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HYDROGEOLOGY OF SOUTH SINJAR PLAIN
NORTHWEST IRAQ

Fakhri D.S. Al-Sawaf, B.Sc., M.Sc., FGS.

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Department of Geology,
University College London,
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ABSTRACT

The general hydrogeology of the south Sinjar plain was studied and correlated with the adjacent anticlinal area to its east.

This old plain is underlain by the Upper Fars Formation of Upper Miocene age while the foothills to the east are underlain by the Lower Fars Formation of Middle Miocene age. The oldest formation is exposed in the core of the highest mountain in the area, Sinjar, which provides the northern limit of the watershed of the area. The extensive aquifers of the Upper Fars Formation bear fresher waters than the less important Lower Fars aquifers, although the latter have played an important role in the deposition of economic sulfur in many of the anticlines.

The average annual rainfall in the area ranges between 200 and 400 mm and provides enough replenishment for the aquifers to be sufficient for agricultural and stock use.

The data collected from the field includes water level measurements in the different aquifers, ground water conductivity, pH, temperature and representative water samples. More than two hundred such samples were analyzed in detail together with previously available analyses, making a total of 326 samples available for interpretation.

The flow of ground water was studied from prepared water level maps and the characteristics of the aquifers studied from the experimental pumping tests in the field. The major problem in this area is the poor quality of the ground water. This feature has been studied with the application of computer programmes which have dealt with all the available analyses and have given clear classification for the different waters in the aquifers. These results have also been correlated with the geological classification of water.

The infiltration through the soil in the area was studied by means of double ring infiltrometer. This helped in understanding the ground water replenishment and pollution from the surface. Surface water data were not available, while meteorological data was lacking in most parts of the area. This makes the calculation of the water budget in the area somewhat doubtful and points to the serious need for further work including detailed collection and documentation of data. The area is currently in a primitive or youthful stage of ground water exploitation and use though localised overdevelopment points to the need for careful management of the aquifer.

This thesis is dedicated to the thirsty
desert dwellers

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CHAPTER ONE

INTRODUCTION

1.1 Location and extent of the area

The study area is located in the northwestern part of Iraq. Its western limit is the Iraqi-Syrian border extending to the river Tigris on the east. The northern limit of the area is the surface water divide of the Sinjar Range; to the south, the lack of information has restricted the boundary to around latitude 35°30', see Figure 1. The total area of study is about 14,670 square kilometres.

1.2 Objectives of research

The purposes of the study are to identify and assess the water resources within the region and to define the optimal utilization of the existing aquifers according to their water availability. The main points considered in this study are the following:-

1) The evaluation of annual recharge and permanent storage of each aquifer,
2) Details of water quality in relation to different use,
3) The collection of information relating to ground water and surface water for the future development of the area,
4) Safe yield and the present use of water,
5) Pollution prevention,
6) Recommendations for the future development of the area.

1.3 Basic data and field work

The available documents are:

1) Topographical maps of the following scales:
    a) 1/25,000, cover most of the area, but are available

Figure 1: Location of study area


Location Map
Surface water shed
Main valley
Paved road
International boundaries
0 10 20 Km.
N
41°30'
42°00'
42°30'
43°00'
36°30'
36°15'
36°00'
35°45'
35°30'
Jabal Sinjar
Sinjar
Tel-Afar
Mosul
Al-Ajij Basin
Al-Tharthar Basin
Wadi Hamam Ali
Qasab
Mishraq
Uppar Zab
River Tigris
B'laij
Ba'aj
Wadi Al-Tharthar
Wadi Al-Ajij
SYRIA
Flat Jezira
Sunaisala
Hadhr

only to governmental offices

b) 1/100,000, cover the whole study area in ten sheets having the following numbers: J37X/SW (Bara), J37X/SE (Sinjar), J38S/SW (Tel-Afar), J38S/SE (Badush), J38T/SW (Mosul), 137F/NW (Wadi Al-Ajij), 137F/NE (Sunaisala), 137A/NW (Ethrai), 138A/NE (Al-Hadhar) and 138B/NW (Qaiyara). These maps are available only to the Ministries of Defence and Oil.

c) 1/250,000 cover the whole area in four sheets of the following numbers NJ37-16 (Sinjar), NJ38-13 (Mosul), N137-4 (Souar), and N138-1 (Sharqat). These sheets are printed in Arabic and are available for researchers. They have been used in the preparation of the basic maps for this study.

2) Regional international maps are available on a scale of 1/500,000 under the following numbers: 340D (Mardin), 340C (Mosul),427A (Deir EzZor) and 427B (Kirkuk).

3) Geological maps:

a) Geological map of Iraq, scale 1/1,000,000 (in English)

b) Geological map (from Parsons report), scale 1/310,500

4) Aerial photographs, approximate scale 1:50,000 cover the whole area in eleven hundred photographs but are available only for Military purposes

5) Well survey cards for wells drilled by the Ground Water Department, Ministry of Agriculture and Agrarian Reform.

6) Existing reports:-

The most important reports are the detailed surveys undertaken by foreign companies through contracts with the government of Iraq. Two such reports are available:

a) The Ralph M. Parsons Co. USA (see reference) Ground Water Resources of Iraq,
b) Ingra Consulting Department, Yugoslavia. Mosul Liwa 100+14 well programme (see reference)

Field Work:

As part of a study of a previously unreported semi-arid area, the field work was planned to cover most aspects of geology and hydrogeology within a short field period of six months. 255 locations were visited and a detailed form was completed in the field for each location as shown below:-

---

HYDROGEOLOGICAL DATA"JEZIRA AREA"

Serial No. Date
Work No. (Well,Spring,Stream) Surface Elev. (asl)
Location Old Ref. No.

Details of well

Total Depth SWL from surface, ASL..
Inside diameter PWL from " , ASL..
Casing: Discharge (L/sec)
Perforation: From... To..Pumping test: From.. to..
Date drilled Type of pump..... Method of drilling.

Details of water

Elec. conductivity Color
Temperature: °C Odour
pH Bacteria
Taste

Utilization

Domestic
Irrigation
Stock

Remarks

The serial number of the sites visited are shown in Figure 2; the work number is used as an analysis number and is tabulated in Appendix 3 (see chapter four for explanation).

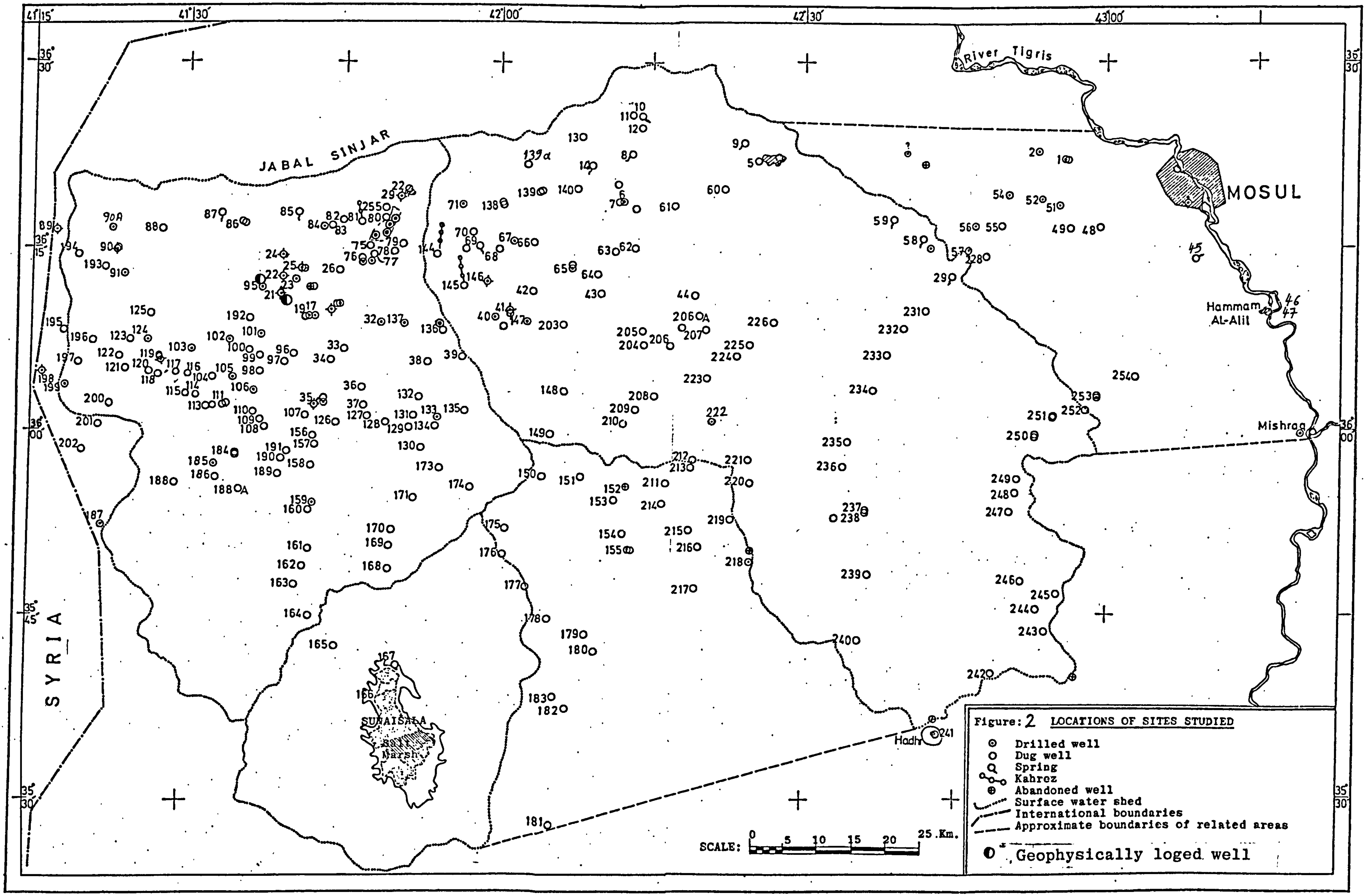


Figure: 2 LOCATIONS OF SITES STUDIED

The surface elevations are taken from the only available topographical map, which has a scale of 1/250,000. The present use of water supply wells and springs, together with the geology are noted under remarks on the same sheet.

1.4. Topography and drainage

Topography

The physical features of the area under study reflect its geological structure. In general, the area can be subdivided on a topographical basis into five subdivisions delineated by water divides or other physical features (see figure 3), as follows:-

1) Al-Ajij Basin: Named after the main wadi, Al-Ajij, which flows to Syria. Its northern limits are the highlands of Jabal Sinjar (1463 meters high above sea level) extending for about 70 kilometres into Iraq. The lowest ground in this basin is less than 300 metres above sea level. The total area of the basin is about 3670 square kilometres.
2) Sunaisala Basin: Named after the Sunaisala salt playa located in the centre of this basin. It is a closed basin the southern limits of which have not been defined due to the flatness of the ground, though it probably extends south of the studied area. The northern water shed is marked by the outcrop of the Lower Fars Formation at an elevation of more than 300 metres above sea level. The lowest ground which is the centre of the basin is less than 200 metres above sea level. The total area of the basin is about 1480 square kilometres.

3) Al-Tharthar Basin: This basin represents the upper catchment of the big Al-Tharthar depression between the rivers Tigris and Euphrates. The lowest point is at sea level in the extreme southern section where the Wadi Tharthar emerges into the depression. Within the area, the limit for the present basin study is taken near the town of Hadhr (Plate 1) in which the lowest point is about 170 metres above sea level. The northern and eastern limits of this basin are the anticlines of the Lower Fars Formation which define the water shed for the basin and rise to more than 500 metres above sea level. The total area of this basin is about 5490 square kilometres.

4) The level land between Sanaisala and Tharthar Basins: This area is essentially flat with relatively little relief. It contains many shallow topographical depressions, which during the rainy season, fill with water and become marshes and shallow lakes (Plate 2). The average elevation of this area is about 250 metres above sea level. This area is taken as a type area being a part of the extensive Jezira area located between the rivers Tigris and Euphrates (Jezira means island). About 2120 square kilometres were surveyed.

5) The hilly area: This represents the major anticlinal structures located between Al-Tharthar basin and the river Tigris. It has been included within the study because of its economic importance and the peculiarity of its water. It has different topographical features from much of the area being represented by high hills and deep valleys (Plate 3). The highest ground is Jabal Zambar, about 560 metres above sea level; its lowest level is about 190 metres near the

river Tigris to the south of the area.(Plate 4). The total area studied in this hilly zone is about 1910 square kilometres.

Drainage

The drainage pattern in this area is governed by the distribution of the wadis (valleys) and the physical features of the ground. Figure 4 shows the drainage system over the area; and it may be seen that there is a major difference between the drainage patterns of the steep mountain slopes in the north and the flat land in the south. In the northern and eastern parts of the area, the water has cut through the limestones of Sinjar and the Lower Fars Formation creating deep gulleys through which most of the surface water flows in the wet seasons (Plate 4).

The drainage pattern on Sinjar mountain is very distinctive. The presence of the thick and massive limestone surrounding the anticline has created a form of impermeable barrier which largely prevents the outflow of the surface water that is collected over the Sinjar anticline. Strike valleys are subsequently formed to collect water from the deep galleys and only in certain points has the water an outlet across this massive limestone creating a fork or comb-like pattern. These outlets are responsible for the distribution of population around the mountain; the amount of water flowing out of these outlets being controlled by the size of its catchment area. The total catchment area of south Sinjar anticline is about 350 square kilometres of which the most important outlets from the mountain are:-

1) Sinjar: The area upstream of Sinjar is about 40 square kilometres covering the highest parts of the Sinjar anticline. It is probably the biggest

Image removed due to third party copyright outlet from the mountain and has the highest density of population. The water flows through coarse limestone alluvium and some kahrez.

2) Gizil Kang: The area upstream of this village is about 22 square kilometres. The flow of water through this outlet is markedly controlled by the seasonal rainfall.
3) Gabare: This area is small in comparison with the surrounding areas, covering only 12 square kilometres.
4) Jaddala: The upstream catchment to Jaddala village is very large and the flow of surface water through this outlet is continuous throughout the year. The total area of the catchment is some 46 square kilometres. The continuous flow of fresh water through this outlet has attracted a higher population to the locality. The discharge in Jaddala stream was measured by a V-shaped notch weir at the end of June 1974, and was about 330 litres per second.
5) Sakiniya: The total catchment to Sakinia is about 23 square kilometres. It has a similar drainage pattern to the other catchments.
6) Kharabet Ikheder: This area also coincidentally covers 23 square kilometres and has a similar pattern of drainage.
7) Umm el Thiban: The catchment area to the village of Umm el Thiban is larger than any of the surrounding basins, covering about 73 square kilometres. The water flowing out of this outlet is modified by the thick alluvium deposit and the karstic features of the underlying Lower Fars Formation. This causes the disappearance of most of the fresh water directly underground, so that no streams flow from the outlets.

The drainage pattern south of these outlets is controlled by the existence of thick, coarse grained alluvium deposits through which most of the water infiltrates leaving dry wadis over most of the area. Some flows continue only in the wet seasons in the main wadis.

Towards the south of the area among the flat lands, the drainage pattern seems apparantly uncontrolled by any specific factor as in most of the Jezira Desert. Drainage is internal and mainly flows into many shallow depressions or playa lakes (see Plate 5). The exception is Wadi Al-Tharthar, the largest stream in the area; this stream is subsequent, and flows intermittently from north to south into the enclosed Tharthar Depression. Along Wadi Al-Tharthar, there are numerous seepages where the water table intersects the surface forming shallow pools (Plate 6). Numerous small wadis drain into this main wadi, but they are mainly concentrated in the eastern part of the catchment. The flow of water in these wadis is controlled by the seasonal rainfall for they are dry in summer and autumn (Plate 7). The area in the south is karstic and the drainage pattern is internal, with flow taking place through sink holes and caves in the Lower Fars Formation. Some sink holes carry water throughout the year and are important for water supply (Plate.8).

In the Lower Fars area, the drainage pattern is partly controlled by the karstic nature of the formation and mainly by the distribution of wadis along the limbs of the anticlinal structures and in the synclinal depressions between the anticlines. Most of the main wadis flow towards the river Tigris in an east and southeasterly direction (Plate 9).

1.5. Climate

The predominant climate of the area has semi-arid characteristics. The following three factors play a significant role in controlling the climate in this area.

1) The Mediterranean sea to the west of the area
2) The high mountain ranges of Toros and Zagros to the north and northeast.
3) The great western desert of Iraq to the south.

The four seasons are very well defined in this area. Winter starts in December and ends by the end of February. During this season the temperature and the potential evaporation are minimal and the relative humidity and rainfall are at a maximum in relation to the remainder of the year.

Spring starts in March and ends by the end of May. This season marking the transition from cold wintry weather to a hot summer and the weather is very pleasant in the study area. Summer starts by June and ends by the end of August each year. The temperature and potential evaporation are at a maximum, while the pressure and relative humidity are at a minimum for the year.

The main climatological elements represented by the rainfall temperature, relative humidity, evaporation,wind and pressure were examined for the existing metecrological stations. Figure 5 shows the locations of meteorological stations and rain-gauges in and around the area under study. The only long term records available for this study are those from Mosul, Sinjar, Tel-Afar and Arah. Most of these data were obtained from the Directorate of Meterology of the Iraqi Government, with the exception of those from the station installed in Tel-Afar by the Institute for

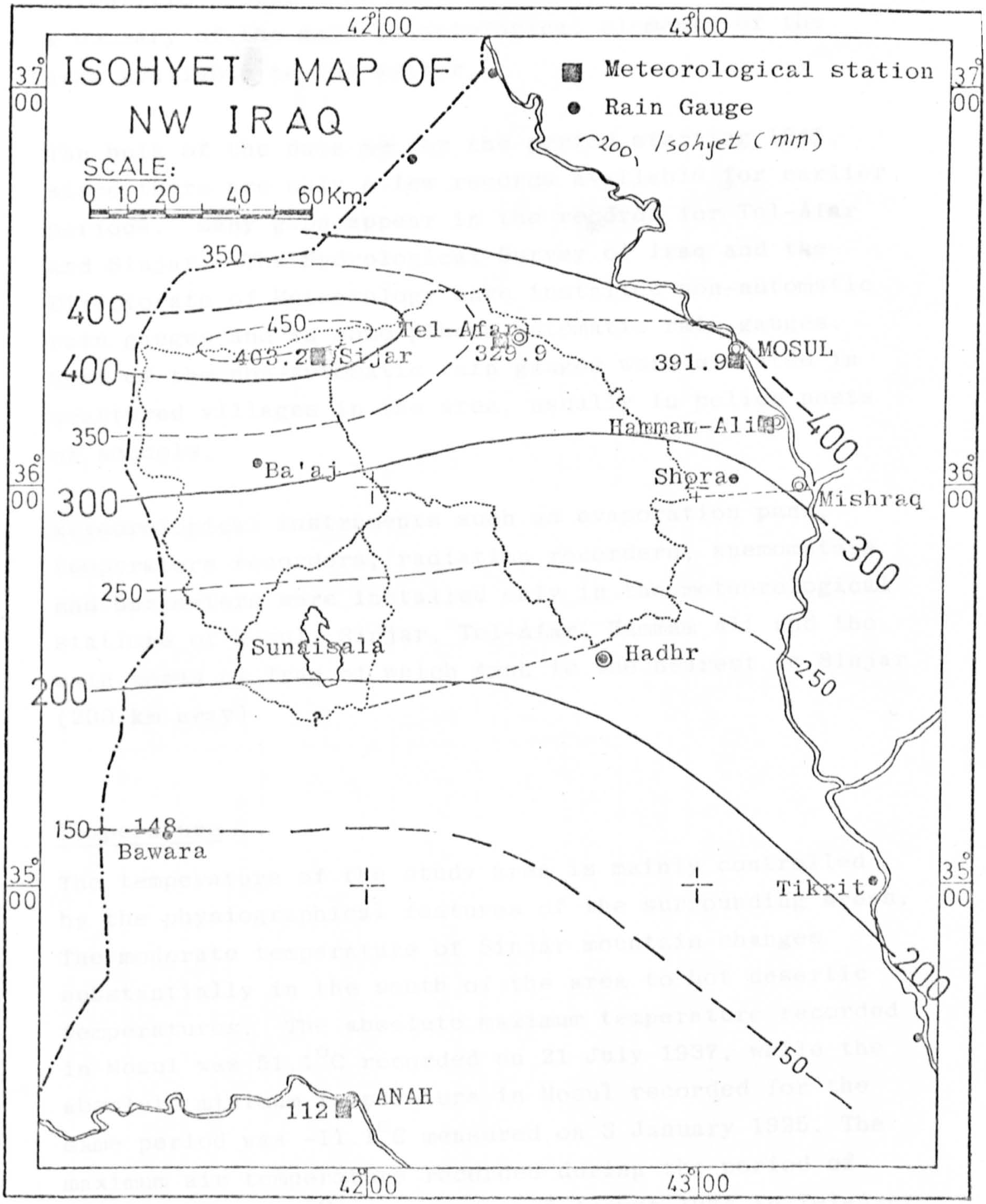


Figure:5 Isohyetal map of NW Iraq .

Scientific Research on Natural Resources. Table 1 is a summary of the main climatological elements of the area available to the writer.

The bulk of the data *are* for the period starting 1941, since there are only a few records available for earlier periods. Many gaps appear in the records for Tel-Afar and Sinjar. The Hydrological Survey of Iraq and the Directorate of Meteorology have installed non-automatic rain gauges and in some places automatic rain gauges. Most of the non-automatic rain gauges were situated in scattered villages in the area, usually in police posts or schools.

Meteorological instruments such as evaporation pans, temperature recorders, radiation recorders, anemometers and barometers were installed only in the meteorological stations of Mosul, Sinjar, Tel-Afar, Hammam Ali and the main towns of Iraq of which Arah is the nearest to Sinjar (200 km away).

Temperature

The temperature of the study area is mainly controlled by the physiographical features of the surrounding areas. The moderate temperature of Sinjar mountain changes substantially in the south of the area to hot desertic temperatures. The absolute maximum temperature recorded in Mosul was 51.1°C recorded on 21 July 1937, while the absolute minimum temperature in Mosul recorded for the same period was -11.1°C measured on 3 January 1925. The maximum air temperature recorded during the period of field work was 46°C measured on 5 August 1974 in Tel-Azer Gharbi, serial number 224.

Generally speaking, the temperature range in this area is neither too hot nor too cold. Being a semi-arid region it varies considerably in the different seasons.

Station	Location Height(m)	Period	Specification of Measurement	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Mosul	36°19'	1941-70	Mean Monthly Rainfall (mm)	67.2	63.4	69.3	50.8	25.3	0.7	0.1	0.0	0.7	9.9	36.1	65.3	391.9
	43 09'	1941-70	Mean temperature °C	7.0	8.7	12.3	17.4	24.1	30.5	34.0	33.0	27.7	20.5	13.5	8.3	19.8
	223	1941-70	Normal monthly relative humidity(%)	82	76	70	62	44	30	26	29	34	49	67	83	54
			Potential evaporation (mm)[1]	27.6	46	82.1	124.8	195.3	248.0	266.2	251.0	172.2	99.4	46.6	23.1	1582.3
		1966-70	Daily mean evaporation in mm	2.4	2.9	3.7	6.2	10.2	13.6	16.7	15.5	10.6	6.0	3.6	2.7	2874.4
		1951-70	Mean wind speed in m/s	2.3	2.7	2.7	3.0	3.1	3.4	3.3	2.9	2.7	2.2	2.0	2.2	2.5
		1941-70	Normal monthly pressure in M.B.S.	1020.2	1018.0	1015.2	1012.4	1009.3	1003.7	998.7	1000.8	1007.3	1014.6	1018.8	1020.0	1011.7
Tel-Afar	36°23'	1941-70	Mean monthly rainfall	61.3	47.3	63.0	43.0	24.0	0.0	0.0	0.0	0.0	0.3	5.3	30.8	329.9
	42°24'	1975	Mean temperature	6.5	7.0	12.1	20.1	24.5	30.8	33.4	32.2	29.8	18.9	14.7	6.9	19.7
	360	1971	Normal monthly relative humidity(%)	64	56	51	60	35	31	23	23	26	-	58	80	
		1975	" " " " " (%)	78	69	54	42	39	27	17	-	16	23	43	69	
		1975	Daily mean evaporation	2.0	2.9	6.3	8.2	10.6	11.5	19.7	17.6	14.1	8.7	4.5	1.8	3198.
		1971	Mean monthly rainfall	4.8	14.5	39.1	95.9	8.5	0.5	0.0	0.0	0.0	0.0	18.2	101.3	232.5
		1975	Mean monthly rainfall (mm)	26.6	79.7	10.3	51.5	13.3	0.0	0.0	0.0	0.0	0.0	1.3	2.5	185.2
Sinjar	36°19'	Avr.22 yrs	Mean monthly rainfall (mm)	77.7	60.7	67.0	53.0	33.1	0.2	0.0	0.0	0.3	8.8	31.6	70.8	403.2
	41.50'	941-70	Mean monthly temperature °C	7.0	8.8	11.5	17.4	24.8	31.5	35.0	34.7	30.1	23.0	16.3	9.0	20.8
	476	962-70	Mean relative humidity (%)	72	66	57	51	36	21	19	19	22	35	50	68	43
			Potential evaporation (mm)	27.0	38.5	60.2	116.2	195.2	265.6	288.6	277.2	197.0	117.3	62.6	22.6	1668.3
Anah	34°28'	941-970	Main monthly rainfall (mm)	18.8	16.9	20.4	22.2	5.7	0.0	0.0	0.0	0.0	5.3	9.8	22.5	112.0
	41°50'		Mean temperature °C	7.7	10.3	15.8	20.9	27.7	32.0	34.1	33.4	29.8	24.0	14.8	8.5	21.6
			Mean monthly potential evaporation[1]	34	62	126	190	236	264	272	240	198	105	51	23	1501
		1966-970	Daily mean evaporation (mm)	1.5	3.1	4.8	6.5	9.9	13.8	16.1	15.1	9.9	5.9	2.8	1.6	2778.7
Habbaniya	33°23'	941-70	Main monthly rainfall (mm)	27.9	12.0	10.5	19.9	6.2	0.0	0.0	0.0	0.2	2.3	20.0	13.1	115.5
	43°30'	941-70	Mean temperature °C	9.5	12.0	16.1	21.7	28.1	32.7	34.8	34.2	30.0	24.1	16.8	11.0	22.6
Bawara	35°08'															
	41°13'															
	260	1970-71	Tot. annual evaporation = 1480mm, Tot. annual rainfall = 148.0 mm.													

Table 1: List of the Meteorological data of the region.

A remarkable change in temperature takes place in the flat regions to the south where the hot air masses, at about 40^{o}C, are replaced by the cold air of the Mediterranean region. The flat desertic land heats rapidly under the effect of strong sunlight during the day, creating hot air masses. The land becomes cooler at night and cool air masses seeping from the west causes a significant drop in temperature. The average monthly temperature in Mosul, Sinjar and Arah are tabulated in Table 1 and are shown in figures 6, 8 and 9 respectively.

Evaporation

Evaporation is the process by which liquid is changed to a vapour or gas. Transpiration is often the largest component of total evaporation. Interception is a minor component in this area owing to the lack of thick vegetation cover.

All the data available for evaporation were obtained from the meterological stations in which open pans were installed. Evaporation is measured volumetrically in a land pan of the U.S. Weather Bureau Class A type. The true value of evaporation, actual or real evaporation, which takes place in specific area differs from the potential evaporation and the free surface water evaporation.

During the 1970 International Course for Hydrologist (ICH) in the Netherlands; the following mean annual values of potential evaporation (PE), free surface water evaporation (FSWE), actual evapotranspiration (AE), and precipitation (P) were presented for Iraq as follows:-

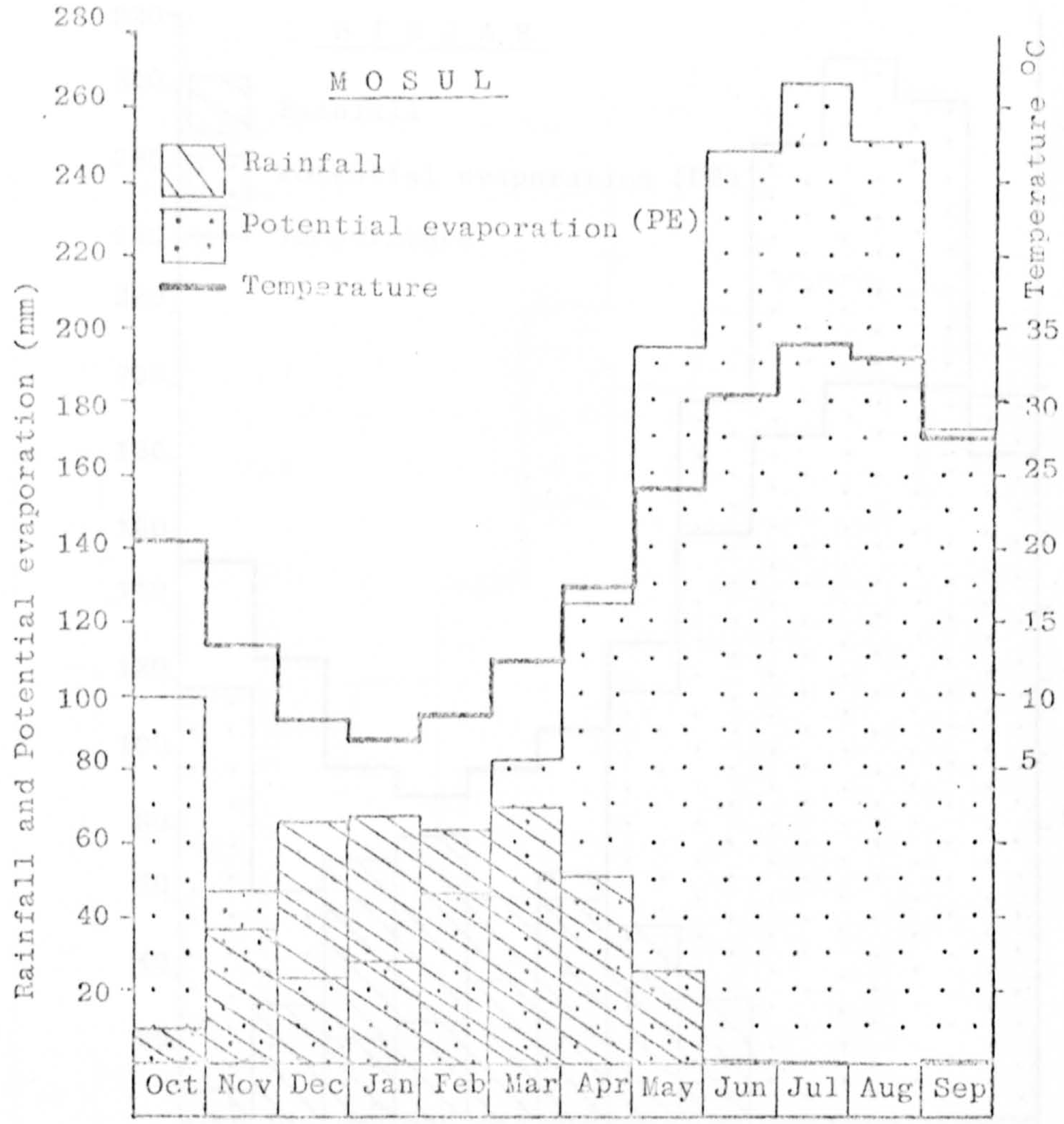


Fig.6 Bar graph of monthly rainfall,PE and temperature in Mosul .

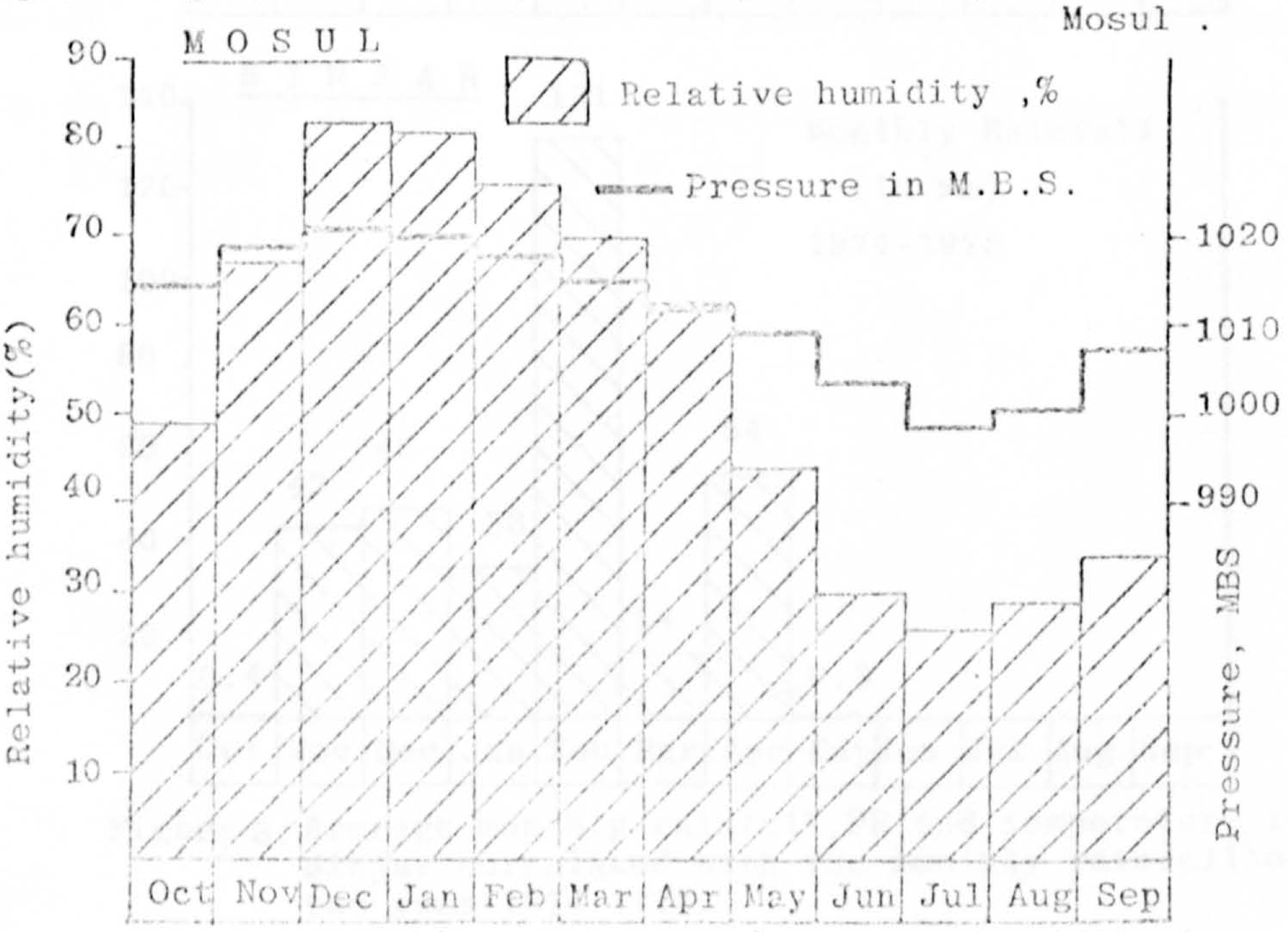


Fig.7 Average monthly pressure and relative humidity in Mosul.

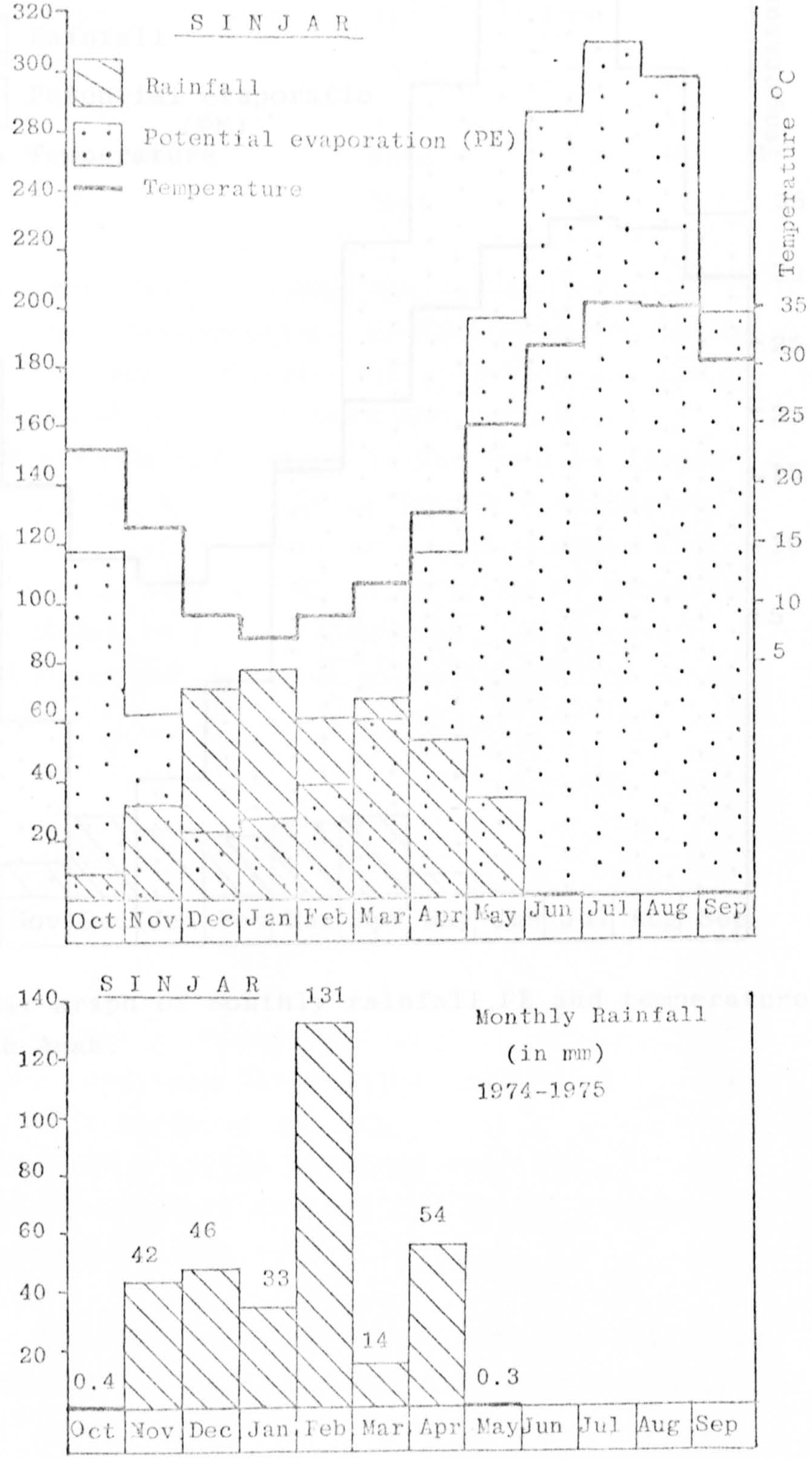


Figure 8: Arerage monthly rainfall,PE and temperature in Sinjar correlated with the monthly rainfall of the year 1974-1975.

