HYDROGEOLOGICAL STUDIES IN MUZAFFARNAGAR AND PARTS OF MEERUT DISTRICT, U. P. (INDIA)

By

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This is to certify that the thesis entitled "Hydrogeological Studies in Muzaffarnagar and Parts of Meerut District, U.P.(INDIA)" that is being submitted by Sri Bishan Lal Gupta, M.Sc. for the award of the Ph.D. degree of the University of Roorkee is a result of bonafide research work carried out by him under my supervision and guidance. The results embodied in this thesis have not been submitted for the award of any other degree or diploma of this University. The candidate has completed the specified period (equivalent to 24 months of full time research) in this University.

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(B.L.Gupta)

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"HYDROGEOLOGICAL STUDIES IN MUZAFFARNAGAR AND PARTS OF MEERUT DISTRICT, U.P. INDIA."

ABSTRACT

A systematic study of the ground water conditions in the districts of Muzaffarnagar and parts of Meerut district was taken up in August, 1964 for determining quantitative and qualitative characters of the ground water reservoir of the area. This was of importance from the point of view of further ground water development in the area.

The investigated area (approximately 7,265.28 sq. kms.) is located within the Ganga-Yamuna Doab which is characterised by the alluvial deposits comprised of sand, silt, clay and kankar.

In order to determine the sub-surface geology of the area, the lithological logs of the wells bored in the area were collected and the data were plotted to delineate the various aquifers and aquicludes. The sand samples were subjected to mechanical analysis and the grain size parameters were determined which are of help in defining the aquifer characteristics. These data were also utilised to plot the C.M. patterns which are of help in determining the conditions of sedimentation.

The drainage characteristics viz: bifurcation ratio and drainage density for the area were determined from one inch

Survey of India topo sheets. These data are of help in getting a quantitative picture of drainage and are also of help in getting an idea of the permeability of the surface formations.

Based on the lithological logs, well assembly and water level, two types of aquifers have been delineated in this region. One of these is the shallow aquifer which extends upto a depth of 80 feet which is under water table conditions. The other are the confined aquifers which are located from 100 - 350 feet below the ground surface. The two types of aquifers are seperated by aquitard comprised of clay and kankar. However, the water table for the shallow aquifer is more or less at the same level as the piezometeric surface for the deeper confined aquifers (upto a depth of 350 feet.).

The periodic fluctuations of the water level in the shallow dug wells and the deep tubewells were observed. The observed data are used in preparing the water table and isopiestic maps for the different seasons. These data alongwith rainfall, and river discharge data have been used for statistical correlation purposes. The correlation factor between various variables have been determined and their significance has been explained. The rainfall penetration has also been worked out on the basis of statistical analysis of rainfall and water level data.

Long range pump tests were carried out from 15 tubewells and both the drawdown and the recovery phases were studied. The data are used to determine the aquifer constants by various methods. The aquifer characteristics have given a complex and interesting picture. This information was utilised for further detailed analysis and it is concluded that the deeper aquifers in the area are under leaky confined conditions.

The quantitative assessment for both the shallow and the confined ground water reservoirs was made and based on this the possibility fof further ground water development in the area has been expressed.

A good emphasis during this work was also given to the chemical characters of ground waters. The water samples were collected from both the shallow and the deeper aquifers for the chemical analysis. Samples were collected twice in a year i.e. in June and again in October so that seasonal variation, if any, in the quality may also be determined. The data have been utilised in classifying the water for determining their suitability for irrigational purposes. It has been found that there are differences in the chemical quality of water from shallow to deep aquifers. There are seasonal variations in the chemical quality and also a lateral variation in the direction of flow. These differences and variations have been explained.

CHAPTER 1

INTRODUCTION

Use of ground water is almost as old as human Civilisation. Wells unearthed among the ruins of Mohenjodaro bear testimony of the already advanced state of knowledge of ground water in Indian sub-continent some 5,000 years ago. But in a country like India with vagaries of monsoons, many towns and villages have to depend on ground water supplies. In the present condition of acute food shortage and the stress on more extensive and intensive agriculture, India's prime need is for more water for irrigation. In India the total irrigated area is approximately 19 % of the total land under cultivation. This underlines the extent of the country's continued dependence on rainfall and the wide spread failure of crops which inevitably follows when the "gamble in rain" does not pay off. A recent example has been provided by the unprecedented drought and near famine conditions which had prevailed in Bihar and Eastern parts of Uttar Pradesh and affected the lives of millions of people in the rural parts of Uttar Pradesh and Bihar. The solution of such a problem lies in the Nation's determined exploitation and management of ground water as the country can not depend on surface water resources only. The problem is not only to find ground water but also to know as how best it could be used for agricultural, industrial and drinking purposes.

The ever increasing demand of ground water and the authors association with the Ground Water Division of the U.P. Irrigation Research Institute*, inspired to take up a systematic study of the ground water conditions in parts of the Indo-Gangetic Alluvium of Muzaffarnagar and Meerut districts of Uttar Pradesh (Plate 1.1).

LOCATION OF THE AREA

The area lies in the quarter inch topo sheet Nos.53 G, 53 H, 53 K and 53 L of the Survey of India. It is in between the longitudes E 77°4' to 78°6'41" and latitudes N 28°45' to 29°45'. The area is bounded by the river Ganga on the east and the Yamuna on the west and therefore, forms a part of the Ganga-Yamuna Doab** within the Indo-Gangetic plain of India. Towards the north the area is limited by the district boundary of Muzaffarnagar with Saharanpur. In the south it is partly bounded by the river Kali and partly by the Hapur-Garhmukteshwar road and the Bagpat-Meerut Road.

Climate

The area has a moderate type of climate. The winter season begins by the middle of October and extends upto March. The hottest summer months are May and June. The rainy season extends from the middle of June to the middle of October. The maximum temperature of the region varies from 40°C to 48°C and the minimum temperature, experienced during extreme cold i.e. the months of January or February reaches as low as -2°C.

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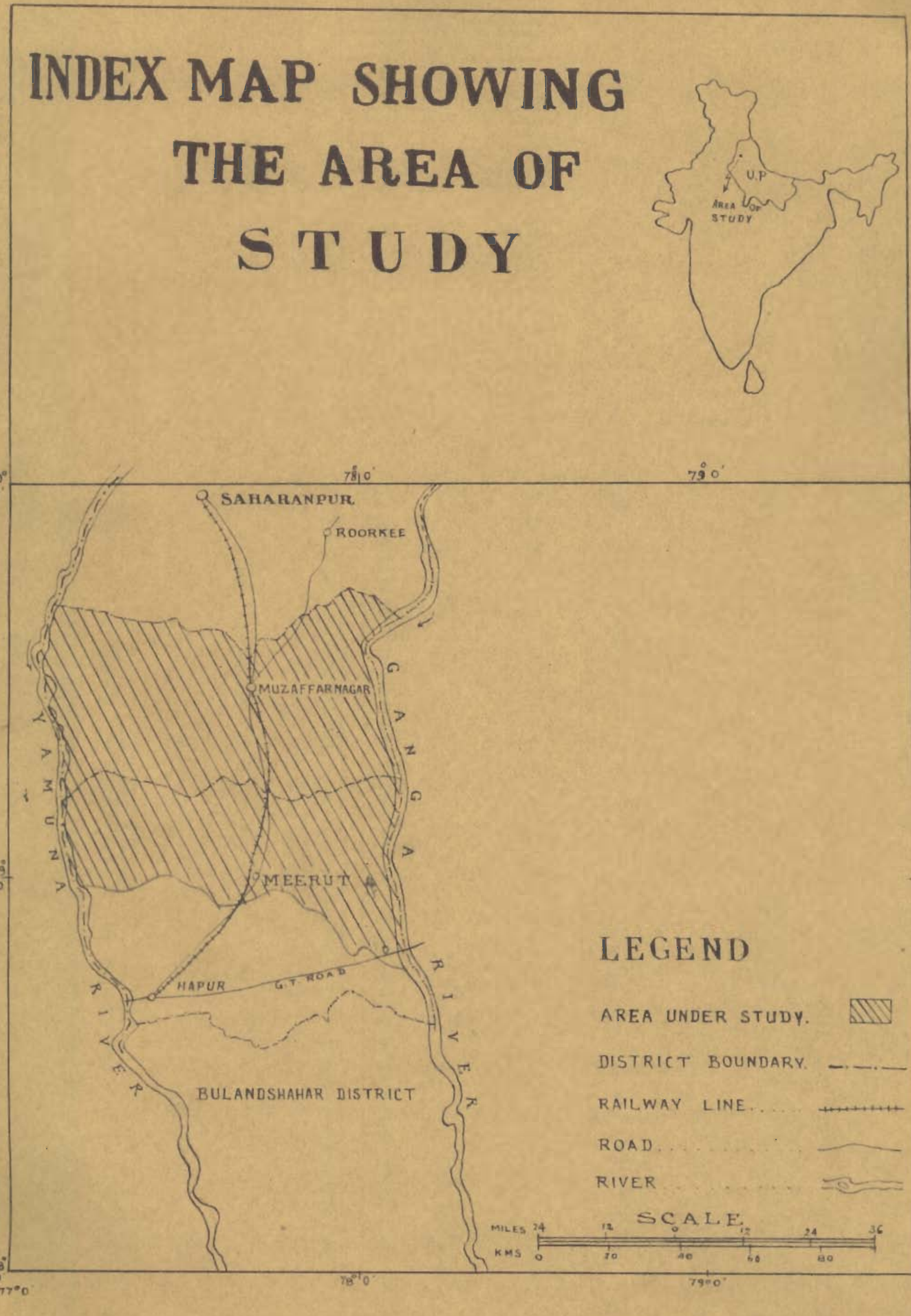
* at present with the Rajasthan Ground Water Board, Jodhpur.

** Alluvial area lying between two major river courses.

PLATE 1.1

INDEX MAP SHOWING THE AREA OF STUDY



Rainfall

The normal annual rainfall of the area varies from 30" - 35" most of which falls during the months of June - October. However, there are also occasional rains (2" to 3") during the months of December and January. A detailed account of yearly rainfall is given in Table 5.16.

Flora and Fauna

The plains of Muzaffarnagar and Meerut are parts of Indo-Gangetic Plain and forms one of the most culturable land. Both these districts are very important from agricultural point of view as the irrigation facilities, both by canal and tubewells, are available. Wheat and gram are the two important crops sown during winters while maize is another cash crop of the rainy season. Besides, these sugarcane forms the most important cash crop of the area to feed the battery of sugar factories almost at every 10 miles.

The area is also rich in the production of fruits as there are numerous big gardens in which mangoes and lichi are grown on a large scale. The choicest varieties of mangoes from Meerut and Muzaffarnagar districts are also exported to foreign countries. The area is however, not important from the point of view of forest wealth, but Sisham, Babul and Neem are the important type of trees met within the area.

The wild life in the area is represented by barking deer (Muntiacus mutgak), spotted deer (Axis axis), peacock (Panaunicolour) and fowls (Gallus gallus).

Communication in the area.

The area under investigation is one of the best developed areas of western Uttar Pradesh. Meerut and Muzaffarnagar are the two most important district headquarter-towns of the area which lie on the main highway from Delhi to Dehradun. Besides these, there are a number of important small towns such as Daurala, Sakauti, Khatauli, Shamli, Budhana, Bagpat and Garhmukteshwar etc. The area is well connected by railways and also by the numerous metalled and unmetalled roads across the country side. Almost all the villages are connected either by a fair-weather road or a cart track.

PREVIOUS WORK

In the alluvial tracts of North India, systematic studies of ground water dates back as long as to the early thirties, when Sir William Stampe[1] started large scale tubewell scheme for the irrigation purposes in the Ganges-Valley of Uttar Pradesh.

Auden[2] also formulated a scheme for the development of ground water by means of tubewells in Uttar Pradesh. In 1936 Machenzie Taylor[3] suggested sinking of 1.5 cusecs tubewells in parts of Indo-Gangetic alluvium of Uttar Pradesh without any depletion of ground water table. Nautiyal[4] carried out investigations on the ground water supplies in the Tarai-Bhabar belt lying in the district of Nainital. Bhattacharya et al[5] approached the problem of depletion of water table in the Western parts of Ganga-Yamuna Doab and derived an empirical formula for the rainfall penetration.

Mathur[6] carried out ground water investigations in the district of Meerut. This work was submitted for the award of Ph.D. degree of Banaras Hindu University in the year 1957-58. The main emphasis of his work was on the behaviour of regional water table and he did not study the hydrologic properties of the aquifers or the quality of the ground water. In 1958, Pathak[7] carried out field investigations in the Indo-Gangetic alluvium of Uttar Pradesh for the selection of suitable sites for ground water development. G.C. Taylor[8] has attempted the delineation of various ground water provinces of India and according to this the area under study forms the northern fringes of the 'axial belt' of the Ganges Brahmaputra Alluvial province. Pathak[9] also carried out work on the ground water conditions in Azamgarh-Ballia districts of eastern Uttar Pradesh and later submitted the same for the award of Ph.D. degree of Banaras Hindu University.

Ahmed[10] has carried out certain short term investigations in Saharanpur district which lie to the north of the area under study. The officers of the U.P. Irrigation Research Institute, Roorkee viz. Dwivedi and Gupta[11] and Daya Prakash et al[12]. have also carried out studies of the behaviour of ground water table in parts of the Ganga-Yamuna Doab. The chemical quality investigations of ground water from the district Bijnor were carried out by Chaturvedi and Mithal[13].

In 1965 Raghava Rao[14] submitted a thesis entitled 'Hydrogeological Studies of alluvial areas in parts of Saharanpur district, U.P.' for the award of the Ph.D. Degree of the University of Roorkee. On the basis of the pump test data from

Muzaffarnagar district, Singhal and Gupta[15] have concluded that the deeper aquifers of the area are under leaky confined conditions. Similar conclusions were derived by Chaturvedi and Pathak[16] for the district of Aligarh and Mathura but for Muzaffarnagar and Meerut districts their conclusions were different (Chaturvedi and Pathak[17]).

In 1966 Paul Jones[18] submitted a programme of ground water development and assessment in parts of Uttar Pradesh to the Government of India.

In recent years, systematic ground water investigations, in some selected regions of Uttar Pradesh, have been taken up by the U.N.D.P., Exploratory Tubewells Organisation, Geological Survey of India and U.P. Irrigation Research Institute.

METHODS OF INVESTIGATIONS

The field work was started during the year 1963 and continued till the end of 1965, which consisted of the observation and collectionof water level data in open wells and tubewells for the months of May and October each year. During October 1964 and June 1965, about 100 water samples from tubewells which tap the confined aquifers were chemically analysed to determine the geochemistry of the water and also their suitability for agricultural purposes. In addition to these 20 water samples were also collected from the dug wells which tap the shallow ground water reservoir which is under water table conditions and these were also analysed. About 80 sand samples for the various tubewells located in Meerut and Muzaffarnagar districts were collected and mechanically analysed to determine the various grain size parameters. Long duration

Aquifer Performance Tests were carried out from 15 tubewells in order to determine the hydrological properties i.e. Coefficient of Transmissibility and Coefficient of storage of the aquifers.

Besides the above field work, data about the rainfall, river discharge, pumping hours and lithological logs of the bore holes of the State tubewells were collected and a ground water inventory has been prepared.

One inch Survey of India topo sheets were utilised for the study of drainage characteristics of the area which could not be submitted alongwith this work as the same are restricted.

SCOPE OF THE PRESENT WORK

So far detailed ground water investigations have not been carried out in the country. In recent years the Indo-Gangetic alluvium of India, which is one of the most promising areas for the ground water development, has attracted the attention of various geologists and hydrologists. The Indo-Gangetic Plain consists of unconsolidated fluviatile formations and can be divided into three roughly parallel belts which are known from north to south as the Bhabar, Tarai and the Axial belts according to Taylor[8]. The present area of study i.e. the districts of Muzaffarnagar and parts of Meerut form the Northern fringes of the Axial belt. The author has selected the area in order to evaluate the geohydrological characters of the aquifer and also to determine quantitatively the ground water potential of the area and the quality of water. The above study has been divided into various chapters from 1 to 8.

The present chapter 1 deals mainly with the introductory aspects such as location of the area, communication, previous work, methods of investigations and the scope of the present study. The second chapter gives an account of geomorphology and subsurface geology of the area. The aquifer material (sand) has been mechanically analysed and an attempt has been made to determine the conditions of deposition. On the basis of geological and hydrological characters, two kind of aquifers have been demarcated i.e. the shallow aquifers and the deeper aquifers which are separated from each other by confining layers of clay and '<u>kankar</u>' (a nodular formation rich in $CaCO_3$). The third chapter deals with the ground water conditions. The disposition of ground water table in the shallow ground water reservoir and of the piezometric surface for deeper aquifers have been shown in Plates 3.1-3.9 It has been further shown that the shallow aquifer is under water table condition and the deeper ones are under confined conditions. With the help of water table contours, seepage pattern has been described.

Chapter 4 deals with the various geohydrological parameters such as coefficient of transmissibility, coefficient of permeability and the storage coefficient of the aquifers. These were computed from the test data using the Theis, Theis-Jacob and Hantush-methods. Taking into consideration the various possibilities it has been concluded that the deeper aquifers are of leaky confined character.

Chapter 5 deals with the analysis of shallow ground water reservoir levels with those of the other factors controlling the ground water regime in the area. The water level data have been subjected to analysis by meansof statistical methods which are in vogue to establish the relationship between the various dependencies controlling the ground water regime.

The chemical quality of ground waters has been dealt in Chapter 6 under the two broad head viz. (i) the chemical quality of shallow ground water reservoir and that (ii) of deeper aquifers. It has been established in this chapter that all waters from the deeper aquifers are suitable for agricultural use. The author has used the various graphical methods to show the chemical/characteristics by means of diagrams such as Piper's diagram, ratio maps etc. In this chapter the seasonal variation in the checmical quality of water from deeper aquifers has also been established. It has also been established that the quality of ground water does not remain constant in the direction of flow.

In Chapter 7 quantitative assessment for ground water has been carried out for the shallow aquifers for the year 1958, 1962 and 1965 and for the deeper aquifers an attempt has been made to find out the total draft due to pumpage and the fluctuations of the piezometric surface.

Lastly, in Chapter 8 a summary of the work carried out by the author during the course of these investigations has been given.

CHAPTER 2

GEOMORPHOLOGY & GEOLOGY OF THE AREA

PHYSIOGRAPHY

The district of Muzaffarnagar and Meerut is a part of the great Indo-Gangetic Plain which occupies roughly an area of 3,00,000 sq.miles. This plain is almost devoid of any significant relief features and is composed of unconsolidated alluvial deposits. The alluvium is composed of the materials derived from the Himalayan ranges by fluviatile action, and which have been subsequently deposited southwards in a depression called the Indo-Gangetic Trough.

The districts of Muzaffarnagar and Meerut present an appearance of a featureless plain. The erosional processes could not, carve out distinct relief features out of the unconsolidated alluvium of the plain. The area slopes down gently from north to south. The average elevation above mean sea level of any point along the northern boundary is about 815.0 feet, while the average elevation along the southern boundary is about 716.0 feet, whereas the distance between the northern and the southern boundary is approximately 50 miles. This gives an average gradient of less than 2.0 ft. per mile for the plain, which, as mentioned above, slopes down in a north tosouth direction. The physiography of the area is marked by the following units which are characteristic of a river flood plain:

1. The River Channel
2. Oxbow lakes
3. Point Bars

At few places in the area, the occurrence of slightly raised mounds of sand, locally known as Bhurs, are seen (Plate 2.1). They vary in height from 20-30 ft. above the ground surface and are composed of brownish coloured sand. In the toposheets these are shown with brown dots. At some places such as Jalalpur, Mundati, Kamatpur, Piplikhera and Ajrara etc. they are found on the convex side of the river curves thereby resembling point bars. However, they are much modified in their shape and alignment by the winds which blow especially during the summers. They are very well seen near Nera-nala on Muzaffarnagar-Meerut Road.

Drainage

The two most important rivers of the area are the Ganga and the Yamuna which flow from north to south. The river Ganga and the Yamuna forms the eastern and the western boundaries of the area respectively. In addition to these other important rivers flowing in the area are the Krishni, the Hindon, the Kali-Nadi (east) and the Kali Nadi west. The Kali Nadi (west) and the Krishni Nadi are the two major tributeries of the Hindon river. The river Kali (west) joins the river Hindon in the Muzaffarnagar district at a place known as Atali while the river Krishni joins the river Hindon in the district of Meerut at Barnawa wherefrom it attains the shape of a major

Plate 2.1

A view of the sandy mounds (Bhurs) on the crossing of Nera-Nala and Muzaffarnagar - Meerut Road river of the area. A few of the important _nalas_ worth mentioning in the area are _Choiya Nala_, _Nara-Nala_ and _Abu-Nala_ which brings at times a great calamity to the towns of Muzaffarnagar and Meerut. All these streams are of perennial character.

The discharge of these rivers varies in different months. The discharge of the river Ganga at Raiwala near Hardwar, which is about 20 miles north the present area, varies from 50,000 cusecs during the month of January to 90,000 cusecs in August while that of river Yamuna varies from about, 4,000 cusecs to about 50,000 at Tajewala. The discharge of the Hindon, the Krishni, the Kali Nadi and the Kali east varies from about 300-2,000, 200-3,000, 200-800 and 300-3,000 cusecs respectively.

The river Ganga emerges out into plains at a place known as Hardwar and thereafter flows almost in a plain country. The river Yamuna emerges out into plains at a place known as Haripur in Dehradun. In the western half the drainage of the area is almost parallel to the Yamuna while in the eastern half it runs parallel to the river Ganga. Although it is very difficult to infer as what could have been the drainage pattern at the time when the alluvial sediments were deposited in the area, but it is certain that thse two major rivers had frequently changed their courses in the past. The important rivers of the area are effluent in nature i.e. the ground water is discharged into the riversin the area. The river Ganga and Yamuna are of braided character as is indicated by the presence of bars of silt and fine sand at the time of low flow. These channels are in the process of aggrading. According to Leopold et al[19] it is true that brading is a pattern often associated with aggradation, but braided channels may represent equilibrium pattern in the transport of the available discharge and load. These two rivers also show wide meandering belts and at places oxbow lakes are formed. One such lake is seen by the side of the Ganga near Tughlakpur while the other is seen by the side of river Yamuna near the town of Kairana. These have been filled up by the finer sediments and have formed swampy regions which occupy at least an area of 30 - 40 sq.miles at Tughlakpur and about 2 sq.miles near Kairana - (Plate 2.2).

The East-West shift of the river Ganga is indicated by the numerous oxbow lakes and old abondoned channel which is locally known as Burhi Ganga (Old Ganga). The Burhi Ganga meets the present course of river Ganga near Garhmukteshwar.

Oxbow lakes represent the cut off portions of meander bands and they represent therefore the areas through which the rivers in past had flowed. These type of oxbow lakes are quite common in this area both along the rivers Ganga and Yamuna. The largest one occupies an area of 30 - 40 sq.miles and is seen in north eastern region. These lakes are often separated from the present day river courses by marshy lands in which thick deposits of clay and fine silt were made. They usually support luxuriant vegetation.

Plate 2.2

A view of Oxbow Lake on the left bank of river Yamuna near the town of Kairana

Besides the above natural drainage courses, the important irrigation systems in the area are formed by the Upper Ganga Canal, the Eastern Yamuna canal and the Anupshahr Branch. The Eastern Yamuna canal was constructed during the Mughal period and the same was remodelled in the year 1832, while the Ganga canal is more than a hundred year old. This system was completed in the year 1854.

DRAINAGE BASIN ANALYSIS

Untill recently the geomorphologists only worked on the descriptive basis and were concerned only with the history of evolution of land forms as geological features. In the year 1945 Horton[20] gave great emphasis and realised that only the descriptive analysis has very little value in the practical field and therefore some geomorphologists have attempted the quantification of land forms description.

The first step in the drainage basin analysis is the designation of stream orders, on a channel net work map including all intermittent and permanent flow lines located in clearly defined valleys (Strahler[21]). The smallest fingertip tributaries are designated order 1; where two first two order channels join, a channel segment of order 2 is formed; where two of order 2 join, a segment of order 3 is formed; and so on and so forth. The trunk stream through which all discharge of water and sediment passes is therefore, the stream of highest order.

DRAINAGE DENSITY

Drainage density of a basin may be defined as the sum of the channel lengths divided by basin area and may be expressed in miles/sq.miles i.e.

$$Dd = \frac{\text{Sum of the channel lengths}}{\text{Basin area}} \quad .. \; .. \; (2.1)$$

In general, as the drainage density number increases, the size of individual drainage units, such as the first-order drainage basin, decreases proportionately.

Measurement of drainage density is made from a map with the help of planimeter and chartometer. According to Leopold et al[19] the detail of a drainage net is dependent on the scale of the map as in a large scale map the shortest channel would also be seen.

The drainage density values varying from 1 to 1000 miles/sq.mile have been determined from idifferent geological, topo graphical and climatic regions (Leopold[19]). DeWiest[22] has quoted values of Dd from less than 1 mile/sq.mile for a poorly drained basin to about 5 miles/sq.mile for well drained basins.

In the present study, Survey of Indid one inch topo-sheets (53 G/2, 53 G/3, G/4, G/6, G/7, G/8, G/10, G/11, G/12, K/2, K/3 and K/4) were used to determine the drainage characteristic i.e. drainage density and bifurcation ratio. The value of drainage density in the area works out to be of the order of 0.77 mile/sq.mile. This value is low in comparison to those given by Leopold et al[19].

The low values of drainage density are usually indicative of high permeability of sub-soil material (Strahler[21]). However, another factor which has to be taken into account is the small scale of the map which was used in the present study. Unfortunately aerial photographs of the area were not available and therefore, it is doubtful whether all those streams which exists in nature are taken into consideration for the above calculations.

BIFURCATION RATIO

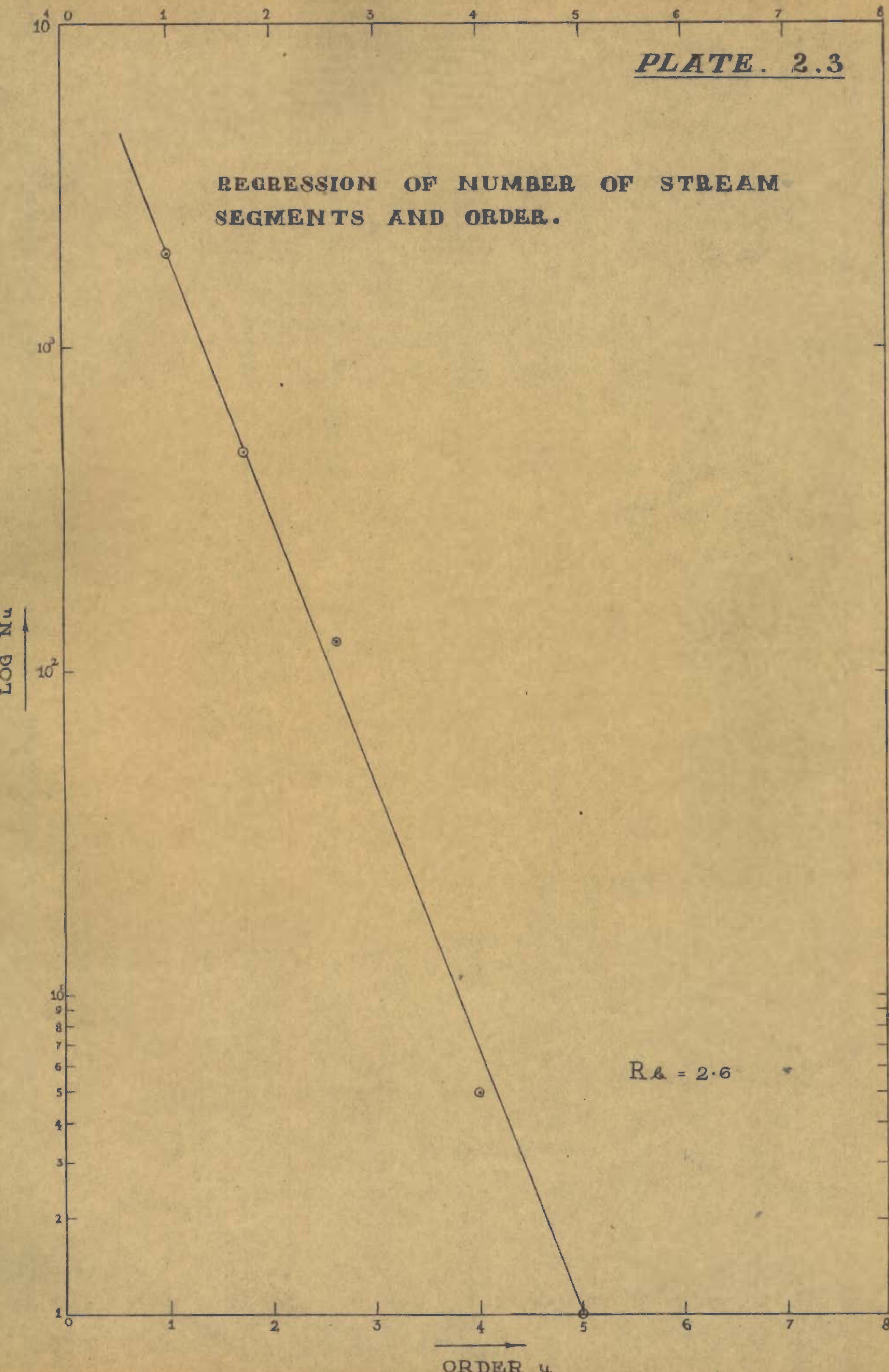
The ratio of the number of segments of a given order Nu to the number of segments of the higher order Nu + 1 is known as bifurcation ratio(R_b) which is expressed by the following equation:

$$R_b = \frac{N_u}{N_{u+1}} \quad \ldots\ldots\ldots\ldots (2.2)$$

Bifurcation ratio characteristically ranges between 3.0 and 5.0 for water sheds in which the geological structures do not distort the drainage pattern (Strahler[23]). The minimum possible value of 2.0 is rarely obtained under natural conditions. Since the bifurcation ratio is a dimensionless property, and because drainage systems in homogeneous material tend to show geometrical similarity, and as such the ratio will show only a little variation from region to region.

For determining the birfucation ratio, a graph has been prepared on a semilograrithmic paper where values of order u have been plotted against log Nu. A straight line was fitted through these plottings (Plate 2.3) and the bifurcation ratio

PLATE. 2.3


REGRESSION OF NUMBER OF STREAM SEGMENTS AND ORDER.
LOG Nu
ORDER u
Rb = 2·6
0
1
2
3
4
5
6
7
8
10^4
10^3
10^2
10^1
9
8
7
6
5
4
3
2
1

was determined which comes to be 2.6 . This value of bifurcation ratio may be taken to be quite representative of the drainage basin under study.

GENERAL GEOLOGY

The area forms a part of the great Indo-Gangetic Plain which separates the Peninsular India from the extra-Peninsular region of the Himalayan ranges. The entire area of this plain is composed of the Pleistocene and the sub-recent alluvium which has been deposited south of the Himalayan ranges by the various rivers emergning out of them. The deposition of the alluvium began after the final upheaval of the mountains and it has continued all through the Pleistocene upto the present time. The past geological records of this region lie completely buried underneath the thick mantle of the alluvium. Therefore, the geology of this region is not fully known.

According to Krishnan[24] the deposition in the Indo-Gangetic alluvium belongs to the last chapter of the earths history and conceals beneath it the northern fringes of the Peninsular formations and the southern fringes of the extra peninsular formations.

