

An example of a complete study of karst hydrogeology (Al Sinn Basin, Syria). I. Methodological Principles

Delcho Mollov¹, Elly Sarkees²

¹Geological Institute, Bulgarian Academy of Sciences, 1113 Sofia

²General Company for Hydraulic Studies, Homs, P. O. Box 752, Syria

(Accepted for publication September 12, 1988)

Д. Моллов, И. Саркис — Пример комплексного исследования гидрогеологии карста (бассейн Ал Сен — Сирия). I. Теоретические основы методологического подхода. Источник Ал Сен находится в центральной части прибрежного района Сирии. Воды источника впитываются большим карстовым массивом, имеющим отметки от 10 до 1500 m над уровнем моря. Часть воды из карстового массива стекает в Средиземное море. На территории приморской равнины окастованные известняки сеноман-туронского возраста перекрыты мощным (200—300 m) мергельным водонепроницаемым комплексом. На дневной поверхности нет никаких видимых признаков, которые могли бы обнаружить места подводного (морского) дренажа. В этих условиях оказалось очень эффективным использование данных геотермии и гидрогеохимии для исследования движения подземных вод.

Анализ дифференциальных уравнений теплопереноса и фильтрационной диффузии показывает, что скорость движения подземных вод оказывает основное влияние на температурный и гидрогеохимический режим карстового бассейна. Выяснилось, что возможно нахождение подходящих критериев, дающих ключ к интерпретации геотермических и гидрогеохимических данных для целей гидродинамики. Совместное рассмотрение гидродинамического, геотермического и гидрогеохимического процессов представляет сущность используемого методологического подхода.

Abstract. The Al Sinn spring is located in the central part of the coastal area of Syria. It drains off a large karst massif rising from 10 m to over 1500 m above sea level. Part of the karst runoff water is carried into the Mediterranean. Within the coastal plain the karst Cenomanian-Turonian limestones are covered by a thick (200-300 m) impermeable marl complex. There are no surface indications of likely places of submarine discharge. Under the circumstances, the use of geothermal and hydrogeochemical data has proved highly efficient in studying groundwater flows.

An analysis of the differential equations of heat transfer and filtration diffusion has shown that groundwater flow velocity has a major effect on the temperature and hydrogeochemical regime in the karst basin. It has been found that criteria providing the key to interpreting the geothermal and hydrogeochemical data for the purposes of hydrodynamics can be derived. The methodological approach used in this study is essentially a combined treatment of hydrodynamical, geothermal and hydrogeochemical processes.

The powerful karst spring of Al Sinn is located approximately midway between the towns of Tartus and Lataheqih. It is the second largest spring in Syria after Raz al Ain. Economically it is very important for the whole coastal area of Syria part of its water being used for irrigation and another part for supplying a number of towns, villages and industrial works. Many explorers and surveyors of the area thought that groundwater of the karst basin drains off partly at the bottom of the Mediterranean but no one has yet located the points of discharge or determined the groundwater outflow. Submarine discharge of groundwater is expected along a front of 20 km, and somewhere along this strip there are open channels letting groundwater to the sea. The aquifer is covered by a thick (200-300 and more meters) impervious complex. There are no direct geological indications as to the location of drainage channels.

That kind of unknowns characterized the situation prior to the start of hydrogeological exploration in the Al Sinn basin the task being not only to make up the groundwater budget in the basin but also to discover the passages through which groundwater escapes into the sea. Finally, the karst channels of discharge were discovered and reached by drill-holes. Fountains of fresh water spouted along the coast. The present paper describes the methods by which the matter was approached and which ultimately led to the successful completion of hydrogeological exploration.

1. Physico-geographical and climatic outline of the basin

The Al Sinn basin occupies an area of about 830 sq. km in the central part of the Coastal Region of Syria. In the west it borders on the Mediterranean and its eastern boundary runs along the surface watershed dividing the El Ghab lowland and the Coastal Region. Its northern and southern boundaries will be defined below.

Hypsometric levels in the basin range from zero to 1700 above the sea level. Terrain profile generally slopes down to the west, i. e. from the watershed to the Mediterranean. The Coastal Plain is a strip 2 to 6-7 km wide adjacent to the shore, to the east of which the ground climbs rapidly up reaching heights of 1500-1700 m over distances of 18-20 km.

The mean multiannual sum total of precipitation in the basin is about 1300 mm. Yearly distribution is characterized by two seasons: rainy and dry. The dry season lasts from June till October most rainfalls occurring during the rest of the year. The mean annual air temperature depends on the altitude. In the Coastal Plain (at the Al Sinn meteorological station) it is 19.6°C, and at 1100 m above sea level (the Slenfeh meteorological station) it is 12.5°C. In winter (December—March), when precipitation is reduced, the mean temperatures are 14.4°C and 6.3°C, respectively.

