HYDROGEOLOGY AND EVALUATION OF BOUTELDJA DUNELIKE AQUIFER (NE ALGERIA) USING A MATHEMATICAL MODEL.

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ABSTRACT:

The Bouteldja dunelike aquifer, covering a surface of about 160 km^2, is supplied by precipitation and the relief bordering the massif at the East. The aquifer outlets consists of the Mediterranean sea to the North, the alluvial aquifer of Oued El-Kebir to the South and domestic water drawn off to supply the towns of Annaba and El-Tarf.

The activities carried out since the end-seventies have shown very interesting hydraulic characteristics, which has been expressed by a great solicitations of this aquifer. This, has produced a fall of the piezometric level which affected natural springs and influenced negatively the hydraulic equilibrium.

The use of a mathematical model based on the method of finite differences will justify the work hypotheses by improving the knowledge of the aquifer hydraulic characteristics, the evaluation of a complete hydrological balance, and the determination of the effect of flow drawn off by the FWS on the aquifer piezometric evolution. An increase of flow, drawn off from drillings, of 10% per year over a 10 year period (from 1994 to 2004) has been simulated. This hypothesis demonstrate the equilibrium weakness of hydrological balance obtained in 1994 and show up important changes of piezometric surface along with a decrease of diffuse emergence and the appearance of many depressions.

I- INTRODUCTION

The first hydrogeological features of the region have been outlined, in consequence of a project dealing with the realisation of a pulp factory in 1968, on the light of many studies carried out on the whole dunelike massif. Seven boreholes called sonic have been operated at first.

The studies have been taken over by the A.N.R.H with the set of new boreholes and piezometers to identify and evaluate the resources of the whole aquifer system which has revealed its hydraulic possibilities.

The system, considered to be the principal aquifer of the region, has paid the particular attention of public powers by virtue of the interest which have regarding water resources for continuous increasing needs in the absence of surface water supply in the region.

Therefore, under the economicconstraint, the appeal to borehole sets in the dunelike massif and in the alluvial aquifer of Kebir Est has been the only palliative to meet the needs especially those of fresh water supply (FWS), where the dunelike aquifer, with excellent chemical quality, made it particularly well suited for the FWS of the wilayas of Annaba and El-Tarf.

As a matter of fact, a number of boreholes has been realised. A total of thirty boreholes for FWS are working steadily 24 hours a day totalling a flow of more than 500 l/s.

The mismanagement led to the exploitation of the aquifer which become more and more intensive, and this could lead to the quality degradation by a flow coming up from the sea North of the aquifer border, by the salted swamps of Mekrada in the Southern part, and by the Western part (Mafragh border) as a result of excessive pumping.

The aquifer system of Bouteldja, potentially rich in water, is miss-managed.

In order to establish an effective solution, our work will be focused, using an up-to-datesynthesis on the assessment of its potentialities, to bring out, on one hand, the geological, hydroclimatological and hydrodynamic parameters, and on the other hand, to undertake a provisional model aimed to calculate and anticipate the use of this resource.

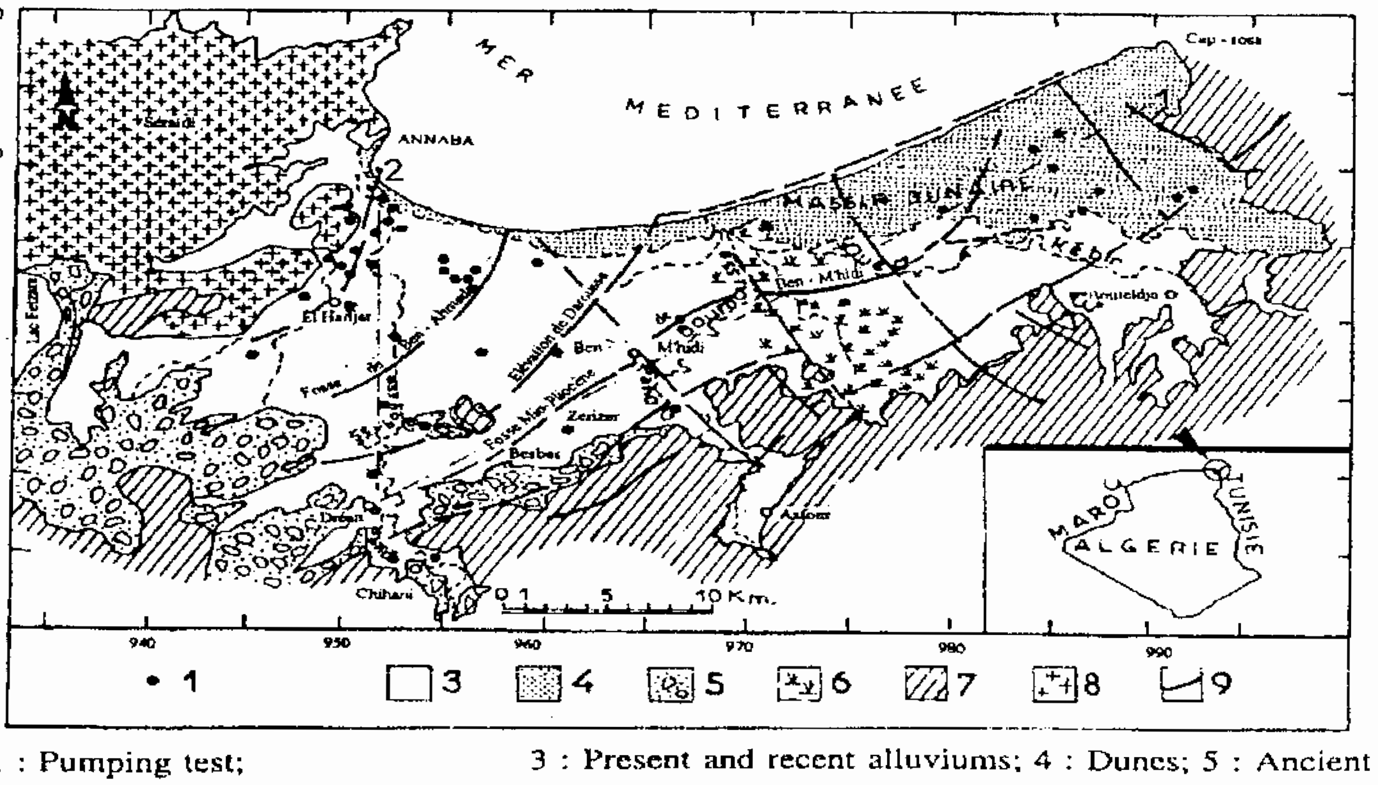
II- GEOGRAPHICAL, GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

The studied area is situated in the easternmost part of the alluvial great plain of Annaba (fig.1), which is located in the North-East of Algeria. It is a part of the Mafragh basin slope which includes the whole Northern slope of the Medjerda over a surface of 2660 km^2. Thereby, it is surrounded to the South and East by a mountainous zone typical of the Algerian Tell.

The aquifer system is composed mainly by a dunary massif over a surface of about 160 km^2 and an alluvial plain resulting from the deposits of Oued Kebir-East and its tributaries over a surface of about 40 km^2.