Edward Suess (1953) has put forward the view that the depression in which the deposition of the alluvium occured was a "Fore deep" which developed as a downwarp in front of the high crust waves of the Himalayan ranges as these waves were checked in their southward advance by the stable land mass of

Peninsular India. Thus, the formation of this depression was intimately connected with the elevation of the Himalayas. In the opinion of Sir Sydney Burrard the Indo-Gangetic Plain is believed to have occupied a deep "Rift valley". This view has, however, not found much support amongs the geologists. A third and a more recent view regards this region as a 'Sag' in the crust which was formed between the northward drifting Indian continent and the extra-peninsular region when the latter was elevated into a mountain system.

As pointed out above, the alluvial deposits of the Indo-Gangetic Plain have been derived from the Himalāyan ranges by the numerous rivers emerging from these ranges during a period of great gradational activity. The continuous upheaving of the mountains must have rejuvenated the streams again and again thus multiplying their eroding and transporting capacities. The enormous thickness of the alluvial deposits has been accounted for by assuming that the deposition of the sediments occured in a slowly sinking region so that the deposition kept pace with the subsidence.

Taylor[8] has divided the Indo-Gangetic Plain into three belts which are named as Bhabar, Tarai and the Axial Belt from north to south.

The Bhabar forms a belt of 6 - 8 miles wide along the foot hill slopes of the Himalayan front. The alluvium of Bhabar is made up of unconsolidated sand-boulder and clay-boulder bed. The northern boundary of this belt is in contact with Siwalk hill ranges and the southern limit is generally the spring line which demarcates the northern boundary of the Tarai belt. The Tarai is a belt some 5 - 10 miles wide parallel to the Bhabar and is chiefly composed of clays, sandy clays, sands and occassional thin lenses of gravels.

The lower slopes of Tarai merge imperceptibly with the Axial belt, which comprises the bulk of the alluvium laid by the larger streams of the Ganga and Brahmaputra system. The present area forms the northern fringes of the Axial belt.

The total thickness of the alluvium is not definitely known. However, the thickness of the alluvium is variable, with a maximum exceeding 8,000 or even 9,000 ft.

Geological classification of the alluvial deposits

There are no distincly marked stages in the deposition of the alluvium. The whole of the alluvium is, in fact, one continuous and conformable series of fluviatile and sub-aerial deposits whose accumulation is, to some extent, still in progress. The alluvium consists chiefly of beds of clay either sandy or calcareous - corresponding to the silts, mud and sand of the modern rivers. Besides these, beds of gravel, compact sand, kankar (a nodular formation rich in $CaCO_3$) etc. are also met with. The classification of the alluvium of the Indo-Gangetic Plain (Table 2.1) is based on the presence of extinct or living species of mammals in these deposits (Wadia[25]).

TABLE 2.1

1. Older Alluvium:	Bhangar of the Ganges valley. Fossil of Elphas antiques, Equus namidicus, Mainis gigantea, extinct species of Rhinoceros, Hippopotami etc.
2. Newer Alluvium:	Khadar of the Punjab. Fossils, chiefly living species, including relics of Man.

3. Deltaic deposits of the Indus, the Ganges etc. Recent.

--- Unconformity ---

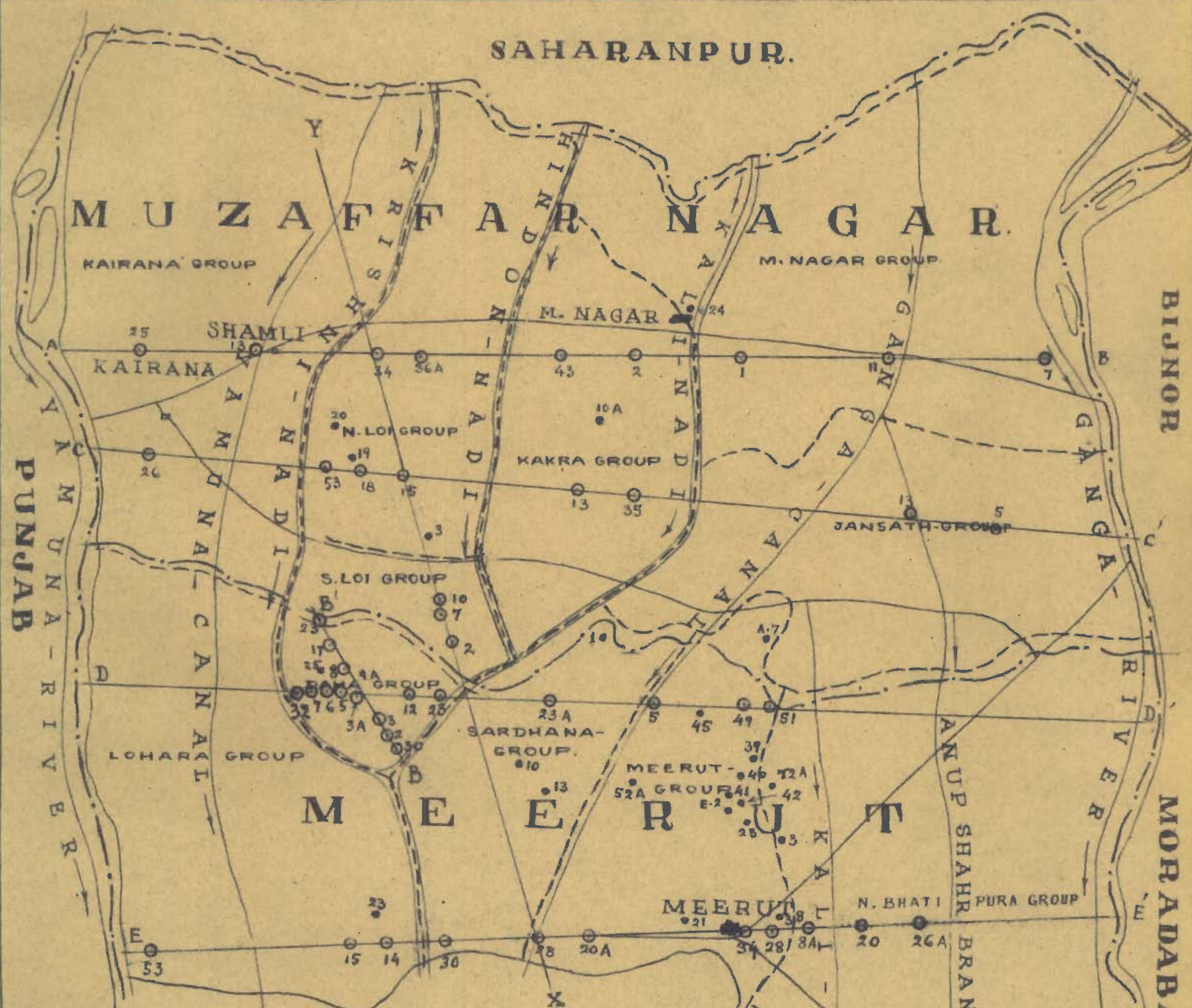
Rocks of unknown age:	Possibly the extension of Archaean, Purana and Gondwanas of the Peninsula and of Nummulitic, Murree and Siwalik of the sub-Himalayas.

Sub-surface geology of the area

An idea of the sub-surface geology can be obtained either by a well log or from other excavations, either artificial or natural, for instance, mine shafts, rail road cuttings or gorges cut by streams. However, no deep excavations of these types occur in Muzzafarnagar-Meerut districts. Therefore, under these circumstances the well logs remain the only source to obtain an idea of sub-surface geology, and as such six cross sections based on bore logs have been prepared. Four of these profiles are in E - W direction i.e. more or less at right angles to the principal river courses which are responsible for the deposition of the alluvium inthis area. The remaining two profiles are in NE - SW direction. The lines of these profiles are shown in (Plate 2.4).

PLATE 2.4

LOCATION OF TUBEWELLS USED FOR GRAIN SIZE ANALYSIS AND LINES OF VARIOUS CROSS – SECTIONS.



LEGEND

1. DISTRICT BOUNDARY —·—
2. GROUP BOUNDARY ----
3. ROADS ------
4. X-LINES ... A———B
5. TUBE WELLS WITH NOS. .... ⊖²
6. TUBE WELLS USED FOR GRAINSIZE ANALYSIS WITH NOS.... •¹⁰

SCALE 8 0 2 4 6 8 MILES

The important lithological units are clay, sand and kankar. The other minor constitutents of these sediments are gravel (Bajri) and Lehel. For the purpose of correlation of the sub-surface geology of the area minor bands of sand or clay, or sand and clay have not been shown separately in the present discussion. With the exception of one or two wells most of the tubewells in the area are more than 300 ft. deep and as such the formations encountered upto that level are discussed in this Chapter.

The clays of the area are generally grey to brown in colour. They are hard and plastic. These clays are generally associated with Kankar.

The term Kankar is given to a nodular formation rich in $CaCO_3$. The individual nodules vary in diameter from half an inch to three inch. It is commonly met in the bore holes of the Muzaffarnagar-Meerut area associated with clay. The Kankar horizons, perhaps, represent the 'B' horizon of the ancient soil profiles. This formation along with the associated clays form the aquicludes or aquitards.

Gravel or Bajri encountered in the bore holes at places are nothing but sobrounded small-pebbles in various colours of pink, grey and white. These are quite hard and compact and are usually, composed of quartzite. The term Lehel is commonly used by the driller for the clay mixed with silt. It varies in colour from grey to dark grey.

The sands are mostly grey to white in colour. The grain size parameters of these sands, were also determined and a detailed description of the same is given in the latter part of this chapter.

Associated with the above lithological units at certain places in the area, the ground surface is covered with a whitish powdery material which is locally known as Reh. Such an occurence is seen along the Muzaffarnagar-Meerut road. The average chemical composition of Reh is given in Table 2.2.

Table 2.2 Chemical composition of Reh (after Brown and Dey[26])

Constituents		Percentage
Sodium Carbonate	--	4.68
Sodium Bicarbonate	--	3.96
Sodium sulphate	--	1.19
Sodium chloride	--	3.88

Auden[27] has given an account of the occurrence and origin of Reh soils in India. Reh is formed due to effloresence and is characteristic of those areas which have a high water table and a low hydraulic gradient, with a corresponding sluggish responsive movement of both ground and surface water. When these exist in a monsoon climate which permits intensive evaporation during the dry season, capillary action soon brings the stagnant solutions to the surface, where their contents crystallize and reh is formed.

CORRELATION OF SUBSURFACE FORMATIONS & PATTERN OF SEDIMENTATION

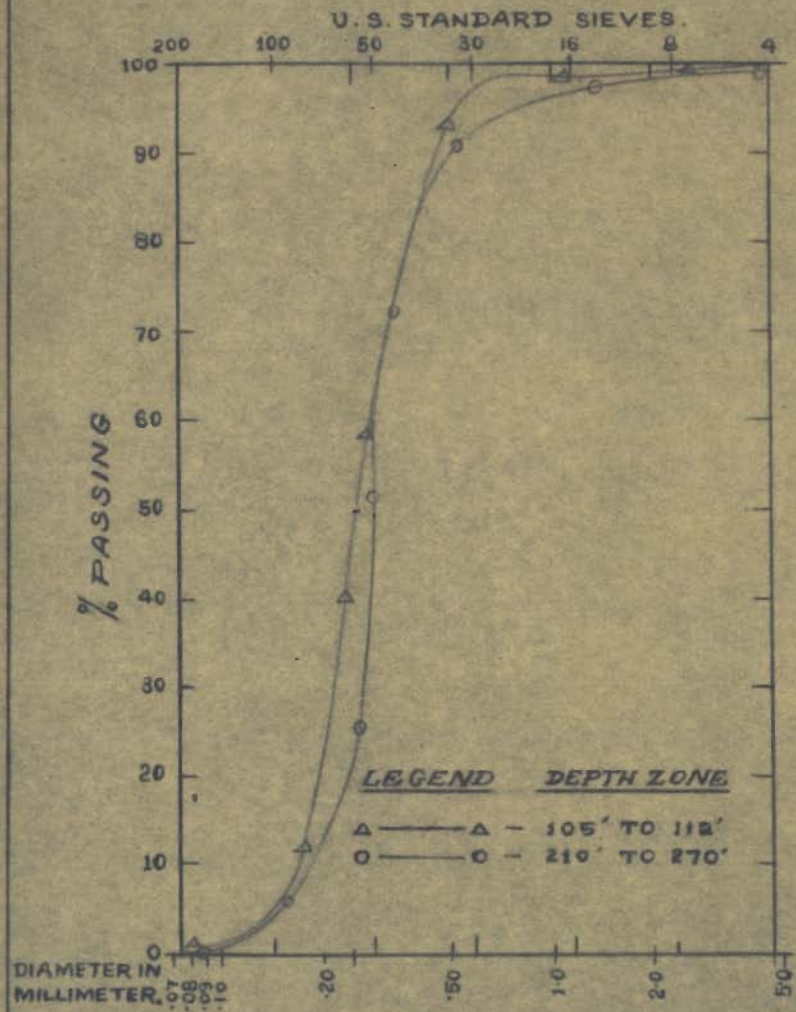
The different lithological cross sections (Plate 2.5 to 2.10) indicate that in general the top layer consists of clay which is as thick as 20 - 25 feet and thereafter sand is encountered which forms the shallow ground water reservoir of the area. Thereafter again a thick layer of clay or clay with Kankar is encountered which forms a major aquiclude or aquitard. These cross-sections further indicate that this layer of kankar and clay is underlain by various sandy horizons which are usually tapped by the tubewells. The various horizons are variable in lateral extent and thickness. Cut-outs and interfingering between different units is a common feature which imparts an anisotropic character to both the aquifers and the confining formations.

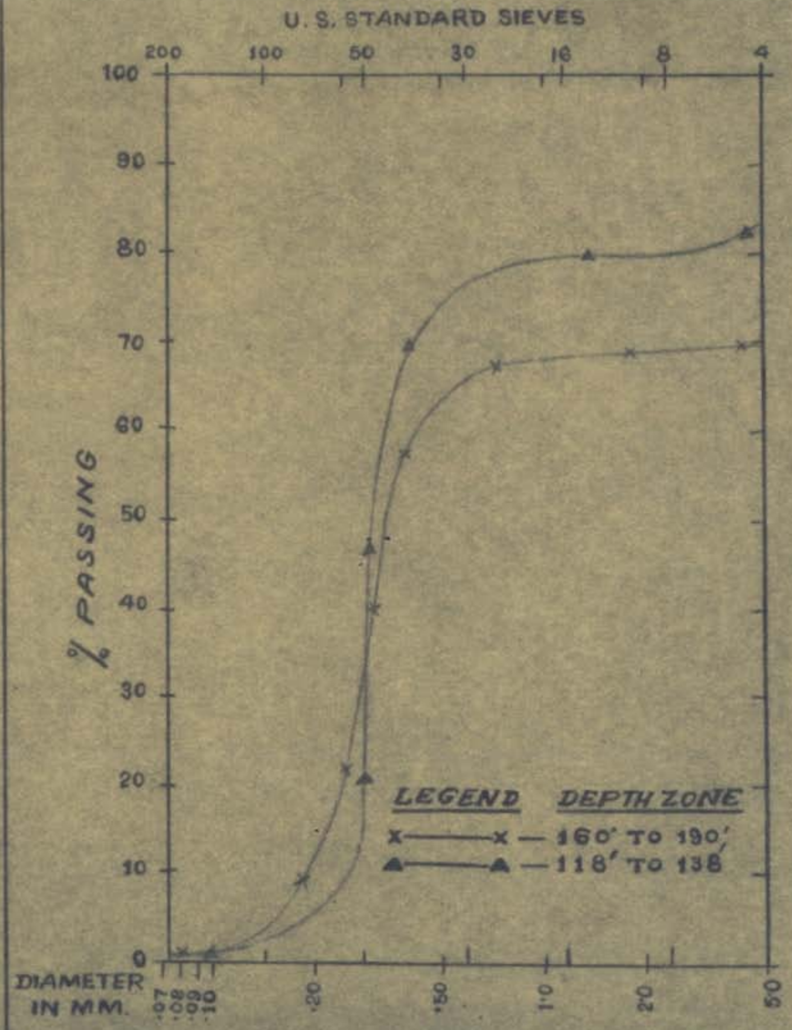
A comparison of the east-west and north-west-south-east or north-south sections indicates certain characteristic differences in the arrangement of various lithological units. The E - W section show invariably a lenticular character of both the sands and the clays, indicating thereby a cut-out feature. On the other hand the other two sections which are in roughly N - S direction indicate more or less uniform extension of a particular horizon. This difference provides an insight in the pattern of sedimentation in the area. It has been mentioned earlier that the alluvial deposits are a result of the activity of the various rivers. These rivers in the area under study, flow in a roughly N - S direction.

However, there has been in the past a lateral shift in the courses of these rivers but the N - S alighnment remained more or less the same. The pattern of sedimentation can be correlated with the orientation of these rivers. The N - S continuation of the various units indicates that they are deposited by the rivers which is also supported by the lateral heterogenity of the lithological units at right angles to the direction of the river courses. The pinching out and the lensoid character of the formations in the E - W direction are indicative of a lateral shift in the river courses.

GRAIN SIZE PARAMETERS OF SANDS

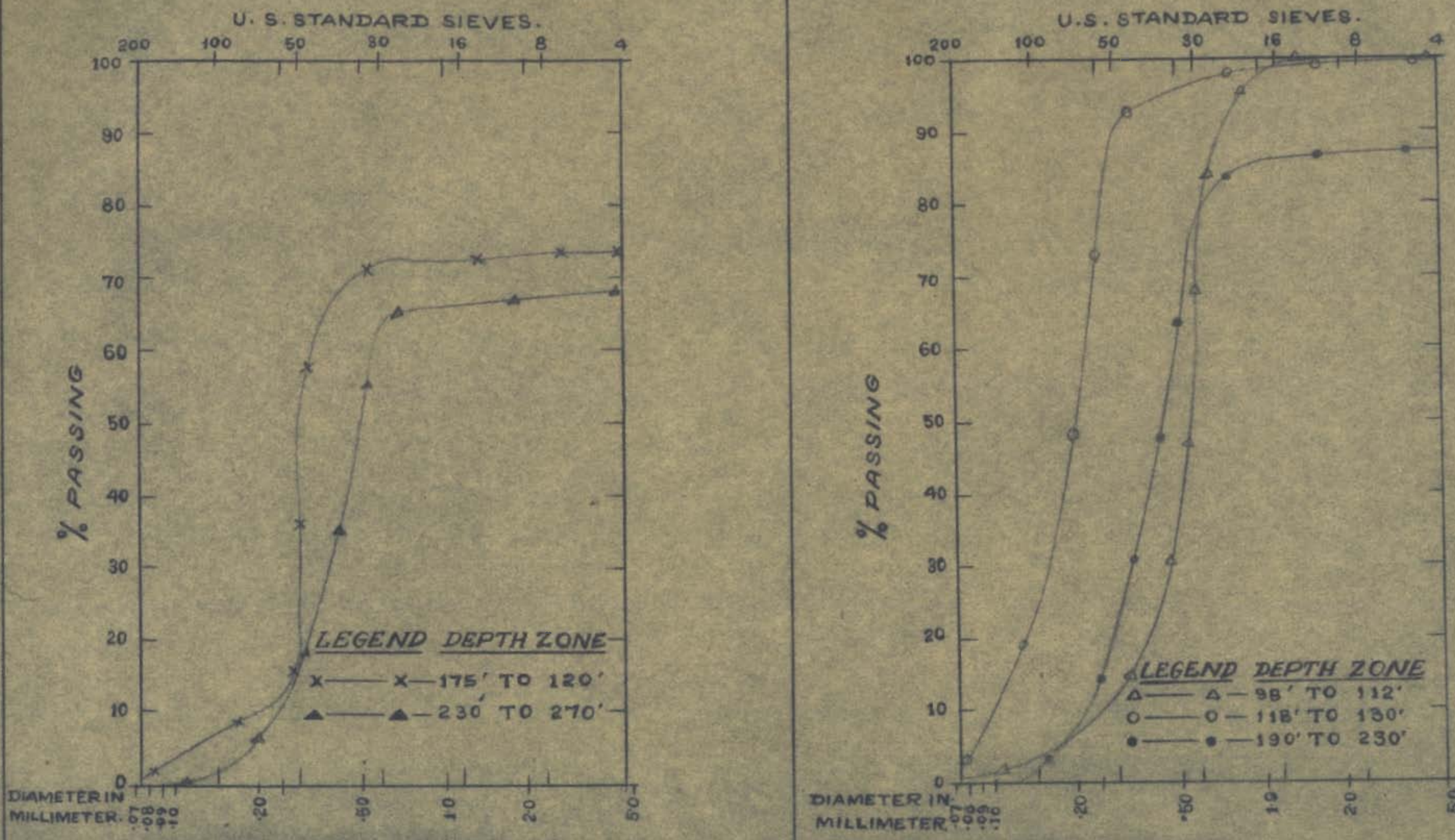
The sand samples representing different depths between 115 to 350 ft. were collected from 35 tubewells. These were subjected to mechanical analysis in order to determin the important grain size parameters i.e. Median (Md), Sorting coefficient (So), Uniformity coefficient and Effective size (de). The last two parameters are of importance from the point of view of ground water movement and design of well screens. The data of analysis are plotted as percent passing (Plates 2.11 to 2.20) and the above statistical parameters are determined from these curves which are given in(Table 2.3) .





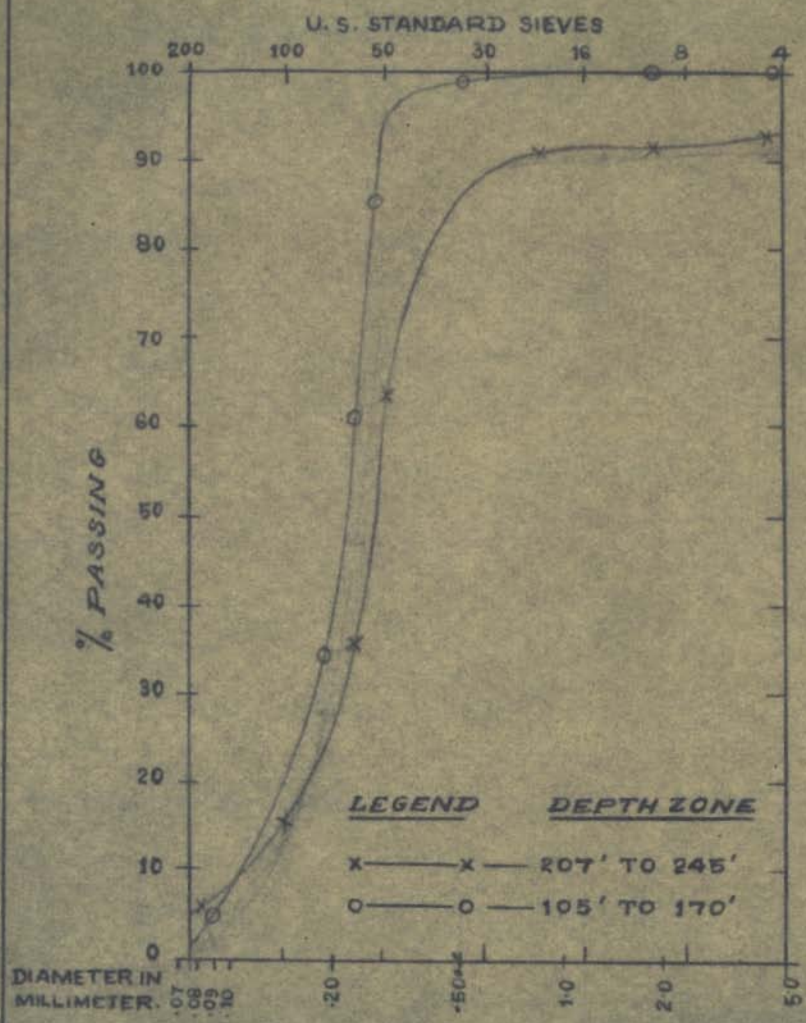
GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFER SANDS (WELL No. 20 N.L01)

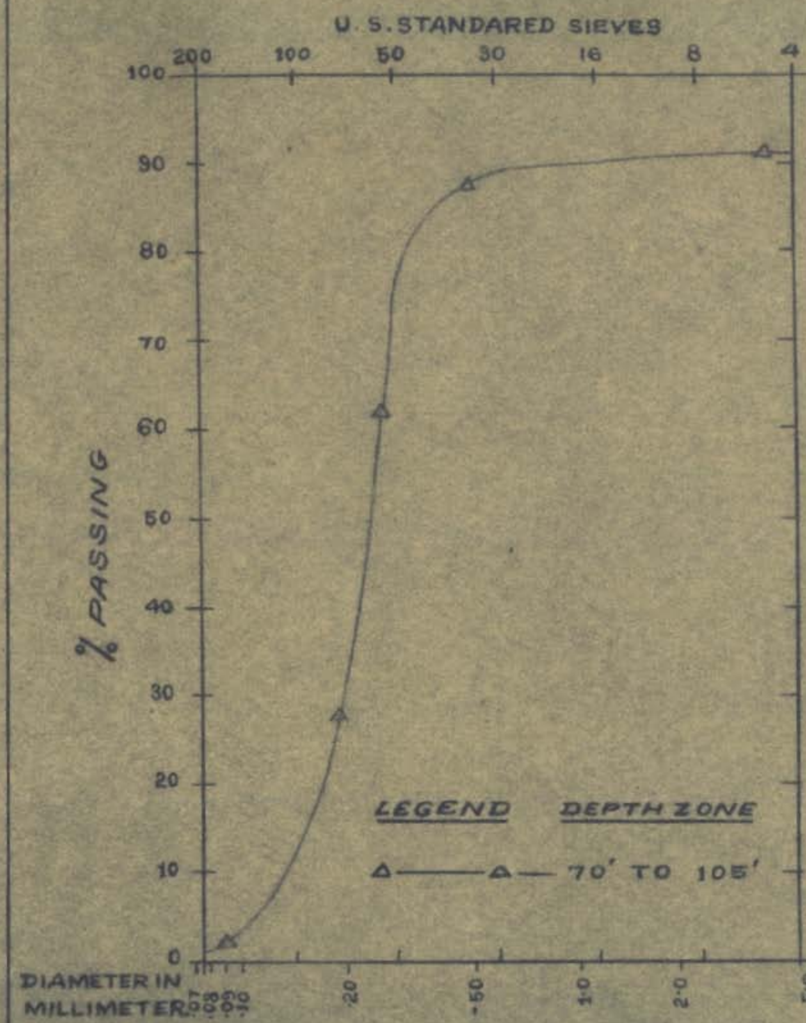
PLATE 2.11



GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFER SANDS (WELL NO. 2 S. L. 01)

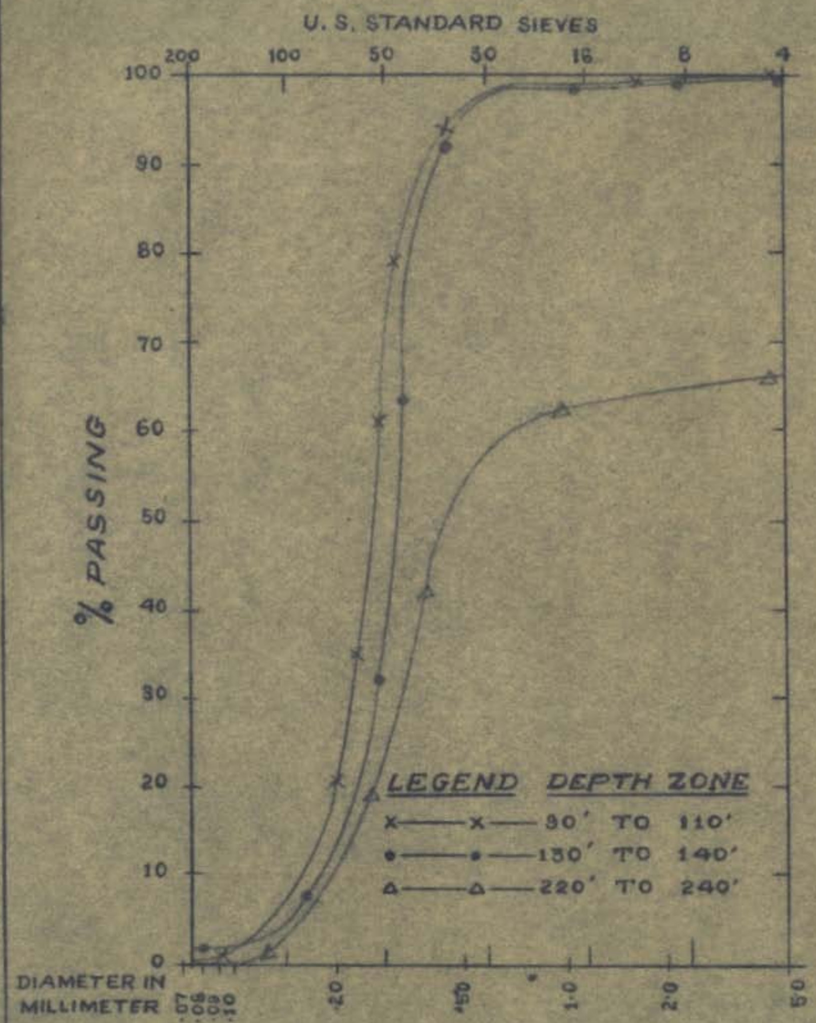
PLATE 2.12

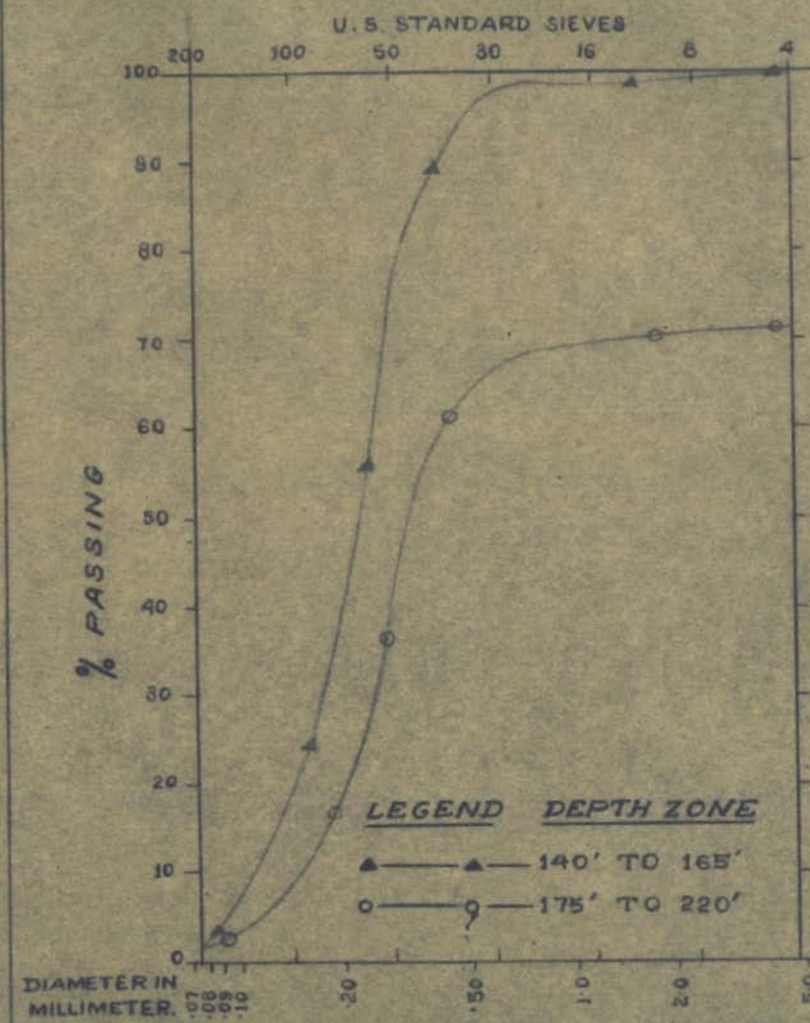




GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFERSANDS (WELL NO.34 BHIKI)