Many rivers flow across the basin. All of them run from the east to the west into the Mediterranean. All rivers cut deeply into the carbonate series forming very steep slopes difficult to climb. All rivers are seasonal with no constant flow. Only after rainfalls water comes down as flood surges lasting several hours but afterwards leaving dry beds.

2. Geological structure and major hydrogeological formations

The Al Sinn basin is a one-sided horst structure (P o n i k a r o v, 1964) which, for hydrogeological purposes, may be described as a monocline. The sequence dips to the southwest at angles of 5-20° (Fig. 1). The monocline is complicated by numerous minor folds. Many faults of northeastern or northwestern orientation cut across the basin. Hydrogeologically, two tectonic dislocations, or more precisely two swarms of tectonic dislocations, are most important. The northern dislocation starts just from the Al Sinn spring extending to the northeast. Its amplitude of displacement exceeds 700-800 m in the coastal area but decreases to the northwest becoming less than 100 m in the highest parts. The other, southern dislocation runs also northeastwards along the River Markie valley (south of the town of Banyas). Its amplitude is about 400 m in the coastal area diminishing to the northeast as in the northern fault. In this way, a stepped series of three tectonic blocks forms the central part of the Syrian Coastal Region. The block in the middle is upthrown relative to the northern one, and the southern block is upthrown relative to the middle one. The drainage area of the Al Sinn spring occupies the central tectonic block which defines the northern and southern boundaries of the basin. These are the two high-amplitude faults described.

The oldest rocks exposed in the basin belong to the Lower Jurassic. All sediments forming the stratigraphic sequence can be grouped in two large series: older than Turonian and younger than Turonian. The first series consists mostly of dolomites, limestones and marls. Marls occur in almost all formations but are best developed in the Upper Jurassic sediments and in the Bab Janneh Formation (Aptian). The lithological composition of rocks

