M. Clouet d'Orval

Case history no. 20

Use of a model for determining optimum rates of artificial recharge of the Cenomanian aquifers in Beirut, Lebanon

1. INTRODUCTION

The population of the city of Beirut has been expanding at a very fast pace; the demand for water was growing every year, owing to the increase not only in the number of inhabitants but also in the average volume of water consumed per inhabitant. Total water consumption in 1973 was estimated to amount to 160,000 m^3 per day, and this figure was expected to rise to 260,000 m^3 per day by 1990.

The water supply is obtained from various surface water sources which are at low water during summer and early fall from June to October. During this period the water supply is barely adequate to meet the current level of consumption. By contrast, during the winter and spring seasons from November to May, the discharges in the coastal rivers in the Beirut area are far in excess of consumption requirements, and the surplus surface water flows out to sea without being used.

The problem of water supply for Beirut accordingly entails making a study of ways and means of storing water during the rainy season and recovering it for consumption during the dry season. This is usually achieved by building dams for the storage of surface water to cover the needs of the dry season. However, the main rivers in the Beirut area, the Nahr Ibrahim, the Nahr el Kelb and the Nahr Beirut, are not very well suited to the construction of such dams for two reasons:

1. The outcropping limestone formations are fractured and could give rise to substantial leakage beneath the reservoirs;
2. The streams carry a heavy sediment load, which is liable to cause early siltation of the reservoirs.

In view of these local conditions, the Ministry of Hydro-Electric Resources has contemplated adopting a more original approach, which sets out to store water in the natural water-bearing geologic formations of the area rather than in surface reservoirs. The formation selected is that consisting of the Hadeth-Hasmyieh Cenomanian limestone, which forms a very favourable natural karst reservoir.

Before the study was launched, the Ministry carried out several artificial recharge tests in the Hadeth Hasmyieh area by drilling injection holes and injecting water from the river Nahr Beirut. The volumes injected were as follows:

400,000 m^3 in April and May 1969;
1,000,000 m^3 in April 1970;
3,200,000 m^3 from October 1970 to May 1971;
4,500,000 m^3 from October 1971 to May 1972.

The purpose of the present study was to determine what volumes could be injected and recovered under optimum conditions, taking into account:

1. the risk of the ground water flowing away towards the sea or the Beirut river, and
2. the possibility of its becoming mixed with the saltwater which is present in the deep layers, while
3. at the same time ensuring that the ground water would not overflow during injection operations or the saltwater rise towards the surface during pumping.

The study was carried out on a digital ground-water simulation model which made it possible to integrate all the data and to check their consistency. The model was subsequently used to simulate a number of sets of alternative operating conditions so as to be able to select the optimum.

2. BRIEF SURVEY OF THE BASIC DATA

The region covered by the study is shown in Figure 1. It is an area of about one hundred square kilometres, bounded to the north and west by the sea, to the south by an arbitrary line running at right angles to the sea, and to the east by the outcrops of the low-permeability formations which limit the Cenomanian limestone water-bearing strata.

The geological configuration is shown in Figures 1 and 2. The most important water-bearing formation is that represented by the well-defined, often karstified Cenomanian-Turonian limestone which is clearly separated from the underlying Jurassic formations by the Lower Cretaceous. The Quaternary sand formations of the coastal plain are in more or less direct communication with the Cenomanian-Turonian, which also form a water-bearing stratum, but to a lesser extend than the Cenomanian.

The two water-bearing strata, the Cenomanian and the Quaternary, are more than 400 meters thick; they probably become decreasingly pervious with increasing depth. The two strata form a water table aquifer whose deeper layers contain salt water owing to the presence of the sea.

The transmissivities in the Cenomanian are high (2 m^2/s) in the Hadeth Hasmyieh area, where the pumping sites for the Beirut water supply system are situated; they are lower in the limestone areas to the north and south (10^{-2} m^2/s) and relatively low in the Quaternary plain (10^{-2} to 10^{-3} m^2/s).

The storage coefficients range from 10 to 15 percent in the Quaternary and 1 to 3 percent in the Cenomanian. Storage is effected by varying the level of the water table.

Infiltration to the aquifer amounts to some 300 mm a year. On the hill flanks to the east, the ground water receives some recharge from the Albo-Aptian formations. In addition, the ground water is sometimes recharged artificially by drawing off water from the Nahr Beirut River.