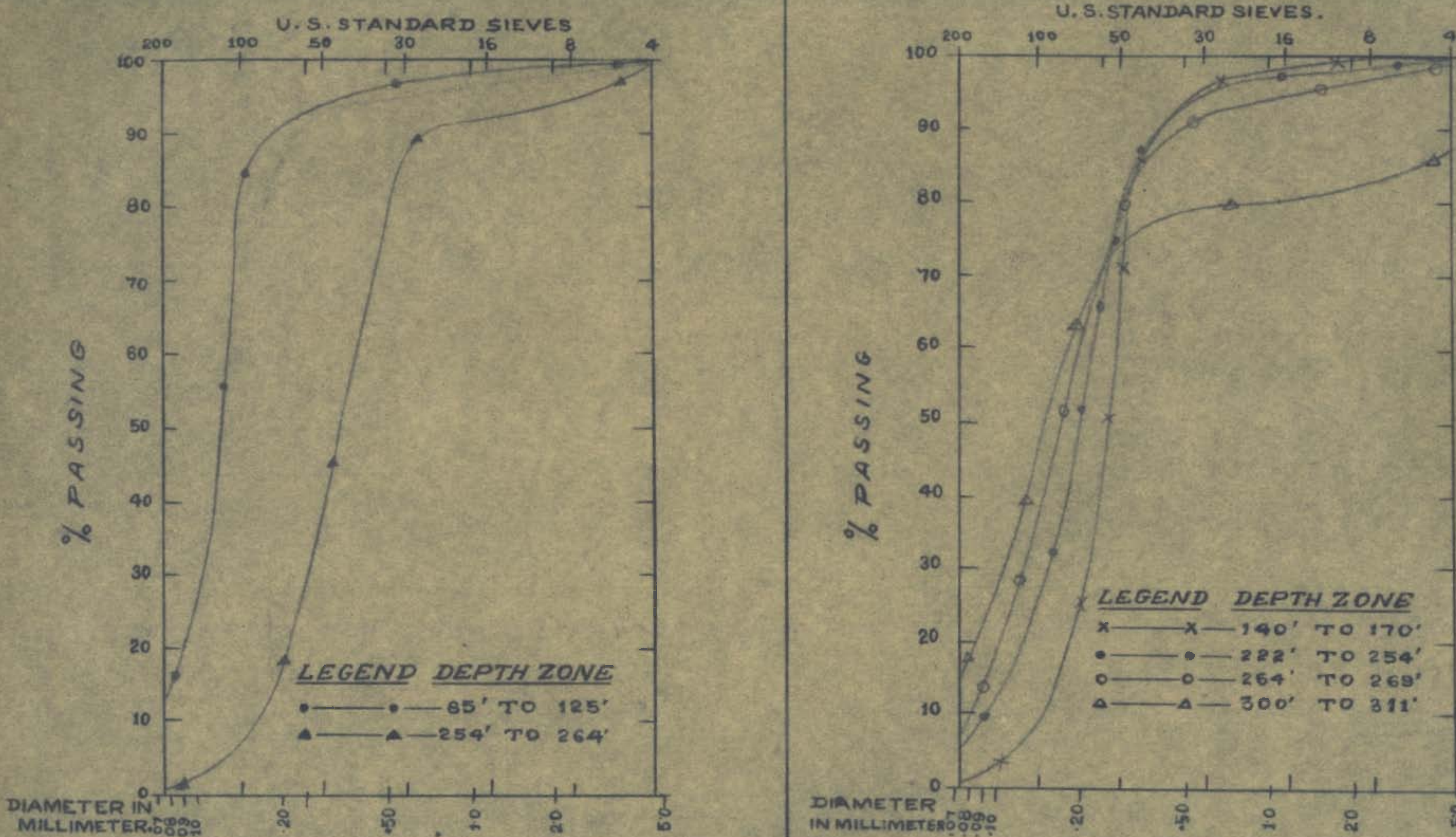
PLATE 2.13





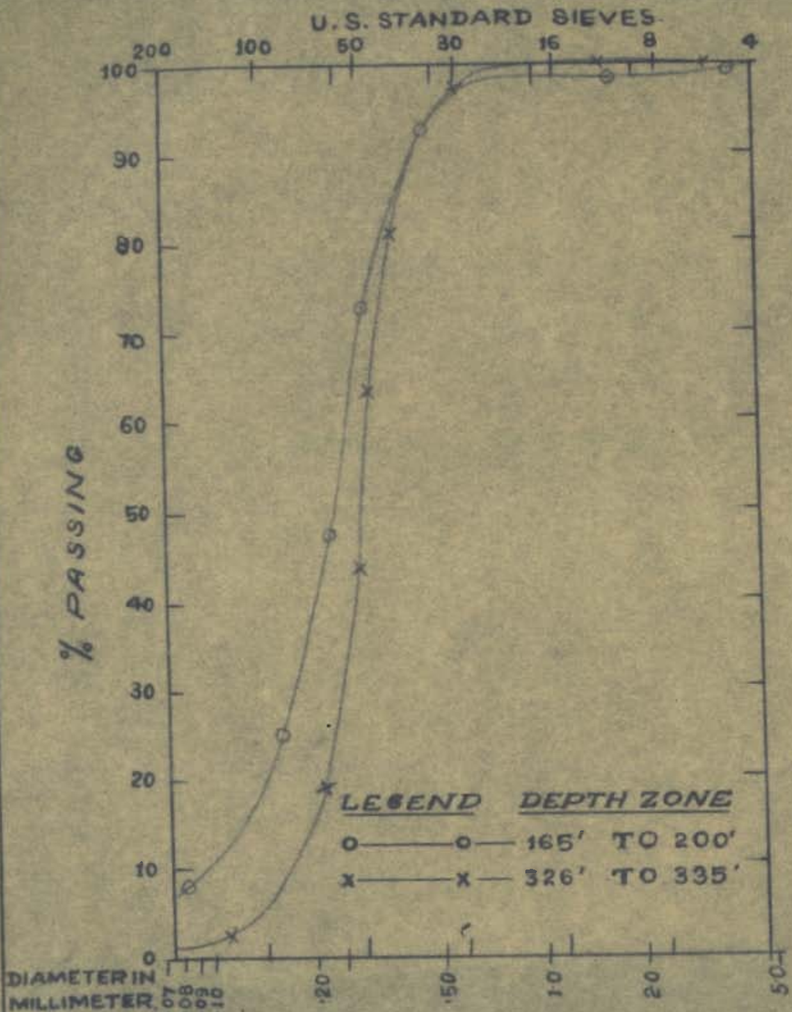
GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFER SANDS (WELL No. 10 AKAKRA)

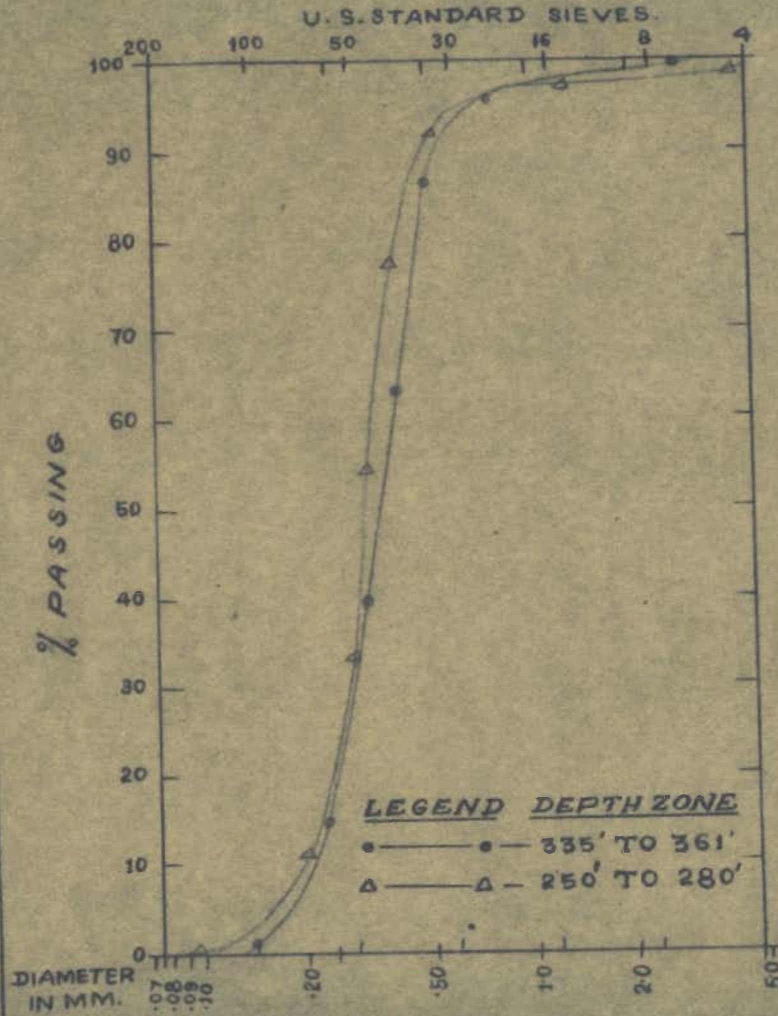
PLATE 2.14



GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFERSANDS (WELL No.23 LOHARA)

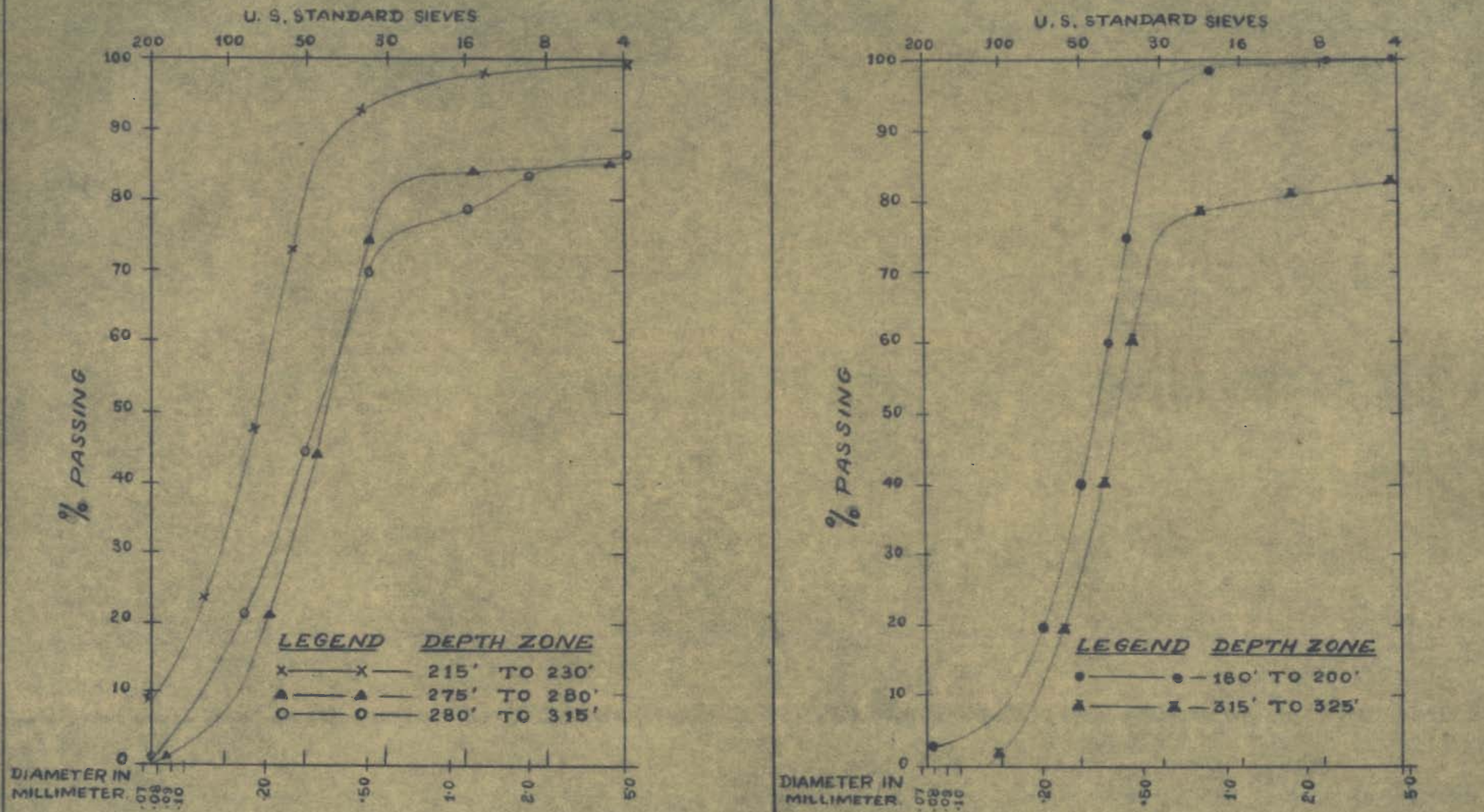
PLATE 2.15





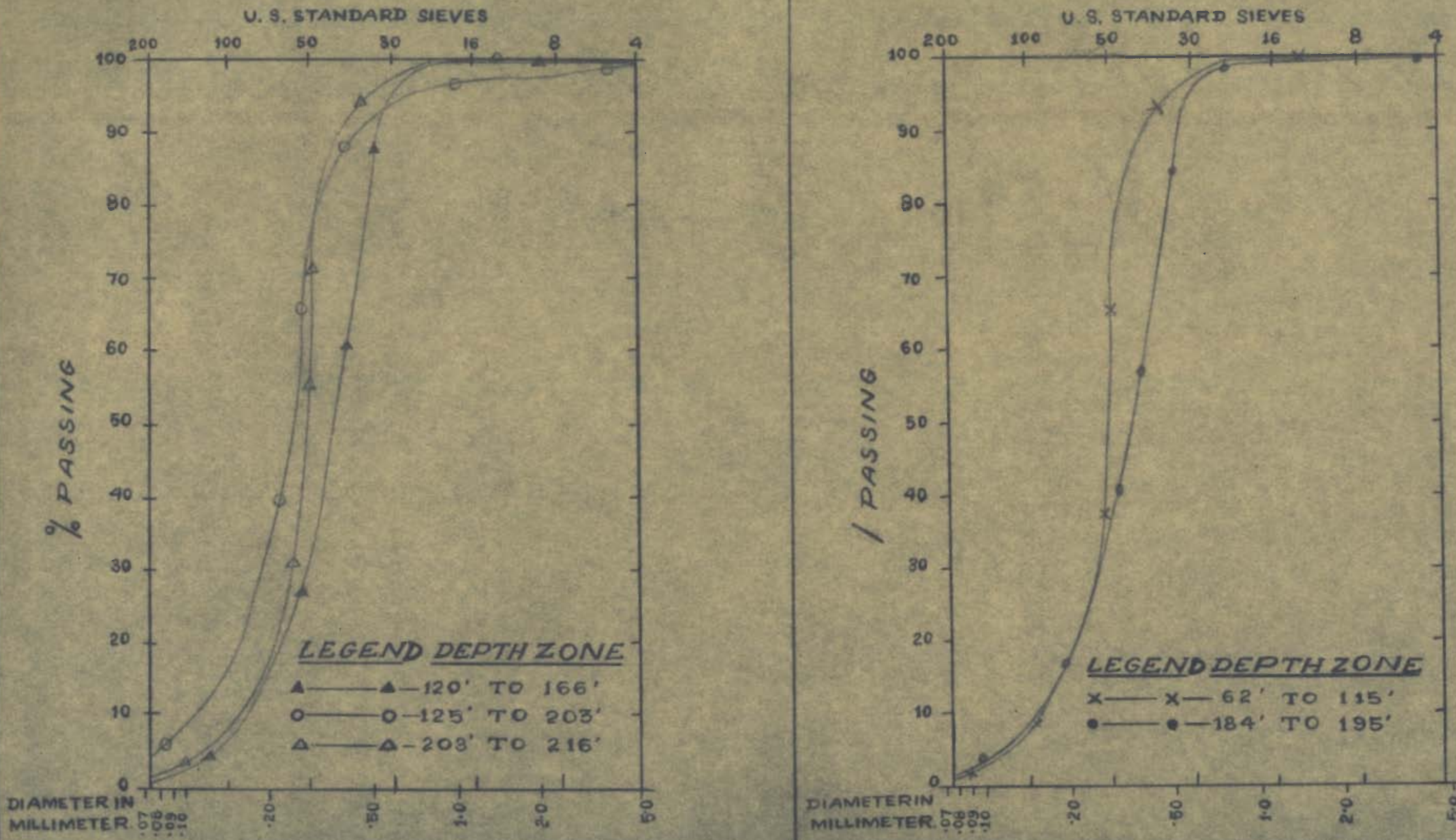
GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFERSANDS (WELL No.30 DAHA)

PLATE 2.16



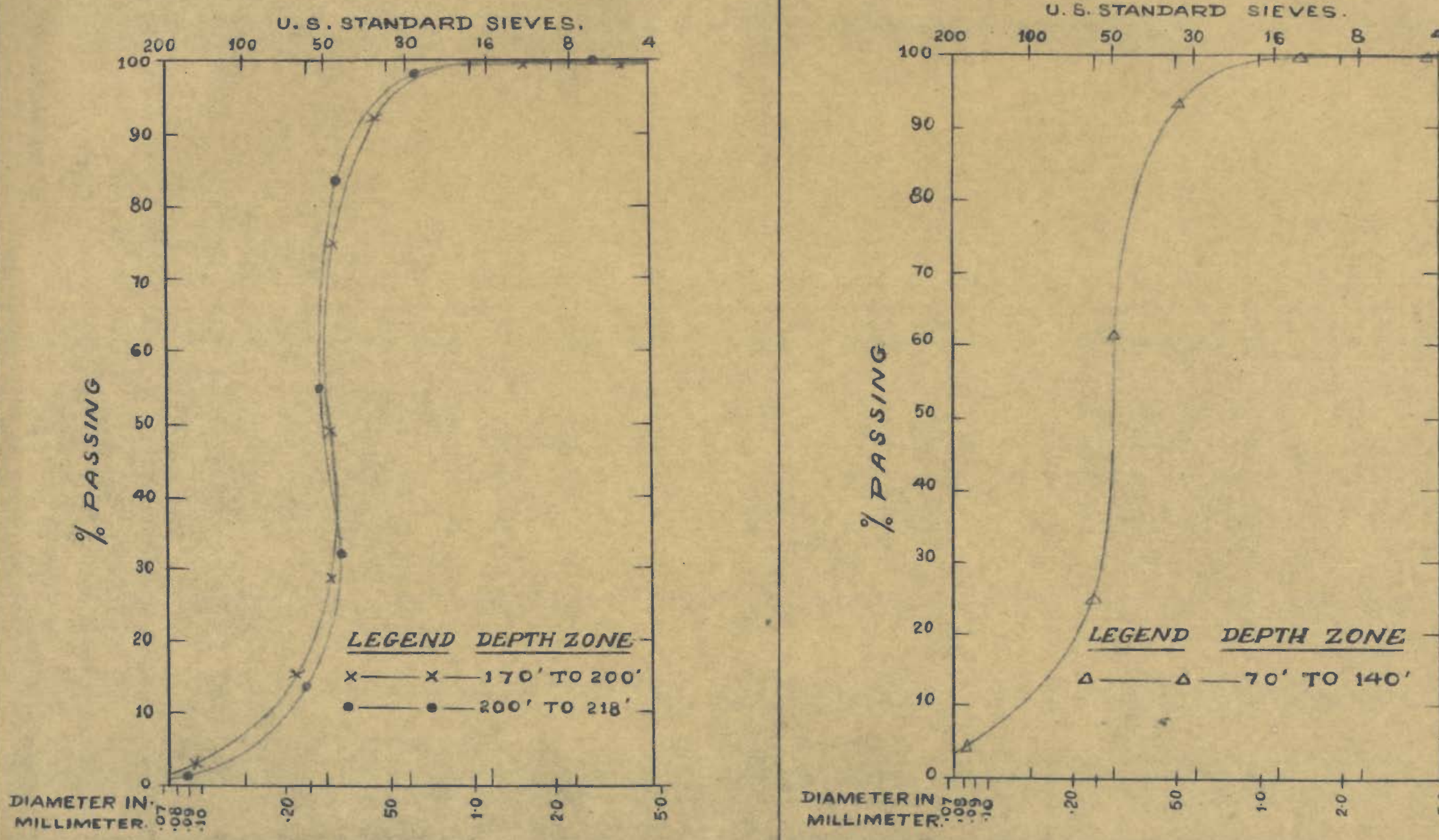
GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFER SANDS (WELL No. 1 SARDHANA)

PLATE 2.17



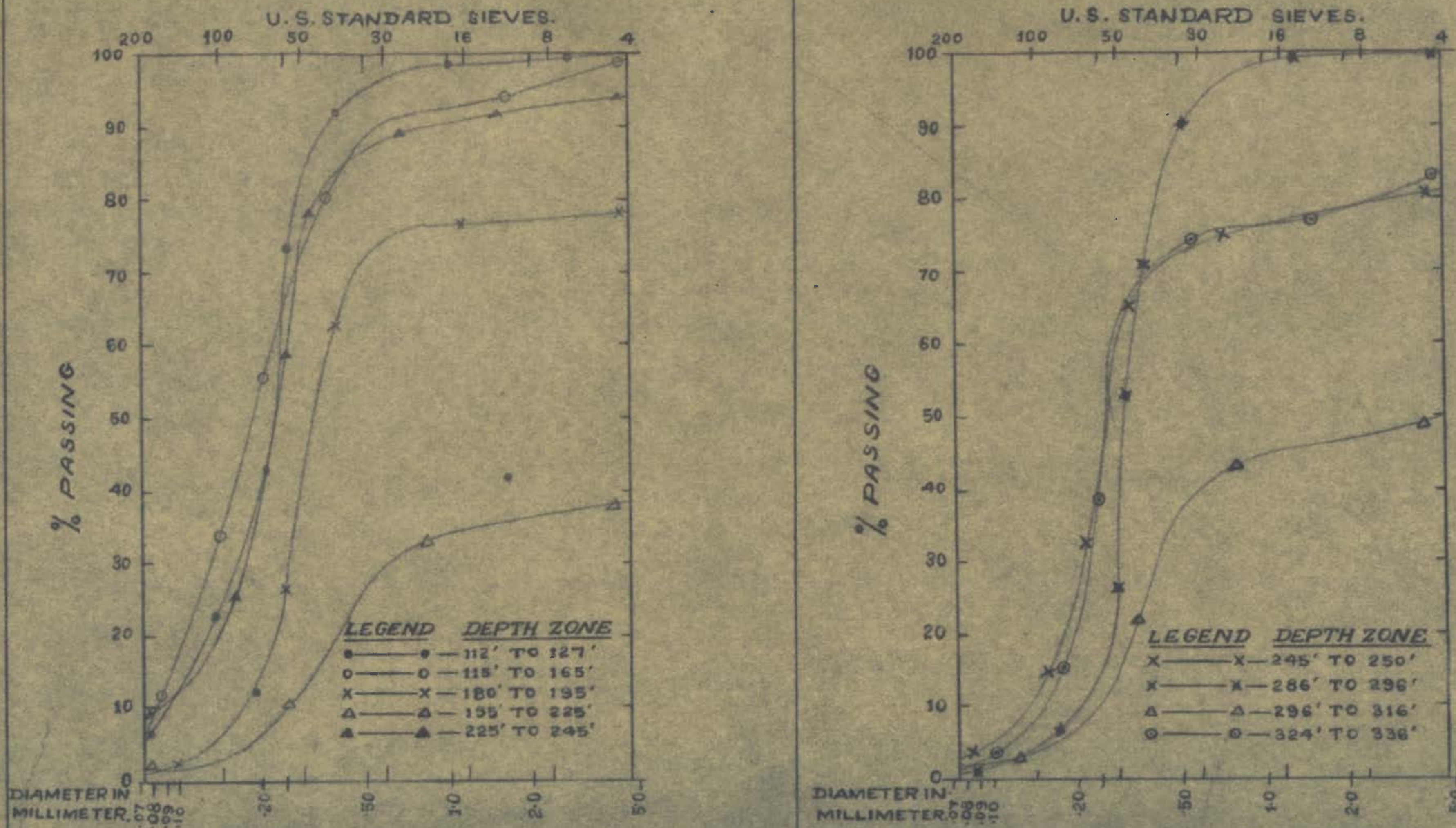
GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFERSANDS (WELL No. A 7 DAURALA)

PLATE 2.18



GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFERSANDS (WELL No. 23 MEERUT)

PLATE 2.19



GRAIN SIZE DISTRIBUTION CURVES FOR AQUIFER SANDS (WELL NO. 3 N. L01)

PLATE 220

Table 2.3 Grain size Parameters of the Aquifer sands from different Bore-Holes in Muzaffarnagar - Meerut Area.

Tubewell No. and Location	Depth in feet.	C (One percentile) in microns	M (Median) in microns.	S_o (Sorting Coefficient. $\sqrt{Q3/Q1}$	Effective size in mm.	Uniformity Coefficient.
1	2	3	4	5	6	7
3 North Loi	112-127	-	210	1.73	0.95	2.42
	155-165	-	190	2.90	0.86	2.44
	180-195	95	320	2.64	0.17	2.23
	195-225	100	-	-	0.26	-
	225-245	-	220	1.75	0.09	2.88
	245-250	-	280	3.70	0.15	2.00
	286-296	90	320	1.20	0.21	1.60
	296-316	90	-	-	0.26	-
	324-336	90	280	3.0	0.17	1.60
19 North Loi	126-140	110	340	1.7	0.17	2.10
	180-216	-	360	1.7	0.16	2.40
	216-220	150	500	2.0	0.26	2.10
20 North Loi	105-112	110	260	1.8	0.17	1.70
	118-138	120	340	-	0.19	2.10
	160-190	115	280	1.8	0.26	1.50
	210-270	120	320	1.4	0.18	1.80
2 South Loi	98-112	100	540	1.4	0.26	2.10
	118-130	75	190	1.6	0.10	2.10
	175-190	80	300	-	0.20	1.70
	190-230	150	380	1.6	0.21	2.30
	230-270	150	500	-	0.23	2.30
34 Bhiki	70-105	85	230	1.4	0.12	2.3
	105-170	78	210	1.6	0.11	2.0
	207-245	-	280	1.7	0.11	2.7

contd.

1	2	3	4	5	6	7
10A Kakra	90-110	100	380	1.5	0.20	3.3
	130-140	100	300	1.2	0.19	1.6
	140-165	75	210	1.8	0.11	2.3
	175-220	75	300	-	0.15	2.0
	220-240	140	260	-	0.18	1.6
23 Lohara	85-125	-	110	1.4	-	-
	140-170	-	250	1.5	0.14	1.8
	222-254	-	210	1.8	0.09	2.4
	254-264	90	340	1.9	0.17	2.1
	264-269	-	170	2.3	0.08	2.2
	300-311	-	150	3.1	0.09	-
30 Daha	165-200	105	290	1.3	0.17	1.9
	250-280	140	320	1.3	0.20	1.6
	326-335	-	230	2.0	0.09	3.0
	335-361	150	340	1.7	0.20	1.9
25 Daha	45-152	-	140	1.8	0.08	2.0
	152-170	-	300	1.9	0.13	2.5
	170-202	-	290	0.09	0.14	2.0
	245-270	-	270	1.4	0.11	2.1
	270-295	70	250	1.7	0.13	2.1
6 Daha	135-150	-	150	2.0	0.08	2.1
	180-188	75	300	1.7	0.13	2.1
	195-218	120	300	1.5	0.17	1.6
	260-297	-	310	1.9	0.12	2.8
1 Sardhana	180-200	-	320	2.09	0.16	2.1
	218-230	80	340	2.10	0.16	2.1
	275-280	-	180	2.10	0.08	2.6
	280-315	75	320	3.1	0.07	3.09
	315-325	120	340	1.9	0.19	2.3

contd.

1	2	3	4	5	6	7
10 Sardhana	160-163	-	210	2.0	0.08	2.4
	165-180	-	180	1.4	0.08	2.2
	200-230	-	380	2.1	0.18	2.7
	233-244	-	190	1.7	0.09	3.1
	260-268	-	210	2.2	-	-
	268-312	90	540	-	0.23	2.7
13 Sardhana	115-145	-	230	1.8	0.12	2.6
	160-165	-	190	2.09	-	-
	165-190	-	260	1.7	0.15	1.8
	190-215	110	310	1.6	0.19	1.7
	262-273	-	140	1.8	0.08	1.8
	273-302	70	410	1.6	0.21	1.9
A 6 Daurala	115-166	150	320	1.5	0.20	1.8
	210-270	110	360	1.9	0.20	1.9
A 7 Daurala	62-115	90	230	1.2	0.16	1.7
	120-166	97	360	1.4	0.17	2.2
	184-195	80	340	1.7	0.15	2.5
	195-203	-	250	1.2	0.11	2.4
	203-216	-	280	1.2	0.16	1.7
E 2 Daurala	100-120	70	280	1.6	0.10	1.4
	170-200	-	290	1.5	0.15	1.3
	200-227	110	320	1.2	0.19	1.1
	227-252	-	280	2.1	0.13	1.6
S 2A Meerut	83-137	120	400	2.0	0.19	2.5
	158-225	150	480	1.5	0.26	1.9
21 Meerut	80-131	75	320	1.9	0.15	2.2
	195-260	140	330	1.5	0.18	1.8
	272-282	85	340	2.1	0.15	2.5
23 Meerut	70-140	-	290	1.4	0.13	2.3
	170-200	75	300	1.1	0.15	1.8
	200-218	95	280	0.9	0.21	1.2

contd.

37 Meerut	135-200	-	260	1.9	0.12	1.6
	210-245	70	280	1.8	0.15	1.5
38 Meerut	80-153	-	300	1.6	0.15	1.4
	153-190	-	230	1.8	0.11	2.8
	190-225	87	320	1.3	0.19	1.9
	230-240	75	190	2.0	0.09	3.3
	240-275	120	300	1.0	0.22	1.3
39 Meerut	88-130	90	270	1.5	0.11	2.63
	130-140	80	260	1.3	0.13	2.07
	192-227	80	280	1.5	0.17	1.7
	240-269	-	250	1.7	0.16	1.6
	269-273	80	220	1.4	0.12	1.9
40 Meerut	99-125	100	280	1.6	0.18	1.6
	240-270	-	300	1.5	0.5	2.0
	245-359	120	320	1.6	0.20	1.7
41 Meerut	80-115	70	360	2.4	0.16	2.5
	115-145	130	230	1.6	0.15	1.8
	195-220	130	400	2.9	0.21	2.14
	225-270	-	210	1.6	0.11	2.27
	270-296	80	220	1.4	0.20	1.15
42 Meerut	80-140	105	340	1.2	0.21	1.6
	165-232	105	350	1.2	0.17	2.1
44 Meerut	90-135	120	400	3.0	0.23	2.2
	158-178	85	260	1.3	0.16	1.75
	212-230	105	280	1.2	0.18	1.55
	278-302	120	290	1.1	0.21	1.33
45 Meerut	100-135	-	210	2.0	0.11	2.5
	173-195	-	218	2.1	0.09	2.6
	195-232	-	240	2.0	0.11	2.5
	232-240	-	270	1.9	0.14	2.1
T 2a Bhati-pura.	82-176	80	280	1.6	0.14	2.0
	195-208	75	290	1.6	0.14	2.1

contd.