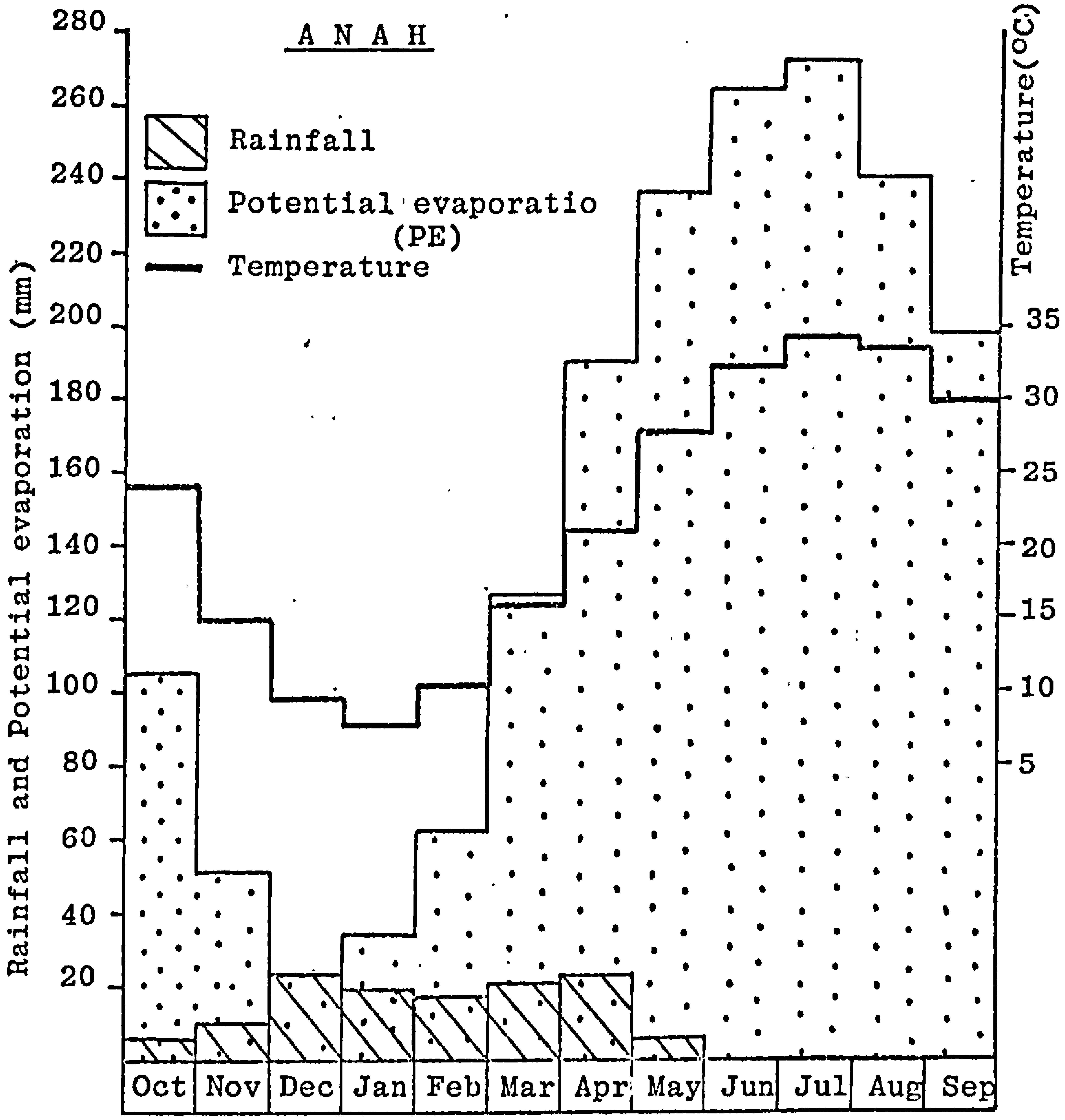


Figure 9: Bar graph of monthly rainfall, PE and temperature in Anah.

Parameters	Mean annual value (mm)
P	150
FSWE	2250
PE	1800
AE	1000

These values were derived using the climatological data for Baghdad metereological station only. Potential evaporation (PE) was calculated on a monthly basis for Mosul, Baghdad and Basrah by both the Penman and Thornthwaite methods and the ratio was used to adjust the PE obtained for the remaining twelve stations in Iraq (Kettaneh, 1974). According to Brichambout and Wallen (1963), the mean annual PE obtained by Penman's approach for Mosul is 1378 millemetres. This result was obtained by computing total global radiation using the formula:-

$$Q_S = Q_A \left(a + b\frac{n}{N}\right)$$

where

Q_S = Mean daily global radiation
Q_A = Observed mean daily global radiation
n = Actual hours of sunshine
N = Maximum possible hours of sunshine
a = constant, 0.18 derived for United Kingdom
b = constant, 0.55 " " " "

According to Gangopadhyaya, Datar and George (1970), the values of the constants (a) and (b) vary substantially from place to place due to variations in the climatic conditions of the atmosphere. The use of proper values of (a) and (b) was adopted by Kettaheh (1974) for the

Iraqi conditions; being a = 0.307 and b = 0.4898. Their validity for Iraq was examined and found successful. All the results obtained for PE by this method are tabulated in Table 1,and shown in figures 6, 8 and 9 for Mosul, Sinjar and Arah stations respectively. In addition, the following values were obtained by the same methods:- 1900 mm for the mean annual PE calculated for the northern portion of the Mesopotamia plain; 1998.2 mm for the mean annual FSWE in Mosul; and 2450 mm for the mean annual FSWE for the northern portion of Mesopotamian plain.

Rainfall

The total annual rainfall in this area is sufficient for dry cereal farming. The isohyetal map of NW Iraq (Figure 5) has been drawn on the limited amount of data available for this work. For most of the raingauges no record is sufficiently long to be used as an average for the area. In Bawara, for example, only one year of records were available, 1970-71; for this station was set for temporary study in the area.

The best available records are those tabulated in Table 1, while the values of rainfall for the rest of the raingauges were estimated from the available isohyetal maps of Iraq published in several technical bulletins. The average annual rainfall over this area lies between 200 and 400 mm. (Figure 5). The maximum amount of rainfall (over 450 mm.) was estimated by taking into account the effect of altitude on precipitation over the mountain of Sinjar. This value decreases southwards towards the western desert of Iraq, so that the total annual rainfall in Anah (200 km to the south of Sinjar) is only 112 mm. Figures 6, 8 and 9 show as bar graphs the mean monthly rainfall in Mosul, Sinjar and Arah respectively. The bulk of the annual rainfall occurs in the seven months starting with November and ending in May. The four months of June, July, August and September are practically dry every year. The maximum amount of rainfall recorded in Mosul was 605.5 mm in the year 1963, while in Sinjar it was 692.3 for the same period. The bulk of the rain originates in the western mediterranean areas and is carried west in the form of thick clouds to fall on the foothills and the mountains of northern Iraq. A considerable number of thunder storms and hail storms occur in Spring in this area and this occasionally leads to major flooding in the main valleys of Tharthar and Ajij. Snowfall is rare in most of the area except for the mountain of Sinjar and the foothills of the Lower Fars.

Relative Humidity

The amount of water vapour in the air is usually called relative humidity and is expressed as the percentage of the maximum amount that the air could hold at the given temperature.

The available humidity data are tabulated in Table 1. The relative humidity in Mosul is also compared with the barometric pressure in Figure 7. The annual relative humidity in Sinjar ranges from 72 percent in January to 19 percent in July and August. This low value of humidity is due to the absence of surface water, the dry nature of the soil and the relatively deep water table in the north of the area. Humidity is expected to be higher over the marshy land to the south where the capillary zone is directly affected by evaporation.

The other important meteorological elements such as wind, sunshine and fog are recorded in Mosul meteorological station and more recently in Sinjar, Tel-Afar and Hammam Ali (College of Agriculture). The average wind speed in Mosul is about 3.1 m/s in May and decreases to 2.0 m/s in November. The highest speed in Mosul was 90 km/hr, as recorded on 22 January 1963, while the highest wind speed recorded in Sinjar was 115 km/hr measured on 25 October 1963.

The maximum hours of sunshine, cloudiness, saturated vapour pressure and actual vapour pressure are recorded in the main meteorological stations of Mosul, Baghdad and Basrah.

1.6. Vegetation, agriculture and land use

Vegetation distribution in this area are greatly controlled by the climate, soil type and agricultural activity of the inhabitants.

1.6.1. Soil and Vegetation

The surface soil type varies considerably throughout the area but generally appears to have a high salt content in the central and southern parts. Figure 10 shows the different types of soils in and around the area of study, after Buringh 1960. In general, three types of soil are distinguishable:

1) The brown soil of the uplands; represented by the numbers 34 and 35 in Figure 10, covering most of the synclinal basins in between the Lower Fars anticlines, it is relatively deep, and forms good agricultural land in the plains around Mosul.

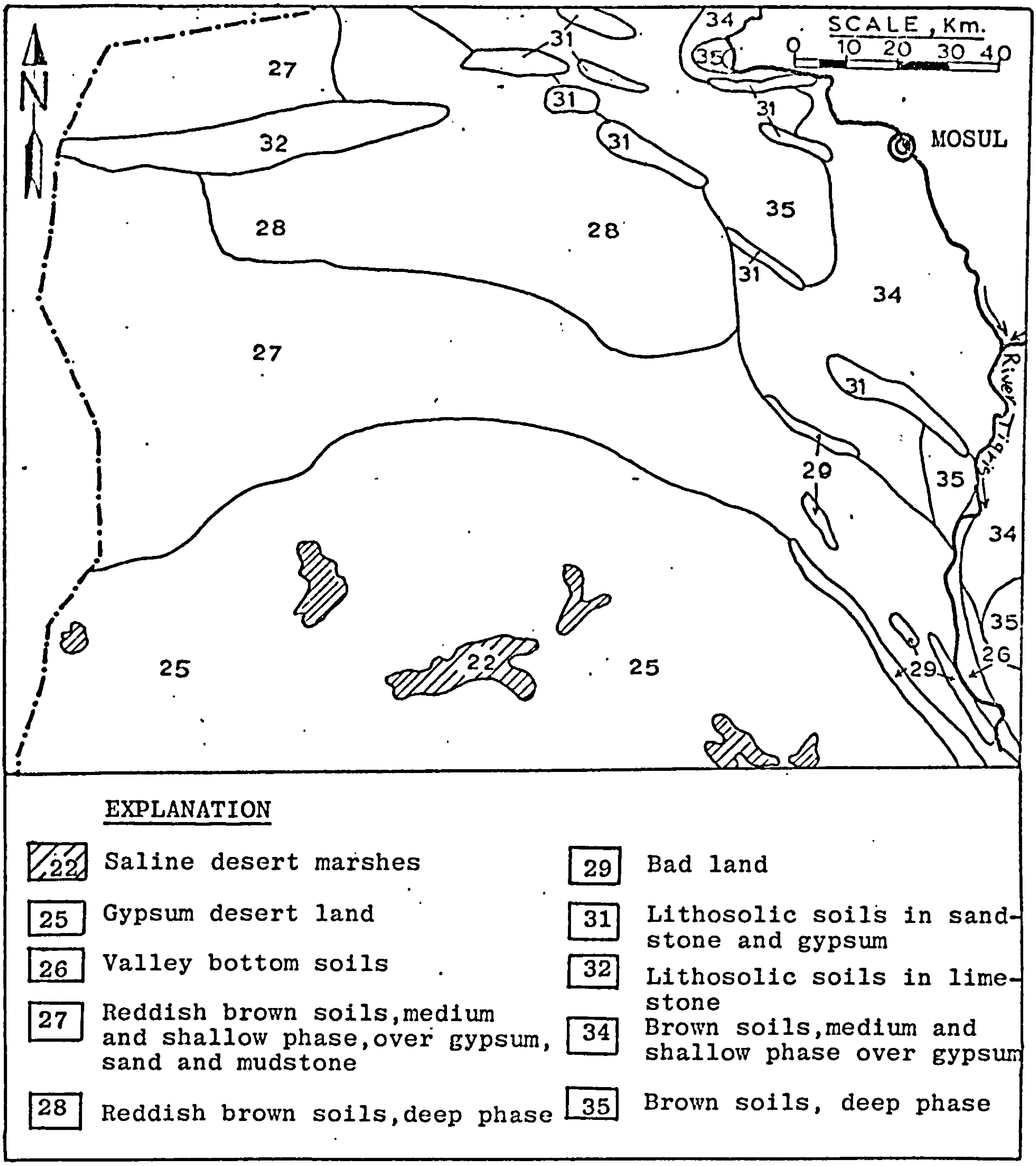


Figure: 10 EXPLORATORY SOIL MAP OF NW-IRAQ , After Buringh, 1960.

2) The reddish brown soil in the transitional area bordering the desert. This is represented by the numbers 27 and 28 in Figure 10. It provides good winter pasture, but is mostly too dry for arable land use except for the northern parts near the mountains of Jabal Sinjar. In the north-eastern section, the soil is typically a greyish brown sandy silt to silty clay.

3) The dry steppe and desert soil; area number 25 in Figure 10, generally a brown Serozem, typical of desert conditions. It is generally thin, and overlies the older sedimentary formations, but is entirely lacking in a "humic" horizon for most of it is underlain by massive cavernous gypsum. It is predominantly sand of aeolian origin, often forming small dome-like hummocks. Small fragments and crystals of secondary and detrital calcium sulfate are distributed through most of the reddish and grey clays and silts. However, these secondary gypsum crystals are more dominant in the subsoil (Plate 10) where they range in size from less than a millimeter to several centimeters.

Vegetation is generally denser in the northern part of the area compared with the southern desert, where some sections are completely devoid of any growth. Where secondary gypsum occurs, a salt-tolerant sagebrush is common and grasses and water plants occur in some of the shallow marshy lakes. Short desert grass is quite common and is the main grazing feed for the many sheep raised by the Bedouins.

Along Wadi Al-Tharthar there occurs various types of reed grasses and small shrubs common to moist stream channels. Some vegetation samples have been collected within the period of field work (June 1974). They were identified by the Institute for Scientific Research in Baghdad as follows:

1) Hypericum sp.; found dominant along the upstream of Wadi Al-Tharthar
2) Artemisia herba alba. This vegetation was predominant downstream and found in association with Salsola species and Peganum harmala. The latter was found to form about 37 percent of the community in the Hadhr area according to Habib, I.M. (1971).
3) Cressa Critica. This palophytic species was found to be dominant around Hadhr area along the Wadi Al-Tharthar. In addition to Caparis spinosa.

The most abundant plant observed around Al-Hadhr was Poa species, Artemisca scoparia, Cornulaca monocantha and Salsola species. It has been found that the Prosopis farcta species form a community of about 13 percent near Al-Tharthar. In this area the salt content of soil was found to be equal to 0.15 percent of which 0.002 percent was chloride and 0.05 percent was sulfate salts (Habib, I.M., 1971).

1.6.2. Agriculture and land use

The main crops grown in the area are wheat and barely. These grains are dry farmed over the whole of the area except in the hilly area of Lower Fars Formation. In the higher parts where most of the soil is stony and difficult to plough, the area is usually left for grazing.

Large areas are cultivated by mechanical methods. In fact this basin and the north Sinjar basin form the richest plains in Iraq for wheat production. The crops are planted in the fall (around November) and harvested in summer every year. The production is totally dependant on rainfall. Thousands of tons of wheat could be wasted in the area if rainfall is not sufficient, though on such occasions the crops are unilized for grazing.

To the south of the town of Sinjar in a radius of about thirty kilometers and at established villages, small tracts of land are irrigated, with water from hand dug wells. Small quantities of rice, maize, cotton, tomatoes, onions and other vegetables are produced. The biggest fruit farms are located near the towns. These farms are irrigated with surface water or springs and considerable quantities of olives figs and pomegranate are cultivated.(Plate 4) shows the farmed area in Tel Afar, dark shaded, irrigated from the main spring of the town.

Recently, the government has tried to increase the grazing area by reducing the area of arable land to attract the Bedouin. In fact the government has distributed areas of land to the nomadic Bedouin which help to establish permanent villages and farms around the area. Many co-operatives and collective farms have been established by the government with these farms irrigated by centifugal pumps from hand dug wells. About 90 such co-operative farms have been established in the area around Sinjar. Each co-operative farm covers an area of 0.03km^2,the main cultivated crops being cotton, onions, cereals and tomatoes. About 50 private farms owned by farmers in the town of Ba'aj and the surrounding villages are also irrigated from hand dug wells situated over alluvium deposit or over a "kahriz". These farms are relatively smaller than the co-operatives.

The total area farmed with cotton in Tel-Afar was 4.785 km^2

km^2 and produced 963 tons. While it was 7.750 km^2 in Sinjar and produced 1127 tons. The lowest production is in the south where 1.497 km^2 were farmed in Hadhr to produce only 152 tons of cotton. While the production of rice was limited to small areas in Tel-Afar and Sinjar. The production in Tel-Afar was 18 tons of rice in an area of 0.152 km^2, while it is 11 tons in Sinjar in an area of 0.125 km^2.The production of lentils was also limited, the production in Sinjar was 11 tons in an area of0.125 km^2, while it is only 3 tons in Tel-Afar in an area of 0.035km^2.Only three tons of sesame was produced in Hadhr in an area of 0.05 km^2.

1.7 Population distribution and water use:

The administrative divisions in Iraq are divided in the following order:-

1) Muhafadha: This forms the main administrative area, county, the area of study is part of Muhafadha Naynawa (ninava). This region was previously called "Liwa". The city (madina) is usually the administrative centre for Muhafadha.

2) Qadha: Is a subdivision of Muhafadha and means canton

3) Nahiya: is a subdivision of Qadha and means "Commune"

4) Qarya: This means village and can be the administrative centre for Nahia

5) Qasaba: Is the smallest village or administrative division in the area.

Figure 11 shows the different administrative divisions and subdivisions for the area under study. It is obvious that the administrative boundaries do not coincide

with the basin boundaries, and this makes it extremely difficult to calculate the total population for each area of the basin.

The administrative boundaries have been altered in the last twenty years, therefore it is not possible to compare the population density with the successive censuses of 1947, 1957, and 1965. However, the estimations taken from the Ministry of Planning in Baghdad shows an increase in the population over the last thirty years. In most of the areas, the population has tripled. The following examples are for areas in which the administrative boundaries have not changed.

Name	1947	1965
Al-Shura	26,109	95,427
Nahiat Sinjar	15,382	44,223
" Al-Shimal	10,920	28,081
Town of Sinjar	5,407	7,081
Total of Qadha Sinjar	31,709	80,288
" " Tel-Afar	44,200	105,249

In the southern part of the area, most of the population are nomadic Bedouin being members of the Shammar tribes. In the census of 1947 these tribes were estimated to be about 70,000 but their number is not known in every region. The majority of them wander around the Iraqi and Syrian Jezira, and in some seasons they even move to Jordan or Saudi Arabia.

Water Use

Industry in the area is limited to a few flour mills. The amount of rainfall in this area is sufficient for seasonal crops like wheat and barley which cover extensive areas of flat land. The bulk of the water is therefore used for domestic and livestock only. Water for irrigation is obtained in limited amounts from the shallow hand-dug wells by the use of centrifugal pumps, powered by diesel engines, which are run only intermittently to avoid over-pumping of the well, which would otherwise run dry in one day's pumping. In the majority of the hand dug wells, only a hand-raised bucket (Dalu or Satla) is used to obtain the water. Fresh water from springs and wells is used for drinking in the northern part of the area, except for the town of Tel-Afar for which a special pipeline pumps fresh water all the way from the river Tigris. Surface and ground water are used in winter and springs over most of the area, although in summer and autumn, ground water becomes the only source. Ground water are used for drinking in areas up to about 30 kilometers south of Jabal Sinjar.

In Ba'aj, the municipality has its own tankar trucks to bring fresh drinking water from Sinjar (33 km to the north) several times daily. Fresh water is supplied free for Ba'aj but for the other remote villages, one cubic meter of water can cost up to two Iraqi Dinar (about £4 sterling). It is common for private tanker owners to bring fresh water from Sinjar and sell it in the bad-water regions in summertime.

Domestic water for the few established villages in the south of the area is obtained from shallow hand-dug wells or springs. Most of these shallow wells are dug near the main wadis or in the alluvium deposits. Surface water from rain pools is used during the wet seasons by nearly all inhabitants in the area.

Domestic water for the hilly area of the Lower Fars formation is hauled daily from the nearest reach of the river Tigris during summer and autumn. Only in few localities is there water suitable for domestic use. Water is used for irrigation in the areas where the quality is suitable and the quantity is sufficient. In fact the biggest farms of olives, figs and pomegranates are irrigated from the main springs in Tel-Afar, Terme, Sino, Shaith Ibrahim and Adaiya (see plate 3). In the areas where the water quality is extremely bad it is utilized only for brick moulding and mud hut plastering. The domestic water supply in such areas is very limited.

1.8 Cultural and Economic Significance

The first evidence of settlement near this area belonged to Neanderthal man who lived in Northwest Iraq between 200,000 and 50,000 years ago. Later in the Neolithic age, a nation in mass migration apparently swept over an area stretching from the mountains to the Mediterranean. Evidence of a transition from the microlithic industry of ca.10,000 BC to the agricultural economy of the Jarmo culture and to that of baked pottery is found in this area. It has been found in Hassuna near Mishraq (5200 - 500 BC) that the transition from one-roomed huts to a house with two or three rooms took place, Beek(1962).

Ancient settlements were also found at the following sites:-

1) Grai Rash (about 10 km south of Sinjar: Tel el Obeid 4500 - 3800 BC: Erech 3800 - 3200 BC

2) Tel Khoshi (near Ma'aj): Sumer and Akad 2500-2000 BC, Old Babylonian 2000-1600 BC.

3) Sinjar: Kassite and early Assyrian 1600-911 BC. Parthian 248 BC - AD 226.

4) Tel-Afar (Nimit Ishtar): Assyrian (911-612 BC) Parthian 248 BC - AD 226.

5) Hadhr (Hatrah): Parthian 248 BC - AD 226 followed by Arab

The majority of these settlements occupied fertile land with an apparent abundance of fresh water. Except for the settlement of Tell Khoshi and Hadhr, these settlements must have developed a good means of fresh water storage or constructed long Kahrez (horizontal galleries or subsurface channels). Many such kahrizes are found in the area extending as far as Beski Al-Shimalia (northern), about 17 km southeast of Sinjar (Serial No.145 Fig.2, Sample No.123, 124 Appendix 2). The Beski Kahriz still function properly by having enough fresh water supply. It is about 14 metre deep in this area. Most of the other Kahrizes are abandoned or have been neglected for a long time. The field indication of the presence of Kahriz under-ground are the small depressions or holes found on the surface. These holes represent the opening of the shaft which were constructed for maintenance. The distance between these holes on the surface is about 400 metres.

Figure 12 shows the location of Kahrizes in the southern part of Sinjar. These Kahrizes are plotted from the details of 1:100,000 scale maps (Balad Sinjar, J.37x-SE) However, most of these Kahrizes were not located in the field. They are concentrated in the area between 15 and 30 km south of Jabal Sinjar. Apparently, they were constructed in the area where the alluvial deposit thins out or disappears, 20-30 km south of the town of Sinjar.

It is still not known who constructed these kahrizes or when they were constructed. However, it appears that the Parthians who lived in this area for about five centuries could have brought from Persia this technique where it had been in use for several centuries. The

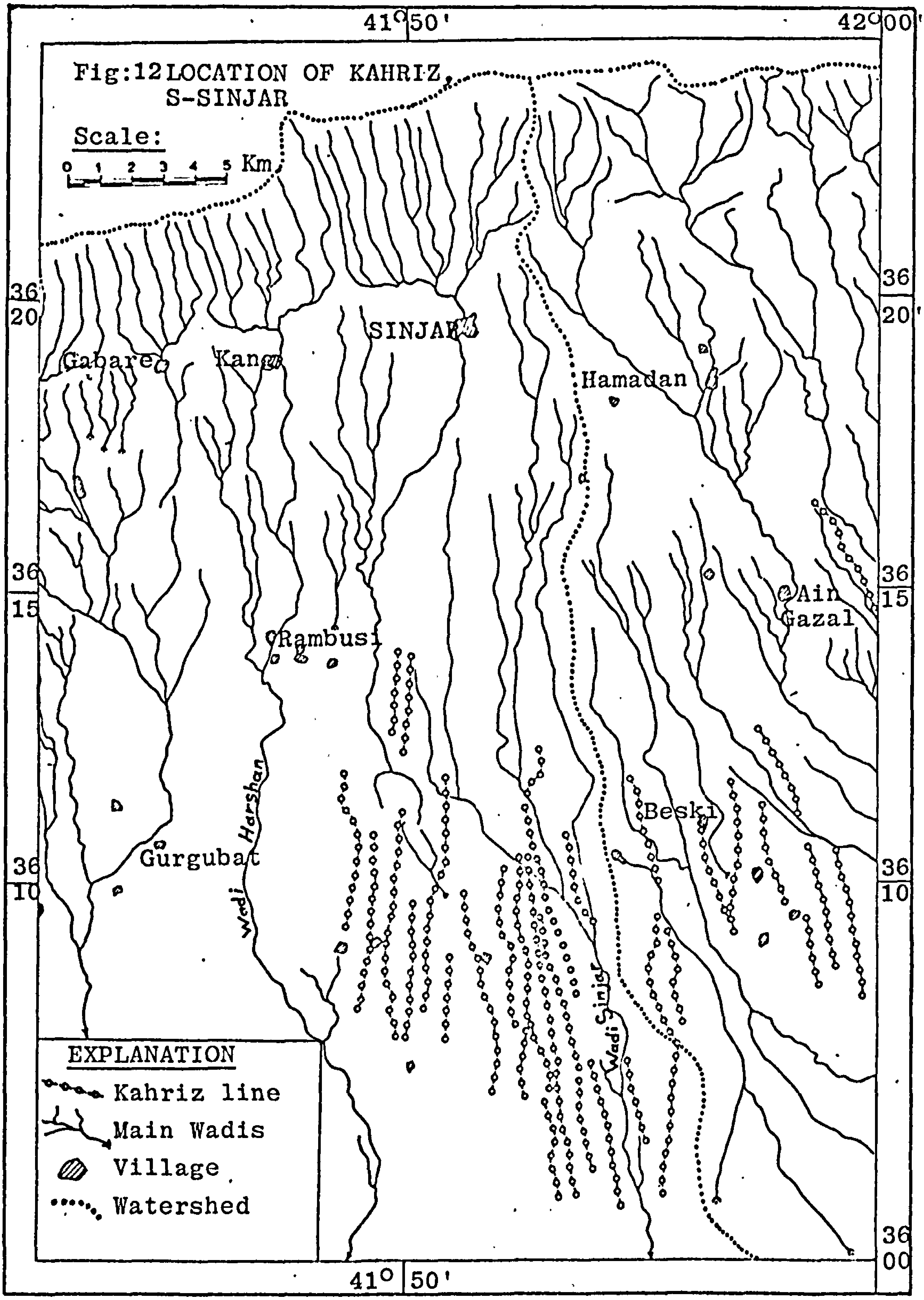


Fig:12 LOCATION OF KAHRIZ, S-SINJAR

presence of many kahrizes around Jabal Sinjar gives a clear indication of water management in this area since the time of the Parthians. Nevertheless, many agricultural and water supply methods used today are still very primitive. The use of sheep or goat skins to haul water from the wells by hand or animal is the same method which was used thousands of years ago. Today this process is still being used in the south of the area. The folded area of the Lower Fars Formation has recently become important since the discovery of economic sulphur deposits in many structures. In Mishraq, one of the biggest economic sulphur deposits in the world, a mine has recently been constructed, producing about one million tons of native sulphur per year.

The presence of several mineral and thermal springs in this area has attracted visitors from all parts of Iraq. The most important is the spa of Hammal Ali, which attracts at least 200,000 visitors every year. However, the bathing facilities in this spa are still primitive and in urgent need of proper development and medical supervision (see plate 4). A feasibility study for the Mosul Dam project by foreign companies was planned to include the possibility of irrigating the northern catchment area of the Tharthar depression. This includes the construction of a complicated system of irrigation channels and drains with water supply tunnel under Jabal Zambar, near Tel-Afar (See plate 3).

The flow of the river Tigris immediately east of the study area safeguards potential overdevelopment of its aquifers. The artificial recharge of fresh water from this river in Spring to replenish the aquifers of the Upper Fars Formation seems feasible in the future.

CHAPTER TWO

GEOLOGY

2.1 Introduction

2.2 Stratigraphy
  2.2.1 Lower Fars Formation
  2.2.2 Upper Fars Formation
  2.2.3 Reworked Upper Fars
  2.2.4 Alluvium and Recent deposits

2.3 Structure

2.1 Introduction

The general geological setting of northwest Iraq is shown in figure 13. This regional geological map is available in colour, scale 1:1000,000 and was first compiled by the Iraqi Petroleum Company (I.P.C.). The system of rock unit classification and nomenclature employed by the I.P.C. authors is that advocated in a set of rules compiled by Ashley and others (1939) as supplemented in a recent paper by Hedberg (1952).

Recently, the Directorate of the Geological Survey in Iraq began detailed geological mapping of the northern Jezira area. This area is on the southwestern and southern flank of an arcuate geosyncline which trends in a northwesterly direction through central Iraq,then swings to the west in the northern part of the country. The southwestern flank has a very shallow, almost imperceptible dip to the northeast or easterly, while folding on the northeast flank gradually increases northwards towards the complexly folded and faulted Nappe Zone near the Iraq-Iran border.

The oldest exposed formation is the Shiranish formation of Cretaceous age in the core of Jabal Sinjar, followed by the Sinjar Limestone formation which constitutes the main exposed formation in Sinjar mountain. The current work was undertaken to study the best aquifers in the upper formations in which the water is within economic reach. For this reason, the deeper formations are only briefly considered while the upper formations are studied in more detail.

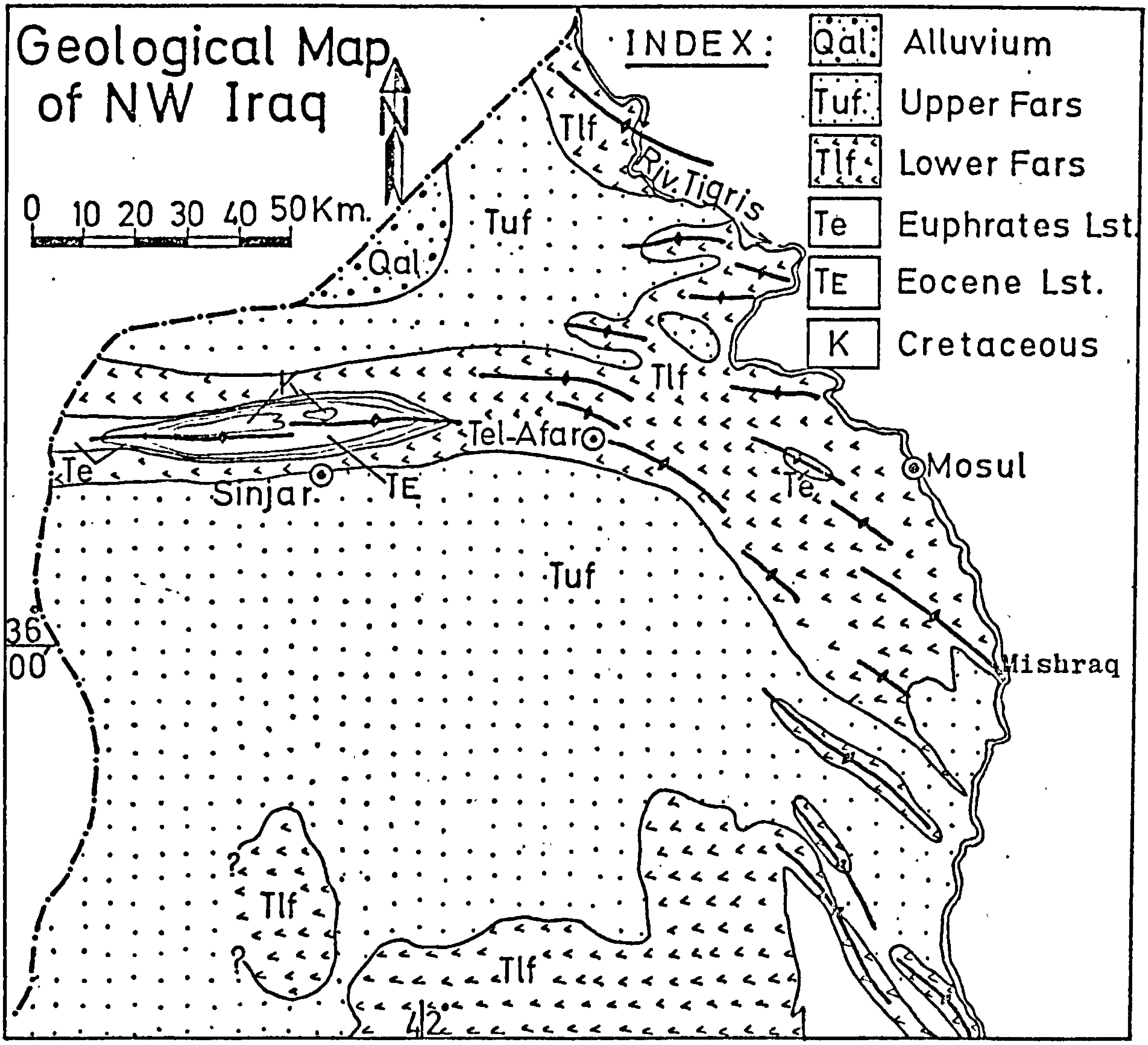


Figure 13: Geological map of NW-Iraq.

2.2 Stratigraphy

In Upper Campanian time of the upper Cretaceous, important tectonic movements commenced in northern Iraq. These influenced considerably not only the thickness of the subsequent sedimentary units, but also the type of rocks which were deposited.

West of the Tigris, two rapidly subsiding troughs developed, on east-west alignments, presumably as a consequent of deep-seated faulting. In the northerly trough, which passes below Jabal Sinjar and Sasan into the Butmah area, open-sea, globigerinal sedimentation persisted through Upper Cretaceous times, more or less keeping pace with subsidence. The trough-filling sediments are the normal rock types of the Shiranish formation which is exposed in the core of the Sinjar anticline.

Table 2 is the summary of the exposed formations in the area of study. The Upper Cretaceous lithological succession is cut short by a Maestrichtian - Palaeocene erosional unconformity, which expands locally to throw Lower Miocene units into transgressive relationship with underlying eroded Maestrichtian formation.

The Sinjar limestone formation, a shoal facies of the Palaeocene-Lower Eocene, is well-developed in the area of Jabal Sinjar. It consists of hard, massive, reef limestones, locally intercalated with bituminus limestone. The thickness of the whole formation is some 125 metres at Kersi. Occasionally, fossiliferous chert nodules and intraformational conglomerates can be observed.Sinjar limestone passes from a reef-facies in the west to marls in the East, near Zerwan which contain chert nodules (Al-Rawi, 1973).

Age Divisions		Formations	Thickness (m)	Lithology	Equivalent formations and remarks
Recent		Recent alluvium	50 m.	Limestone boulders with clayey and sandy matrix	Provides fresh, shallow ground water around Jabal Sinjar
Pleistocene		Old alluvium	?	Limestone fragments, sand and clay	good aquifers
Pliocene		Reworked Upper Fars	10	Gypsiferous silty clay	yields bad quality water in the southern parts of the study area
Miocene	Sarmatian	Upper Fars	300-350	Clay, silt, sand and silty clay	Major aquifer in the area of study
	Vindobonian	Lower Fars	460	Gypsum, anhydrite, marl limestone, dolomite and claystone.	250 m. in Mishraq Sulphur structure, Sulphur bearing in many western Tigris structures
	Burdigalian	Jeribe	73	well bedded limestone recrystalized, dolomitized	Lower Fars Anhydrite Euphrates limestone - Asmari limestone Dhiban Anhydrite
	Aquitanian	Serikagni	145	globigerinal chalky lst. with calcareous bands	Euphrates limestone formation
Eocene	Priabonian	Jaddala	342	Globigerinal marl and limestone	Avanah, Pila Spi limestone and Gercus red bed
	Lutetian	Sinjar	125	reefal or marly limestone	Aaliji, Khurmala and Kolosh clastic formation
Palaeocene					
Cretaceous	Maestrichtian	Shiranish	228	Globigerinal marls and marly limestone	Upper division of 99 metres of blue marls, overlying 129 m. of thin bedded marly limestone
	Upper Campanian				

Table 2: Stratigraphy of Sinjar area

The Pila Spi limestone formation of middle Eocene age extends much further towards the northeast on the eastern side of the river Tigris. In Middle and Upper Eocene times the more offshore Jaddala Formation occupied this area. After the deposition of the Eocene strata a regression of some importance occurred, so that the Lower Miocene Serikagni Formation rests unconformably on Jaddala formation. This formation can be considered as the offshore facies of the Euphrates Limestone with which it interfingers in the Qaiyarah, Jawan and Qasab areas. In the type area, the Dhiban anhydrite formation overlies this unit conformably and gradationally, in other places the Dhiban anhydrite directly overlies the Euphrates Limestone formation.

Jeribe limestone formation overlies the Serikagni Formation unconformably, where no Dhiban anhydrite formation occurs. In turn,the Lower Fars formation overlies this unit, with a thick gravel bed at the base of the Fars and overlying the Jeribe indicating what may be an important unconformity.

2.2.1. Lower Fars Formation

The type locality of this formation is in Iran; a detailed description of the Lower Fars (LF) as found in the Agha Jari oilfield of southwestern Iran, being given in Ion et al (1959).

