GEOLOGICA BALCANICA, 19.5, Sofia, Oct. 1989, p. 45—54.

An example of a complete study of karst hydrogeology (Al Sinn Basin, Syria). II. Hydrodynamic behaviour of the basin

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(Accepted for publication September 12, 1988)

Д. Моллов, И. Саркиз — Пример комплексного исследования гидрогеологии карста (Бассейн Аль Сен — Сирия). II. Гидродинамическое поведение бассейна. Подземные воды бассейна источника Аль Сен приурочены к карбонатным породам юрского и мелового возраста. В горной части бассейна наблюдаются более 200 родников с дебитом от 0,05 dm^3/s до 20—30 dm^3/s. В приморской части выходят три крупных источника: Аль Сен (дебит 8—20 m^3/s), Сурит (1—4 m^3/s) и Баниас (1—3,5 m^3/s). В бассейне обособлены два гидродинамических яруса: ярус верховодок и ярус основного водоносного горизонта. Мелкие родники в горной части дренируют ярус верховодок. Все три большие источника в приморской части питаются основным водоносным горизонтом. В начале сезона осадков (X—XI) дебит источников начинает увеличиваться. Опаздывание начала роста дебита по отношению к начала осадков 5—6 суток. После конца осадков начинается процесс истощения дебита. Как родники верховодки, так и источники основного водоносного горизонта показывают, что подземные воды летом получают питание за счет конденсации водяных паров воздуха. Уровень подземных вод основного водоносного горизонта показывает большие амплитуды колебаний (до 200 m). Увеличение дебита источников связано с уменьшением минерализации вод: от 700—800 mg/dm^3 она уменьшается до 400—500 mg/dm^3. Гидродинамическое поведение бассейна характеризует карст как типично геосинклинального типа.

Abstract. Groundwater in the Al Sinn basin is confined to a carbonate series of Jurassic and Cretaceous age. In the mountainous part of the basin there are more than 200 springs of discharge ranging from 0,05 dm^3/s to 20-30 dm^3/s. Three high-discharge springs spout in the coastal part: Al Sinn (8-20 m^3/s), Sourit (1-4 m^3/s) and Banias (1-3,5 m^3/s). Two hydrodynamic horizons are distinguished in the basin: perched water horizon and main aquifer horizon. The numerous small mountain springs drain off the perched water horizon. The three large springs in the coastal plain are fed by the main aquifer. At the beginning of the rainy season (October-November), spring discharge starts rising with a time lag of 5 to 6 days. Cease of rains (April-May) causes a gradual depletion of spring discharge. In summer, atmospheric condensation replenishes some of the groundwater feeding both the perched water springs and the main aquifer springs. Groundwater level in the main aquifer shows large amplitude variations (up to 200 m). The increasing spring discharge is accompanied by decreasing groundwater mineralization (the latter drops from 700-800 mg/dm^3 to 400-500 mg/dm^3). The hydrodynamic behaviour of the basin characterizes the area as a purely geosyncline type of karst.

Groundwater in the Al Sinn basin is confined to a carbonate series of Jurassic and Cretaceous age (Mollov & Sarkees, 1989). The hydrodynamic behaviour of the basin is essentially controlled by the following geological and climatic features:

— the carbonate sequence contains several more or less continuous marl beds;

— the basin is crosscut by numerous tectonic dislocations;

— the yearly precipitation pattern is dominated by two clearly defined seasons: a dry and a rainy season; their effect on the groundwater regime is manifested in a period of depletion and a period of replenishment of groundwater reserves.