The system having as a whole a triangular shape is limited to the North by the Mediterranean sea, to the South by the Eastern extension of the Numidian sandy-clay range (Cheffia and El-Kala Mounts) striking WSW-ENE, to the West by the Mafragh, and by the Cap Rosa to the East.

The different studies carried out in this region have shown the existence of an important aquifer in the aeolian sands, 20 m thick in the East to 120 m thick in the West. Lenses of clays corresponding to ancient swamp contents are interlayered in this sandy formation. This latter is lying on a Numidian substratum to the East of Bougles and the Mio-Pliocene filling of Ben M'hidi trench to the West. To the South, the sand pass laterally to the gravels of the "deep" aquifer.



1 : Pumping test; 3 : Present and recent alluviums; 4 : Dunes; 5 : Ancient alluviums; 6 : Lake or swamp; 7 : Sandstone or numidian clay; 8 : Metamorphic formations; 9 : Fault.

Fig. 1 Geographical and géological setting of the Bouteldja dunary massif.

III-GROUNDWATER FLOW MODELLING

1- Presentation and characterisation of the model

The ASM program (W. Kinzelbach and R. Raush, 1990) used is a bidimensional model with finite differences. The extension of the aquifer medium has been defined in 27/14 square grid of 1000 m long. The model is therefore, composed of 159 active grid, that is a studied surface of 159 km^2 (fig. 2).

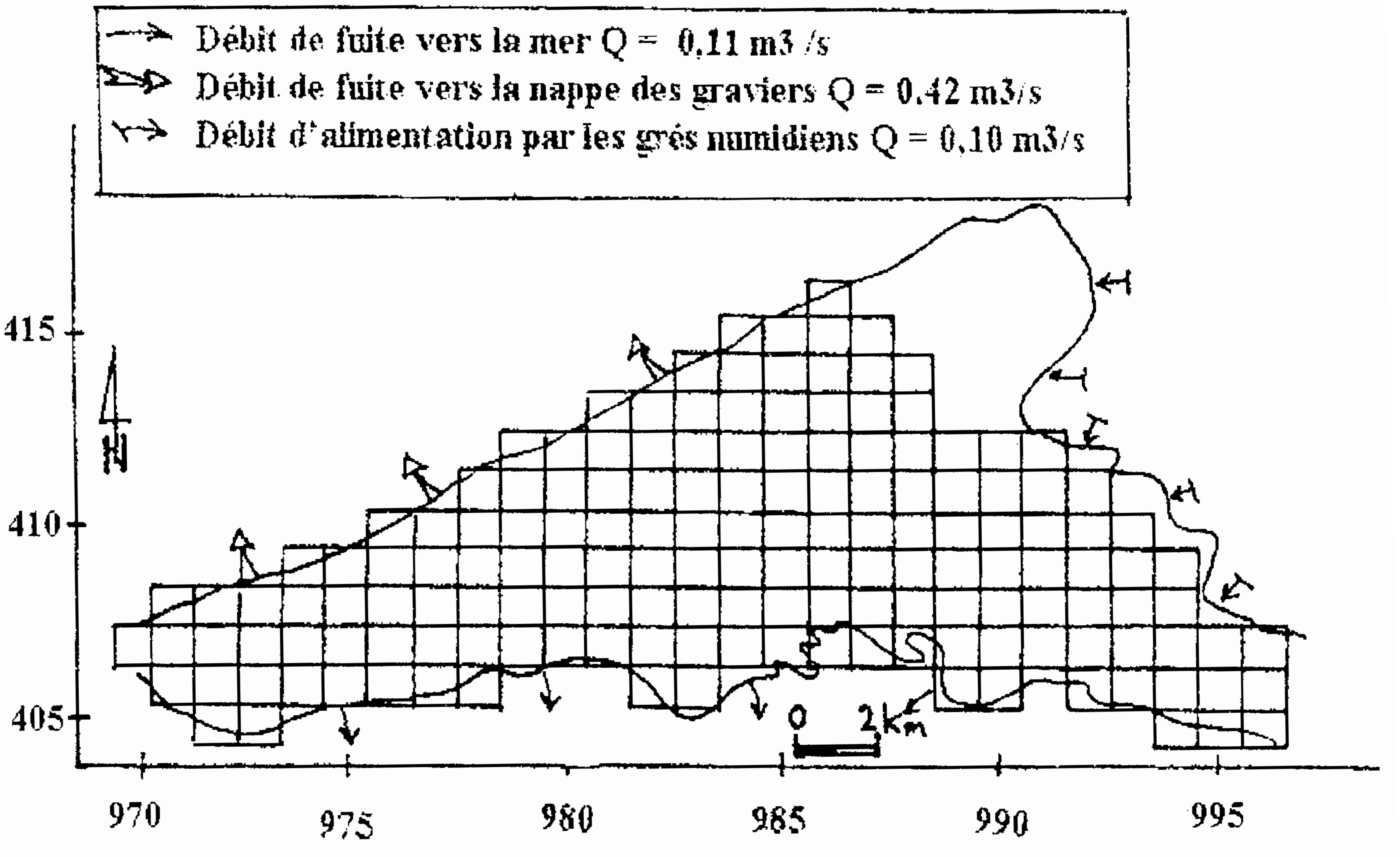


Fig. 2. Grid and conditions at boundaries.

2. Conditions at boundaries

The communication zones of the aquifer have been fixed based on the geological and piezometric data which could identify the incoming and outgoing flows from the aquifer (fig. 62).

The calculated outgoing flow to the sea over a front of 20 km is about 0.11 m^3/s. In the South, the terrace of Kebir-East in contact with the dunes of Oum El-Agreb to the Mafragh over a distance of 25 km receive an evaluated flow of 0.42 m^3/s. In the East, the supply to the aquifer by the sandstone has been estimated at 3.4 $hm^3/yr.$, that is 0.10 m^3/s.

3. Characterisation of the model

It corresponds to a synthetic presentation of hydrogeological data among which are shown those of interest to be modelled. These data are mainly geological, hydrodynamic (pumping test results and piezometric data) and thermopluviometric (precipitation and temperatures).

- The permeabilities have been deduced from calculated transmissivities based on pumping tests distributed through 43 boreholes in the studied area. The permeabilities increase from west to east and range between 10^{-4} and 10^{-6} m/s.

- Precipitation measurements have been taken at Bouteldja station from 1968 to 1993. The annual mean is 685.7 mm. Temperatures measured during the same period have been taken at Ben M'hidi station, 30 km away from Bouteldja. The annual mean over a period of 36 years is 17.2°C.
Effective infiltration has been evaluated, year by year from 1968 to 1993, according to the method of Thornthwaite.

- The extracted flow is considered to be of no value in 1978, period in which the aquifer was inexploited.

- The selected piezometry is that of October 1978 (fig. 3), which seems better convenient for the reproduction of a stable state for the following reasons:
* 24 wells distributed water points in the area have been measured giving a good piezometric representativity.
* The month of October 1978 represent a moderate hydroclimatologic state in the pluviometric column.
* This is the year where the aquifer exploitation did not practically begin. Thus, there will be less fluctuations of the piezometric level.