The isopachytes map of the Lower Fars (Middle Miocene) is shown in figure 14. The environment of deposition of the Lower Fars represents a deep evaporating basin in which deposition was governed by periods of dessication alternating with influxes of sea water. The region can be considered as having been a partially barred basin from

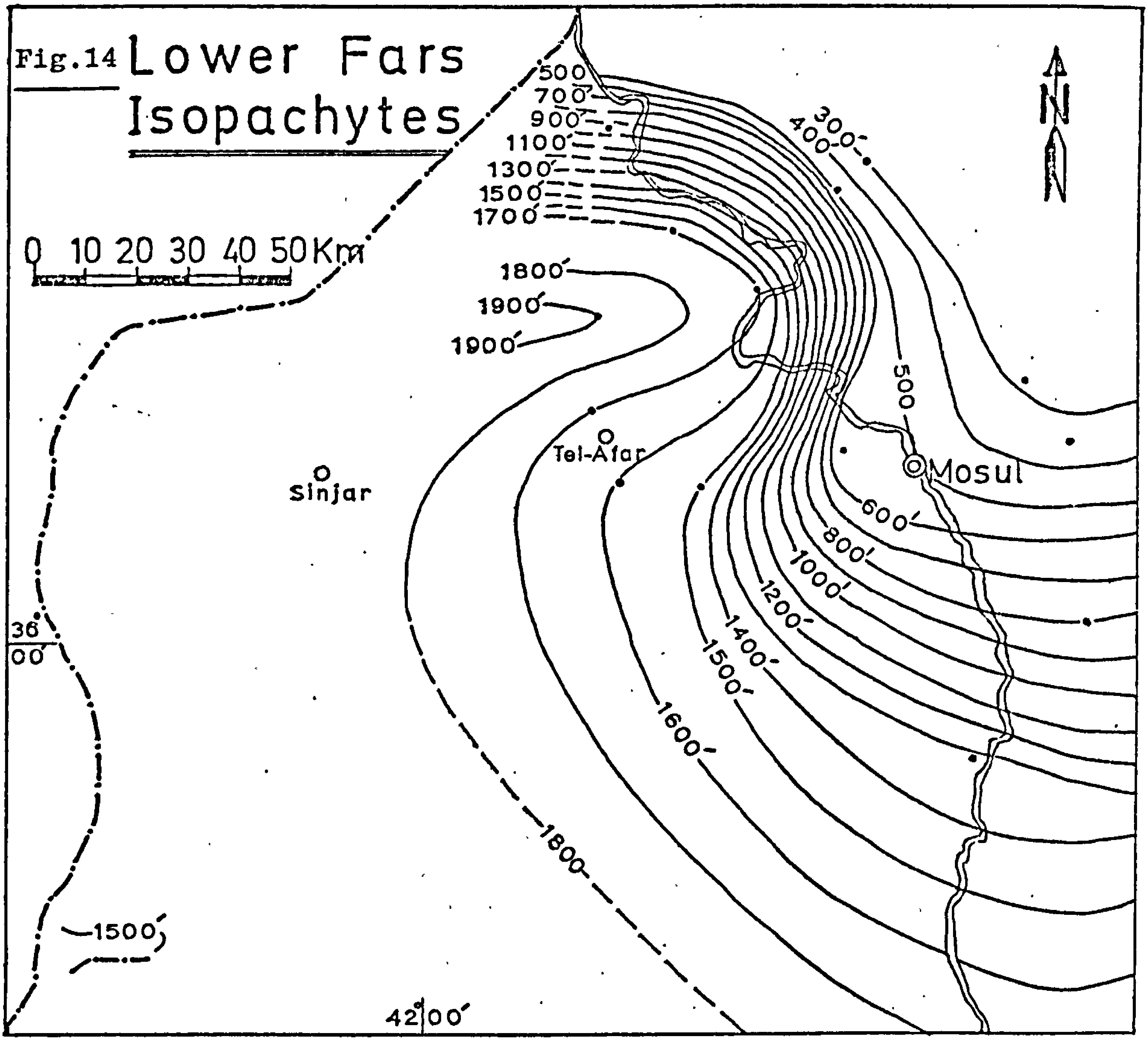


Fig.14 Lower Fars Isopachytes

which access to the sea was probably to the south.

The lower limit of the formation in northern Iraq is marked by a prominent conglomerate, known informally as the Basal Fars Conglomerate. In the area under consideration it marks a very important transgression of the formation over an eroded succession ranging from "Middle" Eocene to "Lower" Miocene (possibly Burdigalian) Jeribe limestone formation according to Bellen (1956).

The upper limit of the Lower Fars is marked by a prominent anhydrite bed. The overlying formation is the Upper Fars (Upper Miocene) and the underlying formation is normally the Euphrates Limestone (Lower Miocene), though in the western parts of the area, the underlying formation is the Jeribe Limestone.

In the study area, the Lower Fars is exposed mainly in the positive areas of the West Tigris structures, (Plate 9). In this area, the presence of limestone interbedded with gypsum and marl acts as a support for the soft beds and leads to the formation of hilly and irregular topographical features.

The Lower Fars formation is covered by thick alluvium to the south and north of Jabal Sinjar though some beds outcrop in the plunging parts of Jabal Sinjar to the east and west. The southern exposure of this formation in the Jezira area is partly covered by loam and alluvium though it is well exposed near the town of Hadhr and along the Tharthar Valley. Figure 15 shows the general succession of beds in the area along three cross sections. Section AA' and BB' are in the direction of dip. while section DD' is along the strike direction (after Ralph M. Parsons & Co. 1954). see Fig. 3 P.22.

Figure 15: Geological cross sections across the area.

The Lower Fars formation consists mainly of gypsum and anhydrite, marl, limestone, and claystone. (Figure 16). Several thin beds of sandstone occur towards the base of the marl or within it. The lithology of this formation changes considerably in the different structures for there has been a considerable change in lithology since deposition. The following are the main factors which have controlled the lithology of this formation:

1) The original shape of the basin of deposition which bordered the shelf of the Arabian Shield. This has been affected by the highlands of the uprising foothills of the Zagros mountains.

2) The palaeoclimatic conditions at the time of deposition. These would have controlled the salinity of water in the basin of deposition leading to the deposition of evaporites or organic and chemical limestone.

3) The diagenesis of the formation, including any secondary changes which have taken place within the formation such as recrystalization, hydration, oxidation and reduction processes.

The thickness of the Lower Fars varies a great deal but can reach as much as 762 metres in the area of Chia Surkh. Over the Kirkuk structure the thickness varies from about 305 metres in the northwest to about 610 metres in southwest. In the studied area, it decreases to 460 metres in the Shaikh Ibrahim anticline and to about 250 meters in the Mishraq structure before thinning out to the north and northeast.

The Lower Fars formation contains the richest native sulphur deposit in Iraq. It can be divided into three members; the lowest of which contains the sulphur deposits

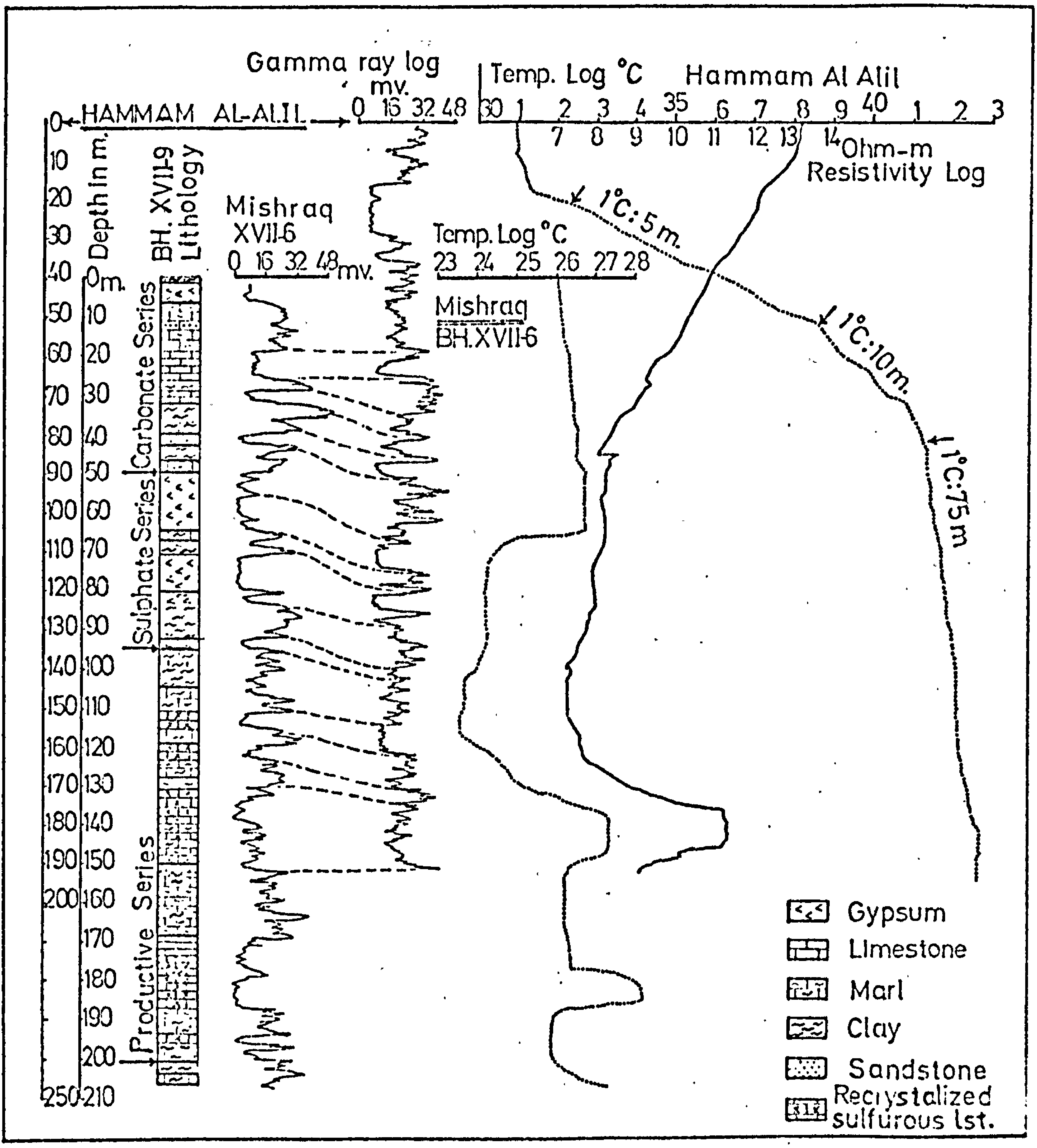


Figure 16: Geophysical logging in Lower Fars wells of Hammam Ali and Mishraq.

in the crests of some anticlines and is thus named the "productive series". It contains secondary limestone, calcite, sulphur and some aragonite interbedded with gypsum, marl or clay in the mineralized areas.

The "productive series" is overlain by the "sulphate series", a member consisting mainly of gypsum and anhydrite with marl. The uppermost member is the "carbonate series", which consists of limestone, marl sandstone and minor gypsum. The sulphate and the carbonate members overlie the sulphur productive member in most of the sulphur bearing anticlines. The detailed petrography of the sulphur-bearing horizons are discussed in more detail in the chapter on Hydrochemistry.

2.2.2. Upper Fars Formation (Upper Miocene)

The type locality of this formation is in Iran; detailed descriptions being given by Ion et al. (1951) for the Agha Jari oilfield. It consists of subcontinental and continental purple, red, brown and grey marls, silts siltstones, sandstones and grits, with minor occurrences of fresh water limestone.

The unit has a widespread surface outcrop in northwest Iraq, with its maximum exposure in the northern Jezira area. The greater part of the study area is covered by Upper Fars Formation (UF) and reworked Upper Fars deposits. Although covered by loam or sand dunes in the central part of the Jezira, the formation is exposed at many localities in the wadi beds. It is separated from the Lower Fars formation stratigraphically by the appearance of the first gypsum bed. The total thickness of the Upper Fars is unknown since none of the drilled wells has penetrated the full thickness of the formation. The maximum thickness of the Upper Fars is probably over 600 metres in the centre of the depositional basin. Drilling by Ingra company has penetrated 200 metres of this formation in Ba'aj (Serial No.35) and 300 metres in Tel-Sfoog (Serial No.198).

Maximum penetration achieved in drilling by the Ground Water Department of Mosul is in Al-Sag'gar (near Serial No.171) where 265 metres were proven (Figure 2). About 180 metres was in the Upper Fars and the rest of the well probably penetrates the Lower Fars formation. Another deep well drilled by the Ground Water Department is Kharab Bajar (near Serial No.32) which has partially penetrated the Upper Fars in 204 metres. The geological sections in Figure 15 give a rough idea of the thickness of the Upper Fars formation. In general, the total thickness of this formation probably exceeds 300 metres towards the centre of this basin. The maximum depth, in the axis of the syncline, is near the line of section DD' shown in figure 15. The axis of the syncline is in the E-W direction, about 30 kilometers south of Jabal Sinjar.

The geological logs prepared by the Ground Water Department for most of their wells is not accurate because of the use of rotary drilling techniques. No coring was made in any well to confirm the lithology. The correlation of wells on the basis of lithology was not possible due to the interbedding and lenticular nature of this formation. Recently, the Ground Water Department has adopted detailed geophysical logging for their new wells though only two logs are available for the study area.

The first log is from new well number 4 in Tel Kuta, near serial number 95 of figure 2. The details of this log are shown in Figure 17. It appears that the dominant lithology is clay, silt, sand and silty clay. It has been calculated that the silty and sandy horizons (which may function as aquifers) make up about 50 percent of the uppermost part of the Upper Fars, being some 80 metres thick.

The second log is from new well number 3 in Tel-Azar Sharqi, near serial number 21 in Figure 2, and the details are shown in Figure 18. The first 30 metres of this well is in alluvium with limestone boulders covering the Upper Fars formation. The silty and sandy horizons in the well make up about two thirds of the upper 90 metres of the Upper Fars.

The Upper Fars formation is limited in its occurrence and extension in the hilly area of Lower Fars making up the west Tigris structures. The formation is preserved only in the synclinal structures between the major anticlines. It is exposed in larger areas to the southeast near Al-Shora and in Wadi Qasab south of Mishraq (Figure 13).

2.2.3. Reworked Upper Fars

This unit overlies the Upper Fars formation in most of the flat plain south of Jabal Sinjar. It is autochthonous, formed as a result of the 'in situ' physical and chemical weathering of the Upper Fars formation, probably since the Pliocene epoch, and is characterized by the presence of thin bands of selenite and secondary gypsum crystals.

It is difficult to differentiate between the reworked Upper Fars (RUF) and the old loam deposits in the southern parts of the area. The reworked Upper Fars forms the subsoil horizon extending for a few metres below the surface. It was well defined in the following sections

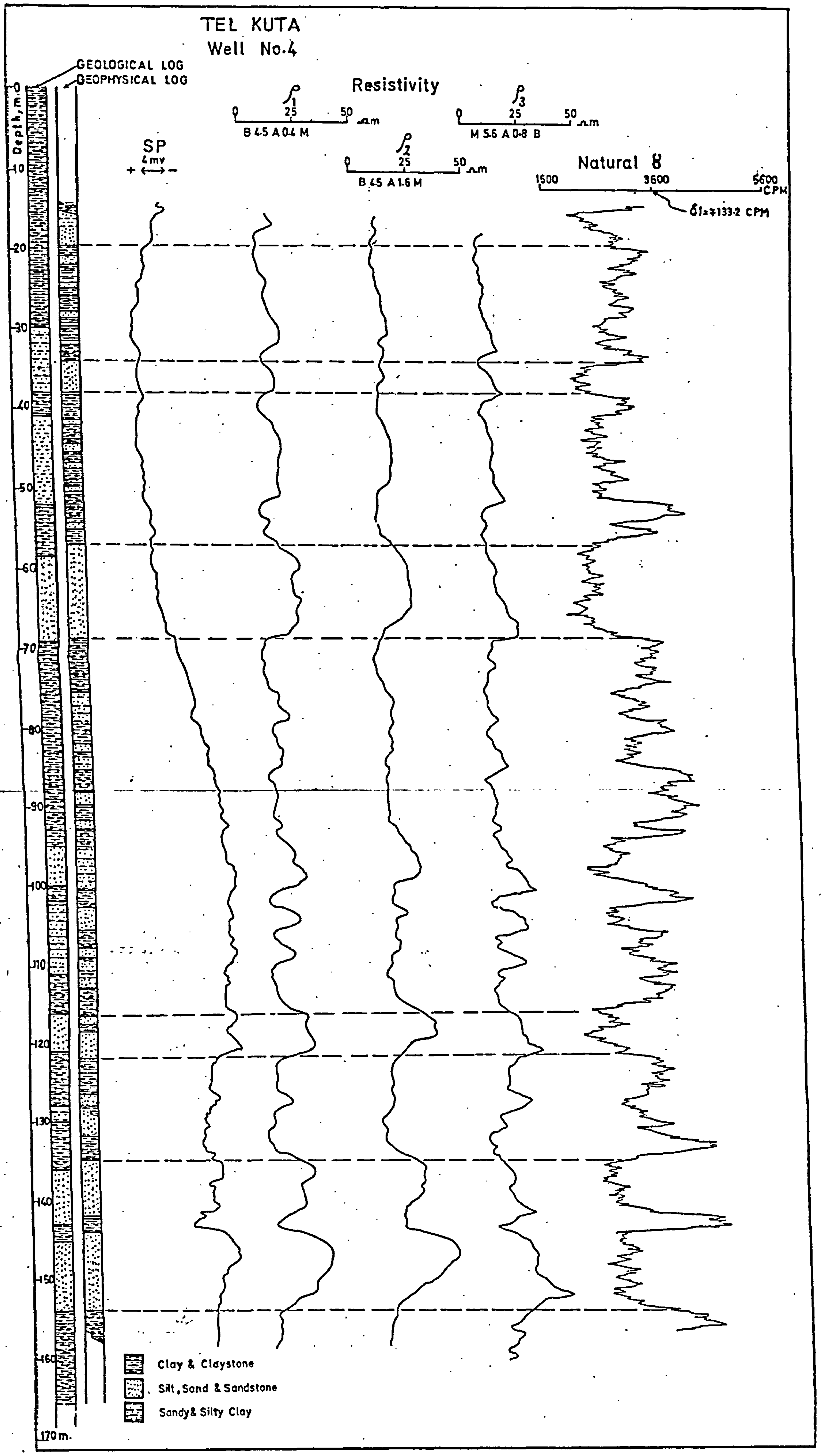


Figure 17: Geophysical logging in Tel-Kuta well No.4

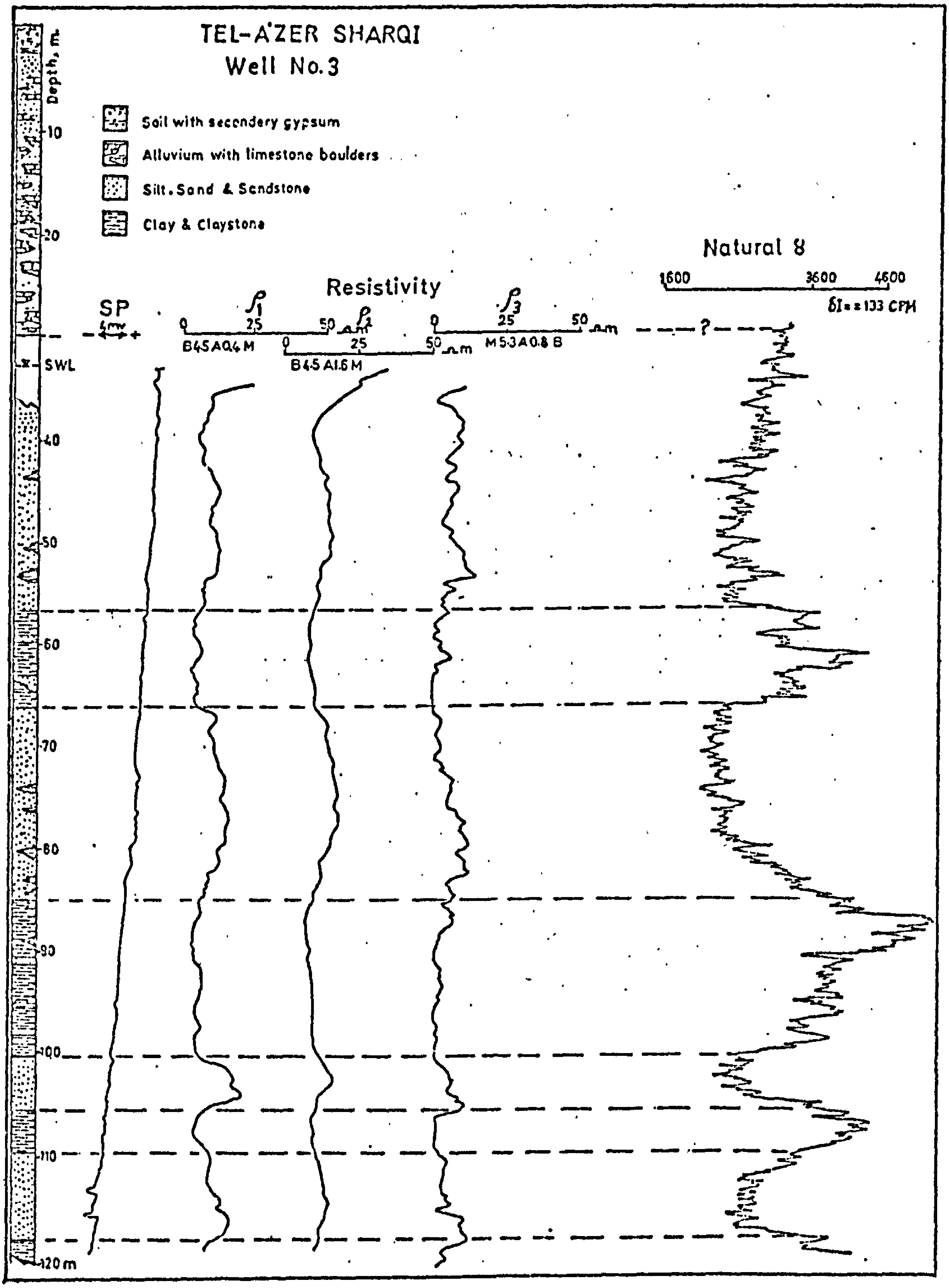


Figure 18: Geophysical logging in Tel Azir Sharqi well No.3

from dug wells situated about 35 km south of Jabal Sinjar:-

1) Mistarehat Hasan Norhar (SN.107), about 33 km south of Jabal Sinjar. The RUF thickness in this area is about 6 metres of silty clay impregnated with secondary gypsum crystals, see plate 10.

2) Almurra, (SN.110 and 111). In this location the gypsiferous clay appears at about 8 metres below the surface and continues for the full depth of the well to 12 metres.

3) Mistarehat Aldeekh (SN.112). The gypsiferous clay is distinctive in this location below some 9 metres of red silty clay. It is the water bearing horizon which supplies very bad quality water for the well.

4) Umm Al-Zanabear, (SN.116). The RUF in this area is covered by 4 metres of loam. It consists of 2-3 metres of gypsiferous clay overlying another 3 metres of gypsiferous silty clay followed by 2 metres of loose sand of the Upper Fars formation.

5) Al-Thiba, (SN.134). The RUF in this area is distinctive below 3 metres of loam. It consists of 3 metres of gypsiferous clay followed by 6 metres of gypsiferous silty clay. The water bearing unit in this location is the RUF.

In general, the unit consists of a mixture of sand, silt, clay and thin bands of selenite and secondary gypsum crystals. Its composition varies substantially within a short distance, giving good indications of the palaeoclimate and the distribution of salt deposits and salt playa overlying the Upper Fars formation.

This unit has a distinctive type of water and in some places the coarse crystalline gypsum horizons carry substantial amounts of water which make it an important aquifer in that particular area.

2.2.4. Alluvium and Recent Deposits

Where sufficiently thick and unconsolidated, the alluvium deposits around Jabal Sinjar form an excellent source of water. Two types of alluvium are distinctive south of Jabal Sinjar; old and new alluvial deposits.

a) The old alluvium of Pleistocene age outcrops as a capping over Upper Fars strata in areas about 3-5 km. south of Jabal Sinjar. It consists of limestone cobbles cemented with calcite and forms a flat iron shaped terrace of natural concrete towards the western parts of the area. In the south it extends to further distances in the form of tongues marking the channelling effect of erosion on the Upper Fars formation. In such areas, it may form perched aquifers, carrying relatively good water.

The thickest and widest extent of this alluvium is in two tongues extending from the central part of Jabal Sinjar (near the town of Sinjar) towards the southeast and southwest.

The exceptionally high quantity and good quality of water in the areas near Dibshia and Tel-Khalil could be due to the extension of this alluvium from Jabal Sinjar. In Dibshia, (SN.100) some 25 km. south of Sinjar a 23 metres deep hand dug well carries about 3 metres of water in a sandy gravel aquifer. Continuous bailing for water does not affect the water level in this area. In Tel-Khalil (SN.106) about 30 km. south of Sinjar, the pumping is continuous in summer for up to 24 hours a day. The water is of good quality, in comparison with that of the surrounding area.

b) Recent Alluvium deposits

The recent alluvium deposits around Jabal Sinjar cover an extensive area providing excellent quality water. It forms huge alluvial fan deposits at the outlets from the mountain extending some five kilometres in the areas of Jaddala, Al-Sikainia and Kharabet Ikheder. The thickest alluvial deposit is found near the town of Sinjar where a thickness of up to 42 metres was proven in well No.4 drilled by the Ground Water Department for the army camp, about 8 km. south of the town of Sinjar. In this camp, eight wells have been drilled by the Department and demonstrated that the thickness of the alluvium varies a great deal averaging about 30 metres.

Several hand dug wells have been drilled for irrigation purposes to the south of Sinjar; the majority penetrate only the top part of the alluvium. For example, the total depth of the hand dug well bordering the Sinjar camp (SN.75) is 13 metres in which the alluvium is very coarse at the base.

At the farm of Sulaiman Murad (SN.79) which is about 7.5 km. south of Sinjar (opposite the camp) the total depth of the hand dug well is 15.3 metres. In this well the dug section was examined. Large limestone boulders up to 70 cm in diameter can be observed in the bottom of the well, at about 15 metres depth, followed by 2 metres of limestone boulders ranging in size from 10 to 30 cm in diameter. The boulder size decreases upwards in the next 4 metres to about 2-10 cm in diameter. The alluvium gradually changes to sandy and silty clay in the top 5 metres and the limestone fragments become scarce. The same type of alluvium was found throughout the area with a tendency to decrease in thickness towards the south.

The coarse alluvium deposit thins out southward until it disappears about 25 km. south of the town of Sinjar. It is more widespread in the SE and SW tongues from Sinjar.

To the southeast at Khnaisi, in Ingra well No.16, about 17 km south of Sinjar, the alluvium covers the Upper Fars formation with 39 metres of varied deposits. It consists, from top to bottom of 16 metres of silty clay, 18 metres of sandy clay with limestone fragments and 5 metres of coarse fragments and cobbles of limestone.

To the southwest, the alluvium persists in its identity up to about 13 km. south of Jabal Sinjar, being well identified in the area of Tel Azer Sharqi (see Figure 18). The first 35 metres of Ingra well No.11 and the Ground Water Department well No.3 is alluvial in origin. It consists from top to bottom of 8 metres of silty clay, 9 metres of limestone boulders, 11 metres of silty clay mixed with limestone boulders and 7 metres of mixed alluvium and limestone boulders in a calcareous matrix.

The alluvium deposits in the hilly areas of Lower Fars formation are confined to the synclinal depressions. They store a considerable quantity of seasonal water which is enough to supply the scattered villages in the area by shallow dug wells.

2.3 Structure

The area under study forms part of the foothills of the Zagros mountain range situated to the northeast. It borders the stable shelf of the Arabian Shield situated to the southwest, and the general structural setting of the area is shown in figure 19. The deep structural zones were first delineated by the Iraq Petroleum Company (I.P.C.) in 1958 after a detailed gravity study of the area. The gravity anomalies were greatest in the depression parallel to Jabal Sinjar, while the minimum value of -30 mgl was observed some 20 km south of the town of Sinjar. This axis of low anomalies continues further to the south with a gentle gradient. The areas

having steep gravity gradients are shaded in figure 19. This steep trough marks the extent of deposition of low density sediments within the geosyncline. The gravity anomaly over Jabal Sinjar is -10 mgl due to the presence of thick low density flysch and marl deposits of the Shiranish Formation (Cretaceous).

The deep fault zones were found by gravity interpretation, with the datum used for gravity at 20,000 feet below mean sea level. (6096 metres). The gravity anomalies were positive around the area of Bawara salt lake (see figure 5) as also was the Hadhr Plateau area. With the exception of Jabal Sinjar, the most prominent structural units are a series of NW striking anticlines, most of which are slightly assymetrical to the northeast. They are separated by broad synclines which preserve units of the Upper Fars formation. Most of these anticlines are gently folded except Jabal Shaikh Ibrahim where the anticline is more strongly folded and is assymetrical to the southwest. All the limestones of the Lower Fars formation are markedly jointed in these anticlines.Caves, sink holes, caverns and faults are common features of the area.

In Jabal Sinjar, the anticline follows an E-W direction and shows axial plunging. It is about 70 km. long in Iraq and its western plunge extends into Syria. The width of the anticline in Jaddala is about 10 km. It is assymetrical to the north; the northern limb has an average dip of 65^{o} while its average is 20^{o} for the southern limb (al-Rawi, 1973). The western axial plunge is smoother than the eastern plunge. This could be due to bathymetric differences in the basin which has resulted in an irregular thickness of the formation. The Jaddala formation for example, is much thicker in the eastern part of the anticlinal fold.

Several faults have been observed in the mapping of this anticline, most of them being concentrated in the western part of the anticline (transversal faults), or on the northern limb of the anticline. Most of these faults have affected the Shiranish Formation and/or Sinjar Limestone formation. Compressional tectonics occur mainly near the core, in the incompetent Shiranish Formation. According to Henson (1951) the folding of the northern geosyncline of Iraq began in Pliocene times.

The plain of the Jezira south of Jabal Sinjar is part of a very wide synclinal basin extending for about 60 kilometres. Its central part is nearly flat and it is slightly assymetrical to the south (see figure 15). The average dip of the northern flank is about 20° towards the south, while the southern flank dips 5° towards the north. The dip becomes very gentle or flattens out completely further to the south.

CHAPTER THREE

HYDROGEOLOGY

3.1. Introduction

The study of ground water with particular emphasis on its quantity, mode of occurrence and movement,chemistry and relation to the geological environment is the main task of the hydrogeologist. This wide subject, hydrogeology with respect to water resources, is becoming increasingly important with the present high growth of population in the developing countries of the world. In arid and semi-arid areas, which make up two thirds of Iraq, the study of ground water and its proper development provides the only answer to the water shortage problems.

The main problems for the hydrogeologist in such areas, when the demand for water arises suddenly, is the lack of essential information and basic meteorological,hydrogeological and geological data. In such cases one has to make use of every possible piece of information and records related to the subject of study regardless of any doubts that may exist regarding the accuracy of the data.

In the area under consideration, there is no information whatsoever about the surface water, though it is known that considerable quantities of water flows out of the main basins of Ajij and Tharthar in the wet seasons and the beginning of the dry season. Hydrogeological information is essential for the understanding of water balance, aquifer replenishment and water loss from these basins. Existing information on the subject is not sufficient for any surface water study. In such cases one has to estimate the runoff from the total precipitation by careful study of the geometry of each basin.

The area of study is well known for its great variation in water quality. With the exception of the springs and the shallow fresh ground water belt around the mountain of Sinjar, the majority of the area suffers from poor drinking water with a total salt content several times higher than the world standard for drinking water. In many locations the water is polluted or has an undesirable smell. For this reason the problem of water quality has equal priority with the provision of a sufficient quantity of water for irrigation. Great emphasis is given to the study of water quality and the possibility of providing better sources of fresh water for the currently increasing population.

In the hilly area of the western Tigris structures, the lack of information about surface water has limited the study to ground water only. Special emphasis is given to the study of mineral and thermal water in this area and its relation to the deposition of economic sulphur in many structures.

In the short period of time available for field work it was not possible to visit every well or source in the area of 14,670 square kilometers. Those points surveyed included springs, kahrizes, hand-dug wells, drilled wells and surface water features; the distribution of which are shown in figure 2. The selection of the points for detailed survey or sampling followed the normal practice in the field.

The data listed on the field cards (see Chapter 1.3) were compared at each successive point. Samples were collected from some points to check any difference in the chemical characteristics of water or the geology of the area. When the data of successive points were similar within a distance of less than 3 kilometers, the area was considered hydrogeologically uniform. This was the only way in which such a vast area with extremely difficult accessibility could be adequately covered.

3.1.1. Basic principles, terminology and definitions

The fundamental hydrogeological principles which govern the physical and chemical characteristics of water are privided in any ground-water text book e.g. Todd (1959), Davis and De Wiest (1967) Walton (1970), Huisman (1975) and others. The basic terms which are repeatedly used in this thesis are listed below together with a short definition.

Soil water: Gravity and pellicular water contained in the soil zone.

Capillary fringe: sub-zone immediately above the water table held by capillary forces. The water in this zone is called capillary water.

Ground water (phreatic water). That part of ground water or sub-surface water that is contained in the zone of saturation. Its lower limit is the zone of rock flowage or the lower confining bed, its upper limits are the upper confining bed or the water table.

Spring:Localized natural hydraulic discharge of water at surface resulting in a small rivulet.

Aquifer: Geological subsurface materials containing and transmitting ground water.

Aquiclude: Impermeable stratum storing but not transmitting ground water.

Water table: Surface separating the capillary fringe from the zone of saturation. It is defined by the water level in the wells which tap an unconfined saturated material; and is the planar surface where the hydrostatic pressure is equal to the atmospheric pressure.

[illegible]-water divide, watershed: Dividing line between two basins.

Specific retention (Sr): Water held against gravity

Specific yield (Sy): Water drained from soil or rock under gravity flow.

Porosity: Ratio of void volume to bulk volume of rock sample expressed as percentage.

Transmissivity (T): Product of coefficient of hydraulic conducitvity and thickness of aquifer.

Hydraulic Conductivity (K): Ease with which water is conducted through an aquifer.

Storage coefficient (storativity,S): Water released or stored per unit surface area of aquifer per unit change in component normal to that surface. It is dimensionless.

Karst: Limestone terrain marked by very large solution openings

Confined water: Water separated from atmosphere by impermeable rock stratum.

Artesian aquifer: Confined aquifer from which piezometric surface can rise above top of aquifer.

Piezometric head: Sum of pressure and elevation head.

3.1.2. Aquifers and Basin Limits

The watershed dividing the different basins in the area of study were drawn on a topographical basis (Figure 3). However, the main basins of Ajij and Tharthar continue southward and the upper catchments of these basins were limited by the amount of data collected in the field. In the area between Sunaisala and Tharthar basins the southern limits were not defined. An arbitrary line was drawn limiting the study of this area to the inaccessible flat marshy land.

The hilly area of Lower Fars structures were the northwards limit around the Mosul - Tel-Afar Highway. The southern limit for this area is taken around the latitude 36°00' between Jabal Jawan and Mishraq sulphur mine.

In the south Sinjar plain, the bulk of ground water is found in the main aquifer of the Upper Fars formation. The detailed study of the lithology of the Upper Fars formation shows that the clayey horizons, because of their lenticular nature are not continuous over the whole basin. The majority of ground-water levels in the area are under water table conditions. The measurements of the water level taken for the deep aquifers are few and rather limited due to the difficulty caused by the mal-construction of the well. There is no access in the well head of the deep drilled wells for water level measurements. Most of the wells were operating during the period of field work and it was not possible to stop the pump or remove the head for any measurement. Therefore, accurate measurements of present day ground water levels are not available for the study of water levels in the deeper aquifers. Many measurements are available however for static water levels in most of the drilled wells which were taken immediately after the well was completed. These have been used to construct the water level maps for the area in general.

With few exceptions, the aquifer of the Upper Fars formation is semi-confined. It was not possible to draw any limits between the aquifers in the south Sinjar basin, Upper Fars and Alluvium aquifers. The basin in general was considered to be one extensive aquifer in which the Lower Fars, Upper Fars, Reworked Upper Fars and the alluvium are in hydraulic continuity. On this basis, a general water level contour map was drawn using most of the available data of static water levels in the drilled wells, dug wells, springs and water bodies in the area.

Figure 20 shows the depth to water beneath the land surface for the shallow aquifers in the area. Such information can be used for locating sites for hand dug wells or for the drillers' information.

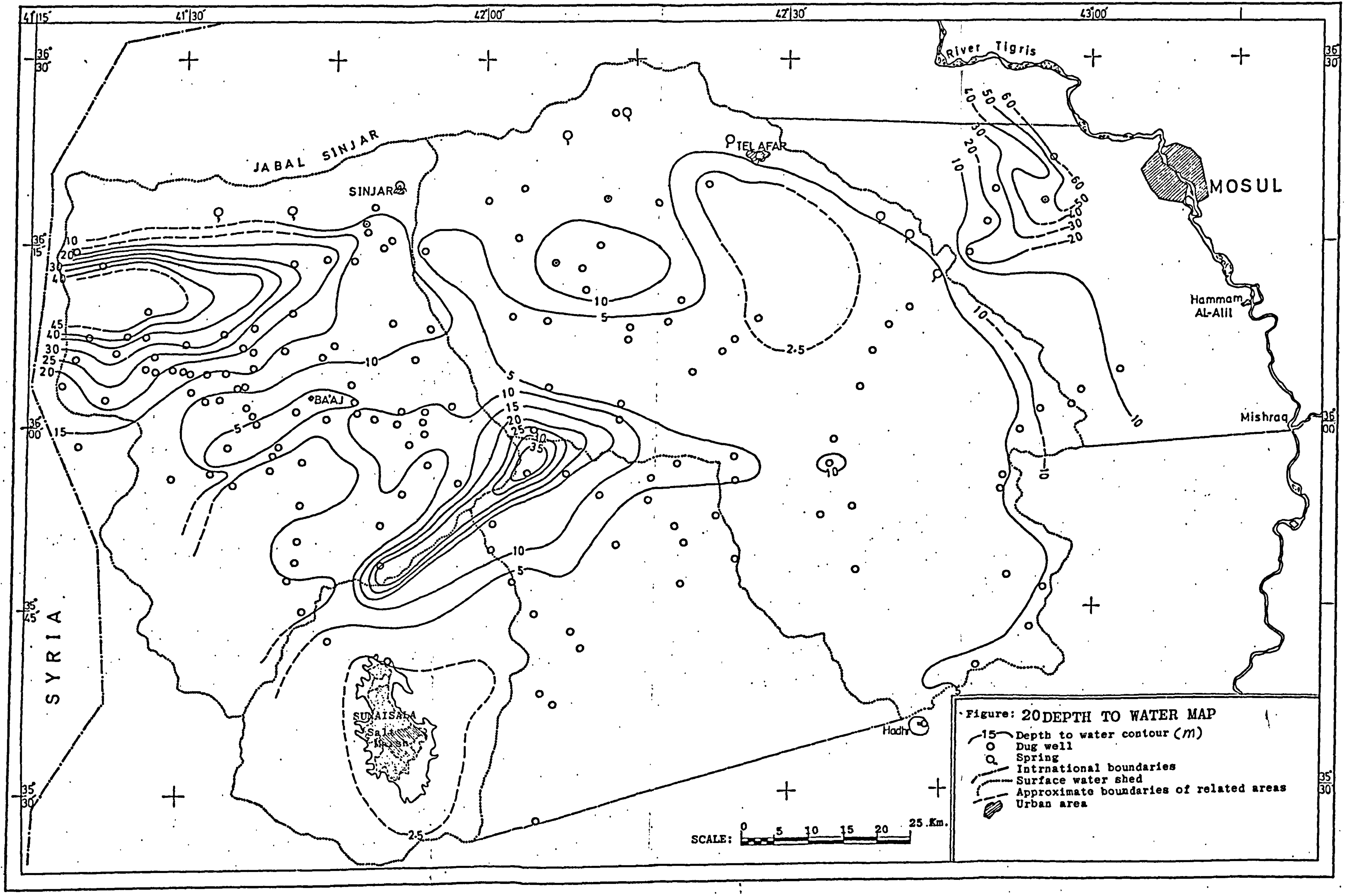


Figure: 20 DEPTH TO WATER MAP

Figure 21 is the generalized water table contour map for 1954. It was possible to differentiate between the water levels of the shallow and deep aquifers in Wadi Al-Ajij basin from the study of the drilled and surveyed wells by the Ralph M. Parson Co.