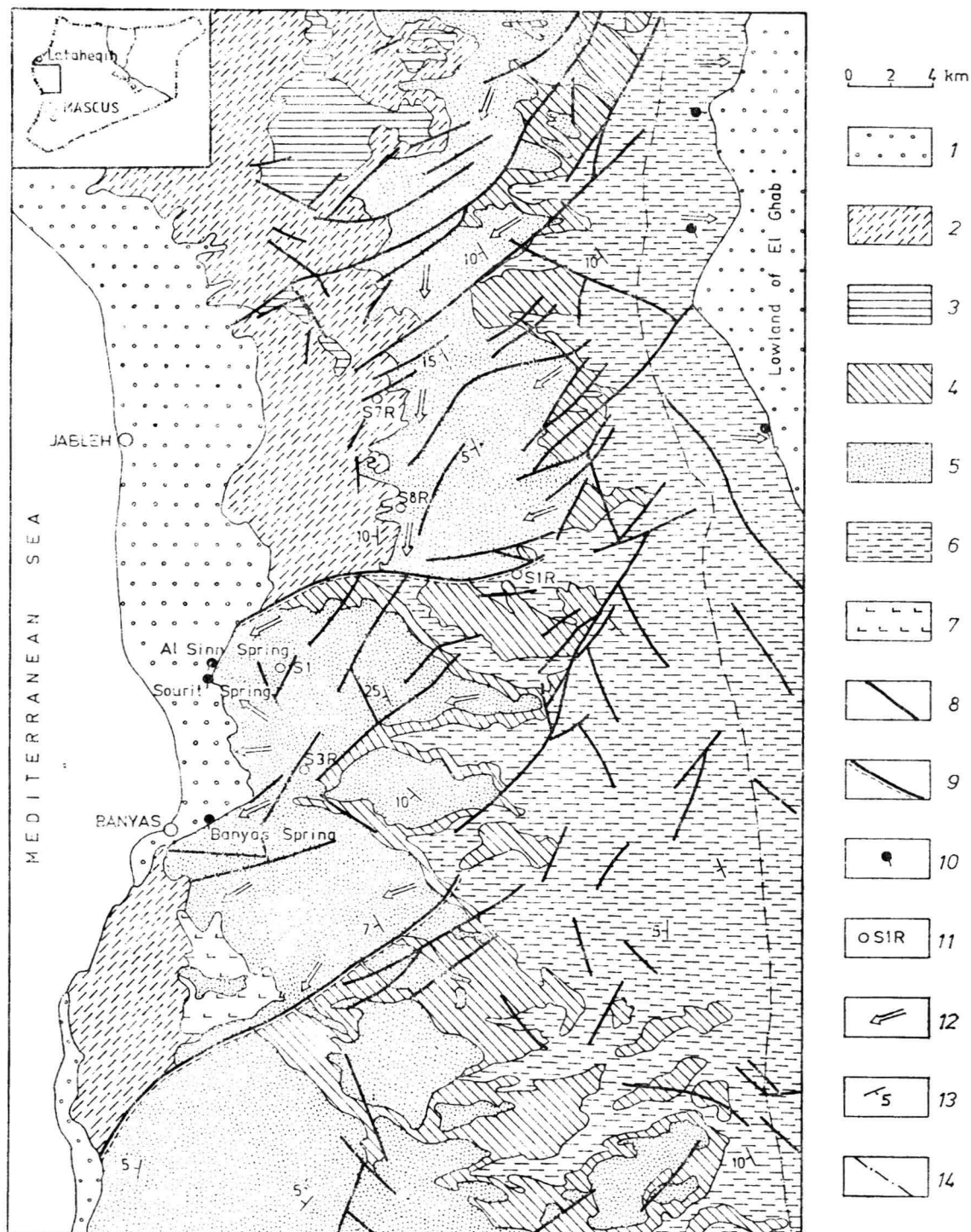


Fig. 1. Hydrogeological map of the basin (based geologically on P o n i k a r o v, 1963)

1 — groundwater in Quaternary deposits; 2 — water-impermeable sediments of the Maestrichtian, Paleogene and Neogene; 3 — groundwater in Middle Eocene sediments; 4 — relatively impervious Lower Cretaceous sediments; 5 — groundwater in Cenomanian-Turonian karst limestones; 6 — groundwater in Jurassic karst limestones; 7 — basalts; 8 — fault; 9 — large amplitude fault; 10 — spring; 11 — exploratory well and its number; 12 — direction of groundwater flow; 13 — strike and dip of beds; 14 — surface watershed between the El Ghab lowland and the Mediterranean basin

n this series indicates that karst phenomena are to be expected not only on the surface but in depth as well including also levels below the Mediterranean floor if there are favourable hydrodynamic conditions. The second sedimentary series starts with a thick Senonian impermeable complex (300-600 m). Lithologically, its deposits consist of marls, marly limestones and chalkstones. All these are materials resistant to karst processes. They are overlain by Paleogene and Neogene sediments represented by alternating marls, chalk, limestones and sandstones which are also resistant to karst processes. A single exception is a packet of Middle Eocene limestones which is of restricted occurrence and of no regional significance. In the Coastal Plain there are marine and detrital Quaternary deposits up to 10-15 m thick which contain some groundwater. It, however, has no relation to the supply and flow pattern of karst groundwater in the Al Sinn drainage basin.

The geological structure of the basin can be briefly summarized as follows. Its easternmost and highest parts are built up of the Jurassic carbonate complex. To the west the ground slopes down, and one after the other the sediments of the Aptian, Albian, Cenomanian and Turonian (K) appear in the geological sequence. These rocks actually exhaust the list of deposits pervious to karst action. The westernmost parts of the basin are occupied on the surface by the water-resistant sediments of the Senonian (K), Paleogene and Neogene.

The following hydrogeological formations can be defined on the basis of the lithological composition of rocks in the Al Sinn basin:

- Hydrogeological formation of Cretaceous carbonate complexes;
- Hydrogeological formation of Jurassic carbonate complexes.

The occurrence of more or less continuous marl beds in the upper horizons of the Upper Jurassic and in the Aptian sediments acts as a kind of hydraulic insulation between the two main hydrogeological formations. Hydraulic communication between them is possible only along the larger tectonic dislocations and fissures.

In the eastern and central parts of the basin the hydrogeological formations outcrop on the surface and it is there that groundwater is formed. In the Coastal Plain the aquifers of the hydrogeological formations are covered by a thick impermeable complex (Fig. 1). The monoclinical geological structure determines the formation of a monoclinical hydrogeological basin.

3. Theoretical principles of the methodological approach

Four types of processes take place in any hydrogeological basin: hydrodynamic, geothermal, hydrogeochemical and biological processes. Generally speaking, the hydrodynamic, geothermal and hydrogeochemical processes are interrelated which means that the parameters of any of them affect those of the other two. The specific hydrogeological conditions in the Al Sinn basin are such that the hydrodynamic process is independent on the other two. On the contrary, geothermal and hydrogeochemical phenomena are largely determined by hydrodynamic parameters which suggests that groundwater dynamics can be studied by solving inverse problems of the geothermal and hydrogeochemical systems. That line of approach cannot be based solely on the general characteristics of groundwater temperature and chemical composition, it should rather employ the laws governing the variation of temperature and chemical composition in time and space derivable only if the problems are treated in terms of the theory of heat and mass transfer. Therefore, the methodological approach followed in this study is essentially a combination of hydrodynamic methods of studying groundwater flows with an analysis of geothermal and hydrogeochemical data.

