SIMULATION OF THE WATER LEVEL IN THE TIANJIN GEOTHERMAL FIELD, NORTH CHINA.

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Dear Sir,

This report is written by Mrs. Lu Run, engineer of the Geology Bureau of Tianjin, People's Republic of China. It concludes her successful training as a UNU Fellow in Reservoir Engineering.

Prior to this work Mrs. Lu Run has sucessfully completed the special course in which the Geothermal Reservoir Engineering Lecture Notes were used as a textbook (UNU Geothermal Training Programme, Report No. 1983-2). We, undersigned served as her supervisors on the research project that is described in this report. She also received tuition in reservoir engineering from Mr. Gísli Karel Halldórsson and Mr. Ómar Sigurdsson.

The objective of the work was to train Mrs. Lu Run in computer file generation, simulation and forecasting of reservoir pressure drawdown of low temperature geothermal fields as well as to interpret and use the results in the investigation and harnessing of geothermal reservoirs.

For this work we used data from the Tianjin geothermal field in China, supplied by Mrs. Lu Run. These data are not the complete data acquired in reservoir engineering investigations in Tianjin. Missing data elements have been supplied by the instructors according to their owm estimate, when this has been necessary in course of the work.

This use of the Tianjin data has the educational purpose only, to train the student in understanding and processing reservoir engineering data, as is the objective of the UNU Geothermal Training Programme. The results and conclusions in this report, therefore, may or may not be compatible or incompatible with Tianjin reservoir engineering practice, without this having any effect whatsoever on Mrs. Lu Run's successful completion of her training and study.

Yours sincerely,

Jónas Elíasson

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ABSTRACT

The distribution of geothermal fields in the Tianjin area is described as well as the geological and tectonic conditions. The reservoir properties are listed, for instance the temperature, water level, and chemistry. The production history of the geothermal reservoir in the Tertiary rocks is described.

Based on the geological and hydrogeological conditions, two mathematical models have been used to compute the parameters of the reservoir. The drawdown of the water level in the geothermal reservoir has been forecasted for the next 15 years with two designed production schedules by utilizing the conceptual model-leakage solution. This has been done both for a constant pumping rate and for increments of 5% per year in the pumping rate. The analyses indicate that the drawdown would be within allowable limits with the constant pumping rate, whereas by increasing the pumping rate gradually with time some wells would be wasted due to too much drawdown.

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LIST OF SYMBOLS

A : Area (m^2)

a : Pressure transient coeffecient (m^2/s)

B : Leakage coeffecient (m)

b : Thickness of semipervious layer (m)

CORR : Linear regression coefficient

H : Piezometric head (m)

H_o : Initial piezometric head (m)

$H_{i,j}$: Piezometric head (water level) at point i,j (m)

$H_{i+1,j}$: Piezometric head (water level) at point i+1,j (m)

$H_{i,j+1}$: Piezometric head (water level) at point i,j+1 (m)

$H_{i-1,j}$: Piezometric head (water level) at point i-1,j (m)

$H_{i,j-1}$: Piezometric head (water level) at point i,j-1 (m)

ΔH : Potential difference between the upper and lower aquifer (m)

HM : Measured piezometric head (water level) (m)

HMM : The mean value of the measured piezometric head (water level) (m)

HR : Computed piezometric head (water level)(m)

HRM : The mean value of the computed piezometric head (water level) (m)

I : Groundwater gradient

K : Permeability of the aquifer (m/s)

kL : Permeability of the aquiclude (m/s)

M : Thickness of the aquifer (m)

N : The total number of wells

V : The total number of the time steps

Q : Flow rate (l/s, tonnes/hour)

R^2 : Explained variance

r : Distance between the observation well and the pumping well (m)

t : Time (second)

s : Drawdown of the water level (m)

S : Storage coefficient

T : Transmissivity (m^2/s)

W(u) : Well function without leakage

w(u,r/B): Well function with leakage

x : Coordinate in horizontal direction (m)

y : Coordinate in vertical direction (m)

1. INTRODUCTION

1.1 Scope of work

This report is the final product of a six month training in reservoir engineering at the UNU Geothermal Training Programme at the National Energy Authority (NEA) in Reykjavik, Iceland.

The programme started with a five week lecture course focussed on the basic aspects of geothermal energy, followed by field studies and lectures on reservoir engineering and borehole geophysics for six weeks.

A two week field excursion included visits to both low and high temperature geothermal fields with various types of utilization of geothermal energy. It is the authors impression that Iceland is rich of geothermal resources and famous for its utilization of geothermal energy.

The author is employed by the Geothermal Company of the Geological Bureau in Tianjin and is mainly involved in the study of reservoir engineering. The aim of this report is to make a simulation of the water level in the Tianjin geothermal field.

2. GEOTHERMAL RESOURCES OF TIANJIN

2.1 Locality

Tianjin City is located on the eastern part of the Hei-Bei plain, 137 km southeast of Beijing in northern China. The terrain is low and flat with a surface altitude only 7 meters above mean sea level. The Tai-Hang mountain is 150 km to the west of the city and the Yan mountain 120 km to its north. Tianjin with a population of about 7 million, is the third largest city in China after Beijing and Shanghai. One of China's main harbours is in Tianjin and the city is also an important industrial and commercial base for the country (Fig.1).

Three geothermal fields surround the city of Tianjin; the biggest is the Wang-Lan-Zhuang geothermal field, located in the south-west part of the city, the other two are named Shan-Ling-Zi geothermal field, and the Wan-Jia-Ma-Tou geothermal field (Fig. 2 and Table 1).

2.2 Geology and tectonics

2.2.1 Regional geological structure

The Tianjin area is located at the northern end of the Cang-Xian horst which is within the subsidence zone of the the north China plain belonging to the Neocathaysian structural system with its south-east side and north-west side adjacent respectively to the Huang-Hua and the Ji-Zhong grabens of the Tianjin area (Fig. 3, from Yao, 1980).

There are two directions of structural lines, a north-northeasterly and a west-northwesterly direction. The former is composed of horsts, grabens and parallel fractures. Examples of these are the Xiao-Han-Zhuang horst, the Cang-Dong fracture, the Xiao-Ying-Pan fracture, east of Bai-Tang-Kou fracture, west of Bai-Tang-Kou fracture, north

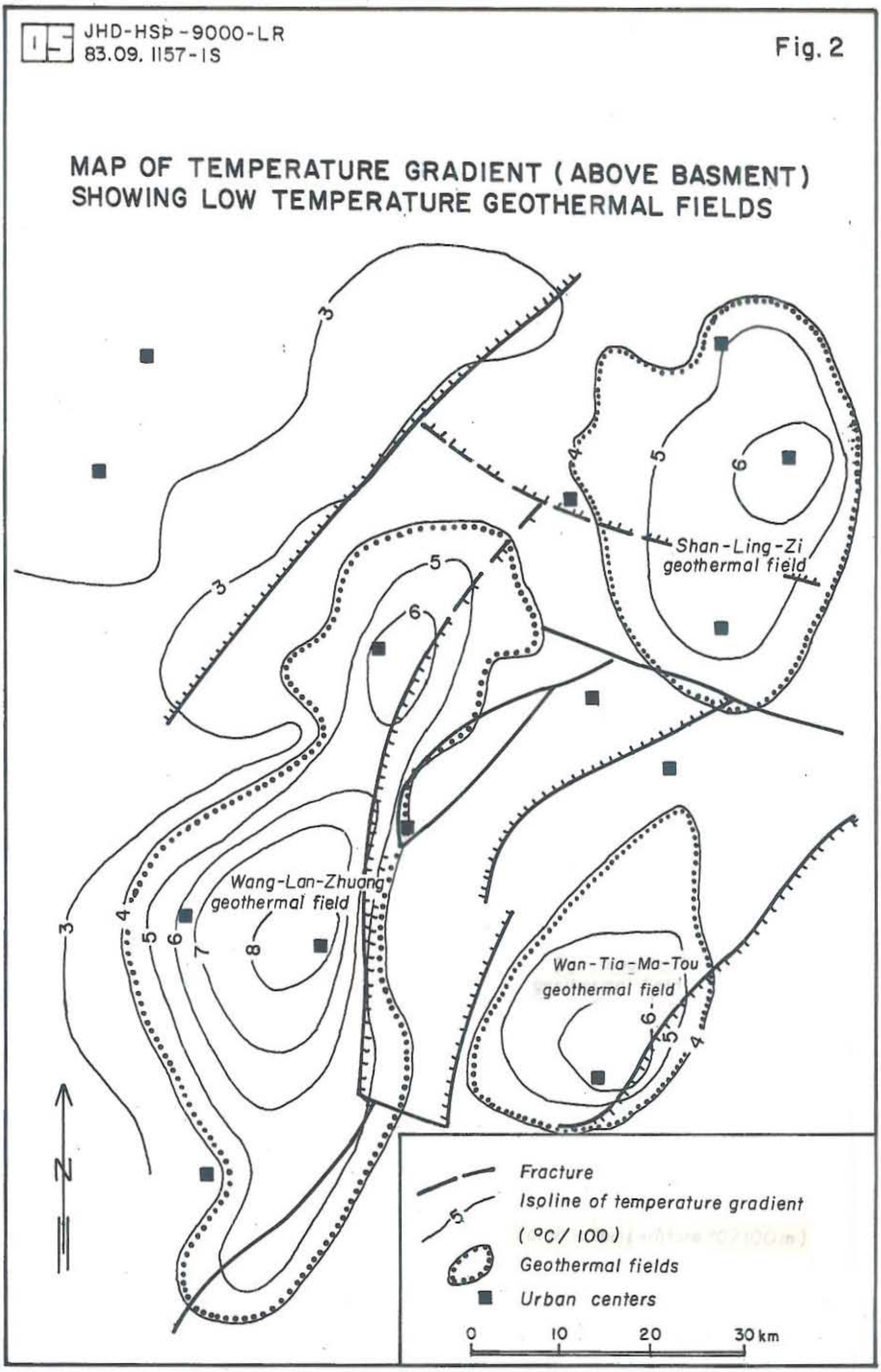
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Fig. 2
MAP OF TEMPERATURE GRADIENT (ABOVE BASMENT)
SHOWING LOW TEMPERATURE GEOTHERMAL FIELDS
Shan-Ling-Zi
geothermal field
Wang-Lan-Zhuang
geothermal field
Wan-Tia-Ma-Tou
geothermal field
N
Fracture
Isoline of temperature gradient
(°C/ 100)
Geothermal fields
Urban centers
0
10
20
30 km

Table 1. Distribution of geothermal fields both in Tertiary system and in basement

Name of reservoir	Location	Area of distribution (km^2)	Average geothermal gradient (°C/100 m)		Depth (m)		Lithological characters	
			Center of Tertiary system	bedrock	Tertiary system	bedrock	Tertiary system	bedrock
Wang-Lan-Zhuang	south urban south-west suburb	609	8.3	1-2	550-600	1100-1400	powdered sand-stone	limestone
Wan-Jia-Ma-Tou	south suburb	119	8.3	1-2	600 +/-	1300-1500	-	limestone
Shan-Ling-Zi	east suburb	171	8.1	1-2	600 +/-	1100-1300	-	limestone

of the Tianjin fracture, etc. The latter group is composed of parallel fractures, the Zen-Fu-Tai, Hai-He, Cheng-Lin-Zhuang and Guan-Zhuang, fractures, etc. (Fig 4).

2.2.2 Structural features of Wang-Lan-Zhuang geothermal field

The Wang-Lan-Zhuang geothermal area is located on the Shuang-Yao horst. The boundaries of the area are represented by the West-of-Bai-Tang-Kau fracture to the east the Zen-Fu-Tai fracture to the south, the North-of-Tianjin fracture to the west, and the Cheng-Lin-Zhuang fracture to the north. The depth of the bedrock in the central area of the geothermal field is 1000 m, being 1100 m on the west side of the field and 2000 m on the east side.

The West-of-Bai-Tang-Kou fracture is active as evidenced by the earth deformation of the upper and lower walls. The east side began to uplift gradually from 1973 and more drastically from 1976 after the big earthquake of Tang-Shan with an average rate of 1-2 mm per year. Up to the present, the upper wall has already attained a height of more than 10 mm relative to the lower one.

2.2.3 The strata in The Wang-Lan-Zhuang geothermal area.

The strata of the Wang-Lan-Zhuang geothermal are is shown in Fig. 5. The uppermost 550 m consist of unconsolidated sediments of Quaternary age. This is underlain by about 800m of fine grained sediments of Tertiary age, which in turn are underlain by limestone formations of Ordovician, Cambrian and Sinian (pre-Cambrian) age.

2.3 Aquifers and aquicludes

Aquifers in the Tianjin geothermal field can be classified into two types, according to the lithological characters, buried characters of geothermal water, as well as the physical and chemical properties of the rock and fluid. One type is the porous aquifer in the Tertiary system, the Min-Hua-Zhen formation. The lithological character is silt and fine grained sand. This aquifer is composed of 15-20 single layers, and the accumulated thickness is about 150 m. Hydrochemically, the geothermal water in this aquifer is characterized by its high alkalinity and low hardness. The Min-Hua-Zhen formation can be distinguished into two parts according to the pressure and flow rate in the reservoir. The upper part is at 500-550 m depth. Its effective average thickness is 25 m. At the beginning of production of the geothermal field in 1973, the water level in this part (Aquifer I) was -5 m (below mean sea level), the average pumping rate was 40 tonnes/hour. The lower part is at 700-750 m depth. Its effective thickness is 30 m. At the beginning of production its water level (Aquifer II) was at 10 m (above MSL). The average pumping rate was 60 tonnes/hour.

There is a stable aquiclude between the two parts of the Min-Hua-Zhen formation. The aquiclude is composed of clay with a thickness of 40-50 m. This report deals mainly with the geothermal water in the Tertiary (Min-Hua-Zhen formation).

The second type of aquifers in Tianjin is the fissure-karst aquifer in the bedrock. It includes two main producing horizons; the upper one is of Ordovician age and the lower one is of Sinian age. The Ordovician limestone is about 308 m thick. The output from single wells is 80-120 tonnes/hour. The minimum thickness of the Sinian limestone is 441 m, but its base has not been penetrated by drillholes yet. The output from single wells is 60-100 tonnes/hour. All wells penetrating the fissure-karst aquifers are artesian.

2.4 Chemistry of the geothermal field

2.4.1 General trend of chemistry

Hydrochemically, the geothermal water of the Wang-Lan-Zhuang geothermal field is also classified into two types (Zhou and Cai, 1982). One is the geothermal water of the Tertiary system, which is characterized by its high alkalinity and low hardness and mineralization. The other one is the geothermal water of the fissure and karst aquifers with a high mineralization, alkalinity and fluorine content, and a relatively low hardness.

The chemical types of geothermal water in the Tertiary system vary from being relatively rich in HCO_3-Na to being rich in Cl-HCO_3-Na, from northwest to southeast. Along the same direction, the mineralization changes from 0.58 to 1.15 g/l, Cl changes from 55 ppm to 260 ppm.

The geothermal water in the fissure and karst aquifer of the Ordovician system is characterized by SO_4-Cl-Na, mineralization is 4.40 g/l, hardness is 9, Cl is 868 ppm. The water quality is not good, and serious corrosion exists. In the Sinian system, the geothermal water is characterized by Cl-SO_4-Na, the mineralization is 1.8 to 2.0 g/l, hardness is 7 to 9, Cl is 574 ppm. The special character of this aquifer is that it contains much more calcium or approximately 40 ppm.

To sum up, mineralization increases with the increase of chloride and sodium with depth. In the horizontal direction the mineralization increases from north to south (Table 2).