1	2	3	4	5	6	7
26 A Bhati-pura.	207-233	-	180	1.9	0.95	3.1
	238-244	-	160	1.7	0.15	1.1
	244-255	-	170	2.3	0.12	1.7
	255-300	80	320	1.6	0.15	2.1
29 A Bhati-pura.	120-135	-	200	2.5	0.09	2.8
	190-212	70	260	1.5	0.13	2.07
	218-224	-	290	1.4	0.15	1.86
	224-232	10	260	1.3	0.17	1.5
	232-282	-	250	1.6	0.11	2.45
3 Bhatipura	110-120	95	280	1.6	0.16	1.8
	220-230	-	340	-	0.18	2.0
	250-260	75	210	1.8	0.11	2.1
	260-265	130	360	1.8	0.21	1.8
	276-286	75	380	1.8	0.17	2.1
	330-342	-	340	-	-	-

In order to keep the number of plates to a minimum only the percent passing curves for sands from 10 wells are given.

Median (Md)

It is the diameter corresponding to the 50 percentile value of the cumulative curve and is expressed here in mm. Half of the particles by weight are coarser than the median, and half are finer. The median values for the sands under study vary from 0.31 to 0.17 mm and therefore, these can be classified as medium to fine sands according to the Wentworth's classification. (Pettijohn[28]).

Trask's sorting coefficient (S_o)

Trask's sorting coefficient is defined as the ratio of 25 percentile value to 75 percentile value. A perfectly sorted sediment has a coefficient of 1.0 . According to Trask S_o value of less than 2.5 indicates a well sorted sediment, whereas a value of 3.0 is normal, and a value greater than 4.5 indicates a poorly sorted sediment.

The sorting coefficient for the sands from the area varies from 3.00 to 1.25 and therefore, these can be regarded as normal to well sorted sediments.

Variation in median and sorting coefficient

An attempt has been made to determine the variation, if any, in the median value from north to south because the principal streams (the Ganga and the Yamuna) which are responsible for the deposition of these sediments, flow from north to south. The variation in the median and sorting coefficient are given in Table 2.3 . A perusal of this table would indicate that the median decreases, within narrow limits i.e. from 0.31 to 0.17 mm from north to south. Raghava Rao[14] has also given values of median (0.50 - 0.25 mm) for the aquifer sands from Roorkee area which lies to the north of the area under study. Therefore it can be concluded that there is more or less a general decrease in the grain size of sands (within depth of 112-360 ft) from north to south. This is natural to expect because the coarser sediments in a channel are deposited first while the finer ones are transported further down.

There is, however, no definite variation in the sorting coefficient from north to south (Table 2.3). No definite variation in either median or sorting coefficient with depth could also be seen.

Effective size

Effective size represents a size in mm so that if all the grains were of that diameter the sand would transmit the same amount of water that it actually does. Hazen determined it as the diameter of sand grains such that 10% of the material is of smaller grains and 90% is of larger grains. The value of effective size for the sands varies from 0.075 to 0.32 in the present area of study.

Uniformity coefficient

The uniformity coefficient of a sand is the ratio of (1) the size of grain which has 60% of the sample finer than itself to (2) the size which has 10 percent finer than itself (Wenzel[29]). The uniformity coefficient is a measure of sorting. The uniformity coefficient for the sand samples from the area under description varies from 1.1 - 3.3. The above two parameters i.e. effective size and uniformity coefficient can be used for determining the permeability of the formations by using the various semi-empirical formulae given by Hazen, Slichter and others (Wenzel[29]).

C. M. PATTERN

During the last few decades there has been a tendency among the geologists to analyse and characterise depositional features of clastic sediments. In modern research the trend has been towards a definition of individual samples of a deposit by parameters of their texture and to define the deposits as a whole by the variation of these parameters.

Passega[30] has used the texture of clastic sediments for determining the environments of their deposition. He suggested the construction of C M pattern after determining the values of 1 percentile grain size (c) and median i.e. 50 percentile grain size (M) from the grain size distribution curves. Values of C and M are expressed in microns and for each sample their values are plotted on a logarithmic paper. The resulting sample point pattern is called the C M pattern. Passega[31] has given many patterns indicative of different depositional environments.

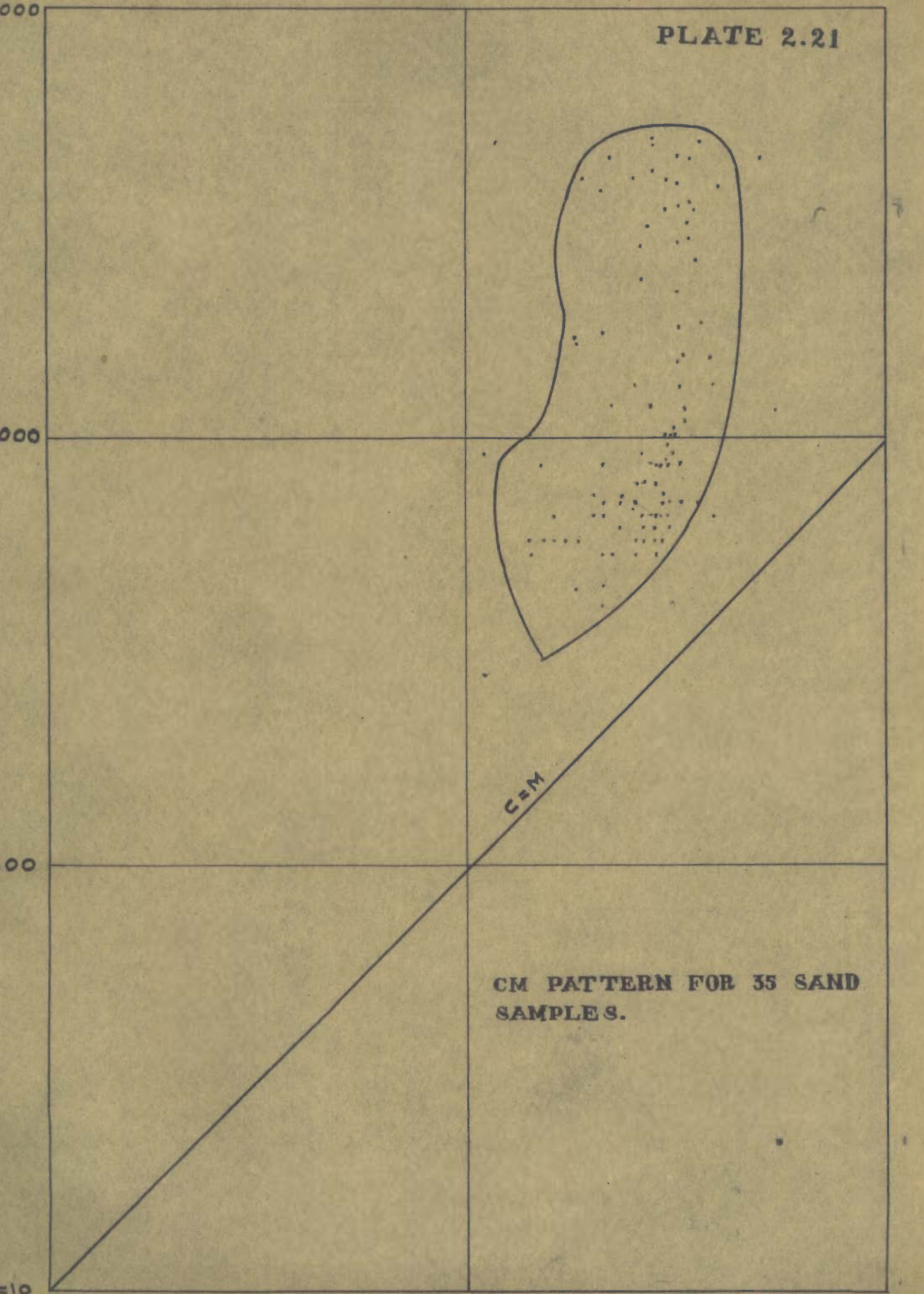
There are various modes of transportation of sediments. Bottom currents which are capable of transporting sediments are of two types (1) Tractive currents and (2) Turbidity currents. Tractive currents are capable of transporting their load either by rolling or in suspension. Turbidity currents normally flow during a limited time and are so rapid that they can not be followed by rolling grains. Their load is entirely a suspension load. Rivers, marine currents and waves touching bottom are the examples of tractive currents.

The values of C and M were t determined from the grain size cumulative curves of the subsurface sandy horizon from the area under study. The values of C and M are given in Table 2.3 and CM pattern is shown in Plate 2.21 The resultant CM pattern is characteristic of tractive current deposits (Passega[31]).

CONCLUSIONS

The CM pattern for the sands from the area under study is comparable to that which is characteristic of tractive current deposits. Therefore, it can be concluded that the sandy horizons were deposited by the tractive currents which were associated by the activity of rivers in this area.

PLATE 2.21



CM PATTERN FOR 35 SAND SAMPLES.

CHAPTER 3

GROUND WATER CONDITIONS

It has been mentioned earlier in Chapter 2 that the sandy horizons which form aquifers are found at two different depths in this area. The first horizon is comparatively shallow and occurs at a depth of 15'-50' from the ground surface. This has been named as the 'Shallow ground water reservoir'. The other occurrence of water bearing horizon (sand) is at a depth of 100' to 350' with thin bands of clay and kankar. This forms the 'deeper aquifer' of the area and it is separated from the shallow aquifer by a thick, more or less continuous, layer of clay intermixed with kankar (Plate 2.5) which behaves as a semi-confining layer or aquitard. According to Davis and DeWiest[32] the term aquitard is used to describe natural materials that stores water and transmits enough water to be significant in the study of the regional migration of ground water but not enough water to supply individual wells.

The water in the shallow aquifer is under water table conditions while in the deeper aquifers it is under confined or semi-confined conditions. The water table is at a depth of 15-30 feet below the ground surface while the cumulative piezometric surface for the confined aquifers is also more or less at the same level. However, the water level in the wells, which tap the deeper aquifer, is always above the base of the overlying confining layer.

In order to determine the behaviour of the water table and the piezometric surface, periodic data of the water levels in the shallow dug wells and the deeper tubewells were collected. The ground water distribution in the area has been described separately for the shallow water table aquifer and for the deeper confined aquifer. It may also be mentioned here that the hydraulic parameters, specially the storage coefficient, as will be discussed in Chapter 4, also point towards the confined character of the deeper aquifers. However, as pumping from deeper aquifers takes places, leakage from overlying aquifers becomes significant.

WATER TABLE AQUIFERS

The shallow ground water reservoir met within 30 feet depth below the surface represents the water table aquifer of the area. The average thickness of the water table aquifers is of the order of 25 feet.

WATER TABLE CONTOUR MAPS

The water table maps have been prepared on the basis of the field observations of static water levels in the shallow wells. Location of these shallow(Observation) wells is marked on Plate 3.1 to 3.8. The alignment of the observation wells is more or less at right angles to the major drainage courses of the area. Two set of water table maps have been

PLATE 3.1

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR- MEERUT AREA FOR THE MONTH OF MAY 1958.
(HEIGHT ABOVE MEAN SEA LEVEL)

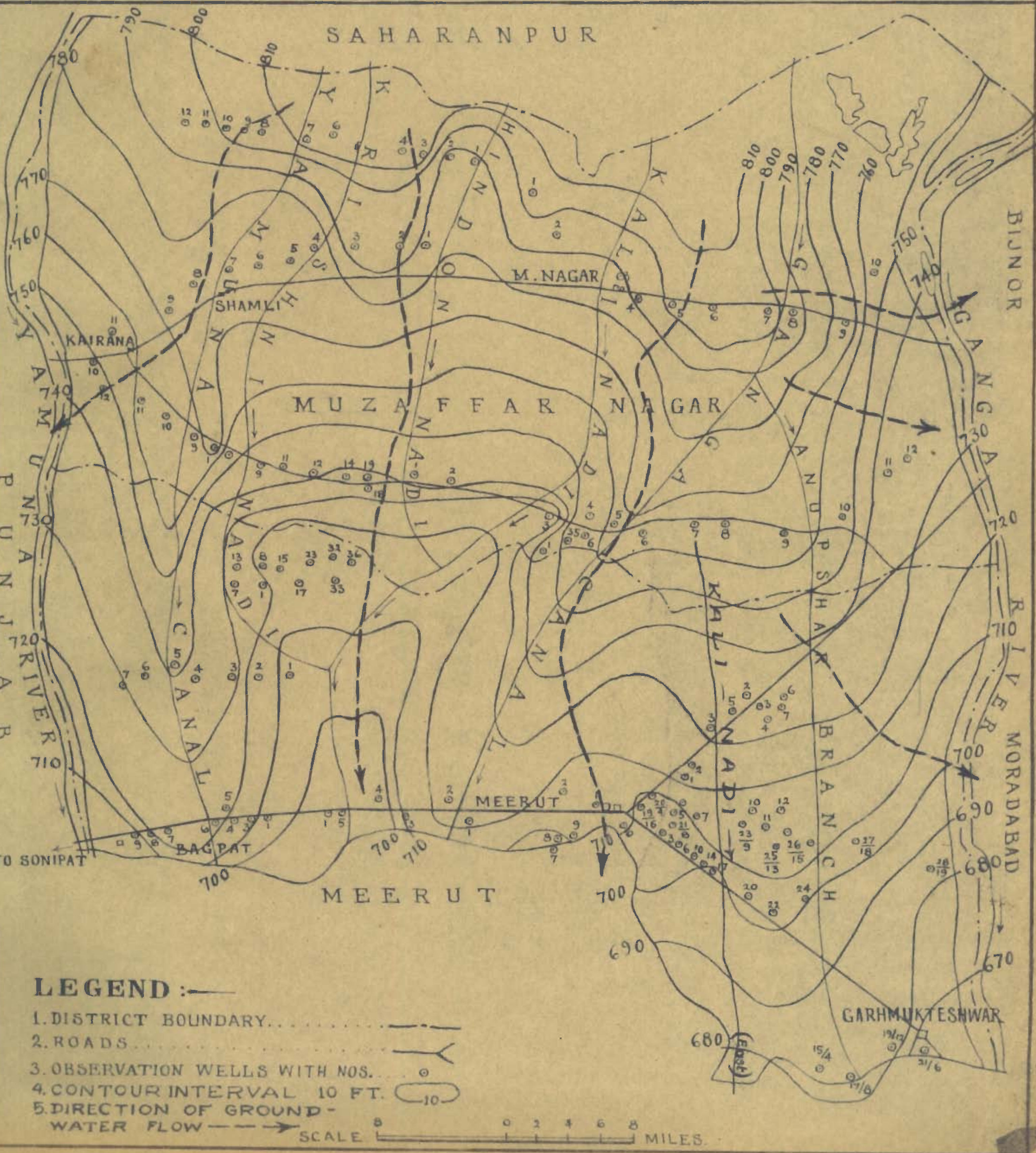


PLATE 3.2

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF OCT. 1958.

(HEIGHT ABOVE MEAN SEA LEVEL)

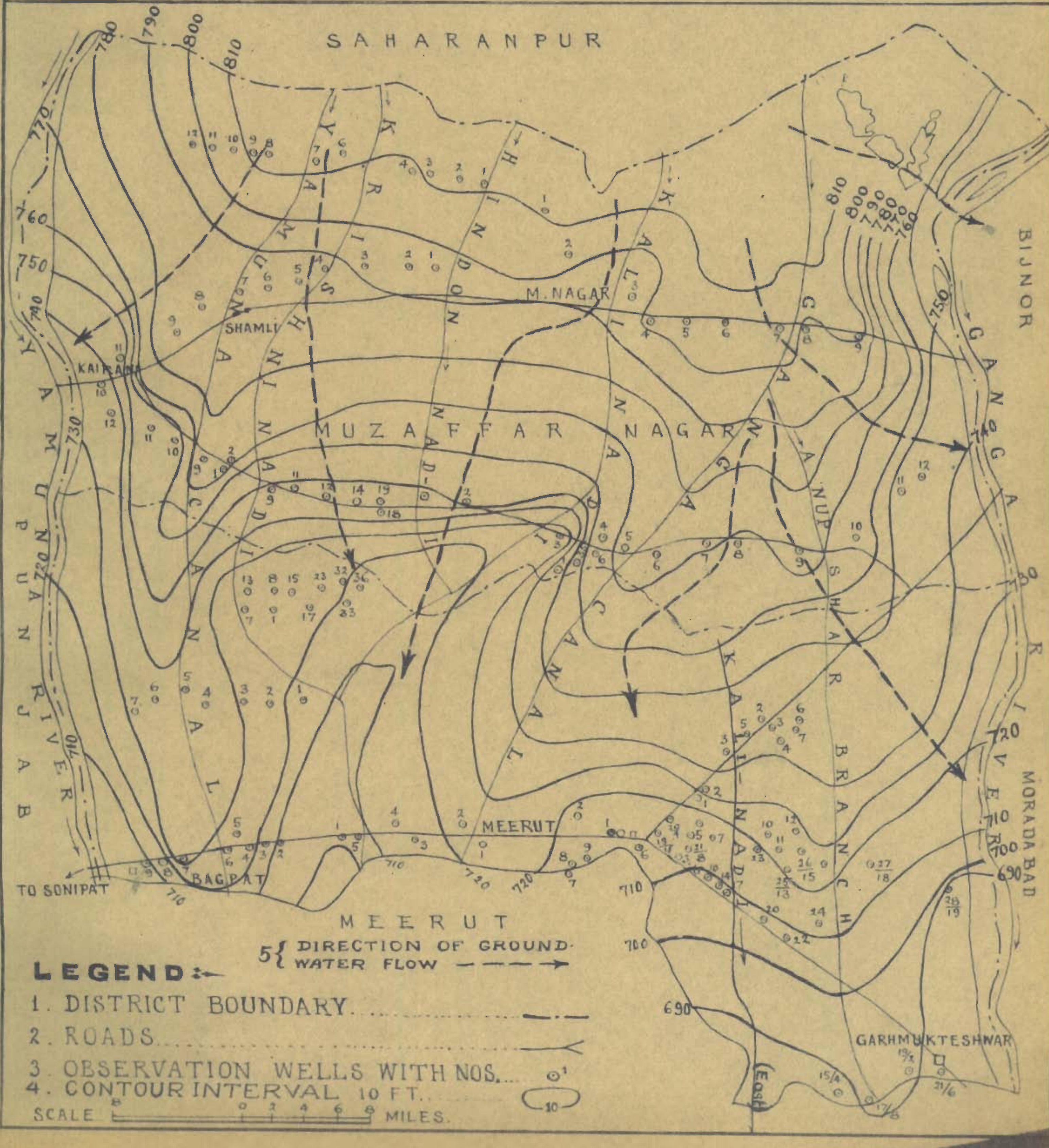
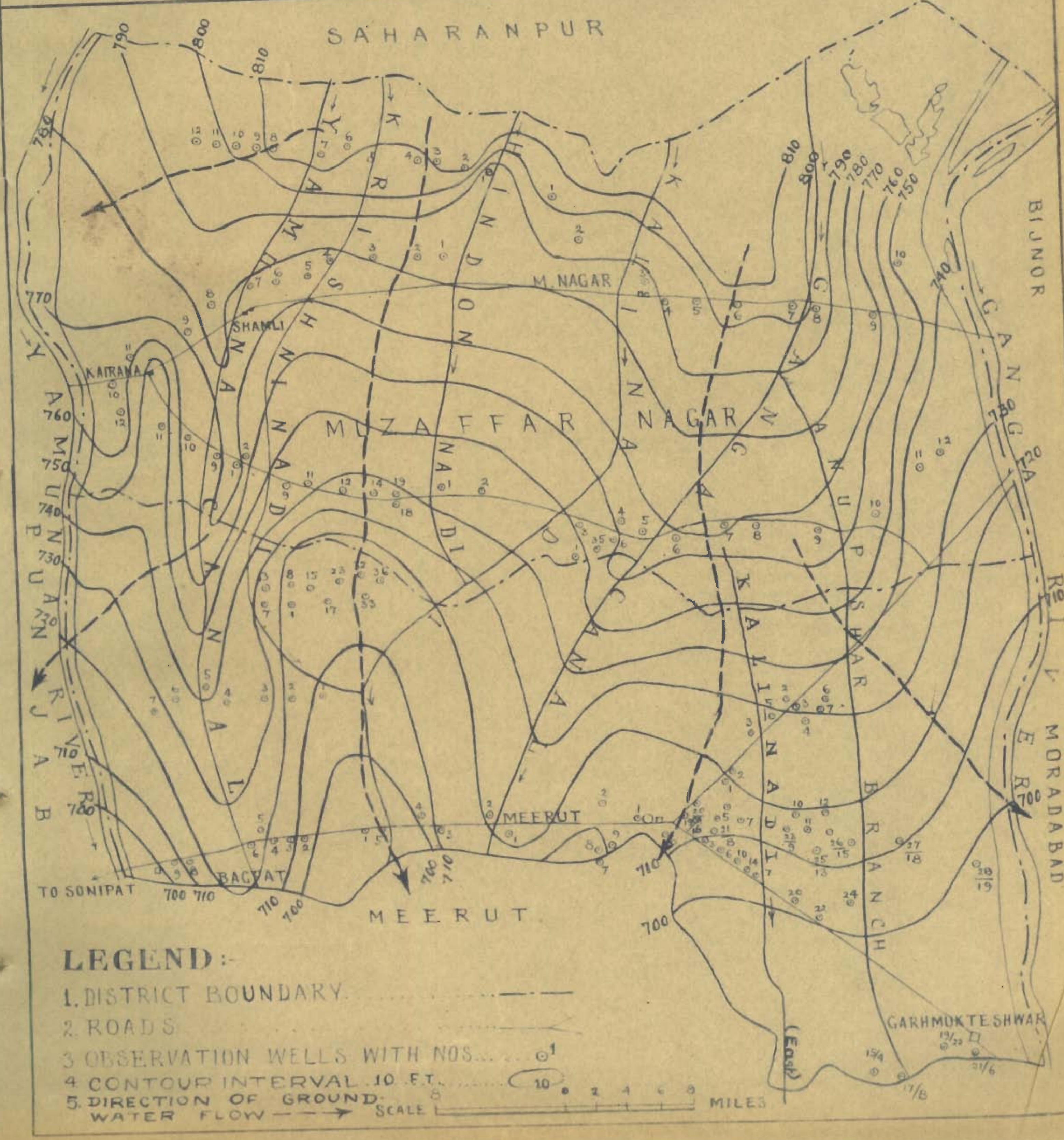


PLATE 3.3

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF MAY. 1962.
(HEIGHT ABOVE MEAN SEA LEVEL)



WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF MAY 1964.
(HEIGHT ABOVE MEAN SEA LEVEL)

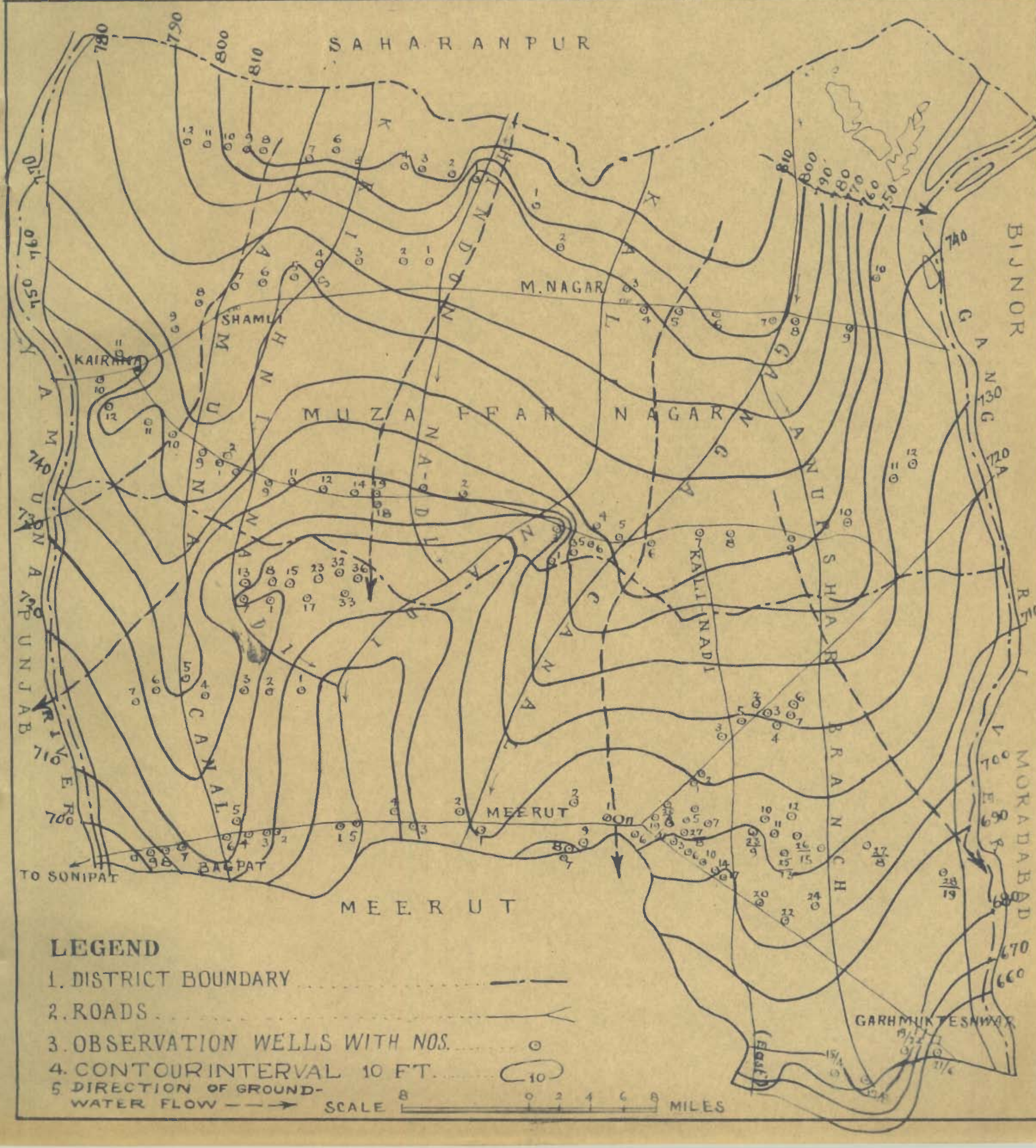


PLATE 3.6

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF OCT. 1964.

(HEIGHT ABOVE MEAN SEA LEVEL)

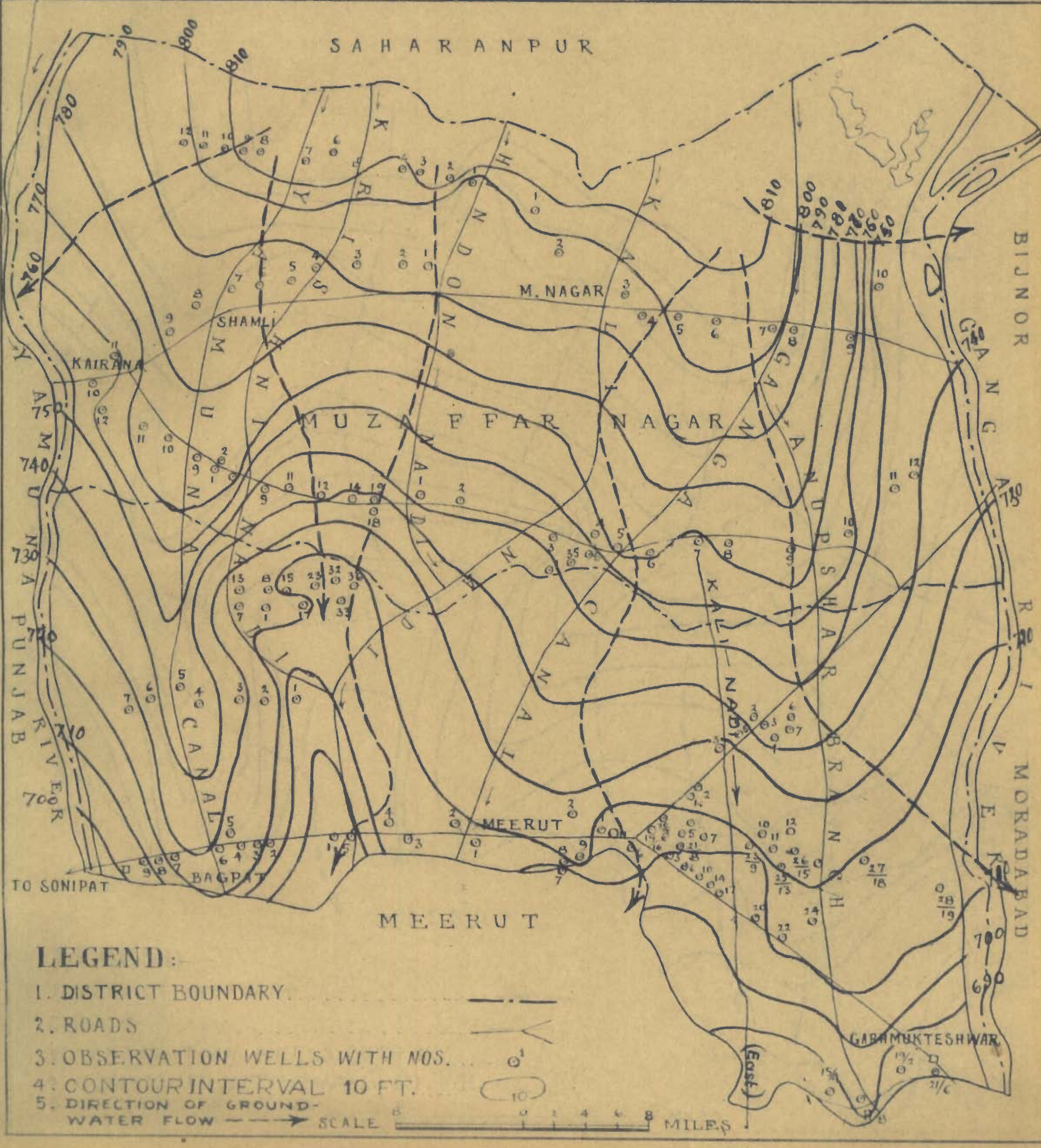
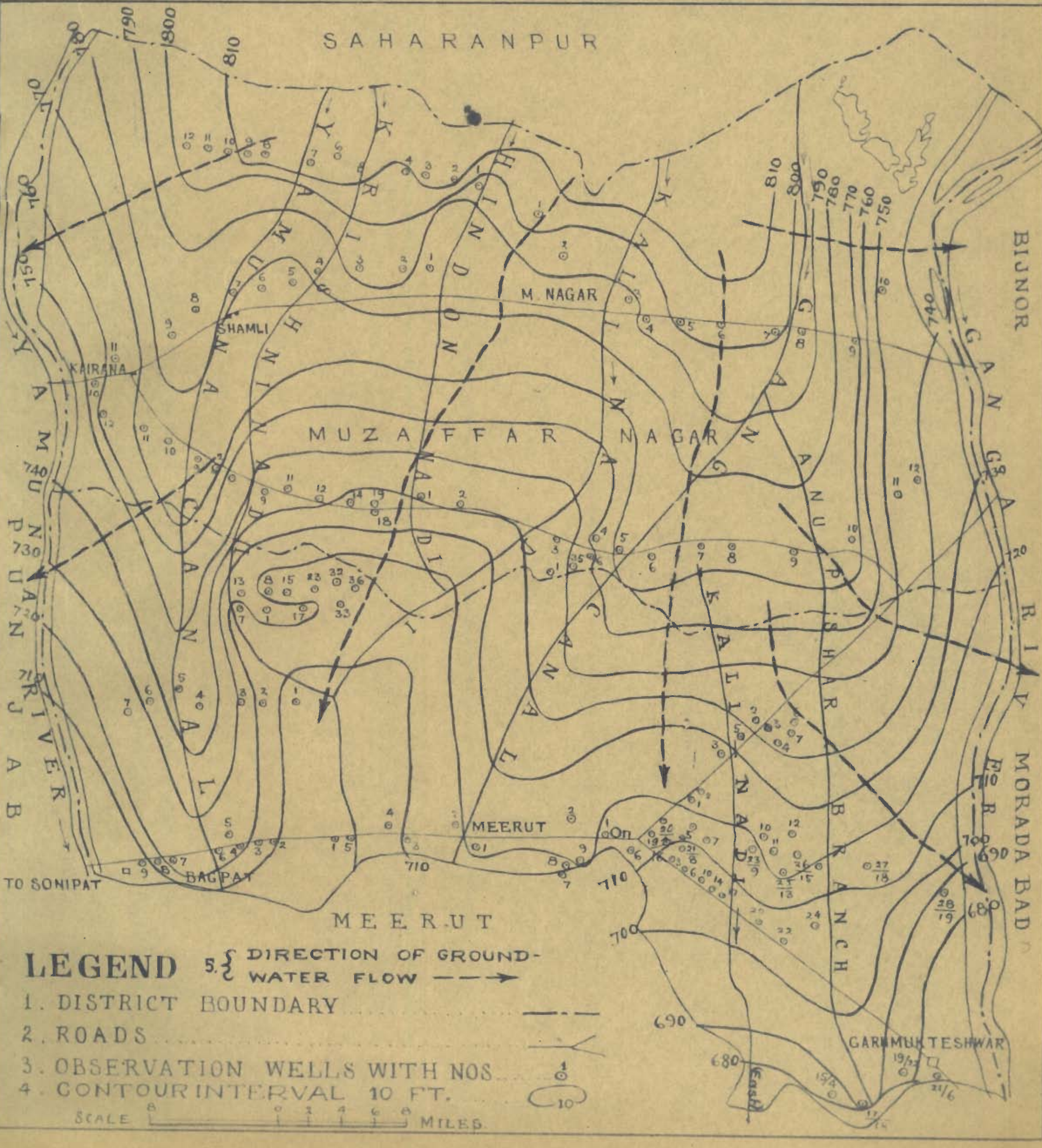


PLATE 3.4

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF OCT. 1962.