3.1. *Hydrodynamic interpretation of geothermal data*

The use of geothermal data in the analysis of groundwater flows in the Al Sinn basin has been determined by the following specific features of the area:

- Elevations above sea level increase rapidly from the west to the east reaching up to 1500-1700 m at some 18-20 km from the Coastal Plain;

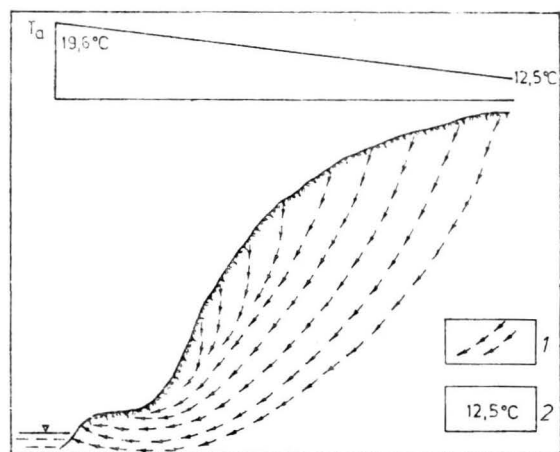


Fig. 2. Hydrodynamic scheme of the formation of geothermal regime in the coastal part of the basin 1 — trajectory of groundwater flow; 2 — mean annual air temperature of 12.5°C

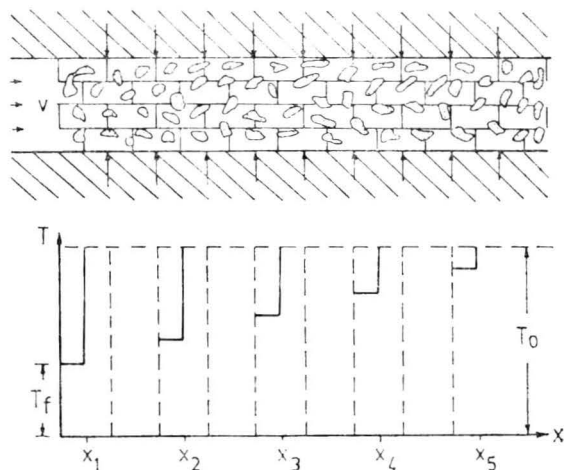


Fig. 3. Cooling scheme of the carbonate massif according to the Lauerier principle of piston-type transfer

— The mean annual air temperature diminishes from the west to the east following the increasing altitude. It is 19.6°C near the Mediterranean dropping to 12.5°C at 1100 m above sea level;

— Groundwater formed uplands drains off to the Coastal Plain or under sea level. Thus, the relatively cool mountain groundwater influences the geothermal regime near seashore;

— The basin lies in a region of intense tectonics manifested in the presence of numerous faults and in neotectonic rising.

The combined picture of these four specific features can be used to construct a model of the geothermal pattern in the basin. It is based on the presumption that the geothermal regime is dominated by groundwater flows.

The geothermal model's physical meaning is illustrated by two figures (Figs 2 and 3). Groundwater formed in the highest parts of the basin travels to the deepest levels (Fig. 2) and in the Coastal Plain it reaches the lowermost horizons of the aquifer. This scheme has a clear hydrodynamic meaning. At 1000 m above sea level the mean winter air temperature is 6.3°C dropping lower at higher altitudes. But winter is the season of precipitations and of groundwater formation. The coolest portions of groundwater are thus able to penetrate the deeper Coastal Plain horizons and to reduce their temperature conceivably even below the mean annual air temperature (19.6°C). We need now to find how the temperature of cool groundwater will change along its way from the mountain part of the basin to the Coastal Plain. To answer the question we shall qualitatively analyze the heat transfer differential equation for the case of one-dimensional flow with both conductive and convective components.

It is known (Л я л к о, 1974, and other authors) that temperature distribution under such conditions is given by the differential equation

$$(1) \quad m_0 \lambda \frac{\partial^2 T}{\partial x^2} - v \rho m_0 c \frac{\partial T}{\partial x} + q_1 + q_2 = m_0 c_i \rho_i \frac{\partial T}{\partial t},$$

where T is the temperature, x — space coordinate, m_0 — aquifer thickness, v — filtration rate, ρ — water density, c — water heat capacity, c_i — rock heat capacity, t — time, ρ_i — rock density, q_1 and q_2 — heat flows from the beds overlying and underlying the zone of active ground-

water percolation. These heat fluxes are given by the solutions of differential equations describing heat transfer above and below the aquifer. In the most general case q_1 and q_2 decrease with time.