Figure 22 is the generalized water table contour map for 1974, for the period of field work, May to August. It was not possible to differentiate between the levels of shallow and deep ground waters due to the great similarity in the levels of the measured wells and to the scarcity of the data.

It is apparent from these figures that the ground water divide is very much the same as the surface watershed over most of the northern limits. The lower limits of the Upper Fars aquifer were not defined due to the great thickness of the aquifer which is not fully penetrated by any well. There is no upper limit for the aquifers in most of the area of south Sinjar, i.e., the aquifer is not confined and the water table is relatively shallow.

The northern ground water divide for the Wadi Al-Ajij basin is Jabal Sinjar. The western divide can not be accurately limited. It is more or less identical with the watershed. To the southwest, the water flows out of the basin towards Syria (Plate 5). The ground water divide between Al-Ajij and Al-Tharthar basins is identical with the watershed.

The northern and northeastern ground water divide for the Tharthar basin is very well defined by the anticlinal structures of Jabal Ishkaft, Sasan, Ibrahim, Adaiya and Jawan, and is identical with the watershed of this area. In the southwestern part of this basin, the ground water flows from the adjacent basin towards the main valley, Wadi Al-Tharthar.

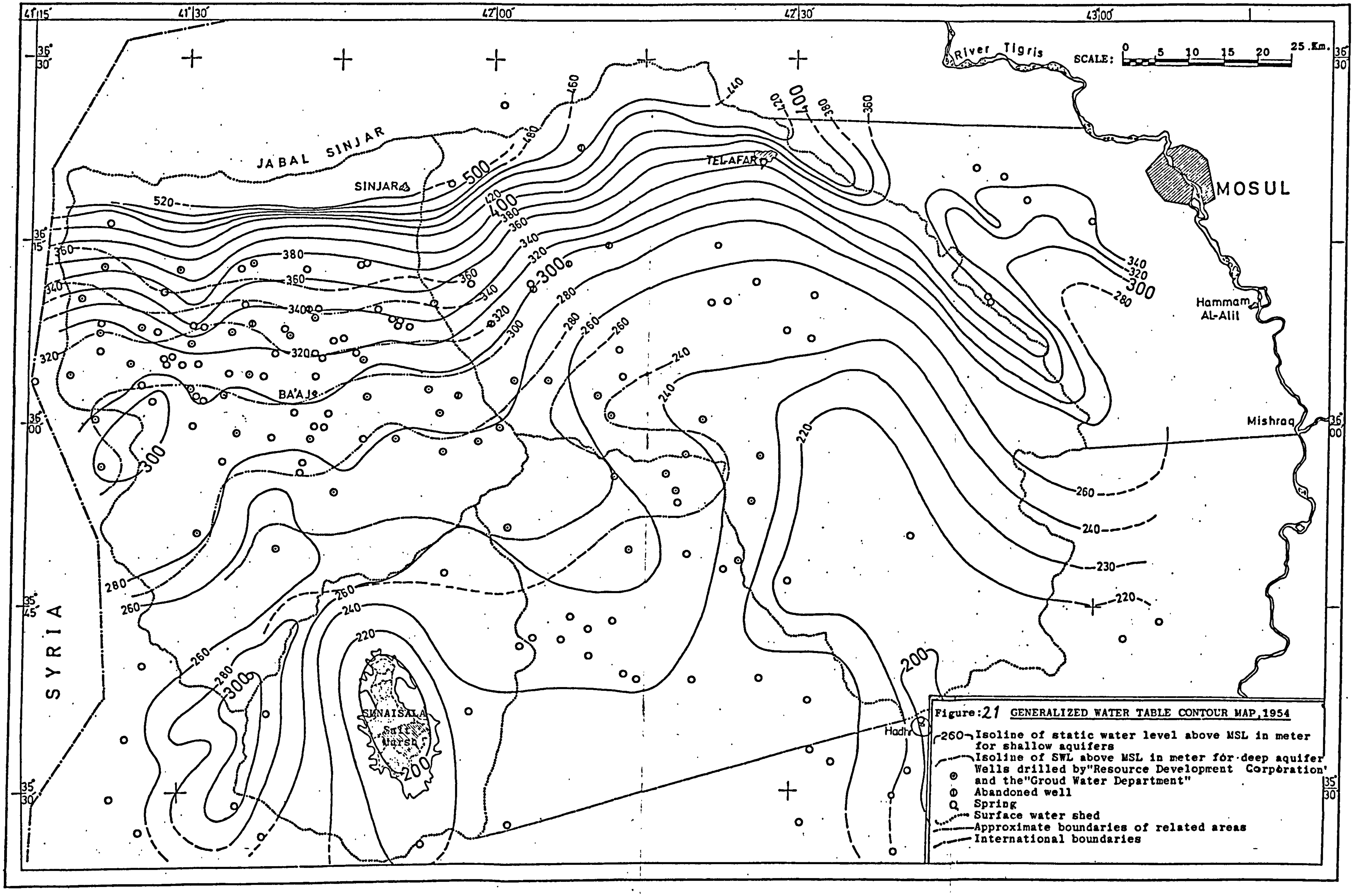


Figure:21 GENERALIZED WATER TABLE CONTOUR MAP,1954

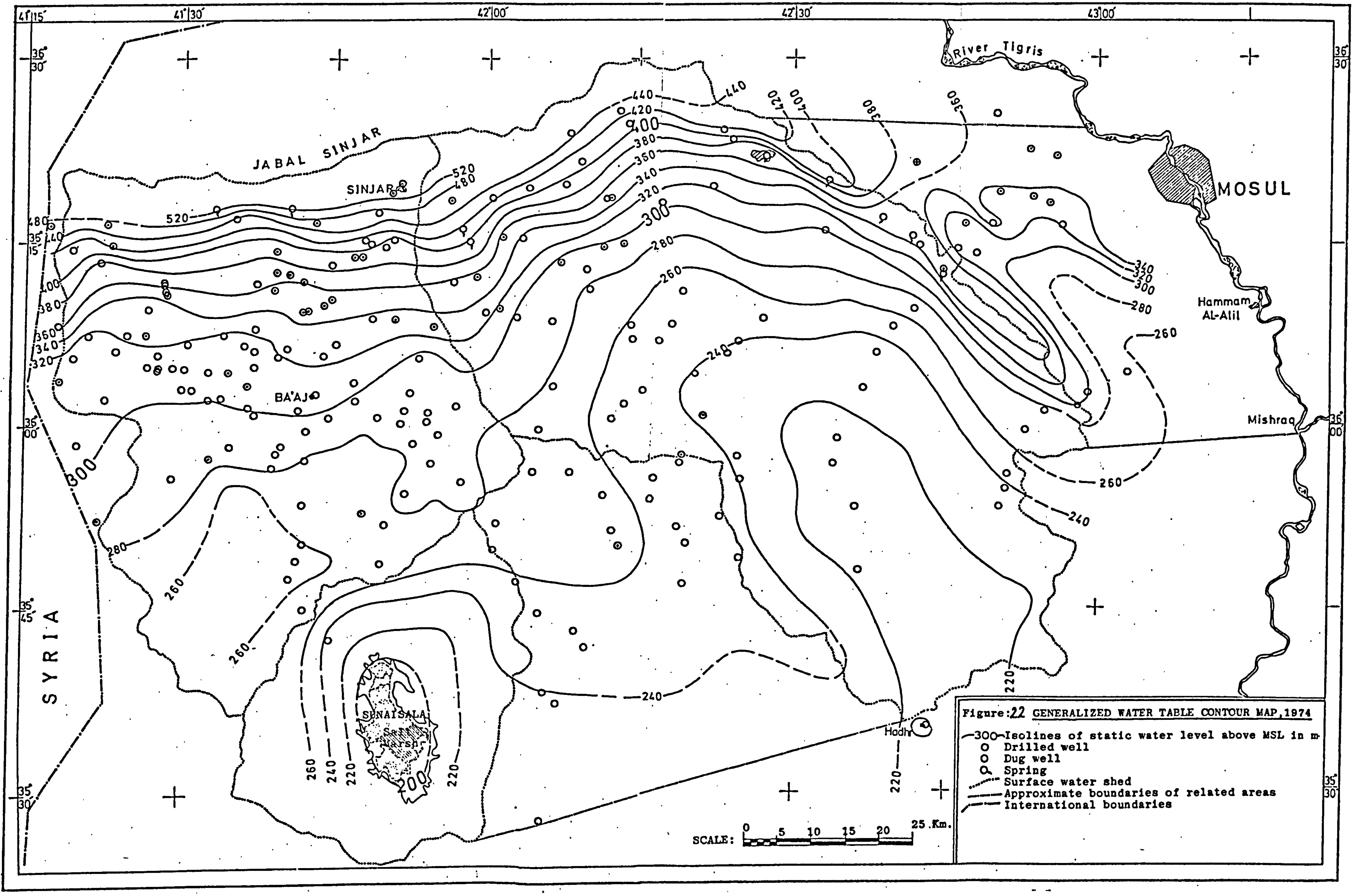


Figure:22 GENERALIZED WATER TABLE CONTOUR MAP,1974

The ground water divide of Sunaisala basin extends northwards beyond the watershed. It is defined by the diversion of flow in Wadi Al-Ajij towards the southwest and southeasterly direction around the latitude 36°00'. This basin is fed from Al-Ajij basin. The western and eastern divide is identical with the watershed. The southern parts of this basin were not surveyed, but the ground water divide may extend to around the latitude 35°15' as expected from the limits of the watershed based on the regional maps of the scale 1:500,000 of the area.

No limits for surface water or ground water are drawn in the area of study of Lower Fars structures. Generally speaking, the watershed of this area lies between the northwestern end of Jabal Athshan and the southeastern end of Jabal Ibrahim. To the southeast of this line, most of the water drains to wadi Al-Qasab. To the north of this line, most of the surface water is collected by wadis flowing northeasterly towards the river Tigris. The ground water divide in this region is beyond the limits of this study.

3.1.3 Springs

The main springs of the area under study have played a most significant role in the distribution of the population. Civilized societies located their settlements near the big rivers and springs long before they achieved the technology of digging or drilling for water.

Table 3 shows the main recorded springs which have been sampled and measured in the field work. The first three springs in the table are the main springs which drain the thick limestone alluvium between Jaddala Limestone and Sinjar Limestone formations. The discharges of these springs are directly proportional to their catchment areas. The seasonal variations in discharge are a clear indication of the source of water; the total discharge

Ser. No.	Sample No.	Location	Discharge 1/s	Source	Water use and remarks
1	63	Jaddala	330	Alluvium	D.I.S., Discharge measured by weir
2	22	Sinjar	200-250	"	D.I.S., Discharge estimated
3	65	Al-S'Kainia	32	"	Domestic, Irrigation, Stock (D.I.S.)
4	64	Al-Majnonia	30	"	Domestic, Irrigation, Stock (D.I.S.)
5	118	Tel Afar	200	Lower Fars	Domestic, Irrigation, Stock
6	-	Mishraq,Z14	140	" "	Discharging to the river Tigris
7	324	Ain Kibrit,Mosul	30	" "	Bathing only
8	9	Tel Muttar Alia	30	" "	Domestic, Stock
9	50	Shaikh Ibrahim	30	" "	D.I.S., Issue from 1st/gypsum contact
10	49	Muhallabia	20	" "	Domestic, Irrigation, Stock
11	-	Ain H'San Shimalia	20	" "	Domestic, Irrigation, Stock
12	116	Sino	14	" "	D.I.S., Discharge measured by weir
13	10	Koulat	12	Lower Fars+Alluvium	Irrigation, Srock
14	7	Terme	9	" "	Domestic, Stock
15	203	Adaiya	6	" "	Domestic, Irrigation, Stock
16	-	Umm Alshababeet	5	Lower Fars+Alluvium	Stock
17	42	Ain Al-Baidha	5	Lower Fars	Irrigation, Stock
18	43	Ain Zahrah	5	" "	Bathing only - Mammam Ali
19	-	Ain Fassosa	2	" "	" " "

Table 3 : Location, source and discharge of Springs of the area

of these springs is dependent on the total annual rainfall. The water of these springs is wholly meteoric in origin and represents the best water in the whole area, its total salt content being about 400 parts per million (ppm). The full analyses of water from these springs are tabulated in Appendix 3.

The discharge in the largest springs (jaddala) were measured by the use of a V-shaped notch weir specially made for the measurement of spring discharge in this area. The discharge of the other springs was estimated by multiplying the cross sectional area cf the rivulet with the speed of the water current which was measured by the use of float and stop watch. It was difficult to estimate the discharge in Sinjar because of the presence of several springs and a major kahrez at the outlet. A considerable quantity of water possibly flows under the houses which are built on the limestone alluvium near the main spring. The discharge in Sinjar is possibly much higher than estimated in the table. Spring number 4 (Al-Majnonia) issues from alluvium deposits south of Jabal Sinjar. Its total catchment is relatively small.

The springs listed as 5 to 19 in Table 3 all originate from the Lower Fars Formation. In addition to such a source, some of the waters of Koulat and Umm Alshababeet are derived from the alluvium deposits overlying the Lower Fars formation. In some areas like Sino, Adaiya, Shaikh Ibrahim, Terme, Muhallabia and Tel-Muttar Alia, spring water forms the main supply for the whole population. At Tel-Afar the main supply was formerly from the spring but more recently has been taken from the River Tigris. The spring still forms the main supply whenever the flow in the supply pipes stops.

Most of the springs originating from the Lower Fars formation have distinctive water which is either thermal, mineral or both. A detailed study of water quality, gas content and temperature of these springs will be considered in the chapter on Hydrochemistry.

Many springs are not easily accessible within Jabal Sinjar and the Lower Fars structures. Some of them form streams or rivulets; the two well-known streams of Al-Ibrah Al Saghira and Al-Ibrah Al Kahira crossing the road between Tel-Afar and Sinjar originate from springs located in the eastern plunge of Jabal Sinjar. The flow in these springs in June 1974 was 20 and 50 l/s respectively. They may have a very high flow of water in the wet season but are sometimes dry by the end of the dry season.

3.2 Ground Water levels

The depth to ground water (water table) for the shallow aquifers is shown in Fig.20. The data used for the construction of this map being dependent on field work in the area. The full records of data and measurements done in the field by the writer are deposited, together with the computer program for water chemistry, in the Hydrogeology Department of the Institute for Applied Research on Natural Resources. This map can be used for locating shallow hand-dug wells, for irrigation and drainage purposes and for estimating the likely extent of direct evaporation in the areas of shallow water table or capillary zone.

The generalized water table contour map for the year 1974 (Fig.22) was constructed for the area by the use of basic surface contour maps of the scale (1:250,000). All the elevations of the drilled wells, hand dug wells and springs were taken from these maps. The contours for water levels above mean sea level (m.s.l.) were interpolated from calculations made by subtracting the depth to water table, measured in the field, from the elevation of point above mean sea level.

It is apparent from figure 22 that the ground water levels are not greatly disturbed by excessive pumping in any particular area. The levels are more or less smooth and greatly related to the general ground levels. The contour interval chosen for this map is 20 metres due to the presence of many estimations used in determining the surface elevation of the different wells. The elevation of some wells was obtained from the available topographic sheets on the scale 1:100,000. A correlation was made between the results found from the two maps of different scales, 1:100,000 and 1:250,000, from which it was concluded that 55 percent of the correlated wells (total 156 wells) have a difference in elevation equal to or less than five metres. Twenty five percent of the correlated elevations have a difference of 5 to 10 metres, the remainder have differences of between 10 and 20 metres.

The total difference in elevation of the water table between Jabal Sinjar, Sinjar springs, and Sunaisala salt playa is about 350 metres. Therefore, the elevations obtained from the contour maps were accepted as the base for the construction of the water-table contour map. The alternative would have been to survey all the wells by levelling, but in terms of time and expense this was beyond the scope of the project.

The data available in the hilly area to the west of the River Tigris are not sufficient to enable the construction of a water-table contour map for the whole area, the area covered is limited by the amount of field work done in this region.

The general water table contour map for the year 1954 (Figure 21) was constructed from the data provided in the reports of Ralph M. Parsons Co., 1954. There data covers the following:-

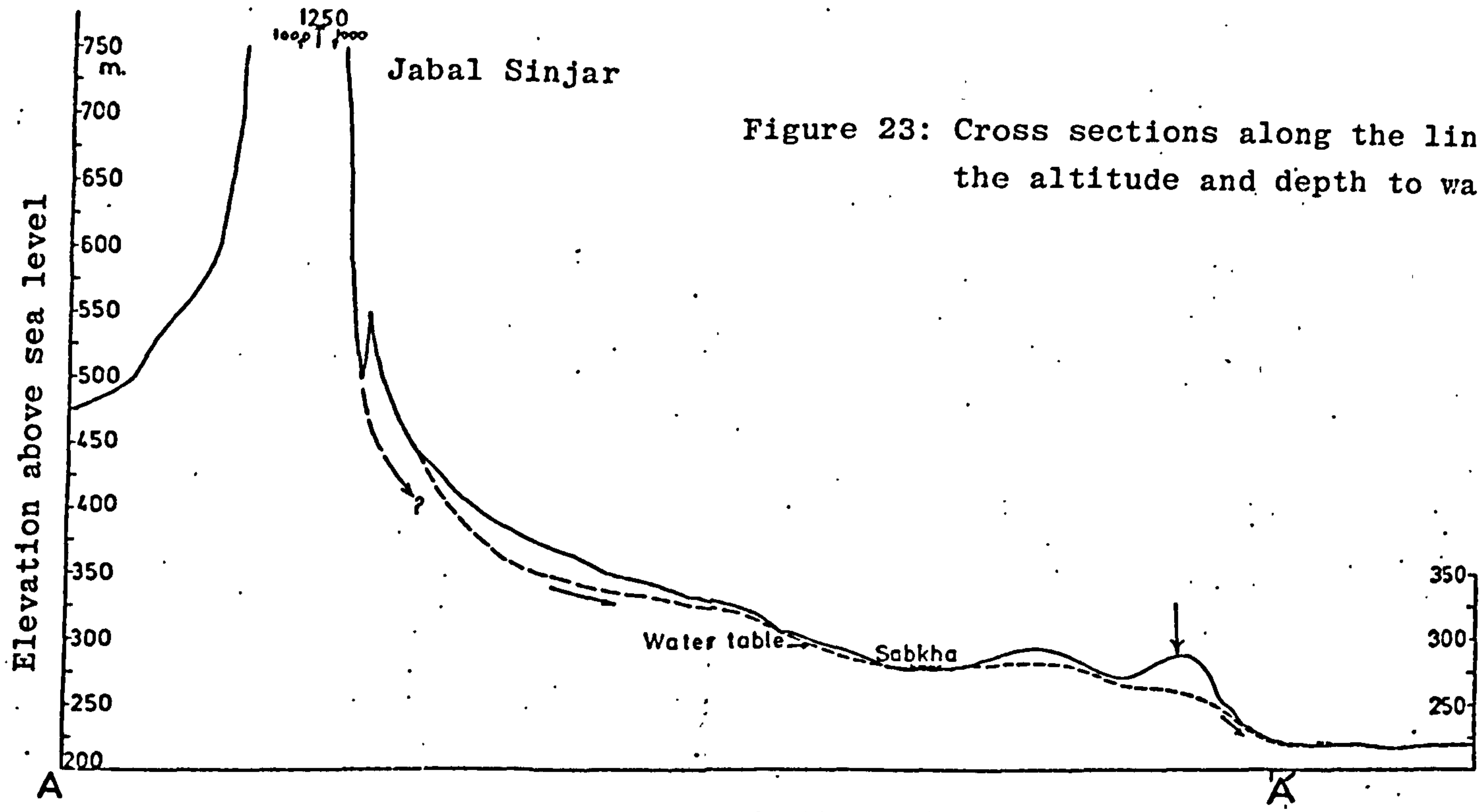
1) the list of existing dug wells, springs, kahrizes and surface water given in Table V11, Vol.2.
2) the existing drilled wells given in Table V1, Vol.2. This includes the wells drilled by the Resources Development Corporation (R.D.C.) and by the Iraqi Geological Department of the Ministry of Economics (I.G.D.)

In these reports the depth to water beneath the land surface is given. The elevations of water table above msl were calculated from the contour map as in the preceeding map for the year 1974.

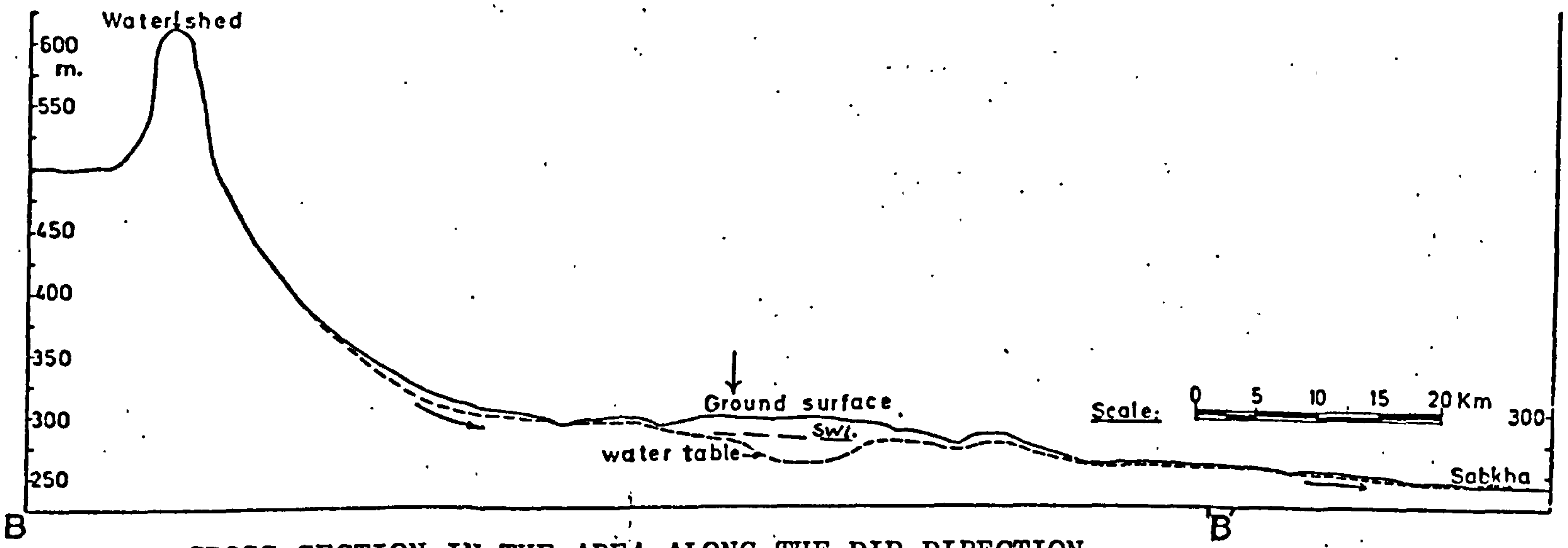
It was possible to differentiate between the water levels of the shallow aquifers, taken from the hand-dug wells, and those of the deep aquifers, taken from the drilled wells, in wadi Al-Ajij basin and parts of the surroundings. Along the line towards the centre of this basin, approximately following the longitude $41^{o}30'$, the water table in the shallow aquifers is slightly higher than in the deep aquifer. In the rest of the area, the water tables in the shallow and deep aquifers are generally similar. The water levels in Sunaisala basin and the flat land between Sunaisala and Tharthar is very shallow. Indeed, in many depressions, the water level is at the surface, forming marshes. In general, the water levels in these areas are less than 5 metres deep and the capillary zone has been affected by direct evaporation, thus creating very shallow saline soil or salt playas.

The general water-table depth in the wide basins south of Sinjar is shown in Figure 23. The lines of section A-A'

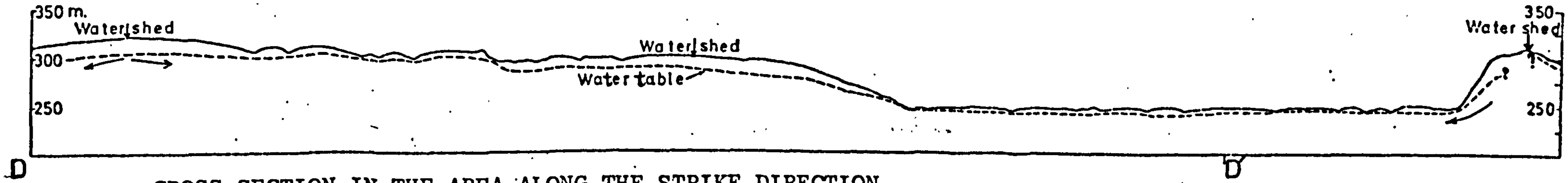
Figure 23: Cross sections along the lines AA',BB',and DD' showing the altitude and depth to water in the area.



CROSS SECTION IN THE AREA ALONG THE DIP DIRECTION



CROSS SECTION IN THE AREA ALONG THE DIP DIRECTION



CROSS SECTION IN THE AREA ALONG THE STRIKE DIRECTION and B-B' are taken in the general direction of dip, with the position of the water table being directly related to the ground surface levels. The apparent depression of the water table in the section B-B', near the watershed between Tharthar basin and the flat Jezira land, is due to the presence of a pumping well in Al-Mashafi, (SN.150), where the watertable measured at the end of July 1974 was 36.40 metres below ground surface. The replenishment to this area is very low due to the presence of the surface watershed and ground-water divide. The water table depth measured from nearby hand dug wells was also deep in this area, being some 34 metres below ground surface. The aquifer here consists of 14 metres of sandstone underlain by marl and overlain by 20 metres of silty clay. The depth of water table in Saltana, about 5 km east of Al Mashafi, is 15.5 metres under ground surface. In Saltana about ten hand dug wells are dug for water supply from the same sandstone aquifer. The difference in water table depth is due solely to the difference in ground level.

3.2.1. Fluctuation of ground water levels

The first measurements of ground water levels undertaken in the area as a whole were done during the period of field work. The existing data on static water levels were measured after the completion of each well so that the data are scattered over a period of more than twenty five years. The continuous recording of ground-water-level fluctuations is essential for the study of annual replenishment to the aquifers and the change in ground-water storage. Unfortunately, there are no observation wells for continuous water level measurements anywhere in the entire area of study. All existing wells are in use, and furthermore the nature of construction of the deep wells made the measurement of water levels impossible. In fact, the wells constructed by Ingra Consulting Department have pressure gauges for measuring the water level. These gauges were out of order during the period of field work; the maintenance of these wells being very poor.

The hand dug wells in the area are constructed in a very primitive way, most of them being without lining or any cover to protect them from surface contamination,therefore there is no fixed head to be used as a datum level for water level measurements.

The author has suggested that some suitable existing wells should be measured monthly, with proper marking and protection from surface contamination or mis-use. Following this suggestion, several measurements of ground water levels have been taken from 65 wells scattered over the area. These measurements were taken by the Institute for Applied Research on Natural Resources in October 1974, and January and March 1975. Although most of the data were not available to the writer the following general conclusions were derived from measurements in some scattered wells:-

1) The lowest levels occurred in September and October 1974; the highest levels being in May and June 1975.
2) The lowest fluctuations of ground water level correspond with marked drainage axes and the highest fluctuations correspond with recharge zones.
3) The correlation of ground-water levels between the periods of October 1974 and March 1975 shows a general increase in water levels of 0.5 to 1 metre.

The writer has also learned from local people that the water level may rise up to 5 metres in many areas of shallow ground water. The rise which takes place after heavy rainfall in the wet season was observed in the hand dug wells. The continuous bailing of some wells may cause the well to run dry and the resultant recovery period, in which the water level may rise two to three metres, may take a few hours in the alluvium aquifers or be achieved overnight in the silty clay beds. Therefore, bailing the hand dug well or pumping the drilled well has a direct affect on ground water levels over most of the area. The conclusions drawn from the water level measurements made by the Institute for Applied Research on Natural Resources in that they were not very reliable due to the following:-

1) The measurements are made in wells currently being used. The observer might find the well not in use for a few hours, but the need for water in every village is paramount, so water will certainly have been obtained from the measured well or the adjacent wells. In many cases, hand dug wells are located about 30 metres apart, and in some cases this distance may be no more than 5 metres.

2) There is no fixed label or reference point for the measured wells. This makes locating the same well after a few months quite difficult because of the presence of several hand dug wells in each village.

3) There is no fixed head to be used as a standard level or datum for continuous measurement. The pulley used in many wells may come out of its place by use and this is usually replaced again by mounting it to mud brick pillars on the side of the well head. Such pulleys can not be used as a datum level, nor can the well tops.

4) The majority of the hand dug wells have no shelter or cover for protection. The opening of the well is exposed to the atmosphere and the well head is not protected by a wall, therefore direct supply of rainwater or surface runoff water may cause a considerable rise in water level in the well only. This may lead to an illusionary conclusion concerning the water levels in the aquifer as a whole.

5) Occasionally the locals deepen the well or clear it of debris. This may result in a considerable rise in water level and the increase of water supply.

6) Some of the hand dug wells penetrate down to the kahrez line"subsurface water channel". This will certainly give a false measurement of water level. It has no relation with the surrounding water bearing beds and the level in such wells can suddenly be affected by pumping in the same well or in the preceding well located on the same kahrez line.

To estimate any fluctuation in ground water levels the following should be taken into consideration:-

1) The depth to the aquifer: deep aquifers need a much longer time to receive any recharge from the surface, therefore the increase of water levels in the deep aquifers may take place after two months of rain, i.e., end of December or in January each year. The shallow aquifers may receive considerable supply within the first month of rainfall which may cause a sudden increase in its water levels.
2) The morphology of the area which affects the amount of ground water recharge and surface runoff.
3) The nature and texture of the soil which controls the amount of infiltration into the shallow aquifers.
4) The total actual evapotranspiration from the shallow aquifers in which the capillary zone is located near the surface.
5) The total abstraction of water from the aquifer.

The fluctuation of ground water levels in the aquifers of the Lower Fars formation has been studied in the areas of the Mishraq Sulphur structure and in Hammam Ali. A sudden increase of about three metres took place in the aquifers of Mishraq after one week of intense rainfall in the spring of 1971. The presence of thick marls and clay beds in this formation has led to different ground water levels in the different horizons. However, the levels are the same in areas of extensive faulting or fracturing where the aquifers are interconnected. The lowest levels in these aquifers are observed to occur in January while the highest levels are observed in June each year. This is due to the deep nature of the aquifers which need a longer time ro receive surface water replenishment.

3.2.2 Regional declination of ground water levels

The study of regional declination of ground water levels or the changes in ground water storage was done by the calculation of annual recharge to the aquifers, the total annual losses or discharge, and the total annual abstraction. The correlation of the general water table contour maps of the years 1954 (Figure 21) and 1074 (Figure 22) give the following conclusions:-

1) The water table level in the area of Tel-Afar has risen by about 20 metres within the last 20 years. In fact the increase must have begun to take place since the beginning of pumping the fresh water to supply this town. The fresh water supply from the River Tigris to Tel Afar started in 1963.

2) The water level rose in 1974 in the area to the east and southeast of Ba'aj compared with the levels of 1954. This could be due to the introduction of centrifugal pumps to raise water from the hand dug wells for irrigation, domestic and stock supply. Most of these wells have been constructed over Kahrez shafts. The presence of many Kahrez to the north of this area helped to draw water from the north to supply the shallow aquifers in the south (see Figure 12).

3) In the area to the south of Jabal Sinjar, along the longitude 41°30' , the water levels declined in 1974 compared with those of 1954. This was possibly due to the establishment of the three villages of Abu Takia and Umm Al Thiban. In the villages of Abu Takia (SN.92, 93 and 94) three wells were drilled by the Ground Water Department for water supply and is relatively new. These villages did not exist in the early fifties, and pumpage since that time is undoubtedly the cause of the fall in water levels.

In the area located to the south of Kharabet Ikheder and Umm Al-Thiban the supply from Jabal Sinjar to the shallow aquifers via the alluvium was much greater in the early fifties before many wells were drilled for water supply from this alluvium and from the Upper Fars formation.

With the exception of the three areas mentioned above, the general regional ground-water levels have not changed much in the last twenty years. The main reason is the continuous use of the surface and spring waters for the periods of winter and spring and the use of dry farming methods over most of the area.

3.3 Physical and hydrological properties of water-bearing rocks:

The major water supply in the area of study comes from three main aquifers. The extensive aquifer in south of Sinjar is the Upper Fars aquifer. The other two aquifers are the Lower Fars and the recent alluvium. A considerable quantity of fresh water is supplied from the thick alluvial deposit in the vicinity of Sinjar mountain.

The physical and hydrogeological properties of the three aquifers in the area are relatively different. The aquifer characteristics of the Upper Fars and the alluvium are studied from the analysis of the pumping and recovery test data. Seven tests were carried out within the period of field work. Only one of them is confined to the alluvium aquifer.

A detailed study of the aquifer characteristics was carried out in the Lower Fars aquifer in Mishraq sulphur structure. However, the mine field of Mishraq may represent other sulphur bearing structures but its extent is rather limited.

The infiltration rate through the soil was studied by three experiments of double ring infiltrometer over different locations in the area.

The pumping tests were limited to the newly drilled wells and old wells in the Upper Fars aquifer. No test was made in the Lower Fars aquifer due to inaccessibility for water level measurements in the wells. No core is available for the laboratory determination of rock properties except in Mishraq where sulphur exploitation is controlled by the physical and hydrological properties of the sulphur bearing horizons.

3.3.1 Infiltration test

Infiltration is the movement of water from the surface into the soil through the effect of gravity. Infiltration is a process of vital economic importance. It is the process that provides water for nearly all terrestrial plants and for much of the animal life; it furnishes the ground water for wells and most of the stream flow in the drier periods; it reduces floods and soil erosion.

Various methods have been used to obtain comparative results of infiltration rate; among these being:-

1) Measurement of the rate of intake of water (infiltration) on areas defined by concentric rings of various sizes;
2) Measurement of infiltration on areas defined by tubes of differing size;
3) Measurement of runoff of water applied to small sample areas by rainfall simulators of various kinds;
4) Measurement of infiltration on areas defined by irrigation practice, particularly flooding;
5) Measurement of precipitation compared with surface runoff.

The first method mentioned above was adopted for the measurement of instantaneous infiltration rate at three different locations in the study area. Double-ring infiltrometers were used for this prupose. They consist of two shallow concentric rings of sheet metal (see Figure 24.) The diameter of the inner ring is about 30 cm., while the diameter of the outer ring is about 60 cm.

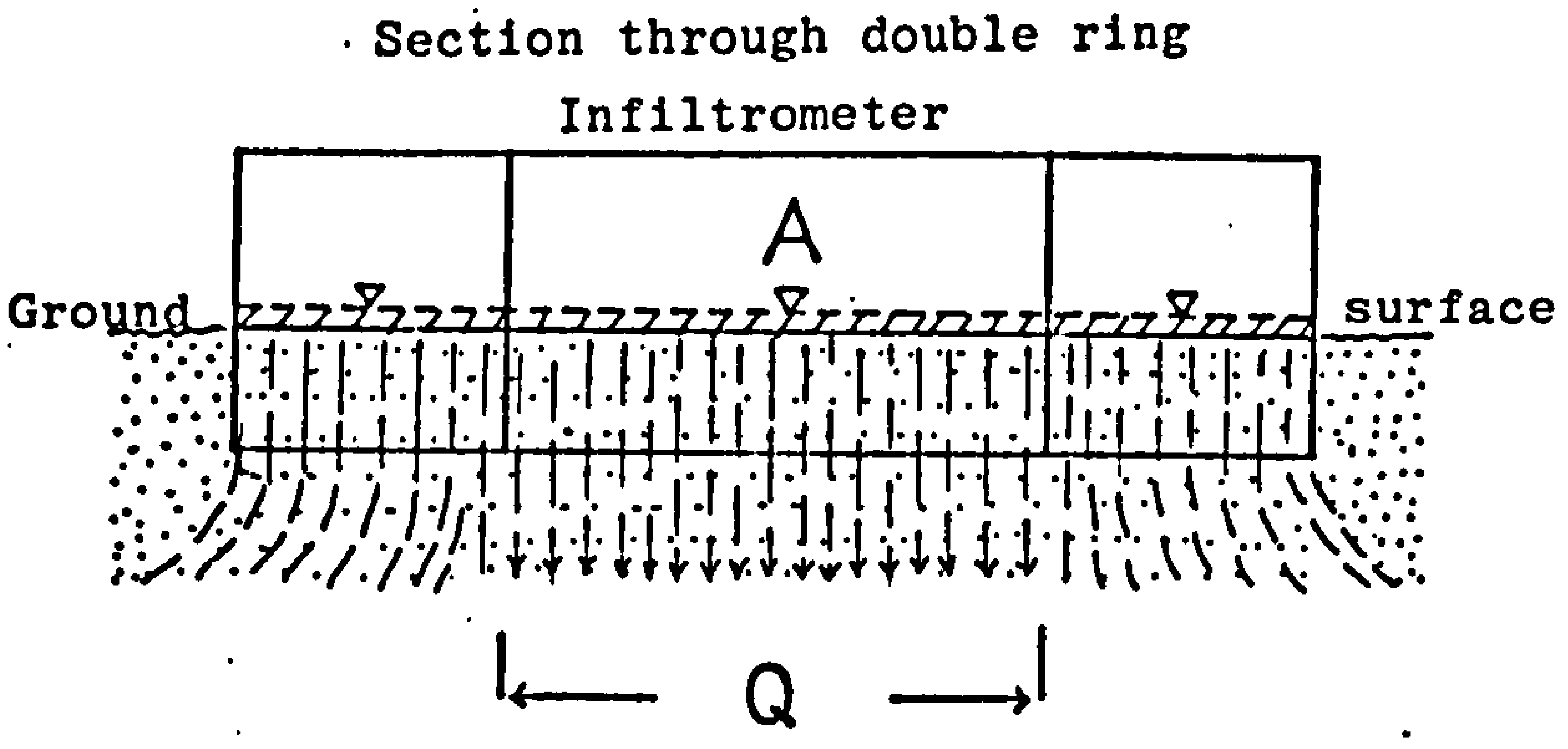
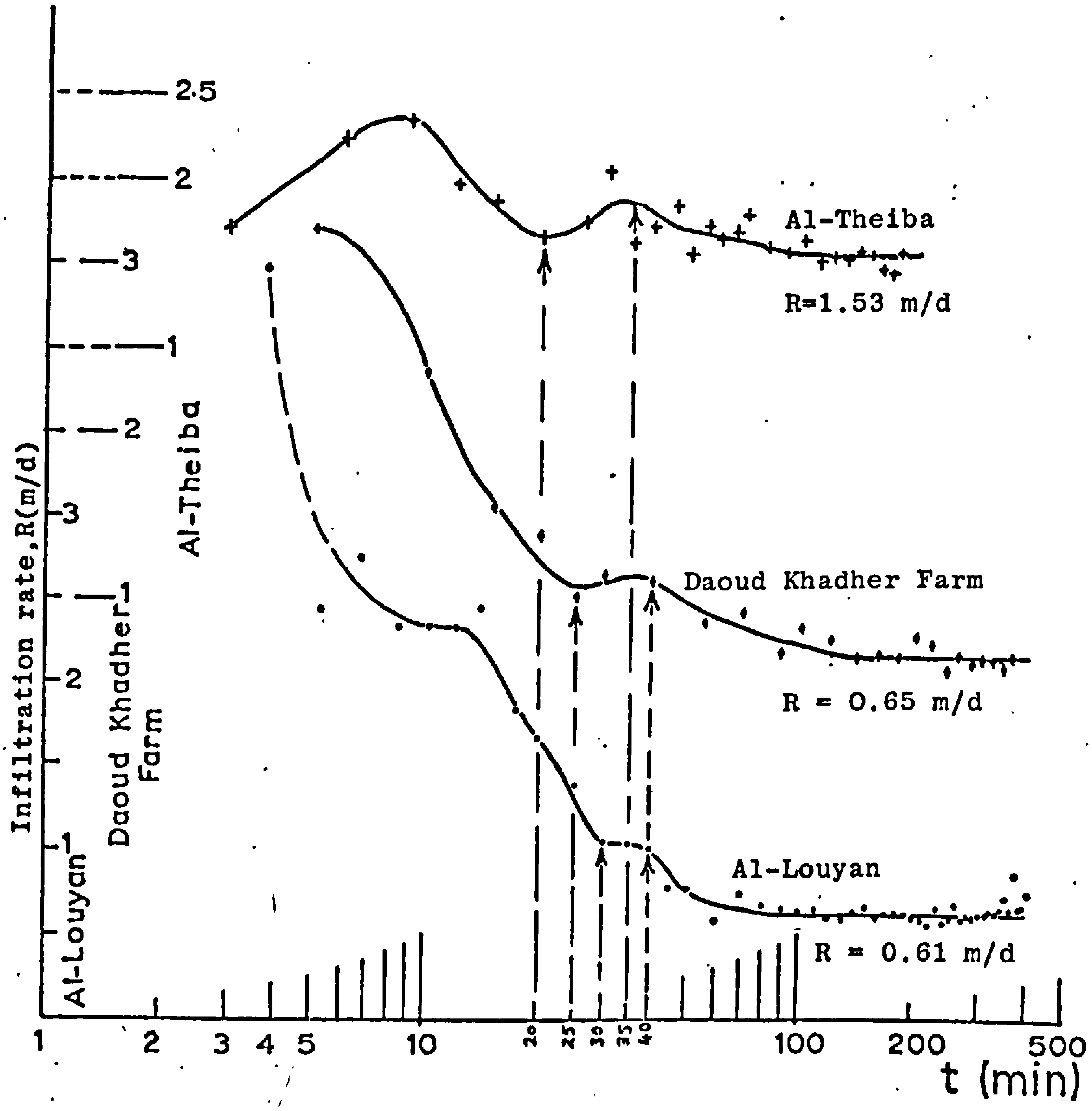


Figure 24: Infiltration test in the area of study



The rings are pressed about 10 to 15 cm. into the selected soil profile, and water is added at such a rate that the water levels in the outer and inner rings are kept constant throughout the test. The depth of the free water in both rings is maintained at about 1 or 2 cm. and water is added frequently so that the levels do not exceed this depth or reach below the ground level. The frequency of measurements and the instantanuous infiltration rates are shown in Tables 4, 5 and 6.