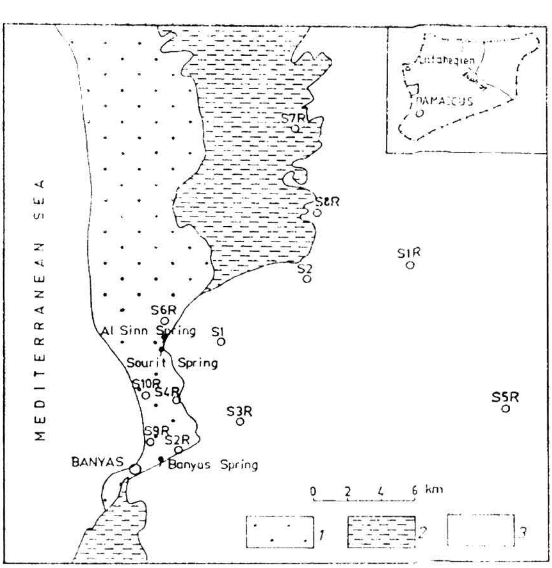

Fig. 1. Location of exploratory wells in the basin: 1. Coastal part of the basin; 2. Water impermeable rocks; 3. Mountain part of the basin

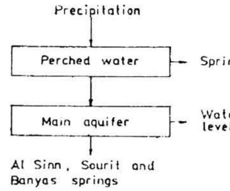

Fig. 3.

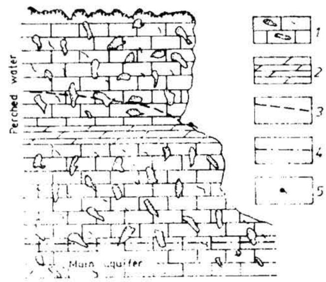

Fig. 2. Principle hydrodynamic scheme of the karst massif:
1. Karts limestones; 2. Impermeable bed (marls); 3. Perched water level; 4. Water level in the main aquifer; 5. Perched water spring

In the basin, there are more than 200 springs at various altitudes (between 100 and 1000 m). They drain off all lithostratigraphic units from the Lower Jurassic to the Turonian included. Their discharge ranges between 0,05 and 20-30 dm^3/s. The largest spring has a maximum discharge of 290 dm^3/s. Further on in this study, this group of springs will be called perched water springs. Besides, there are three large springs in the coastal plain: Al Sinn (8-20 m^3/s), Sourit (1-4 m^3/s) and Banias (1-3,5 m^3/s). They well out at altitudes of 12 to 14 m and are confined to Cenomanian karst limestones.

There are large differences between the perched water spring altitudes and the groundwater levels measured in exploratory hydrogeological drillholes. For instance, groundwater level in the S1R drillhole (Fig. 1) varies from 350 to 500 m above sea level; the nearest spring spouts at an altitude of 985 m. The highest groundwater level measured in the S8R drillhole is about 135 m above the sea whereas the nearest spring is at an altitude of 305 m. Perched water springs throughout the basin are of considerably higher altitudes than groundwater levels in the drillhopes. This illustrates the hydrogeological role of marl beds. They hold up part of the infiltrated precipitation water and it feeds into the perched water springs. Since marl beds occur at various levels across the stratigraphic sequence, springs also drain off all lithostratigraphic bodies coming out at various altitudes. Thus, the mountainous part of the Al Sinn basin may be divided into two hydrodynamic horizons: a perched water horizon and a horizon of the main aquifer. Figure 2 is a principle hydrodynamic scheme of the mountain part of the basin.

Precipitations infiltrate first the perched water horizon. A smaller portion is retained above the marl beds feeding the springs. The major part percolates downwards and reaches the main aquifer. Tectonic dislocations, larger fractures and/or sections free of marl beds provide abundant pathways for deeper percolation. The hydrodynamic relations in the Al Sinn basin obey the cause-and-effect scheme shown in Fig. 3. This is a two-element system (i. e. a perched water horizon and an aquifer) with one input (precipitations) and three output units (perched water springs, water level and springs of the main aquifer).

In order to clearly describe the hydrodynamic behaviour of the basin it is necessary to find out the relationship between precipitations, on the one hand, and spring discharge and groundwater level, on the other. Solving the problem will provide a basis for hydrogeological characterization of the basin as a whole and of its constituent elements.

1. Analysis of perched water spring discharge

As may be expected from the yearly distribution of precipitations, the hydrograms of spring discharge consist of two elements: a) increasing discharge during the rainy season, and b) depletion of water reserves during the dry season. These two elements carry information about two different stages of the hydrodynamic process. Therefore they will be considered separately.