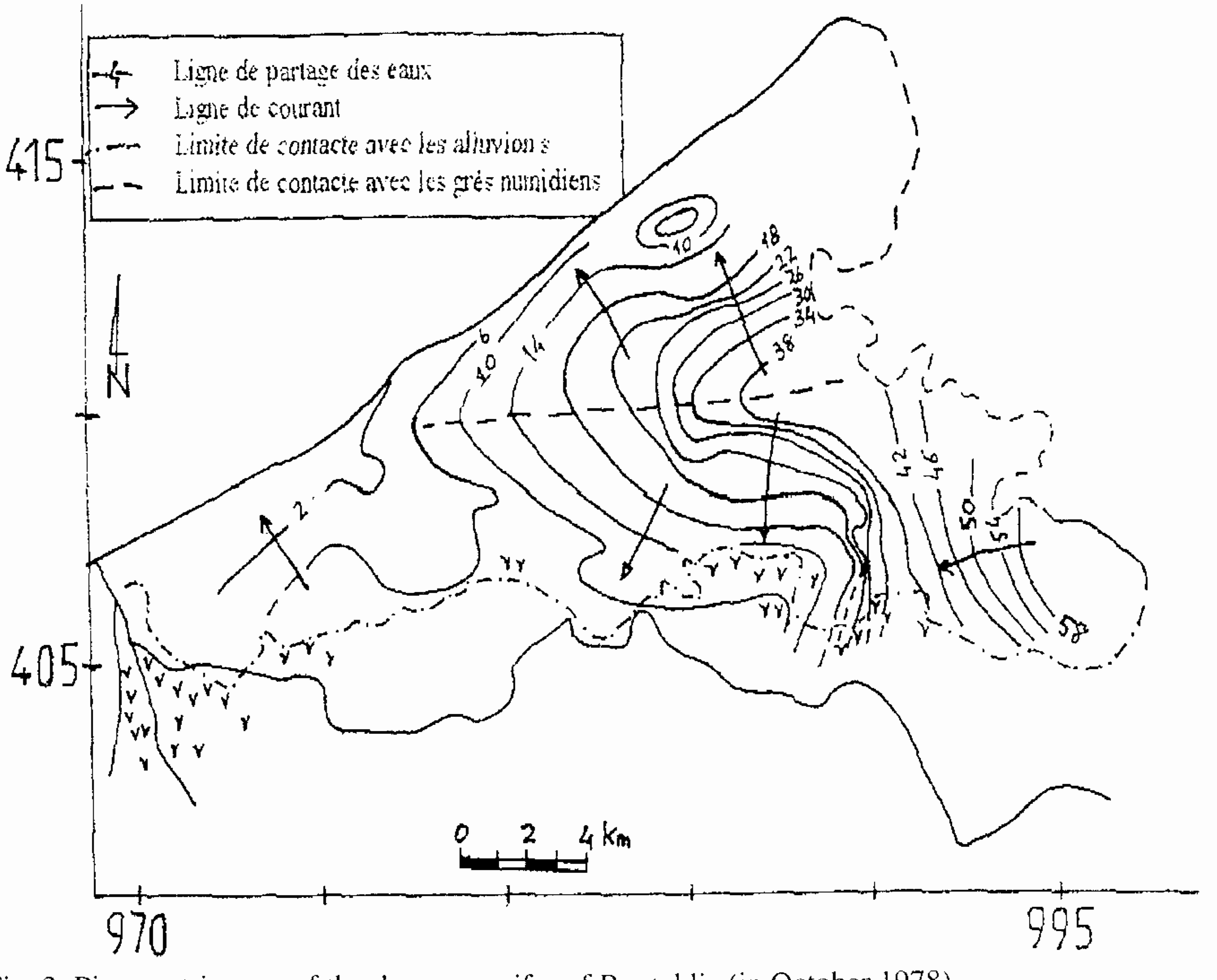


Fig. 3: Piezometric map of the dunary aquifer of Bouteldja (in October 1978).

IV- MODEL CALIBRATION

1- Results of permanent simulation

1.1 Piezometric reconstitution

The figure 4 illustrate the calculated piezometry during the final stage of setting versus the measured piezometry. A perfect similarity is shown between the real curves and those calculated using the model.

The spacing between the curves are not important. They have a mean of 1.5 m calculated in all the grids and in the lower majority to ±1 m. These express perfectly this similarity in the curves 18, 26, 30, 34 and 50 which are characterised mostly by no-spacing.
However a spacing of about 3 m shown by curves 22 and 38 results from the measurements of water points located around the swampy zone. Important spacing in some grids needed the lowering of permeabilities at a factor of 10, particularly in the swampy zone.