The purpose of the outer ring is primarily to provide a buffer or wetted area around the inner ring which is the critical or test area. This wet area prevents the water within the inner space from spreading laterally over a larger area after penetrating below the bottom of the ring.

The rate of application of water necessary to maintain the predetermined depth of water in the inner ring is the instantaneous infiltration rate (R). This rate is measured as follows:-

$$R = \frac{Q}{A}$$

Where R = instantaneous infiltration rate in metres per day

Q = the observed quantity of water added to the inner ring in cubic metres per day

A = bottom area of the inner ring in square metres

According to Stallman (1967) the observed value of Q in the inner ring may be determined from the following equation:-

$$Q = RA = cK$$

Table 4: Infiltration tests near Al-Louyan village,SN.49.

Time (min)	T	Q (ml)	$R=\frac{Q}{A}$ m/d	Time (min)	T	Q (ml)	$R = \frac{Q}{A}$ m/d
0.0		2000		150	10	320	0.65
2.25	2.25	2000	18.1	160	10	290	0.59
3.75	1.50	330	4.48	170	10	305	0.62
5.25	1.42	170	2.44	180	10	305	0.62
6.75	1.50	200	2.72	190	10	300	0.61
8.50	1.75	200	2.33	200	10	290	0.59
10.25	1.75	200	2.33	210	10	285	0.58
12.00	1.75	200	2.33	220	10	275	0.56
14.50	2.50	300	2.44	230	10	320	0.65
17.42	2.92	260	1.82	240	10	280	0.57
20.00	2.58	210	1.66	250	10	290	0.59
	5	340	1.385	260	10	330	0.67
30	5	255	1.04	270	10	290	0.59
35	5	255	1.04	280	10	300	0.61
40	5	245	1.00	290	10	290	0.59
45	5	190	0.774	300	10	300	0.61
50	5	190	0.774	310	10	300	0.61
60	10	285	0.58	320	10	310	0.63
70	10	350	0.713	330	10	300	0.61
80	10	330	0.67	340	10	320	0.65
90	10	320	0.65	350	10	270	0.71
100	10	310	0.63	360	10	310	0.63
110	10	310	0.63	370	10	1130*	0.86
120	10	290	0.59	380	10	320	0.65
130	10	290	0.59	390	10	320	0.65
140	10	310	0.63	400	10	360	0.73

*Free water level raised by 1 cm. in the rings

Table 5: Infiltration test near.
Daoud Khader Farm,SN.77.

Time (min)	T (min)	Q (ml)	$R=\frac{Q}{A}$ m/d
0.0	5	2220	25.84
5	5	510	3.2
10	5	580	2.36
15	5	380	1.55
20	5	340	1.385
25	5	250	1.02
30	5	280	1.14
40	10	540	1.10
55	15	640	0.87
70	15	670	0.91
88	18	600	0.68
100	12	480	0.815
120	20	740	0.754
140	20	620	0.63
160	20	650	0.66
180	20	640	0.65
200	20	765	0.78
220	20	700	0.71
240	20	560	0.57
260	20	640	0.65
280	20	585	0.596
300	20	610	0.62
320	20	600	0.61
340	20	570	0.58
360	20	630	0.642

Table 6: Infiltration test near Al-Theiba village, SN.133

Time (min)	T	Q (ml)	R = $\frac{Q}{A}$ m/d
0.0	3	2280	15.48
3	3	250	1.70
6	3	330	2.24
9	3	345	2.34
12	3	290	1.97
15	3	275	1.87
20	5	410	1.67
26	6	510	1.73
30	4	400	2.04
35	5	395	1.61
40	5	420	1.71
45	5	450	1.83
50	5	380	1.55
55	5	420	1.71
60	5	400	1.63
65	5	415	1.69
70	5	440	1.79
80	10	780	1.59
90	10	770	1.57
100	10	800	1.63
110	10	740	1.51
120	10	750	1.53
130	10	745	1.52
140	10	775	1.58
150	10	760	1.55
160	10	720	1.466
170	10	700	1.426
180	10	770	1.57

Where K = effective hydraulic conductivity (vertical component)

c = constant depending on the depth of the water zone (Lw), the depth of ponded water over the ground-surface (H_s) and the height of the capillary rise in the soil (H_c)

$$c = \frac{H_s + H_c + L_w}{L_w}$$

In the field it is not possible to measure the amount of H_c and L_w, but after a few hours, when $(H_s + H_c)$ is small compared to L_w, the above equation can be simplified to a form of Darcy's Law as follows:

$$Q = AK$$

The calculated values of infiltration rates are given in Tables 4,5 and 6 for the tests carried out in Al-Louyan village, Daoud farm and Al-Theiba village respectively. The rate of infiltration with time is shown in Figure 24.

In Al-Louyan village, SN 103, it is apparent from the curve with R (in m/d) and t (in minute) that the infiltration rate is initially very high, possibly due to the presence of cracks in the ground surface. The soil in this location is clayey and the cracks would have developed due to the contraction caused by the dehydration of the hydrous clay minerals in the soil. The infiltration rate became more or less steady after about 8 minutes, possibly as a result of closure of the mud cracks by down-washed fine grained materials, or may be due to the expansion of clay in the soil, or more likely by both effects.

The infiltration rate continued to decrease up to about 30 minutes and then became static for about ten minutes, probably due to the trapping of air by the infiltration front of water. The infiltration reaches steady state after about 80 or 90 minutes and continued steady for the remainder of the test period (400 minutes), see Figure 24.

In Daoud Khader Khader farm (SN 77) the infiltration rate decreased substantially in the first 25 minutes; and became more or less steady for the next ten minutes possibly due to the trapping of air by the down-moving water front. The infiltration became more or less steady after about two hours of the test and continued steady for the remainder of the test period (about 6 hours).

In the village of Al Theiba (SN 134) the infiltration tests were carried out about 1 km to the south of the village. The area surrounding the village has been affected by the impact of the large number of sheep and stock which has resulted in loose very fine clay particles over the ground surface.

It is apparent from the curve in Figure 24 that the infiltration rate in this location increased in the first 9 minutes. This could be due to the washing down of the thin clayey layer covering the ground surface, and the opening of the mud crack after being washed by the infiltration water from the filling dust. The infiltration rate decreased thereafter up to 20 minutes of the test then started to increase for another 20 minutes. This could be due to the escape of the entrapped air under the front of the down moving water. The infiltration became steady after about one hour and continued steady for the rest of the test (three hours). The infiltration tests in the three locations were carried out during the same period of pump testing in the adjacent wells.

The soil type plays a significant role in controlling the amount of water infiltrating into the ground. The soil in Al-Louyan is reddish brown, medium and shallow overlying gypsiferous subsoil. In this location, the clay content of soil is relatively high and the level of free water in the inner ring was kept constant, about 1.5 cm. The infiltration rate was in steady state condition after an hour and a half and for the rest of the test was about 0.61 m/d. The expansion of clay caused the ground surface inside the inner ring to rise and subsequently the predetermined level of free surface water had to be increased by one centimetre. This water has increased the pressure on the infiltrating water causing a small increase in the infiltration rate.

In Daoud Khader farm the soil is reddish brown and deep. It overlies alluvial deposits of silty and sandy clay. The average infiltration rate in this location was 0.65 m/d, measured when the infiltration became steady after about an hour and a half of the test and for the rest of the test.

In the village of Al-Theiba, the soil is reddish brown, medium to shallow, overlying gypsiferous clay and silts of the reworked Upper Fars unit. The infiltration rate in this location is relatively uniform over most of the period of testing. It had the highest measured infiltration in the area. The average rate of infiltration measured after about an hour of the test was 1.53 m/d. This high infiltration could be due to the underlying gypsiferous silty clay and loam. The high infiltration rate in this location has played a significant role in ground water pollution of the shallow aquifer from the surface and will be discussed in detail in the section on Hydrogeochemistr

3.3.2. Methods used for well construction and well logging

The majority of water supply wells in the area of study are hand-dug wells. The deep drilled wells are concentrated in the northern and northwestern parts of the area, while in the southern parts, hand dug wells provide the main water supply. All the wells constructed in the shallow aquifers are hand dug, while the deep drilled wells penetrate to the deeper aquifers.

1) Methods used for well construction in the shallow aquifers:

The construction of the hand dug wells in this area is similar to that used thousands of years ago. Experienced people from the area dig the wells following an arrangement with the landowners. The usual cost is two Iraqi dinars per metre for wells dug in unconsolidated rocks, rising to four Iraqi dinars (eight pounds sterling) per metre in the hard rock. Two men help to dig the wells, the driller using a chisel for the hard rock and a shovel for the soft materials in order to drill the well, while the second man hauls the cuttings to the surface.

The deepest hand-dug well in the study area was dug by the Germans during the first world war when an international railway was being constructed in an attempt to connect South Iraq with Germany. This well is about 1 metre in diameter and penetrates about 69 metres in the Lower Fars Formation. It is located in Al-Thalja (SN.1) Fig.2. The inside of the well is lined with limestone boulders. This well was the only water supply for the village until recently when the Ground Water Department drilled a deeper well to 90 m. for domestic and stock supply.

Two types of hand dug wells exist in the area of the South Sinjar plain. The first type is that designed to draw water by means of a bucket (dalu or salta). This type is usually 1 metre in diameter and penetration of the aquifer is very shallow. Most of these wells have no inside lining. See Figure 25.

The second type of hand dug well is that designed to be used with a pump. This type is more costly to construct and is rarely deeper than 25 metres. The pump chamber, steps and exhaust pipe shaft are constructed separately, see Fig. 25.

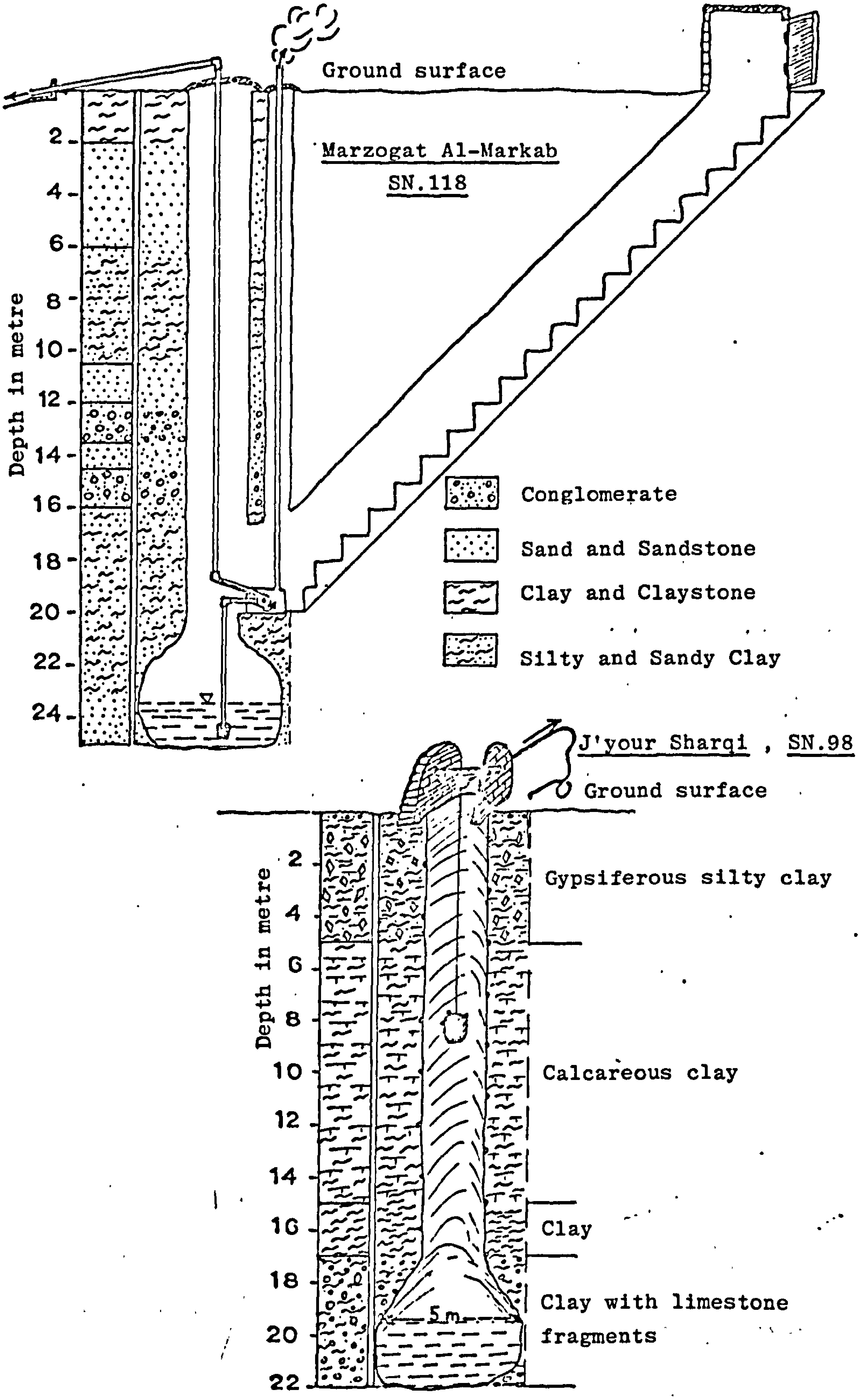
2) Methods used for well construction in deep aquifers:

In the major villages of the area, deep wells have been bored. These wells are designed to be operated by pumps giving higher water yields. In most cases, the decision to drill a deep well is taken regardless of the existing shallow aquifers in that particular location. Therefore deep wells can penetrate both shallow and deep aquifers even though the shallow aquifers can provide the total need for fresh water in that location.

Three types of drilled wells are in operation in the study area:

A) The wells drilled by the Resource Development Corporation, Harold Smith Drilling Co., and Ralph M. Parsons Co. U.S.A. (41 wells). These wells were drilled in the late forties and early fifties. Most of them were drilled by rotary methods with the exception of some of the wells drilled in the hard rock areas of Jabal Sinjar and the hilly region. Some of these wells still

Figure 25: Hand dug wells in the shallow aquifers.



supply water, though the casings have been changed or alternatively maintained by the Ground Water Department. The water is pumped from these wells by the use of a submersible turbine pump driven by a Lister FR4 Deisel engine, and these wells are protected by a pump house accompanied by a concrete tank for water storage.

B) The wells drilled by the Ingra Consulting Department. Twenty five wells were drilled in the study area of which three were dry and subsequently abandoned. The other 22 wells were constructed according to the contract with the Iraqi Government. Each well was furnished with a gravel pack around the casing which was perforated at intervals opposite the permeable horizons. The water was pumped out of these wells by a submersible pump driven by an electric motor. The pump house was supplied with a diesel generator and an iron tank of 22 cubic metre capacity was provided for water storage. The casing of the wells was galvanized steel, 150 mm in diameter, so that it could resist corrosion. In some wells (e.g 93 and 109) cathodic protection was made by the use of Zn or Mg electrodes inside the well. Water level gauges were supplied for each well extending below the pumped water level of that particular well. Most of these wells were completed in 1966-67 and have been functioning since then, having been designed for at least 15 years of operation.

C) The wells drilled by the Ground Water Department which was established in 1932 in Baghdad. Its activity has been extended with Departments in each county. The Ground Water Department of Mosul operates in the area of study where the total number of wells drilled by this Department exceeds 120 deep wells. About 10 percent of these wells were abandoned either due to very low yields or to the poor quality of water. Only one well, in Hadhr, was abandoned due to gas seepage from pockets in the Lower Fars Formation.

All the wells drilled by the Department in this area were cased with 6 inch cast-iron pipes. The average length of the perforated pipes used for casing the wells was 22 percent of the total depth calculated from 60 wells drilled in the area of study. The perforation of the pipes was made in the workshop of the Ground Water Department by the use of an oxy-acetylene cutter. Plate 11 shows the type of perforated 6 inch pipe used opposite the water-bearing horizons. The average size of perforation measured by the writer in the workshop of the Ground Water Department in these types of pipes was less than 3 percent of the total surface area of the pipe. The average depth of wells drilled by this Department calculated from 60 wells was 95 metres.

Two types of drilling rigs were used by this Department for drilling in the area. Percussion drilling by the use of hammer was used in the areas of hard rocks like limestone, while the rotary drill technique was used in South Sinjar plain, in the weaker formation of Upper Fars. Submersible pumps were used in most of the deep wells, driven by diesel engine, though in other wells a suction pump was used. There is no access in the well head for water level measurement, except in those wells fitted with suction pumps, where the casing is wider than the pumping cylinder and allows enough space for water level measurement (e.g. SN.133 Tel-Amir).

Most of the wells drilled by the Department are left exposed to air for a few months. The construction of a pump house or storage tank may take a year or so after the completion of the well. In most cases the water is pumped directly to the ground surface where it is used for domestic purposes or stock watering.

Well logging:

The detailed geological description of the drilled wells in the area of study are available in two forms:-

1) the Ingra Consulting Department record of drilled wells; and
2) the Ground Water Department of Mosul.

The details given in Ingra records include the lithological description and the geophysical logging of the wells. The lithological description is based on the geological observation of the cuttings which are cleaned out of the drilling fluid; no coring was made in the area to confirm the lithological description. The geological logging of such a formation is very difficult due to the mixing which takes place in the drilling fluid. The loose sand in the succession can intermix either with the drilling fluid continuously with no regard to depth. Also the thin clay beds are difficult to differentiate from the silty clay or sandy clay. The drilling speed can help in this respect, but the drilling rigs used in this area have no weight control of the drilling stem. Therefore the weight used in different depths is variable and so is the drilling speed.

The only available way of confirming the lithology of Upper fars formation in this area is the use of geophysical techniques. Recently, the Ground Water Department has begun to use this technique to define the water bearing horizons for the optimal well design. Some of the wells drilled by Ingra Consulting Department were geophysically logged. The spontaneous potential and resistivity of two wells are recorded in the area, namely well no. 5A'selan and well no. 101 in Ghazlani Camp of Mosul. These logs were made only in the lower parts of the wells and were incomplete, and are not useful for correlation of wells. Cathodic protection was made in two wells, namely well No.93 Marzoogat Al-Margab and well No.109 Bab Al-Khair. The solution potential was measured in these wells before and after protection by the use of Zn or Mg electrodes.

Two loggings were made available to the writer from the Central office of the Ground Water Department. These are Tel Azer Sharqi (well No.3 SN.21) and Tel Kuta (well No.4, SN.95). The detailed geophysical logging in Tel Kuta is shown in Figure 17, while the detailed geological and geophysical logging of Tel Azer Sharqi is shown in Figure 18. The horizons marked in these figures are the sandstone beds which are considered to be the best water bearing horizons. Perforated casing of the type shown in Plate 11 is used opposite such horizons.

The correlation of the geological and geophysical logging of Tel Azer Sharqi shows the importance of the geophysical logging in such a formation. The results obtained by resistivity and natural gamma ray measurements are very useful in defining the boundary between the permeable sandy and silty horizons and the impermeable clay beds. Obviously the geophysical logging is more reliable here. The correlation shows that many sandy horizons that appear by the use of geophysical techniques, were missed by the geologist or the driller, whoever made the geological logging. Also, the clayey materials, which can stay in suspension for a long time in the drilling fluid misled the observer.

The sandy and silty beds measured from the geological logging made about 35 percent of the total thickness in the well of Tel Kuta, while it makes up to 50 percent of the total thickness measured from the geophysical logging.

The majority of the wells drilled before 1976 were screened according to the data provided from the geological logging. It is for this reason the total length of the perforated screen was only 22 percent of the total depth of the well. This led to less efficient wells in terms of using shorter and less efficient perforation for the aquifer.

3.3.3 Pumping test determination of aquifer characteristics

Pumping tests provide one of the most important procedures in practical ground-water investigations. The productive capacity of the completed well and the aquifer characteristics can both be measured from pumping test data. Thus, a pumping test may serve two main objectives; firstly, to provide data from which the transmissivity, storativity and hydraulic conductivity of the tested aquifer can be calculated. Such a test is often called an "aquifer test" because it is the aquifer, rather than the pump or the well, which is being tested. Secondly, the pumping test can provide information about the performance and efficiency of the well being pumped. Knowledge of the productive capacity of the completed well is essential for the selection of the pumping equipment.

The principle of an aquifer test is rather simple. Water is pumped from a screened well during a certain time and at a certain rate. The effect of this pumping on the water levels or piezometric surfaces is measured in the pumping well and in the available piezometers in the surrounding area. The hydraulic characteristics of the aquifer can then be calculated by substituting in the appropriate formulae the drawdown(s) measured in the pumping well and/or the piezometers, the distance of the observation well from the pumping well, and the measured discharge.

In the case of well testing intended to determine the capacity of the well, piezometers are not required and only the well yield and drawdown are measured. Well test data may be used to derive approximate aquifer characteristics, provided that one accepts a certain degree of error. The fundamental principles of aquifer and well test analysis are provided in many ground water and subsurface hydraulics text books e.g. Kruseman and de Ridder (1970).

In the area of study, pumping tests were performed for one to five hours in all the wells drilled by the Ground Water Department. Such tests provide only one reading of the maximum drawdown of water level in the pumped well. The well yield was measured and subsequently the pump was selected on the basis of the data obtained from this test.

The wells drilled by Ingra Consulting Department were tested in a different way. The relation between yield and drawdown was found by step pumping with three different discharges. However, the duration of test seemed too short to be realistic for practical use. Many wells were tested for only a quarter of an hour. With the exception of well No.5, most of the wells were tested for less than one hour. Well No.5, in A'Aselan, was tested for three and a half hours due to its low yield of 3 1/sec.

Those wells drilled by the Resources Development Corporation prior to 1954 were tested and the apparent transmissibility and permeability were calculated by a selected drawdown. Some of the above data were used for the calculation of specific capacity of the different wells.

During the period of field work, six pumping tests were carried out in the Upper Fars aquifer and one in the alluvial deposits. Four of these tests were carried out immediately after completion of the well. The other tests were carried out on the pre-existing abstraction wells. Only in one locality, Kurkubat Sufla SN.14, was a hand dug well used as an observation well, and that was located 24 metres away from the pumping well, APP.2

In most of the tests, it was not possible to measure the drawdown in the pumping well. For this reason, the recovery of the well was measured and used for the determination of the aquifer transmissivity. The recovery method has the advantage that the rate of recharge Q can be regarded as constant and equal to the mean rate of discharge Q during pumping. This means that the drawdown variations resulting from slight differences in the rate of discharge do not occur during recovery. All the tested wells partially penetrate the Upper Fars aquifer. However, in most cases, the wells penetrate the permeable horizons of the Upper half of the Upper Fars formation. It is not known if the lower horizons contribute to the yield of the well and therefore correction for partial penetration has not been made.

A summary of the results of pumping and recovery tests in the seven locations are given in Table 7. The locations of Tel-Alamir (SN.133) and Al-Louyan (SN.103) were chosen because a gap between the pump and the casing provided access for lowering of the water level measuring device. It was not possible to test any of the other existing abstraction wells in the area. One test was carried out on a shallow abstraction, hand-dug well in Daoud Khadher Farm (SN.77) located opposite Sinjar camp.

It is not possible to determine the conditions within the aquifer without the use of a proper observation well which can provide data for the calculation of the storativity of the aquifer. The storage coefficient of the confined parts of an aquifer depends on the elasticity of the aquifer materials as well as the fluid, and has an order of magnitude of 10^{-4} to 10^{-6}.

No.	Location	Total Depth	SWL (m)	PWL (m)	Discharge m^3/d	Q/s m^2/d	T m^3/d/m	m (m)	K (m/d)	Test	Aquifer condition
1	Ain Al-H'san SN.6	96	4.5	38.5	130.9	4.2	1.052 1.06 1.0	50	0.02	P&R	confined
2	Kurkubat SN.14	76	9	26.91 18.45	432	35.8	108.3 95.5 143.2	40	2.89	R	Confined
3	Sinjar Camp SN.74	160	20.30	49.30	510.55	12.6	1.766 1.791	90	0.02	R	Semi -confined
4	Daoud Farm SN.77	13.50	10.0	11.70	518.4	871	154.4 145	20	7.72 7.25	P & R	Unconfined to semi-confined
5	Al-Louyan SN.103	75.3	33.5	51.77	50.11 77.76 103.68	50.34	5.81 45.85	50	0.12	P&R	semi-confined
6	Tel-Alamir SN.133	143?	6.24	8.41	22.46 23.33	7.85	2.65 3.787	50	0.064	P&R	semi-confined
7	Irfa'i SN.136	160	10.44	28.98	820.8	29.5	14.04	100	0.14	R	semi-confined

SN=serial number, P = pumping, R = recovery.

Table 7: Tesults of pumping test analyses in the area

The specific yield is commonly regarded as approximately equivalent to the storativity in the unconfined parts of an aquifer. The storage coefficient and the specific yield are both defined as the volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface. Both are designated by the symbol S and are dimensionless. For details concerning analysis of pumping test data for determination of aquifer characteristics, the reader is referred to Kruseman and de Ridder (1970). The data collected from the seven pumping tests are treated individually below.

1) <u>Ain Al-H'san:</u> In this location, a new well was drilled by the Ground Water Department of Mosul to a total depth of 96m. The shallow aquifer in this location is contaminated with the bad quality water of the Lower Fars aquifer outcropping to the north. For this reason, the first 30 metres of the well were sealed by solid casing and concrete perforated screen was used for the lower parts of the well. According to the Ground Water Department, the well was tested before sealing of the upper part. The yield of the well was 654.5 m^3/d and the pumping water level was constant (steady state condition) for most of the test duration of 4 hours at a level of 25m. below ground surface. This means that the total drawdown was 20.5 m due to pumping.

The pumping test carried out on 27 May 1974 after the completion of the well. It was not possible to undertake any measurements in the pumping well, until after the pump was removed and a recovery observed. The recovery of the well is the rise of the water level after pumping has been shut down. This rise can be measured as residual drawdown s', i.e. the difference between the original water level prior to pumping and the actual water level measured at a certain moment t' since pumping stopped. The observed data of recovery are plotted on double logarithmic paper for the application of Theis's method, Theis (1935) as shown in Figure 26.

The plotted points fit very well to the "reversed Theis type curve. This indicates that the aquifer is confined and the flow of water towards the pumping well is unsteady. However, the following assumptions should be satisfied for the application of this method:-

1) the aquifer is confined
2) the flow to the well is in unsteady state, i.e. the drawdown differences with time are not negligible nor is the hydraulic gradient constant with time.
3) the water removed from storage is discharged instantanously with a decline of head.
4) the diameter of the pumped well is very small, i.e., the storage in the well can be neglected.
5) the aquifer has a seemingly infinite areal extent.
6) the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by the pumping test.
7) prior to pumping, the piezometric surface and/or pheatic surface are (nearly) horizontal over the area influenced by the pumping.
8) The aquifer is pumped at a constant discharge rate.
9) the pumped well penetrates the entire aquifer and thus receives water from the entire thickness of the aquifer by horizontal flow.

A match point on the overlapping portion of the Theis curve and the observed measurement is selected and the coordinates W(u), 1/u, s and t are determined for this match point (Figure 26). The transmissivity of the aquifer is calculated by substituting the values of W(u), s and Q into the equation:

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

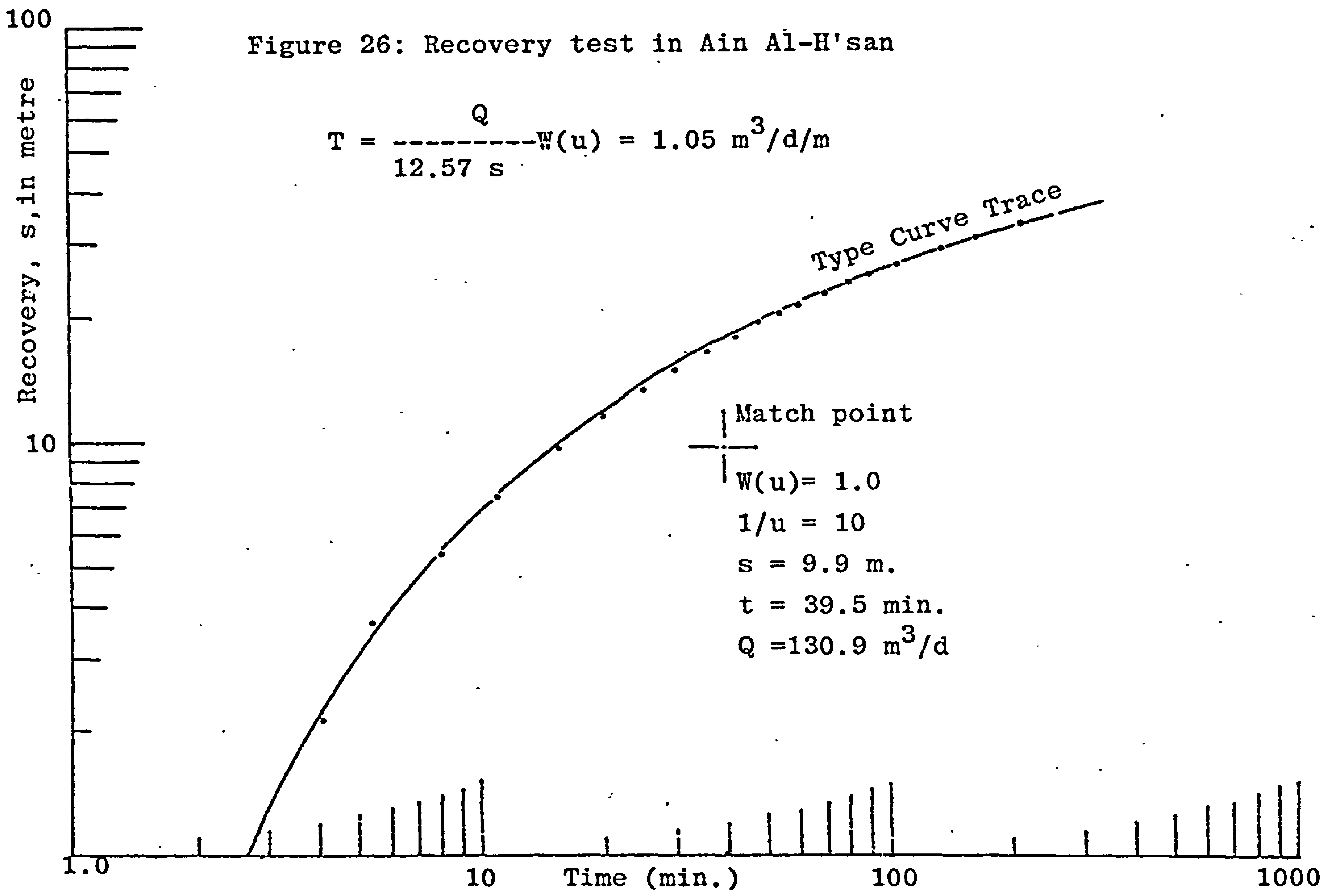


Figure 26: Recovery test in Ain Al-H'san

$$T = \frac{Q}{12.57\ s} W(u) = 1.05\ m^3/d/m$$

Match point

W(u)= 1.0

1/u = 10

s = 9.9 m.

t = 39.5 min.

Q =130.9 m^3/d

where

T = transmissivity of the aquifer in $m^3/d/m$
W(u) = well function of U' or Theis well function.
s = drawdown or recovery in metres.

The coefficient of storage of the aquifer cannot be determined from the results of a test on the pumping well because well loss is appreciable and the effective radius of the well is unknown.

The observed data of recovery have also been plotted on semi-logarithmic paper for the application of the straight-line method. It will be noticed that $\Delta s = .183Q/T$ is the expression of the slope of the straight line. This means that when a straight line has been fitted through the plotted points, the value of s' is measured and T may be determined (Figure 27). The plotted points are best fitted in the later part of the recovery test. The points measured in the early stages were affected by the water standing in the rising main, which pours down immediately after the pumping ceases.

Theis's recovery method, Theis (1953), has been used for the calculation of aquifer transmissivity in the same wells so that it can be compared with the results obtained by Jacob's straight line method. In this method, the residual drawdown, s' is plotted versus t/t' on semi logarithmic paper and a straight line is fitted through the plotted points (Figure 28). The results obtained by the above methods compare very well with one another and are listed in Table 7.