The discharge of more than 70 springs has been monitored for over three years. All springs have similar hydrograms, two of which are shown here (Fig. 4). The ordinate is in logarithmic scale because discharges vary within very wide limits. An important feature of the spring discharge is the manner in which it increases at the beginning of the rainy season. In this respect, all springs may be divided into two groups. The majority react very quickly to the rains the time lag being about 5 to 6 days. Yet there are springs whose discharge starts increasing one to two months after the first rains. This may be interpreted as follows:

— the perched water horizon is of multilayer structure;

— some perched water springs are fed by direct infiltration of precipitations; water in the others seeps down from higher perched water layers.

Depletion regimes of spring discharges are greatly variable. There have been even cases when depletion curves recorded during different years differed in one and the same spring. Applying the known methods for refining spring discharge data (C a s t a n y, 1967) we have found that depletion processes are described by relations of the type

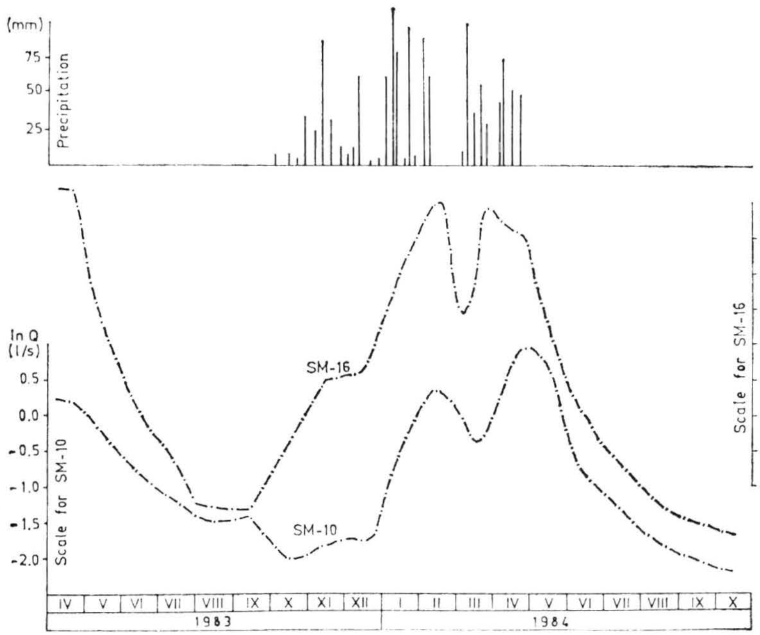

Fig. 4. Hydrograms of the SM-16 and SM-10 perched water springs

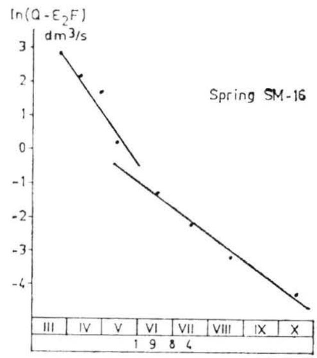

Fig. 5.

$$(1)\qquad Q-Q_k=(Q_0-Q_k)\exp(-\alpha t),$$

where Q is the discharge at a moment t; Q_0 — the discharge at a moment $t=0$; Q_k — the water influx into the aquifer during depletion.

It is the Q_k value that is responsible for the great variety of depletion curves. In the special case of $Q_k=0$, the discharge is a straight line in $\ln Q \div t$ coordinates. Now, a question immediately arises as to the nature of the continuous influx Q_k. In the mountain part of the basin there is no underground supply from nearby aquifers. A plausible alternative is feeding from condensed atmospheric vapor. Starting from this assumption, we shall demonstrate one of the possible methods for determining Q_k. The method is based on the following reasoning:

— The spring wells out of a tectonic dislocation which plays the role of a linear drainage channel. On either side of it, the underground flow is one-dimensional. The influx per unit length of the channel is q(t).