2.4.2 Distribution trend of silica and fluoride

The concentration of silica is a function of temperature, i.e. the concentration of silica increases with temperature. In the Tertiary system, for example, at a temperature

TABLE 2. Hydrochemistry of the geothermal water in the Tianjin geothermal field

	Aquifer	Type of rock	Depth of well (m)	Measured temp. (°C)	SiO_2 ppm	K ppm	Na ppm	Ca ppm	Mg ppm	SO_4 ppm	CO_2 ppm	Cl ppm	F ppm	pH/20° kg/l	M	Hard-ness	Alkali-nity	Geothermometer Quartz °C	Chalcy-dony °C
Tertiary system	I	silt	672	35.4	19.4	0.99	260.00	4.99	0.99	43.19	336.70	99.29	3.26	8.40	671.30	0.90	25.00	60.3	30.5
Tertiary system	II	silt-stone	987	43.7	19.4	5.09	814.00	53.09	5.79	894.78	136.47	677.04	2.00	8.30	2563.90	1.18	25.00	60.8	31.1
bedrock	Ordo-vician system	lime-stone	1543	58.0	27.7	45.90	789.90	501.10	91.14	1981.27	145.24	866.75	4.26	7.10	4404.68	4.40	25.88	75.5	45.5
bedrock	Sinian system	dolomi-tite	2016	93.0	52.0	59.99	600.00	36.66	7.29	272.82	325.70	570.81	10.61	7.20	1791.95	7.01	20.00	101.9	71.90

of 25-30°C the concentration of silica is 16.2 ppm, at 35-40°C it is 22.1 ppm and at 45-55°C it is 28 ppm. In general, when the temperature increase by 10°C, the concentration of silica will increases by 12-14 ppm. The central part of the geothermal field has a high concentration of silica. Similarly, the highest concentration of fluoride exists in the center of the geothermal field. We can therefore define the geothermal field according to the distribution trend of silica and fluoride.

2.4.3 Recharge direction of geothermal water

According to the results of isotope analyses (Zhou and Cai, 1982) the deuterium value of the geothermal water is between 70% -75% , while the SO^{18} (oxygen 18) value is between 9% -10% . The plotting of deuterium versus oxygen 18 shows that most of the points are very near the standard Lei-Ge rainline without drift. The deuterium value increases from northwest to southeast. In the northern part of Tianjin the oxygen 18 value is higher than that in the southern part and its value is very similar with the meteoric water of the Yan Mountains (120 km north of Tianjin). Thus, the conclusion can be made that the groundwater is coming from the mountains to the north of Tianjin. In addition, according to the background value of tritium, (the content of tritium in the Zen-3 well is 0.7 TU), Zhou and Cai (1982) concluded that the geothermal water in the Tianjin area was precipitated approximately 40 years ago. Fig. 6 shows a schematic model of the Tianjin geothermal field (by Yao, 1980). The recent isotopic work indicates that the water flows rather from the Yan mountains in the north than the Taihang-shan mountains to the west.

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Schematic model of Tianjin low temperature geothermal field

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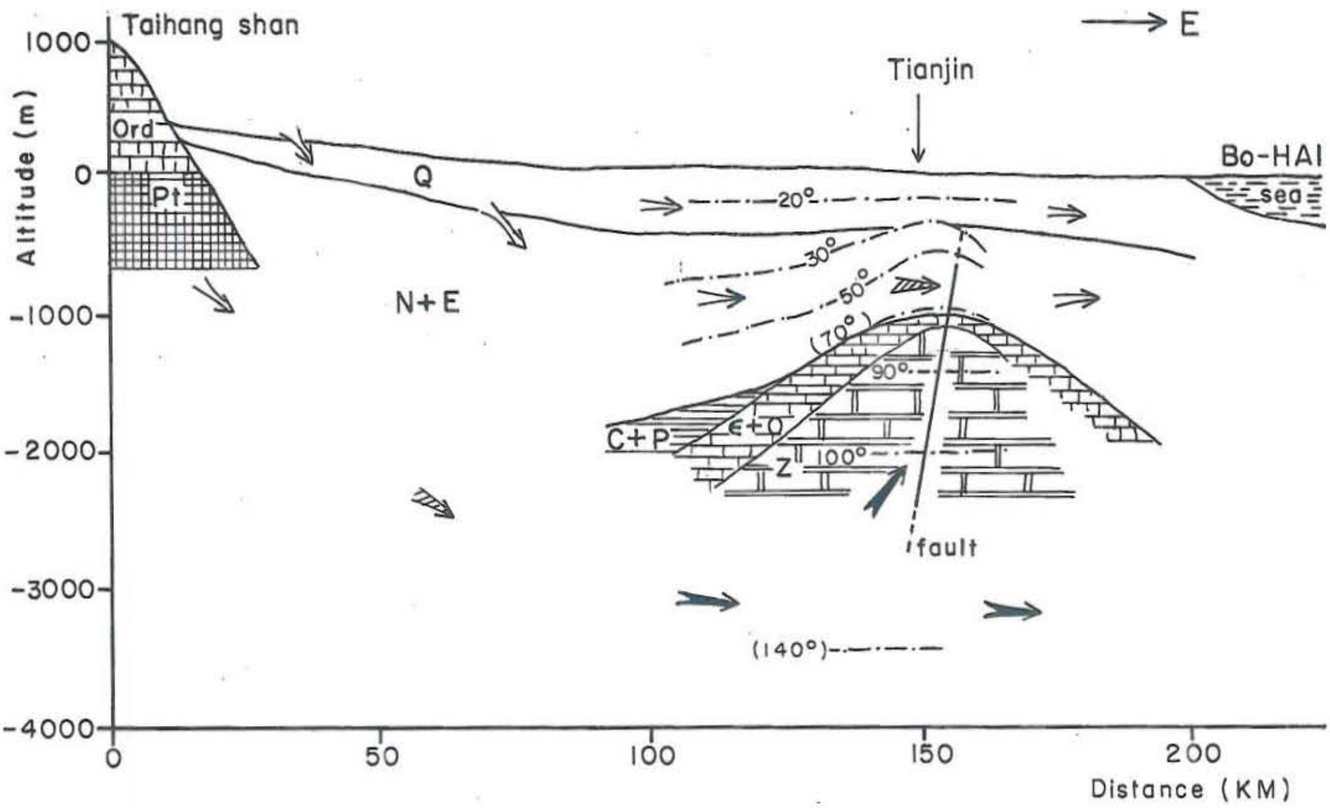
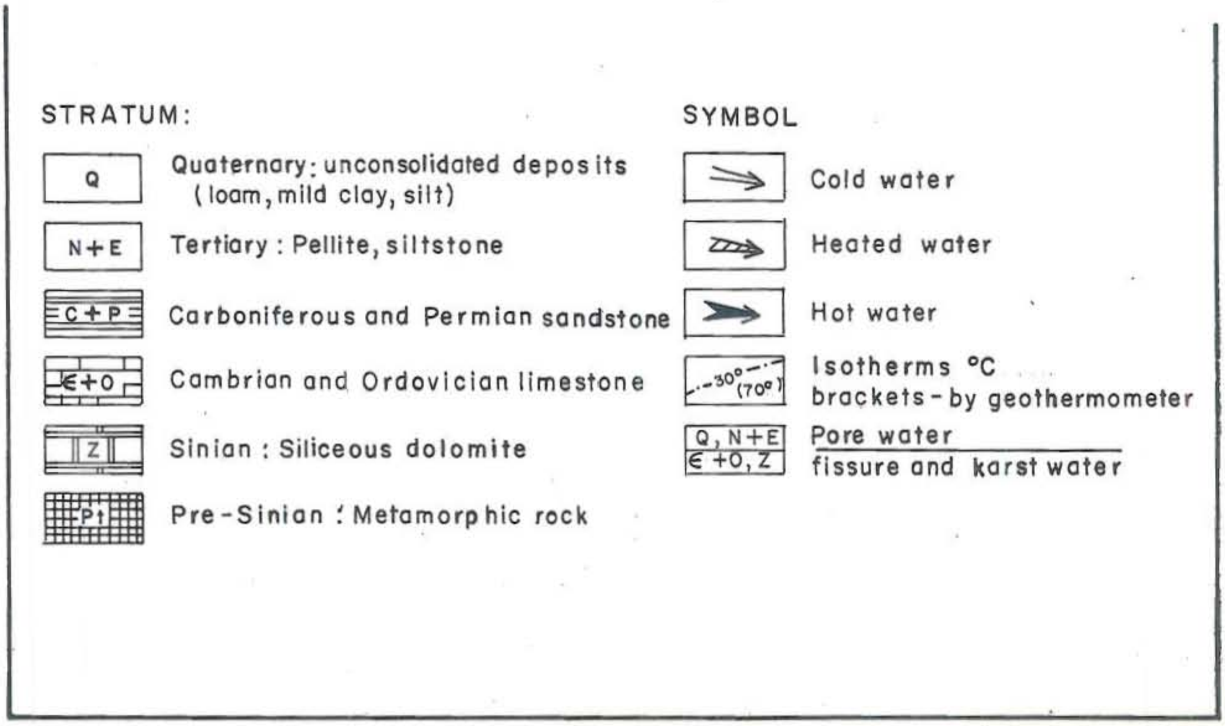
Fig. 6





2.5 Temperature and water level

2.5.1 Temperature

The Wang-Lan-Zhuang geothermal field is located on the Shuang-Yao horst. It is defined by the temperature gradient which is over 4°C/100 m. From Fig. 2 we can see that the highest temperature gradient in the Wang-Lan-Zhuang geothermal field in the Tertiary system is 8°C/100 m. The temperature in the shallow system increases with depth along nearly a straight line. It indicates the heat source to be the deeper bedrock and the heat transfer into the Tertiary system is presumably by conduction. The average measured temperature in this system is 56°C.

It must be pointed out that the highest temperature gradient is not centralized in the most shallow bedrock area. It is inclined to the west of the Bai-Tang-kou fracture and appears also on the east side of this fracture. Consequently, the West-Wang-Lan-Zhuang fracture is an active fracture and hot water moves along it from depth to shallower parts.

Comparing with the shallow system, the temperature gradient in the bedrock changes unregularly. The temperature gradient in the Ordovician system is greater (3°C/100 m) than that in the Sinian system (1°C/100 m). The highest measured temperature in the Ordovician system is 58°C but in the Sinian system it is 78°C.

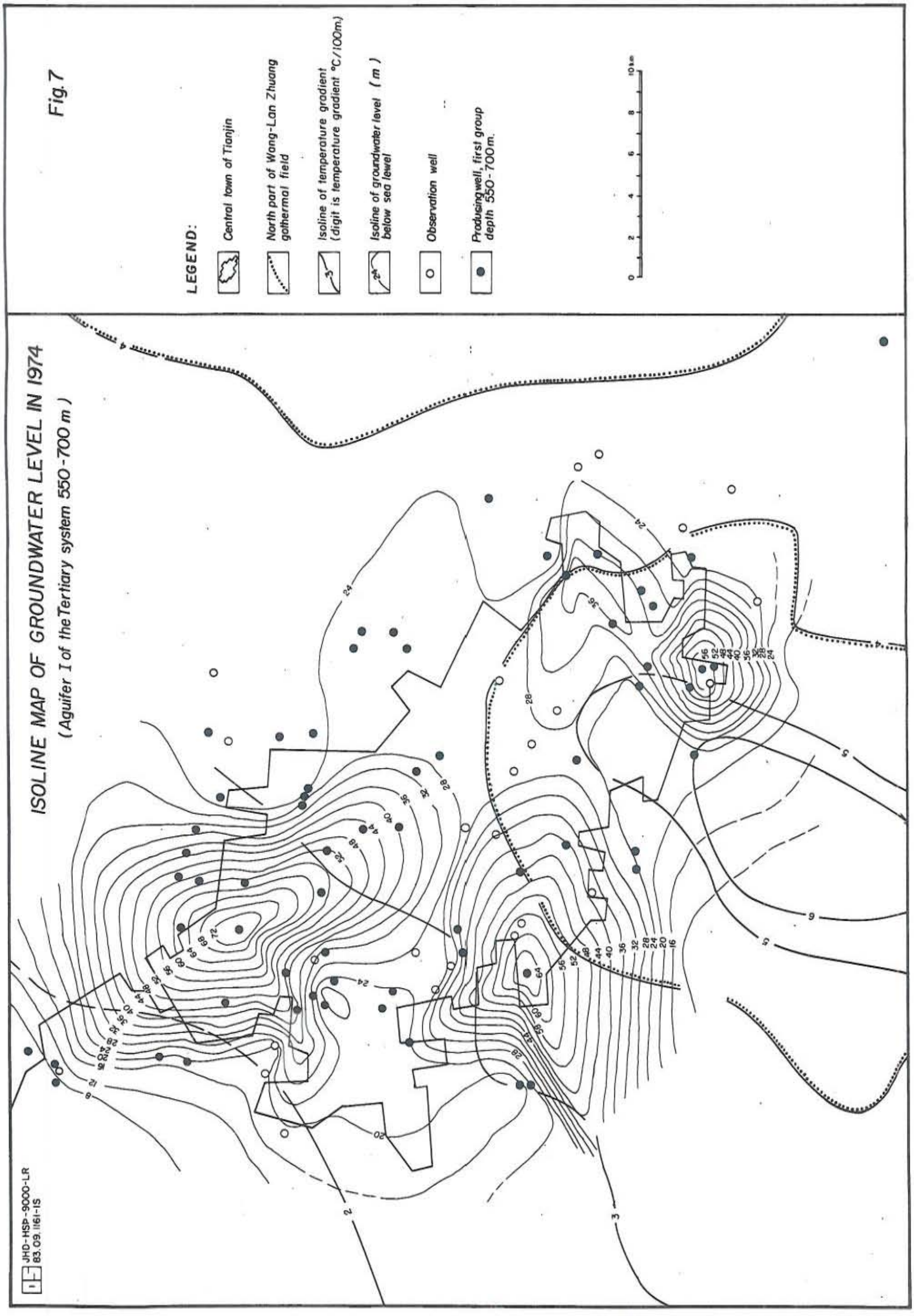
2.5.2 Water level

Because of the low hydrostatic gradient between Tianjin and the supposed recharge area in the Yan mountains, the flow into the geothermal system is probably very slow. Thus the recharge into the system is probably much lower than the discharge caused by pumping.

According to the water level in the first well drilled in 1934, the original pressure in the Tertiary system, by inference, was 12 m. Before 1972 every well was artesian. Due to the increasing output quantity of geothermal water, year by year, the water level drawdown has increased greatly, especially since the latter half of 1972. The artesian flow had stopped in all the wells by the end of 1982, and the total drawdown in this shallow reservoir was measured 45 to 55 m. The average drawdown has been 3.0 to 3.5 m/year in the recent years. As there is more control on the production of geothermal water from the three central parts of the town and as the output is increasing in the suburban areas, the increase in the water level drawdown is now much greater in the suburban areas than that inside the three central parts of the town. The cone of depression of the groundwater in the town has changed from shape V to shape U. Fig. 7 shows the isolines of the ground water level in 1974. Fig. 8 shows the increase in the drawdown from 1974 to 1982. In Fig. 8 one can see that the total drawdown in the suburb area is 35 to 40 m and in the central areas it is 5 to 10 m.

Fig. 9 shows the history of the water level drawdown in the Tertiary system from 1974 to 1982.

In the Ordovician and the Sinian systems in the basement, the water level in every well is still artesian. So far they are still free flowing. However, the water level is decreasing with time, even without production. For example, in August of 1980 the water level in the well WR1 of the Ordovician system was 15.35 m. In December of 1982 its water level was 3.43 m. The drawdown is almost 5 m/year. The water level in Z4 in the Sinian system changed from 31.9 m on 31 December 1978 to 28.5 m on 30 September 1982. The average drawdown is 0.7 m/year.