In the literature there are many solutions of equation (1) for a variety of boundary and initial conditions (K a p c л o y & E r e p, 1964). All of them show that temperature variations in the aquifer bed (or zone) depend primarily on the rate of filtration. This dependence is expressed by the so-called Peclet number ($Pe = \frac{v l}{a}$; l is the filtration bed length along the axis x). For instance, an analysis of the Brenner's solution (B r e n n e r, 1962) shows that when Pe numbers exceed values of 100-150 heat transfer follows the so-called piston-type transfer pattern. The presence of the q_1 and q_2 terms in equation (1) leads to a temperature pattern which may be called a modified Lauverier scheme.

Now let us compare the Al Sinn hydrogeological environment with the main properties of the modified Lauverier scheme. There is no need of quoting analytical solutions since qualitative analysis is sufficient to answer the question mentioned already. As shown, the basin is characterized by abundant tectonic dislocations, numerous enough to define it as highly heterogeneous in terms of its filtration properties. Groundwater moves along the larger tectonic dislocations with a velocity reaching or even higher than several tens of meters per day (data will be given in the following parts of this paper). In the space between tectonic faults filtration rates are many times lower. It follows immediately that heat transfer patterns will also differ at and away from the tectonic faults. The logical principles of that difference are shown in Fig. 3.

An aquifer (or aquifer zone) of initial temperature T_0 is invaded by water of temperature T_f . With time, cooling will advance along the aquifer. Cooling pattern is of the piston-type at any moment across any section of the bed. Away from the entrance, however, groundwater temperature will gradually rise due to the heat influx from the beds underlying and overlying the aquifer. In this connection we should point out that the term "piston-type heat transfer pattern" is used in the sense that first, cooling spreads over a portion of the bed's length at some moment of time, and second, the temperature is equal throughout the bed thickness. The higher the rate of filtration (V), the better defined piston-type pattern and the greater the cooling effects.

Applying the analysis of the scheme shown in Fig. 3 to the specific Al Sinn hydrogeological environment we arrive at the following principal conclusion:

— The zones of tectonic dislocations, which are also zones of maximum filtration rates, are the coolest. And vice versa, if at some point the groundwater temperature is lower, it is a reliable indication that at that point the filtration rate is high and the aquifer is water saturated. This is the substance of the principle of hydrodynamic interpretation of horizontal groundwater temperature distribution.

In the Coastal Plain the aquifer is covered by a thick impermeable complex (exceeding 200-300 m). Hence, cooling affects zones at depths greater than 200-300 m. It is interesting to find if that cooling may reflect on the surface layers 20-30 m deep. To answer the question let us consider the diagram on Fig. 4.

An aquifer is covered by an impervious layer of thickness m . The initial temperature across the geological section increases with the increasing depth (the most common case in nature). At some moment ($t=0$) the aquifer is infiltrated by water of temperature T_f lower than the initial temperature at the respective depth. Temperature equalizes across the entire aquifer thickness as follows from the principle of the piston-type heat transfer. A transitional temperature distribution arises in the impermeable cover of the aquifer. The temperature depression starts migrating upwards until it reaches the ground at some moment (t_0). After that temperature begins to drop also in the surface layers of the profile. A stationary temperature distribution differing from the initial one will be reached after a sufficiently long period (theoretically infinite). The time t_0 can be calculated using a formula taken from hydrodynamics (D e g a l l i e r, 1969, and other authors) treating the same type of differential equation, viz.

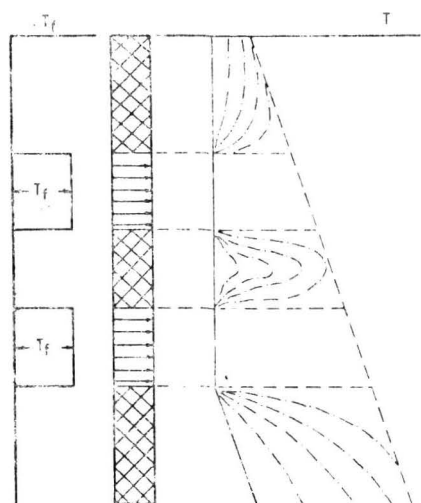


Fig. 4. Cooling scheme of the carbonate massif in a geological profile with two aquifers

