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LAND SUBSIDENCE IN SHANGHAI : HYDROGEOLOGICAL CONDITIONS AND SUBSIDENCE MEASUREMENTS

LE TASSEMENT DES SOLS À SHANGHAÏ : CONDITIONS HYDROGÉOLOGIQUES ET MESURE DES TASSEMENTS

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Introduction

Based on the results of the Quaternary geology study, three aquifer layers are involved in the studied zone :

— *The phreatic aquifer*, in connection with the Huang-Pu River, corresponds to sandy and silty zones of maximum 5 m thickness, included in the clayey layer called "first compressible". This aquifer has a very limited extent. No information is available on its characteristics.

— *The first aquifer* is a sandy and silty layer; the thickness is between 0 and 15 m but, in the southern part of the study area, it appears in close connection with the "*second aquifer*". As it does not constitute the main pumping aquifer, little information is available about its characteristics. Nevertheless, some data are deduced from the pumping tests results which have been completed in the *second aquifer* with piezometric monitoring in the *first* and *second aquifer*.

— *The second aquifer* is the main pumping aquifer and is of fine sand. The thickness is between 10 and 35 m and the top of this layer is situated at a depth of about 70 m. Some pumping test results are available for this aquifer and a synthesis of this information will be presented.

Since 1920, the quantity of pumped groundwater (mainly from the *second aquifer*) increased year after year until 1962. The annual total amount of extracted water, distributed between the different pumping areas has caused the increase of effective stress in the saturated loose sediments provoking the compaction of the compressible layers.

The total measured subsidence has reached about 2.5 m in some sensitive places. Since 1962, the recharge of the aquifer during winters contributed to decelerate the subsidence, but a mean residual consolidation of 3 mm/year is still recorded.

Hydrodynamic parameters of the aquifers

On the basis of previous pumping tests performed in the *second aquifer*, some values of the permeability coefficient (K) and specific storage coefficient (S_s) have been obtained (Table 1).

For this study, an additional pumping test has been performed (its location is shown on the map of Figure 7) and the results were interpreted using different methods. The location of the piezometers in the different layers is given on Figure 1. Each of the methods of interpretation supposes that some particular assumptions can be accepted to represent the reality of the pumping test.

Table 1 : Interpretated results of previous pumping tests.

Pumping tests	K (m/sec)	S_s (m^{-1})
CKB 143	$0.6\ 10^{-4}$	–
CKB 140	$1.3\ 10^{-4}$	–
F 18	$8.7\ 10^{-4}$	$1.2\ 10^{-4}$
CKB 114	$2.1\ 10^{-4}$	–
CKB 117	$1.2\ 10^{-4}$	–
20–1	$5.3\ 10^{-4}$	$3.7\ 10^{-5}$

In the transient state, the radial diffusivity equation of the horizontal flow in a porous media can be written :

$$\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot\frac{\partial h}{\partial r}\right)=\frac{S}{T}\cdot\frac{\partial h}{\partial t}$$

where r = radial coordinate from a central reference point

S = storage coefficient

T = transmissivity

h = piezometric head

In practice, we have applied the following well known methods :

- The Jacob method of the straight line which constitutes the first and classical method for interpreting the pumping test results from a semi-log diagram (log(t), drawdown).

- The curve-matching method of the Theis formula using a bi-log diagram (log(t), log(drawdown)); this method provides the values of T and S.

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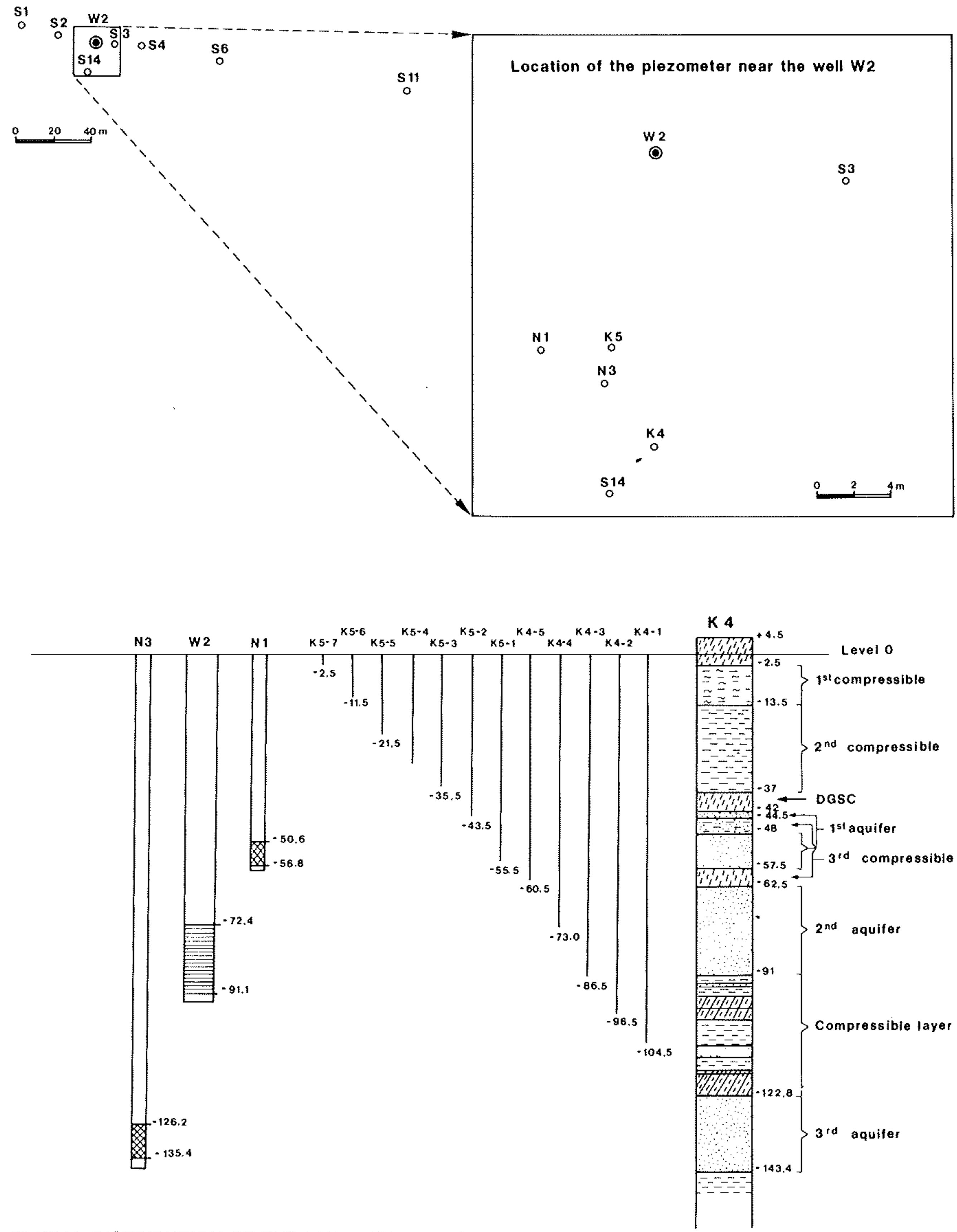