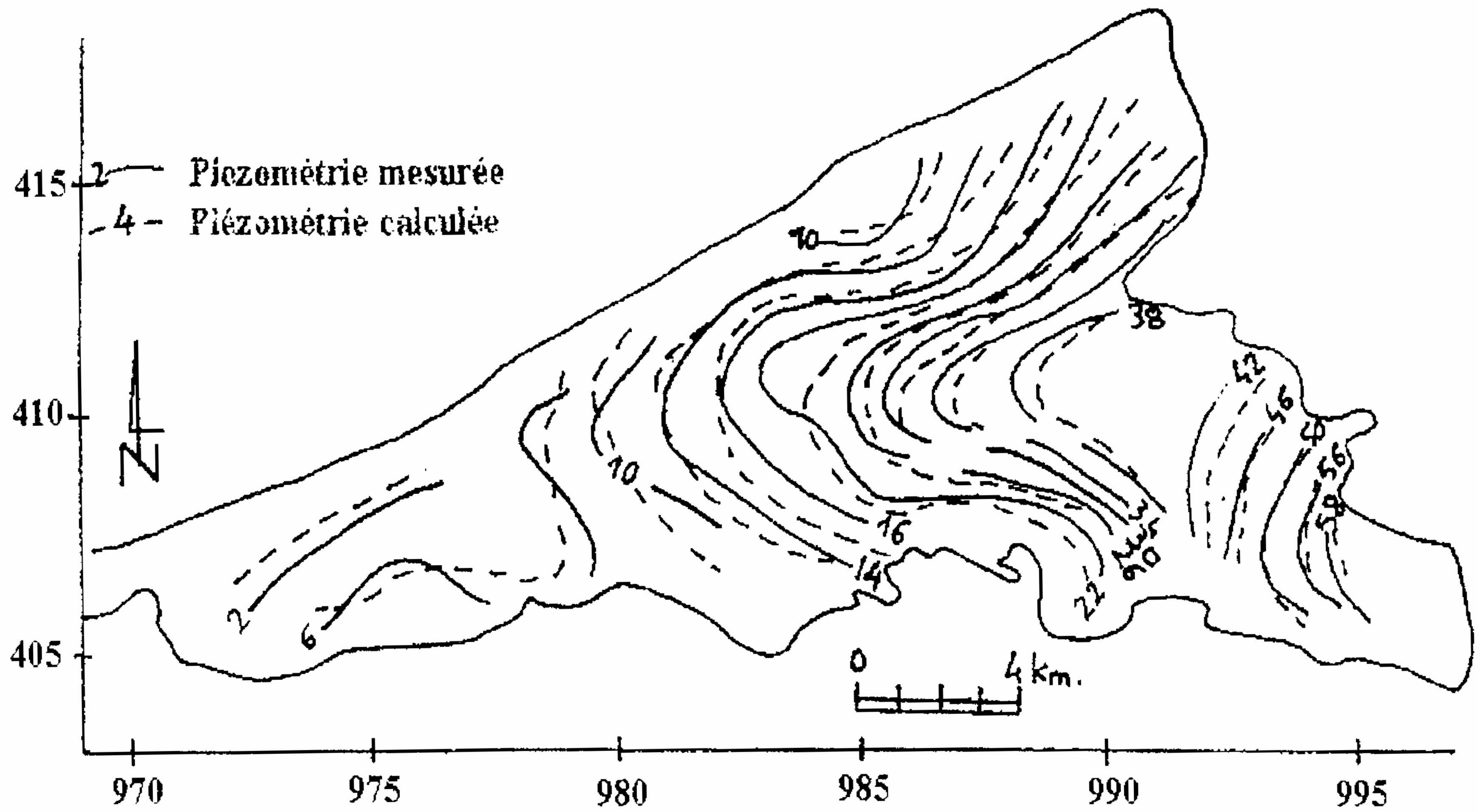


Fig. 4: Comparison of measured and calculated piezometric maps after calibration in permanent regime.

1.2 Permeability distribution

In general, the distribution of permeability coming out from the calibration shown in fig. 5 is practically the same as that obtained from punctual tests in boreholes. However, some details could be noted :
A slight modification of calculated permeabilities which become practically improving to the east, and range between 10^{-4} and 10^{-3} m/s. In this area the permeabilities are in harmony with the physical features of the reservoir of good transmissivity. This modification is also expressed by a decrease in permeabilities in the west and in the south-east to 10^{-7} m/s. On the whole, we note the same distribution of permeabilities which increase from west to east. The values range from 1 to 9.10^{-6} m/s in the west, whereas those of the centre vary from 1 to 10.10^{-5} m/s.

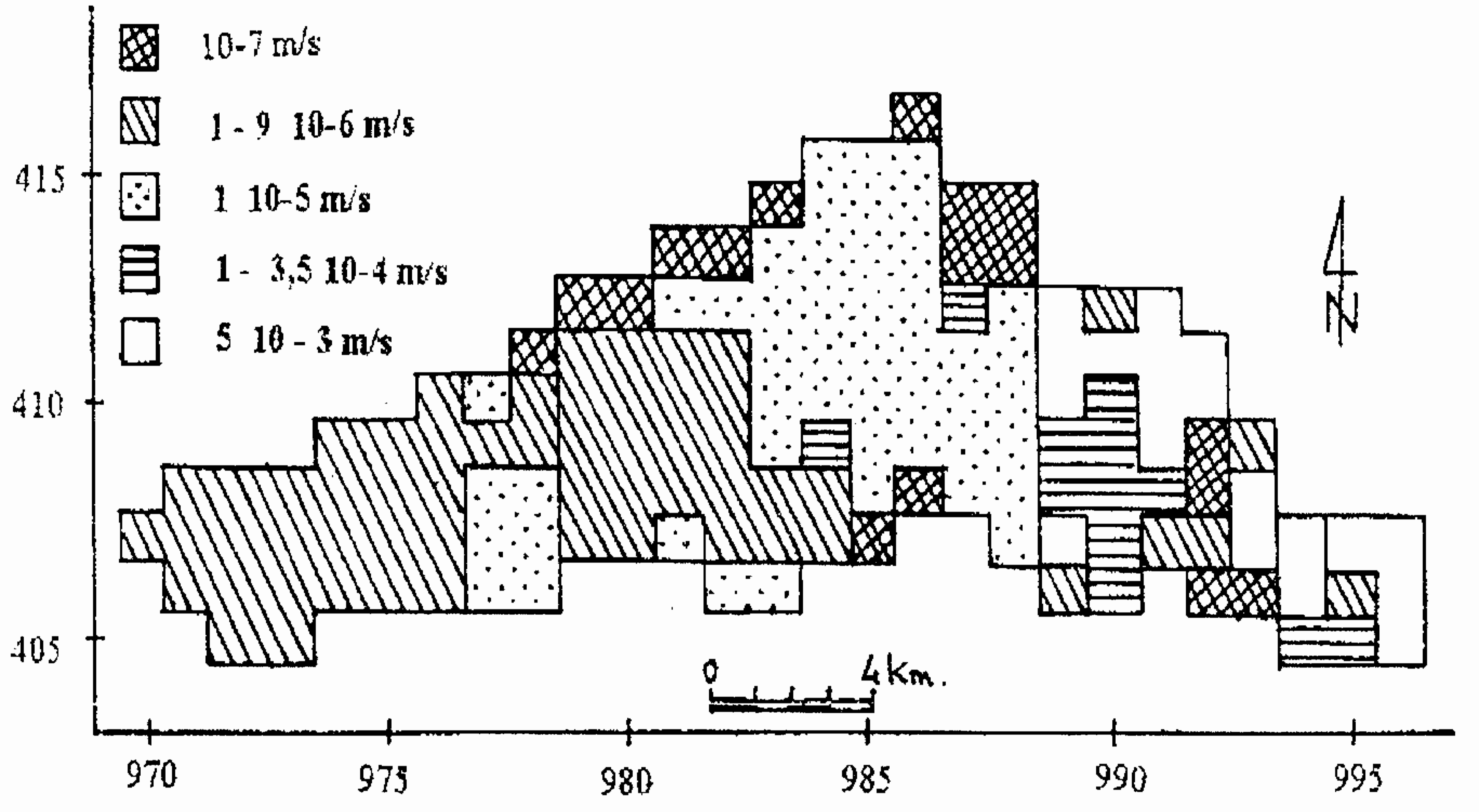


Fig. 5: Geographical distribution of permeabilities after calibration in a permanent regime.

1.3 Hydraulic balance derived from the calibration

The calibration phase in permanent regime allowed the establishment of the following balance :

- flow leakage to the sea: 0.102 m^3/s; that is, 102 l/s,
- flow draining by the gravels aquifer and springs: 0.834 m^3/s; that is, 834 l/s
- a supply by numidian sandstone: 0.105 m^3/s; that is, 105 l/s.

The estimated results, especially the exits to the sea and the supplies by the numidian sandstone, go together with those calculated by the model. Regarding the hydraulic balances achieved by the B.R.G.M., the draining of the free aquifer towards the gravels aquifer calculated by the model led to similar results. The draining and the exits by springs evaluated by the B.R.G.M. are 480 l/s and 360 l/s respectively. However, the leakage flow to the sea calculated by the B.R.G.M. is 305 l/s instead of 102 l/s.

2- Simulation of piezometric fluctuations in non-steady flow

2.1 Introduction

The obtained results at the end of the final calibration are in harmony with the initial piezometry. The superposition of simulated piezometry to that of measured piezometry (fig. 6) is correct, with average spacing from 1 to 1.5 m. The spacing between simulated and measured piezometric columns could be probably related to the fact that the location of boreholes do not concur in the middle of a grid when using the model. The same observation could be made for a pumping situated near a measurement point. These affects the calibration precision and hence, do not give a perfect similarity between the simulated and the observed piezometries.