— During the rainy season groundwater is replenished by infiltration of precipitations. The duration of infiltration replenishment is t_1, and its intensity is ε_1.

— During the period of decreasing discharge ($t>t_1$), the aqufer is partly replenished by some other flow (probably originating from condensed water vapor) of intensity ε_2.

— The spring discharge equals q(t) multiplied by the length of the tectonic dislocation (b) within the spring's catchment area ($Q=qb$).

The law of the variation of q(t), respectively Q(t), in time is derived by solving the one-dimensional Boussinesq equation. Omitting the mathematical operations, the final solution is

$$(2)\qquad \frac{Q(t)}{\varepsilon_1 F}=f(t')+\frac{\varepsilon_1}{\varepsilon_2}[1-f(t')];\quad t'=t-t_1$$

$$(3)\qquad f(t')=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[-(2n-1)^2\frac{\pi^2 Tt'}{4\mu l^2}\right],$$

where T is the bed permeability; μ — the water loss; F — the catchment area of the spring; l — the mean halfwidth of the catchment basin.

The denominator in the left-hand part of equation (2) is nothing other than Q_0 of equation (1) ($Q_0=\varepsilon_1 F$). The continuous influx Q_k equals $\varepsilon_2 F$. As known, the $\frac{\pi^2 T}{4\mu l^2}$ term is the depletion coefficient (α).

Spring discharge data are refined by the standard curve method. For the purpose, equation (2) is plotted in coordinates $\ln\frac{Q}{\varepsilon_1 F}\div \ln F_0$ ($F_0=\frac{Tt'}{\mu l^2}$). A curve is obtained for each $\varepsilon_2/\varepsilon_1$ value. Thus, ascribing various values to the $\varepsilon_2/\varepsilon_1$ ratio, we obtain a set of standard curves. Spring discharge data are plotted in coordinates $\ln Q\div \ln t'$ using the same scale as in plotting the standard curves. Then we follow the same procedure like in all other standard curve methods. The standard curves of equation (2) are not shown here because they are quite easily constructed and the interested reader may plot them with all details desired.

We shall exemplify our argument with the refinement and interpretation of the SM-16 spring discharge data. The hydrograph of that spring is given in Fig. 4. In coordinates $\ln Q\div \ln t'$, the discharge data plot on the standard curve of $\varepsilon_2/\varepsilon_1=0{,}02$. This gives a value of 2,67 dm^3/s for the initial discharge $Q_0=\varepsilon_1 F$; the continuous influx, or condensation replenishment, ($Q_k=\varepsilon_2 F$) equals $0{,}02\varepsilon_1 F=0{,}053$ dm^3/s. To compare the data with equation (1), the discharge of the same spring is plotted in coordinates $\ln(Q-Q_k)\div t$ (Fig. 5). The data satisfactorily fit two straight lines. This proves that the discharge decrease is indeed described by equation (1) which is an indirect indication of condensation replenishment of groundwater in the Al Sinn basin. Furthermore, the two straight-line plots suggest double porosity of water-bearing rocks (S c h o l l e r, 1967).

2. Analysis of the Al Sinn, Sourit and Banias springs discharge

The three large springs (Al Sinn, Sourit and Banias) drain part of the groundwater in the main aquifer. They are located along the eastern boundary of the coastal plain where the outcropping Cenomanian karst limestones come into contact with Neogene impervious sediments. Some distance downstream from the Al Sinn spring, a barrage has been constructed to raise the water level with 5 or 6 m damming up the spring. The Sourit spring is located some 200 m south of Al Sinn. It appeared after the damming up of Al Sinn.

Before approaching the discharge analysis of these three springs, it is quite relevant to draw attention to a compositional peculiarity of groundwater in the Al Sinn basin. It concerns the hydrogeochemical effect of double porosity (М о л л о в, 1987) directly related to the spring discharge. Groundwater chemical composition changes in time. During the rain season, groundwater is rapidly replenished filling all karst forms, from the large karst voids to the microcracks. The bulk of water, however, accumulates in the large karst forms.