SPATIAL DISTRIBUTION OF THE DIFFERENT PIEZOMETERS NEAR W2
(The "S" piezometers are all situated in the 2nd aquifer)

Fig. 1 : Location of well W2 and piezometers.

• The interpretation of recovery curves by the Horner method; the drawdown is plotted versus log $(1 + \frac{tp}{t})$ (tp is the duration of the pumping, t is the time from the cessation of pumping) on a semi-log diagram; Jacob method is then applied providing the transmissivity but not the storage coefficient.

• The Hantush solution, taking into account the leakage from the aquitards or from the overlying aquifers which can percolate through the aquitards. After defining a Hantush leakage factor, the solution can be found using the same procedure as for the Theis curve.

• The Neuman and Witherspoon solution additionaly taking into account the storage of the confining beds and their induced transient effect. After defining a constant β which depends on the transmissivity and storage coefficient of the aquifer and semi-pervious aquitard, the solution can be found as for the Hantush solution. This method provides the values of T, S and a value of the ratio $\frac{T'}{S'}$ or $\frac{K'}{S_s'}$ for the aquitard.

For the *second aquifer*, the results of the interpretation are shown in Tables 2 and 3, giving respectively transmissivities and storage coefficients found in the different piezometers and at the pumping well. The comparison with the previous results (Table 1) leads to the conclusion that the value of the permeability coefficient is between $0.6\ 10^{-4}$ m/s and $8.7 10^{-4}$ m/s for the *second aquifer* with a specific storage coefficient of between $1\ 10^{-6}$ and $1.2\ 10^{-4}$ m/s.

Pumping and recharge conditions

For more than 100 years, groundwater has been pumped in the central area of Shanghai.

Before 1950, most of the pumping wells were drilled in order to supply the water needed for cotton mills situated near the Huang-Pu River and its affluent the Su-Zhou Creek. Without any available data relative to this period, estimations of the total amount of the water pumped in the *second aquifer* are provided by the Shanghai Geological Center.

After 1950, the spatial distribution of the pumping covered a larger zone, but two main pumping areas were still distinguished : the Pu-Tuo district and the Yang-Pu district, respectively in the western part and in the north-eastern part of the study area (Fig. 2).

Total annual data of groundwater withdrawal are available until 1965 and bi-annual data of pumping and recharge are known after this year. The evolution in time of the groundwater withdrawal quantity is illustrated on Figure 3, showing a maximum in 1961. Since 1962, important restrictions have been imposed and the *second aquifer* has been recharged. Globally the pumping and recharge cycles are distributed as follows :

- from the beginning of April until the end of September : pumping phase;
- from the beginning of October until the end of March : recharge phase.

The quantity of water recharged in the *second aquifer* each year has most often been greater than the pumped amount, in order to restore progressively the high water pressure in this aquifer.

The recharge of the aquifer is performed using the same wells as for pumping; their spatial distribution is therefore known.

From 1975 until now, all the pumping and recharge values and their locations are known on a monthly basis; these data have been entered in a data-base file

Table 2 : Interpretated transmissivity (in m^2/sec) of the second aquifer by different methods.

Method \ Piezometer	S1	S2	S3	S4	S6	S11	S14	K4.5	W2 (well)
Jacob	1.96-2.44 10^{-2}	2.05 10^{-2}	1.29-2.15 10^{-2}	2.34 10^{-2}	2.25-5.3 10^{-2}	2.47-7.2 10^{-2}	1.92-2.82 10^{-2}	2.37 10^{-2}	1.4 10^{-2} 2.09 10^{-2}
Recovery	2.2 10^{-2}	2.12 10^{-2}	2.1 10^{-2}	2.17 10^{-2}	2.31 10^{-2}	2.82 10^{-2}	2.17 10^{-2}	–	2.65 10^{-2}
Theis	2 10^{-2}	1.78 10^{-2}	1.31 10–2	2.01 10–2	2.38 10–2	2.18 10–2	1.63 10–2	–	–
Hantush	1.96 10^{-2}	1.7 10–2	1.4 10–2	1.78 10–2	2.31 10–2	2.06 10–2	1.53 10–2	–	–
Neuman-Witherspoon	1.8 10^{-2}	–	–	–	–	–	–	–	–

Table 3 : Interpretated storage coefficient of the second aquifer by different methods.