(HEIGHT ABOVE MEAN SEA LEVEL)



WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF MAY 1965.

(HEIGHT ABOVE MEAN SEA LEVEL)

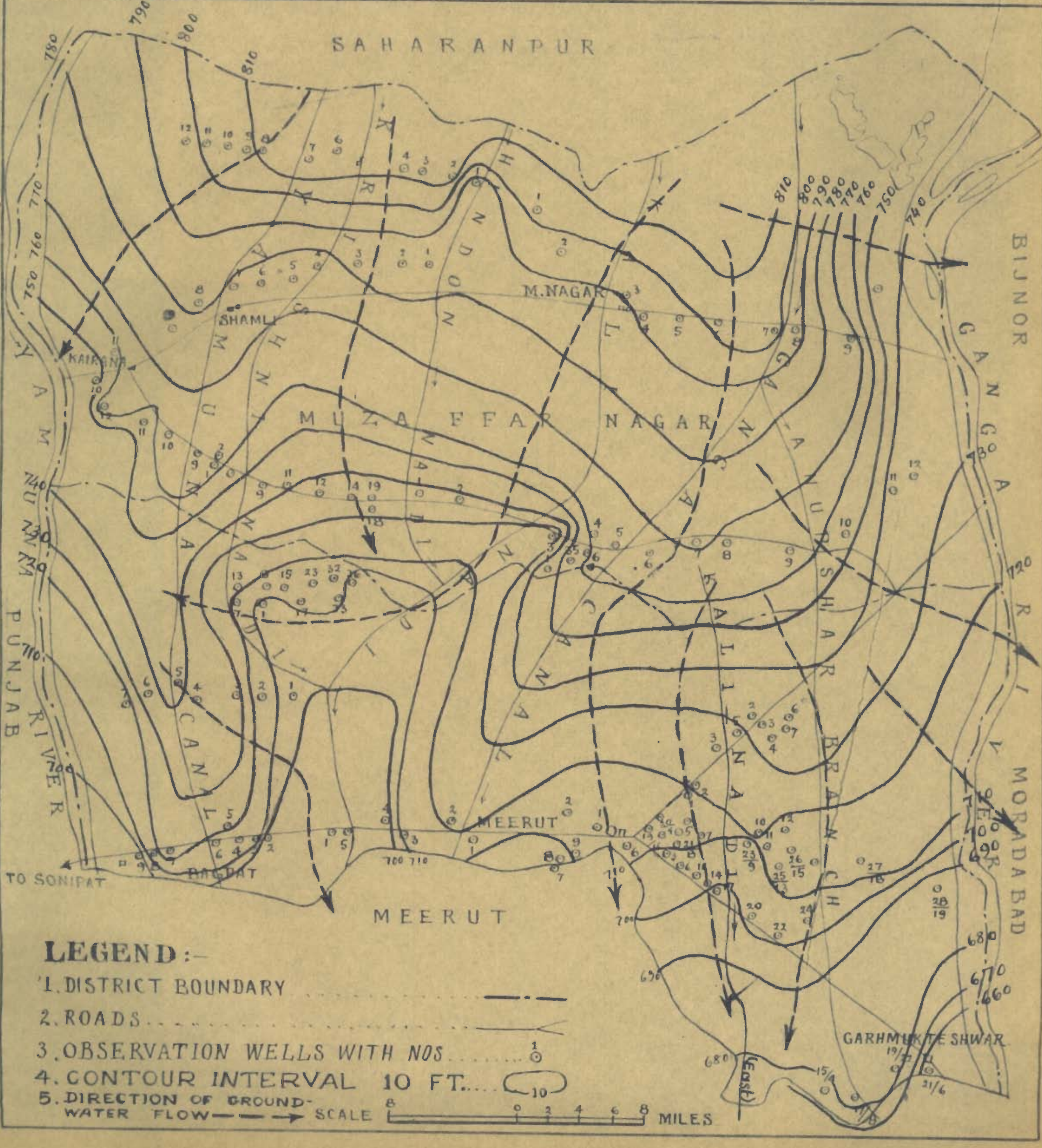
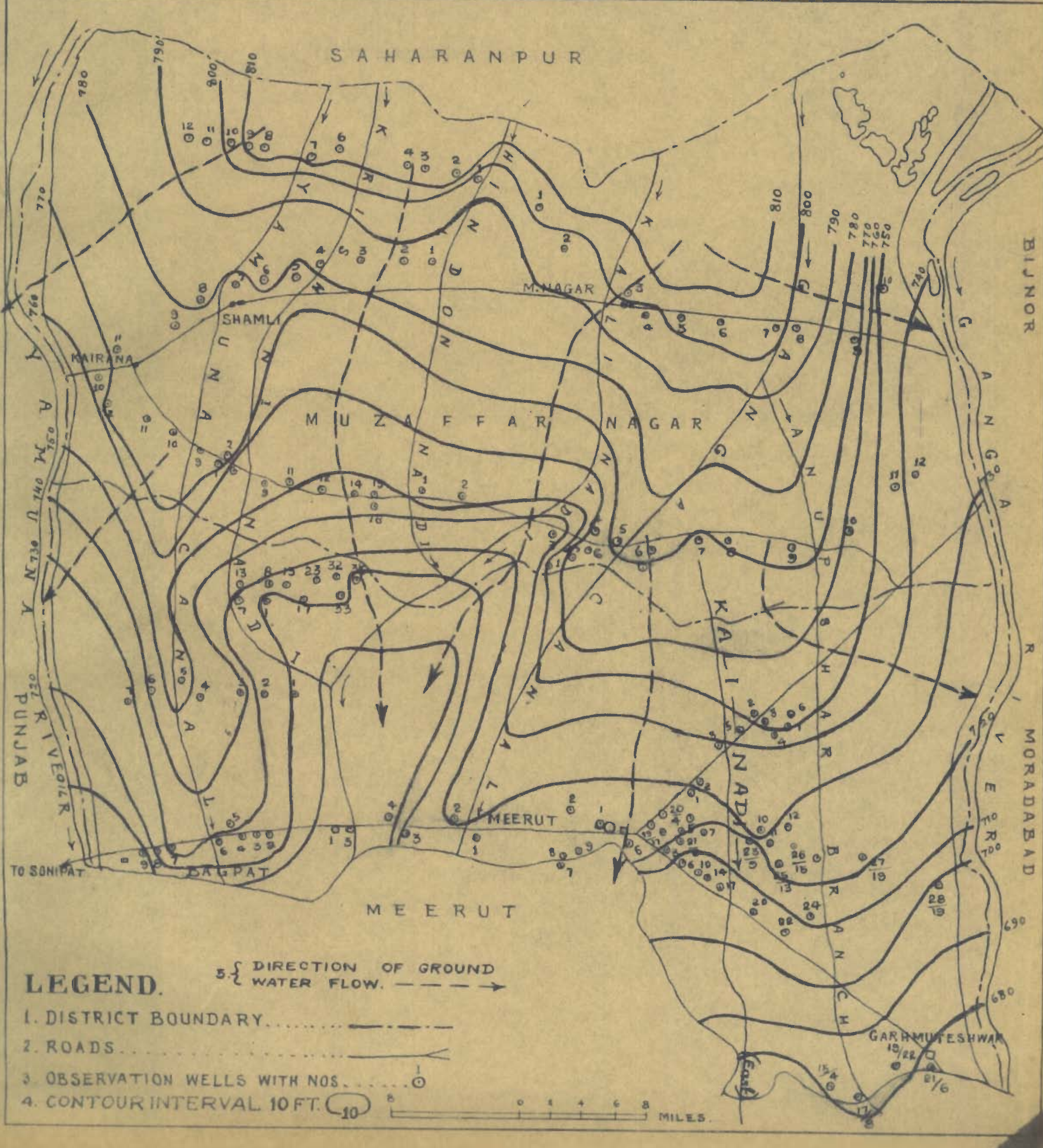


PLATE 3.8

WATER TABLE CONTOUR MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF OCT. 1965.

(HEIGHT ABOVE MEAN SEA LEVEL)



LEGEND.

1. DISTRICT BOUNDARY.........
2. ROADS..........
3. OBSERVATION WELLS WITH NOS.......
4. CONTOUR INTERVAL 10 FT.
5. DIRECTION OF GROUND WATER FLOW.

8 0 2 4 6 8 MILES.

prepared for the year 1958, 1962, 1964 and 1965, one for the premonsoon (May) and the other for the postmonsoon periods (October) for (Plate 3.1 to 3.8). From these plates it can be seen that the configuration of water table contours remains more or less, the same during the premonsoon and the postmonsoon periods but the values of various contours differ indicating thereby the effect of recharge. These maps not only indicate the distribution of ground water in the shallow reservoir but also indicate the direction of ground water flow.

A study of these water table maps indicates that the general ground water movement in the area is from north to south except at few places near the main rivers where it is north to southwest or north to southeast. The flow lines also indicate that, in general, the ground water moves towards the rivers indicating thereby the effluent nature of these streams. From the shape of the water table contours it is seen that wherever the contours cross a nadi (Stream) there is a bend of the contour in the upstream direction indicating effluent character of the streams (Tolman[33], Davis and DeWiest[32]).

It may further be added here that due to accumulation of silt in the canals there is no appreciable amount of seepage from the canals into the shallow ground water reservoir.

Near the northern boundary of the area, the water table contours are closely spaced. This feature is again noticed from the town of Khandla in the west upto the confluence of river Hindon and Krishni and also in between the town of Muzaffarnagar and river Ganga.

As there is a relation between the slope of water table and the permeability of the formations, the closeness of the water table contours would indicate a low permeability and therefore the finer grain size of the aquifer material. On the other hand the widely spaced water table contours are indicative of the presence of coarser sediments in the shallow aquifer.

The hydraulic gradient, as worked out from the water table maps, ranges from 2.8 to 3.0 ft. per mile.

The main source of recharge to the shallow aquifers is from the atmospheric precipitation (rainfall). This is also indicated by the statistical correlation of water level and rainfall data as will be discussed in Chapter 5.

DEEPER AQUIFERS

It has been pointed out earlier in this Chapter that the deeper semi-confined aquifers occur between the depth zone of 100-350 feet. The number of confined beds met within this zone are usually two to three. Generally these confined aquifers are met within the depth zones of 110-175, 200-270 and 280-350 feet. These are inter-connected with each other and therefore represent one single hydraulic unit of the area under study. Practically all the tubewells in the area tap this unit.

PIEZOMETRIC MAPS OF THE CONFINED AQUIFERS

A piezometric map (Plate 3.9) for the month of May 1965 has been prepared based on the cumulative pressure head of the aquifers lying within the depth of 100 to 300 feet. On the piezometric map a few flow lines have also been drawn to indicate the direction of ground water flow in the deeper aquifers of the area.

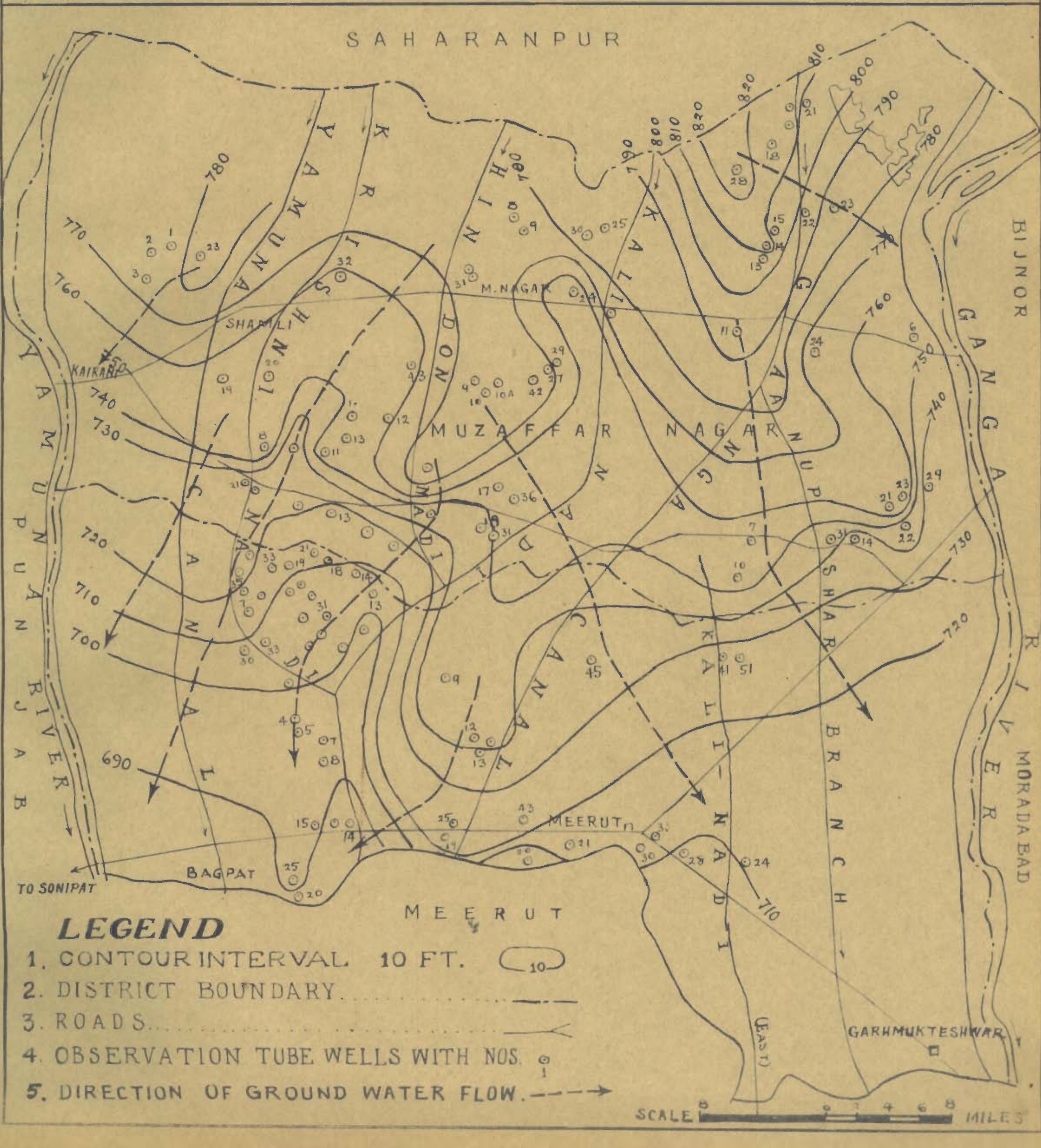
The piezometric map (Plate 3.9) indicates that isopiestic curves for the S-E portion of Muzaffarnagar area have wide spacings which is indicative of higher permeabilities. In contrast to this the contours are closely spaced in the S.S.W. part of the town. Therefore, it may be inferred that the prospects for further yield of ground water development are better in the area S-E of Muzaffarnagar in comparison to the one lying towards SSW.

The hydraulic gradient as worked out from the piezometric map ranges from 3.0 to 4.0 ft. per mile.

A comparison of the water table contour map (Plate 3.7) and Piezometric surface map (Plate 3.9) for May 1965 indicates that the configuration and the shape of the contours in two plates are quite different which indicates that the shallow and the deeper aquifers do not form a single hydraulic unit. The deeper confined aquifers are separated from the overlying water table aquifer by a thick layer of clay and kankar which is relatively impermeable. Therefore, the confined aquifers are not directly recharged from the

PLATE 3.9

PIEZOMETRIC MAP OF MUZAFFARNAGAR-MEERUT AREA FOR THE MONTH OF MAY. 1965.
(HEIGHT ABOVE MEAN SEA LEVEL)



atmospheric precipitation which takes place in this area. It appears that these aquifers are interconnected towards north with sub-surface formation of the Tarai and the Bhabar belts and these represent the most important source of recharge to the deeper aquifers. However, at places there are also interconnections between the deeper aquifers and the shallow water table aquifer in the Axial belt itself. In addition to this, during pumping from the deeper aquifers, good amount of water is also added locally due to leakage from the overlying water table aquifer. In conclusion, therefore, it must be mentioned that the recharge to deeper aquifers takes place both by lateral subsurface percolation from north and also due to vertical leakage from the overlying aquifers.

CHAPTER 4

HYDRAULIC CHARACTERISTICS OF THE AQUIFERS.

ooo

INTRODUCTION

The value of any aquifer as a fully developed source of water depends mainly on two inherent characteristics i.e. (a) its ability to store and (b) its ability to transmit water. The first is expressed in terms of coefficient of storage or storavity and the second in terms of coefficient of Transmissibility or transmissivity (DeWiest[32]). These provide the very basis on which quantitative studies are based. In this Chapter the various aquifer characteristics are described as determined from the pump tests carried out from a number of tubewells in the area. It will be necessary to define the various aquifer characteristics and describe methods which have been used before giving the actual application of the methods and the evaluation of the various hydrological characteristics of alluvial aquifers. Fifteen pump tests were conducted during the present investigations and both the drawdown data and the recovery data were collected from the observation wells. These were analysed by (1) Theis-type curve method, (2) Theis-Jacob straight line method, (3) Hantush - Jacob leaky-artesian type curve method and (4) Hantush leaky - artesian aquifer straight line method. The methods employed and the interpretations made are described in the following pages.

DEFINITION OF HYDRAULIC CHARACTERISTS

1. COEFFICIENT OF TRANSMISSIBILITY (T) is defined as the rate of flow of water, at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer one foot wide and having the height a equal to the thickness of the aquifers, under a hydraulic gradient of 100 percent or one foot per foot. It is expressed in gallons per day per foot (gpd/ft.) or cubic metres per day per metre ($m^3/d/m$).

2. COEFFICIENT OF STORAGE (S) is defined as the volume of water that an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Generally it is expressed as a decimal fraction. For artesian conditions the value ranges from about 0.00001 to 0.001 and for the unconfined aquifers the value varies from about 0.05 to 0.30 (Ferris et al[34]). For phreatic ground water (water table conditions) it is equal to the specific yield.

3. FIELD COEFFICIENT OF PERMEABILITY (P_f) is expressed as the rate of flow of water at the prevailing field temperature in gallons per day through a cross section of aquifer one foot thick and one mile wide under a hydraulic gradient of one foot per mile (Wenzel[29]). It is expressed in gallons per day per square foot ($gpd/ft.^2$).

METHODS OF AQUIFER PERFORMANCE TESTS

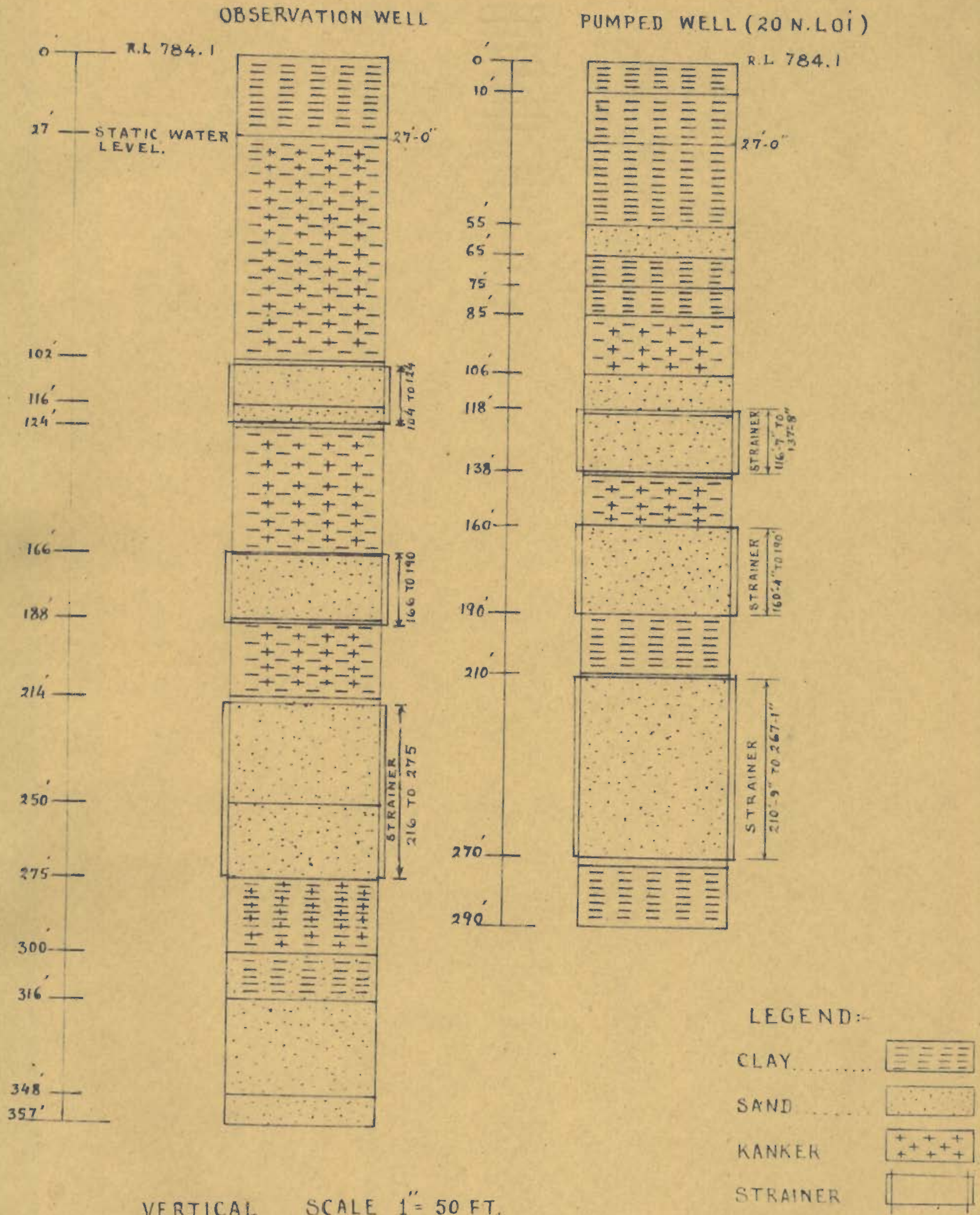
In order to determine the aquifer constants, 15 pump tests were conducted in Muzaffarnagar-Meerut districts. The individual tests were run for varying periods but the maximum duration was not more than 40 hours. The abondoned tubewells in the neighbourhood of the newly constructed tubewells (Pumped well) were used as observation wells. The pumping was carried out by a deep well turbine pump. Location of these pumped wells is shown in (Plate 4.1).

The wells were pumped at a constant rate of discharge varying from 377 U.S. gpm to 667 U.S. gpm. In all the hydrological tests, measurements for the quantity of water pumped at a constant discharge from the pumped wells were made with the standard V-notch fixed to the tubewells. The water level measurements were made by a steel tape lowered along with a copper electrode connected to the battery. Wherever available the observations of water level in the shallow dug-wells were also made.

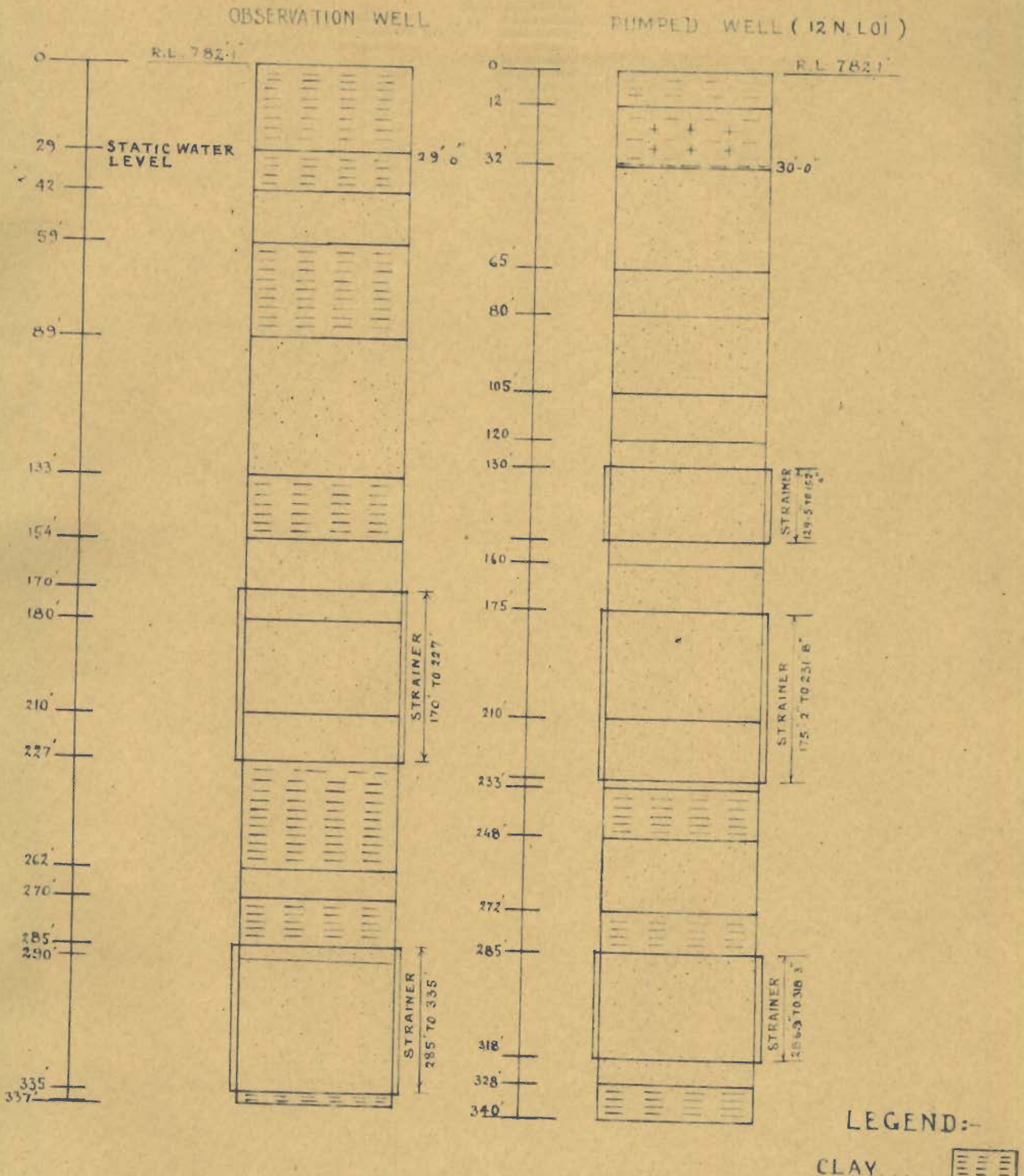
The observations of drawdown were taken in the observation wells which almost tap the same aquifers. The lithological log and position of the strainers in the pumped wells and the observation wells of only 7 bore holes have been shown in Plates 4.2 to 4.8. From the lithological logs it can be seen that both the pumping wells and the observation wells are tapping water from the aquifers which are overlain by comparatively impermeable clay formations intercalated with

PLATE 4.1

LOCATION OF TUBEWELLS USED- FOR PUMPTEST.

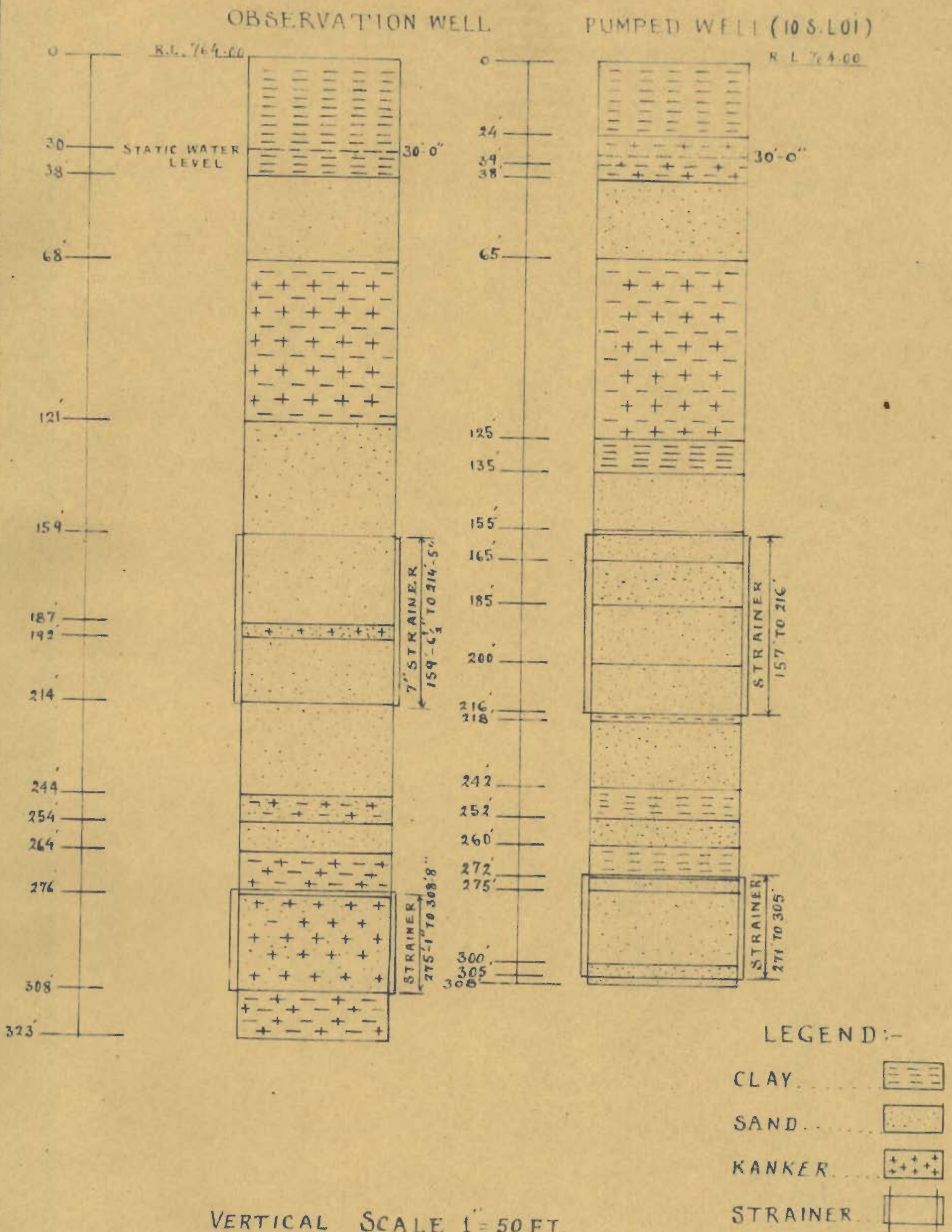


LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 80 FT. FROM PUMPED WELL.