ISOLINE MAP OF GROUNDWATER LEVEL IN 1974
(Aguifer I of the Tertiary system 550-700 m)
Fig.7
LEGEND:
Central town of Tianjin
North part of Wang-Lan Zhuang gothermal field
Isoline of temperature gradient (digit is temperature gradient °C/100m)
Isoline of groundwater level (m) below sea level
Observation well
Producing well, first group depth 550-700m.
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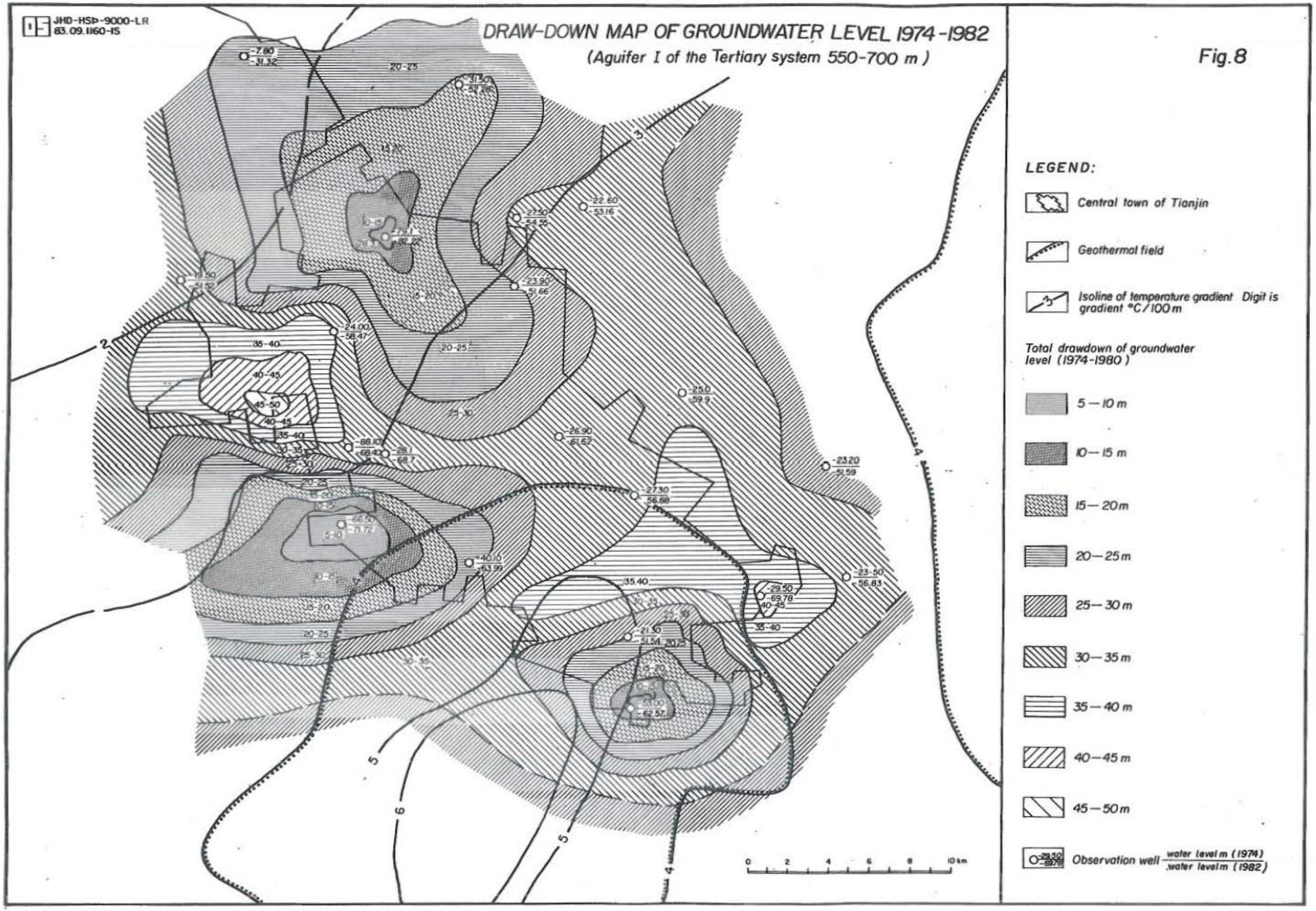
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DRAW-DOWN MAP OF GROUNDWATER LEVEL 1974-1982
(Aguifer I of the Tertiary system 550-700 m)
Fig. 8
LEGEND:
Central town of Tianjin
Geothermal field
Isoline of temperature gradient Digit is gradient °C/100 m
Total drawdown of groundwater level (1974-1980)
5—10 m
10—15 m
15—20 m
20—25 m
25—30 m
30—35 m
35—40 m
40—45 m
45—50 m
Observation well water level m (1974) / water level m (1982)
0 2 4 6 8 10 km

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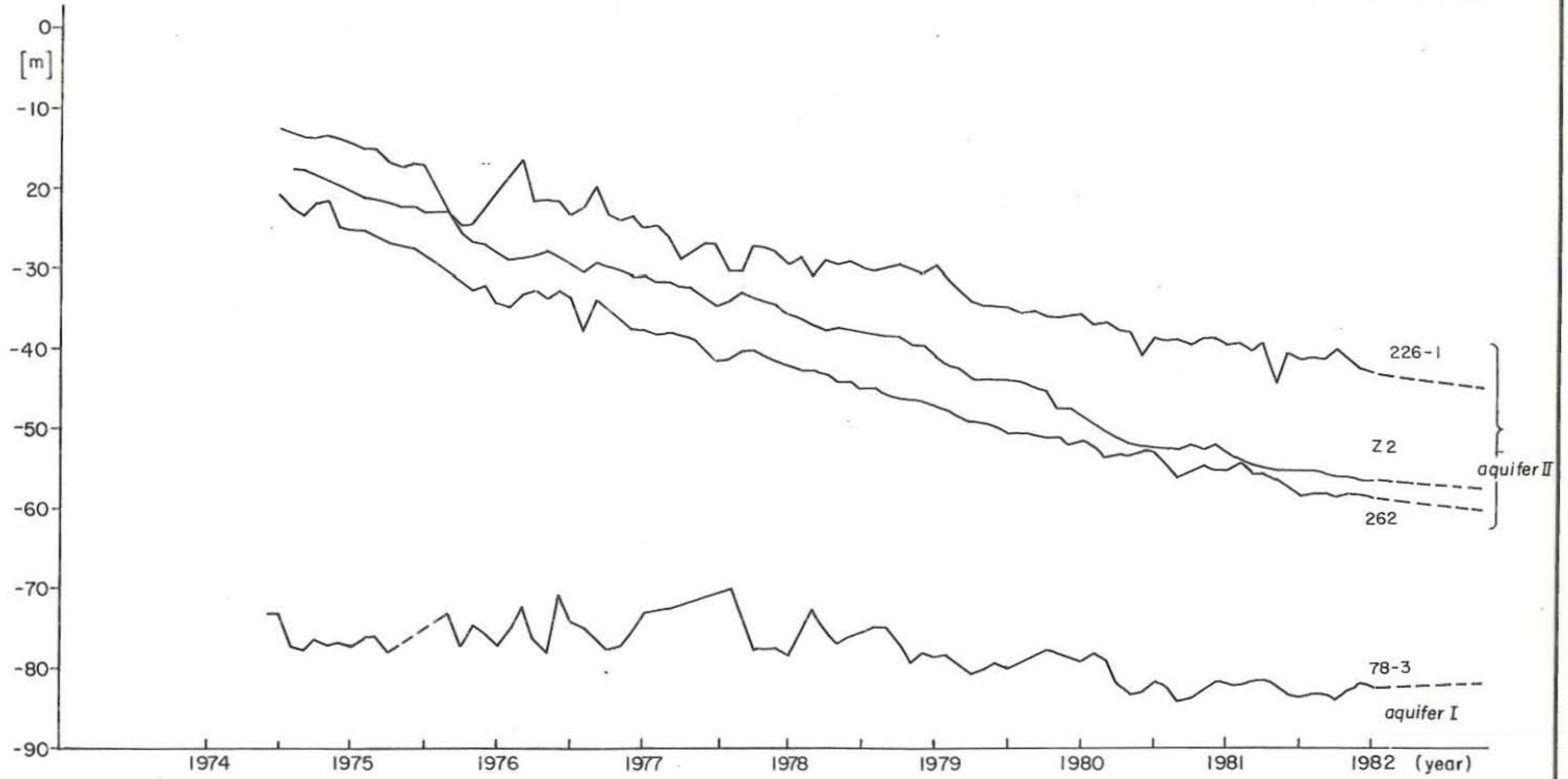
Fig. 9

DRAWDOWN HISTORY OF OBSERVATION WELLS IN TERTIARY SYSTEM



2.6 Production history

The first geothermal well in the Tertiary system was drilled in 1934, with a depth of 863.8 m and a producing temperature of 34°C. Drilling of new geothermal wells was then discontinued for a period of 33 years. By the end of the sixties, drilling was again started, and new geothermal wells have since been drilled every year. In 1973, the climate of the He-Bei plain in north China was seriously arid, so that the surface water was not enough to satisfy the water supply for industry. To deal with this problem of water shortage, wells were drilled in the urban area with a producing depth of 550 to 750 m. Most of these wells produced geothermal water for about 320 days per year. As a result of the continously increased producing quantity of geothermal water production year by year, the pressure in the reservoir of the Tertiary system faced a severe draw-down and the single well output decreased accordingly. The water levels of one third of the producing wells have now reached a drawdown to the critical pumping depth, and production of geothermal water from these wells has therefore been stopped.

After 1975, the production of geothermal water from the central town has been controlled. At the same time, most new geothermal wells have been drilled in the suburb areas to a depth of 800 to 1100 m. As an example all the 11 wells reaching to the lower Tertiary aquifer in the south suburb of Tianjin are located on the northern end of the Wang-Lan-Zhuang geothermal field.

2.7 Present status of utilization

The geothermal water resources in the Tertiary system in Tianjin were put into use in the beginning of the seventies and have since been extracted for use on a large scale. By the end of 1982, there were 211 geothermal wells in the area, of which 146 wells are actually utilized. So far, the total output is about 26 million tonnes per year, of which about 70% are used in industry, 25% for household requirements, and 5% in agriculture.

Industrial use: The geothermal water is mainly used as processing water for cotton and wool spinning, knitting and dyeing works and as a water supply for boilers. Among the advantages are the reduction in the use of coal, saving of both electricity and industrial salt for water softening, and whiteness of the fabrics and increased speed in colour dyeing and printing of the textile products. In addition, attractive results have been achieved by the utilization of geothermal water in making paper, in wood processing, food processing and chemical processing.

Public use: Here, the utilization of the geothermal water is mainly for space heating, for swimming pools and tubs in hotels, clubs and office buildings, resulting in large savings of coal.

Agriculture: Satisfactory results have been obtained from the use of geothermal water in simple greenhouses for growing seedlings, vegetable cultivation, poultry hatching and so on.

Seismic monitoring: In the west suburb, there is a seismic observatory which monitors the composition of geothermal water from well Z4 and correlates variations in the chemistry with the seismic activity and the earth deformation in the area.

2.8 Orientation and long-range planning

There is an appreciable increase of energy consumption in Tianjin city as a result of the development of urban construction and the progress of industrial and agricultural productivity, as well as the general improvement of the living standards of the people. It is therefore important to economize the geothermal energy. The geothermal energy is an important constituent of the local energy sources. According to the features both of the geothermal water and the distribution of the geothermal fields, the main uses of thermal water in the Tianjin area will in the future be oriented as follows: The geothermal water in the Tertiary system in the south suburb of the city will mainly be used for industrial processing. Emphasis will in the near future be laid on the reconnaissance and increased exploitation of the warmer fissure and karst geothermal water in the bedrock. At present there are 6 wells that penetrate into the bedrock. The bedrock thermal water has not yet been utilized to any marked extent. In the future, the bedrock geothermal water will be utilized for a district heating system in the area north of the sports college (Sun 1981).

3. RESERVOIR SIMULATION OF THE TERTIARY SYSTEM

3.1 Economical aspects

The geothermal water of the Tertiary system is a very important energy resource in the Tianjin area. To give a practical example of this, the local wool-washing factory using the 49°C hot water of the Tertiary system, can make annual savings of 2400 tonnes of coal and 1500 kW of electricity. Furthermore it saves salt for water softening, and finally due to the good quality of the water, considerable improvements are obtained in the production quality. Due to the advantages of the hot water from this system, both regarding temperature and the chemical content, additional new wells will be drilled in the near future, especially into the lower aquifer (Aquifer II) of the Tertiary system.

Based on the experience of the upper aquifer (Aquifer I) of the Tertiary system, it can be inferred that with increased production from Aquifer II the water level will decline year by year. The decline of the water level is a function of the pumping rate. As there are technical and economic limits to the acceptible decline in the water level, there are some interesting economic factors concerning the functional relationship between the flow rate and the decline in the water level.

These factors include the number and depth of wells, the depth at which deep-well pumps have to be placed to attain the desired flow rate, and the energy requested to lift the water from depth.

At present, there are 89 wells located in the reservoir Aquifer I and 11 wells are located in the reservoir of Aquifer II. The latter are in the northern part of the Wang-Lan-Zhuang geothermal field. The maximum lifting capacity of pumps presently used in Tianjin is 90 m, and the maximum depth of the existing 12" well casings is also 90 m. The minimum submerged depth of the pumping head is

5 m. When the pumping is started the initial drop in water level is 10 to 15 m in 4 hours. In general terms, on one hand we need to increase the production from the reservoir, on the other hand a protection of the water resources is required in order to prevent the water level from falling and thus to secure future successful utilization of the existing wells.

3.2 Reservoir properties of Aquifer II

The depth to the feeder zone in the individud wells varies from 13 to 57 m. The effective average thickness of the reservoir is 30 m. The lithological character of the reservoir is the fine grain size. Based on a number of physical laboratory experiments, some of the reservoir parameters have been obtained. For example, the porosity of the fine grain is 0.32 to 0.36, while effective porosity is only 0.1 to 0.15; the density of the aquifer matrix is 2.6 g/cm3, while the fluid density is 0.99 g/cm3. According to the field exploitation results, the average temperature is 50°C. Experimental results indicate that the conductivity of the reservoir is 0.3 to 0.4 cal/cm sec deg; specific heat is 0.23 cal/g deg.

The most important parameter governing the water level versus the flow rate relationship is KM, the permeability thickness of the reservoir. In order to calculate these parameters, a interference well test was conducted in 1973. Table 3 shows the test results. By using the type curve matching method of the Theis solution, the following parameters were obtained:

$$W(u) = 0.0381$$
$$s = 0.1 \text{ m}$$
$$1/u = 0.443$$
$$t = 365 \text{ min}$$

Hence, the transmissibility coefficient can be calculated:

$$T = \frac{Q}{4\pi s} \cdot W(u)$$

$$= 56.4 \ m2/day = 0.00065 \ m2/s.$$

The calculated pressure transicent coefficient:

$$a = \frac{r2}{4t} \cdot \frac{1}{u} = 9.18 \cdot 10^5 \ m^2/day$$

The calculated coefficient of storage:

$$S = T/a = 0.0000614$$

The distance between the observation well and the producing well is 1450 m.

By using the water level of build-up period of 8445 minutes to calibrate the water level drawdown the following calculations can be made:

$$s = \frac{Q}{4\pi T} \left(W(\frac{r^2}{4at}) - W(\frac{r^2}{4a(t-t_0)}) \right)$$

$$= \frac{77.45 \cdot 24}{4 \cdot \pi \cdot 56.4} \cdot \left(W(\frac{1450^2}{4 \cdot 9.18 \cdot 105 \cdot 8445}) - W(\frac{1450^2}{4 \cdot 9.18 \cdot 105(8445-6210)}) \right)$$

$$= 2.62 \cdot 1.087 = 2.847 \ m.$$

The measured value of 2.870 m for a period of 8445 miniutes compared to the calculated value of 2.847 m gives an error of only 0.0227 (1%). Hence, the calculated parameters T and S can be considered as accurate (Zhang Dao-Zhen, 1974).