The total effective thickness of the aquifer is the sum of the permeable sandy and silty horizons which may serve as aquifers. The impermeable clay beds are excluded for the calculation of the hydraulic conductivity of the

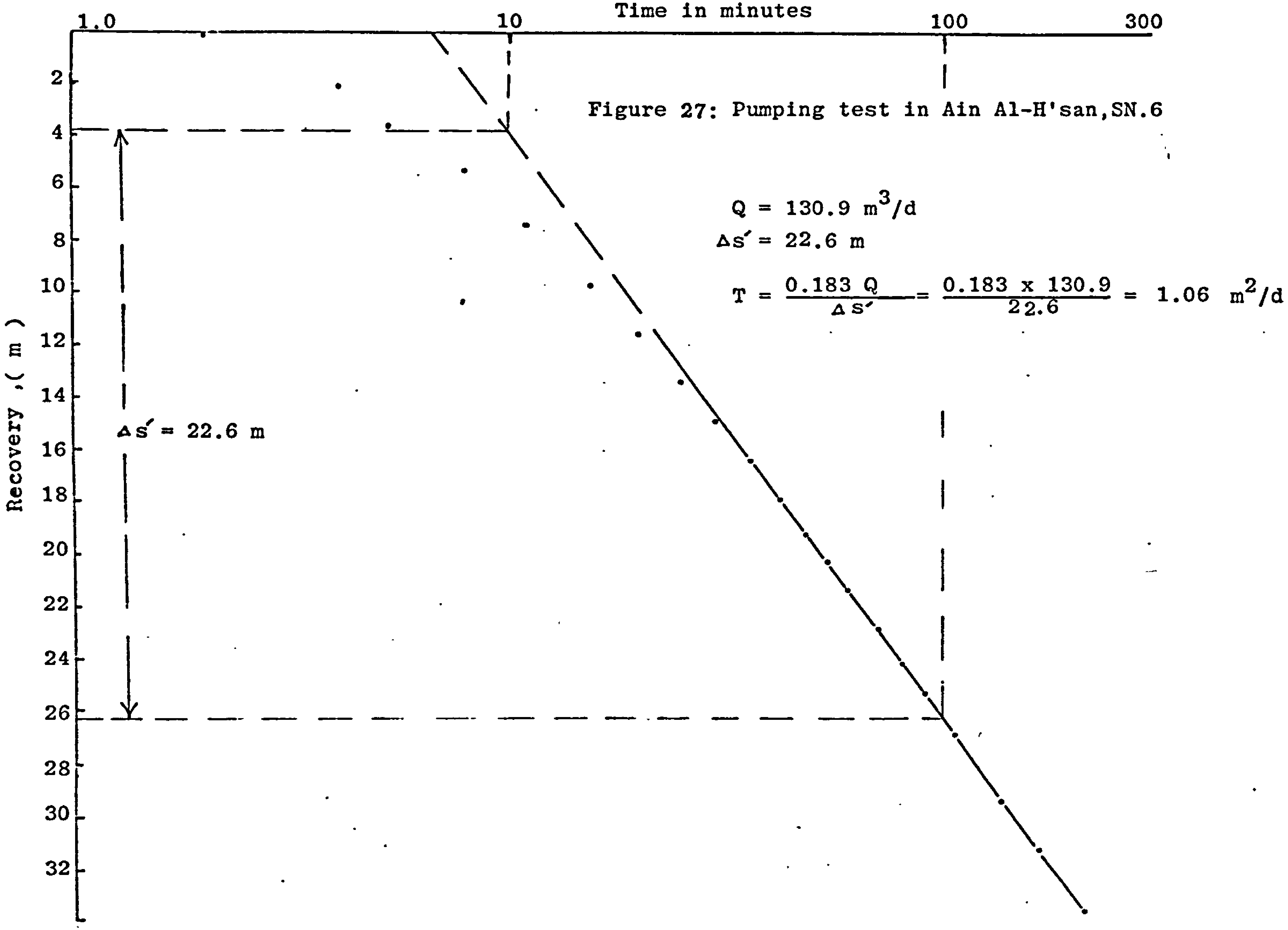


Figure 27: Pumping test in Ain Al-H'san,SN.6

$Q = 130.9 \text{ m}^3/\text{d}$

$\Delta s' = 22.6 \text{ m}$

$$T = \frac{0.183\,Q}{\Delta s'} = \frac{0.183 \times 130.9}{22.6} = 1.06 \text{ m}^2/\text{d}$$

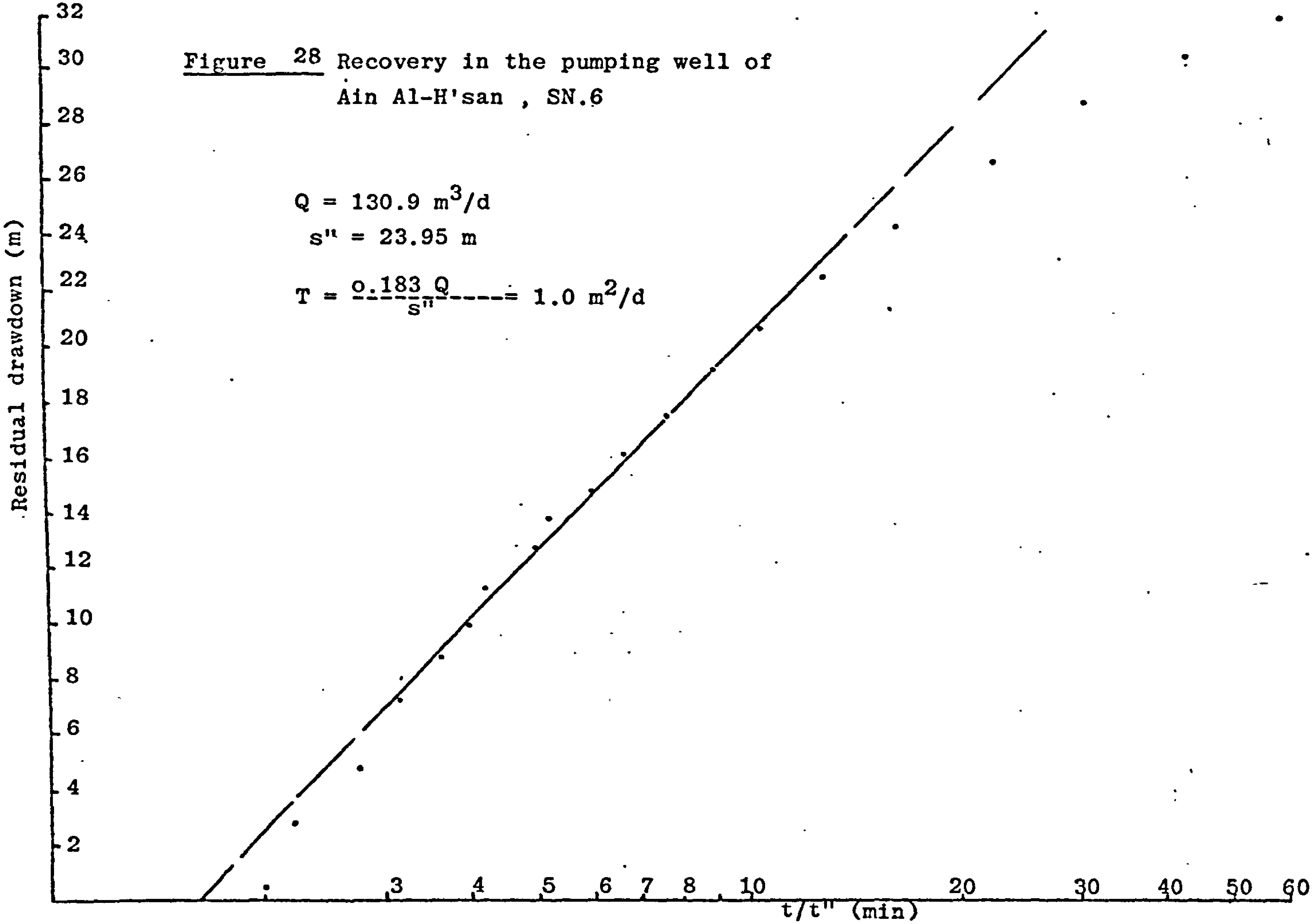


Figure 28 Recovery in the pumping well of Ain Al-H'san , SN.6

$Q = 130.9\ m^3/d$

$s'' = 23.95\ m$

$T = \frac{0.183\ Q}{s''} = 1.0\ m^2/d$

aquifer. This is due to the fact that these horizons do not contribute to the yield of the well, though they may act as semi permeable boundaries across which the water may leak from one horizon to another. The value of the hydraulic conductivity in this location, 0.02 m/d, is the lowest of the tested locations and is indicative of a confined silty clay aquifer.

2) Kurkubat Sufla (SN.14): The well in this location was drilled by the Ground Water Department to be used as a water supply for a co-operative farm. It was completed and tested on 28 May 1974, though it was not possible to measure the drawdown in the pumping well. However, the recovery of the water levels were observed in the pumping well and in the adjacent hand-dug well. The latter was used as an observation well and is about 24 metres away from the pumping well and some 20 metres deep.

Figure 29 shows the recovery data in the pumping well. These points are plotted on semi-logarithmic paper using Jacob's method and analysed as in the previous pumping test. The value of transmissivity determined by this method seemed rather high, so the measurements observed in the pumping well were also plotted on double logarithmic paper and were fitted to the Theis curve (Figure 30). The value of transmissivity was calculated by this method and was found to be 95.5 m^2/d. This value is similar to that determined previously and provides confirmation of what otherwise might be an anomalous value.

The hand-dug well used as an observation well is 24 m away from the pumping well and about 20m deep with an inside diameter of about 1 m. The recovery measurements obtained from the observation well have been plotted in

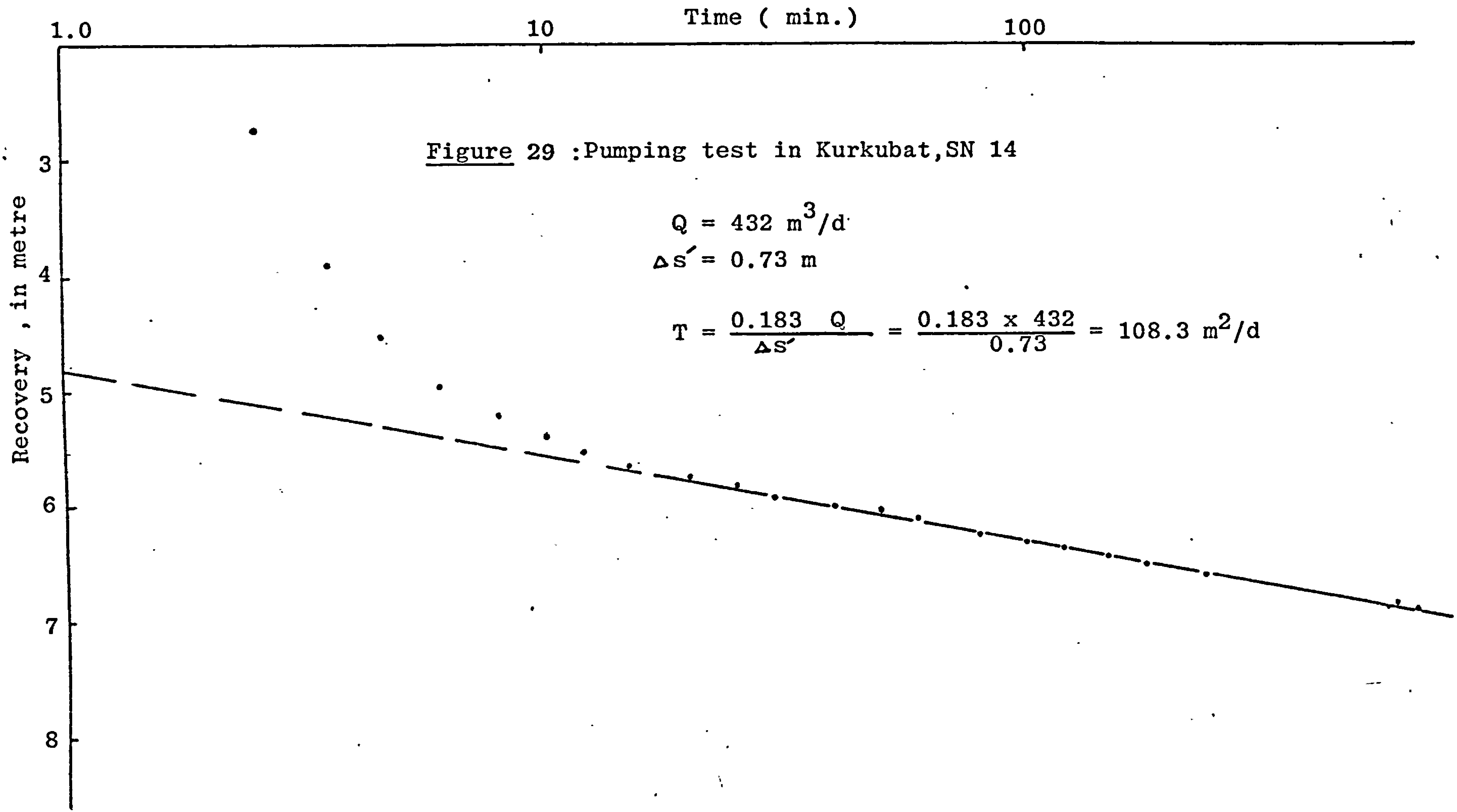


Figure 29 :Pumping test in Kurkubat,SN 14

$Q = 432\ m^3/d$

$\Delta s' = 0.73\ m$

$$T = \frac{0.183\ Q}{\Delta s'} = \frac{0.183 \times 432}{0.73} = 108.3\ m^2/d$$

Figure 30 : Recovery test in Kurkubat pumping well.

$$T = \frac{Q}{12.57\ s} W(u) = 95.5\ m^3/d/m$$

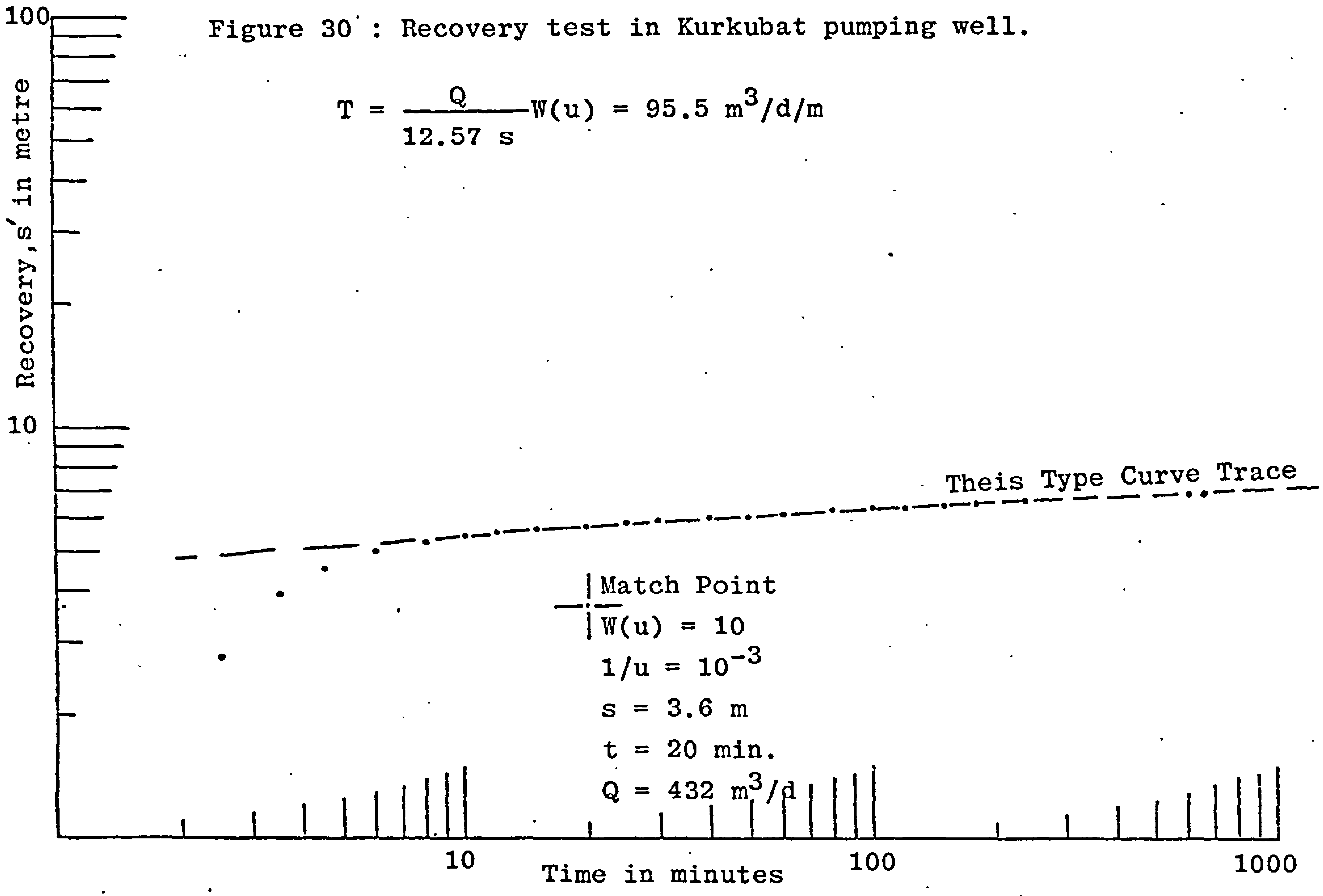
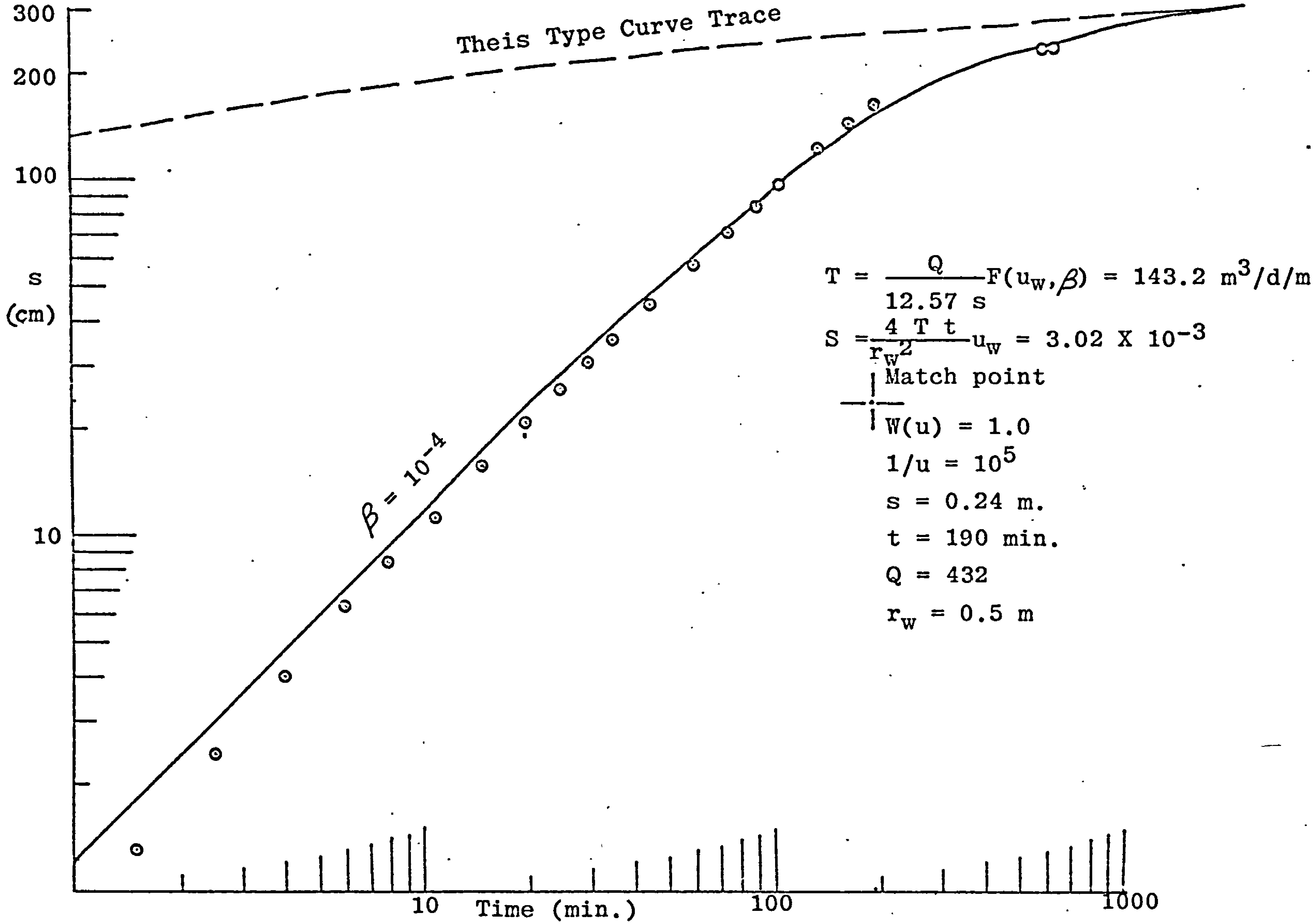


Figure 31 on double logarithmic paper for the application of the Papadopulos method for large diameter wells (Papadopulos, 1967). This method takes into account the storage capacity of the well itself which is assumed to be negligible in the Theis method. The assumptions and conditions for the application of this method are otherwise the same as those listed for the previous pumping test with the exception of assumption 4 which is replaced by: "The well diameter cannot be considered very small; hence, storage in the well cannot be neglected, also the well losses are negligible, i.e. the entrance resistance of the well is zero.

The values of transmissivity and storage coefficient were calculated by fitting the data points to one of the family of Papadopulos and Cooper type curves namely that having a value of $\beta = 10^{-4}$. The method and procedure for this calculation being described in Kruseman and de Rodder (1970, p156). The results obtained by this method are not very reliable due to the shallow depth of the observation well which is only 20m. compared with the 76 m depth of the pumping well, i.e. these results are not representative of the whole aquifer from which water was withdrawn by pumping. It may, however, represent the upper parts of the aquifer which is made up of coarser alluvial deposits.

The determined value of transmissivity of 143.2 m^2/d is rather high for the Upper Fars aquifer though of the same order as previous pumping well calculations, and can only be referred to the coarse alluvial deposit, as in the value of storativity at $3x10^{-3}$. This would indicate a leaky condition which is not apparent in the analysis of pumping test data in the pumping well. The total thickness of the permeable horizons which are considered to function as an aquifer are 40m. and this value has been used to calculate the hydraulic conductivity of the



$T = \frac{Q}{12.57\ s} F(u_W, \beta) = 143.2\ m^3/d/m$

$S = \frac{4\ T\ t}{r_W{}^2} u_W = 3.02 \times 10^{-3}$

Match point

$W(u) = 1.0$

$1/u = 10^5$

$s = 0.24$ m.

$t = 190$ min.

$Q = 432$

$r_W = 0.5$ m

Figure 31: Recovery in the Observation well of Kurkubat, SN.14 .

aquifer which at this hudraulic conductivity 2.9 m/d is indicative of a fine grained sand and sandy clay aquifer.

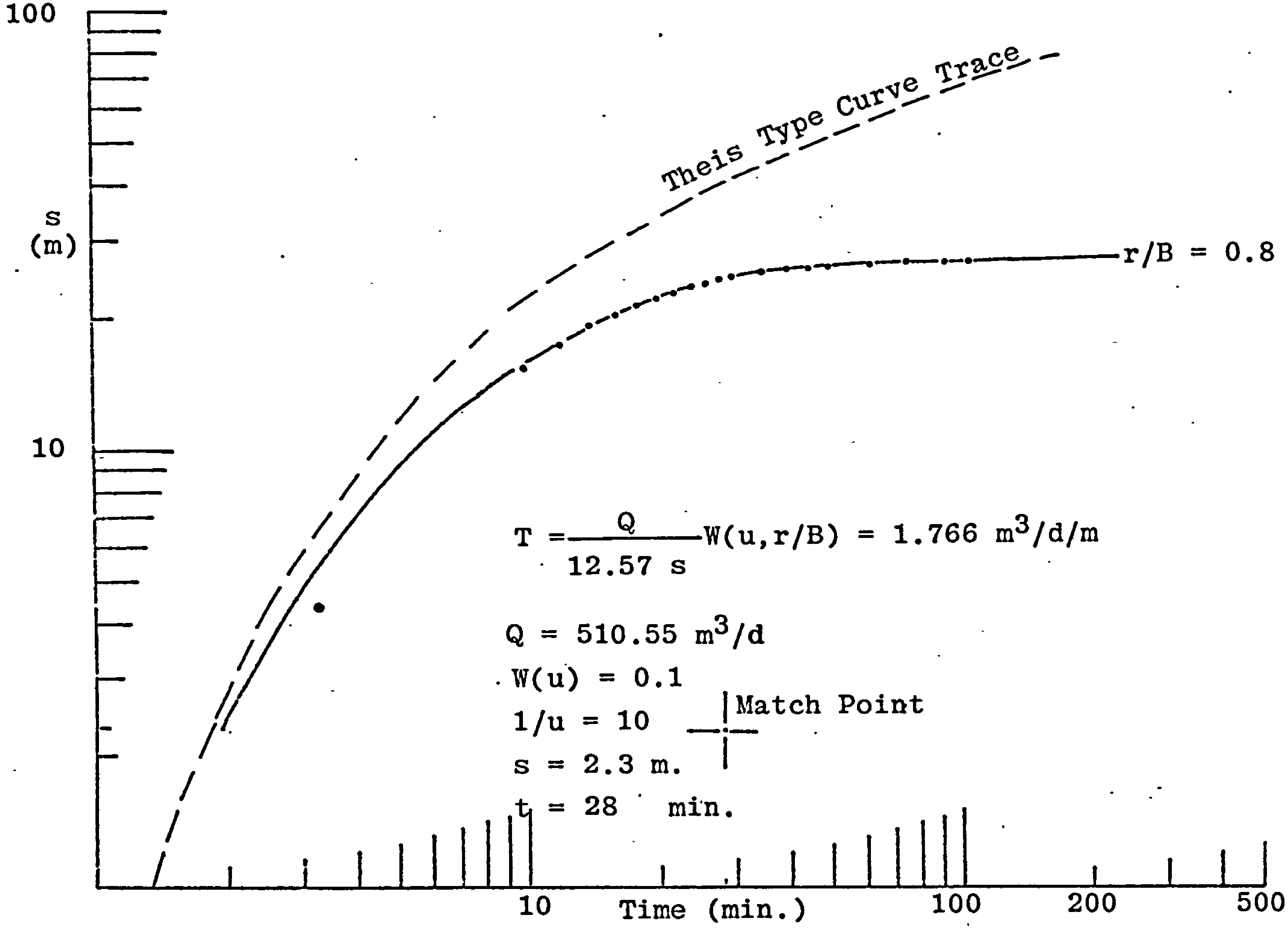
3) Sinjar Army Camp (SN.74): The pumping and recovery tests were carried out in the newly drilled and cased well No.7. It is one of the nine wells drilled by the Ground Water Department in this location. The well penetrates 160m. of alluvium and Upper Fars Formation, with the top 50m. of the well cased at 11⅝" diameter while the remaining 110 m were cased with 6" pipes, 48m of which were slotted as shown in Plate 11.

The test took place on July 2, 1974 at the rate of 595.64 m^3/d for the first 145 minutes and then decreased to 510,55 m^3/d for the rest of the test. The total duration of test was 211 minutes. The recovery was observed in the pumping well immediately after the pumping was stopped. The observed measurements of recovery were plotted on a double logarithmic paper as in Figure 32. The early recovery measurements fit to the Theis type curve though the later measurements show the deviation from the type curve and indicate the beginning of the effect of leakage. This part is fitted to a leaky type curve having a value of $r/B = 0.8$. The transmissivity of the aquifer has been calculated from the formula of Hantush and Jacob (1955) where:-

$$T = \frac{Q}{4 \pi s} W(u, r/B)$$

This equation has the same form as the Theis well function but there are two parameters in the integral; u and r/B. The values for W(u, r/B) for certain values of r/B as u varies were compiled by Hantush (1956). The assumptions and conditions for the application of this method are the

Figure 32: Recovery in the pumping well of Sinjar Camp, SN 74



$$T = \frac{Q}{12.57\ s} W(u, r/B) = 1.766\ m^3/d/m$$

$Q = 510.55\ m^3/d$
$W(u) = 0.1$
$1/u = 10$
$s = 2.3$ m.
$t = 28$ min.

same as those listed previously with the exception that the first assumption is replaced by: "The aquifer is semi confined". The resultant transmissivity value of 1.766 m^2/d is relatively small for a well that is 160 m. deep. However, the geological logging shows a succession of silty clay and clay covered with rubble. The hydraulic conductivity will also be low, 0.02 m/d.

The measurements of recovery in the pumping well have been plotted on a semi logarithmic paper for the application of the Hantush method of solution as shown in Figure 33. This method uses the inflection point of the time-drawdown or recovery curve which is determined by extrapolation of the steady-state drawdown. This drawdown should be known either directly from observation or from extrapolation providing the pumping or recovery tests were carried out for sufficient time.

The curve of s (drawdown or recovery) versus t (time since pumping or recovery starts) on single logarithmic paper has an inflection point, (S_p) where the following relationship hold:

a) $$sp = \frac{1}{2}\, sm = \frac{Q}{4\pi\ T}\ Ko\ (\frac{r}{L})$$

p means 'at the inflection point'

where

ko is the modified Bessel function of the second kind and zero order

b) $$Up = \frac{r^2 S}{4\ Tt_p} = \frac{r}{2L}$$

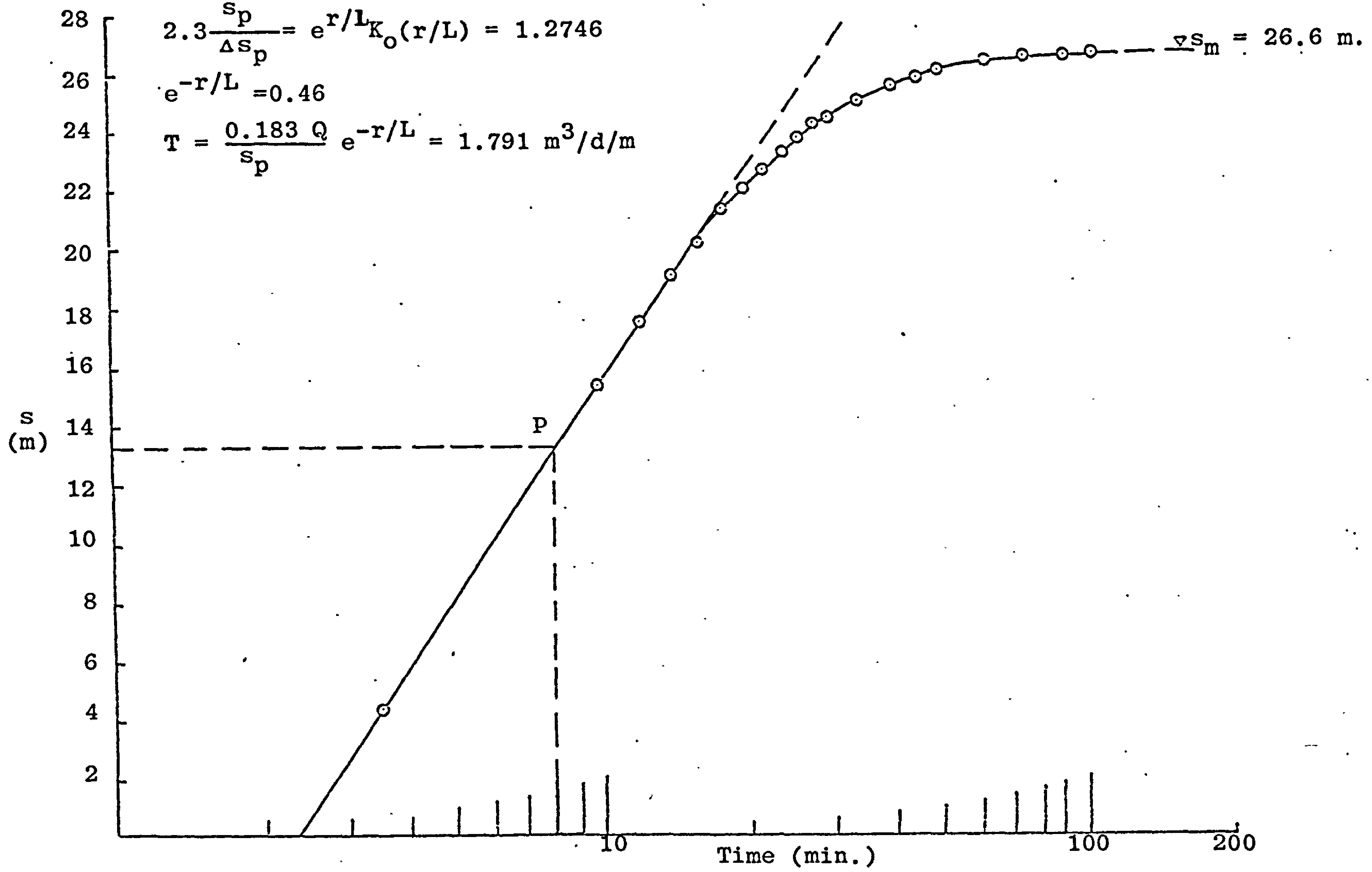


Figure 33: Recovery test in the pumping well of Sinjar Camp, SN 74 .

c) The slope of the curve at the inflection point, Δsp, is given by:-

$$\Delta sp = \frac{2.3\ Q}{4\pi\ T}\ e^{-r/L}$$

or

$$r = 2.3L\ (\log \frac{2.3\ Q}{4\pi\ T} - \log \Delta sp)$$

d) at the inflection point the relation between the drawdown and the slope of the curve is given by:-

$$2.3\ \frac{s_p}{\Delta s_p} = e^{r/L} . Ko\ (r/L)$$

Δs being the slope of a straight line, i.e. the drawdown difference per log cycle of time. The result obtained by the application of this method confirm the presence of leakage and gives a low value of transmissivity, 1.791 m^2/d, similar to that calculated previously.

4) Kaoud Khadher Farm (SN.77): The test was carried out in the hand dug well opposite Sinjar army camp, about 10 km south of the town of Sinjar. The inner diameter of the well is about 2m. and the total depth is 13.50 m. The well was pumped for about five hours at a rate of about 518 m^3/d, then observations were started to measure the recovery in the same pumping well. The well partially penetrates a coarse alluvium aquifer. The water-bearing materials are coarse limestone cobbles and rubble but the total thickness of the aquifer is not known in this locality. The average thickness of the recent alluvium deposits is 30m in Sinjar army camp which is about 1 km to the northwest. Rosłonski

(1924) developed a method by which the hydraulic conductivity (K) can be calculated from the recovery test data in a partially penetrating hand dug well or large diameter well. This method was adopted to calculate K using the following formula:

$$K = \frac{1.57\ r\ \Delta h}{t\ (s_1 + s_2)}$$

where

K: the hydraulic conductivity of the aquifer in m/min

r = radius of the well in metres

s_1 = total drawdown in metres

s_2 = residual drawdown in metres, this is equal to the difference between the static water level and the water level measured after time = t since pumping stopped.

t = time since pumping stopped in minutes

Δh = recovery of the well after time t; it is the difference between the total and residual drawdown in m.

The above formula was applied for seven different times as shown in Table 8 below:

No	t (min)	s_2 (m)	s_1+s_2	Δh (m)	K m/d
1	5	2.874	5.874	0.126	9.7
2	10	2.767	5.767	0.233	9.13
3	25	2.463	5.463	0.537	8.888
4	70	1.876	4.876	1.124	7.45
5	100	1.606	4.606	1.394	6.84
6	130	1.41	4.41	1.59	6.27
7	160	1.267	4.267	1.733	5.74

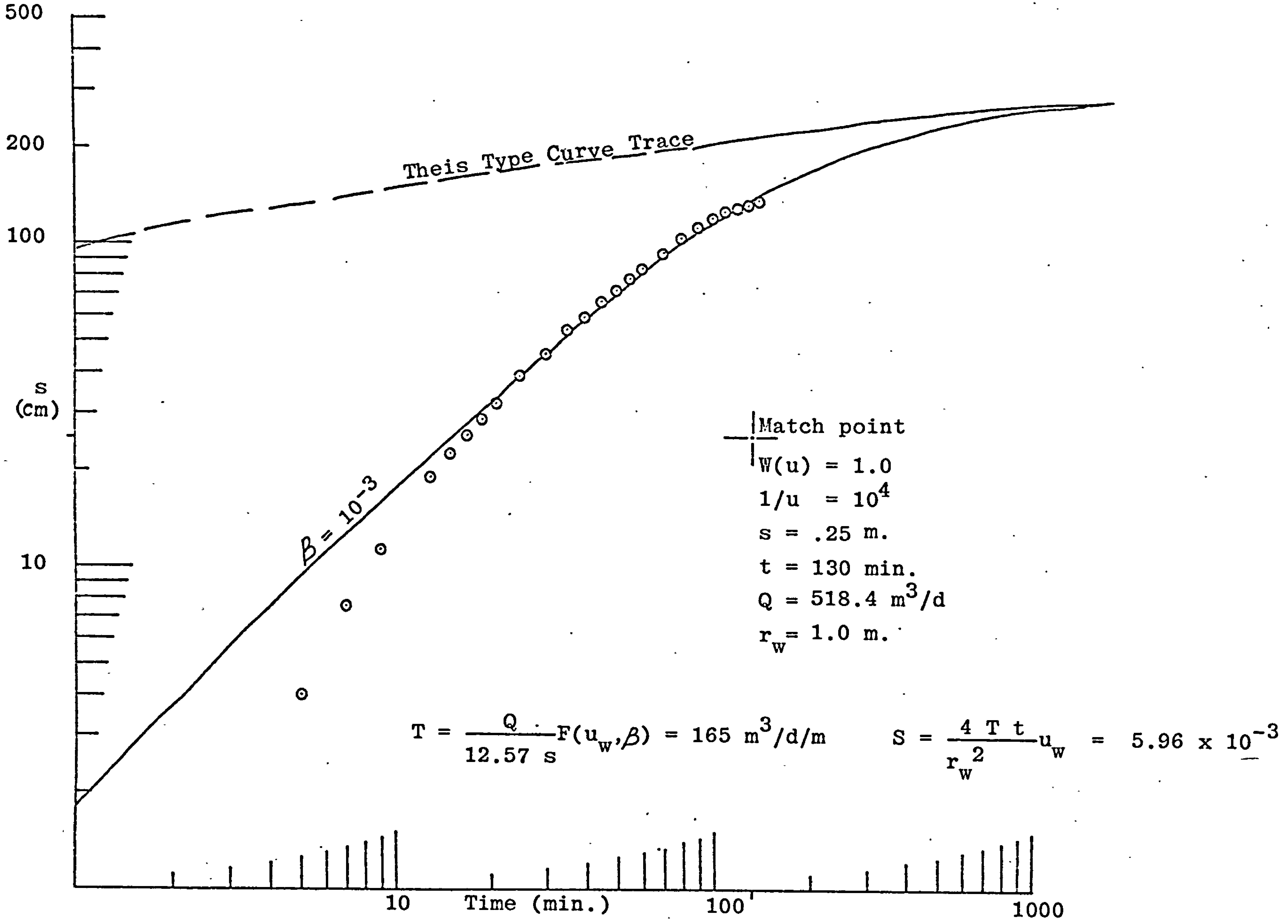
Table 8: Hydraulic conductivity of recent alluvial aquifer

The average value of K taken from the seven determinations is equal to 7.72 m/d.

This value is the highest measured value in the area and may be representative of sandy or alluvium aquifer. The total recovery was about 1.7 m. in 160 minutes. If the total thickness of the alluvium is 30m. as in Sinjar army camp, the total saturated thickness will therefore be equal to 20m. The transmissivity of the aquifer is calculated on this basis and found to be relatively high, 154.2 m^2/d. see Table 7.

The pumping and recovery data in this large diameter well was also analysed by the use of the Papadopulos and Cooper method for unsteady-state flow in a confined aquifer. The measurements were plotted on logarithmic paper as in Figure 34 where the points were fitted to one of the type curves of Papadopulos with the value of $\beta = 10^{-3}$ and a match point were chosen for the calculation of aquifer transmissivity of 165 m^2/d. The transmissivity and storage coefficient could be effected by the presence of a leaky confining layer overlying the alluvium. At the time before pumping started, the water level in the well was higher than the top of the aquifer. It is believed that for this reason the value of S is of the order of 10^{-3} which may indicate leakage from the upper layer. It should be noted that the almost straight portion of the curve corresponds to the period when most of the water is derived from storage within the well. However, at the start of pumping, the drawdown is higher than in the rest of the straight line. This is due to the irregularity of the well diameter, it is narrowest at the top being about 1.5 m increasing downward to about 2 metres. For this reason, the beginning of the pumping does not fit the straight line in Figure 34.

The measurements of the recovery in the pumping well were analysed also by the use of Papadopulos method (Figure 35). where the plotted points fitted very closely to the curve of $\beta = 10^{-2}$. The value of transmissivity was calculated



Match point

$W(u) = 1.0$

$1/u = 10^4$

$s = .25$ m.

$t = 130$ min.