The aquifer discharges to the sea, but the main discharge occurs through the large number of wells, which have an outflow ranging between 0.33 and 0.61 m^3/s., depending on the season.

The River Nahr Beirut replenishes the aquifer during the early summer when its flow has not yet fallen to zero.

The ground water has a high salt content at depth; it changes quickly from a salinity of less than 1 gram per litre to 20 grams per litre.

It was assumed in the study that there was an "interface" separating a surface fresh water phase, with a density near to 1, from a deeper salt water phase, with a density of 1.025. Depending on the season, this interface is situated at a depth ranging between 100 and 400 metres in the Hadeth Hasmyieh area; near the coast the interface is located at a depth of only a few metres.

The hydrodynamic pattern in the aquifer is summarized in Figures 3 and 4. The two factors outlined below make this aquifer eminently suitable for artificial replenishment. These are:

1. The presence of the Quaternary, with its low permeability, and, above all, the unconformity between the Cenomanian and Quaternary formations, which ensures that the Cenomanian is isolated from the sea;

2. The presence of salt at depth, which inhibits the flow of the freshwater "bubble" towards the sea, so that freshwater is stored in two ways during the rainy season:
   a. by the rise in the level of the water table; and
   b. by the fall in the interface level (or rather by the decrease in salinity in the deeper layers).

Water storage will be enhanced by the artificial recharging operations carried out in the Hadeth Hasmyieh area. The digital model study has made it possible to determine the optimum conditions for using the Cenomanian water-bearing stratum as a natural reservoir.