TABLE 3. Interference well test

time minutes	pumping rate tons/hr	observation well water level m	drawdown of water level m
0	77.45	3.404	0.0000
285	77.45	3.455	0.0051
1245	77.45	3.435	1.0310
1725	77.45	4.965	1.5610
3165	77.45	6.495	3.0910
4125	77.45	6.655	3.2510
4605	77.45	6.885	3.4510
5564	77.45	7.250	3.8460
6045	77.45	7.425	4.0210
6210	0.00	-	-
7005	0.00	7.213	3.8090
7485	0.00	6.855	3.4510
8445	0.00	6.274	2.8700
8925	0.00	6.061	2.6570
9885	0.00	5.730	2.3260
10365	0.00	5.510	2.1060
11325	0.00	5.320	1.9160
11805	0.00	5.201	1.7970
12765	0.00	5.090	1.6860

3.3 Reservoir simulation

3.3.1 Previous study

This section describes some presvious reservoir modelling studies on both Aquifer I and Aquifer II of the Tertiary system.

Analysis method without leakage of Aquifer I in 1981

This method was based on the assumption that the reservoir is infinite, homogeneous and uniform in thickness and confined by impermeable insulated boundaries. This method was used to define the parameters of the reservoir of Aquifer I. According to the Theis equation we have

$$s(r,t) = \sum_{k=1}^{V} \sum_{i=1}^{N} \frac{1}{4\pi T} \cdot (Q_{k,i} - Q_{k-1,i}) \cdot W(u)$$

$$u = \frac{r_i^2 \cdot S}{4T(t-t_{k-1})}$$

The optimum seeking method has been used to determine the parameters T and S. The optimum parameters

$$T = 100\ m^2/day = 0.0012\ m^2/sec, \qquad S = 0.001.$$

The finite difference method

The method is based on the same assumptions as the one previously described. In the Tertiary system, Aquifer I, the finite difference method has been used to calibrate the parameters T and S. By using this method, the whole area was divided into 282 small elements by using a net of regular squares. By using the conservation of mass and the conservation of momentum, the finite differential equation was established as follows:

$$T = \left(\frac{H^{k+1}_{i-1,j} - 2H^{k+1}_{i,j} + H^{k+1}_{i\ 1,j}}{\Delta x^2} + \frac{H^{k+1}_{i,j-1} - 2H^{k+1}_{i,j} + H^{k+1}_{i,j\ 1}}{\Delta x^2}\right) + Q$$

$$= S\ \frac{H^{k+1}_{i,j} - H^{k}_{i,j}}{\Delta t}$$

The initial waterlevel and boundary conditions are known from previous measurements.

To solve the equation, the implicit method was used. The SOR programme was used to compute the parameters T and S, by minimizing the standard deviation of measured and computed values. The calculated parameters are as follows:

$$T = 80.0\ m^2/day = 0.00093\ m^2/s, \qquad S = 0.0008.$$

3.3.2 A simplified conceptual model of the reservoir

The average water level drawdown in Aquifer I and Aquifer II is 3.8 m/year and 4.2 m/year respectively. Prior to production from Aquifer II in 1972, the initial water level difference between the two aquifers was 15 m. By the end of 1981, the water level difference had been reduced to 8 m. The explanation for this is a) that the storage coefficient of Aquifer I is bigger than that of Aquifer II, and b) that analysis has shown that some leakage could possibly take place from Aquifer II through the semi-porous layer across to Aquifer I. Thus, a simplified conceptual model of the reservoir has been established. The hydrogeological section including the aquifers and aquicludes is described in Fig. 10.

In this conceptual model, the heat enters from the basement by conduction. The extent of the reservoir from west to east measures 13 km, and from north to south 9 km, a total area of 117 km^2.

The assumptions used for this conceptual model are as follows:

1) The reservoir is infinite, homogeneous and uniform in thickness with equal transmissivity in every direction.

2) The ground water flow in the aquifer is two dimensional and follows Darcy's Law.

3) The top and bottom of the Tertiary system are assumed as being impermeable boundaries.

4) In case of water level decline, the water is released from the pore of the aquifer instantaneously and the storage coefficient of the aquifer is assumed constant.

5) Given that the potential difference of the water level of the two aquifers is only in the vertical direction and that the leakage is one dimensional, the storage released from the semiporous layer is neglected.

6) It is assumed that the potential of Aquifer I does not change with time.

3.3.3 Method of analysis - leakage solution

The total leakage through the semiporous layer is

$$Q = \int_0^\infty 2\pi r \frac{s(r)}{b} \cdot k \, dr$$

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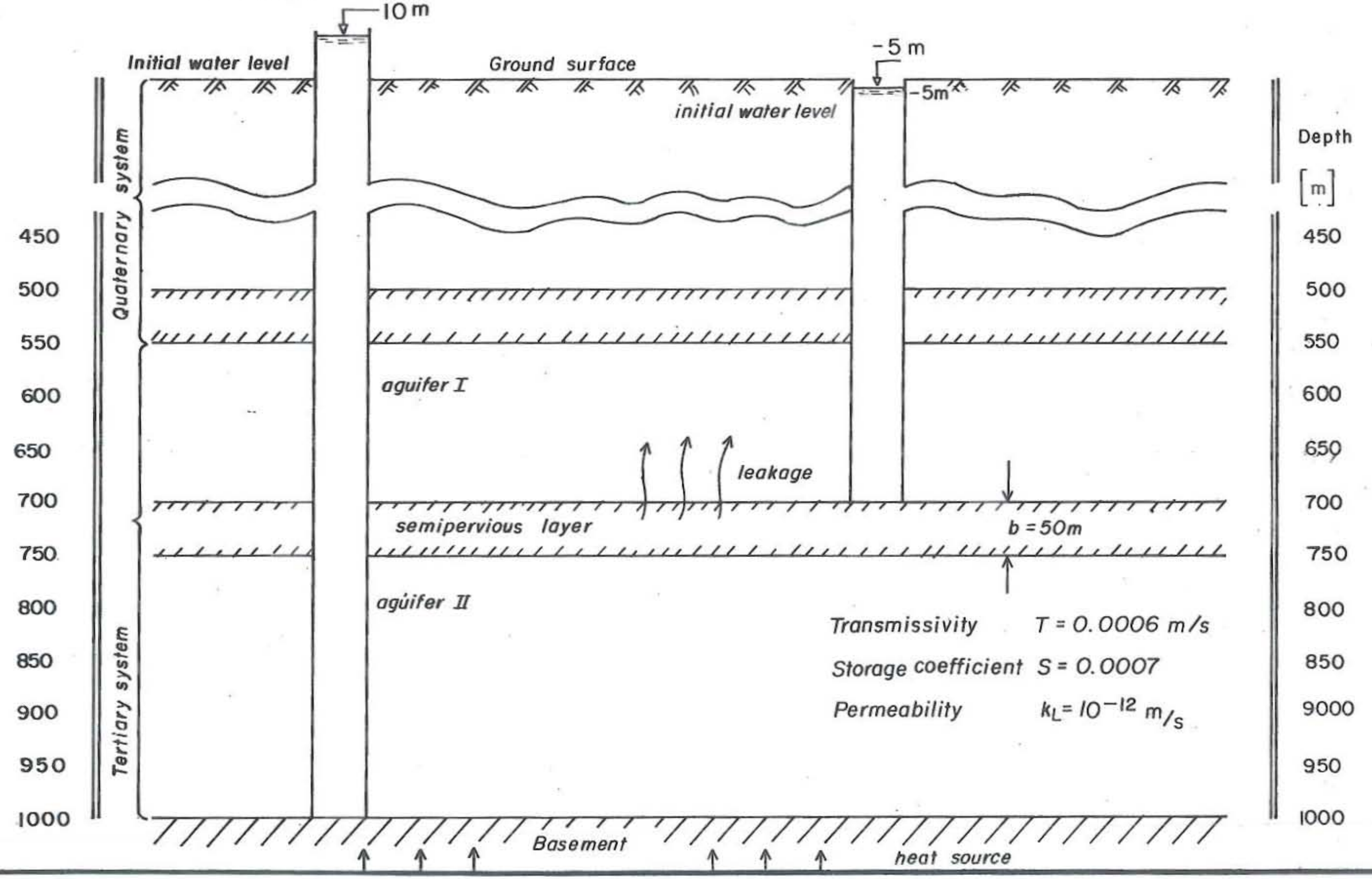
Schematic cross-section of north part of Wang-Lan-Zhuang Geothermal field in Tianjin

Fig. 10



By including the leakage in the continuity equation, the differential equation is as follows in terms of drawdown:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial s}{\partial r} - \frac{s}{B^2} = \frac{S}{T}\cdot\frac{\partial s}{\partial t}$$

where

$$B^2 = \frac{Tb}{k}$$

The boundary condition:

$$s(r,o) = 0 \qquad r > 0$$

$$\lim_{r\to\infty} s(r,t) = 0 \qquad t > 0$$

$$\lim_{r\to 0} (2\pi r\cdot\frac{\partial s}{\partial r}\cdot T) = Q \qquad t > 0$$

The solution of the above equation is

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{1}{y}\, e^{-y-\frac{r^2}{4B^2y}}\, dy$$

$$= \frac{Q}{4\pi T}\, W(u,\frac{r}{B}); \qquad u = \frac{r^2 S}{4Tt}$$

The superposition pattern of the equation both in space and time is

$$s(r,t) = \frac{1}{4\pi T}\cdot\sum_{k=1}^{V}\ \sum_{i=1}^{N}\cdot(Q_{k,i} - Q_{k-1,i})\cdot W\cdot(u,\frac{r_i}{B})$$

$$u = \frac{Sr_i^2}{4T(t - t_{k-1})}$$

3.3.4 Preparation of data

Pumping rate

The geothermal field is divided into five producing areas, A1 - A5 (Fig. 11). Two wells are placed in each of the producing areas A1 to A4 and three wells are placed in producing area A5. Pumping is located in the center of each area, and every area is regarded as one big well. Hence, the calculated results, using this model, can only give a rough approximation. Table 4 and Fig. 12 - 16 show the pumping rate in each producing area in tonnes/month.

In order to prepare the data for calculation of the water level drawdwon, the following computer programmes are used:

1) The RADATE programme, for storing and filtering of raw data in tonnes/month.

2) The PUMPLS programme, to change the units of the pumping rate into l/s.

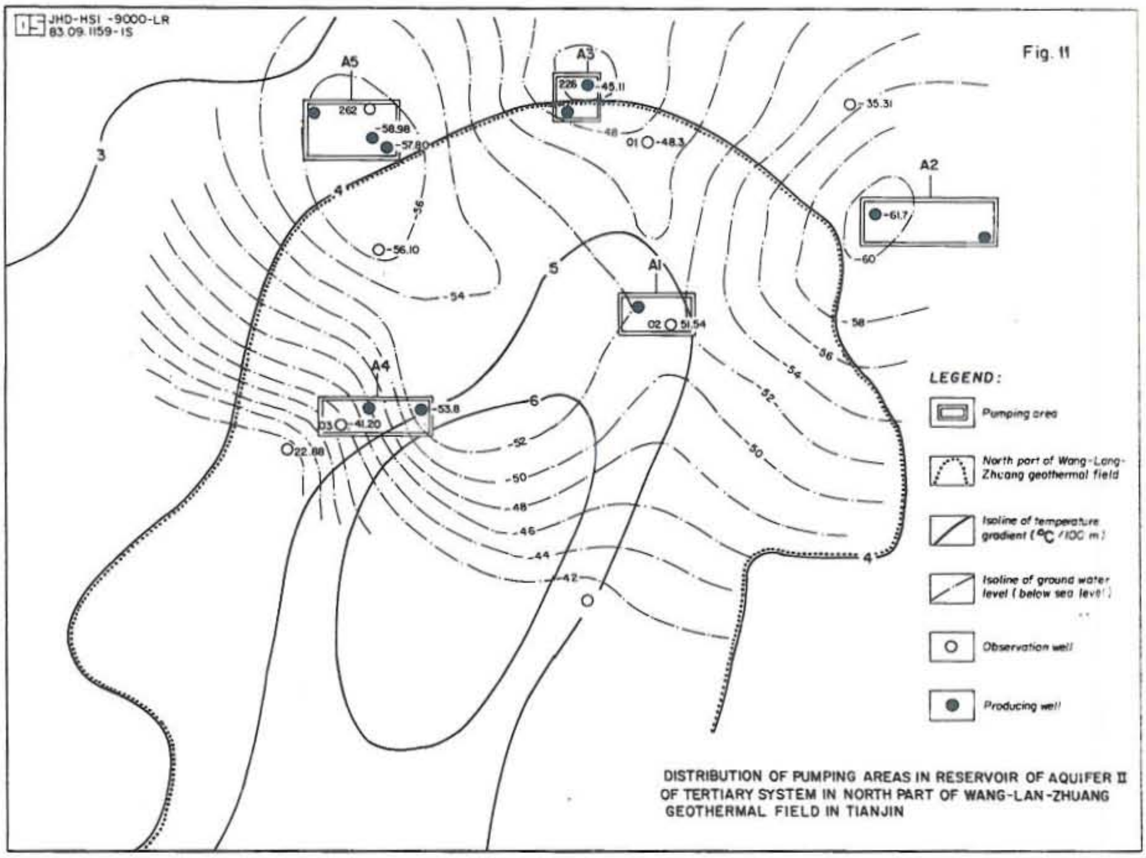
3) The SMOO programme, to smoothen the step function. The data is run through the SMOO programme three times over.

The SMOO programme uses the following equation:

$$Q(I) = \frac{Q(I-2) + Q(I+2) + 4(Q(I-1) + Q(I+1)) + 6\,Q(I)}{16}$$

$$I = 3, \ldots V-2$$

These programmes are supplied by VATNASKIL Consulting Engineers Ltd.



DISTRIBUTION OF PUMPING AREAS IN RESERVOIR OF AQUIFER II OF TERTIARY SYSTEM IN NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

TABLE 4. Pumping rate in tonnes/month from producing areas A1-A5 in Aquifer II of the Tertiary system, 1974 - 1981.