1 — impermeable bed; 2 — bed of rapid flow of cooler groundwater; 3 — initial temperature of the massif; 4 — temperatures during the transitional geothermal regime; 5 — stationary temperature of the modified geothermal regime

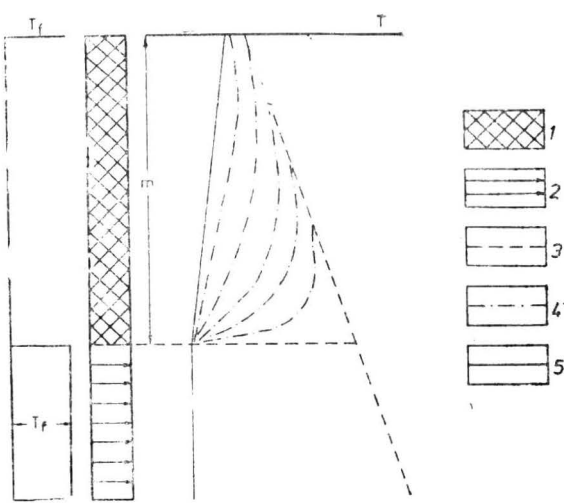


Fig. 5. Cooling scheme of a carbonate massif with two zones of increased aquifer permeability

1 — impermeable interval; 2 — interval of rapid flow of cooler groundwater; 3 — initial temperature of the massif; 4 — transitional temperatures; 5 — stationary temperature of the modified geothermal regime

$$(2) \quad t_0 = \frac{m^2}{13a},$$

where a is the thermal diffusivity of the water impermeable cover. In marls a is of the magnitude of $0.70 \text{ m}^2/\text{d}$. If the cover thickness is $m=300 \text{ m}$, the temperature drop will reach the surface after a time

$$t_0 = \frac{300^2}{13 \cdot 0.07} = 98900 \text{ days} = 270 \text{ years}.$$

Geologically, a time t_0 of about 270 years is a very short period. This implies that thermal processes taking place at depths of 300 to 500 and more meters reflect on the Earth surface which provides still another possibility for a hydrodynamic interpretation of geothermal data.

The analysis of the diagram on Fig. 4 has led us to two major conclusions concerning the hydrogeological significance of geothermal data:

— Horizontal temperature distributions in the surface layers (20-30 m) permit tracing out zones of active groundwater percolation in deep-seated aquifers. In the special case of the Al Sinn basin, the lower temperatures of surface layers indicate that the aquifer of Cenomanian-Turonian limestones contains a system of drainage conduits through which groundwater escapes into the sea;

— Temperature decrease in depth indicates that somewhere below there are horizons of active percolation of cooler water.

Heat transfer in an aquifer water-impermeable cover is described by a differential equation solved for many cases of hydrodynamics, heat transfer and diffusion (Шестakov, 1964; Карслоу & Егер, 1965; Пехович & Жидких, 1968; and other authors). An analysis of these solutions shows that the temperature of surface layers decreases only if a zero boundary condition of the second kind is met along the surface. So far, physical interpretations of thermal processes at the earth surface-atmosphere interface have not considered the question about the kind of boundary conditions to be met

there. Measurements in the Coastal Plain provide data showing that in some areas the surface layer temperature is about 4°C lower than the mean annual air temperature. Thus, it seems justified to consider a zero boundary condition of the second kind as being truly valid for those areas.

From the viewpoint of vertical temperature distribution across the geological profile there is another scheme which merits scrutiny (Fig. 5). Prior to the effects of filtration on the temperature pattern, the geothermogram would be a straight or almost straight line of positive gradient. At some moment $t_0=0$ cooler groundwater flows into two karst channels located at different levels and separated by an impervious bed. The cooling effect of groundwater will result in a transitional temperature regime along the geological profile. After an infinitely long period the temperature pattern will reach a new stationary state. The transitional regime is characterized by temperatures higher in the impermeable parts of the profile than in the karst channels. Therefore, in interpreting geothermograms positive temperature anomalies should be allotted to impermeable parts of the section. Here, we restrict the analysis to two karst channels but the same can be done with a greater number of conduits with analogous results — all impermeable intervals will correspond to positive temperature anomalies.

The treatment here is valid for the Al Sinn basin where groundwater cools the massif. There are areas where groundwater heats the rocks. The same reasoning is valid for them, too. Interpretations should only allow for the fact that zones of active groundwater percolation would be associated with increased temperatures of the massif. This concerns both vertical and horizontal temperature distributions.