$Q = 518.4\ m^3/d$

$r_w = 1.0$ m.

$$T = \frac{Q}{12.57\ s} F(u_w, \beta) = 165\ m^3/d/m \qquad S = \frac{4\ T\ t}{r_w^{\ 2}} u_w = 5.96 \times 10^{-3}$$

Figure 34: Pumping in the large diameter hand dug well of Daoud Khadher Farm, SN 77

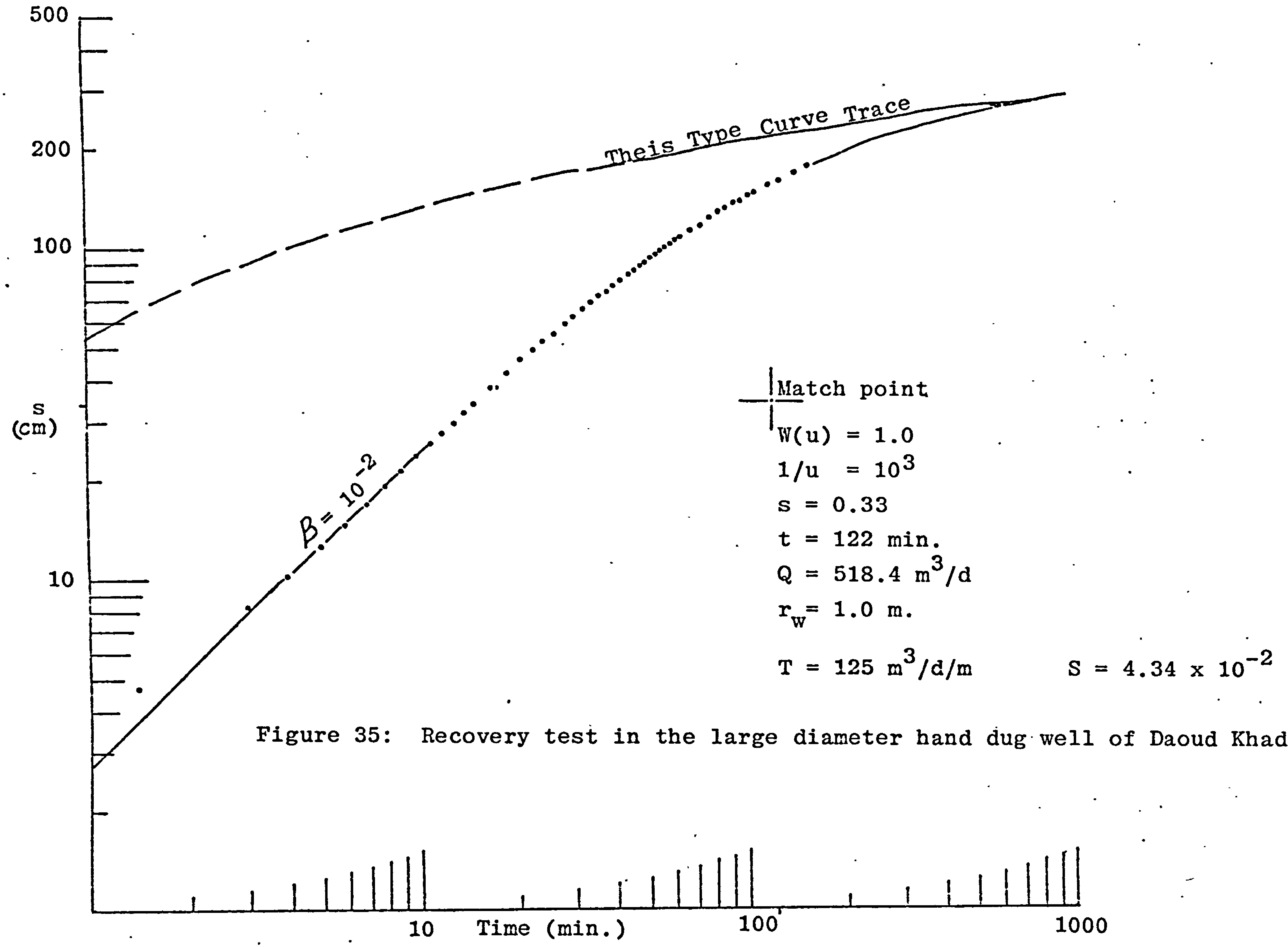


Figure 35: Recovery test in the large diameter hand dug well of Daoud Khadher Farm, SN 77

by extrapolating the values of discharge, Q, before pumping stopped. s_w, being the recovery in metres after pumping stopped at time t and F (U_w, β). The value of transmissivity calculated from the recovery measurement is 125 m^2/d, and is rather low compared with 165 m^2/d calculated from the pumping test data by the same method. In both cases, the values of T and K found in this locality represent the highest in the whole of the study area. These values may be taken as representative of the very coarse alluvium aquifer of the recent alluvial deposits in the area.

5) Al-Louyan (SN.103): The tested well in this location was drilled by the Resource Development Corporation prior to 1954. It is 75 metres deep and screened along 44m; the water being pumped by jack pump to a nearby concrete tank. The step pumping technique was applied with the well pumped on 29 September 1974 in three different stages. The results of pumping test are listed in Table 7 and the measurements of the pumped water level is plotted in Figure 36. The first stage of pumping was maintained for an hour with a constant discharge of 50.11 m^3/d. The second stage followed immediately for 76 minutes with a constant discharge of 77.76 m^3/d, while the third stage was maintained for a longer period, two hours, with a constant discharge of 103.68 m^3/d. The data are plotted on a semi-logarithmic paper in Figure 36 for the application of Jacob straight line method. The first step of pumping is used to calculate the value of transmissivity of 45.85 m^2/d for the aquifer by the use of Jacob and Cooper's method. The discharge rate was rather low due to the use of Jack pump and this may have provided unreliable results. When the discharge rate doubled in the third stage, it was found that the recovery data are more reliable for this calculation.

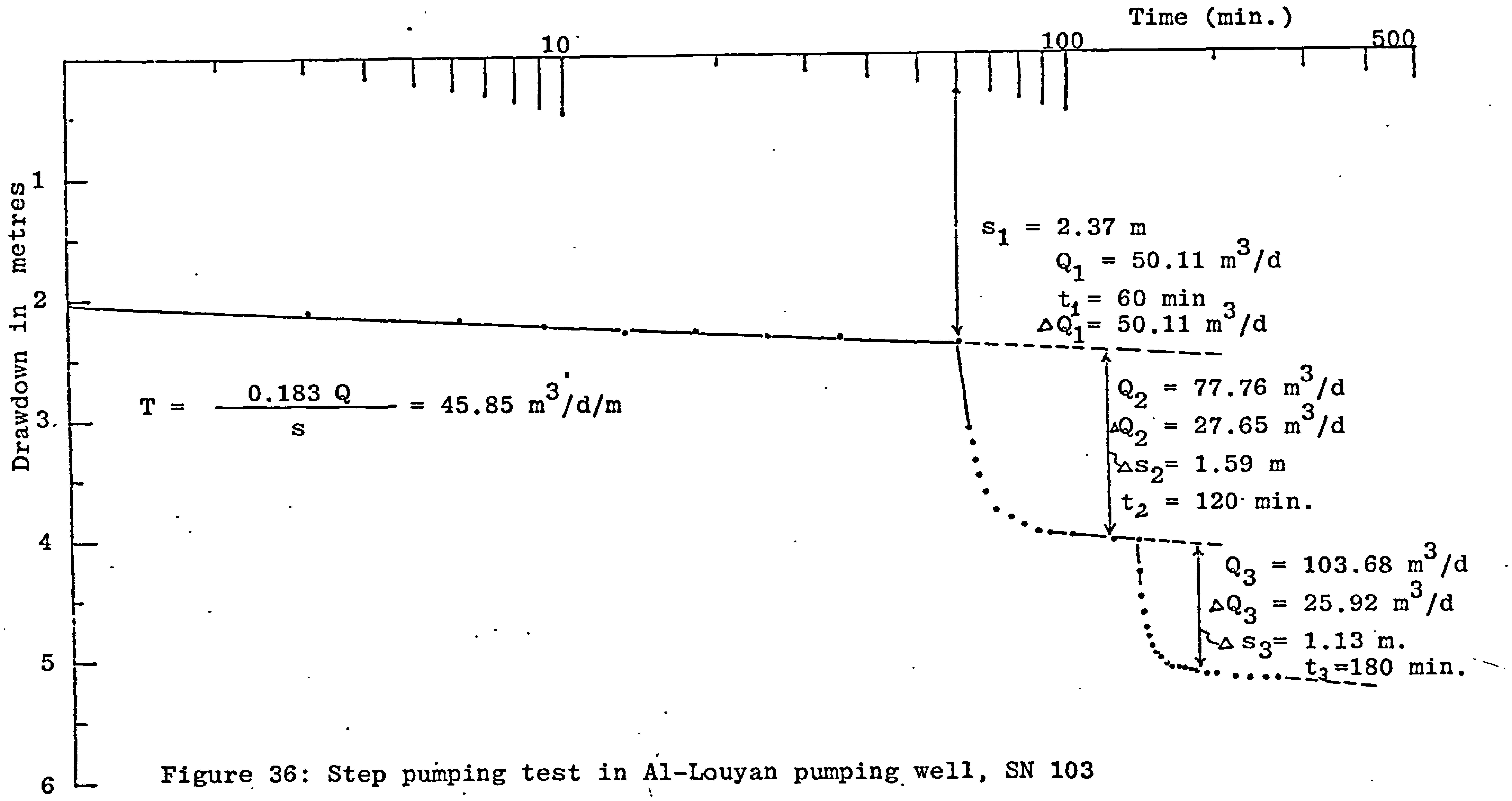


Figure 36: Step pumping test in Al-Louyan pumping well, SN 103

The measurements of the recovery of the water levels in the pumping well were plotted on logarithmic paper in Figure 37 and show a clear indication of leakage in the last part of the test. The plotted measurements were fitted to the family of type curves for non-steady state, leaky artesian conditions and the value of T was calculated to be 5.81 m^2/d. This value is more acceptable than the first one calculated from the drawdown data. The saturated thickness of the aquifer was estimated in Table 7 to be 50 metres from which the hydraulic conductivity was calculated to be 0.12 m/d. This value is representative of the silty clay and sand aquifer of the Upper Fars formation in this location.

The well efficiency was also calculated by the use of step pumping. The main components of drawdown in the production well are due to aquifer loss and well loss. The latter may be represented approximately by the following equation (Jacob, 1946):-

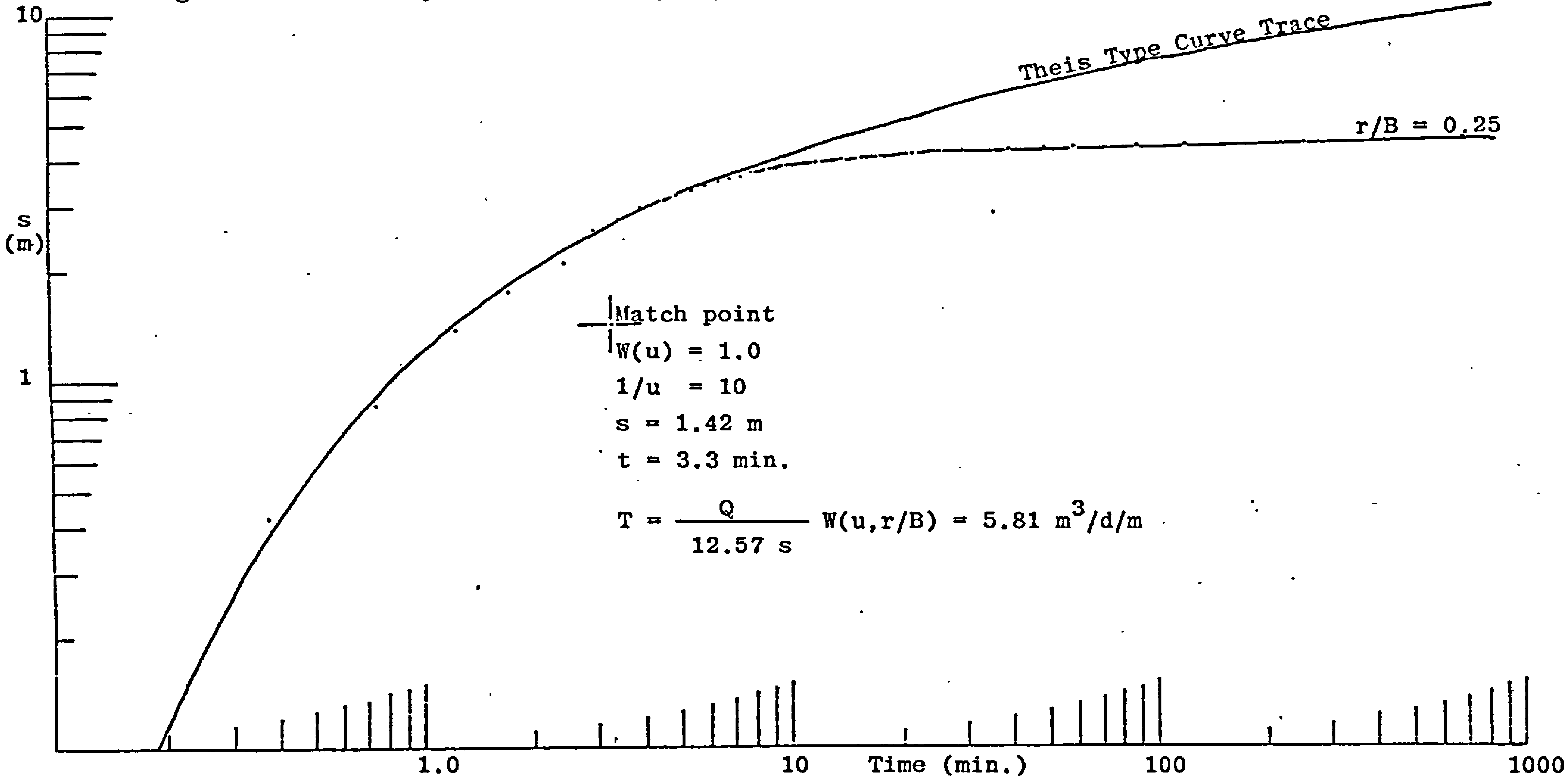
$$s_{wl} = CQ^2$$

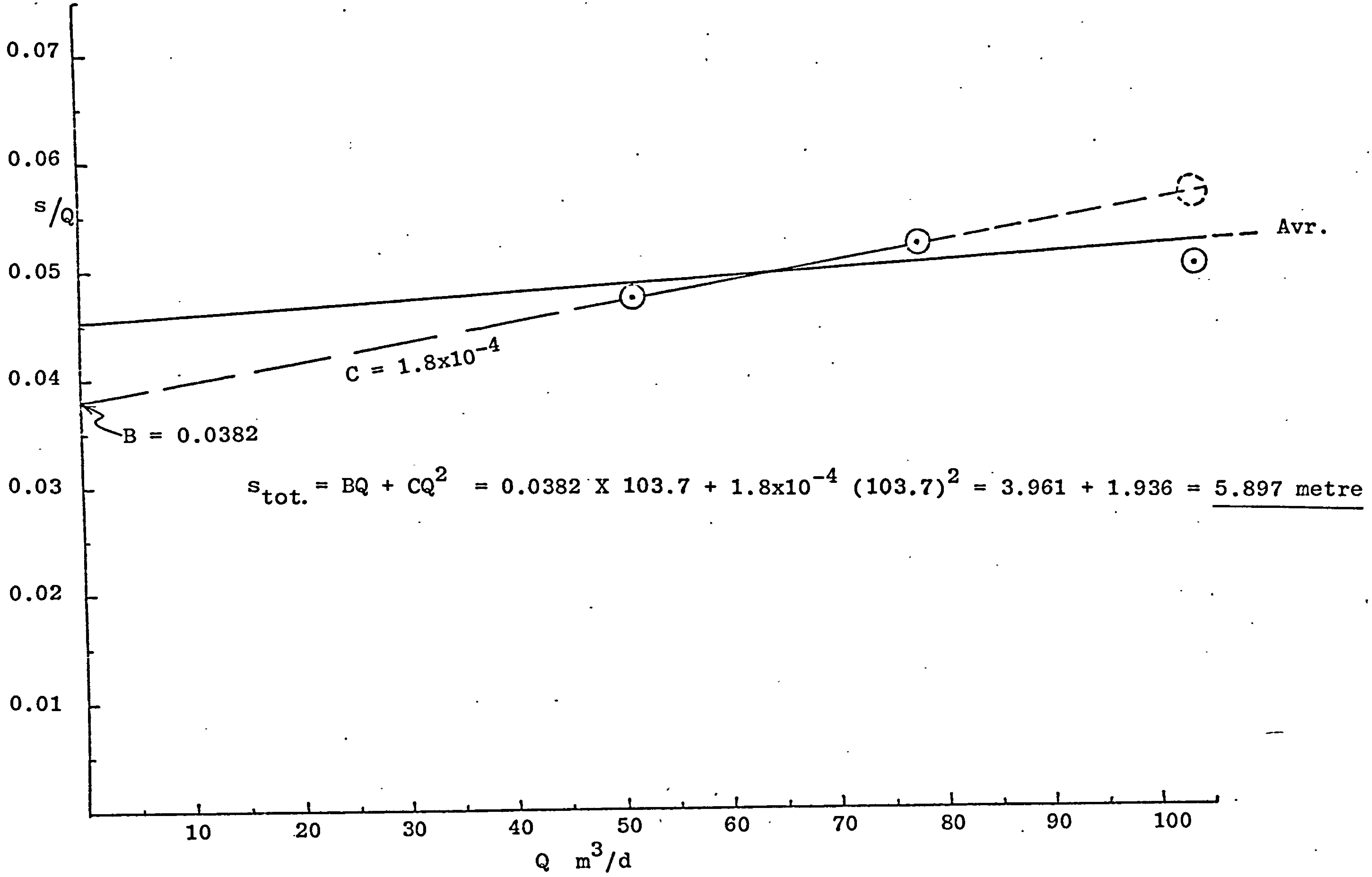
where

s_{wl} = well loss, in feet
C = well loss constant, Sec^2/ft^5
Q = discharge in cubic feet per second (cfs)

The value of C may often be computed from the data collected during a variable rate well-production test and the relation between specific drawdown (s/Q) and the discharge rate (Q). The graphical method of Bruin and Hudson (1955) was employed here as shown in Figure 38. The straight line fitted through the first two points was used to calculate the value of C and B. The well loss constant C represents the slope of the straight line. Point B is the intersection of the straight line and the specific drawdown axis.

Figure 37: Recovery test in Al-Louyan pumping well, SN 103





$$s_{tot.} = BQ + CQ^2 = 0.0382 \text{ X } 103.7 + 1.8\text{x}10^{-4}\ (103.7)^2 = 3.961 + 1.936 = \underline{5.897 \text{ metre}}$$

Figure 38: Discharge-drawdown relationship in Al-Louyan pumping well, SN 103

Aquifer loss and well loss are both calculated from the following relation:

$$s_t = BQ + CQ^2$$

Where s_t = total drawdown in metres
BQ = aquifer loss in metres
CQ^2 = well loss in metres

$$s_t = 0.0382 \times 77.76 + 1.8 \times 10^{-4} (77.76)^2$$

$$s_t = 2.97 + 1.0884 = 4.05 \text{ metres}$$

The value of discharge used for the third step of pumping was applied in the above formula for the determination of aquifer and well losses as follows:-

$$s_t = 0.382 \times 103.7 + 1.8 \times 10^{-4} \times 10753.7$$

$$s_t = 3.961 + 1.936$$

$$s_t = 5.897 \text{ metres.}$$

The actual drawdown measured in the end of the third step is 5.25 m. This indicates that the well is unstable, i.e. either significant development takes place during the pumping period or leakage was taking place in the last period of pumping.

The value of C may also be calculated by using the equation (Jacob, 1946)

$$C = \frac{\left[{}^{\Delta si}/_{\Delta Q_i}\right] - \left[\Delta s^{i-1}/\Delta Q_{i-1}\right]}{\Delta Q_{i-1} + \Delta Q_i}$$

Δs represents increments of drawdown produced by each increase ΔQ in the rate of pumping. Increments of drawdown are determined by taking in each case the difference between the observed water level and the extension of the preceeding water level curve, see Figure 36. Steps of 60 minutes were used for each step, i.e. drawdown for each step was measured from Figure 36 for the first, second and third step in the periods of 60 minutes from the beginning of each step. The results are shown in Table 9 below.

Table 9: Drawdown and Pumping Rates for Al-Louyan production well.

Step	Q m^3/d	s m	ΔQ m^3/d	Δs m
1	50.11	2.37	50.11	2.37
2	77.76	4.035	27.65	1.59
3	103.7	5.17	25.92	1.13

For steps 1 and 2 the value of C is calculated from the above equation as follows:-

$$C_{1\&2} = \frac{\Delta s_2/\Delta Q_2 - \Delta s_1/\Delta Q_1}{\Delta Q_1 + \Delta Q_2}$$

$$C_{1\&2} = 1.311 \times 10^{-4} \ d^2/m^5$$

For steps 2 and 3, the solution of the above equation gives $\Delta s_2/\Delta Q_2$ greater than $\Delta S_3/\Delta Q_3$. This is probably due to significant development of the well during the pumping period or it could be due to the effect of leakage which became effective in the last part of pumping period as was seen from the analysis of the recovery data. Thus, it is often possible to appraise the stability of a well with variable-rate well-production test data.

6) Tel-Alamir (SN.133): This well is 143 m. deep and was drilled by the Resource Development Corporation before 1954. It is operated by a jack pump and the pumping test was carried out on 1 October 1974 with a pump capacity being rather low, 23.33 m^3/d. The water level was measured directly in the pumping well through a gap between the pump and the casing. The water level became more or less static after 16 minutes of pumping at a constant rate of 22.464 m^3/d. It remained static until the pump speed suddenly increased to 23.33 m^3/d and the water level fell slightly. It became static again after only ten minutes of the discharge increase and remained so for the rest of the pumping period. The results of measurements of pumping test in the pumping well were not accurate due to the oscillation of water by jack pumping. The recovery of the water level was measured immediately after pumping. All the measurements were plotted on logarithmic paper as shown in Figure 39, and the resultant curve was fitted to one of the family of non steady state leaky artesian type curves. The value of transmissivity calculated from the match point shown in Figure 39 was found by this method to be 3.787 m^2/d.

The measurements made for water level recovery were also plotted on semi-logarithmic paper in Figure 40 for the application of Hantush method of solution. The first part of the recovery data was fitted on a straight line with the exception of the very early measurements which are believed to be affected by the water released from the pumping stem immediately after pumping stopped. The transmissivity of the aquifer was calculated from the inflection point and found equal to 2.65 m^2/d. This value is smaller than the result obtained by the application of the type curve method. The average value of T was

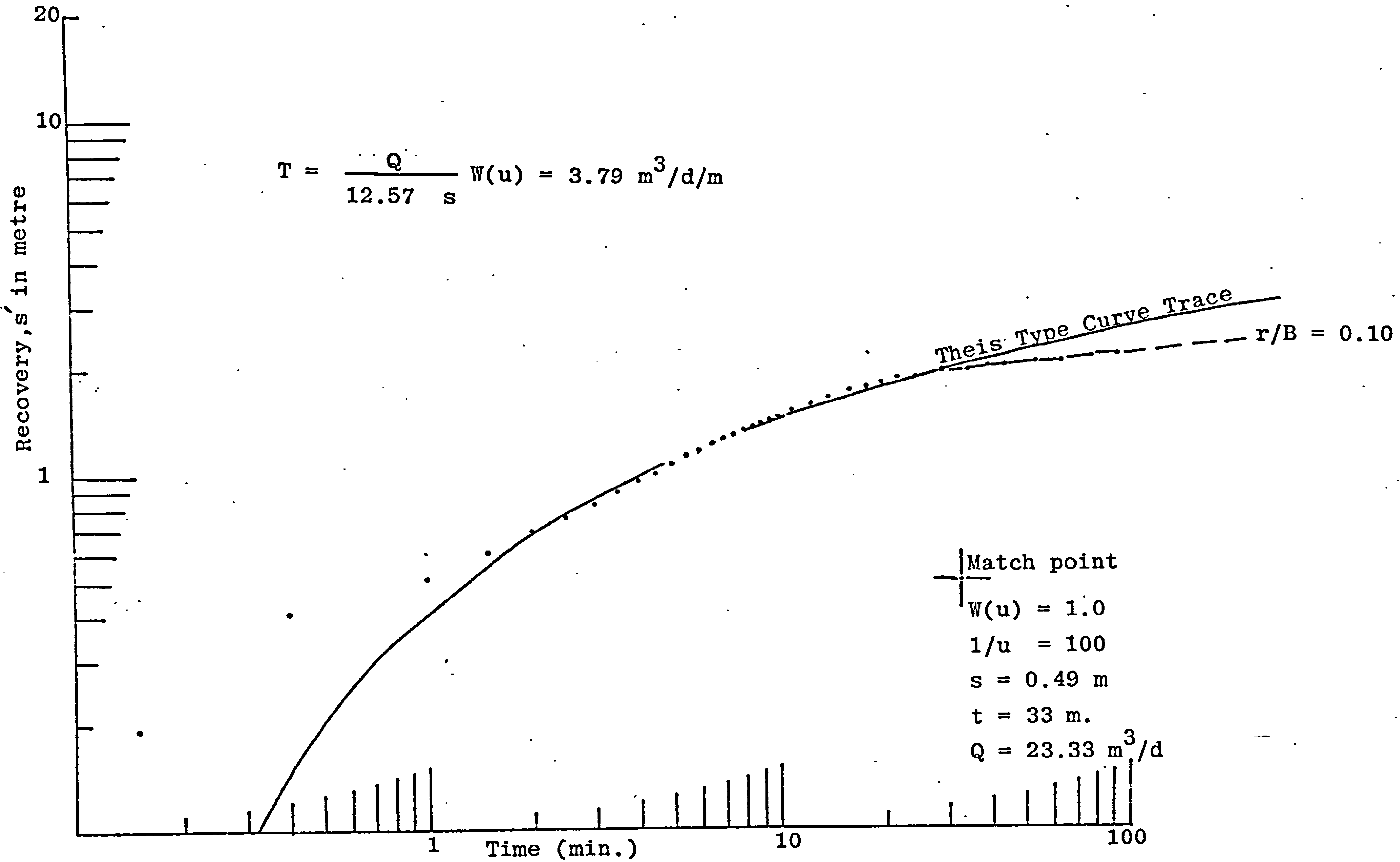


Figure 39: Recovery test in Al-Alamir pumping well, SN 133

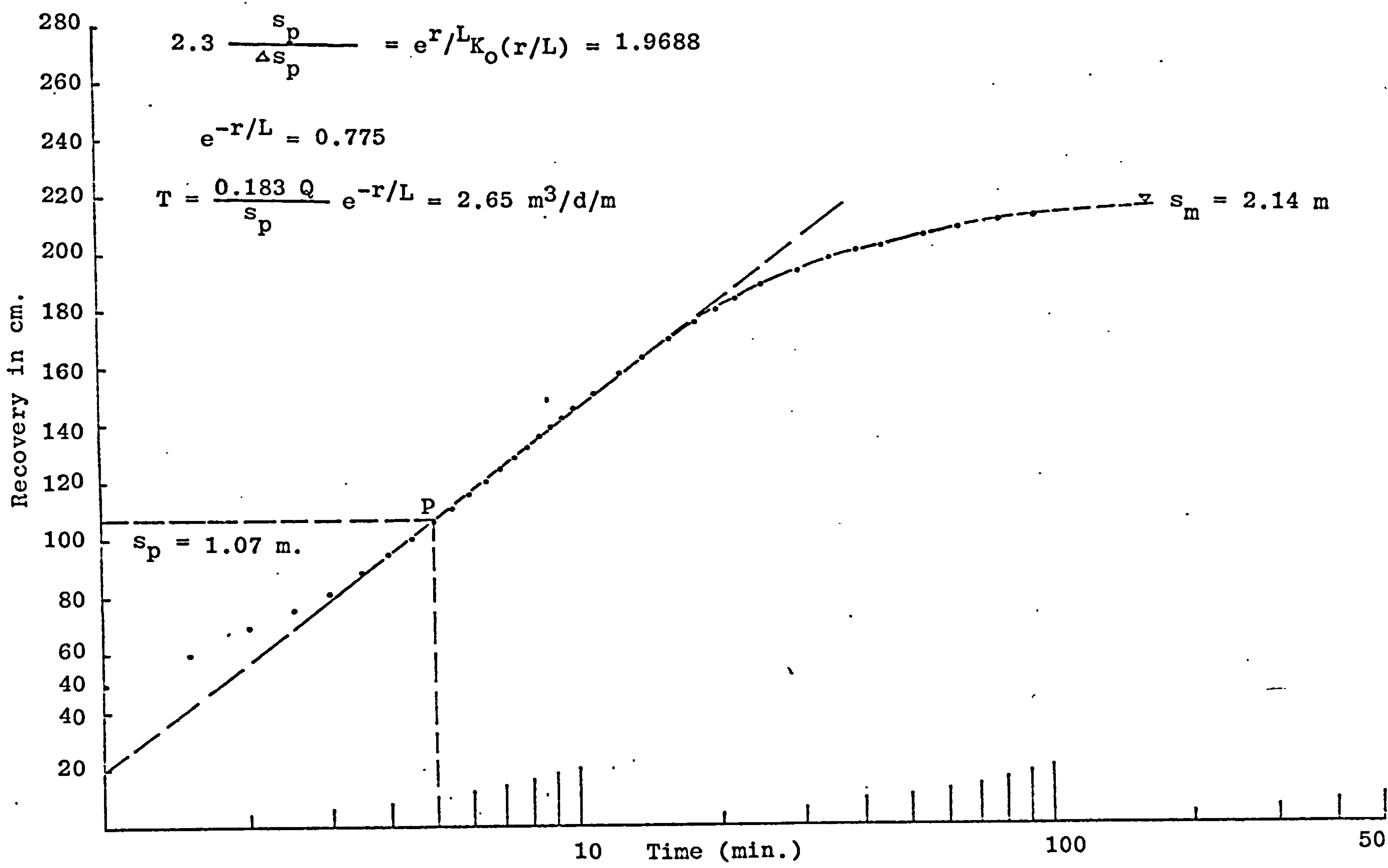


Figure 40: Recovery in the pumping well of Tel-Alamir, SN 133

taken from the two results and used for the calculation of the hydraulic conductivity K of the aquifer. The total saturated thickness of the aquifer was estimated about 50 m and this gave a value of K = 0.16 m/d.

7) Irfa'i (SN.136): The pumping test in this well was carried out immediately after the completion of the well, which is one of the eight wells drilled by the Ground Water Department near the village of Irfa'i in Al-Anwar Cooperative farm. The well was pumped for 282 minutes at a constant rate of 820.8 m^3/d, this yield being the highest measured discharge in the area of study. The recovery of the water level was measured immediately after the pumping was stopped and the data plotted as in Figure 41.

The plotted points were fitted to one of the non-steady leaky artesian type curves and a value of transmissivity was calculated to be 14.04 m^2/d which is relatively low for this location in which the well yield was found relatively high in the rest of the nearby drilled wells. A total saturated thickness of some 100 metres of water bearing strata was calculated from the geological logging of the eight drilled wells in this location. The hydraulic conductivity of the aquifer was calculated from the transmissivity and was equal to 0.14 m/d.

3.3.4 Specific Capacity of drilled wells

Specific capacity of a well is the value of discharge available for a unit drawdown. It is the ratio of well discharge to corresponding drawdown, expressed in gallons per minute the well produces for each foot of drawdown or cubic metres per day for each metre of drawdown.

The specific capacity of a well is not constant. It represents an estimation of the water yield available from an aquifer. The yield of each well is dependant on the depth of penetration

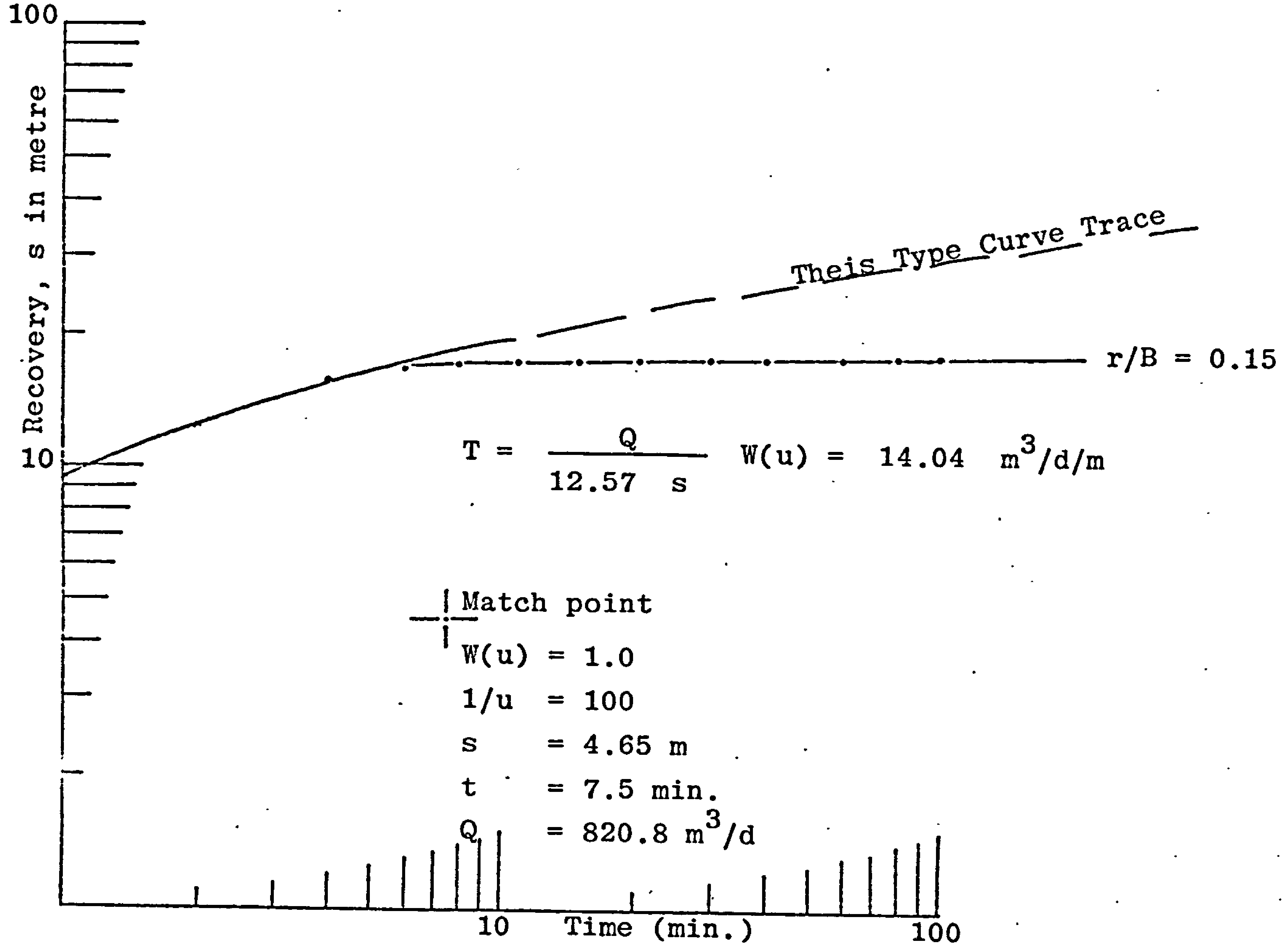


Figure 41: Recovery test in Irfa'i pumping well, SN 136

through the aquifer, the thickness of the aquifer, aquifer properties and well design.

For combined wells, the percentage increase in yield resulting from doubling the well diameter is generally about 7 percent (Johnson, 1972). In general, the specific capacity of the well is constant at any pumping rate as long as the aquifer is not dewatered. For a well in a water-table aquifer, the part of the formation within the cone of depression is actually dewatered during the pumping. This influences the ratio of drawdown to yield. When the drawdown is doubled, the well yield is less than doubled. The specific capacity decreases with increased drawdown; in fact, it decreases directly in proportion to the drawdown.

Optimum well operating characteristics are obtained when the product of yield and specific capacity is at a maximum. It can be demonstrated mathematically that this occurs at about 67 percent of maximum drawdown. This fact is the basis of the design practice of screening approximately the lower one-third of homogeneous water-table formation.

In the area under study, well depths are variable and the aquifer is only partially penetrated. Correction has been made for the calculation of specific capacity data taken from the Ground Water Department records and Ingra Company reports. This correction has been made in order to compare the values of specific capacity. It is a function of aquifer thickness concerned. The following formula was applied to calculate the specific capacity of all the drilled wells in which a value of discharge and drawdown was available together with the well depth and static water level.

$$SC = \frac{100Q}{(TD-SWL)s}$$

Where

SC = Specific Capacity of well in m^2/d
Q = rate of discharge in m^3/d
TD = total depth of well in metres
SWL = static water level in metres
s = corresponding drawdown in metres

This specific capacity represents an estimation of water quantity available from an aquifer whose thickness is 100 m., per drawdown of one metre. The aquifer thickness of the Upper Fars is over 100 metres but the permeable horizons penetrated by most of the drilled wells are in the first 100 m. of the Upper Fars formation.

The average specific capacity was calculated from the above formula for eighteen wells drilled by Ingra Consulting Department in the Upper Fars aquifer and for 26 wells drilled by the Ground Water Department in the same aquifer. All the results are shown in Table 11 and in Figure 42. It was possible to distinguish areas of high specific capacity and axes of prevailing specific capacity along which most of the ground water flow towards the south of Jabal Sinjar. Most of the drilled wells situated along these prevailing axes are of relatively high yield. These axes correspond more or less with the distribution of the alluvial deposits over the Upper Fars formation. They may also indicate the distribution of coarse sand and sandy clay horizons which function as a good aquifer in the Upper Fars formation.

The areas of maximum specific capacity were distinguished to the south and southwest of Balad Sinjar in which the specific capacity exceeds 500 $m^3/d/m$. The two axes to the east and west of the area in Figure 42 are not certain due to the scarcity of data in these areas.The total number of wells drilled in these areas are relatively small due to the bad quality of water flowing from the Lower Fars aquifer in the plunging parts of Jabal Sinjar,

Ser No.	Location	Q m^3/d	s (m)	total depth	SWL (m)	Specific capacity (m^2/d)	Est. T m^2/d	Time min.
1	Umm Jres	345.6	27.43	260	23.8	5.33	4.7	60
2	Tel-Sfoog	553.	10.35	81	27.5	99.87	115	50
3	A'selam	259.2	57.02	136.5	6.7	3.5	3	270
4	Tel Azer	241.9	26.8	72.5	22.9	18.2	18.2	10
5	Kharbat Tatar	578.9	7.42	70.3	29.65	191.93	230	17
6	Tel-Azer Sharqi	1864	3.5	95	25.7	256.22	450	10
7	Karbat Kawala	691.2	4.7	90	23.5	221.15	270	120
8	Al-Majnoniya	172.8	6.7	60.1	11.2	52.74	58	40
9	Rambosi Sharqi	518.4	39.6	76.5	7.15	18.88	19	12
10	Sinjar	1037	12	113	16.8	98.83	110.3	20
11	Khanesi	691.2	12.16	145	8.4	41.61	44	10
12	Kakhurt	432	9.2	76	32.6	173.11	210	25
13	Kharbit Birki	432	12.65	71	28.9	81.12	92	50
14	Al-Wardia	518.4	13.42	115	7.1	35.80	38	90
15	Kurkubat Sufla	518.4	5.08	80	15.07	157.16	185	40
16	Al-Ba'aj	518.4	46.5	140	15.0	8.92	8.4	30
17	Blaij	1037	49.27	200	6.4	10.87	10.7	12
18	Marzoga	691.2	40.28	168	18.	11.44	11	10
19	Ghazlani	2160	4.45	150	4.3	333.15	420	5
20	"	2160	1.4	150	34.05	1311.37	1800	10
21	Bab Al-Khair	691.2	21.15	117	23.3	34.88	37	20
22	Sinjar Camp 1	981	10	100	18	119.6	140	60
23	Sinjar Camp 2	545	53	186	17	6.08	5.25	300
24	Sinjar 2	1296	9	70	16	266.66	330	60
25	Sinjar Camp 5	545	10	134	18	46.98	50	300
26	Blaij 1	180	12	87	15	20.83	21	60
27	Abu Alkhashab	708	5.5	56	9.5	276.8	340	300
28	Abu Rasain	196	7	36	3	84.85	97	60
29	Delakhan	218	10	72	5	32.54	34.5	60
30	Umm Althebam 2	218	4	150	67	65.66	83	300
31	Hamadan 1	180	17	78	5	14.5	14.5	60
32	Jlemed 1	512	9	104	18.3	66.38	75	60
33	Kharab J'ab 1	708	14	120	16	48.63	61	240

Table 11: Specific capacity of drilled wells .