Pumping area	1974	1975	1976	1977	1978	1979	1980	1981
A1	45000	51830	48540	51000	58000	67000	75000	79000
A2	29200	37400	55480	54640	52560	50370	47350	44824
A3	40800	38500	40880	46000	59000	67000	72000	80000
A4	7812	9200	22000	25000	31000	38000	45000	51000
A5	91980	82828	78353	63770	67890	63700	58400	54810
Total	214792	220758	245253	240410	268450	286070	297750	309634

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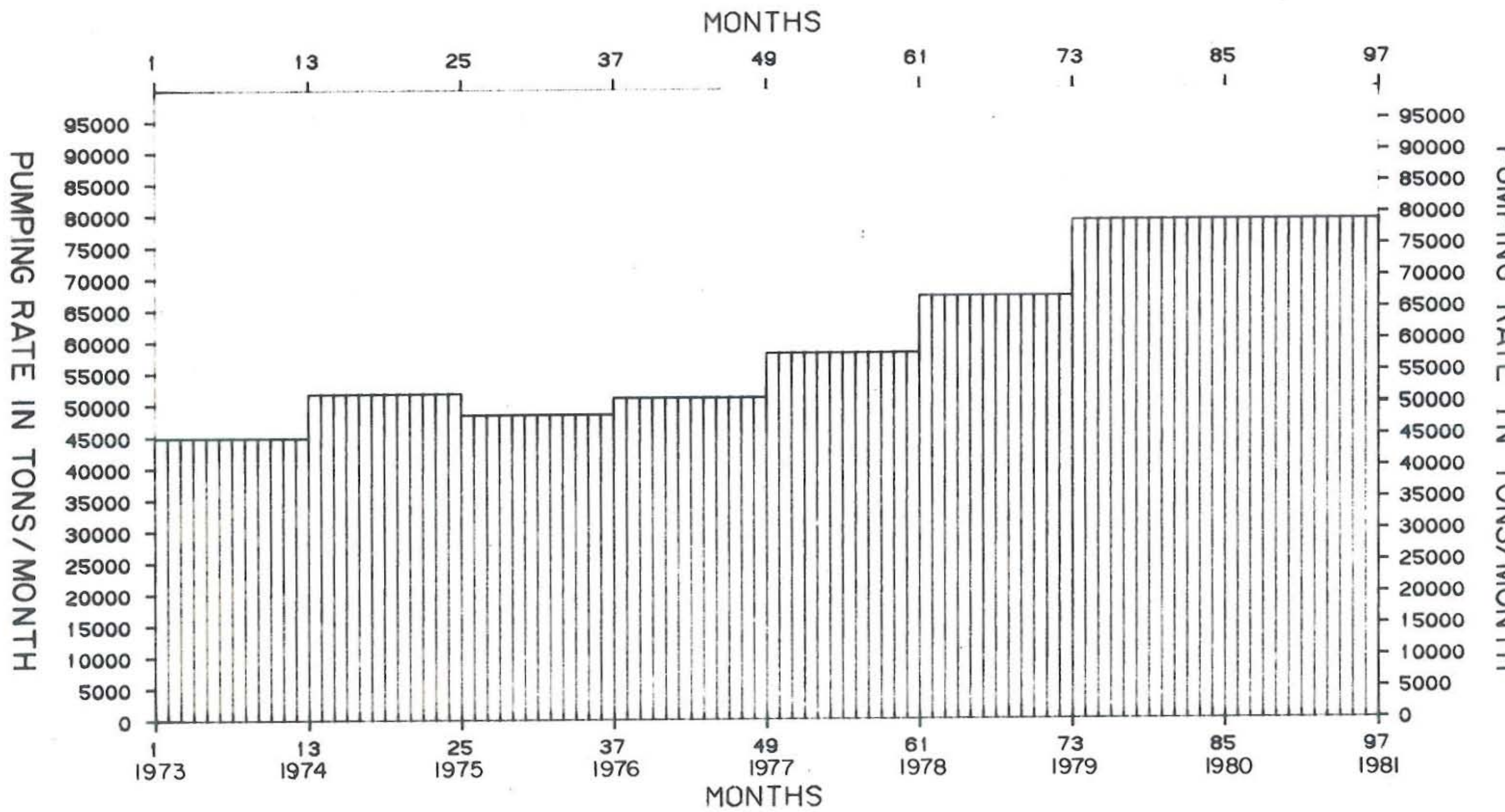
NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

Fig. 12



PUMPED WATER FROM PRODUCING AREA A1

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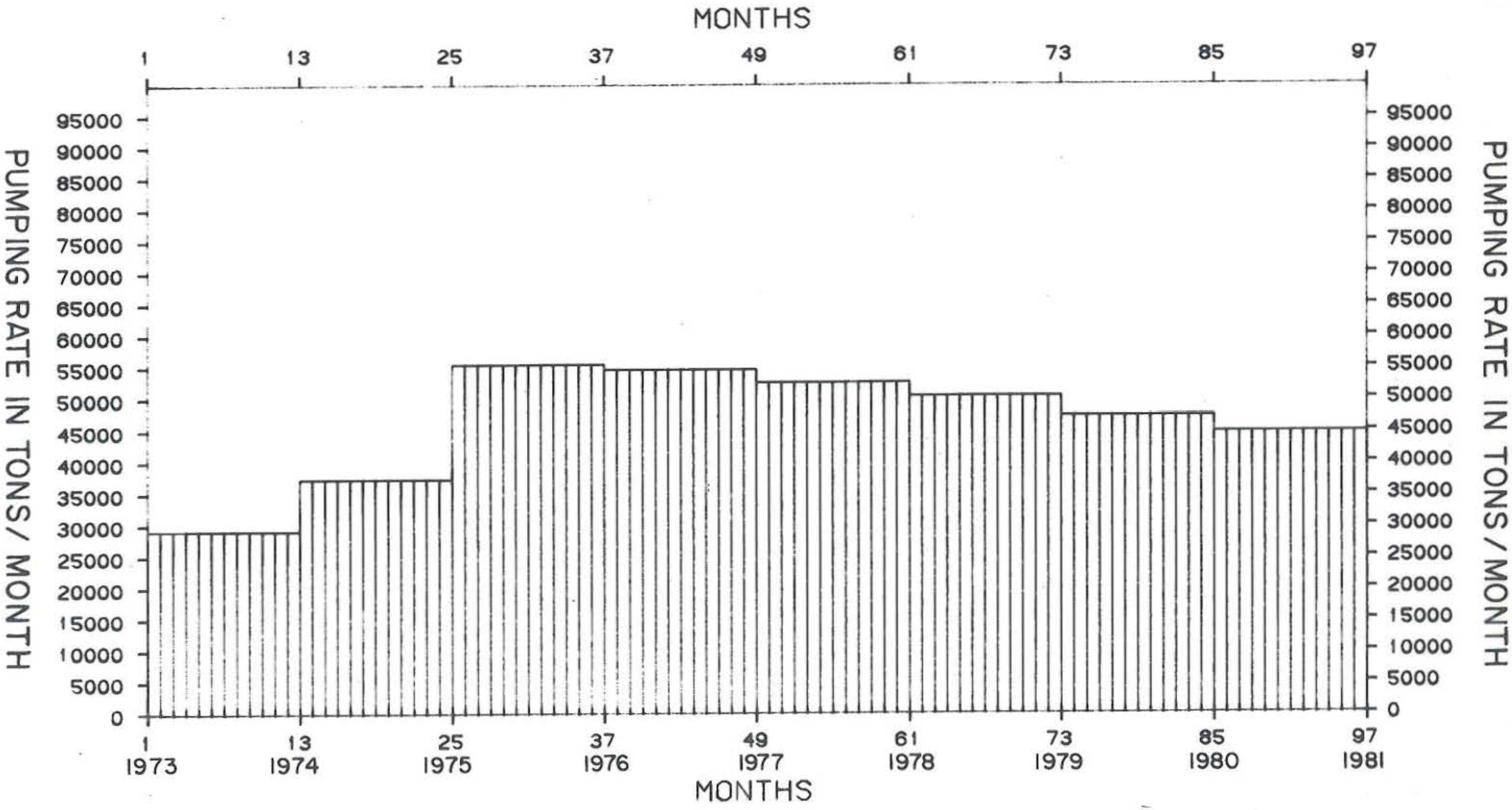
NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

Fig. 13



PUMPED WATER FROM PRODUCING AREA A2

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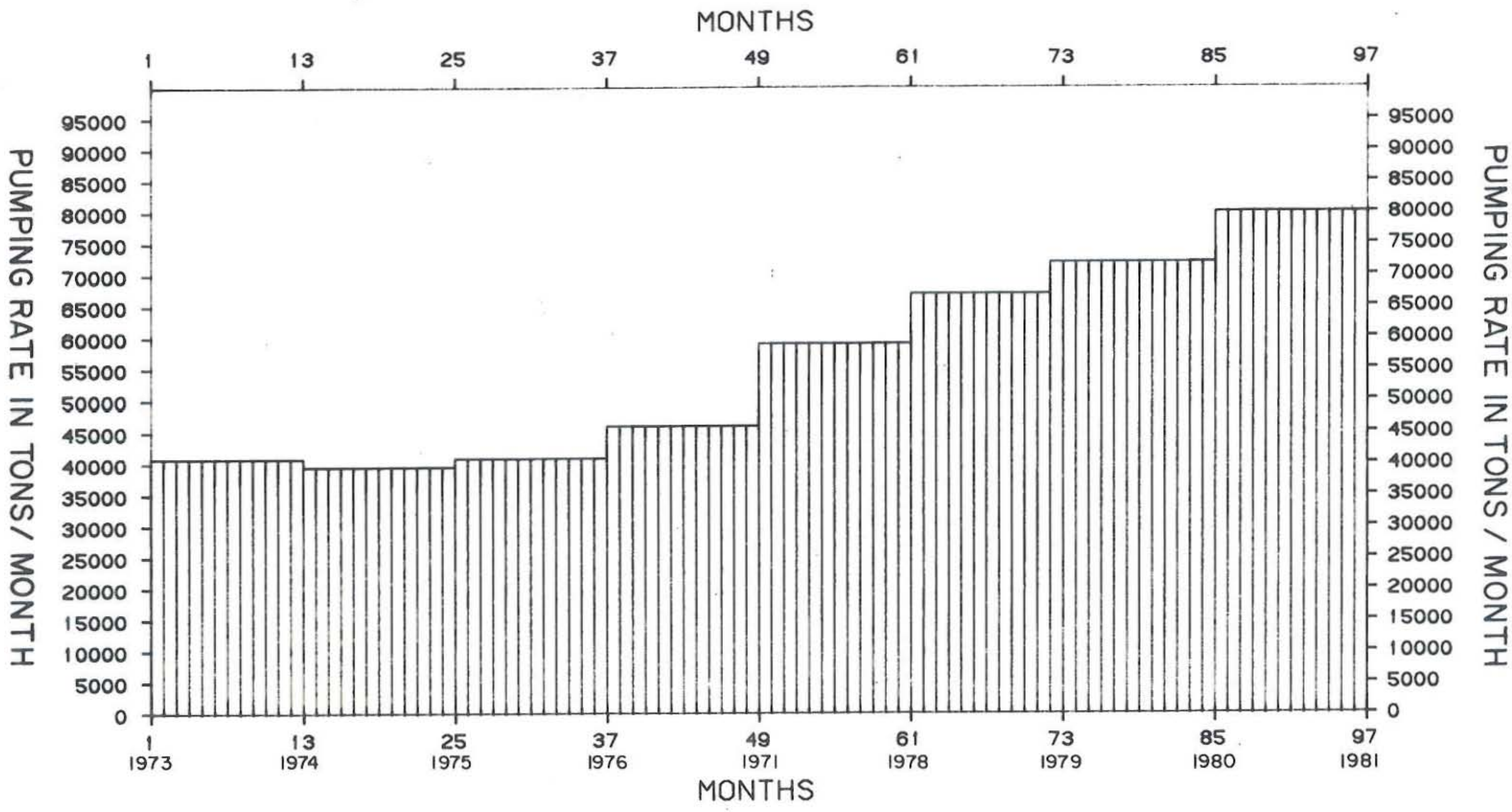
NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

Fig. 14



PUMPED WATER FROM PRODUCING AREA A3

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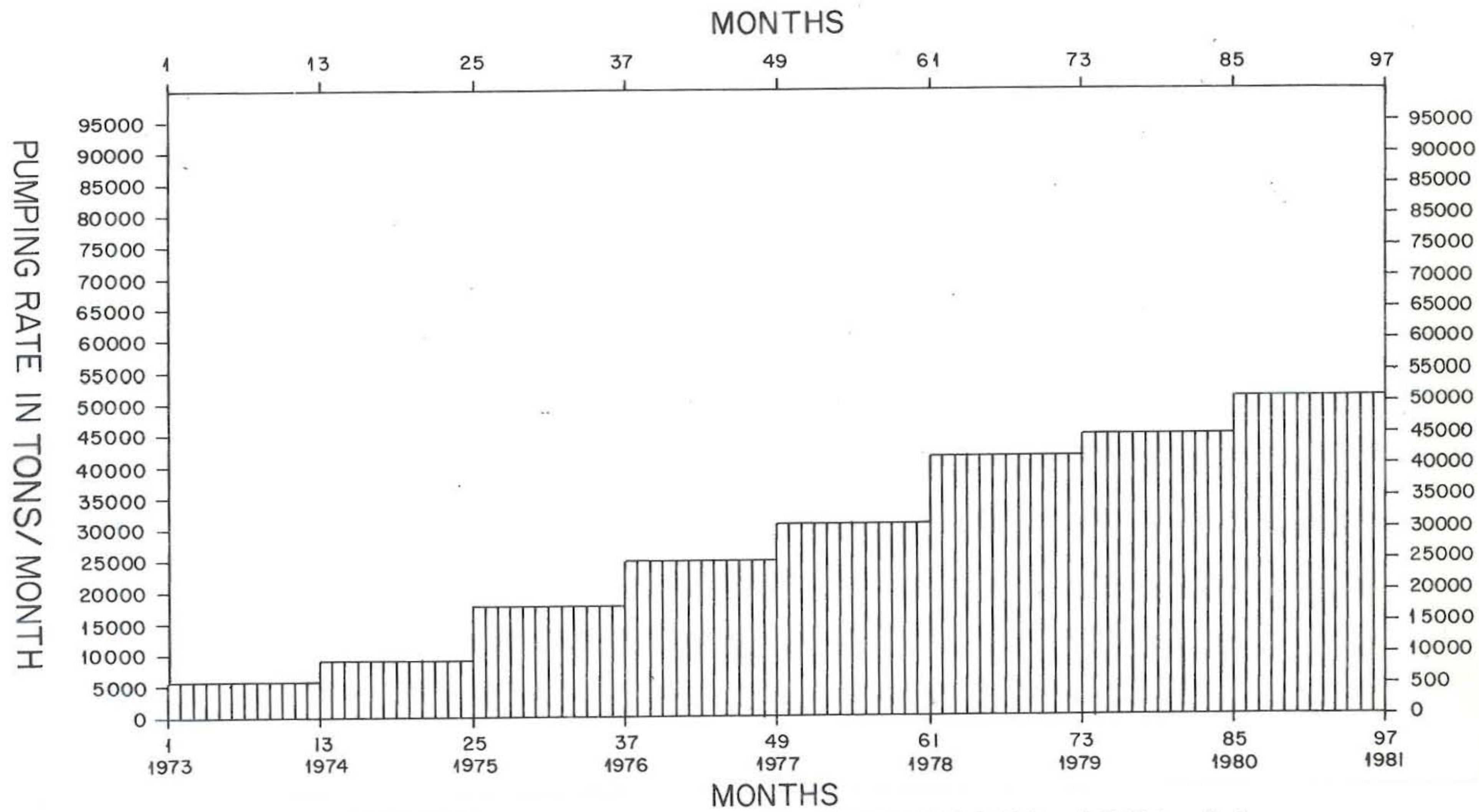
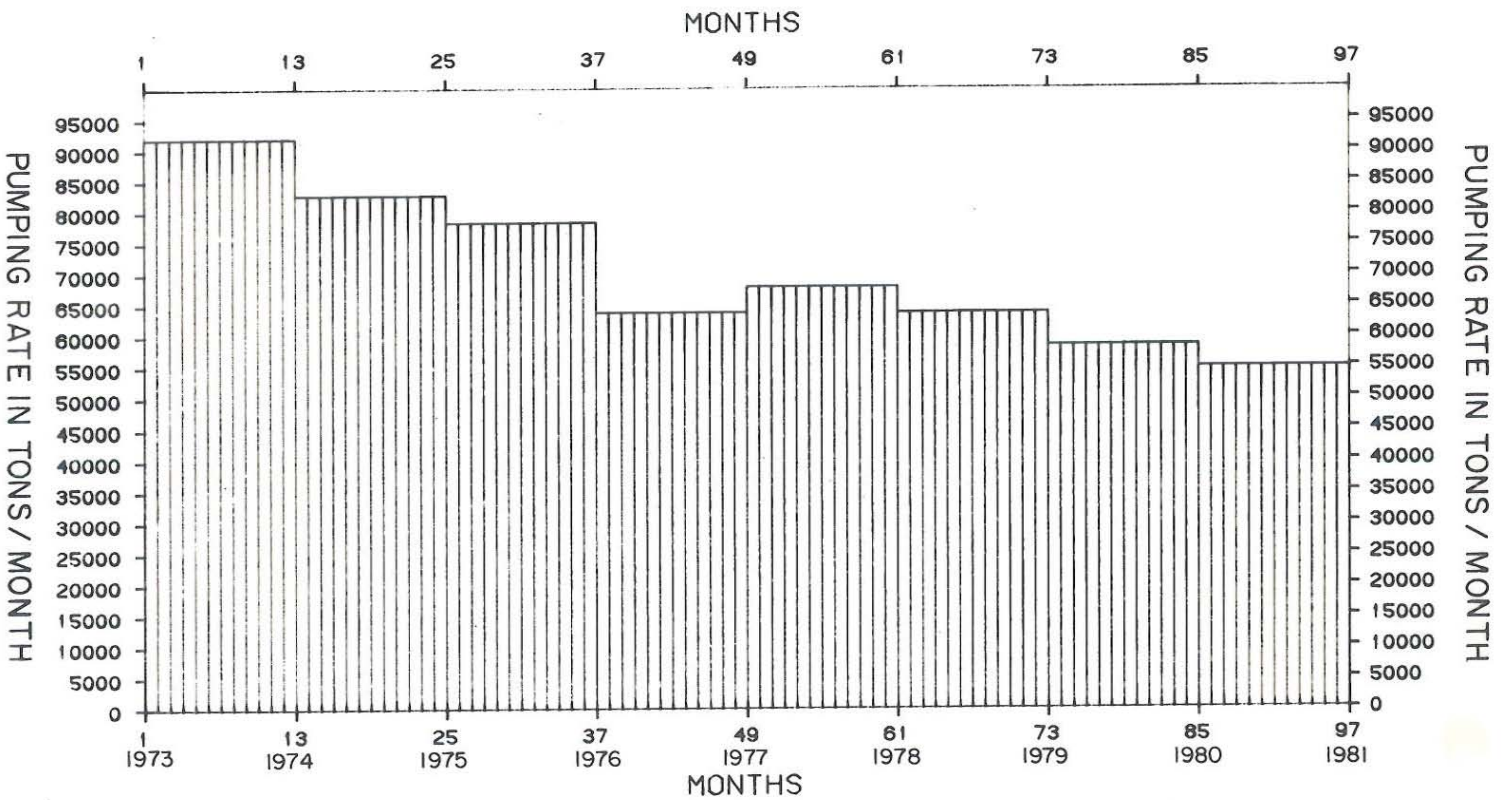
NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