Method \ Piezometer	S1	S2	S3	S4	S6	S11	S14	K4.5	W2 (well)
Jacob	3.0 10^{-4} 2.64 10^{-5}	7.65 10–4	3.08 10^{-3} 4.91 10^{-4}	2.92 10^{-4}	4.66 10^{-4} 0.84 10^{-6}	4.63 10^{-4} 0.8 10^{-5}	6.13 10^{-4} 2.46 10^{-5}	8.4 10^{-3}	–
Recovery	–	–	–	–	–	–	–	–	–
Theis	3.4 10^{-4}	1.09 10^{-3}	3.39 10^{-3}	4.27 10^{-4}	4.49 10^{-4}	5.46 10–4	1.07 10^{-3}	–	–
Hantush	4.9 10^{-4}	8.67 10^{-4}	3.03 10^{-3}	6.78 10^{-4}	5.06 10^{-4}	5.16 10^{-4}	8.4 10^{-4}	–	–
Neuman-Witherspoon	4.7 10^{-4}	–	–	–	–	–	–	–	–

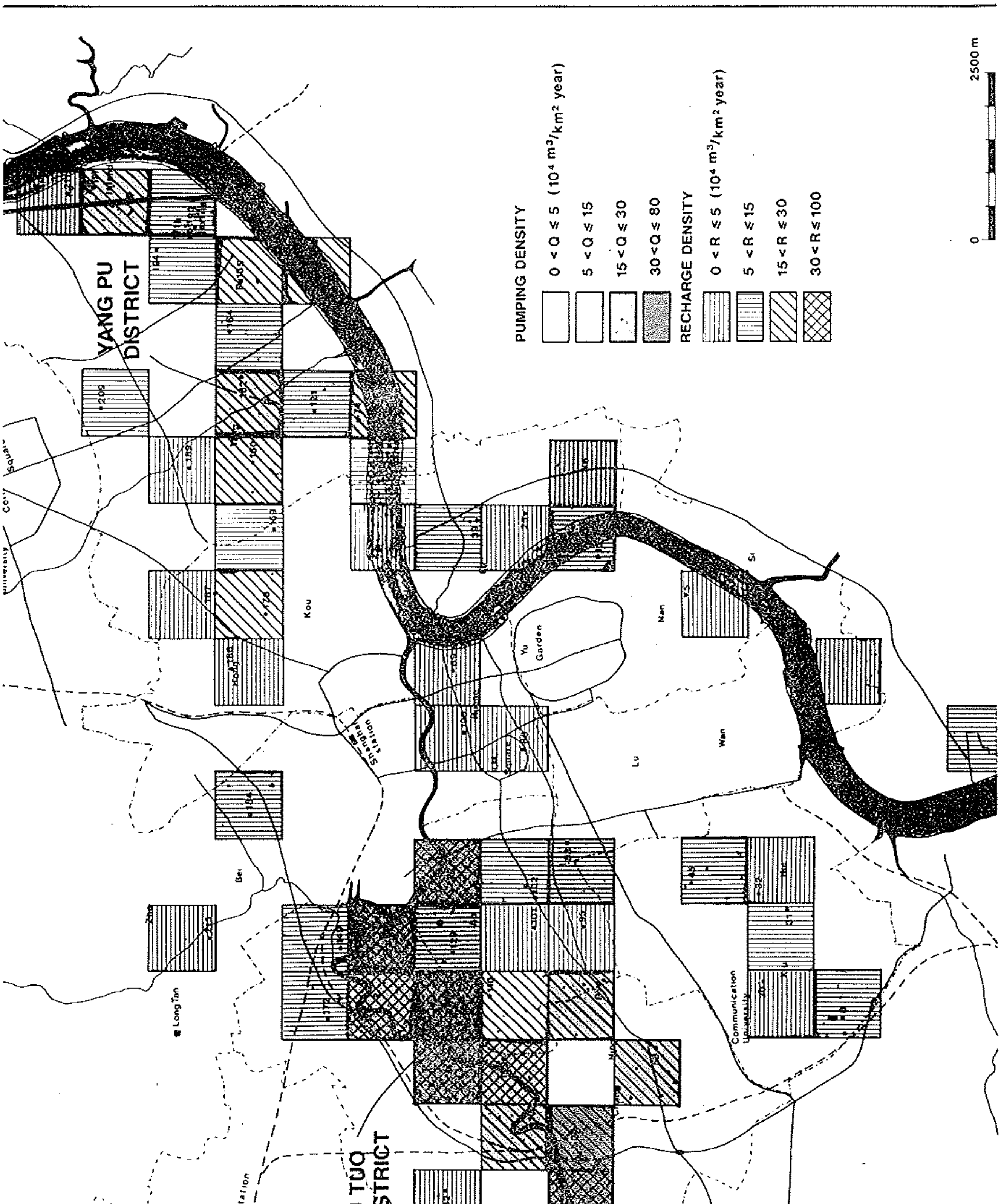

Fig. 2 : Pumping and recharge densities.