3.2. Hydrodynamic interpretation of hydrogeochemical data

The hydrodynamic interpretation of hydrogeochemical data is comparatively more difficult than that of geothermal data. The main reason is the great influence of aquifer rocks on the groundwater chemical composition. Nevertheless, there are many cases in which the analysis of the basic equations of filtration diffusion demonstrates the controlling role of the filtration rate. If so, then still another group of methods for studying groundwater flows can be added to hydrodynamics.

The formation, distribution and temporal variation of salt contents in groundwater are described by a system of differential equations rigorously derived in terms of the so-called filtration diffusion. We shall consider the special case of one-dimensional groundwater flow (Бочев е р, 1979, and other authors)

$$(3) \quad D \frac{\partial^2 M}{\partial x^2} - v \frac{\partial M}{\partial x} = n \frac{\partial M}{\partial t} + n \frac{\partial N}{\partial t},$$

where M is the groundwater mineralization, D — the coefficient of molecular diffusion in the aquifer, n — the active porosity of aquifer, v — the velocity of groundwater flow, N — the quantity of matter capable of feeding salts into the groundwater flow (this point will be discussed in greater detail below).

There are many analytical solutions of the differential equation (3). It is difficult to refer the reader to all sources but we recommend instead two studies summarizing the known solutions (В е р и г и н & Ш е р ж у к о в, 1969; Б о ч е в е р et al., 1979). The existing solutions, however, could not assist us in solving our problem without a logical analysis of the separate terms in equation (3). In our case, the second term on the right in (3), $n \frac{\partial N}{\partial t}$, is the most important. In the environment studied here, salts are fed into the groundwater flow by dissolution of rocks. The existing studies concentrate mostly on the dissolution of chlorides and sulphates, i. e. readily soluble salts. They are concerned with soil desalination, a case in which the salt content (N) is a finite and known quantity. Dissolution of carbonate rocks has also been studied but in such contexts the results are difficult to use in analyzing the relative contribution of the $n \frac{\partial N}{\partial t}$ term in equation (3).

In the study of filtration leaching of saline soils (Веригин, 1957), the process kinetics is described by the equations

$$(4) \quad \frac{\partial N}{\partial t} = -\alpha_p(M_{\text{II}} - M)\sqrt{N}$$

for dispersed salt particles in soil, and

$$(5) \quad \frac{\partial N}{\partial t} = -\alpha_p(M_{\text{II}} - M)$$

for salt crusts coating soil particles, where α_p is the dissolution rate constant, M_{II} — the concentration of the saturated solution, M — the actual concentration of solution.

It has been theoretically proved and experimentally verified (Веригин, 1957) that the dissolution rate constant (α_p) depends on the velocity of groundwater flow (v), the variation being of the type $\alpha_p = f(\sqrt{v})$.

Dissolution of carbonate rocks differs considerably from salt leaching of soil. The most important features of the process are:

— The amount of matter to be dissolved (N) is practically limitless;

— The carbon dioxide content of groundwater is the main factor in carbonate rock dissolution. Water is enriched in carbon dioxide from the atmosphere and from the soil horizons. The faster it infiltrates the carbonate massif, i. e. the higher its velocity, the more aggressive its action.

Considering the specific features of carbonate rock dissolution we conclude that the kinetic equation (5) is better suited to describe the process. We should note at once that equation (5) applied to the dissolution of carbonate rocks leads to results which differ at least in two ways from those for soil desalination. First, the dissolution rate constant is related to the velocity of groundwater flow by a different type of function. Second, the infinitely large quantity of N prevents the occurrence of the second dissolution phase as defined by Verigin. The process will always remain in its first phase, i. e. the matter being dissolved is inexhaustible.

After this analysis we transform the differential equation (3) into

$$(6) \quad D \frac{\partial^2 M}{\partial x^2} - v \frac{\partial M}{\partial x} - n \frac{\partial M}{\partial t} - n \alpha_p (M_{\text{II}} - M).$$

Omitting discussions of the analytical solutions of equation (6) we shall analyze two cases of appreciable influence of groundwater flow velocity on groundwater mineralization.

Let us consider a carbonate massif containing karst zones at different levels one above the other. Groundwater moves rapidly in the karst zones whereas in the water-resistant zones inbetween its velocity is many times lower. At high flow velocities the conductive contribution to mass transfer $\left(D \frac{\partial^2 M}{\partial x^2}\right)$ is negligibly small. Furthermore, the convective removal of salts $\left(v \frac{\partial M}{\partial x}\right)$ prevails over the supply of salts through dissolution $(n \alpha_p (M_{\text{II}} - M))$.