Fig. 15



PUMPED WATER FROM PRODUCING AREA A4



PUMPED WATER FROM PRODUCING AREA A5

Water level in Aquifer II

There are three observation wells 01, 02, 03 in the reservoir of Aquifer II. To create the necessary draw-down files, the input data of the average value of the water level during a period of one month is run by the RADATE programme. The necessary preparation of the data is then obtained by use of the two programmes, HRLIST and HRVDB.

Observation well 01 is located near producing area A3.
Observation well 02 is located inside producing area A1.
Observation well 03 is located inside the producing are A4.

For a more detailed flow diagram see Fig. 17. The relative distance between observation wells and producing areas is given in Table 5.

3.4 Calibration of reservoir parameters

The NELL2 computer programme calculates the water level drawdown by using the actual pumping rate and the parameters T, S, k, b, X, Y. To calibrate these parameters the HRPPLO programme is used to calculate the following equations:

1) The average value of the calculated water level

$$HRM = \frac{\sum_{i=1}^{N} HR}{N}$$

2) The average value of the measured water level

$$HMM = \frac{\sum_{i=1}^{N} HM}{N}$$

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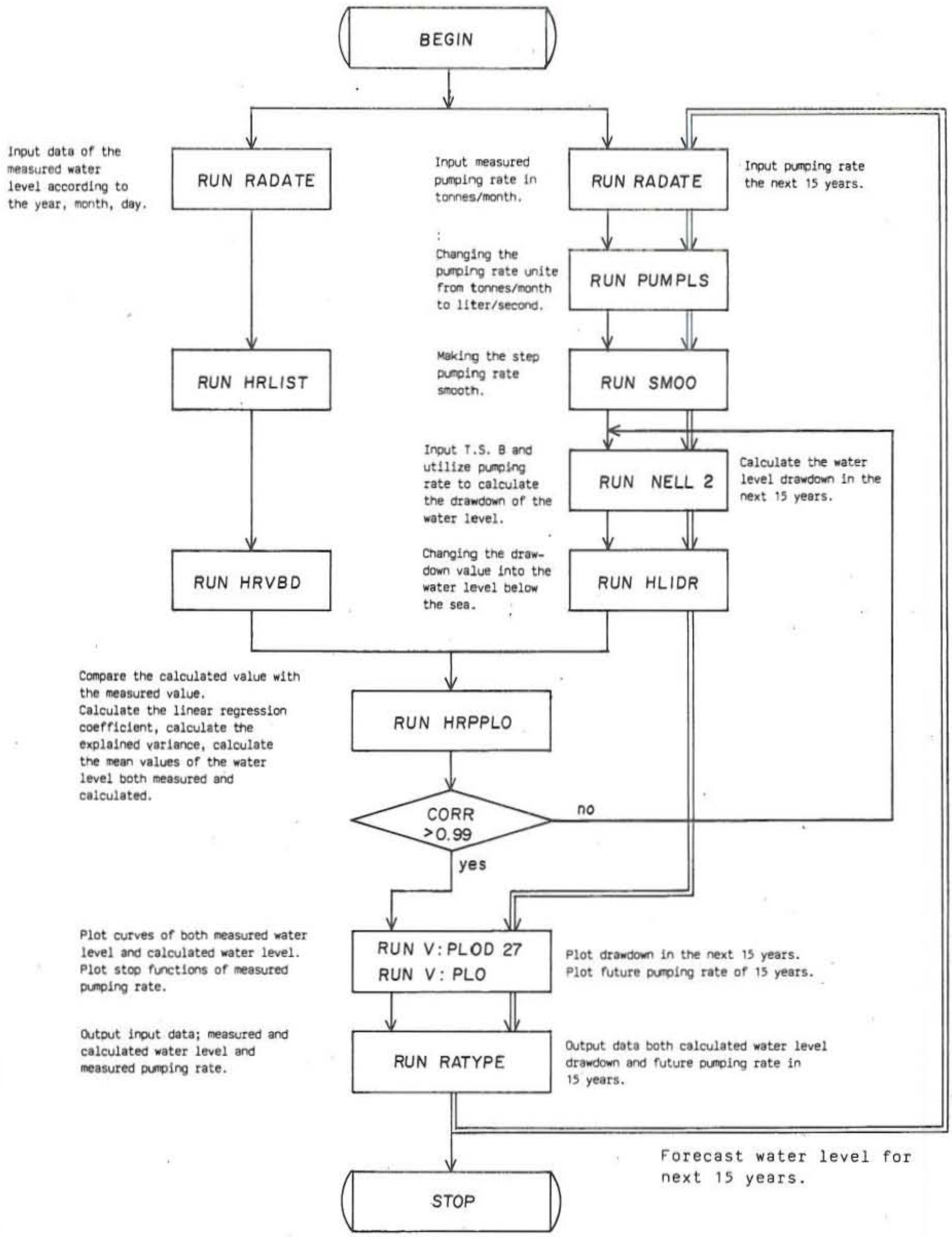
Fig. 17

FLOW DIAGRAM OF COMPUTR PROGRAM



3) The regression coefficient:

$$CORR = \frac{\sum_{i=1}^{N} \left(HM \cdot HR - \frac{\sum_{i=1}^{N} HR \cdot \sum_{i=1}^{N} HM}{N} \right)}{\left(\sum_{i=1}^{N} HM^2 - \frac{\sum_{i=1}^{N} HM}{N} \right) \cdot \left(\sum_{i=1}^{N} HR^2 - \frac{\sum_{i=1}^{N} HR}{N} \right)}$$

4) The explained variance:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (HR - HM)^2}{\sum_{i=1}^{N} \left(HM^2 - \frac{HM}{N} \right)}$$

When CORR > 0.99, $R^2 > 0.98$ calibration should terminate.

Table 6 and Fig. 18 - 20 show the calibration results. Finally the parameters T, S and k are defined.

$b = 50$ m; $T = 0.0006\ m^2/s$;

$S = 7 \cdot 10^{-4}$; $kL = 10^{-12} m/s$.

The leakage coefficient, B, is then calculated;

$$B = \sqrt{\frac{Tb}{kL}}$$

$$= \sqrt{\frac{0.0006 \cdot 50}{10^{-12}}} = 1.732 \cdot 10^5 m$$

Attention should be drawn to the fact that some of the pumping data from the producing areas A1 and A3 are not very accurate. This has caused readjustment of pumping data collected after the year of 1978.

TABLE 5. Location of observation wells.

Observation wells	Pumping areas A1 X	Y	A2 X	Y	A3 X	Y	A4 X	Y	A5 X	Y
01	150	-2850	4850	-1250	1000	1000	-4650	-4600	-5050	200
02	-250	200	4450	1700	-1400	4050	5000	-1500	-5400	3300
03	5400	1700	11000	3400	5750	4250	650	150	200	5000

The observation wells are placed in origo.

TABLE 6. Calibration results

Calibrated result	Observation well 01	02	03
Linear regression coefficient	0.9933	0.9988	0.9936
Explained variance	0.9831	0.9840	0.9770
Average calculated water level, msl.	-30.5100	-36.7900	-20.2200
Average measured water level, msl.	-29.8800	-37.0600	-21.1200

NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

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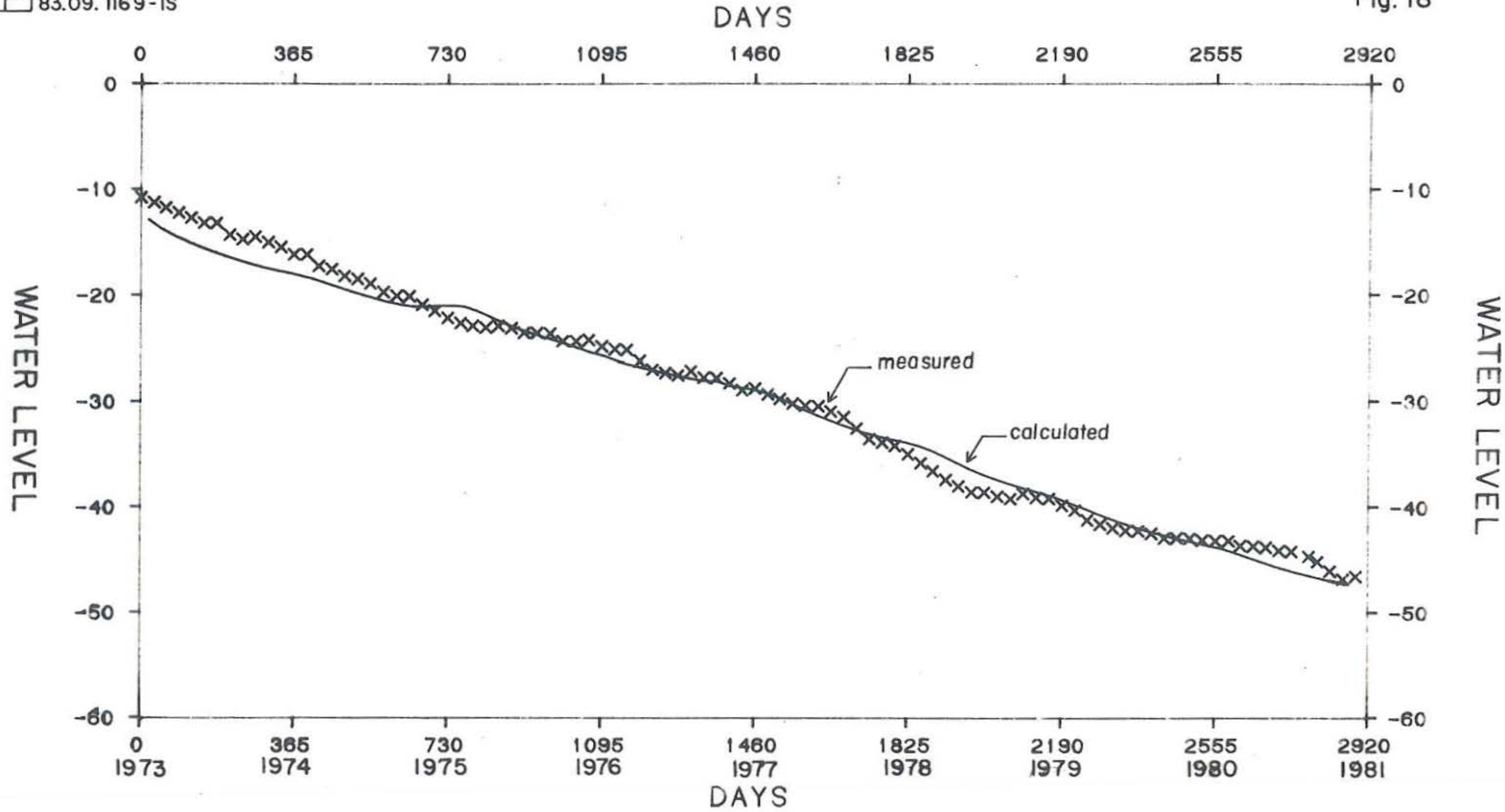
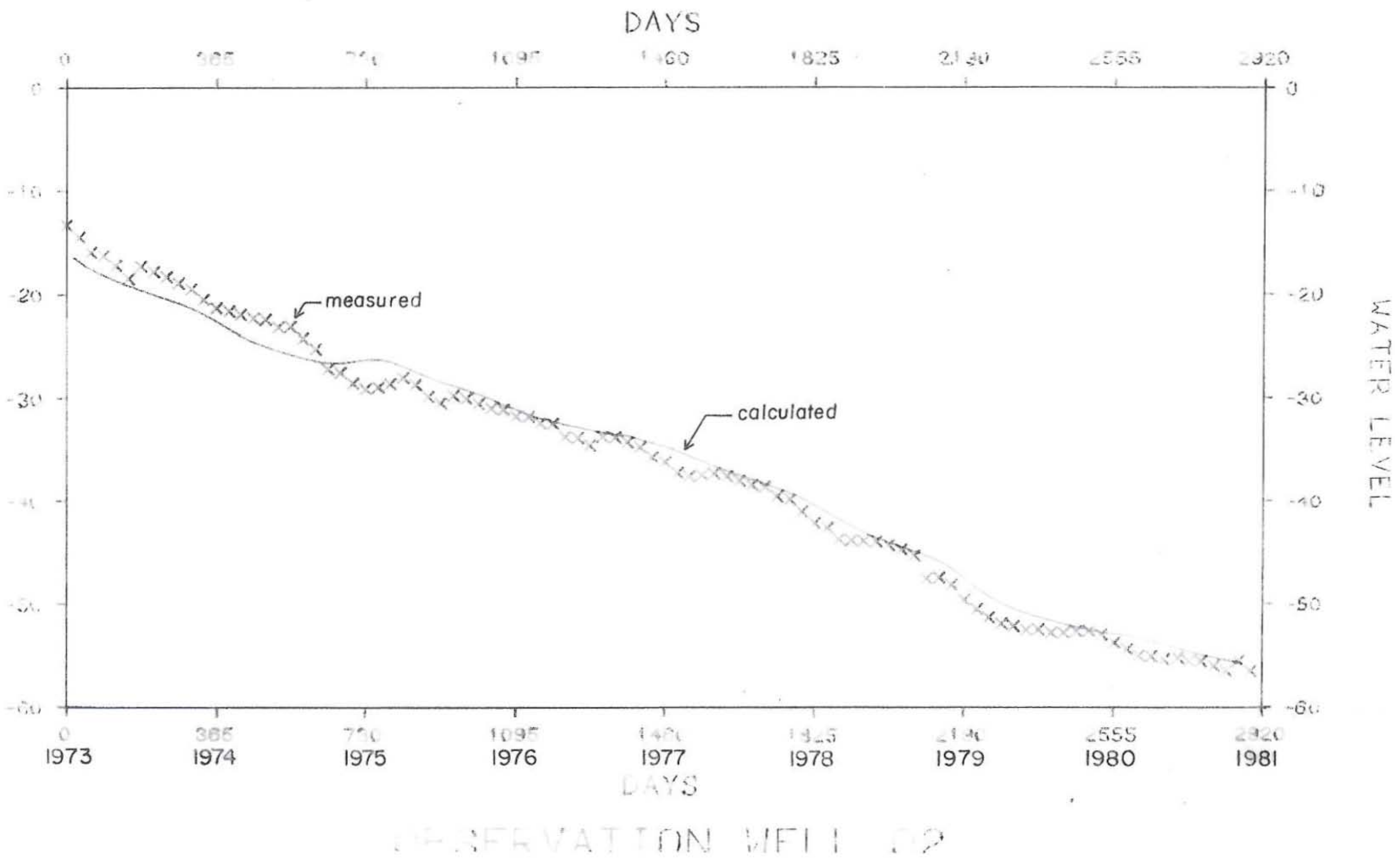
Fig. 18