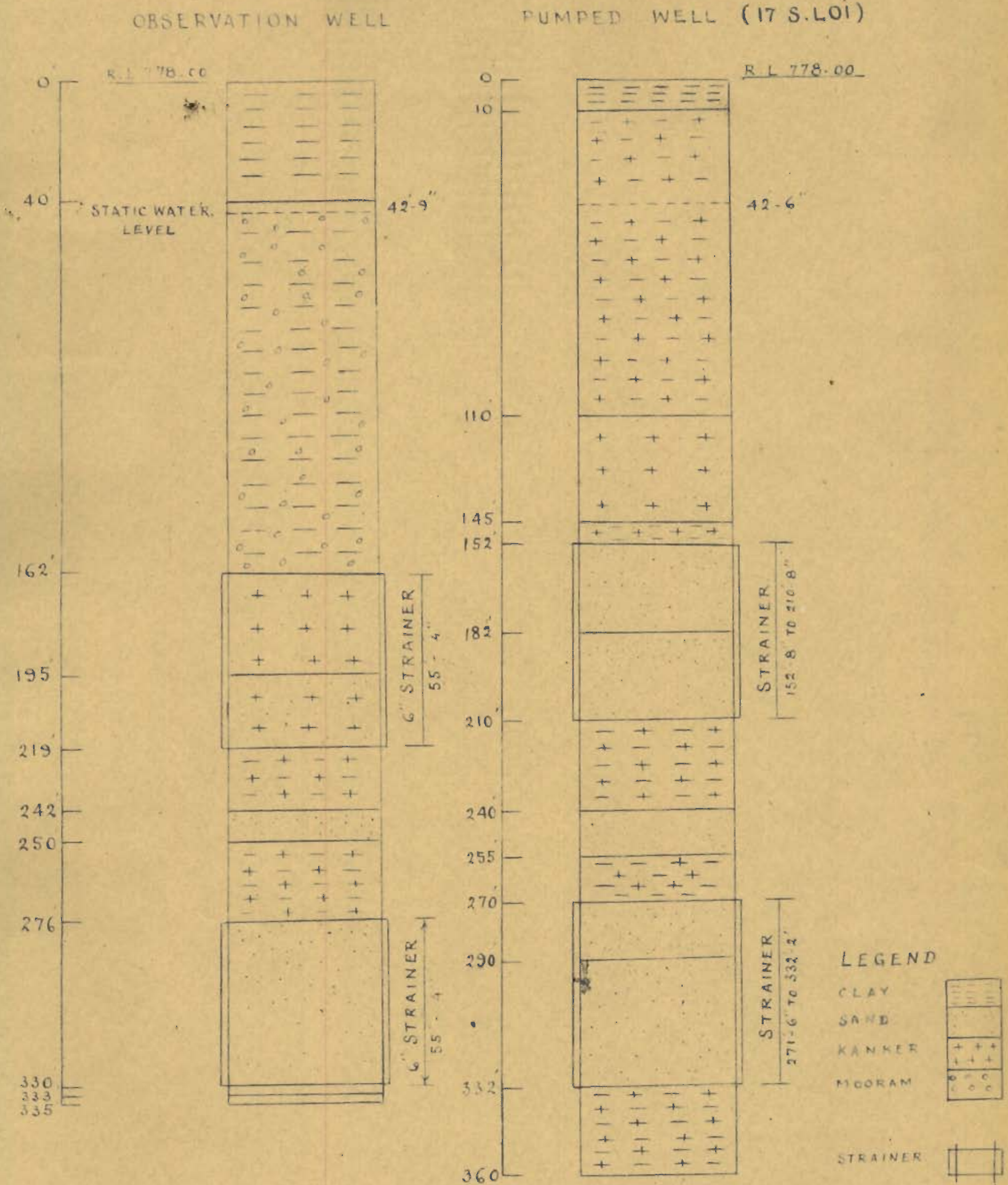


VERTICAL SCALE 1" = 50 FT.

LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 133 FT. FROM PUMPED WELL.



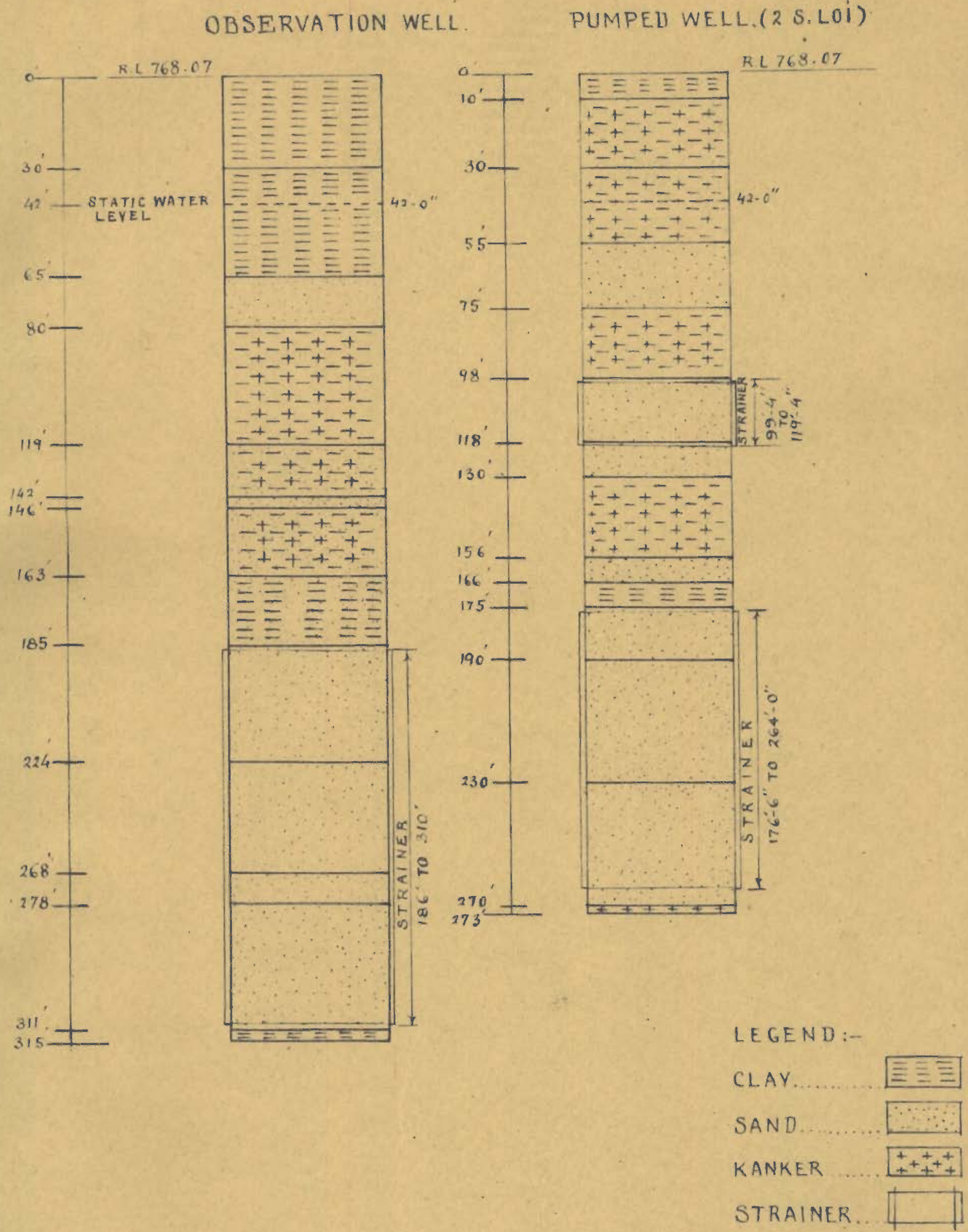
LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 33 FT. FROM PUMPED WELL.



VERTICAL SCALE 1" = 50 FT.

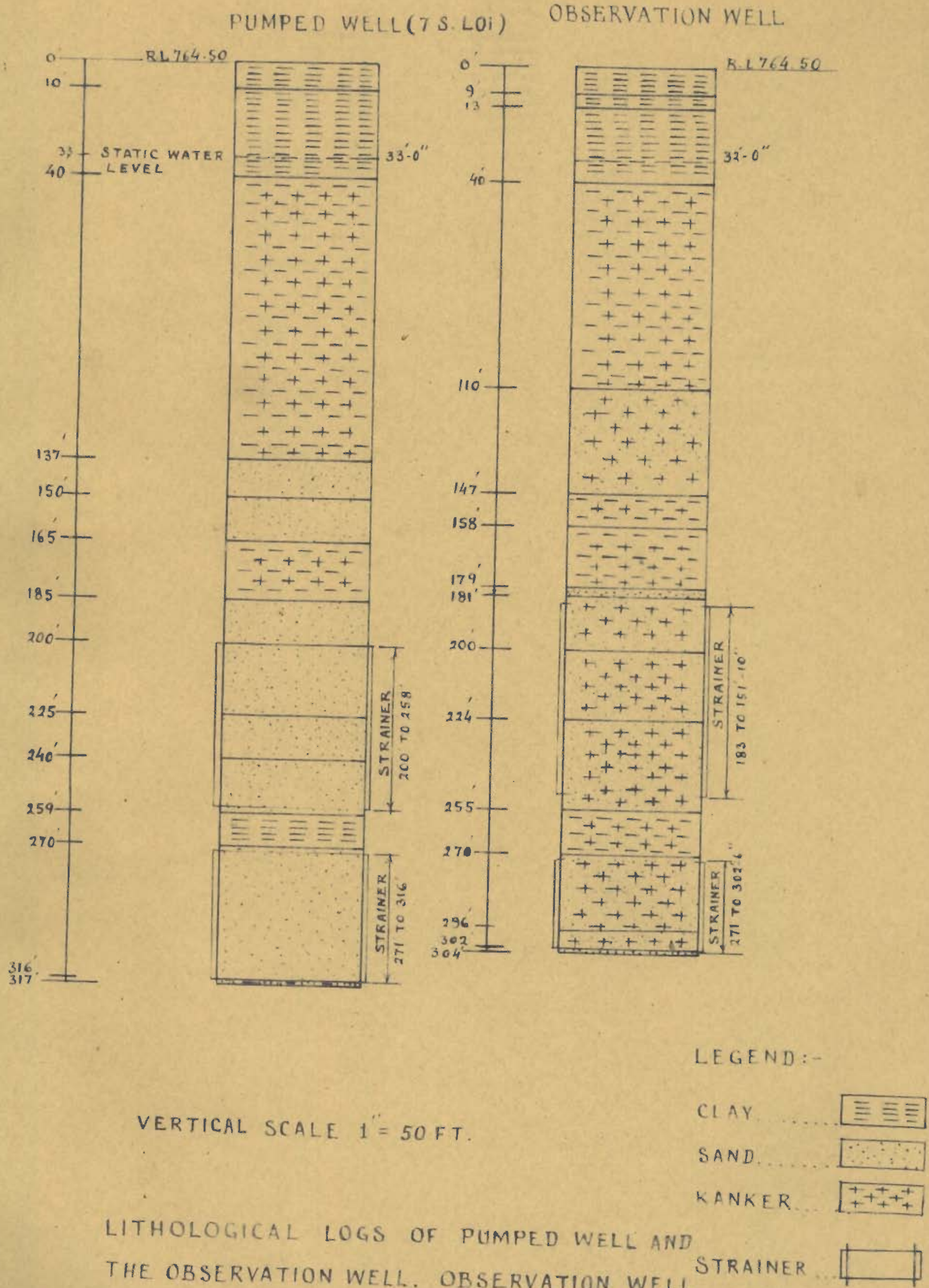
LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 103 FT. FROM PUMPED WELL.

PLATE 4.6



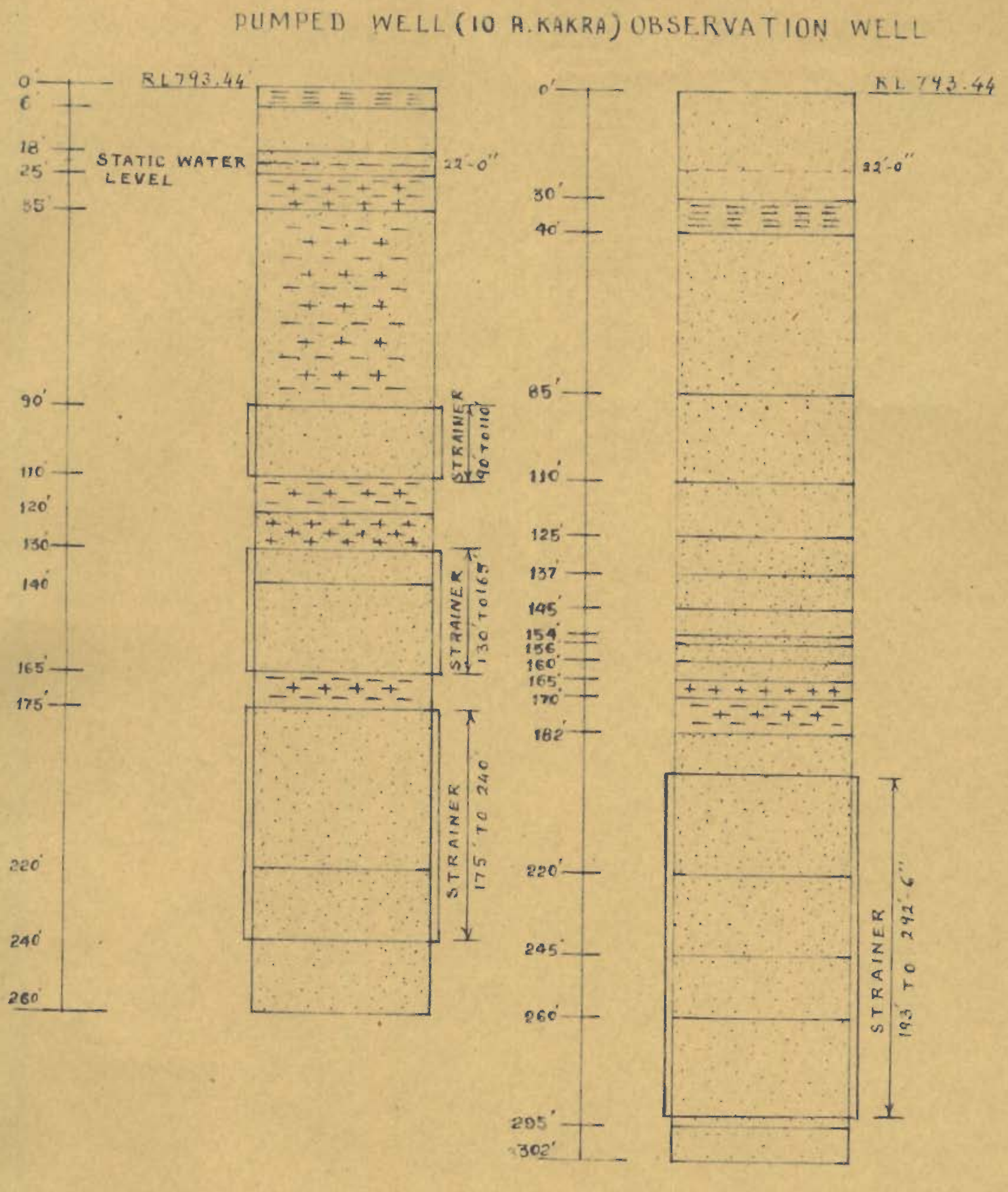
VERTICAL SCALE 1" = 50 FT.

LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 40 FT. FROM PUMPED WELL.



VERTICAL SCALE 1" = 50 FT.

LITHOLOGICAL LOGS OF PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 44 FT. FROM PUMPED WELL.



VERTICAL SCALE 1" = 50 FT.

LEGEND:-
CLAY
SAND
KANKER
STRAINER

LITHOLOGICAL LOGS OF THE PUMPED WELL AND THE OBSERVATION WELL. OBSERVATION WELL IS 95 FT. FROM PUMPED WELL.

mooram and kankar in a few cases. These comparatively impermeable units represent the formations through which leakage occurs during pumping and therefore these can be classified as aquitards (DeWiest[32]). The regional nature of the lithological formations have already been discussed in chapter 2 which clearly indicates that the overlying confining layers are laterally quite extensive. In each test, the drawdown and recovery data were collected from one observation well. Data from only one such pump test are given in Table 4.1 while the data from other 14 tests are not given in the tabular form. This is to keep the number of pages to a minimum. However, data from all these tests have been plotted and analysed by various methods. The drawdown data have been analysed by (1) Theis - type curve method, (2) Theis-Jacob straight-line method, (3) Hantush-Jacob leaky artesian type curve method and (4) Hantush leaky-artesian aquifer straight line method.

(Table 4.1 on page 44)

Table 4.1 PUMP TEST DATA OF OBSERVATION WELL NEAR TUBEWELL No. 20 NORTH LOI IN MUZAFFARNAGAR DISTRICT

Sl. No.	Location of tested well.	Distance of observation well from pumped well (in ft)	Date of test	Hour	Depth to water level (in ft.)	t	t'	t/t'	Residual drawdown (in ft.) s'
1	2	3	4	5	6	7	8	9	10
1.	Tubewell No. 20 North-Loi	80	7.3.1965	5:50	27.0				
				5:55	27.0				
				6:00	Pump started constant discharge 408 (US)GPM				
				6:1.0	27.92				
				6:1.5	28.17				
				6:2.0	28.25				
				6:2.5	28.33				
				6:3.0	28.42				
				6:3.5	28.46				
				6:4.0	28.50				
				6:4.5	28.54				
				6:5.0	28.58				
				6:5.5	28.62				
				6:6.0	28.67				
				6:6.5	28.71				
				6:7.0	28.75				
				6:7.5	28.79				
				6:8.0	28.83				
				6:8.5	28.83				
				6:9.0	28.87				
				6:9.5	28.92				
				6:10	28.92				
				6:11	28.96				

contd.

1	2	3	4	5	6	7	8	9	10
				6:12	29.00				
				6:13	29.04				
				6:14	29.08				
				6:15	29.13				
				6:16	29.17				
				6:17	29.21				
				6:18	29.25				
				6:19	29.33				
				6:20	29.37				
				6:21	29.42				
				6:22	29.46				
				6:23	29.50				
				6:24	29.54				
				6:25	29.58				
				6:30	29.67				
				6:35	29.71				
				6:40	29.75				
				6:45	29.79				
				6:50	29.83				
				6:55	29.92				
				7:00	29.96				
				7:10	30.04				
				7:20	30.08				
				7:30	30.13				
				7:40	30.17				
				7:45	30.17				
				8:10	30.17				
				8:40	30.21				
				8:55	30.21				
				9:00	30.25				
				9:15	30.29				
				9:30	30.33				
				10:00	30.33				
				10:30	30.33				
				11:00	30.33				
				11:30	30.33				
				12:00	30.33	Pump stopped			

1	2	3	4	5	6	7	8	9	10
				12:01	29.75	361	1.0	361	2.75
				12:01.5	29.67	361.5	1.5	241	2.67
				12:02	29.58	362	2.0	181	2.58
				12:02.5	29.50	362.5	2.5	145	2.50
				12:03	29.42	363	3.0	121	2.42
				12:03.5	29.37	363.5	3.5	103	2.37
				12:04	29.33	364	4.0	91	2.33
				12:04.5	29.291	364.5	4.5	81	2.291
				12:05	29.25	365	5.0	73	2.25
				12:05.5	29.21	365.5	5.5	66	2.21
				12:06	29.17	366	6.0	61	2.17
				12:06.5	29.13	366.5	6.5	56	2.13
				12:07	29.13	367	7.0	52	2.13
				12:07.5	29.083	367.5	7.5	49	2.083
				12:08	29.042	368	8.0	46	2.042
				12:08.5	29.04	368.5	8.5	43	2.04
				12:09	29.00	369	9.0	41	2.00
				12:10	28.96	370	10.0	37	1.96
				12:11	28.92	371	11.0	33	1.92
				12:12	28.87	372	12.0	31	1.87
				12:13	28.83	373	13.0	28	1.83
				12:14	28.79	374	14.0	26	1.79
				12:15	28.75	375	15.0	25	1.75
				12:16	28.71	376	16.0	23.5	1.71
				12:17	28.67	377	17.0	22	1.67
				12:18	28.67	378	18.0	21	1.67
				12:19	28.62	379	19.0	19.5	1.62
				12:20	28.58	380	20.0	19	1.58
				12:21	28.54	381	21.0	18	1.54
				12:22	28.50	382	22.0	17	1.50
				12:23	28.46	383	23.0	16.6	1.46
				12:24	28.42	384	24.0	16	1.42
				12:25	28.37	385	25	15.4	1.37
				12:30	28.33	390	30	13.0	1.33

contd.

1	2	3	4	5	6	7	8	9	10
				12:35	28.25	395	35	11.3	1.25
				12:40	28.21	400	40	10.0	1.21
				12:45	28.17	405	45	9.0	1.17
				12:50	28.08	410	50	8.0	1.08
				12:55	28.00	415	55	7.5	1.00
				13:00	27.92	420	60	7.0	0.92
				13:10	27.87	430	70	6.0	0.87
				13:20	27.83	440	80	5.5	0.83
				13:30	27.75	450	90	5.0	0.75
				13:40	27.67	460	100	4.6	0.67
				13:55	27.58	475	115	4.1	0.58
				14:10	27.46	490	130	3.8	0.46
				14:25	27.42	505	145	3.4	0.42
				14:40	27.37	520	160	3.2	0.37
				14:55	27.33	535	175	3.0	0.33
				15:00	27.25	540	180	2.9	0.25
				15:30	27.17	570	210	2.7	0.17
				16:00	27.08	600	240	2.5	0.08
				16:30	27.04	630	270	2.33	0.04
				17:00	27.04	660	300	2.20	0.04
				17:30	27.00	690	330	2.09	0
				18:00	27.00	720	360	2.0	0

(Table 4.1 contd.)

Tubewell No.	Hour	Time since pumping began t: Minutes	Days.	Drawdown in ft.	r^2/t (ft.^{2})day
1	2	3	4	5	6
20 North Loi		1.0	6.94×10^{-4}	0.92	9.2×10^{6}
		1.5	1.04×10^{-3}	1.17	6.2×10^{6}
		2.0	1.39×10^{-3}	1.25	4.6×10^{6}
		2.5	1.74×10^{-3}	1.33	3.7×10^{6}
		3.0	2.09×10^{-3}	1.42	3.0×10^{6}
		3.5	2.44×10^{-3}	1.46	2.6×10^{6}
		4.0	2.78×10^{-3}	1.50	2.3×10^{6}
		4.5	3.12×10^{-3}	1.54	2.0×10^{6}
		5.0	3.47×10^{-3}	1.58	1.8×10^{6}
		5.5	3.81×10^{-3}	1.62	1.6×10^{6}
		6.0	4.17×10^{-3}	1.67	1.5×10^{6}
		6.5	4.51×10^{-3}	1.71	1.4×10^{6}
		7.0	4.86×10^{-3}	1.75	1.3×10^{6}
		7.5	5.20×10^{-3}	1.79	1.2×10^{6}
		8.0	5.51×10^{-3}	1.83	1.1×10^{6}
		8.5	5.90×10^{-3}	1.83	1.1×10^{6}
		9.0	6.25×10^{-3}	1.87	1.0×10^{6}
		9.5	6.50×10^{-3}	1.92	9.9×10^{5}
		10.0	6.96×10^{-3}	1.92	9.1×10^{5}
		11.0	7.60×10^{-3}	1.96	8.3×10^{5}
		12.0	8.33×10^{-3}	2.0	7.6×10^{5}
		13.0	9.10×10^{-3}	2.042	7.0×10^{5}
		14.0	9.72×10^{-3}	2.083	6.5×10^{5}
		15.0	1.04×10^{-2}	2.13	6.1×10^{5}
		16.0	1.11×10^{-2}	2.17	5.7×10^{5}
		17.0	1.19×10^{-2}	2.21	5.3×10^{5}
		18.0	1.25×10^{-2}	2.25	5.1×10^{5}
		19.0	1.31×10^{-2}	2.33	4.8×10^{5}
		20.0	1.40×10^{-2}	2.37	4.6×10^{5}
		21.0	1.45×10^{-2}	2.42	4.4×10^{5}
		22.0	1.52×10^{-2}	2.46	4.2×10^{5}
		23.0	1.59×10^{-2}	2.50	4.0×10^{5}

contd.

1	2	3	4	5	6
		24.0	1.67×10^{-2}	2.54	3.8×10^{5}
		25.0	1.73×10^{-2}	2.58	3.6×10^{5}
		30.0	2.09×10^{-2}	2.67	3.0×10^{5}
		35.0	2.43×10^{-2}	2.71	2.6×10^{5}
		40.0	2.77×10^{-2}	2.75	2.3×10^{5}
		45.0	3.12×10^{-2}	2.79	2.0×10^{5}
		50.0	3.47×10^{-2}	2.83	1.8×10^{5}
		55.0	3.82×10^{-2}	2.92	1.6×10^{5}
		60.0	4.17×10^{-2}	2.96	1.5×10^{5}
		70.0	4.86×10^{-2}	3.042	1.3×10^{5}
		80.0	5.55×10^{-2}	3.083	1.1×10^{5}
		90.0	6.25×10^{-2}	3.13	1.0×10^{5}
		100.0	6.80×10^{-2}	3.17	9.2×10^{4}
		115.0	7.98×10^{-2}	3.17	8.3×10^{4}
		130.0	9.02×10^{-2}	3.17	7.1×10^{4}
		160.0	1.11×10^{-1}	3.21	5.7×10^{4}
		175.0	1.22×10^{-1}	3.21	5.2×10^{4}
		180.0	1.25×10^{-1}	3.25	5.0×10^{4}
		195.0	1.36×10^{-1}	3.29	4.7×10^{4}
		210.0	1.46×10^{-1}	3.35	4.4×10^{4}
		240.0	1.67×10^{-1}	3.33	3.8×10^{4}
		270.0	1.80×10^{-1}	3.33	3.4×10^{4}
		300.0	2.08×10^{-1}	3.33	3.0×10^{4}
		330.0	2.22×10^{-1}	3.33	2.8×10^{4}
		360.0	2.50×10^{-1}	3.33	2.5×10^{4}

ANALYSES OF DATA

Nonequilibrium Formula

In 1935 a major advancement was made in well hydraulics by Theis (Ferris et al[34]), who derived the non-equilibrium formula introducing the time factor and the storage. He derived the non-equilibrium formula by analogy between the flow of ground water and the flow of heat by conduction.

Based on the non-equilibrium theory, it is possible to predict future performance of the well and to determine the Coefficient of Transmissibility (T) and the Coefficient of Storage (S) which are also known as formation constants. Another distinct advantage of the non-equilibrium method over the equilibrium method is that it enables the determination of hydrological boundaries.

The non-equilibrium formula is

$$s = \frac{114.6Q}{T} \int_u^{\infty} \frac{e^{-u}}{u}\, du \quad .. \quad .. \quad (4.1)$$

where $u = \frac{1.87\, r^2\, S}{Tt}$

s = drawdown in feet, at any point of observation in the vicinity of a well discharging at a constant rate,

Q = discharge of a well in gallons per minute,

T = transmissibility, in gallons per day per foot,

r = distance in feet, from the discharging well to the point of observation,

S = Coefficient of storage, expressed as a decimal fraction,

t = time in days since pumping started.

The non-equilibrium formula is based on the following assumptions:

1. The aquifer is homogeneous and isotropic.
2. The aquifer is of infinite areal extent.
3. That its transmissibility is constant.
4. That it is confined between impermeable beds.
5. The coefficient of storage is constant and
6. The water is released from storage instantaneously with a decline in artesian head.

The integral expression in equation (1) cannot be integrated directly, but its value is given by the series.

$$\int_{1.87\, r^2 S/Tt}^{\infty} \frac{e^{-u}}{u}\, du = W(u) = -.577216 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} \quad (4.2)$$

Whereas given earlier $u = \frac{1.87\, r^2\, S}{Tt}$ .. .. .. (4.3) and W (u) is known as well function of u or well function of non-leaky aquifers.

Hence equation (4.1) can be re-written as

$$s = \frac{114.6\, Q}{T}\, W(u) \quad \text{.. .. .. (4.4)}$$

It is not possible, however, to determine T and S directly from the above equations. Two methods are used in the application of this formula i.e. (1) The type curve method and (2) The straight line method.