The calibration of the model in transitory regime of the Bouteldja aquifer has been carried out by interpreting the response of the model to the charge, supplies and sampling changes during the period 1978-1994.

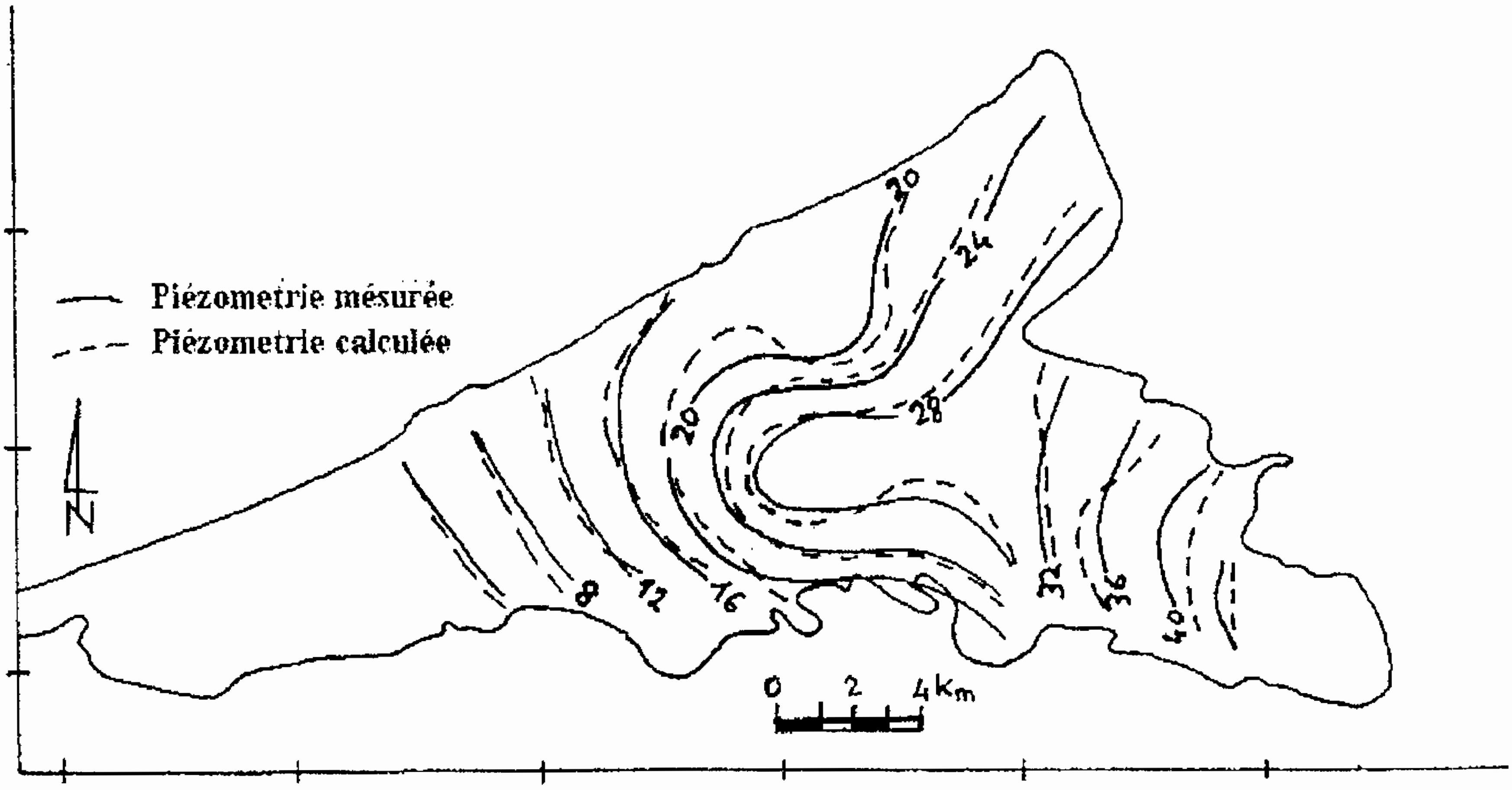


Fig. 6: Comparison of measured and calculated piezometric maps after calibration in non-steady flow.

2.2 Calibration in non-steady flow

The aim of the calibration is to simulate the measured piezometry in 1994, period for which a map has been established. The piezometric state of October 1978 constitute the starting point for a simulation in an annual-time step until October 1994.

2.3 Calibration over sixteen years

Interannual calibration of 16 years (1978/79 to 1993/94) has been taken in order to reconstitute the observed potentials during the year 1994. The principal variables introduced for each year are mainly the outgoing flows which vary with efficacious rainfalls and boreholes of exploitation.

A big shifting has been noted between calculated and measured piezometries during an exploitation with constant flow at 0.500 m^3/s imposed over 29 knots of the model grid. This has led us to introduce slight modifications regarding the permeability values as well as those of the storage coefficient.

2.4 Distribution of the storage coefficient values

The adjustment of the storage coefficient values by the calibration of the model (fig. 7) gives:

- values ranging between 4 and 9% in the north-western sector,
- high values (10 to 20%) particularly in the north and the south-east of the studied area.