OBSERVATION WELL 01


DAYS
measured
calculated
WATER LEVEL
0
-20
-30
-50
1973
1974
1975
1976
1977
1978
1979
1980
1981
365
1095
1825
2555
2920

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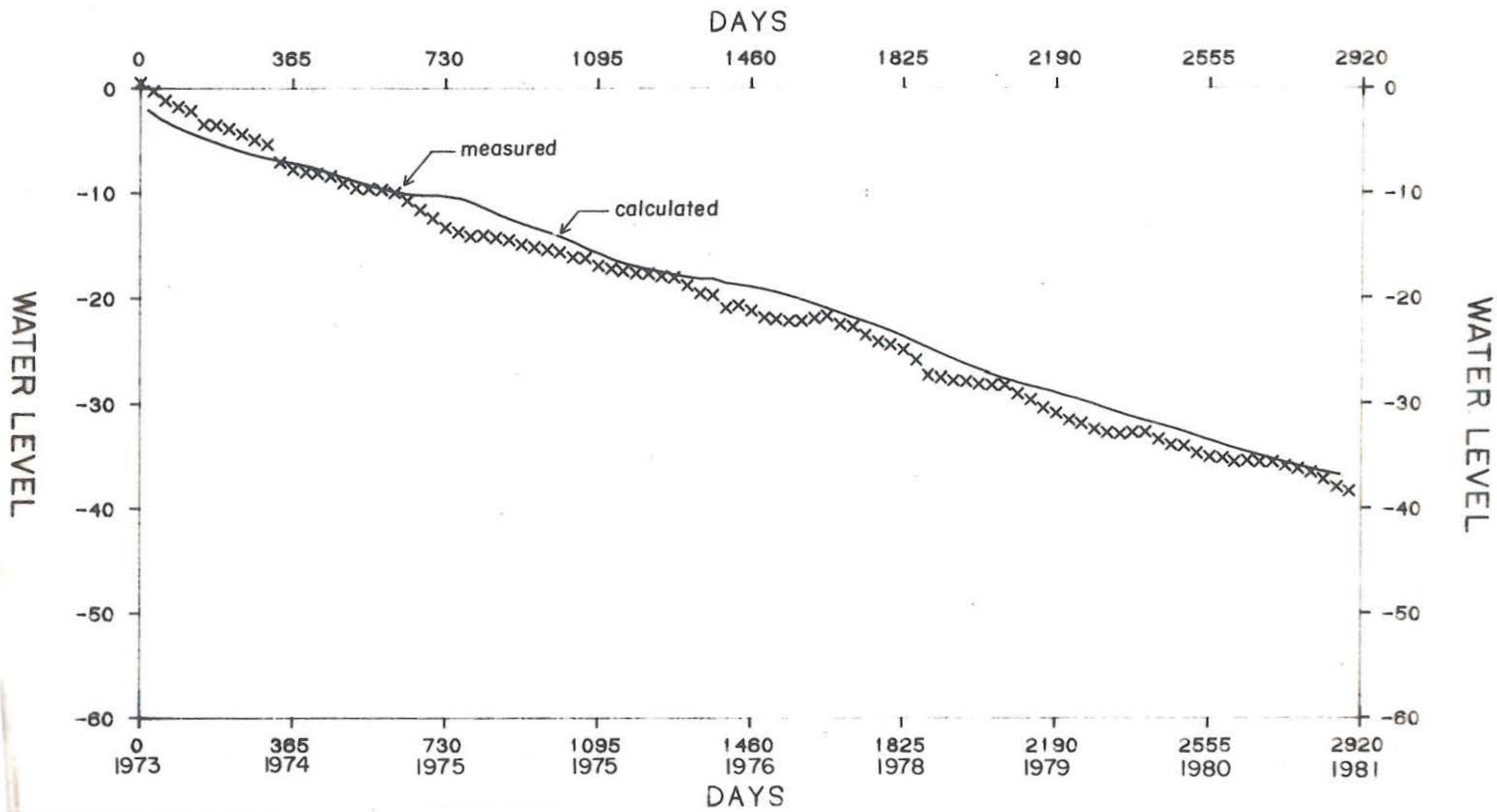
NORTH PART OF WANG-LAN-ZHUANG GEOTHERMAL FIELD IN TIANJIN

Fig. 20



OBSERVATION WELL 03

4. SIMULATION OF FUTURE DRAWDOWN

On the basis of the above obtained results and the calibrated parameters T, S, k and b, the NELL2 computer programme can be used to forecast the water level drawdown for the next 15 years. To do so a production schedule is needed. Two such production schedules are listed in Table 7 and shown in Fig. 21 - 22.

4.1 Constant pumping rate

The schedule is designed to keep the pumping rate constant in the period from 1982 until 1997, without the drilling of additional new wells. The total pumping rate of this aquifer is 118.5 l/s, giving an average production rate of 38.78 tonnes/h for each well. The calculated deepest water level for observation well 01 in the year 1997 is -66.92 m, for observation well 02 it is -75.53 m, and in observation well 03 it is -56.79 m. In accordance with the present economic and technical conditions, all 11 wells could produce hot water for the next 15 years and therefore this can be regarded as a practical schedule.

4.2 Increasing pumping rate

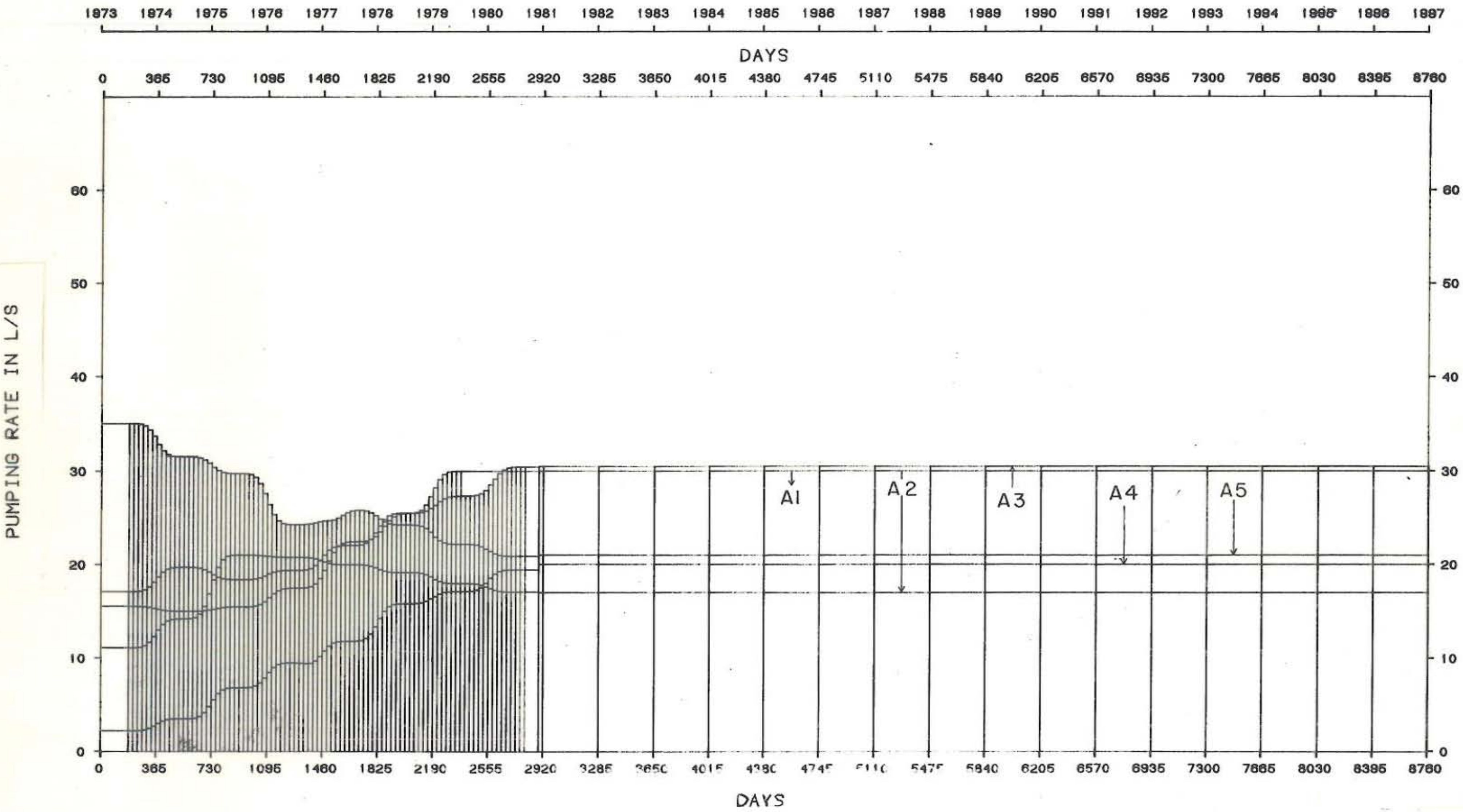
The second schedule is to increase the pumping rate by 5% each year in the period from 1982 to 1997. This means that the total pumping rate of this aquifer will increase from the present rate of 118.5 l/s to reach a rate of 260.8 l/s in the year 1997 giving an average pumping rate of each well of 85.35 tonnes/h. One well has to be drilled each year until 1997 in order to increase the total pumping rate by 5% per year while maintaining the average pumping rate of individual wells constant at the present pumping rate of 38.78 tonnes/h. The total number of wells will thus increase from 11 to 24. However, some problems are apparent for this schedule. From Table 8 we can see that observation well 01 will reach the critical water level in the year

TABLE 7. Pumping rate in l/s in the next 15 years in producing areas A1, A2, A3, A4, A5.

Years, Days		A1		A2		A3		A4		A5	
		I	II	I	II	I	II	I	II	I	II
1983	3650	30.0	33.07	17.0	18.74	30.5	33.62	20.0	22.05	21.0	23.15
1984	4015	30.0	34.72	17.0	19,67	30.5	35.30	20.0	23.15	21.0	24.31
1985	4380	30.0	36.46	17.0	20.66	30.5	37.07	20.0	24.30	21.0	25.52
1986	4745	30.0	38.28	17.0	21.70	30.5	38.92	20.0	25.52	21.0	26.80
1987	5110	30.0	40.28	17.0	22.78	30.5	40.47	20.0	26.79	21.0	28.14
1988	5475	30.0	42.21	17.0	23.90	30.5	42.91	20.0	28.13	21.0	29.54
1989	5840	30.0	44.32	17.0	25.11	30.5	45.06	20.0	29.54	21.0	31.02
1990	6205	30.0	46.53	17.0	26.37	30.5	47.31	20.0	31.01	21.0	32.07
1991	6570	30.0	48.86	17.0	27.69	30.5	49.68	20.0	32.57	21.0	34.20
1992	6935	30.0	51.30	17.0	29.07	30.5	52.17	20.0	34.19	21.0	35.91
1993	7300	30.0	53.86	17.0	30.52	30.5	54.77	20.0	35.90	21.0	37.71
1994	7665	30.0	56.56	17.0	32.06	30.5	57.51	20.0	37.70	21.0	39.59
1995	8030	30.0	59.38	17.0	33.66	30.5	60.33	20.0	39.58	21.0	41.57
1996	8395	30.0	62.25	17.0	35.34	30.5	63.40	20.0	41.57	21.0	43.65
1997	8760	30.0	65.47	17.0	37.10	30.5	66.57	20.0	43.82	21.0	45.84

I : Constant pumping rate in l/s

II : Increasing pumping rate by 5% each year



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CONSTANT PUMPING RATE IN 15 YEARS
IN PRODUCING AREAS A1. A2. A3. A4. A5

Fig. 21

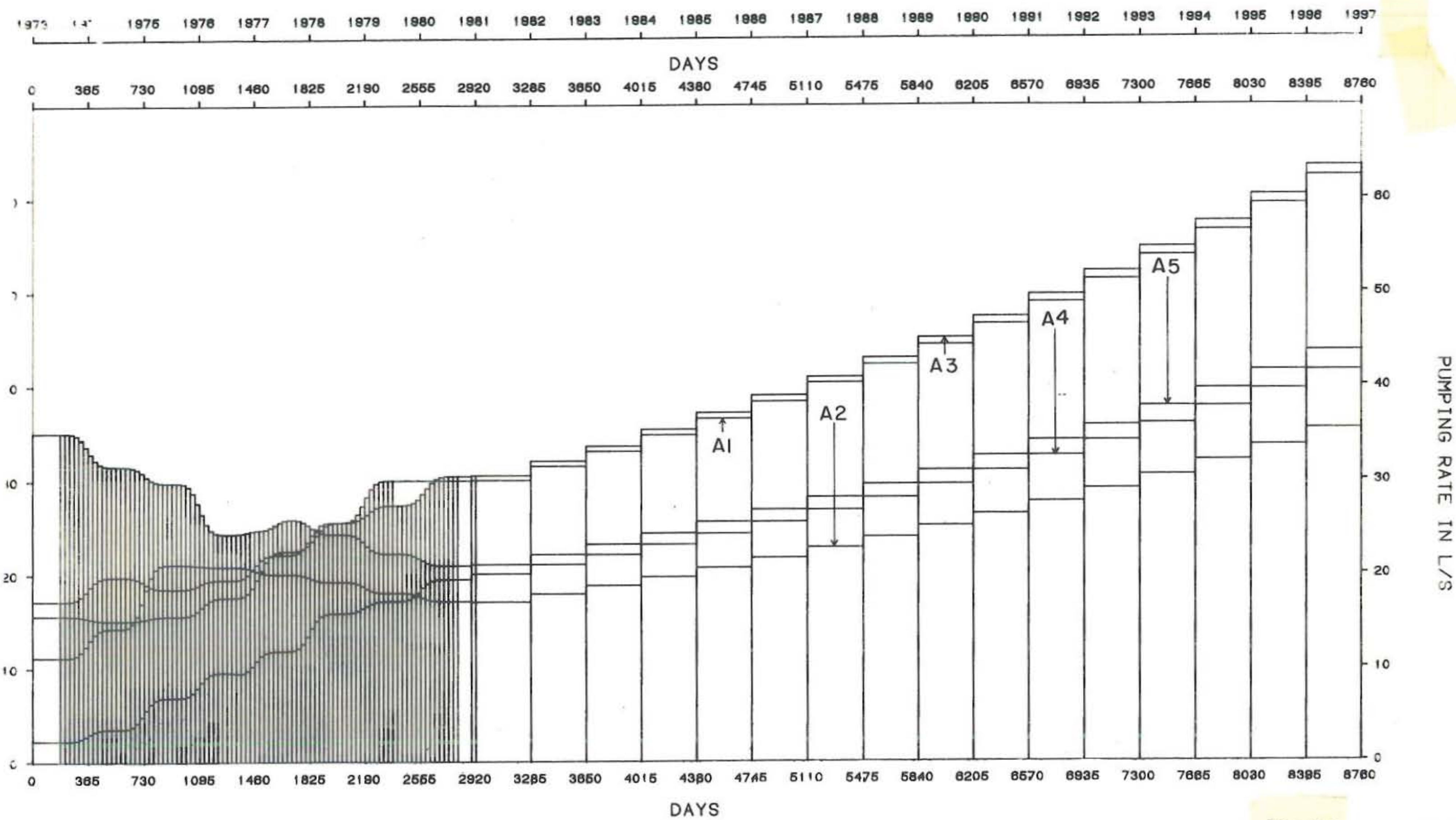

Fig. 22

INCREASING PUMPING RATE OF 5% PER YEAR IN 15 YEARS
IN PRODUCING AREAS A1. A2. A3. A4. A5

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83.09.1230. T/Sy.J.