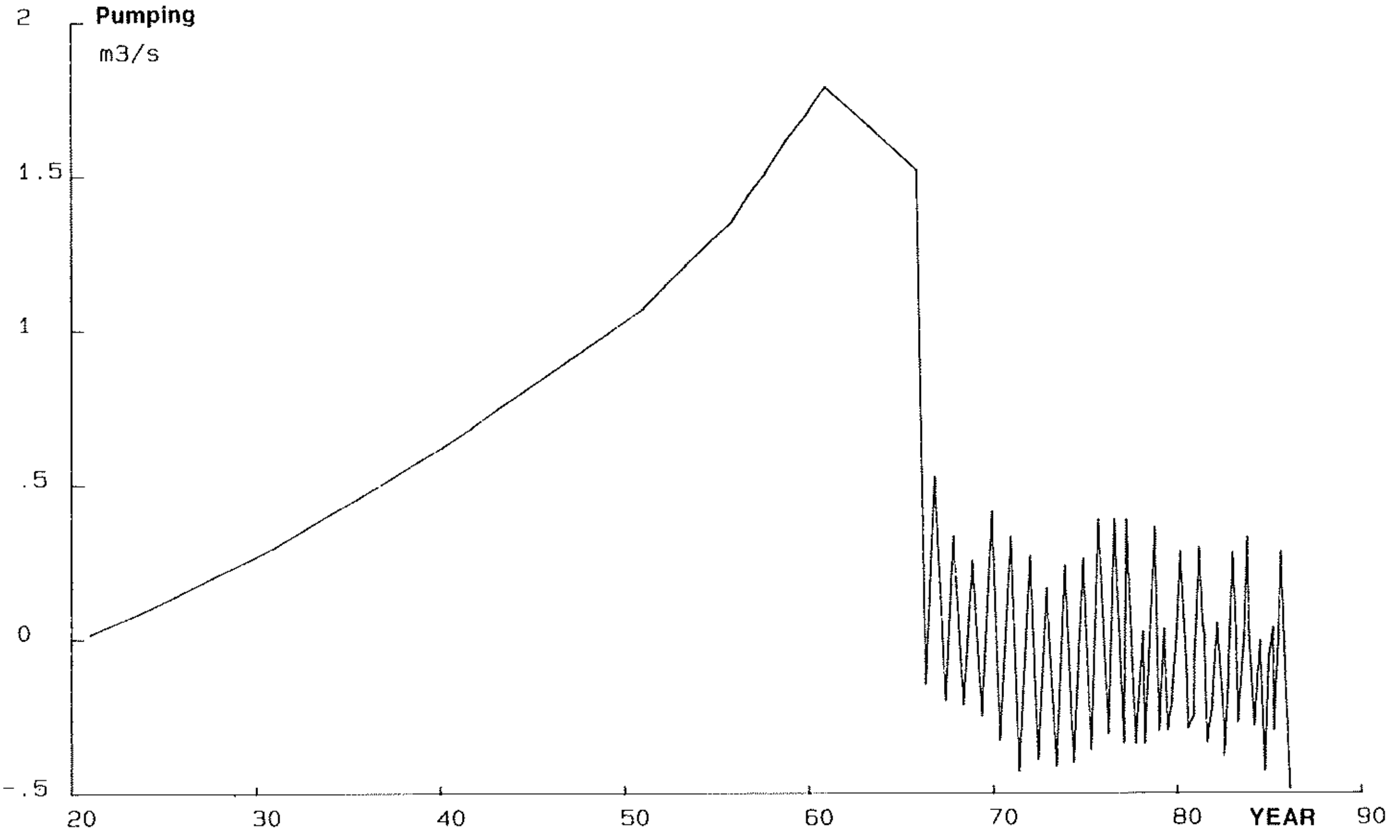

Fig. 3 : Pumping evolution as a function of time (second aquifer).

by the Shanghai Geological Center. A preprocessing program has allowed all the data to be entered automatically in the LAGAMINE code. Table 4 summarizes this information, with mean annual values for the studied zone.

Table 4 : Annual pumping and recharge values in the second aquifer.

YEAR	Pumping (× 10^4 m^3)	Recharge (× 10^4)
1975	527.89	649.52
1976	436.35	641.03
1977	419.57	601.30
1978	648.16	686.73
1979	585.88	690.80
1980	549.25	697.25
1981	596.59	824.11
1982	541.85	822.56
1983	618.59	892.47
1984	586.41	830.38
1985	599.31	862.03

The mean annual values of rainfall and evapotranspiration are estimated respectively to 1142 and 1427 mm of water (data from the Shanghai Geological Center).

Generally, about 52 % of the rainfall takes place in September and 68 % of the evapotranspiration during the period of May to September. Moreover, the runoff seems to be very important due to the high degree of urbanization in the central area of Shanghai. Because of these facts, it is considered that only very small infiltration is coming from rainfall and that the main part of the infiltration is leaking from the "phreatic aquifer" and the Huang-Pu River. This infiltration is limited by the low permeability of the semi-pervious layers.

Water pressure variations in the aquifers and aquitards

Due to the intensive withdrawal of water, the pore pressures of the *first and second aquifers* have progressively decreased to reach a maximum decrease of 33 to 35 meters of water between 1960 and 1965 in the Pu Tuo district (western part of the study area).

Piezometric maps have been drawn with data from about 40 piezometers located in (or near) the zone. For example, Figures 4 and 5 show the piezometric maps of September 1960 and September 1981.

At five monitoring points the piezometric heads have been continuously recorded from 1962. For instance, Figure 6 shows the water pressure evolution as a function of time at different points, respectively called 10-4, H5-5 and 143-1 (the location of the points is shown on the map of Figure 7).