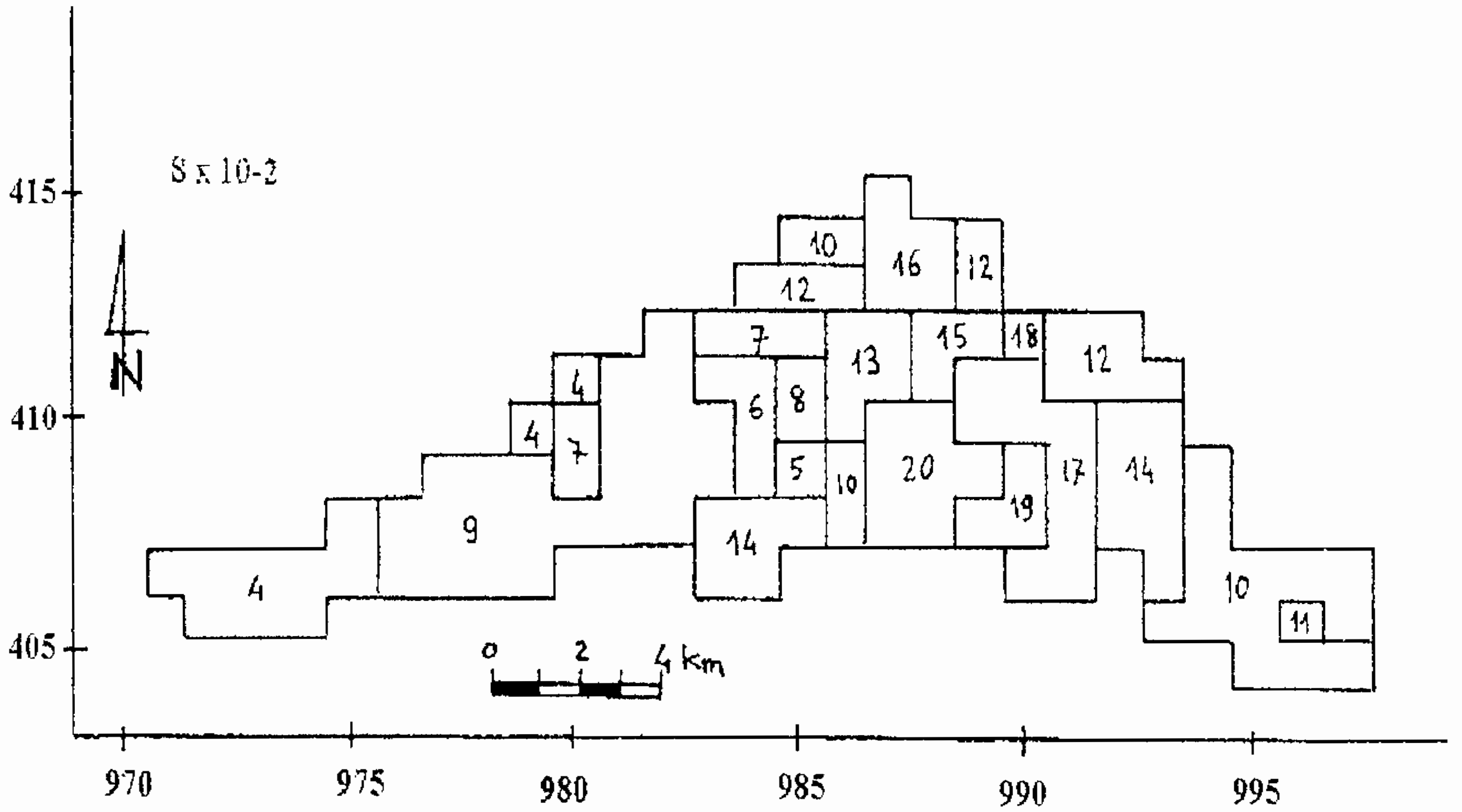


Fig. 7: Distribution of storage coefficients after calibration in non-steady flow.

2.5 Evolution of simulated piezometry

The simulated piezometric maps allowed us to give back the evolution history of the aquifer level in an annual-time step from two piezometers (B19 and 6909). The B19 piezometer was observed from 1982 et 1989, and the 6909 from 1978 to 1994. The piezometric evolution has been compared to that measured in the field during the same period (fig. 8).The spacings have been evaluated between 0.5 and 2.81m (table 1) for a total piezometric variation of 5 m at the 6909 situated near the field of exploitation. From the B19 and 6909 piezometers, situated at 0.75 km and 6 km away from the sea respectively, several observations could be made:

- an aquifer beat of 0.80 m with a rise from 1982 to 1983,
- a rise in 1986 and 1990 (fig. 8) due to abundant precipitation (686.6 mm and 1019.0 mm, respectively),
- a decline since 1987/88 cycle which concurs with the operation of twelve boreholes.

2.6 Balance evolution derived from calibration

During each time-step, the model restitute a hydraulic balance and evaluate the different flowing components, namely:

- the net recharge, pumping, storage or de-storage of the aquifer, flows and lateral supplies.

The total balance establishment of the aquifer system is to control the incoming and outgoing water which allow to evaluate the storage variation by the following expression:

$Q_r + ESE - (Q_p+Q_{es}) = W_r$ where all parameters are expressed in m^3/s.

With: Q_r + ESE = recharge + incoming surface flow (lateral supplies)

Q_p = extracted flows from the aquifer

Q_{es} = outgoing flow

W_r = storage variation between the incomings and outgoings and the total balance.

W_r is positive in the case of additional water to the aquifer, and negative in the case of de-storage.

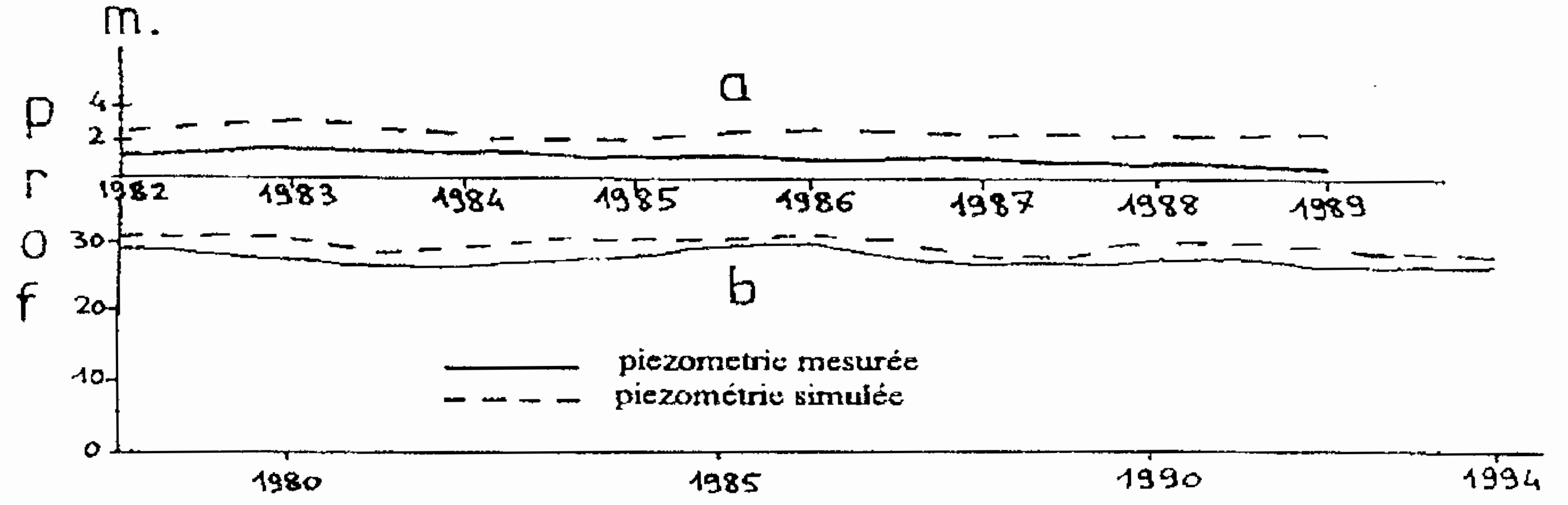


Fig. 8: Evolution of measured and simulated piezometry of: a) piezometer B19; and b) piezometer 6909.

Table 1: Measured and simulated piezometries by model on observation wells 6909 and B19 from 1978 to 1994.