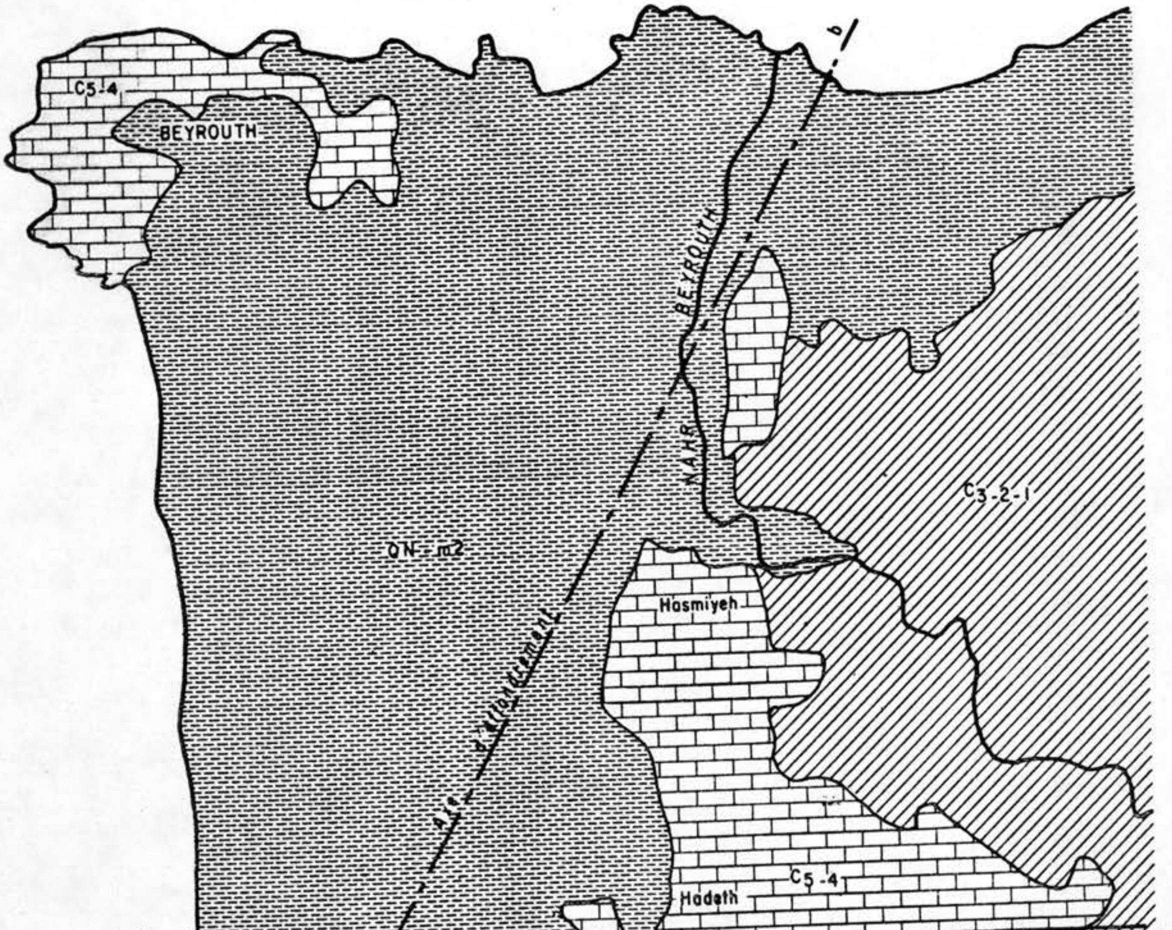

Figure. 1. Geological cross-section of Beirut and surrounding area. (1 km; (see Figure 2 for legend).

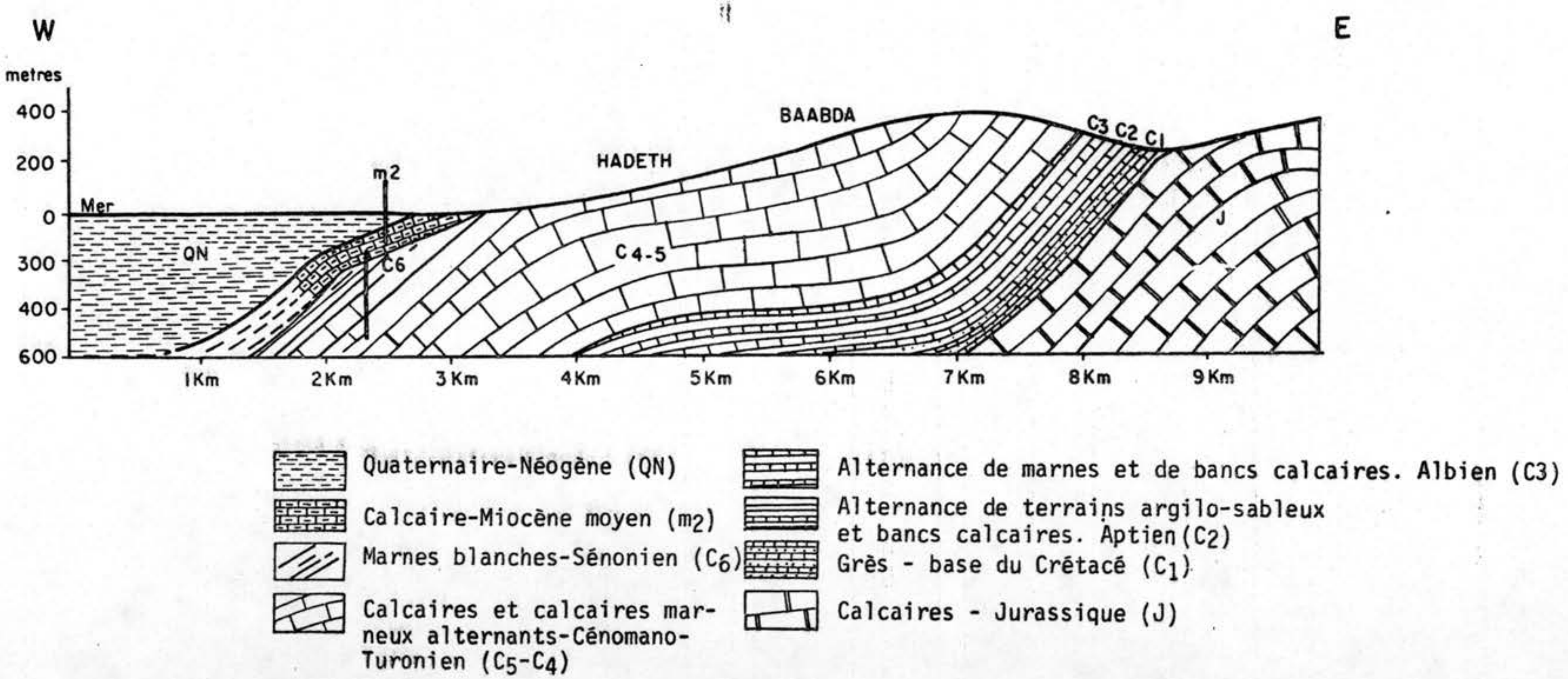

Figure 2. Geological cross-section of the Hadeth area. (Source: Figure No. 29 of report DP/SF/44 Lebanon).