During the rain season, groundwater flowing along large karst conduits represents the main portion of spring discharge. With the end of rains, a gradual exhaustion of water reserves sets in the aquifers. Large karst forms are drained off first. Thus, the portion of microcrack water in the spring discharge increases with time.

Data given in the two tables below (Tables 1 and 2) clearly illustrate the dynamics of groundwater chemical composition in the two hydrodynamic horizons.

When spring water comes from the large karst cavities, it is of hydrocarbonate-calcic composition. The increasing portion of water from microcracks rises the contents of HCO^-_3 and $Na^+ + K^+$, increasing the overall spring water mineralization as well. In autumn, spring waters are already of hydrocarbonate-sodium composition. This kind of compositional dynamics of groundwater is possible only in young karst terrains where microcracks still contain a certain amount of easily soluble salts while all soluble compounds are already leached away from the walls of large karst channels. It should be noted that karst formation has developed in analogous manner both in the perched water horizon and in the main aquifer.

Table 1

Average chemical composition of perched water springs

Period	Ion concentrations in mg/dm³						
	Cl^-	SO_4^{2-}	HCO_3^-	$Na^+ + K^+$	Ca^{2+}	Mg^{2+}	mineralization
Winter and spring	36	34	253	31	71	15	446
Summer and autumn	36	35	398	87	61	30	679

Table 2

Average chemical composition of the Al Sinn, Sourit and Banias springs

Period	Ion concentrations in mg/dm³						
	Cl^-	SO_4^{2-}	HCO_3^-	$Na^+ + K^+$	Ca^{2+}	Mg^{2+}	mineralization
Winter and spring	31	35	275	20	71	22	445
Summer and autumn	36	52	454	108	64	22	746

In addition to the evidence concerning the extent of karst development, the compositional variations of groundwater carry also information about the relationship between precipitations and spring discharge. The rapid drop of water mineralization after the beginning of the rain season indicates that atmospheric water has reached the spring.

Spring discharges of Al Sinn, Sourit and Banias show cyclicity which is directly related to the yearly distribution of precipitations. Minimum values are recorded during October and November. Maximum discharge spreads over a wide time span, from February till May. An element of the Al Sinn spring hydrogram will be given as an example (Fig. 6). Two characteristics of spring discharge changes are relevant to this study: how long it takes for rainwater to reach the spring, and what is the exact manner of discharge depletion.