Hence, groundwater will be less mineralized in the karst zones. At low groundwater flow velocities, the relative contributions of the terms $\left(D \frac{\partial^2 M}{\partial x^2}\right)$ and $(n \alpha_p (M_{\text{II}} - M))$ become greater.

At the same time the convective removal of salts $\left(v \frac{\partial M}{\partial x}\right)$ decreases. All this results in a relatively higher groundwater mineralization in the water-resistant horizons of the carbonate massif. In practical terms, the arguments above impose constraints on the possible interpretations of logging data. Thus, a reduced groundwater mineralization (increased electric resistivity, respectively) infers extensive karst zones. This analysis is valid for the Al Sinn basin. In a different hydrodynamic and hydrogeochemical environment the same reasoning may lead to a different interpretation of logging data. In the Mhardeh area, for

instance (M o l l o v, S a r k i s, 1987) karst zones show at times increased mineralization, at others reduced mineralization. This means that the specific hydrogeological conditions should always be considered.

The coastal part of the basin represents a specific hydrogeochemical environment. In the marl cover of the aquifer in the Cenomanian-Turonian limestone series, groundwater is practically stagnant, or if it flows its velocity is very low. Salts are exchanged in this cover chiefly by conduction (influence of the $D \frac{\partial^2 M}{\partial x^2}$ term in equation (3)). In the Cenomanian-Turo-

nian limestones, salts are taken up by karst flows which creates conditions for a vertical conductive salt transfer in the marl cover described by a differential equation analogous to that in conductive heat transfer. Therefore, formula (2) can be used to estimate the period of time (t_0) during which vertical salt transfer will spread throughout the water-resistant cover and mineralization of surface groundwater will start to get lower. For a coefficient of molecular diffusion $D=10^{-4}$ m²/day, $t_0=70 \cdot 10^6$ days=190 000 years. The hydrogeochemical process is considerably slower than the geothermal one yet, over a comparatively short period of geological history, the effect of karst zones in the Cenomanian-Turonian sequence may reach the surface reflecting on groundwater mineralization there. Therefore, the hydrogeochemical behaviour of groundwater in the surface layers may serve as indication of the hydrodynamic situation in depth.

The so-called double porosity hydrogeochemical effect has been observed in the Al Sinn basin (M o л л о в, 1987). It consists in a specific variation of groundwater chemical composition in time. Water is of hydrocarbonate-sodium composition during summer and autumn changing to hydrocarbonate-calcium composition during winter and spring. This hydrogeochemical effect is directly related to the nature of karst and to the extent of its development, and is determined primarily by the neotectonic elevation of the area. Neotectonics more or less hastens or retards hydrodynamic processes, therefore the double porosity hydrogeochemical effect may at least supply useful indications concerning the hydrodynamic structure of the underground flow. The effect, if present, suggests that the bulk of groundwater flows along large karst channels.

Translated by I. Vesselinov

References

- Brenner, H. 1962. The diffusion model longitudinal mixing in beds of finite length. — *Chem Engin. Sci.*, 17; 229-243.
- Degallie, P. 1967. Interpretation des variations naturelles du niveau des nappes. — *Bul. BRGM*; 7-56.
- M o l l o v, D., S a r k i s, I. 1987. A "hydrogeochemical pendulum" in the Mehardeh Area, Arab Republic of Syria. — *Geologica Balc.*, 17, 4; 91-97.
- P o n i k a r o v, V. P. 1963. Geological Map of Syria, scale 1:200 000, sheet I-37 XIX. M., v/o Technoexport.
- Бочевер, Ф. М., Лапшин, Н. Н., Орадовская, А. Е. *Защита подземных вод от загрязнения*. М., Недра; 252 с.
- В е р и г и н, Н. Н. 1957. О кинетике растворения и выноса солей при фильтрации воды в грунтах. — В: *Растворение и выщелачивание горных пород* (ред. П р и к л о н с к и й, В. А.). М., Госстройиздат 84—114.
- В е р и г и н, Н., Ш е р ж у к о в, Б. С. 1969. Диффузия и массообмен при фильтрации в пористых средах. — В: *Развитие исследований по теории фильтрации в СССР (1917—1967)* (ред. П о л у б а р и н о в а - К о ч и н а П. Я.). М., Наука; 237—313.
- К а р с л о у, Г., Е г е р, Д. 1964. *Теплопроводность твердых тел*. М., Наука; 487 с.
- Л я л ь к о, В. И. 1974. *Методы расчета тепло- и массообмена в земной коре*. Киев, Наукова думка; 135 с.
- М о л л о в, Д. 1987. Об одном гидрогеохимическом эффекте. — *Доклады БАН*, 40, 7; 87—90.