Year	Water level of piezo 6909		Spacing	Water level of piezo B19		Spacing
	Measured	Simulated	(m)	Measured	Simulated	(m)
1978	30.8	29.3	1.5			
1979	28	3.8	2.8			
1980	30.8	28	2.8			
1981	28.4	26.7	1.7			
1982	29.4	26.6	2.8	1.26	1.26	1.54
1983	30.19	26.5	2.69	1.52	3.10	1.58
1984	30.5	27.8	2.7	1.30	2.20	0.90
1985	30.8	29.7	1.5	1.25	2.20	0.95
1986	30.8	30.3	0.5	1.15	2.70	1.55
1987	30	27.6	2.4	1.10	2.50	1.40
1988	28.2	27.3	0.9	0.70	2.50	1.80
1989	27.8	26.9	0.9	0.56	2.60	2.04
1990	30.8	28.4	2.4			
1991	30.8	28.1	2.7			
1992	29.35	27.1	2.25			
1993	28.8	26.9	1.9			
1994	29	26.7	2.3			

From table2, a very low storage (0.016 m^3/s; that is 0.50 hm^3) of the aquifer is observed. This leads to an equilibrated balance between the hydraulic supplies and the outgoing flows. If new pumpings are to be operated, considering the increasing demand of the region particularly the wilaya of El-Tarf et Annaba, it is possible to foresee the aquifer fluctuations.

Table 2: Summary of the balance of the dunary aquifer restituted by the model after setting over a period of 16 years (1978/79 to 1993/94).

Units m^3/s	Recharge (+)	Lateral supply (numidian sandstone) (+)	Pumping (-)	Outlet to the sea (-)	Leakage to the gravels aquifer	Storage variation storage (+) de-storage (-)
78-79	0.433	0.034	0.151	0.170	0.480	-0.334
79-80	0.866	0.062	0.151	0.215	0.517	+0.045
80-81	0.615	0.083	0.151	0.195	0.421	-0.069
81-82	0.363	0.100	0.151	0.160	0.260	-0.108
82-83	0.435	0.108	0.151	0.157	0.327	-0.092
83-84	0.506	0.115	0.151	0.230	0.318	-0.078
84-85	0.735	0.116	0.151	0.222	0.399	+0.079
85-86	0.964	0.117	0.151	0.341	0.470	+0.119
86-87	1.115	0.117	0.289	0.341	0.441	+0.161
87-88	1.267	0.117	0.289	0.350	0.497	+0.248
88-89	1.116	0.122	0.289	0.407	0.368	+0.174
89-90	1.062	0.126	0.492	0.331	0.296	+0.069
90-91	0.931	0.131	0.492	0.271	0.244	+0.055
91-92	0.801	0.136	0.492	0.300	0.191	-0.046
92-93	0.931	0.134	0.492	0.305	0.237	+0.031
93-94	1.062	0.136	0.492	0.428	0.276	+0.002
Total	13.202	1.754	4.535	4.423	5.742	+0.256
Annual mean	0.825	0.109	0.283	0.276	0.358	0.016
%	100	13.2	34.3	33.4	43.3	1.9

The extracted flows represent 34.3% of the infiltration with a value of 8.92 hm^3. We note that, over an annual mean, the recharge is relatively important. It totalizes a volume of 26 hm^3 where 33.4% are discharged in the sea. The draining towards the gravels aquifer corresponds to 43.4%; that is, a volume of 11.3 hm^3. From a graphical illustration (fig. 9), characterising the balance evolution at annual time-step, the following points are noted:

- the dunary aquifer is marked, in the whole simulated period, by important recharges,
- the lowest observed from 1978, then from 1980 to 1994 are originated from the decrease of the reserves. A more important exploitation of the aquifer since 1987 has also involved a decrease of the reserves. Otherwise, the draining flow to the gravels aquifer in the south decreases due to the excessive pumping of 1987. However, in the north, the leakage flow to the sea increases progressively. This could be due to the fact that the boreholes with high flow are located in the southern sector of the watershed.

Fig. 9 also illustrate the evolution of the different components of the balance where the lateral supply flows (supply through numidian sandstone) do not vary grately. The annual mean flow of supply is about 0.109 m^3/s. However, the drained flows towards the aquifer outlets are mostly related to the variation of the recharge and the extracted flows.

3- Exploitation of the model

The main advantage of modelling is to come to the previsional phase showing up the future state of the aquifer for a rational exploitation. Based on final calibration of the piezometry, only one variable is taken into account; this is to find out the reaction of the aquifer, being on sea border, with respect to extensive exploitation.

The aim is, then, to simulate additional sampling and to observe the system reactions. The main purpose of an exploitation is to optimise the sample so that they do not entail any harm to the aquifer whose principal constraints are mainly not to exceed the lowerings so as to preserve the aquifer protection against marine invasion and to maintain the springs flows

We have tried to simulate a scenario of exploitation by a steady increase of sampling of 10% per year over 6 years with a very low supply. An additional flow of 300 l/s has been distributed over