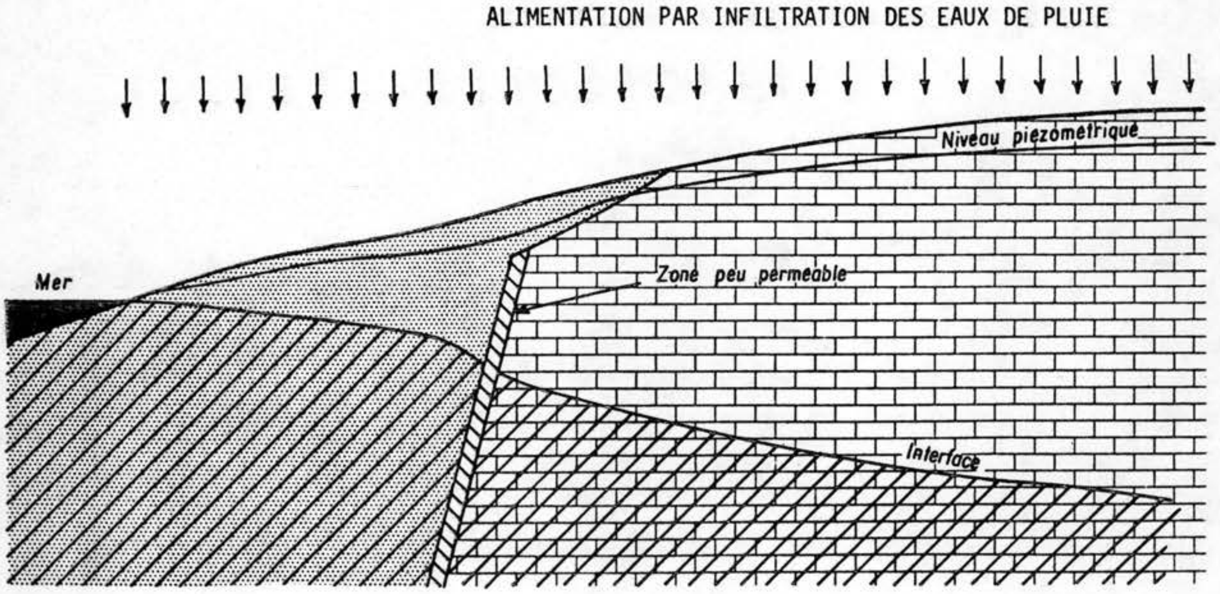

Figure 3. Diagrammatic representation of the ground-water layer at high-water periods.

