of my Yugoslav colleagues who gave their unpublished data at the disposal.

Sanacija zaslanjenega kraškega izvira Almyros v Grčiji

Povzetek

V kraškem vodonosniku neenakomerne prepustnosti se pretaka kraška podzemna voda skozi žile, ki so lahko rovi, kaverne, razpokane ali skrasele cone. Sladka voda, ki doteka po dovodni žili, se zaslani v razcepu žil s težjo morsko vodo, ki doteka skozi spodnjo žilo. Mehanizem takega zaslanjenja so pojasnili Gjurašin (1943), Kuščer (1950) in Breznik (1973).

Izvir Almyros na otoku Kreti v Grčiji s srednjim pretokom okrog 7 m^3/s in gladino 3 m nad morjem, je pretežni del leta zaslanjen z do eno četrtino morske vode. Ob večjih pretokih pa ima krajši čas sladko vodo. Zadnjih 20 let so bile izvršene obsežne raziskave, ki naj bi razjasnile mehanizem zaslanjevanja in ugotovile možnost sanacije. Slanost je odvisna predvsem od pretoka in le delno od gladine izvira.

Z obsežnimi raziskavami smo ugotovili, da morska voda ne doteka v razcep žil iz okrog 1 km oddaljenega morja. Spodnja žila mora biti zelo dolga, podobno kakor na otoku Kefallinija pri znanih mlinih na morsko vodo. Točen položaj spodnje žile ni poznan, zato izvira ni možno sanirati z izolacijo morskega vpliva z injekcijsko zaveso, ki bi zatesnila spodnjo žilo.

Manjši del vode izvira bi bilo možno prestreči v razdalji okrog 4 km od morja s 300 m globokimi vrtanimi vodnjaki z višino črpanja 200 m.

V področju Irakliona niso nikoli opazili podmorskih izvirov, tudi ne ob poplavnem pretoku Almyrosa z okrog 50 m^3/s. Zato sklepamo, da se spodnja žila od razcepa žil proti morju spušča v večjo globino, kar je posledica pogrezanja tektonskega jarka Iraklion-Festos. Spuščajoča se spodnja žila omogoča sanacijo z dvigom gladine izvira. Posledica je splošen dvig gladine sladke vode v kraškem masivu. Povečan pritisk sladke vode v razcepu žil pa naj bi onemogočil vdor morske vode vanj. Analize so pokazale, da je v času, ko je izvir sladek, pri pretokih nad okrog 12–13 m^3/s, piezometrična gladina v razcepu žil predvsem pod vplivom tlačnih izgub v zgornji žili. Poleti 1977 so s pregrado dvignili gladino izvira na 10 m nad morje. Poizkus ni bil pozitiven, ker se slanost ni zmanjšala in tudi ne negativen, ker se pretok ni zmanjšal. Očitno je bila pri tem poizkusu piezometrična gladina v razcepu žil nižja, kakor je pozimi ob sladkovodnem izviru. Umetni dvig gladine izvira ni nadomestil manjših tlačnih izgub v zgornji žili pri pretoku okrog 4 m^3/s poleti 1977. V sušnih obdobjih bi bil potreben mnogo večji dvig gladine izvira. Na osnovi analize razlike tlačnih izgub pri različnih pretokih in gladine podzemne vode v oddaljenosti okrog 4 km v notranjost kraškega masiva cenimo, da bi bil potreben dvig gladine izvira na 20 do 30 m. Vendar bo možno ugotoviti končen pozitiven rezultat samo s terenskim poizkusom.

Ker so takšne raziskave izredno drage predlagamo postopne raziskave in tudi izgradnjo injekcijske zavese, namesto nasute pregrade. Ocenjujemo da je 20 % možnost za neuspeh, ker zaradi prepustnosti morda ne bi mogli dovolj dvigniti gladine v razcepu žil ob suši. Zato bi bila gradnja pregrade ali injekcijske zavese še vedno poizkus, končen uspeh ni zagotovljen v naprej, vendar je velika verjetnost, da bo uspel. Preseneča počasnost raziskav tako pomembnega izvira, ki je predvsem posledica nezaupanja v predlagan način sanacije.

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