The following observations can be made about these evolution curves :

— no continuous measurement is available before 1962;

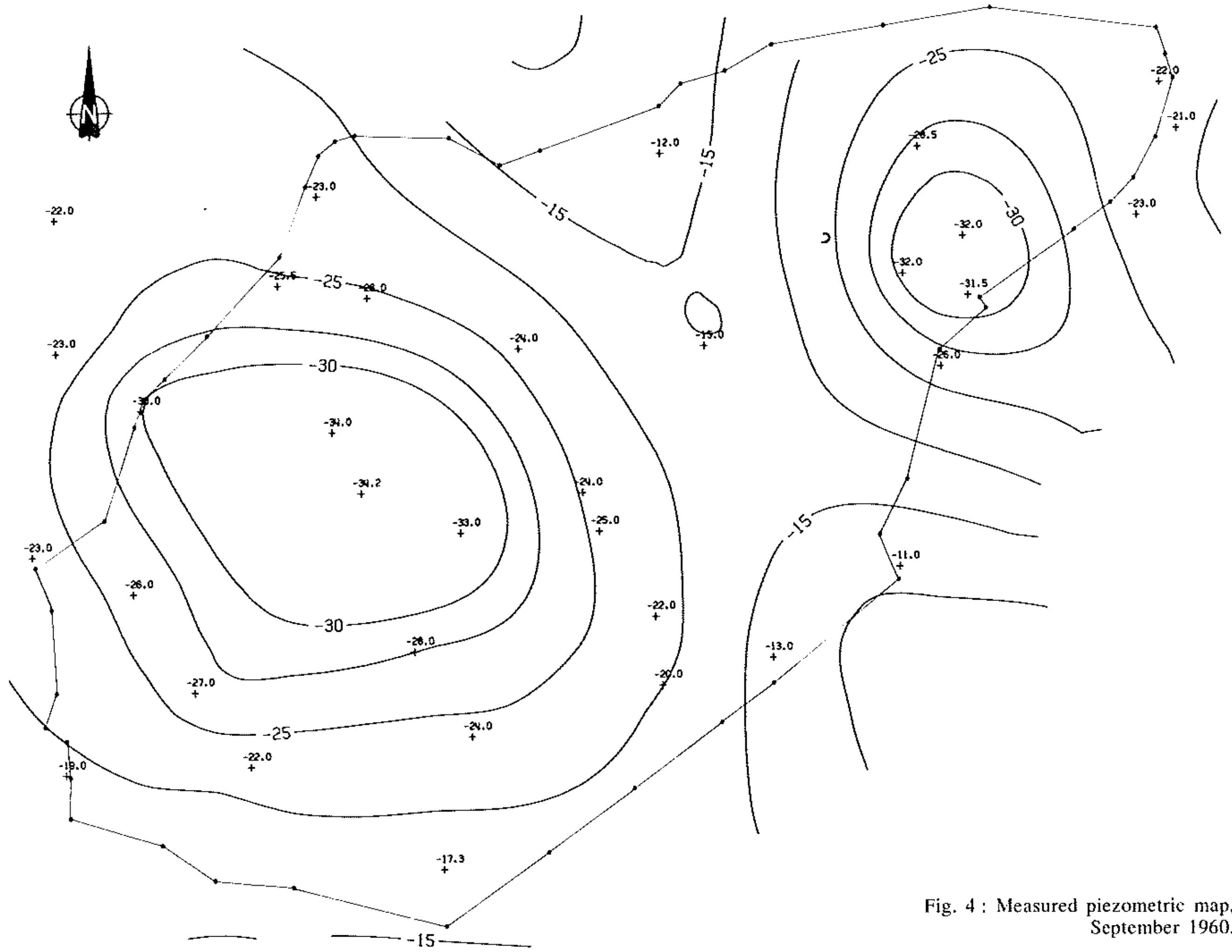

Fig. 4 : Measured piezometric map, September 1960.