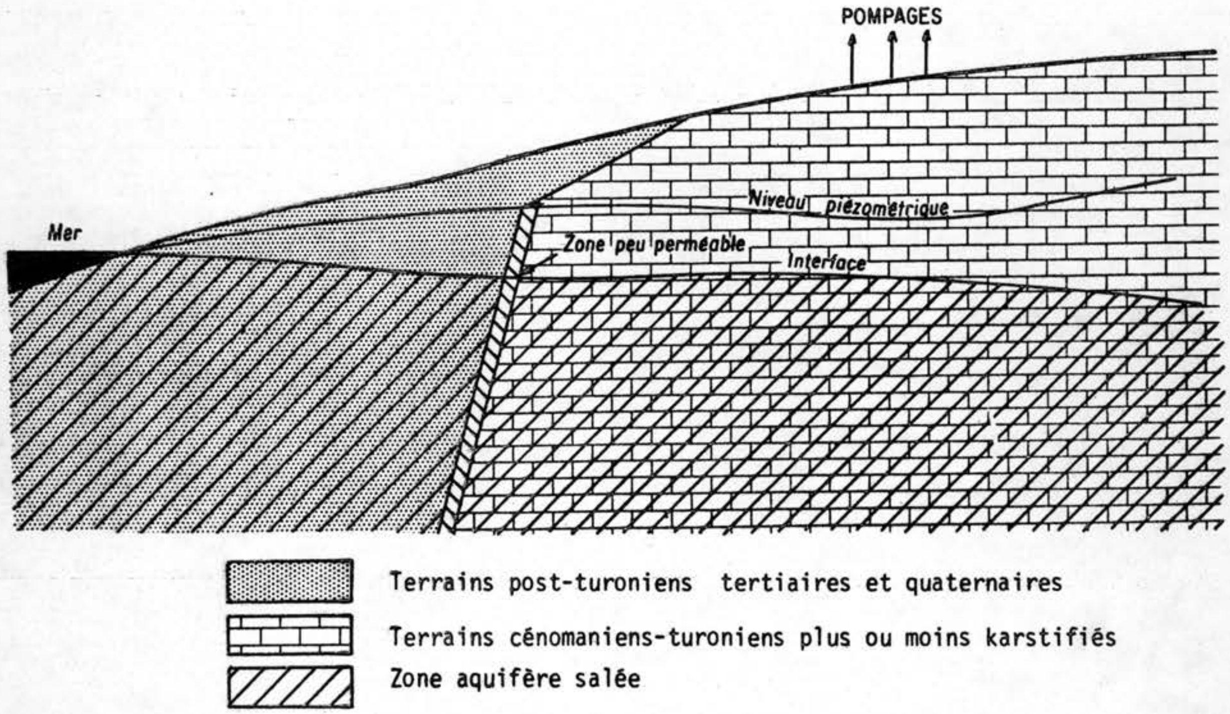

Figure 4 Diagrammatic representation of the ground-water layer at low-water periods.

3. THE MODEL

The digital model used is based on the use of differential equations which express the elementary physical laws governing flow in a permeable medium. The equations used take account of the mass conservation (continuity), Darcy's law and the hypothesis of Dupuit. These equations are as follows:

For the fresh water phase,

$$\frac{\partial}{\partial x}\left[K_d(h+p)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_d(h+p)\frac{\partial h}{\partial y}\right] = S_d\frac{\partial h}{\partial t} + S_s\frac{\partial p}{\partial t} + I$$

For the salt water phase,

$$\frac{\partial}{\partial x}\left[K_s(D-p)\frac{\partial}{\partial x}\left(\frac{\gamma d}{\gamma s}h - \frac{\gamma s - \gamma d}{\gamma s}p\right)\right] + \frac{\partial}{\partial y}\left[K_s(D-p)\frac{\partial}{\partial y}\left(\frac{\gamma d}{\gamma s}h - \frac{\gamma s - \gamma d}{\gamma s}p\right)\right] = -S_s\frac{\partial p}{\partial t}$$

where:

K_d, K_s = permeability coefficients of the fresh water (d) and salt water (s) phases

S_d, S_s = storage co-efficients of the fresh water and salt water phases

γ_d, γ_s = the fresh water and salt water densities

h = the height of the water table in relation to sea-level

p = the depth of the interface in relation to sea-level

D = the depth of the impermeable substratum in relation to sea-level

I = recharge (discharge) for the region as a whole, per unit of surface area

These equations are discretized according to the method of finite differences. It should be noted that the equations are not linear but are linearized at each time step by taking for h and p the values calculated at the previous time step. These discrete-representation methods have now become common practice, and we shall not go into the formulation of the discrete equations. After the space to be represented has been discretized into a number of cells, we obtain a system of linear equations consisting of two equations per cell. This system is solved implicitly at each time step.

The model used consisted of 97 square (two-dimensional) cells with 1-km sides. The number of cells had to be severely limited so as to enable the model to be run on a very small computer (an IBM 1130, with a 16 K core memory).

After the model had been designed and constructed, it had to be calibrated, i.e. the parameters introduced had to be adjusted so as to reproduce the piezometric trends observed over the previous four years. Calibration proved to be a long and difficult exercise because of the rather approximate nature of the data.

4. RESULTS AND CONCLUSIONS

The model was then used for a number of sets of alternative recharge and operating conditions, taking into account the discharge available in the Nahr Beirut for injection purposes and the amounts of water needed to supply Beirut during the dry season. Operating case N° 1 is shown in Figures 5 through 9.