Type curve method

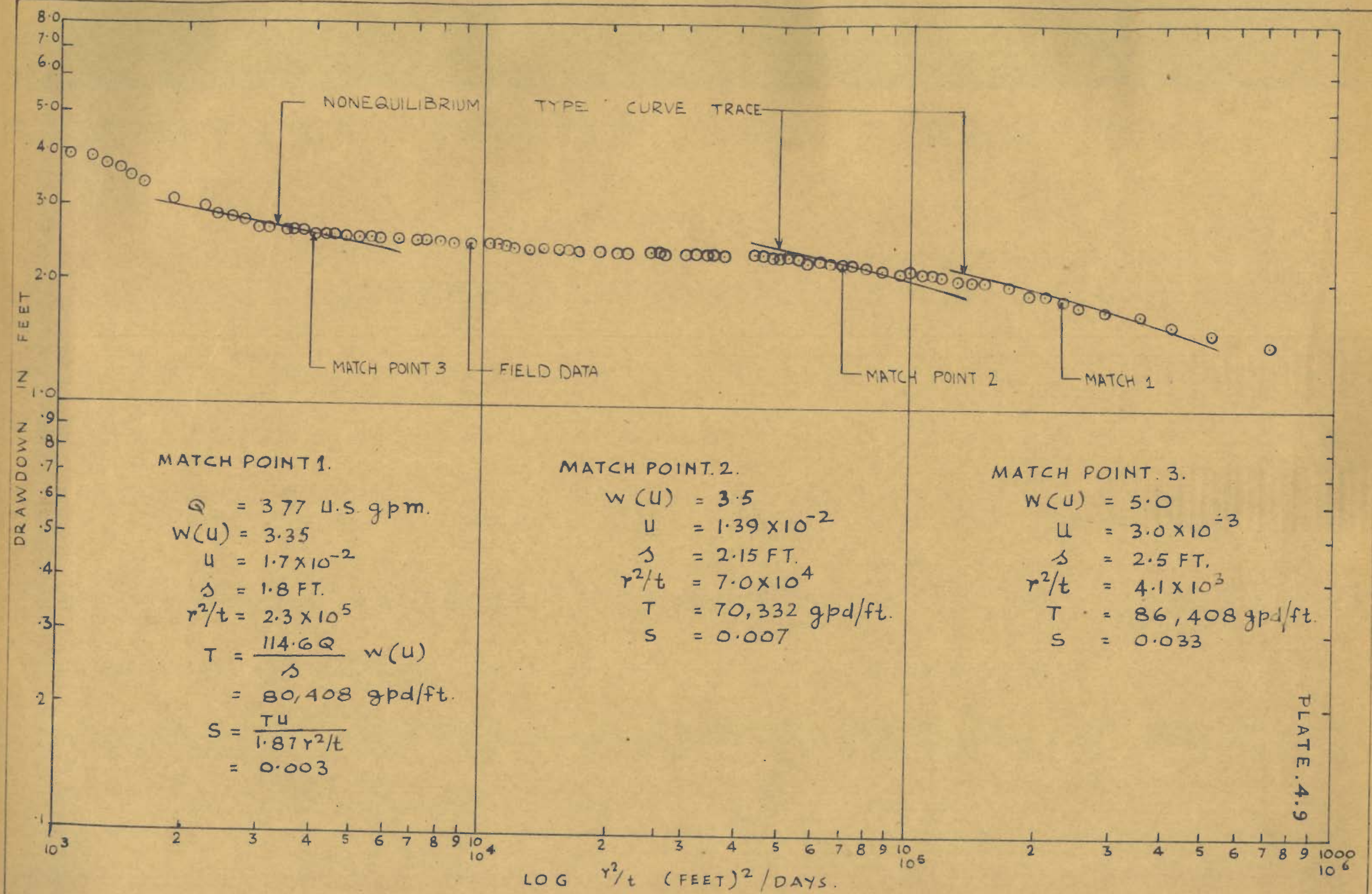
First a plot of W(u) versus u is made on a logarithmic paper. This plot is known as the type curve. On another logarithmic paper of the same scale r^2/t is plotted against s to obtain the data curve. The data curve is superposed on the type curve and a match point is obtained for which values of r^2/t and s are read from the data curve sheet and W(u) and u from the type curve sheet. Transmissibility coefficient (T) and storage coefficient (S) are calculated from these data by rewriting equation (4.4) and (4.3) as

$$T = \frac{114.6\ Q}{s} W(u) \qquad \ldots \ldots \ldots (4.5)$$

and $$S = \frac{Tu}{1.87\ r^2/t} \qquad \ldots \ldots \ldots (4.6)$$

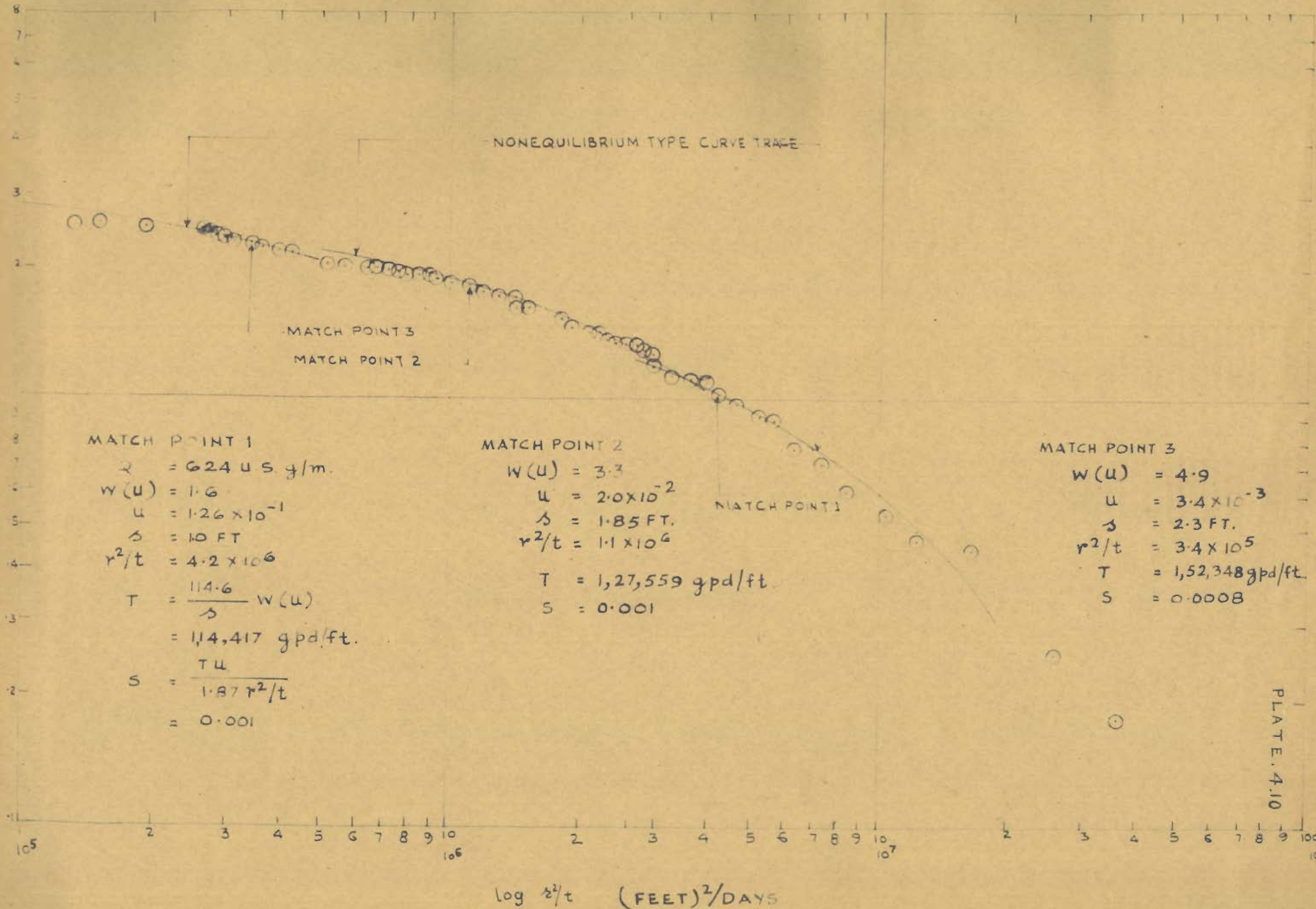
The non-equilibrium formula is theoritically applicable from the very start of the pumping test; however, the earlier data may not be reliable due to the assumptions of instantaneous release of water from storage and constant value of S . It is therefore, desired that pumping should be allowed as long as possible so that S becomes fairly constant.

For the tests carried out in the present area, the data curves do not match completely with the type curves but parts of the two curves match for various tests. For each test, three match points have been determined as 1, 2 and 3 (Plate 4.9 to 4.23). Point 1 is for the earlier part of pumping and point 3 for the later part while point 2 is for the intermediate period. T and S have been calculated for the various match points and their values are given in Plates 4.9 to 4.23. In Table 4.2 is shown the variation in the computed values of T and S with time of pumping.



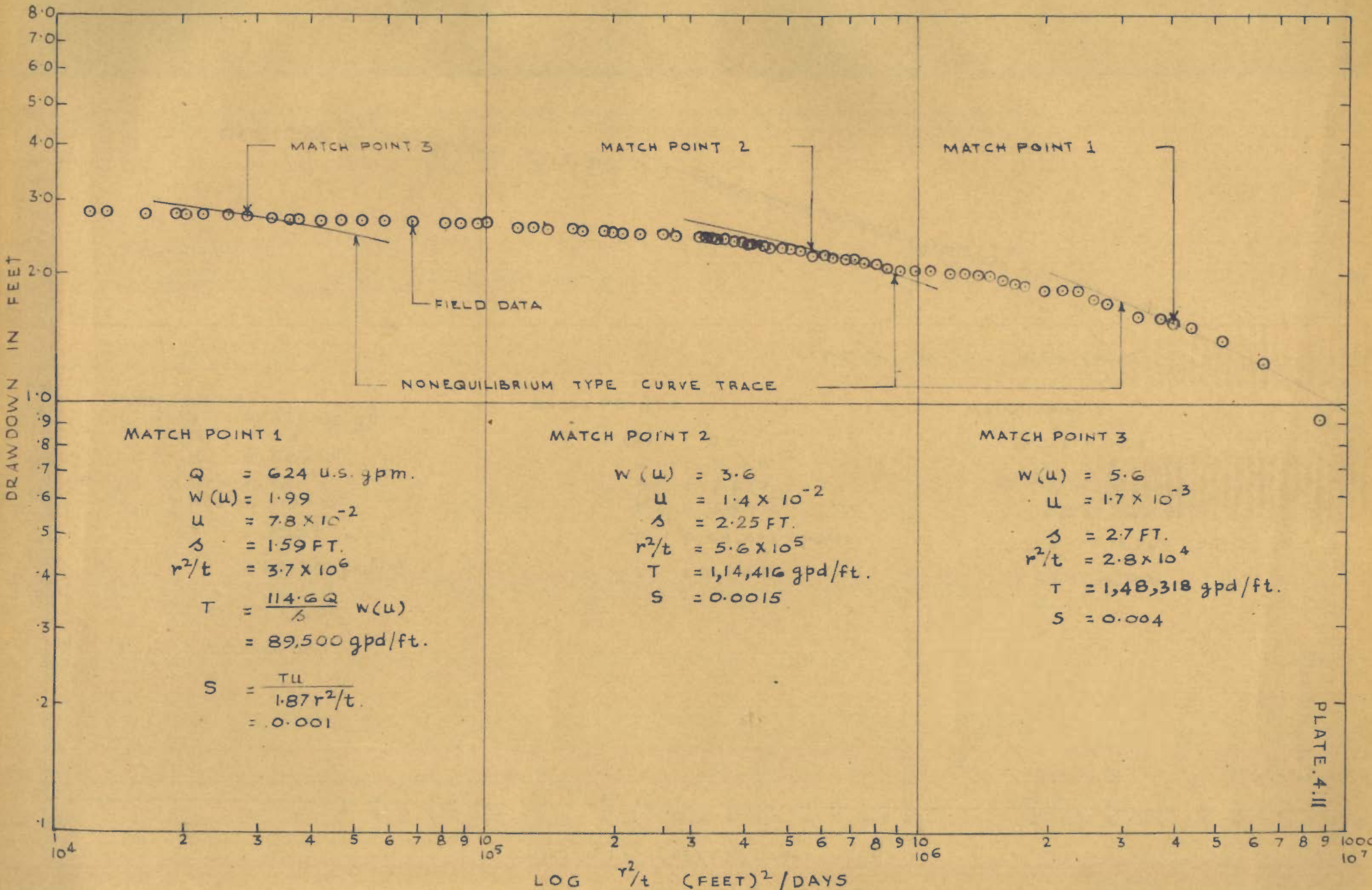
TIME DRAWDOWN GRAPH FOR WELL No. 11 N.L

PLATE. 4.9

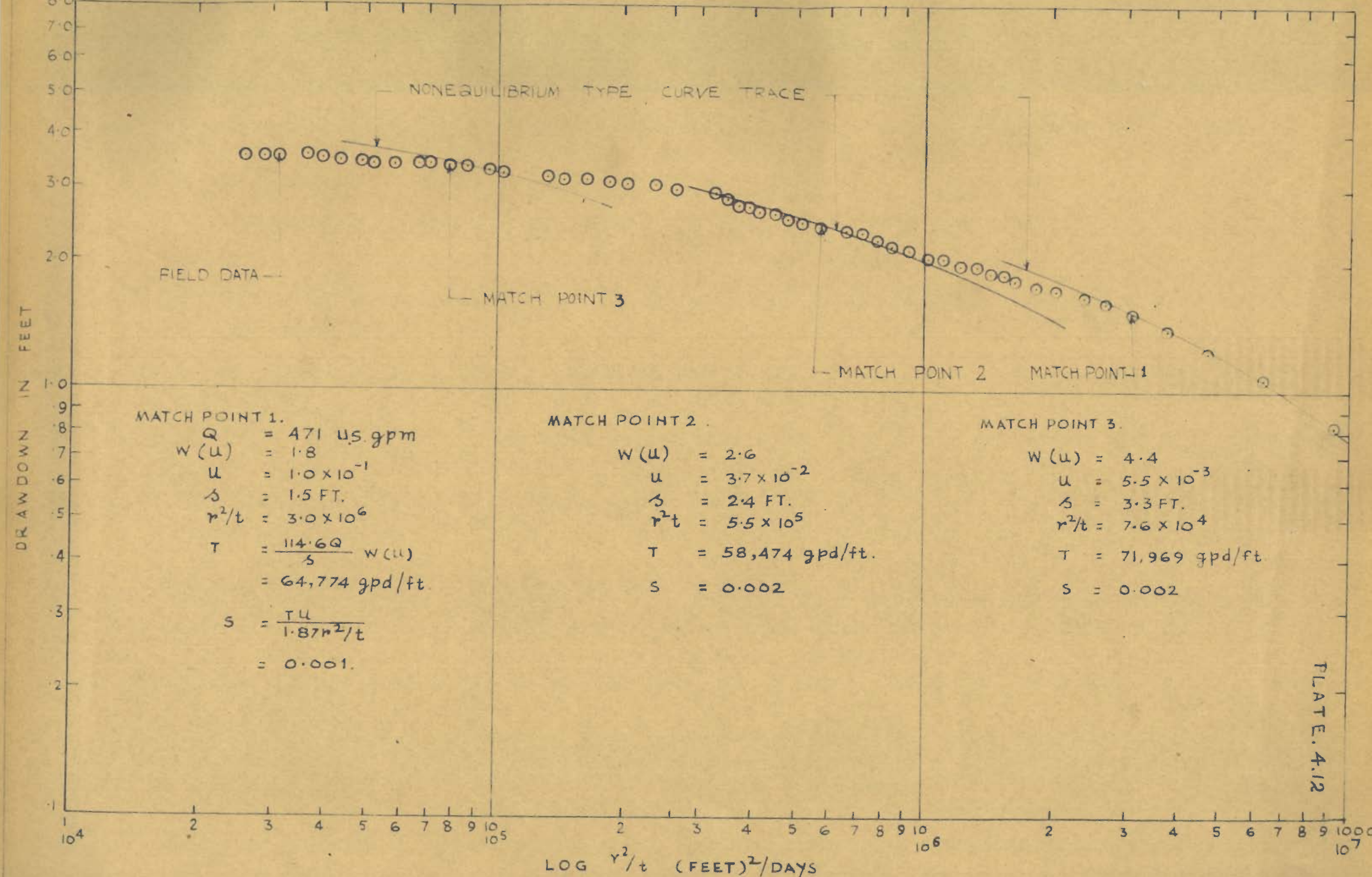


TIME DRAWDOWN GRAPH FOR WELL No. 12.N.L.

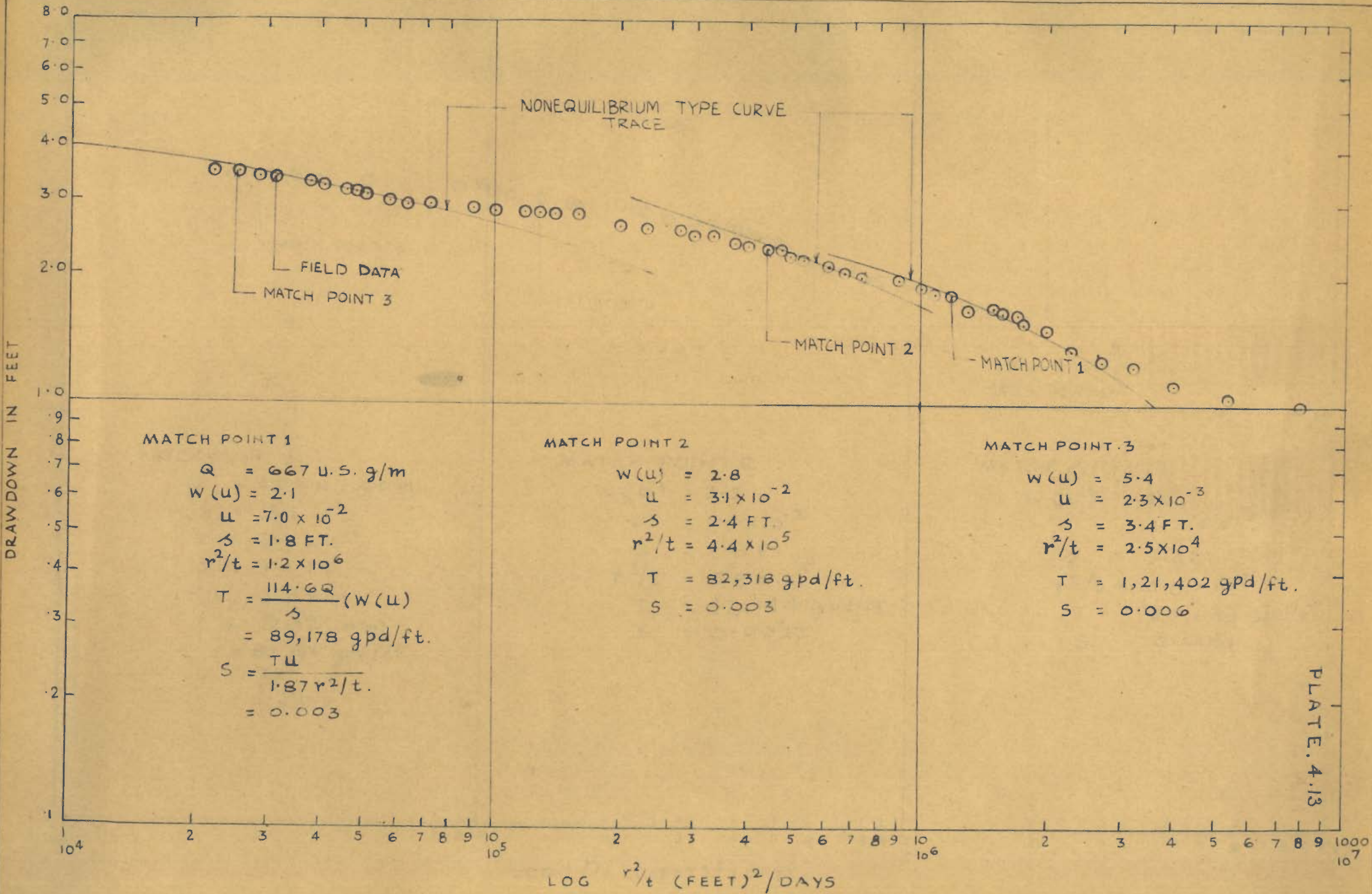
PLATE. 4.10



TIME DRAWDOWN GRAPH FOR WELL No. 13 N.L.



TIME DRAWDOWN GRAPH FOR WELL No. 17. N.L



TIME DRAWDOWN GRAPH FOR WELL No. 19 N.L.

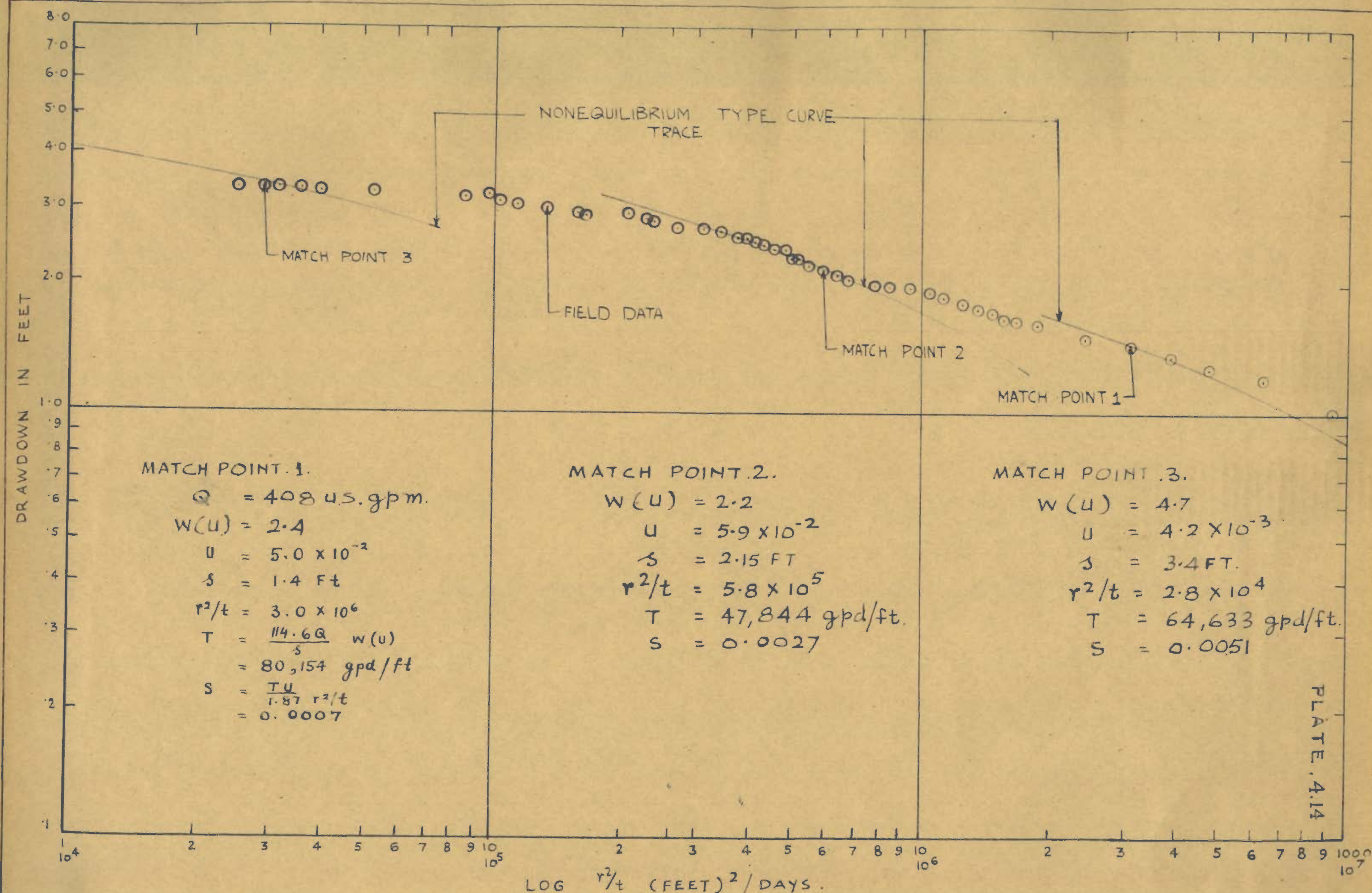
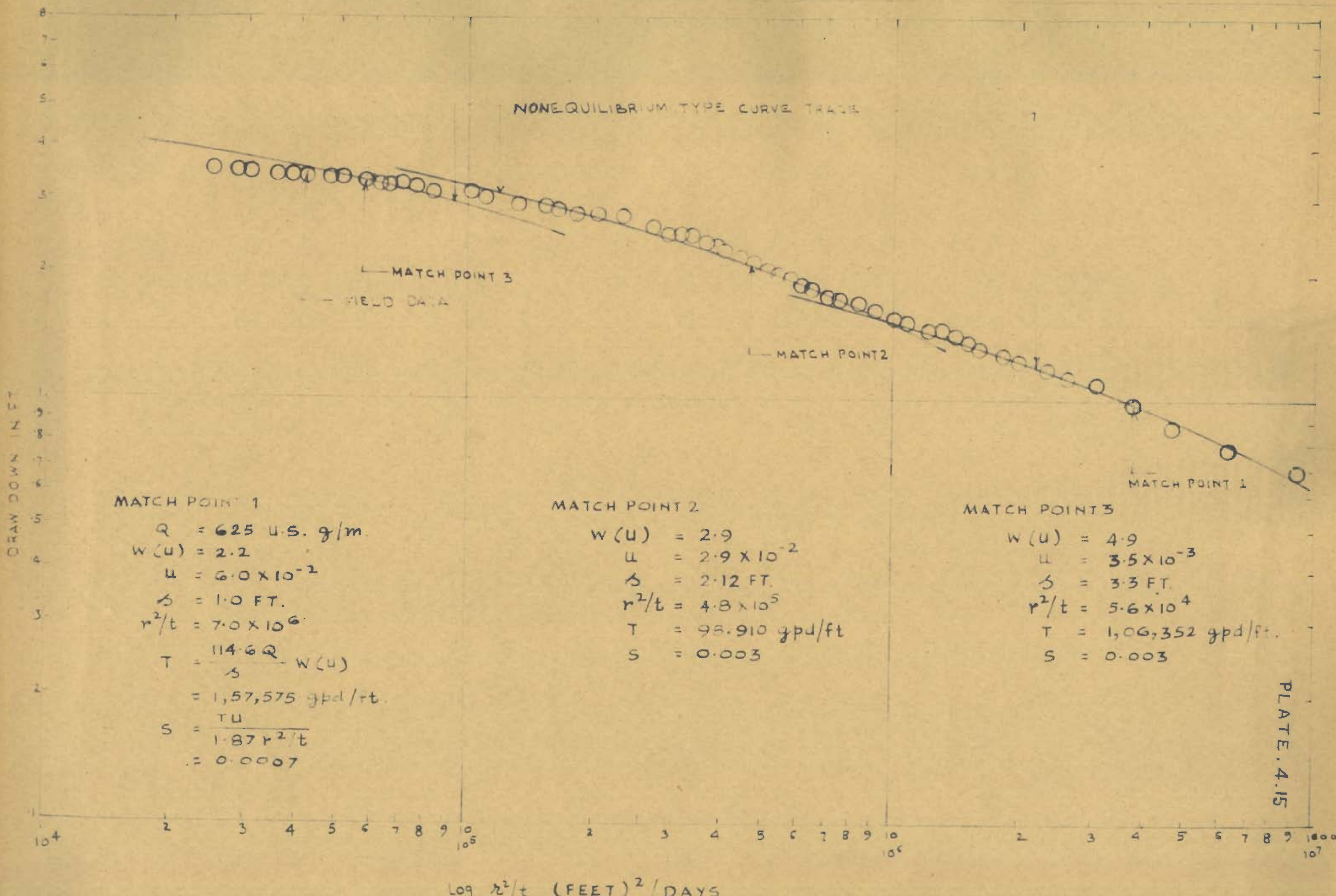


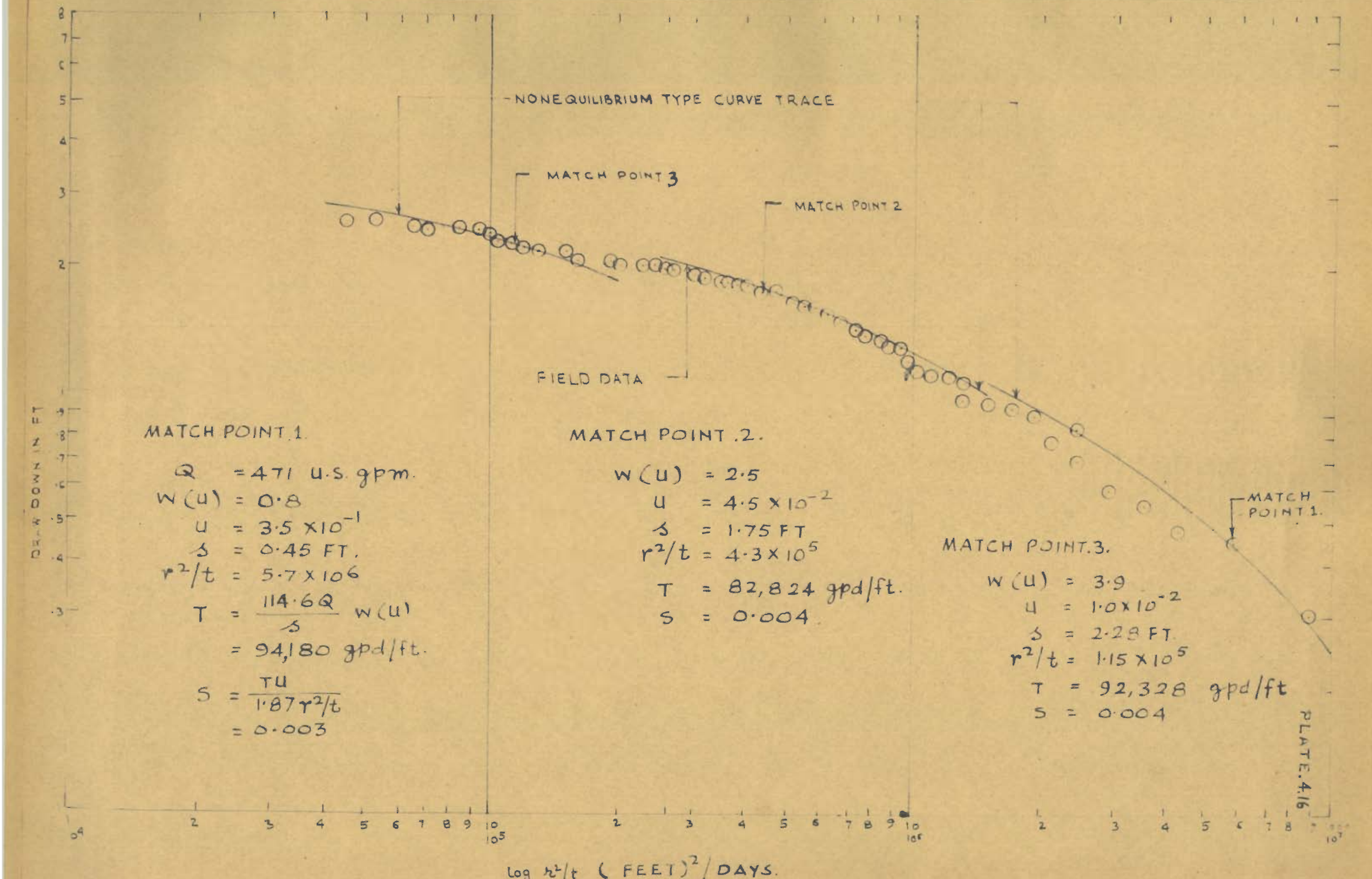
PLATE. 4.14

TIME DRAWDOWN GRAPH FOR WELL No. 20. N.L

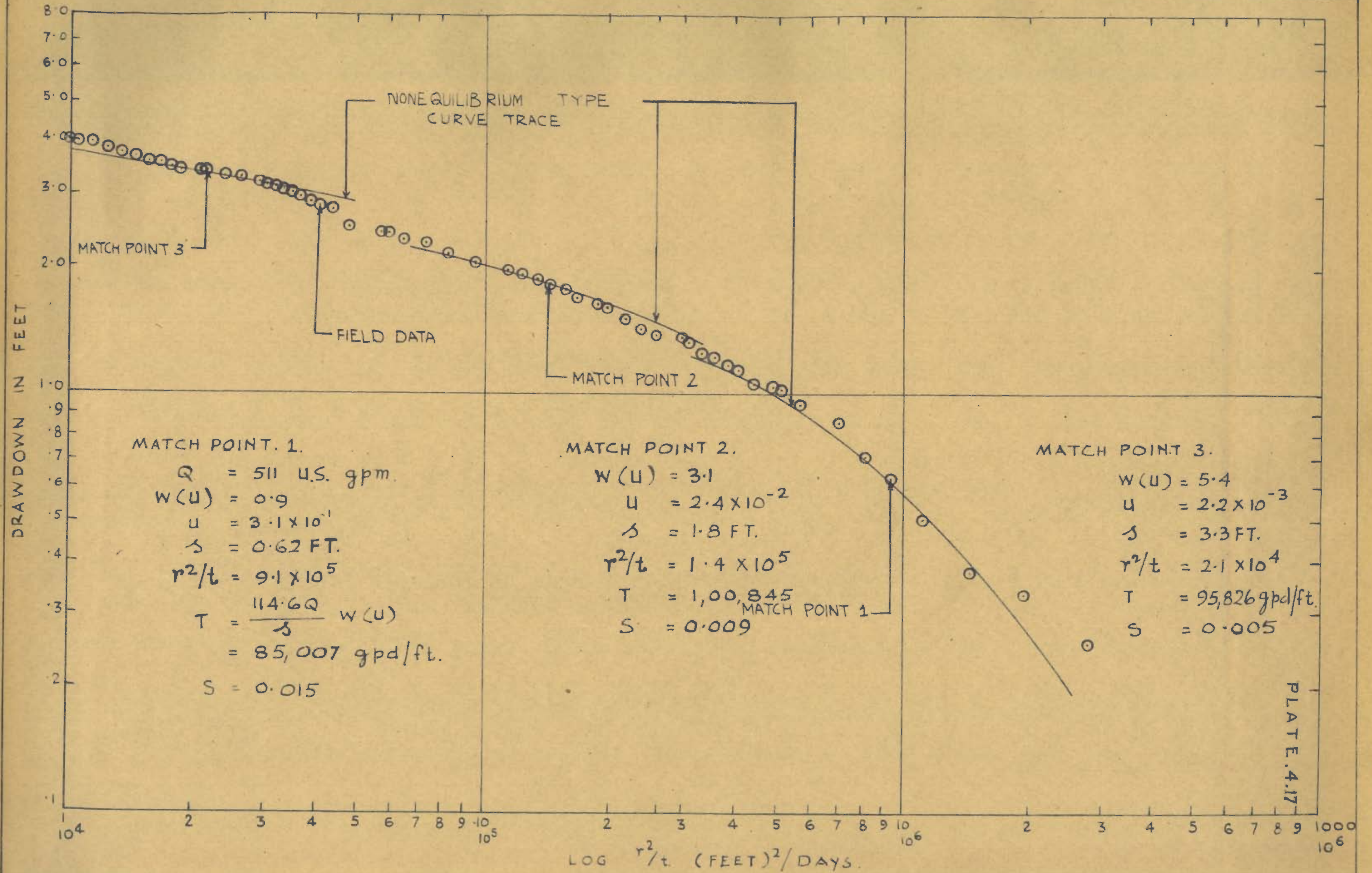


TIME DRAWDOWN GRAPH FOK WELL No. 22 N.L.