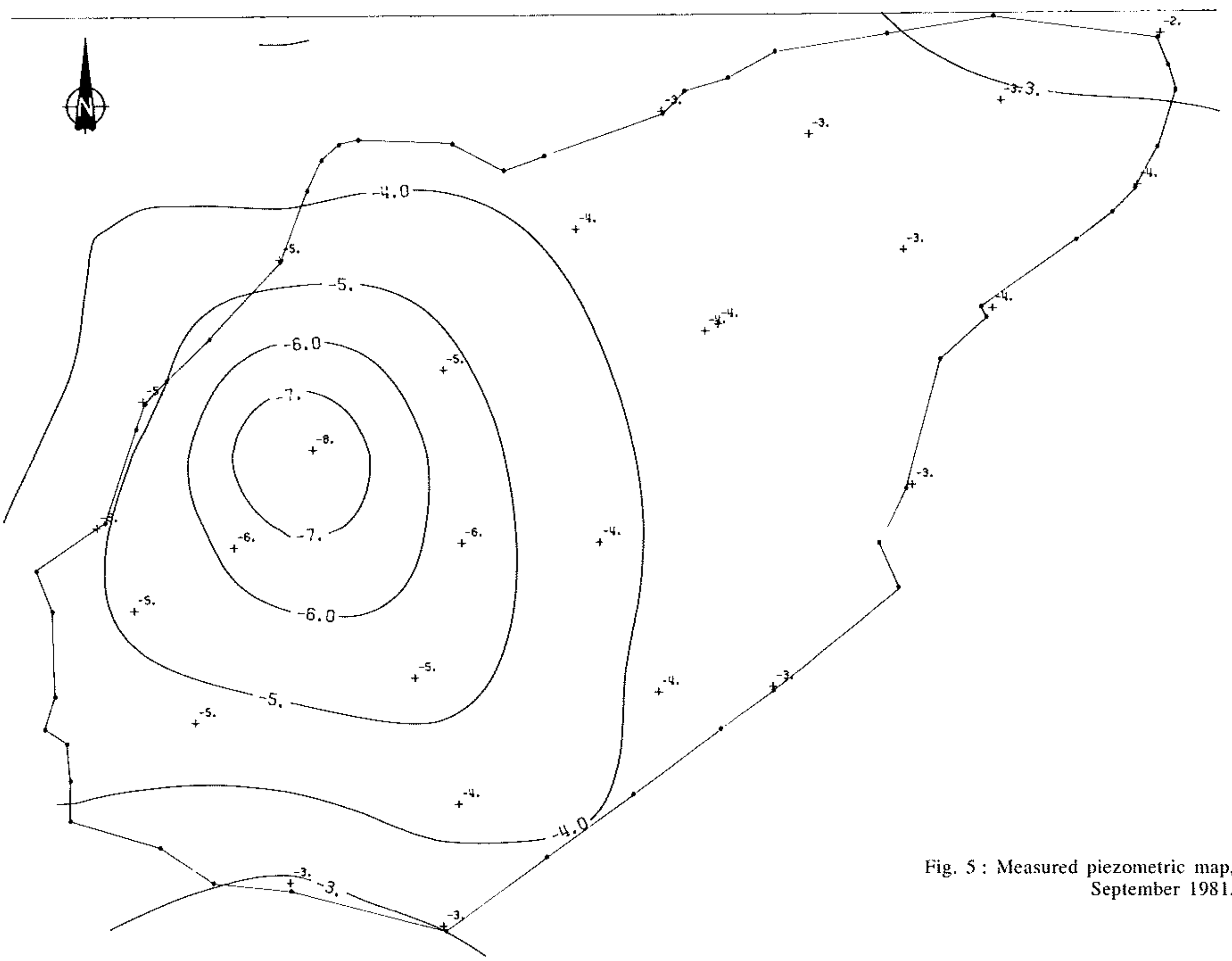

Fig. 5 : Measured piezometric map, September 1981.

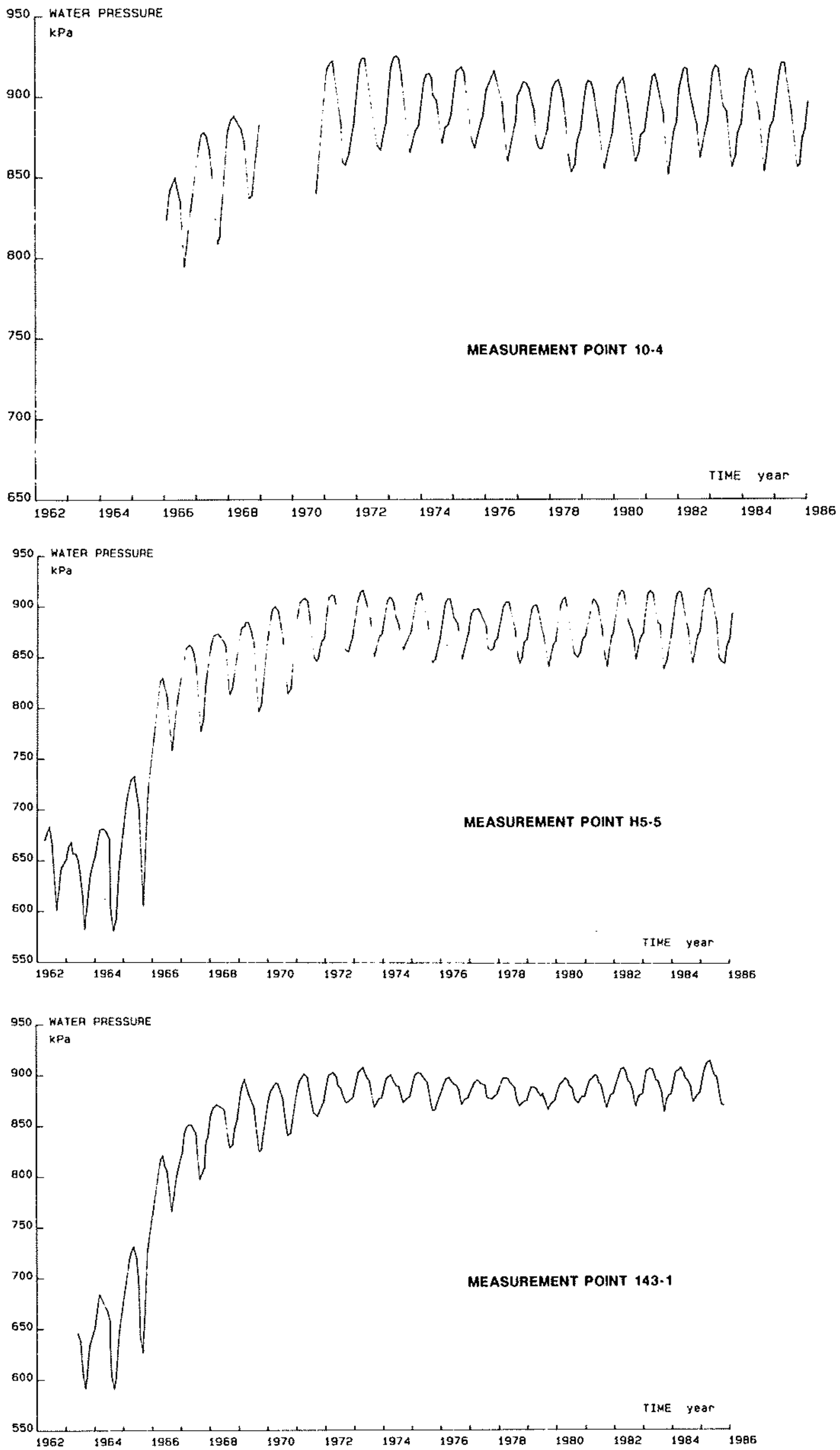

Fig. 6 : Water pressure evolution at different points.