Ser No.	Location	Q m^3/d	s (m)	total depth	SWL (m)	Specific capacity (m^2/d)	Est T m^2/d	Time min.
34	Kubbat Alwahbi	218	0.25	55	6.1	1783.2	-	60
35	Hamdaniat Jezira	338	39	109	15	9.22	10.5	60
36	Rambosi 1	136	1	54	22	425	540	60
37	Kojo 1	926	18	116	12	49.47	64	240
38	Ain H'san	180	12	56	3	28.3	30	60
39	Kharab Bajar	1090	1	2040	14	573.7	750	300
40	Kurzuruk	763	44	147	19	13.55	13.4	300
41	Tel Albanat	436	37	100	8	12.81	12.6	60
42	Tel Hajir 1	98	7,35	106	35.4	18.87	19	90
43	Tel Askai	87	4.2	95	4.8	22.96	24	240
44	Tel Takia 4	436	14	140	34	29.4	36.5	300
45	Tel Takia 3	409	24	129	36	18.32	29	60
46	" " 2	109	7	89	46	36.21	29	60
47	Tel Alshaikh	109	7.7	55	4.5	28.03	29	60
48	Tel Keni	6.5	7.6	116	19.8	0.9	0.73	60
49	Tuwin	1.6	1	25	11	11,43	13.5	60
50	Hadhr 1	9.4	25	68	9	0.64	-	60
51	Hammam Ali	12.26	57	98	23	2.87	2.35	-
51	Athbah	9.8	4	60	40	12.25	12	60
53	Al Tibnah	213	5	70	20	85.2	109	60
54	Almawali	454	2	41	26	1513.33	2100	60
55	Kharbat Said	13	42	82	40	0.74	0.6	60
56	Al Rihania	130	3.10	91	60	135.3	160	90
57	Al Taha	356	23	45	8	41.83	45	60
58	Al Thalja	97	1	90	68	440.9	530	60
59	Halawa	110	3	61	37	152.77	185	60
60	Abu Shukka	130	0.1	43	30	10,000	-	60
61	Mustantik	181	6.1	73	3.0	42.39	45.5	60
62	Tel Khazaf	95	7	218	65	8,87	10.2	120
63	Ijba Gharbi	216	6	46	6	90	102	60
64	Al Dahbona	26	7.2	200	10	3.99	3.5	60
65	Al Dirnaj	113.2	1.1	174	52.6	84.75	96	120

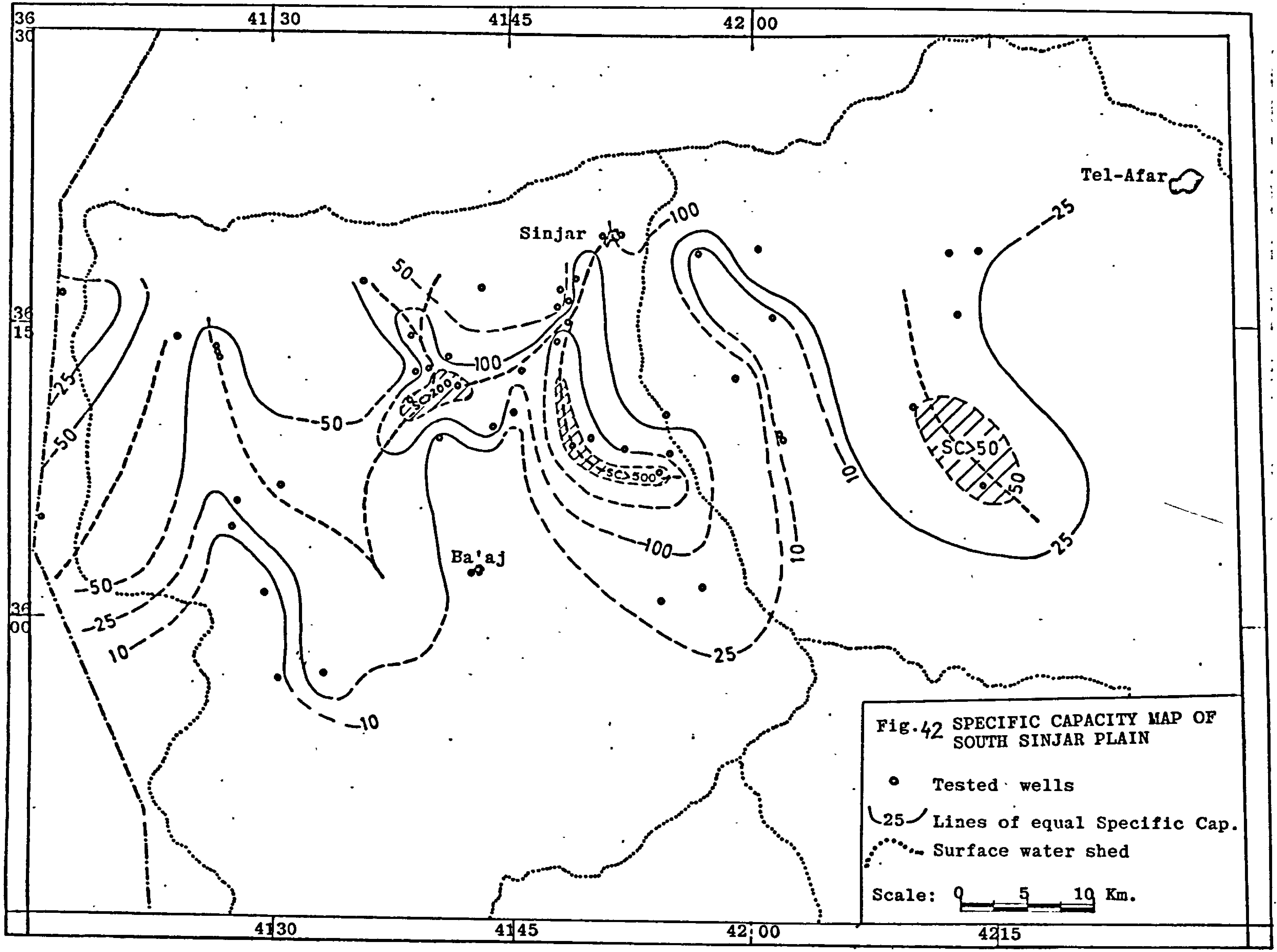


Fig.42 SPECIFIC CAPACITY MAP OF SOUTH SINJAR PLAIN

mixing with the better quality water of the Upper Fars aquifers.

The specific capacity of the wells drilled in the Lower Fars aquifers are variable and not comparable with the values calculated from the Upper Fars aquifers. The presence of local permeable zones in the Lower Fars formation led to a very high specific capacity values in the wells drilled in such zones. It was not possible to map the specific capacity data in the Lower Fars aquifers due to this variation. In some wells drilled in the eastern parts of Mishraq sulphur structure, a discharge of over 10,000 m^3/d causes no measurable drawdown in the water level of the pumping well. Such wells are often located in highly fractured areas or highly cavernous reflecting the karstic nature of the Lower Fars formation.

3.3.5 Transmissibility of water bearing materials

In many cases of reconnaissance groundwater investigations where no pumping tests are available,the hydrologic properties of an aquifer must be estimated from well logs, water level and specific capacity data.In the area under study, the specific capacity of the Upper Fars aquifers was determined from the discharge-drawdown relationship (see 3.3.4). The specific capacity of a well cannot be an exact criterion of the coefficient of transmissibility because specific capacity is often affected by partial penetration, well loss, duration of pumping, and hydrogeologic boundaries. However, an attempt was made to estimate the coefficient of transmissibility from the existing specific capacity data because of the potential usefullness of even rough estimates of T.

The theoretical specific capacity of a well discharging at a constant rate in a homogeneous, isotropic, nonleaky artesian aquifer infinite in a real extent is given by the following equation (after Walton, 1970):-

$$\frac{Q}{S} = \frac{T}{264 \log\left(\frac{Tt}{2693 r_w^2 S}\right) - 65.5}$$

where
$\frac{Q}{S}$ = specific capacity, in U.S. gpm/ft
Q = discharge, in U.S. gpm
s = drawdown in feet
T = coefficient of transmissibility, in U.S. gpd/ft
S = coefficient of storage, fraction.
r_w = nominal radius of well, in feet
t = time after pumping started, 'in minutes.

The equation assumes that: (1) the production well penetrates and is uncased through the total saturated thickness of the aquifer, (2) well loss is negligible, and (3) the effective radius of the production well has not been affected by the drilling and development of the well and is equal to the nominal radius of the production well.

In most of the wells drilled in the Upper Fars aquifer the well penetrates only the upper 100 metres of the formation. This constitutes about half the total thickness of the formation but it is assumed that the more permeable horizons are within the upper part of the formation. Additionally, the wells are cased by a badly perforated screen which has increased the well loss. However, the graphical relationship between the specific capacity and the coefficient of transmissibility for confined, semi-confined and water-table conditions is presented in Figure 43. The coefficient of storage of the aquifer was assumed in the above formula for different values of T to estimate specific capacity of the well. Storage coefficient values of 0.0001, 0.001 and 0.01 were assumed in constructing the graphs for the

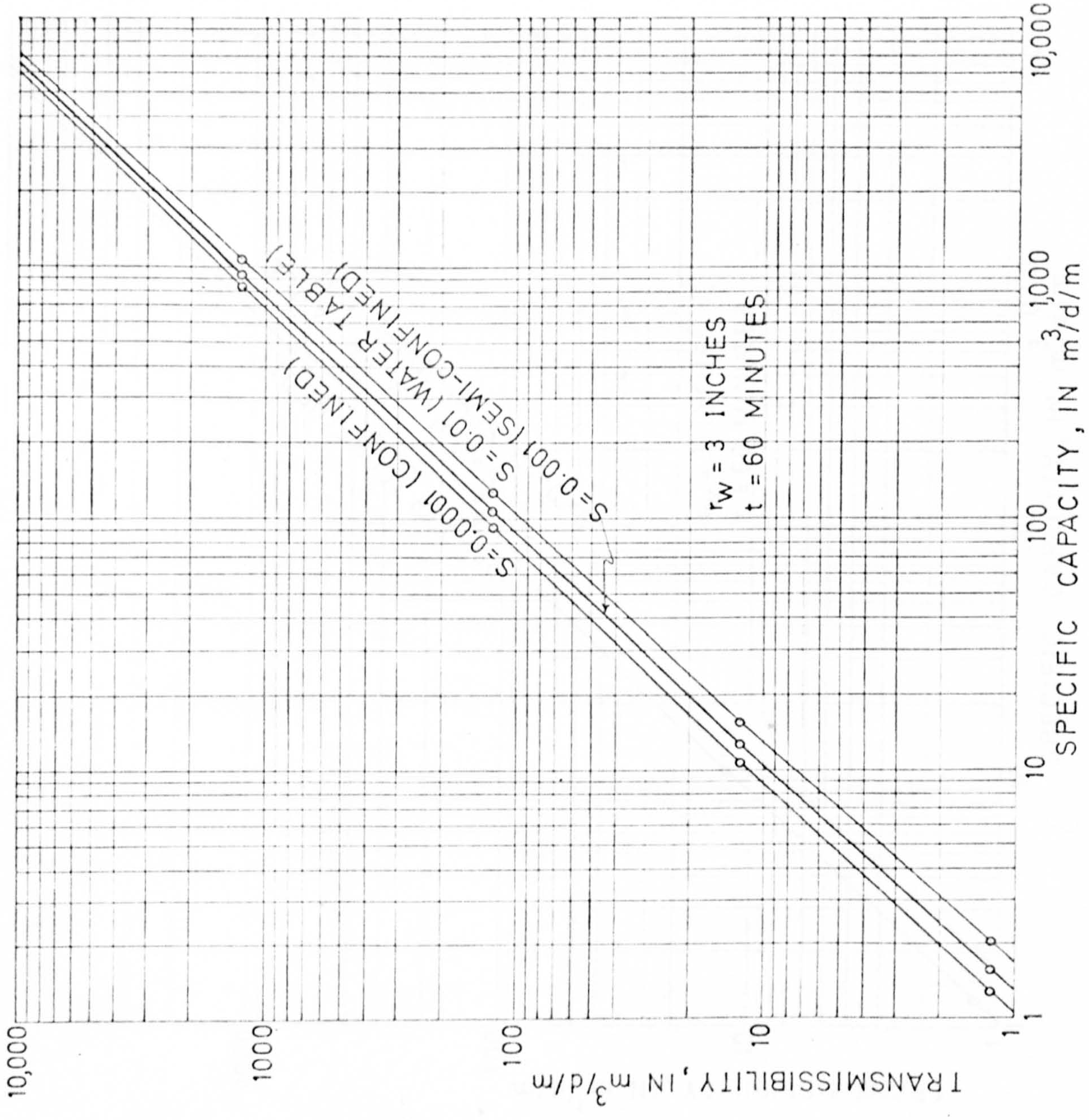


Figure 43: Graphs of specific capacity versus coefficient of transmissibility

confined, semi-confined and water table condition. The dimension of the screened parts in most of the wells drilled by the Ground Water Department and Ingra Consulting Department is uniformly 6 inches diameter. A pumping period of 60 minutes is used for the estimation of transmissibility due to the fact that most of the tests undertaken after the completion of the well were for 60 minutes duration. Some wells were tested for very short periods, others were tested for as long as five hours.

The graphs shown in Figure 43 were used to obtain rough estimates of the transmissibility from corrected specific capacity data shown in Table 11. The coefficient of transmissibility is selected from the point of intersection of the S line and the known specific capacity. The graph of S = 0.001 (semi-confined condition) was used for the estimation of T since it was assumed that the condition over most of the Upper Fars aquifer is semi-confined, leaky as demonstrated by the analysis of the pumping and recovery test data in six wells.

The estimated values of T are plotted in Figure 44 which represents the general pattern of transmissibility over most of the area. This map confirms the general conclusions drawn from the specific capacity map in Figure 43 with the following main variations:-

1 - the two areas of high specific capacity towards the south and southwest of the town of Sinjar extend further north in the transmissibility map.

2 - the contour line representing a value of 100 $m^3/d/m$ specific capacity extends further north beyond the town of Sinjar.

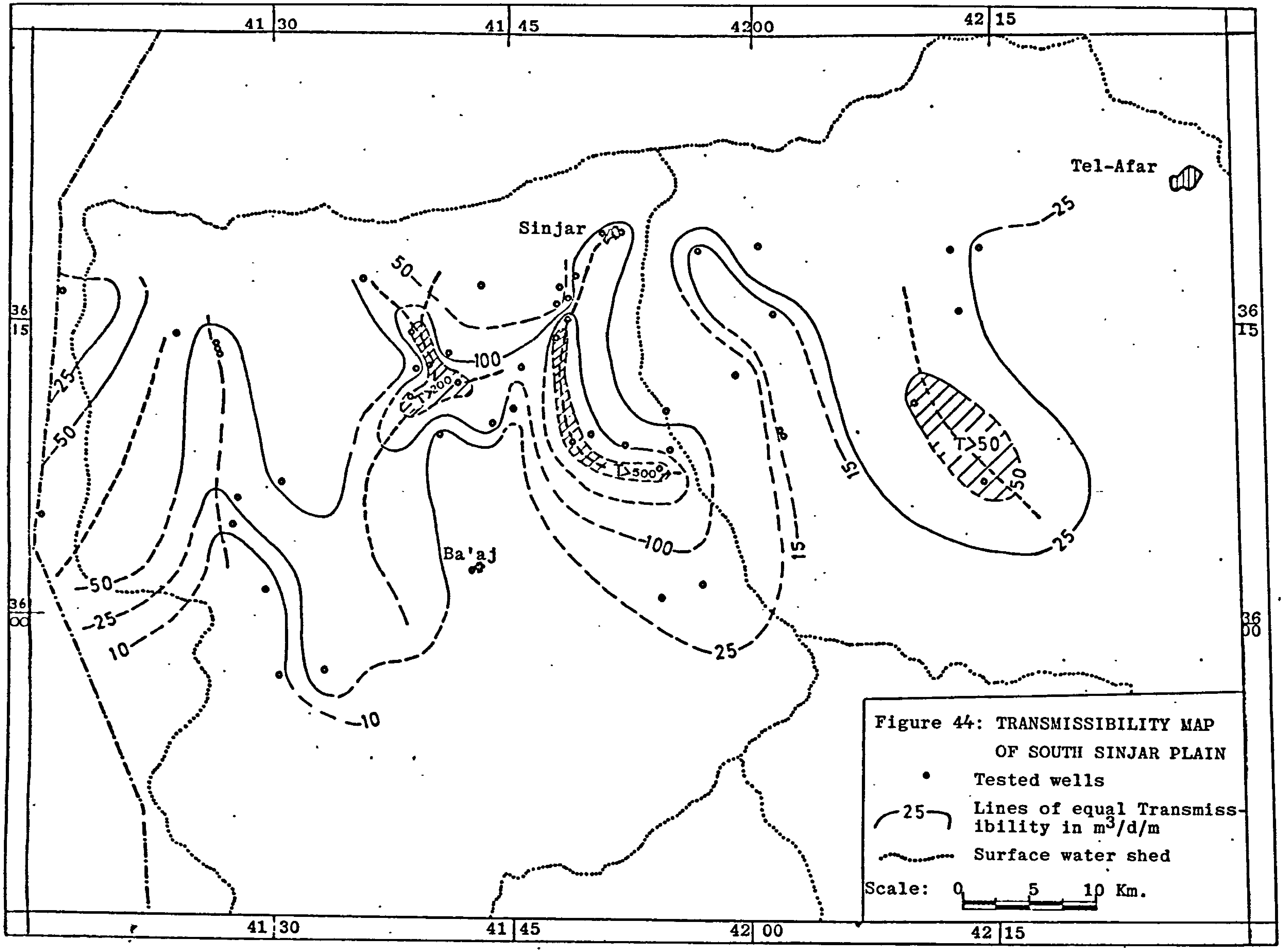


Figure 44: TRANSMISSIBILITY MAP OF SOUTH SINJAR PLAIN

3 - substantial variation in the directions of the main axes of high specific capacity were made in the map of transmissibility.

In general such a map could be useful for locating main abstraction wells and for the evaluation of ground water resources in the area. The permeability of the Upper Fars formation varies from place to place and under different depths. The bulk of water in this formation occurs in the permeable sandy and silty horizons. While the occurrence of water in the Lower Fars formation is principally controlled by the distribution of solution openings, caverns, caves and fractures. The joints developed in the brittle limestone rocks control the water occurrence in the folded structures.

The permeability of the alluvium deposits is relatively high. The flow of ground water in this aquifer takes place through the coarse deposits of limestone boulders, sand and rubble.

3.4 Ground Water movement:

The movement of water underground is one of the important parts of the hydrological cycle. Most of the water-bearing materials are open to the atmosphere, i.e. they receive recharge from precipitation or surface water through infiltration.

The aquifer may serve as a storage reservoir and may contain trapped water or juvenile water. In most cases it serves as a transmission conduit through which water moves from recharge areas to lower areas by the action of gravity or under confining pressure. The discharge of water from the aquifer can either by natural or artificial. Natural flow of ground water may take place towards the bottom of surface bodies of water, wet lands, springs, areas of evapotranspiration or towards other subsurface reservoirs. Artificial discharge of water from an aquifer, by means of wells and other water collecting devices, is the major factor which controls the ground water movements in the developed aquifers. Most rocks and water-bearing materials contain numerous interstices, in which water may move or be stored.

The movement of water through rock interstices is largely dependent on the aquifer properties. According to Darcy's Law the rate of flow of water through a porous medium is proportional to the head loss, inversely proportional to the length of the flow path, and proportional to a coefficient of permeability or hydraulic conductivity of that medium.

Some values of the hydraulic conductivity of various types of materials are given in Table 9 below (after Schoeller, 1962):-

Material	K (m/day)
Clay	10^{-5} to 10^{-7}
Silt	10^{-2}
Fine sand	10^{-1} to 10
Coarse sand	10 to $2x10^{2}$
Gravel	10 to 10^{3} or more

The hydraulic conductivity of dense competent rocks,like the limestone of the Lower Fars aquifer, develops through the interconnected fissures, joints and solution openings. The flow through the dense rock itself is very low due to its fine texture. A considerable quantity of water may flow through the coarsly crystallized or dolomitized limestone. In the areas of sulphur deposits of the Lower Fars structures, hugh quantities of water flow through the secondary, cavernous and recrystallized sulphur bearing limestone and gypsum.

The hydraulic conductivity measured by pumping tests in several wells in Mishraq shows the great variation in the ground water movement through the Lower Fars aquifers. It ranges from less than 1 m/d to over 100 m/d within a distance of less than one kilometer. The hydraulic conductivity of the Upper Fars aquifer is shown in Table 7. It ranges from 0.02 m/d in the silty clay aquifer to about 3 m/d in the sandy and sandy clay aquifer.

The hydraulic conductivity of the alluvial deposits is relatively high, being about 7.5 m/d. However only one test was made in the recent alluvium and the movement of water in the different parts of this aquifer may vary substantially.

3.4.1. Ground water potential lines:

The water table or piezometric surface of an aquifer can be represented by a family of curves termed equipotential lines. Any point on the equipotential line represents the elevation of the water level in a well tapping the aquifer at that point. This elevation of water levels may be referred to the sea level or any datum level.

A map of equipotential lines or ground water contour map may represent one aquifer or more. The generalized water table contour map for the area under study is shown in Figures 21 and 22, for the years of 1954 and 1974 respectively.

The flow of ground water from the higher potential towards the lower one can be represented by a family of flow lines, these being the paths followed by particles of water as they move through an aquifer in the direction of decreasing head. The flow lines intersect the equipotential lines at right angles. The general direction of ground water flow may be appraised by graphical interpretation, the flow lines being constructed perpendicular to the equipotential lines of the different aquifers.

The major aquifers of the Upper Fars formation may collectively be considered as one extensive homogenous aquifer for the study of the general water movement pattern and for the estimation of ground water quantity moving across the aquifer.

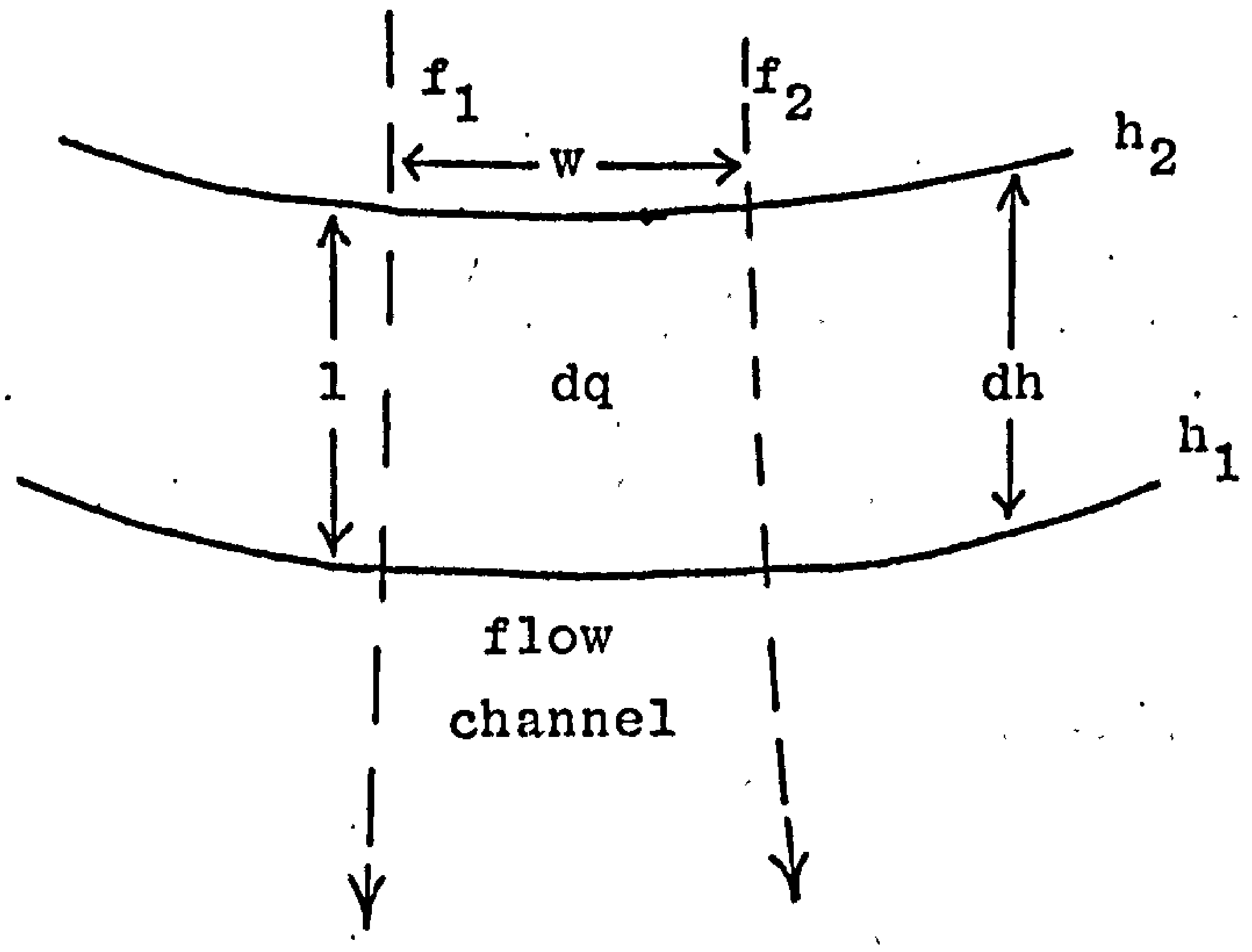
It is unjustified to establish a detailed flow net or equipotential line map for the Lower Fars aquifer given the present limitations of data and its karstic nature.

3.4.2. Flow net analysis:

The general trend of flow of ground water within an aquifer can be interpreted from the ground-water-contour map and indicated by a family of lines or curves. A flow line is the path followed by particles of water as they move through an aquifer in the direction of decreasing head. Intersecting the flow lines at right angles is the set of curves termed equipotential lines, which represent peizometric surface or water-table contours.

The graphical analysis of flow nets is a useful technique for the estimation of quantity of ground water movement and storage within certain aquifers. Such quantitative analysis of flow nets is limited to steady-state two-dimensional flow fields in homogeneous and isotropic aquifers. The aquifer of the Upper Fars formation can be considered as one homogeneous, relatively isotropic, aquifer for the estimation of ground water movement through the area concerned.

The quantity of ground water percolating through a given section (flow channel) of an aquifer delimited by two flow lines and two piezometric surface contours can be calculated by use of the Darcy equation for ground water flow. An idealised square representing the flow lines and equipotential lines is as follows:- (below)



Where

d_q = rate of flow of water through cross section of aquifer limited between two flow lines, in m^3/d

T = coefficient of transmissibility in $m^3/d/m$

w = length of contour between adjacent flow lines in m or width of flow channel in m.

I = hydraulic gradient = $\frac{dh}{l}$

If the flow lines are selected within intervals so that the average length of contour between the limiting flow lines, w is equal to the average width or distance between the contour, the resultant shape is square, i.e. l is equal to w.

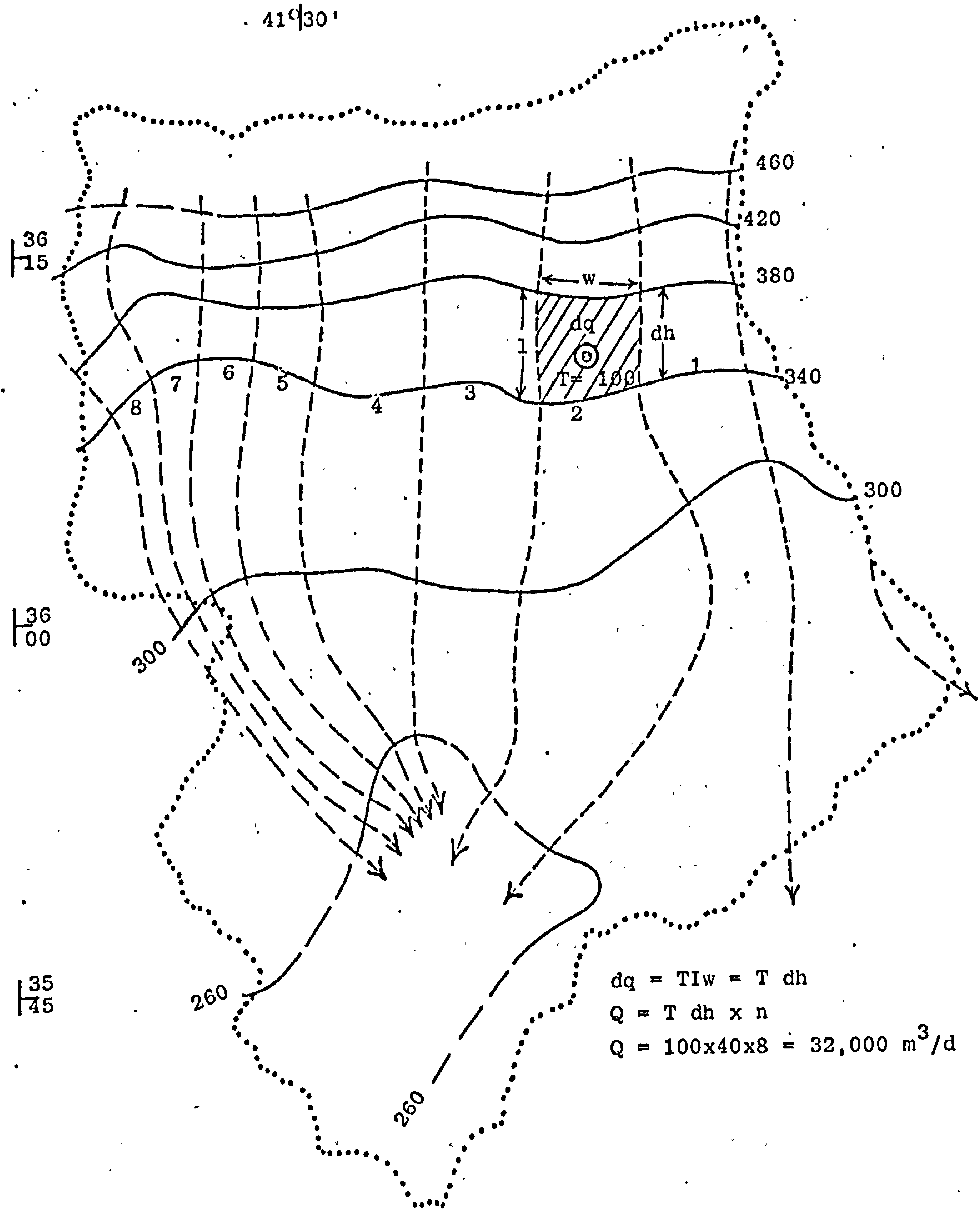
$\therefore$ $d_q = Tdh$ or the rate of flow per each flow channel is equal to the transmissibility times the contour interval

The total amount of ground water flowing through the aquifer is therefore equal to d_q times the number of flow channels, n or

$$Q = dq \times n$$

The flow net for Wadi Al-Ajij was constructed from the ground water contour map of 1974. (see Figure 22). The area selected for an idealized square is where the coefficient of transmissibility is known from the pumping test analysis.

Figure 45 represents the flow net for the Wadi Al-Ajij catchment in which the contour interval is 40 m. and the idealised square was taken in the area of Kirkubat. The coefficient of transmissibility measured from the recovery data in the pumping well of Kirkubat was 115.66 $m^3/d/m$ (see Section 3.3.3). The average value for transmissibility, used for the calculation of the total quantity of ground water flow through the Upper Fars aquifer was 100 $m^3/d/m$. This value is smaller than the calculated value in Kirkubat due to the fact that the transmissibility decreases towards the south, east and west, but is regarded as a realistic figure.



$dq = TIw = T\ dh$

$Q = T\ dh \times n$

$Q = 100 \times 40 \times 8 = 32{,}000\ m^3/d$

Figure 45: Flow net of Wadi Al-Ajij basin

The total rate of ground water flow was calculated from the above formula as follows:-

$$Q = 100 \times 40 \times 8 = 32,000 \text{ m}^3/\text{d}$$

This value represents the flow through the section of the Upper Fars aquifer across Wadi Al-Ajij under natural conditions, i.e. the quantity of ground water flow should be the same in the other parts of the basin which are limited by the same number of flow channels. This value does not take into account the amount of ground water flowing through the overlying alluvial aquifer. The actual amount of ground water flowing through the Upper Fars and the alluvial aquifer would be much higher than the calculated value.

The quantity of ground water flow through the lower parts of Al-Ajij basin were calculated from Figure 46. The idealized square is taken in the area of Al Louyan in which the coefficient of transmissibility were calculated from the step pumping test and was 7.5 $\text{m}^3/\text{d}/\text{m}$. However, the average value of transmissibility used for the calculation of ground water flow across this area is taken equal to $10\text{m}^3/\text{d}/\text{m}$, and the contour interval used for this calculation is 20m. The total amount of ground water flow were calculated from the same formula used in Figure 44.

$$Q = 10 \times 20 \times 9 = 1800 \text{ m}^3/\text{d}$$

The above value of Q is very low compared with the value calculated in the upper part of the basin. This could be due to the gradual alteration of the lithology of the Upper Fars aquifer. It is more clayey towards the south. Also, the value used for the coefficient of transmissibility

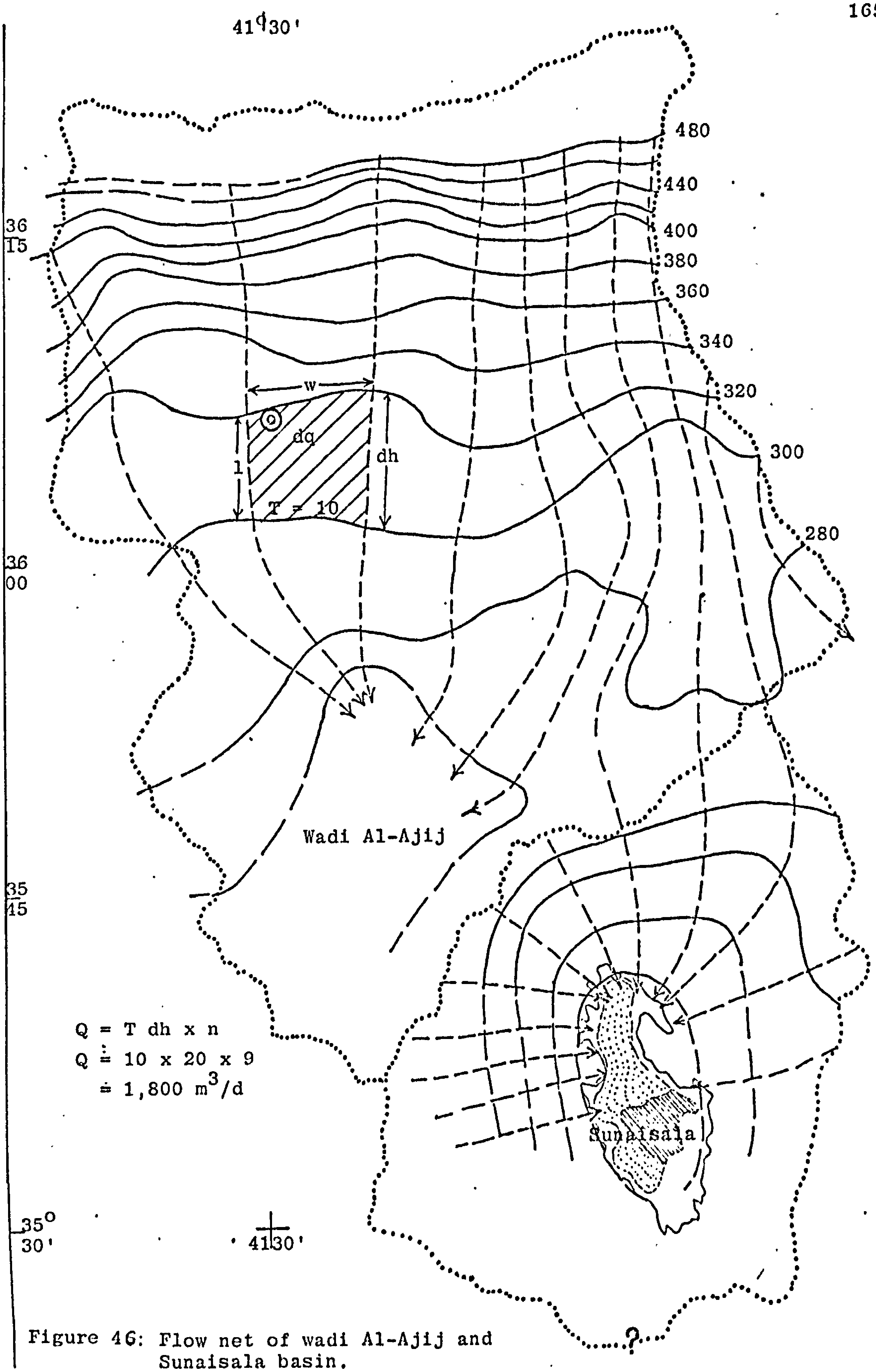


Figure 46: Flow net of wadi Al-Ajij and Sunaisala basin.

is unreliable due to the paucity of data in this part of the study area.

The general trend of ground water flow towards Sunaisala basin is shown in Figure 46. The flow of ground water from Al-Ajij basin towards this basin could be represented by two flow channels. The total amount of ground water flowing through the two flow channels could amount to 400 m^3/d. Being a closed basin, the majority of water flowing towards the centre of this basin is from its own catchment area.

Construction of a flow net for Wadi Tharthar basin is not possible due to the paucity of the data for aquifer characteristics. However, the total amount of ground water flow across this basin could be double the amount flowing across Al-Ajij basin.