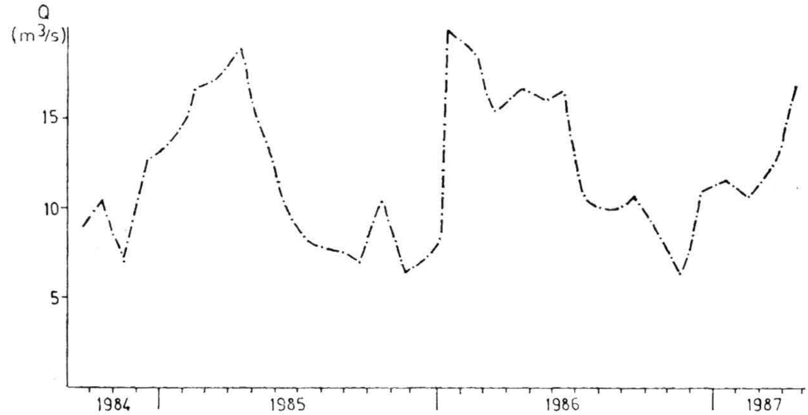

Fig. 6. Hydrogram of the Al Sinn spring

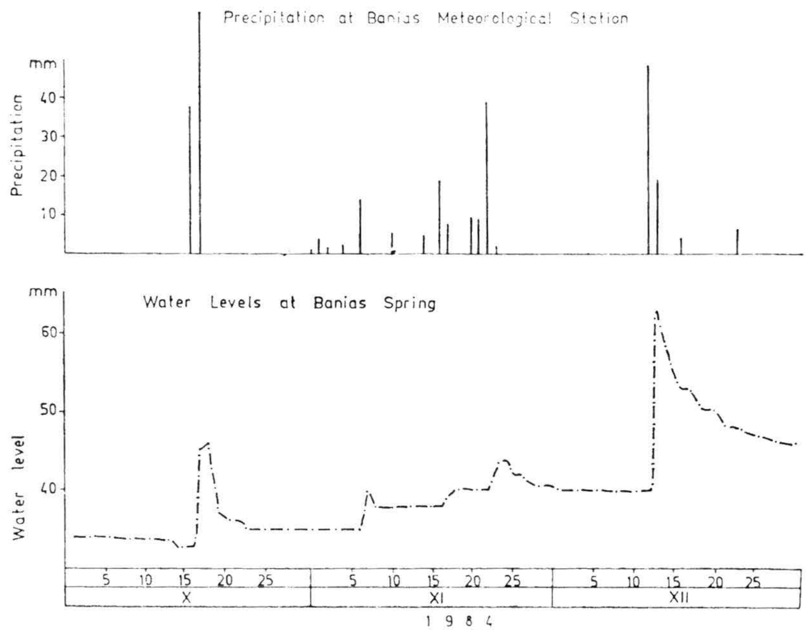

Fig. 7. Relationship between the Banias spring discharge and precipitations

Comparing the Banias spring discharge with the precipitations in October, November and December, 1984 (Fig. 7) shows a quick response to the atmospheric supply. Spring discharge is expressed as the water level read from the staff gage. The hydrometric station at Banias measures not only the spring discharge but also the surface flow (if present). Since surface flows last for not longer than 24 hours after heavy rains, the plot on Fig. 7 permits evaluating the time lag of discharge increase with respect to rainfalls within a margin of error less than 24 hours. Spring discharge responds to any rainfall exceeding 5 mm the time lag being about two days. An appreciable part of the Al Sinn springwater is used for civil needs and irrigation which makes it difficult to determine precisely the time lag of rate increase with respect to rainfalls. Nevertheless, the data on precipitation and discharge for October and November, 1985, give a general idea of its value. The average distribution of rainfalls in the basin during those two months based on data from 5 precipitation stations is:

Oct. 9-14 — 76 mm; Oct. 16-21 — 45 mm; Oct. 25-26 — 45 mm; Nov. 1 — 2 mm; Nov. 9-13 — 15 mm; Nov. 17-20 — 4 mm.

The yield of the Al Sinn spring (water used for civil needs excluded) in the middle of October, 1985, is given in Table 3. That yield expressed as the discharge of the Al Sinn River (i. e. spring discharge minus the amount taken for water supply) shows two pronounced increases. The first one was on Oct. 12, and the second one on Oct. 16, 1985. They are clearly related to precipitations, the time lag of discharge increase with respect to rainfalls being about 2 or 3 days. Chemical composition changes in springwater provide explicit evidence on the time of arrival of rainwater (Table 4). The considerable decrease of springwater mineralization indicates that sufficient quantity of rainwater has reached the spring to dilute the more mineralized groundwater supplied from the microcracks in the karst massif. It follows that less than a month after the beginning of rains, the large karst channels are already filled, their content determining the chemical composition of springwater.

The decreasing discharge after the end of the rain season is best followed in the Banias spring (Fig. 8). During the first 3 or 4 months it obeys the Millet law which gives a straight line in coordinates $\ln Q \div t$ (Castany, 1967). At the end of July or the beginnig of August, the discharge starts rising regardless of the lack of precipitations. Some springs outside the Al Sinn basin show a similar behaviour. That rise towards the end of summer may be explained with condensed vapor replenishment of groundwater.