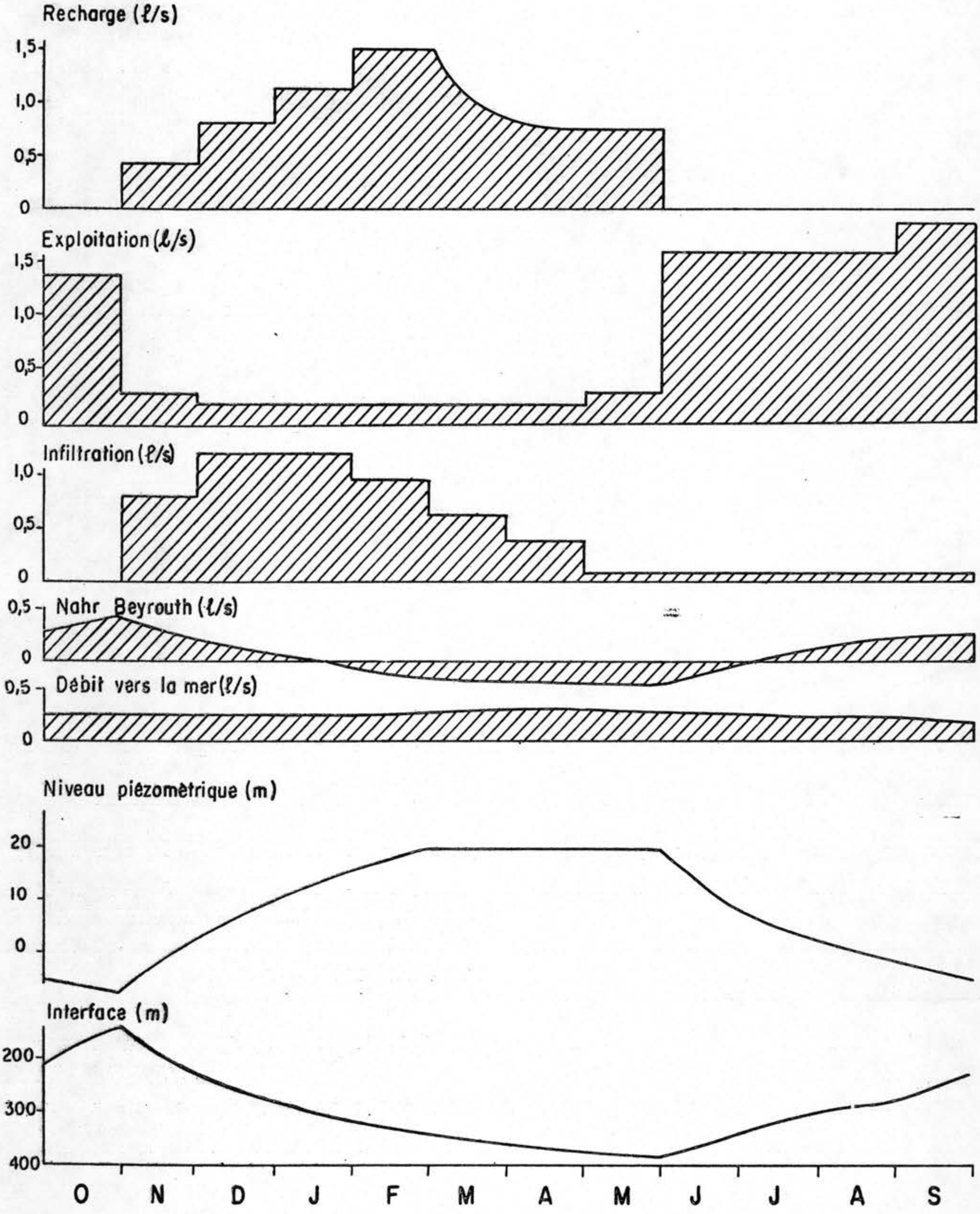

Figure 5. Case No. 1, average year: recharge 16.5 million cubic meters; operation 24 million cubic meters.

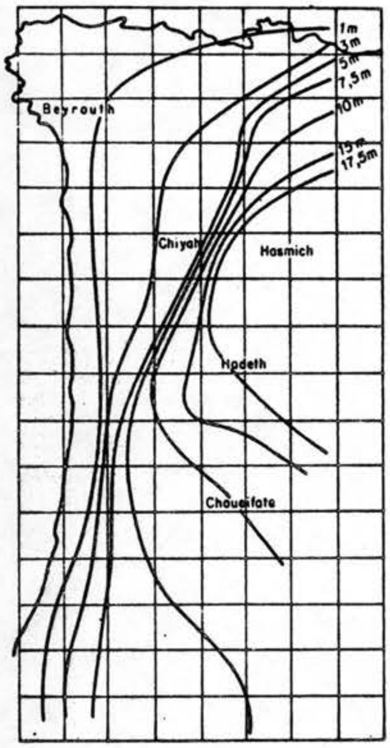

Figure 6. Case No. 1, Potentiometric Map for an Average Year (May).