— before 1965, the lowest levels are reached with piezometric heads between – 20 and – 33 m from the reference zero level;

— after 1970, variable amplitudes of piezometric oscillations are observed (from 6 to 12 meters), depending of the proximity of an important pumping/recharge well.

Due to the contrast in permeability between aquifer layers and the aquitards, it is evident that the water pressure variations propagate more rapidly through the aquifers and by their connections than vertically through the aquitards of low permeability. Some clayey zones, where the variation of pressure takes years penetrate completely, are entirely surrounded by zones where the variation of pressure in the sandy layers takes only 1 or 2 days. As an example, we can apply the analytical solution to the Fourier equation describing the propagation of a pressure variation (Δp) in a porous medium. The following results are found :

— in aquifers ($K = 1\ 10^{-4}$ m/s and $S_s = 1\ 10^{-4}\ m^{-1}$) 80 % of any Δp is propagated at 100 m in 1 day;

— in aquitards ($K = 1\ 10^{-9}$ m/s and $S_s = 1\ 10^{-3}\ m^{-1}$) 80 % of any Δp is propagated at 1 m in 100 days.

Measured subsidence

If geostatic pressure is assumed constant (the compressibility of the water being neglected in comparison with soil compressibilities) and if the Terzaghi principle is applied, the increase in effective stress in a confined aquifer system is equal to the reduction in pore pressure. In the clayey interbeds and confining beds (aquitards), the full dissipation of the variation of pore pressure and the full increase of effective stress may require many years or even decades. Anyway, if the sediments are somewhat compressible, it is admitted that the decrease of water pressure must cause compaction.

The first measurements of the subsidence in Shanghai were made in 1921. Since this date, the subsidence rate has increased continuously until 1962-1965. After 1965, stabilization was obtained with a small rebound and followed by residual subsidence of between 1 and 3 mm/year.

The measured total subsidence presented on Figure 7 concerns the 300 m i.e. the total thickness of the loose sediments overlying the bed rock in Shanghai.

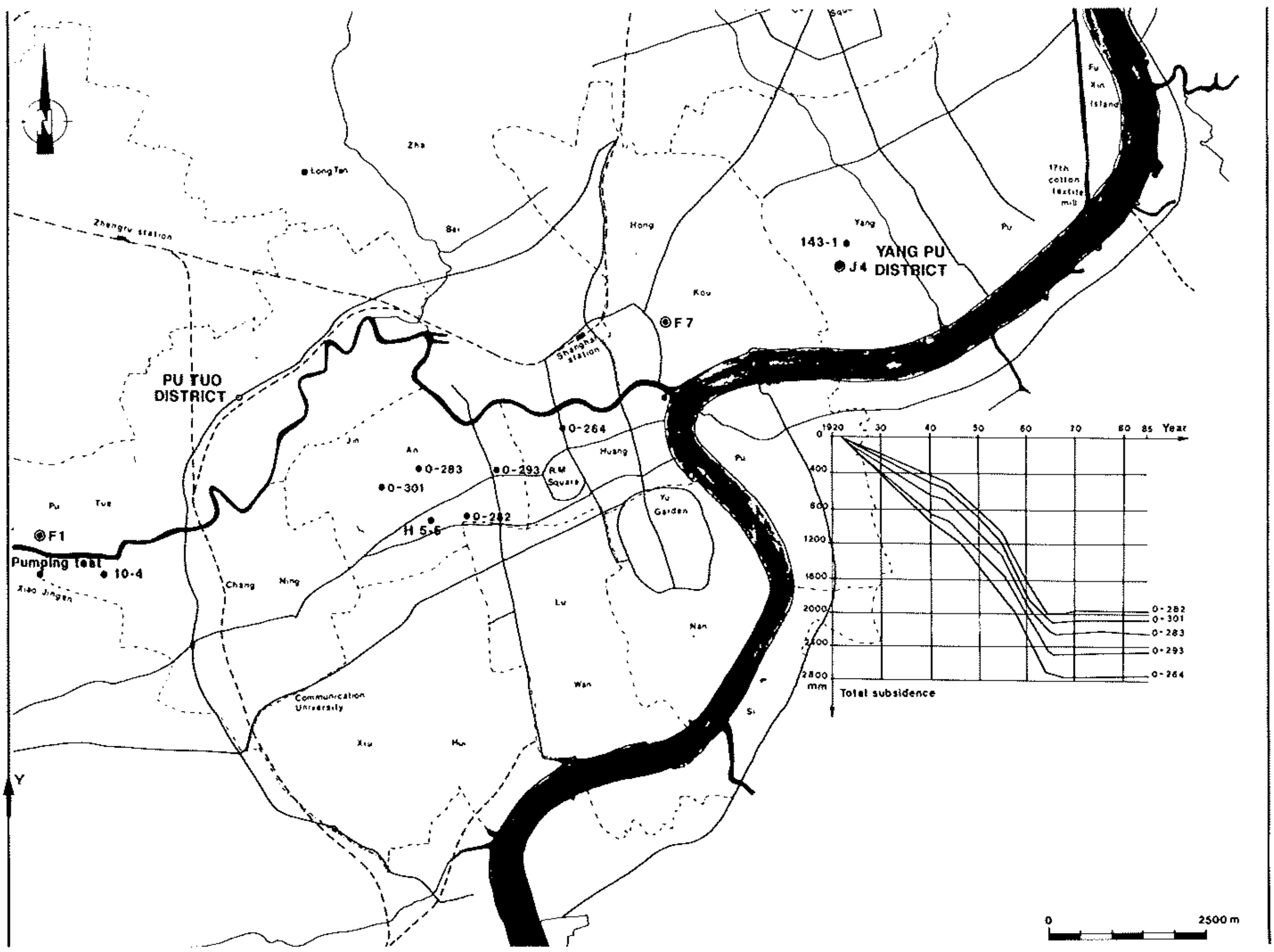

Fig. 7 : Location map of the measurement points. Total measured subsidence.