Table 3

Discharge of the Al Sinn River in October, 1985

Date	11	12	13	14	15	16	17	18	19
Discharge (m^3/s)	3,30	4,68	3,90	3,60	3,90	5,16	5,68	5,16	5,96

Table 4

Water mineralization of the Al Sinn, Sourit and Banias springs during the autumn of 1985

Al Sinn		Sourit		Banias	
Date	mineralization (mg/dm^3)	date	mineralization (mg/dm^3)	date	mineralization (mg/dm^3)
23. 09. 1985	669	22. 09. 1985	868	23. 09. 1985	683
13. 10. 1985	814	13. 10. 1985	872	13. 10. 1985	814
14. 10. 1985	784	16. 11. 1985	484	14. 11. 1985	535
14. 11. 1985	535				

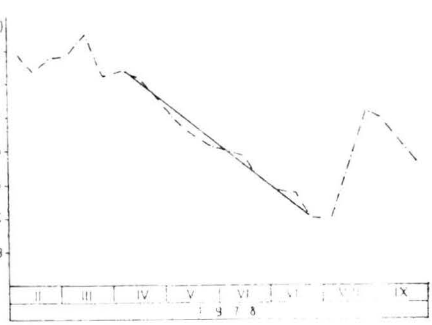

Fig. 8. The Banias spring discharge decrement during 1978

Indications of condensation replenishment of groundwater are found both in the springs of the perched water horizon and in those draining the main aquifer. Such an interpretation finds support in some published data (Славянов, 1955; Тугаринов, 1955; Глухов, 1965; and other authors) although they do not concern the Mediterranean part of Syria. According to Глухов, the condensation replenishment in the Crimea is 59 mm/year. The Mediterranean part of Syria resembles the Crimea both in climate and hydrogeology. Therefore, a condensation mechanism of groundwater replenishment in the Al Sinn basin is a very realistic assumption. If the estimate of Глухов (59 mm/year) is used to calculate the condensed vapor contribution in the Mediterranean part of Syria, it is found that condensation may account for a total discharge of about 1200 dm^3/s in the Al Sinn basin.

3. Analysis of groundwater levels in the main aquifer

Groundwater levels in the main aquifer lie at various depths generally decreasing from the east to the west, i. e. from the mountain part of the basin towards the Mediterranean. In the eastern and central parts, groundwater occurs at 300 to 500 m from the surface. Towards the sea the depth decreases to only several meters in the coastal strip with local free discharge onto the surface. Regardless of the great differences in the depth of groundwater levels, its variation in time is almost identical throughout the basin (Fig. 9). The level responds in analogous manner no matter whether it is at 60-80 m (S2R) or 200-400 m (S1R) under the surface. The time in which rainwater reaches groundwater levels is practically equal everywhere. All these facts indicate that the entire rock series above the water table is crosscut by a network of tectonic dislocations, shattered zones and fractures dense enough to permit very rapid downward pervasion of rainwater. The abundant marl beds are thus no efficient barrier against the downward flow.

Large amplitudes (up to 200 m) are typical of water level variations in the main aquifer. Amplitudes of such magnitude are rarely encountered in hydrogeological phenomena throughout the world. Another example has been reported from Lebanon (Mijatovic & Bakic, 1967). Large water level amplitudes are probably an inherent feature of karst hydrology along the eastern coast of the Mediterranean. Both the water level depth and the amplitude of its variation are highly variable (Table 5).

Variation amplitudes provide direct indications as to the conditions under which groundwater flows to the main points of discharge. The S7R and S8R wells (Fig. 1) are located at about the same distance from the sea as S1R yet the amplitude in S1R is almost 3 times greater than that in S7R, and 6 times greater than that in S8R. It is clear that the area of the S7R and S8R wells provides better conditions of underground flow towards the drainage base level, i. e. towards the Al Sinn spring.

Besides being fairly thick, the zone of seasonal variations is in a more advanced stage of karst formation than the zone of constant saturation. This is evidenced by water withdrawal data for the S2R and S8R wells. Water has been drawn two times from S2R, first at a static level of 78,4 m below the surface, then at a static level of 64 m. Discharges were 0,38 dm^3/s and 7,35 dm^3/s, respectively. Water drawn from the S8R well at high and low water stages came out at relative rates of 6 dm^3/s and 3,5 dm^3/s, respectively.