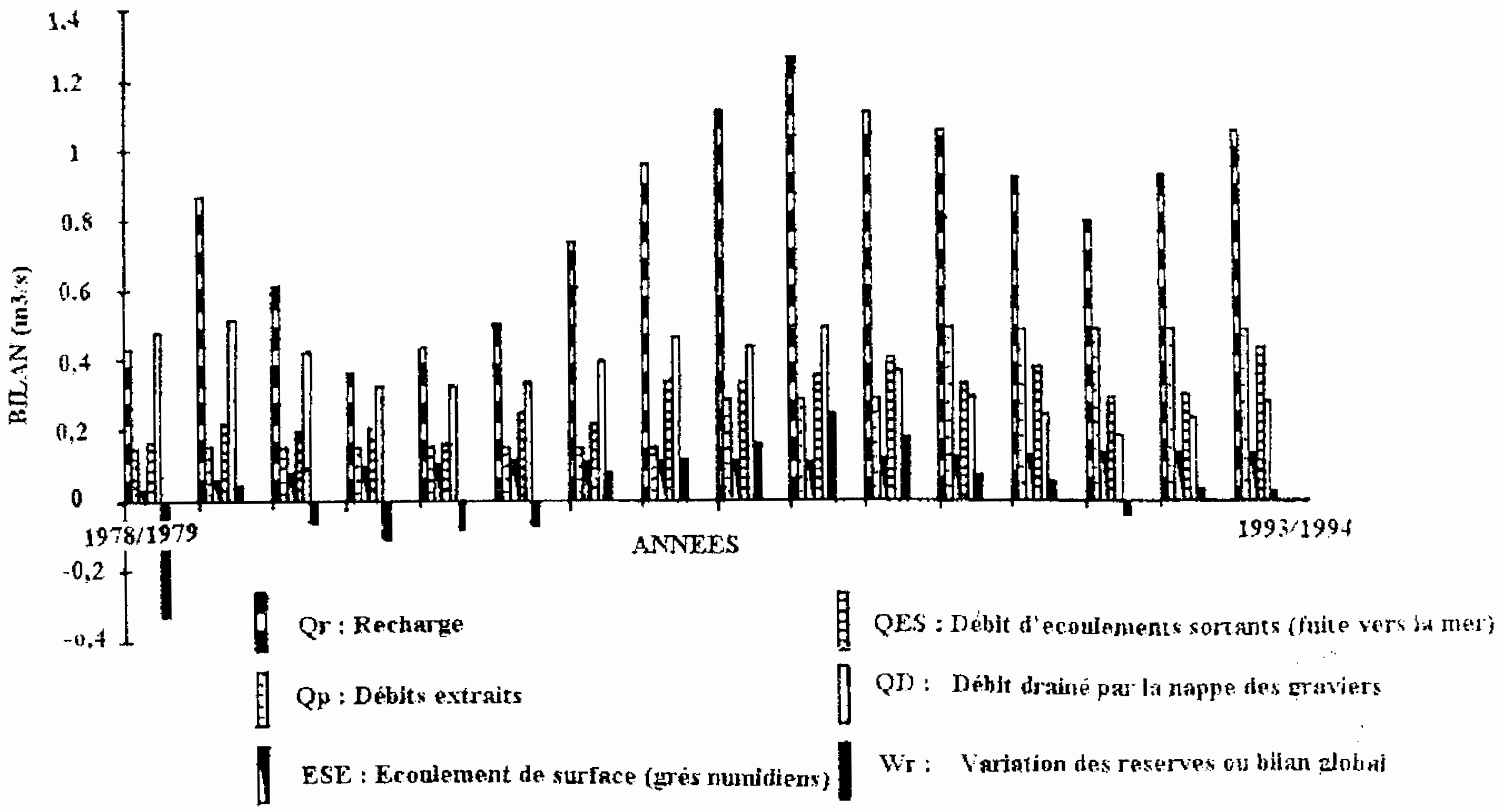


Fig. 9: The total balance of the dunary aquifer after calibration, over a period of 16 years (1978-94).

10 grids located in the area of good permeability. During this period, the obtained total balance (table 3) reveals that, for a very low recharge, if the samplings are risen, the outgoing flows to the aquifer outlets (sea and gravels aquifer) will be reduced respectively from 35 to 50% of the initial value at the expense of the variation which passes to -0.899 m^3/s in the year 2000.

Fig. 3 shows the stock variation which decreases in parallel to an increase of the extracted flows.

Pumping intensification allied to a low charge leads, in the south-eastern sector, to an average lowering of 6 m (fig. 10). Imposed additional flows cause decrease of lowering of 10 to 15 m in the grids X17/Y10. On the aquifer borders the lowering do not exceed 2 m. This shows that the aquifer can sustain the consequences of an exceptionally very low supply.

Table 3: Previsional hydrologic balance over 6 years; from 1994 to 2000.

Units m^3/s	Recharge (+)	Lateral supply (numidian sandstone) (+)	Pumping (-)	Outlet to the sea (-)	Leakage to the gravels aquifer	Storage variation storage (+) de-storage (-)
94/95	0.081	0.156	0.532	0.110	0.096	-0.501
95/96	0.037	0.160	0.580	0.092	0.148	-0.623
96/97	0.055	0.162	0.628	0.097	0.181	-0.689
97/98	0.073	0.165	0.676	0.102	0.221	-0.761
98/99	0.064	0.167	0.724	0.097	0.263	-0.853
99-2000	0.062	0.169	0.772	0.082	0.169	-0.899

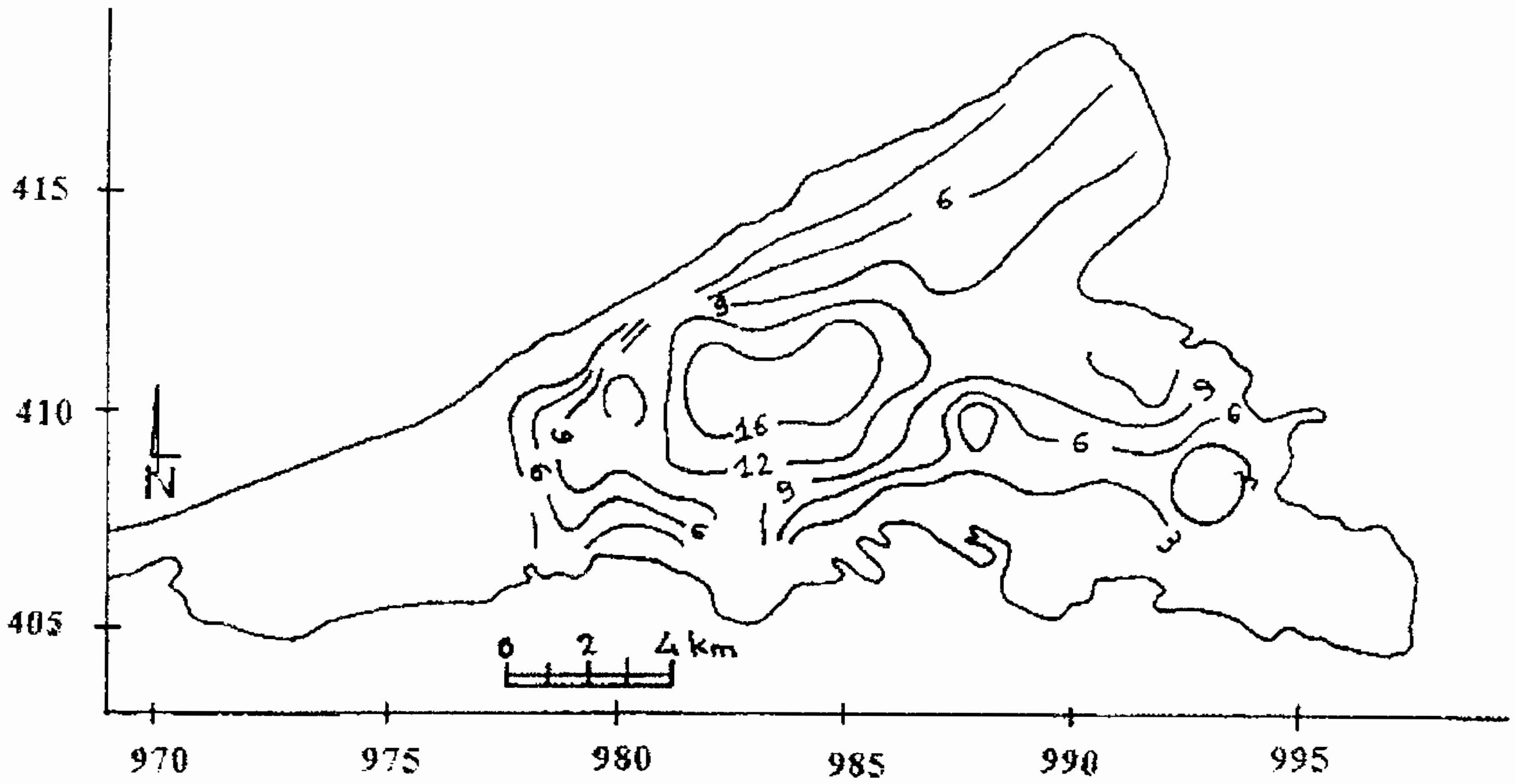


Fig. 10: Map of the dunary aquifer lowering after increasing flow exploitation over a period of six years (1994-2000).

V- CONCLUSION

The implement of a mathematical model based on the method of finite differences made it possible to reconstitute the history of the piezometric variation grid by grid according to the observed situation in the field. On the hydrodynamic point of view, this model shows up an improvement and a redistribution of permeabilities and storage coefficients, which are the features of the reservoir behaviour. The simulation of a scenario of exploitation (increase of flows), combined with a very low recharge have shown a reserve variation (de-storage) where the outlets have decreased of 35% towards the sea and of 50% towards the gravels aquifer.

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