Since 1962 and mainly after 1965, measurements in separate layers are provided by extensometers, placed in different monitoring holes. Results of these measurements in holes 10-4 and F7 are shown on Figure 8.

Sometimes the compaction measured by extensometers, relative to the upper 70 meters appears more important than the value of the total subsidence (relative to the 300 m) measured by a bench-mark. This observation illustrates that the quality and the reliability of the measurements depend to a large extent on the methods which are used : extensometers or bench-marks. Moreover, in this area, the elevation levelling has to be integrated in a very large network which is linked to reference points situated at about 100 km from Shanghai (where bed rock outcrops are supposed to represent a fixed level).

According to the specialists of the Shanghai Geological Center (Bao Manfang, and Su Heyuan) 65 % to 85 % of the total subsidence may objectively be attributed to the compaction of the upper 70 meters of sediment.

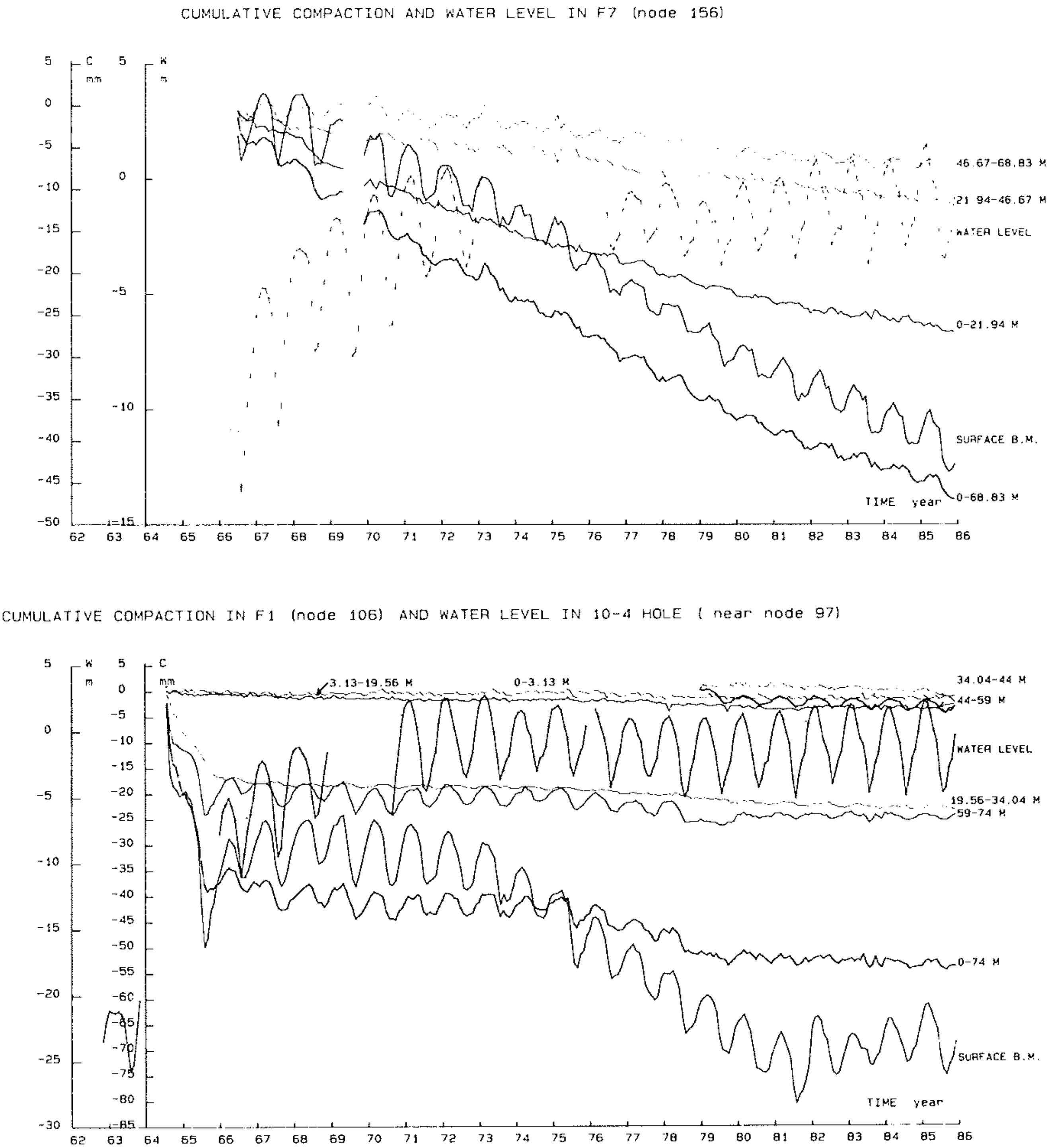

Fig. 8 : Compaction measurements.

Conclusions

The *first* and *second aquifers* constitute two confined sandy aquifers interbedded in impervious clayey layers. Their horizontal dimensions are very large in comparison to their thickness. The differences in pore water pressure, induced by pumping or recharge are more easily propagated horizontally than vertically because of the permeability contrast between aquifers and aquitards.

However, in the southern part, the connections between the first and second aquifers provoke in this zone a faster propagation.

The measured piezometric maps and the evolution of the piezometric heads at different points will be used in the calibration of the 3D model.

The total measured subsidences since 1920, and the compactions measured in the different layers since 1962, will be used in the calibration procedure of the flow-compaction model.

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