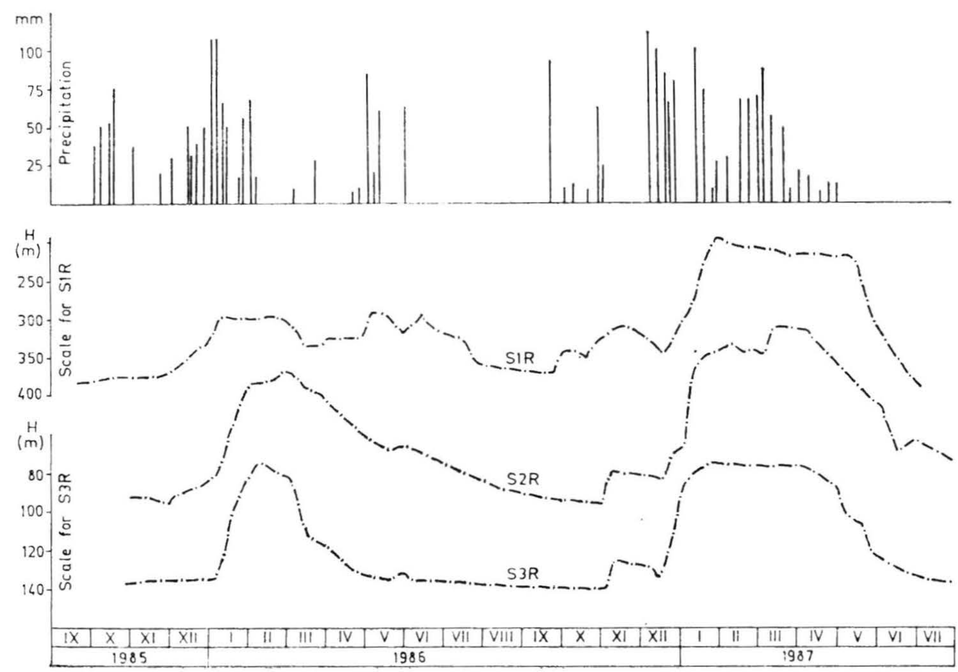

Fig. 9. Water level variations in the main aquifer measured in the S1R, S2R and S3R wells

Table 5
Amplitudes of groundwater level variations

Well	S3R	S1R	S2R	S4R	S7R	S8R	S1
Amplitude (m)	64.0	172.6	19.7	14.1	54.8	28.0	43.5

The hydrodynamic behaviour of the Al Sinn basin gives us an idea of the karst nature and the extent of its development. Let us recall the relevant facts:

— The discharge of the Al Sinn, Sourit and Banias springs rises appreciably (and the groundwater composition changes) shortly after the beginning of rains. Chemical changes of springwater require voluminous fresh supply which means that large parts of the drainage are involved. The average distance from the springs to the basin central parts being about 10 000 m and assuming water dilution period of 20 days, we obtain 500 m/day as an estimate of the real groundwater flow velocity. Such flows may occur in large karst channels only.

— Water table variations are as a rule of large amplitudes. Furthermore, the maximum water stages are reached 1 to 1,5 months after heavy rains. The time lag does not depend on the depth of groundwater level.

In addition, the double porosity hydrogeochemical effects are observed in the basin.

All these features characterize the Al Sinn karst as a typical geosynclinal type. It develops vertically due to the rapid neotectonic uplifting. Naturally, karst forms deepen along zones favouring the groundwater flow which are exactly the tectonic dislocations and the shattered zones. It is just such dislocations that have developed into the large karst channels feeding the Al Sinn, Sourit and Banias springs. The spaces between dislocations, being less pervious, are also less affected by the karst processes. They still contain certain amounts of easily soluble salts.

As a filtration medium, the carbonate massif of the Al Sinn basin is a system of random large karst channels separated by spaces of low filtration properties. The large karst channels drain the entire carbonate massif. The practical value of this model of filtration environment consists in the inference that groundwater prospecting can be successful only near tectonic dislocations.

Translated by I. Vesselinov

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