1988, observation well 02 will reach the critical water level in 1986 and observation well 03 will reach the critical water level in 1991. Should the decision to follow this schedule be taken, a recommended solution to this problem could be to extend the 12" casing below the 90m, and to develop new pumping equipment with high-lift capacity.

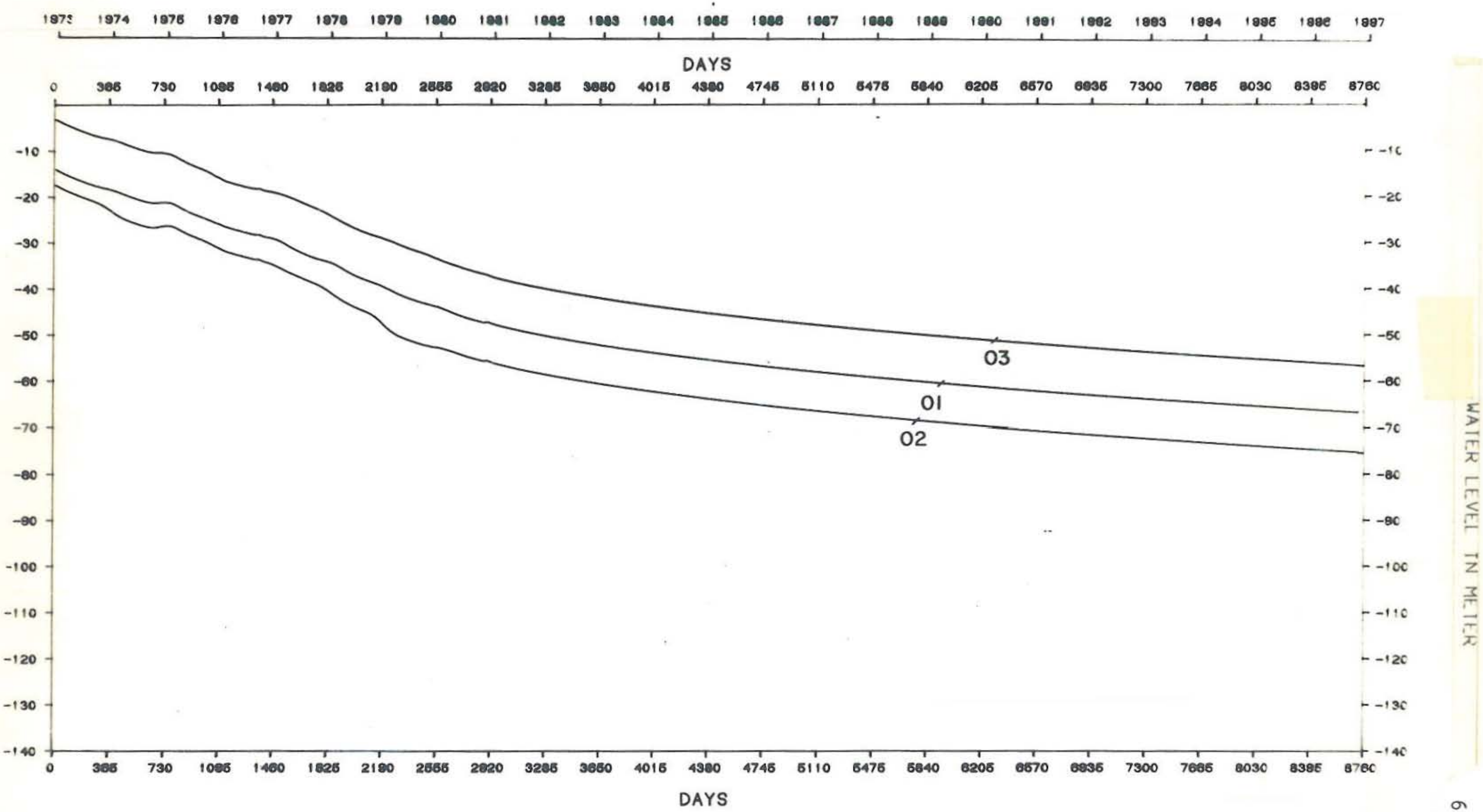
Fig. 23 and Fig. 24 show the water level drawdown curves with the two different pumping rate schedules.

TABLE 8. Calculated waterlevel, msl in the next 15 years.

Years	Days	01		02		03	
		I	II	I	II	I	II
1983	3650	-52.25	-53.78	-60.85	-62.87	-42.11	-43.29
1984	4015	-53.97	-57.52	-62.65	-67.03	-53.84	-46.98
1885	4380	-55.48	-61.30	-64.07	-71.24	-45.37	-49.49
1986	4745	-56.90	-65.15	-64.80	-75.80*	-46.74	-52.67
1987	5110	-58.18	-69.23	-66.77	-80.55	-47.96	-56.27
1988	5475	-59.32	-73.50*	-67.91	-85.25	-49.12	-59.99
1989	5840	-60.38	-78.48	-68.96	-90.63	-50.22	-64.19
1990	6205	-61.35	-83.25	-69.94	-96.04	-51.21	-68.26
1991	6570	-62.27	-88.31	-70.86	-101.67	-52.15	-72.50*
1992	6935	-63.17	-93.58	-71.77	-107.90	-53.02	-76.99
1993	7300	-64.03	-99.06	-72.62	-113.83	-53.86	-81.67
1994	7665	-64.54	-104.80	-73.36	-120.63	-54.62	-86.57
1995	8030	-65.54	-111.22	-74.14	-127.54	-55.40	-92.08
1996	8395	-66.92	-124.21	-74.84	-134.69	-56.10	-97.47
1997	8760	-66.92	-124.21	-75.53	-142.98	-56.79	-103.11

I : Constant pumping rate

II : Increasing pumping rate by 5% each year



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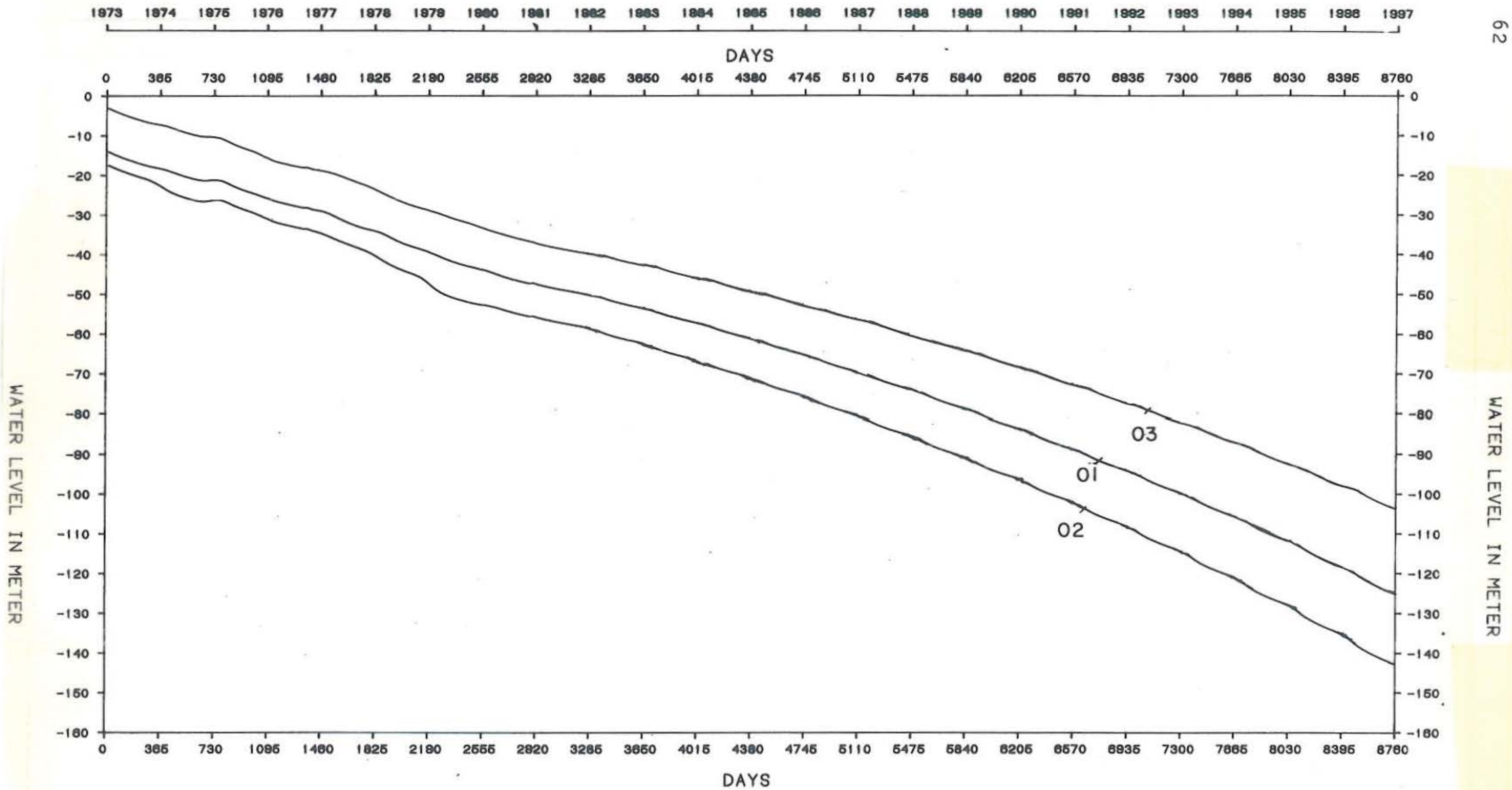
DRAWDOWN OF THE WATER LEVEL IN 15 YEARS
IN OBSERVATION WELLS 01. 02. 03

Fig. 23



DRAWDOWN OF THE WATER LEVEL IN 15 YEARS
IN OBSERVATION WELLS 01. 02. 03

Fig. 24

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83.09.1228. T/Sy.J.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Reservoir parameters

The main object of this report has been to calibrate the parameters of the reservoir in Aquifer II of the Tertiary system and to devise a model for the calculation of the water level drawdown for the next 15 years according to the production requirements.

The calculated results have provided the following parameters: For Aquifer I, the transmissivity coefficient, T_I = 0.0012 m^2/s, with a storage coefficient, S_I = 0.01. For Aquifer II, the transmissivity coefficient, T_{II} = 0.0006 m^2/s, with a storage coefficient, S_{II} = 0.0007. This concludes that the ability of released water from the storage of Aquifer I is larger than that of Aquifer II. This explains why Aquifer II has more average drawdown per year than Aquifer I.

5.1.2 Assumption of models

Both previous as well as present studies of the reservoir have used the same assumptions which included a simplification of many of the complicated geothermal conditions. The assumptions include that the reservoir is infinite, homogeneous and uniform in thickness, bounded on top and bottom by impermeable, insulated boudaries.

5.1.3 Permeability of the reservoir

The permeability of the Aquifer II can be calculated according to the calibrated transmissivity, T:

$$T = K \cdot M$$

$$K = T/M = 56.4/30 = 1.88 \text{ m/day} = 2.18 \cdot 10^{-5} \text{ m/s.}$$

The M is the effective thickness of the Aquifer II.

5.1.4 Calibrated permeability of the aquiclude

$$Q = V \cdot A = k \cdot I \cdot A = 1 \cdot 10^{-12} \cdot 8/50 \cdot 117 \cdot 10^{6}$$

$$= 0.187 \cdot 10^{-4} = 0.0187 \text{ l/s.}$$

This result indicates that the leakage is very small, so that we can conclude that there is virtually no leakage between the two aquifers.

5.1.5 Factors influencing the water level drawdown

The calculated water level drawdown is very sensitive to both the distance between the observation well and the production well and the pumping rate. For instance, as observation well 02 is very close to the producing area A3; a slight change of the pumping rate in the A3 area will immediately influence the calculated water level drawdown of observation well 02.

5.1.6 Recharge of the reservoir

The practical schedule is to keep the pumping rate constant for the next 15 years, so that most of the wells can be used without the danger of being wasted. However, the water level will continue to decline year by year as it has been concluded that there is a small or no recharge into the reservoir and the discharge rate exceeds the recharge rate to the reservoir.

5.2 Recommendations

5.2.1 Application of a numerical model

The hydrogeothermal conditions in the Tianjin area are fairly complicated. Since there are many production wells, each with a different production schedule, it is not possible to obtain satisfactory results by only using the simple analysis of the mathematical model. In fact the hydrogeothermal conditions of the Tianjin geothermal field are neither homogeneous nor uniform in thickness. As mentioned before this present method is just an approached simulation.

To obtain more detailed and accurate results in the future, the new numerical model could be used with the aid of the present calculated results. Hence, the best way of simulating the complicated reservoir is:

1) to use the well test results to obtain the first estimates of the parameters of the reservoir.

2) to use the long-range observation data to calibrate the parameters of the reservoir.

3) to divide the whole geothermal area into several sub-areas according to the different T and S values.

By using the numerical model to recalibrate the parameters, more accurate forecasts for future drawdown can be obatined.

5.2.2 The effect of the boundary

The boundary conditions are very important to the mathematical model of the reservoir. The whole boundary that we have determined before is an infinite boundary as well as a permeable boundary. However, in the Wang-Lan-Zhuang geothermal area there are faults around the whole area. The question is whether they represent permeable or impermeable boundaries. It is therefore necessary to test the same model with different boundaries.

5.2.3 The effect of the fault

There is a fault, the West-Bai-Tau-Kou fracture across the geothermal field with a SW-NE direction. The temperature survey has proved that there is a convection of heat up the fault, and it must be investigated what significance this has for the geothermal resource.

5.2.4 Reinjection

If we want to maintain the pressure in the reservoir in the furture, a reinjection schedule should be considered. Reinjection of water into the reservoir has both advantages and disadvantages. The advantage is that the water level can be recovered and full use can be made of the heat conducting media. The disadvantage is that the chemical composition of the water will be changed from that of hot water to cold water and the temperature of the water will decline. Furthermore, the injection water will create a bigger pressure in the reservoir which will resist the heat convection from the basement.

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