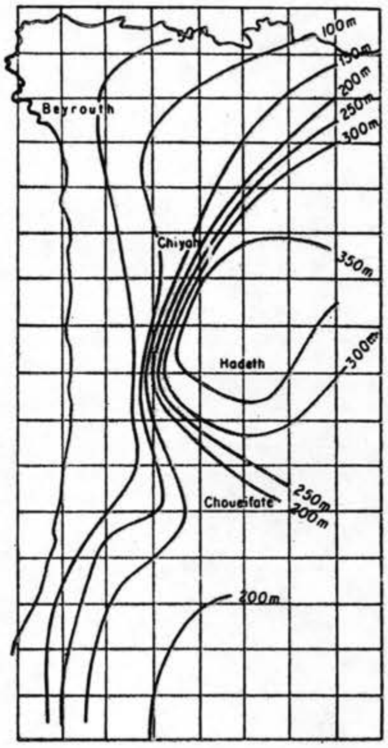

Figure 7. Case No. 1, Map of Interface Depth for an Average Year (May).

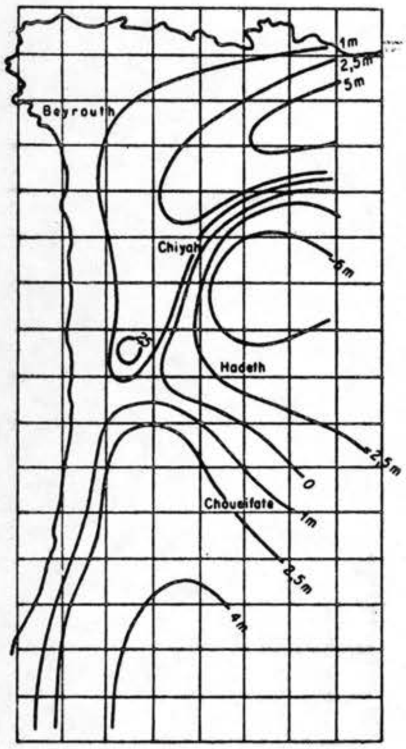

Figure 8. Case No. 1, Potentiometric map for an average year (October).

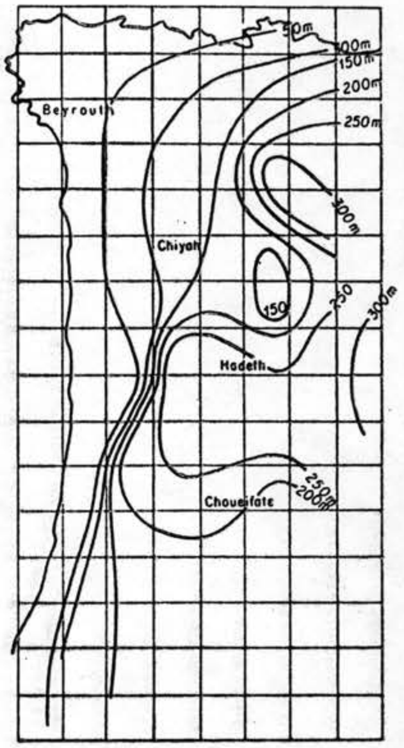

Figure 9. Case No. 1, Map of interface depth for an average year (October).

The conclusion reached in the study was that it was possible to inject the following quantities of water in the Hadeth area:

November: $0.38\ m^3/s$.
December: $0.50\ m^3/s$.
January to May: $0.77\ m^3/s$.

making a total of some 12 million cubic metres a year spread over seven months.

It would be possible in the same area, to extract the following amounts of water from the aquifer:

June to August: $1.16\ m^3/s$.
September: $1.38\ m^3/s$.
October: $1.23\ m^3/s$.

or a total of some 15.8 million cubic metres a year spread over five months.

Ground-water models

Volume I. Concepts, problems, and methods of analysis with examples of their application

Prepared for the International Hydrological Programme, Working Group 8.1

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