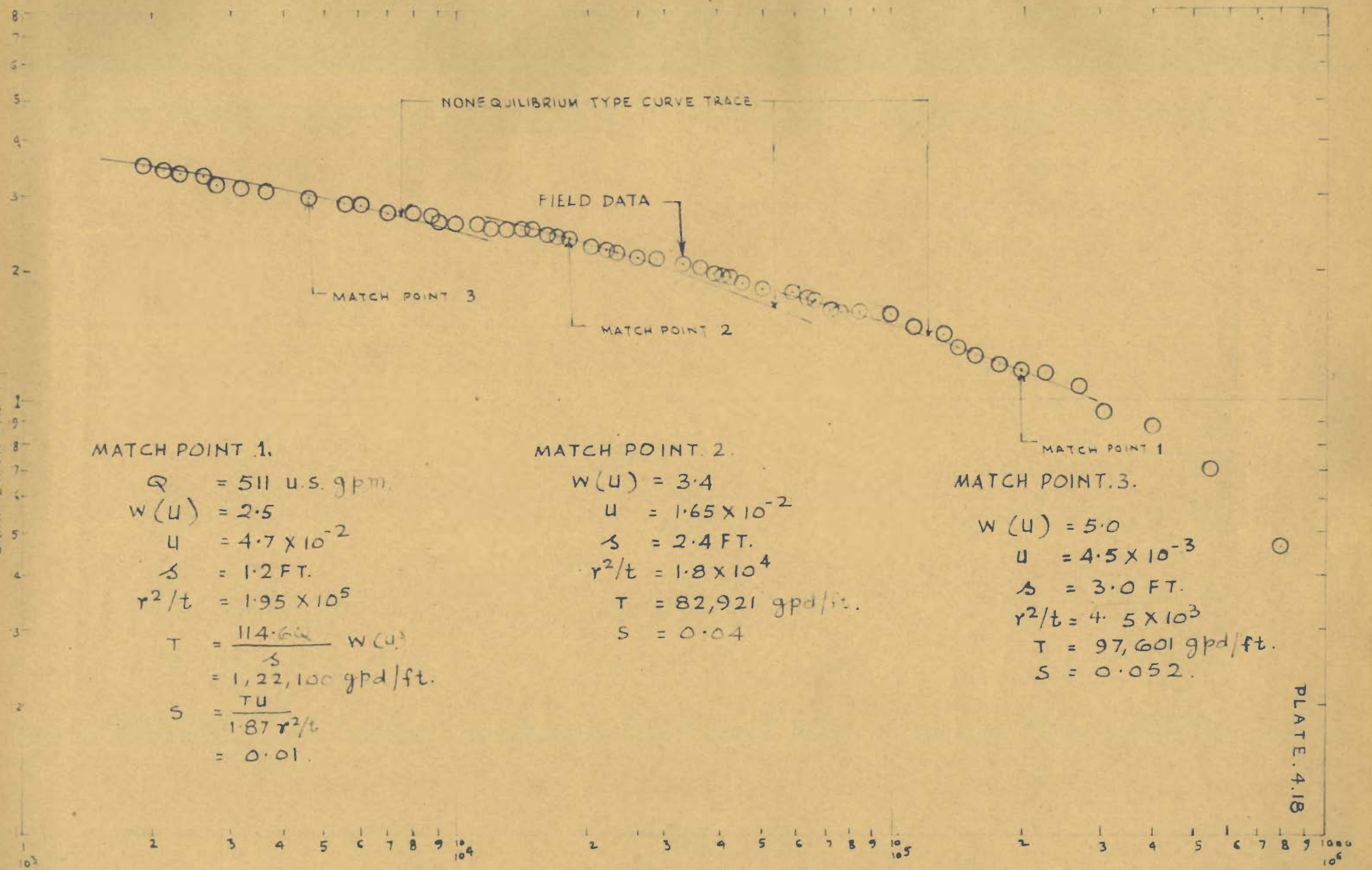
PLATE. 4.15



TIME DRAWDOWN GRAPH FOR WELL No. 2. S.L.

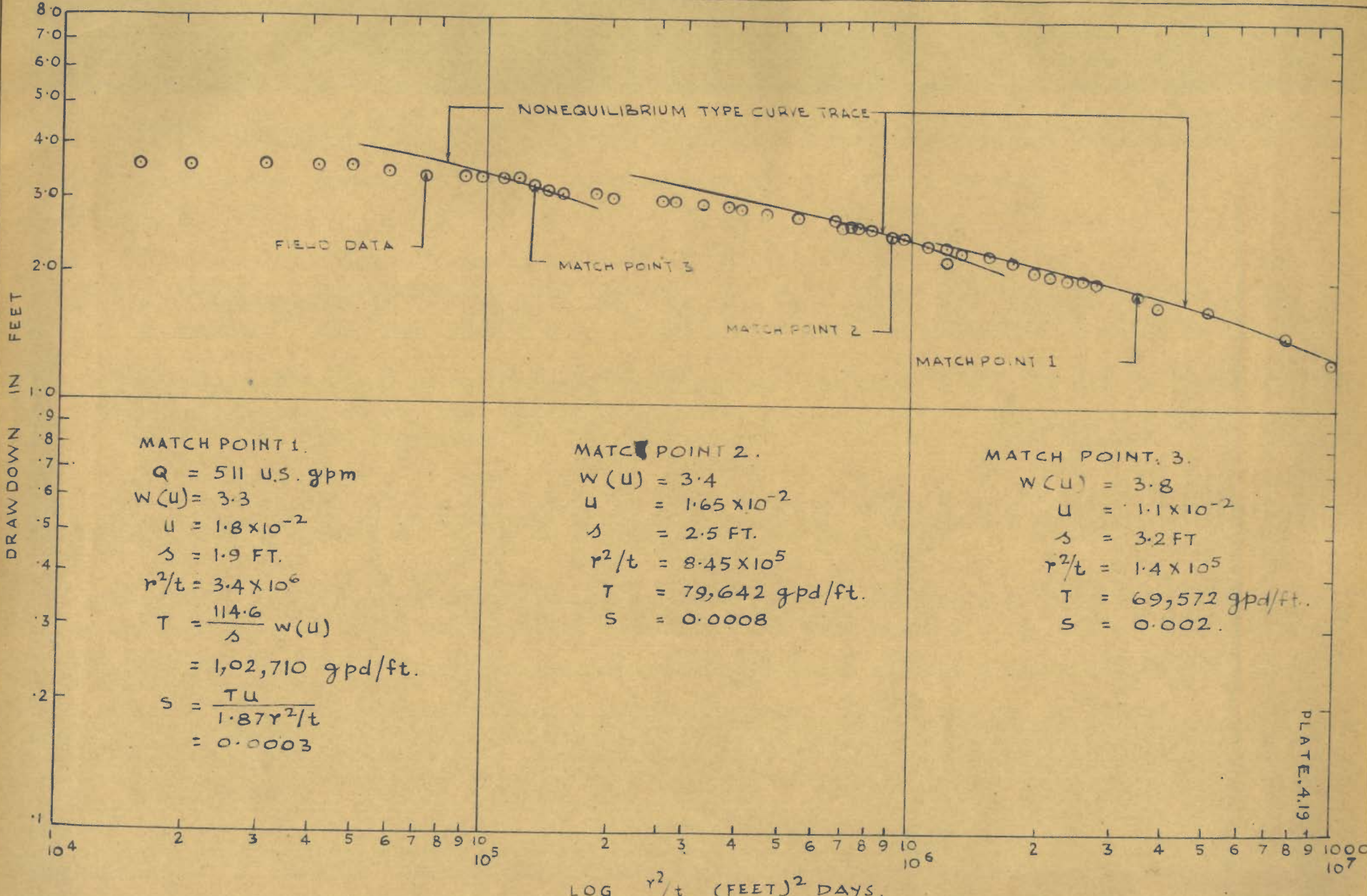


TIME DRAWDOWN GRAPH FOR WELL No. 7 S.L.

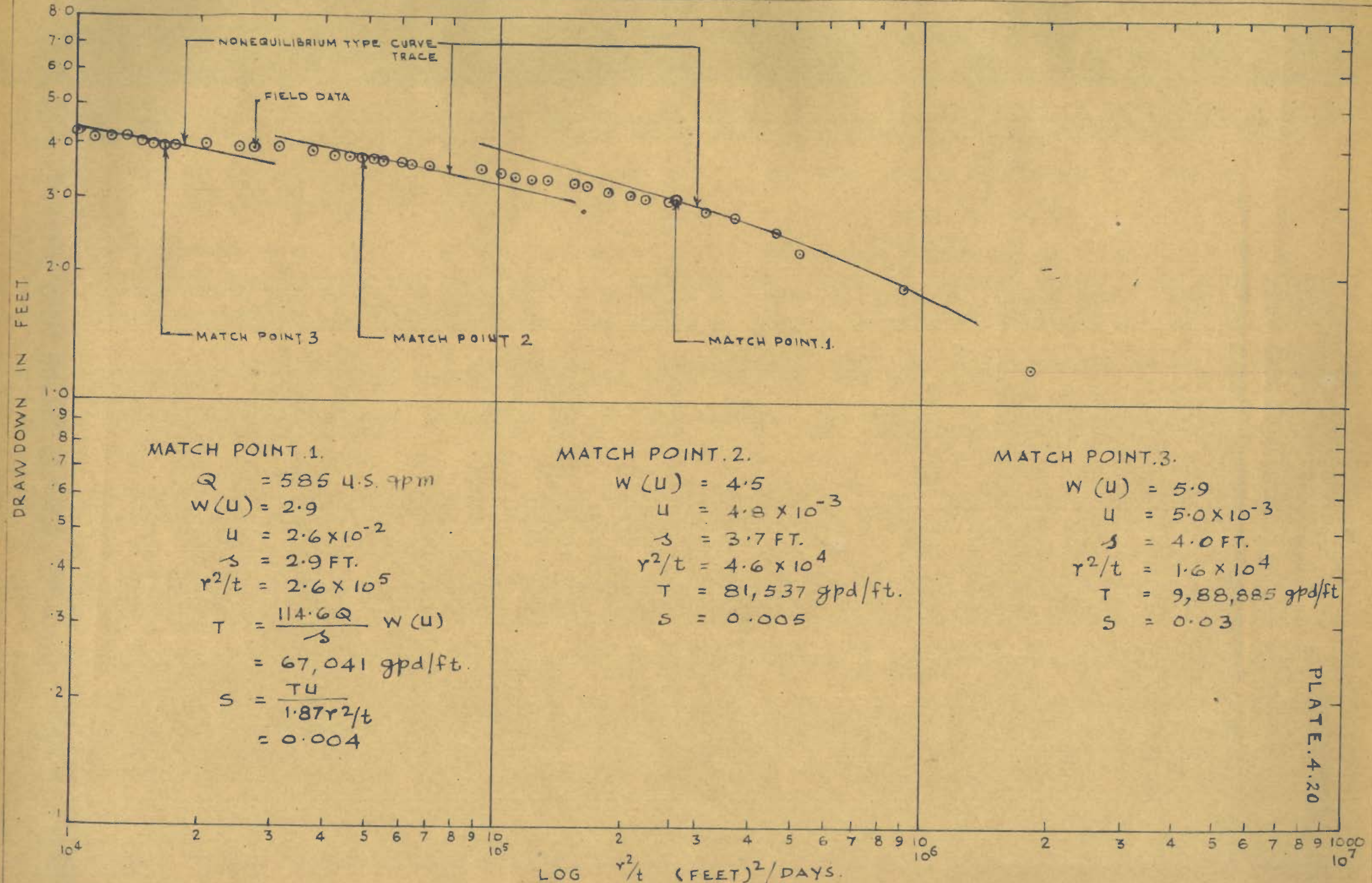


log r²/t (FEET)²/DAYS.

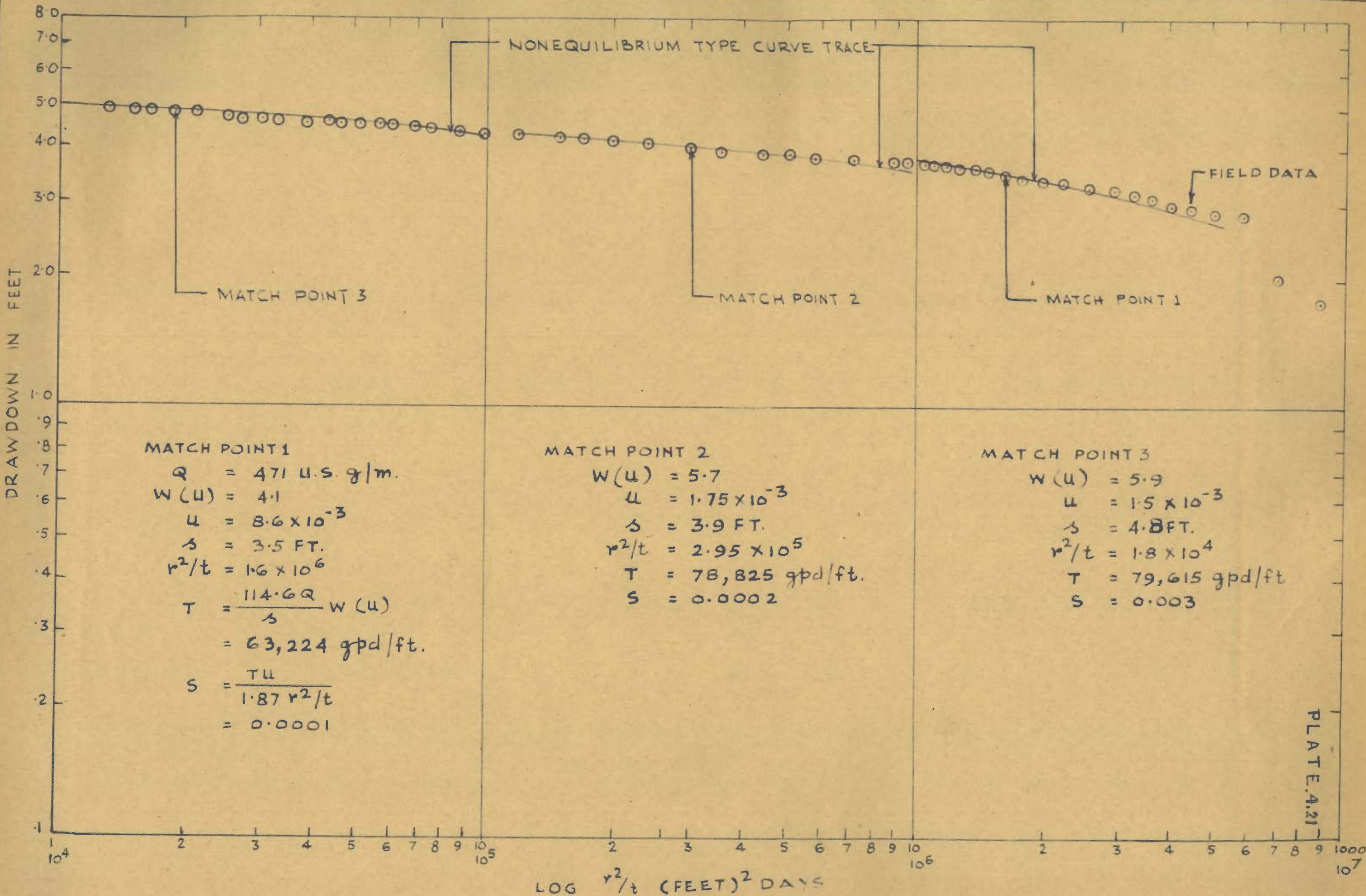
TIME DRAWDOWN GRAPH FOR WELL No. 10 S.L



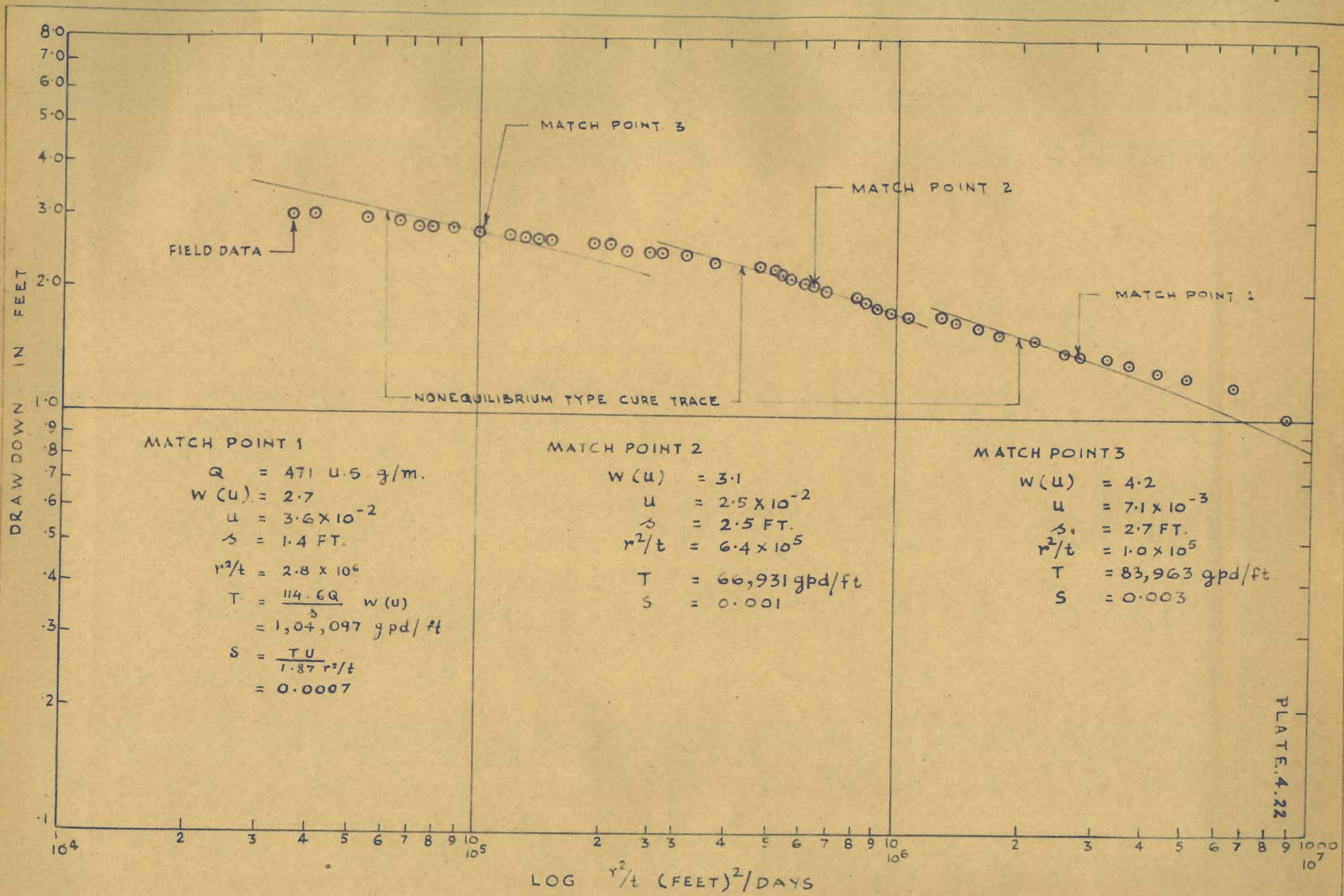
TIME DRAWDOWN GRAPH FOR WELL No. 17 S.L



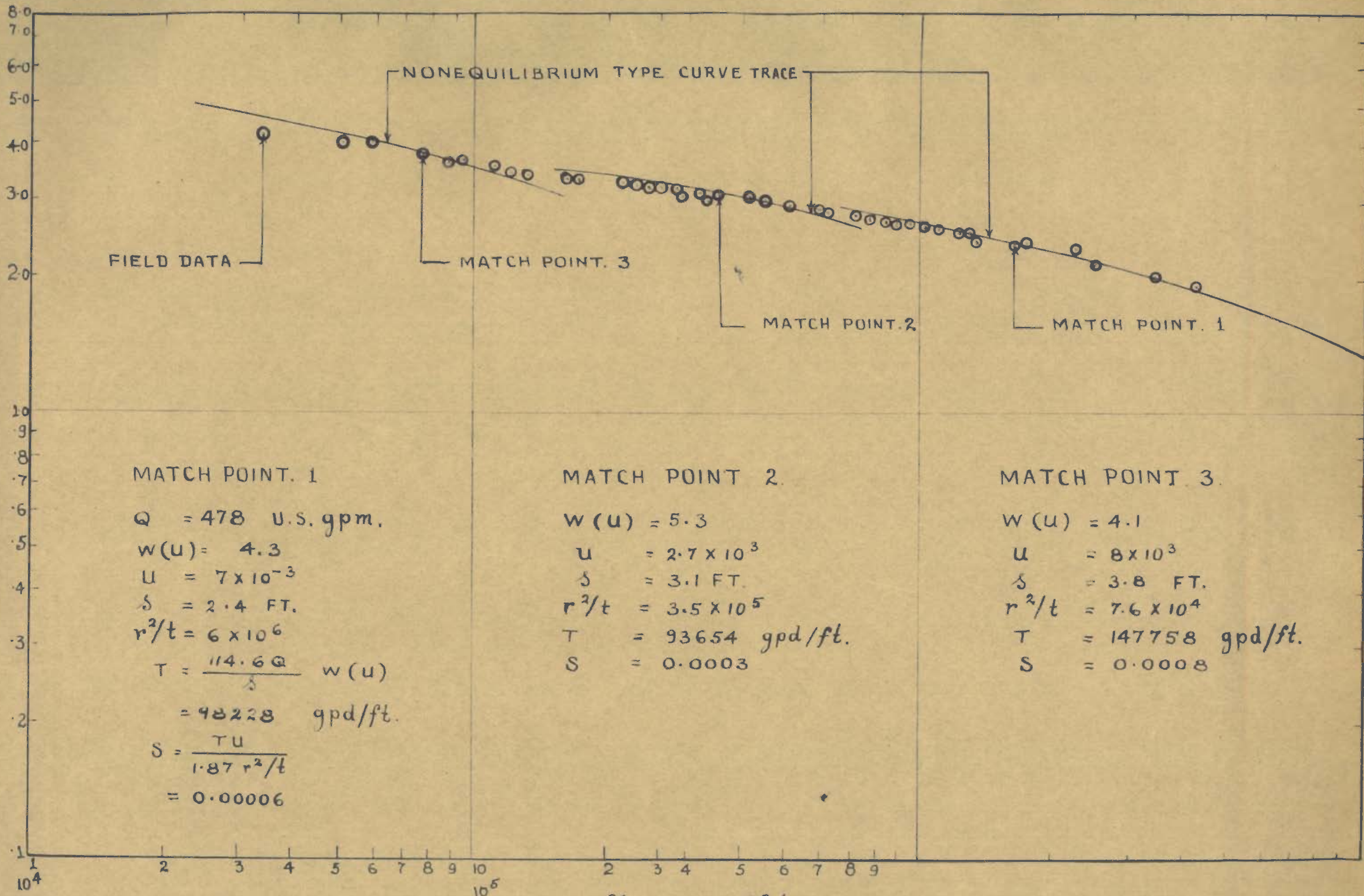
TIME DRAWDOWN GRAPH FOR WELL No. 20 S.L.



TIME DRAWDOWN GRAPH FOR WELL No. 3 KAIRANA



TIME DRAWDOWN GRAPH FOR WELL No.10 A KAKARA.



TIME DRAWDOWN GRAPH FOR WELL No. 9 DAHA

PLATE. 4.23

Table 4.2 - VARIATION IN T & S AS DETERMINED BY THE THEIS TYPE CURVE METHOD FOR DIFFERENT MATCH POINTS

Sl. No.	Tube well No	Match point	W(u)	u	r^2/t	s	T gal/day/ft	S
1	2	3	4	5	6	7	8	9
1.	20 North Loi	1	2.4	5.0×10^{-2}	3.0×10^{6}	1.4	80154	.0007
		2	2.2	5.9×10^{-2}	5.8×10^{5}	2.15	47844	.0027
		3	4.7	4.2×10^{-3}	2.8×10^{4}	3.4	64633	.0051
2.	3 Kairana	1	4.1	8.6×10^{-3}	1.6×10^{6}	3.5	63224	.0001
		2	5.7	1.75×10^{-3}	2.95×10^{5}	3.9	78825	.0002
		3	5.9	1.5×10^{-3}	1.8×10^{4}	4.8	79615	.003
3.	17 NL	1	1.8	1.0×10^{-1}	3.0×10^{6}	1.5	64774	.001
		2	2.6	3.7×10^{-2}	5.5×10^{5}	2.4	58474	.002
		3	4.4	5.5×10^{-3}	7.6×10^{4}	3.3	71969	.002
4.	7 SL	1	0.9	3.1×10^{-1}	9.1×10^{5}	0.62	85007	.015
		2	3.1	2.4×10^{-2}	1.4×10^{5}	1.8	100854	.009
		3	5.4	2.2×10^{-3}	2.1×10^{4}	3.3	95826	.005
5.	11 NL	1	3.35	1.7×10^{-2}	2.3×10^{5}	1.8	80408	.003
		2	3.5	1.39×10^{-2}	7.0×10^{4}	2.15	70332	.007
		3	5.0	3.0×10^{-3}	4.1×10^{3}	2.5	86408	.033
6.	10 SL	1	2.5	4.7×10^{-2}	1.95×10^{5}	1.2	122001	1.01
		2	3.4	1.65×10^{-2}	1.8×10^{4}	2.4	82961	0.04
		3	5.0	4.5×10^{-3}	4.5×10^{3}	3.0	97601	0.052
7.	22 NL	1	2.2	6.0×10^{-2}	7.0×10^{6}	1.0	157575	.0007
		2	2.9	2.9×10^{-2}	4.8×10^{5}	2.12	98910	.003
		3	4.9	3.5×10^{-3}	5.6×10^{4}	3.3	106352	.003
8.	12 NL	1	1.6	1.26×10^{-1}	4.2×10^{6}	1.0	114417	.001
		2	3.3	2.0×10^{-2}	1.1×10^{6}	1.85	127559	.001
		3	4.9	3.4×10^{-3}	3.4×10^{5}	2.3	152348	.0008

contd.

1	2	3	4	5	6	7	8	9
9.	19 NL	1	2.1	7.0×10^{-2}	1.2×10^{6}	1.8	89178	.003
		2	2.8	3.1×10^{-2}	4.4×10^{5}	2.4	82318	.003
		3	5.4	2.3×10^{-3}	2.5×10^{4}	3.4	121402	.006
10.	10A kakra	1	2.7	3.6×10^{-2}	2.8×10^{6}	1.4	104097	.0007
		2	3.1	2.5×10^{-2}	6.4×10^{5}	2.5	66931	.001
		3	4.2	7.1×10^{-3}	1.0×10^{5}	2.7	83963	.003
11.	17 SL	1	3.3	1.8×10^{-2}	3.4×10^{6}	1.9	102710	.0003
		2	3.4	1.65×10^{-2}	8.45×10^{5}	2.5	79642	.0008
		3	3.8	1.1×10^{-2}	1.4×10^{5}	3.2	69572	.002
12.	13 NL	1	1.99	7.8×10^{-2}	3.7×10^{6}	1.59	89500	0.001
		2	3.6	1.4×10^{-2}	5.6×10^{5}	2.25	114416	0.0015
		3	5.6	1.7×10^{-3}	2.8×10^{4}	2.7	148318	0.004
13.	20 SL	1	2.9	2.6×10^{-2}	2.6×10^{5}	2.9	67041	0.004
		2	4.5	4.8×10^{-3}	4.6×10^{4}	3.7	81537	0.005
		3	5.9	5.0×10^{-3}	1.6×10^{4}	4.0	988885	0.03
14.	2 SL	1	0.8	3.5×10^{-1}	5.7×10^{6}	0.45	94180	0.003
		2	2.5	4.5×10^{-2}	4.3×10^{5}	1.75	82824	0.004
		3	3.9	1.0×10^{-2}	1.15×10^{5}	2.28	92328	0.004
15.	9 Daha	1	4.3	7.0×10^{-3}	6.0×10^{6}	2.4	98228	0.00006
		2	5.3	2.7×10^{-3}	3.5×10^{5}	3.1	93656	0.0003
		3	4.1	8.0×10^{-3}	7.6×10^{4}	3.8	147758	0.008

MODIFIED NON-EQUILIBRIUM FORMULA (STRAIGHT LINE METHOD)

In 1950 Jacob (Ferris et al[34]) established that in the series of equation (4.2) the sum of the terms beyond $\log_e u$ is insignificant if u becomes small. The value of u decreases as t increases and r decreases. Therefore, for large values of t and small values of r, the terms beyond $\log_e u$ in equation 4.2 can be neglected and then the Theis formula can be written as

$$T = \frac{264\,Q\,(\log_{10} t2/t1)}{s_2 - s_1} \quad \ldots \ldots \quad (4.7)$$

Where Q = discharge of a well, in gallons per minute,

T = transmissibility in gallons per day per ft,

t_1 and t_2 = are two selected times in any convenient units, since pumping began or stopped and

s_1 and s_2 = are the respective drawdown or recoveries at the noted times in feet.

The above equation (Jacob - Theis formula) is applied by plotting the observed data for each well on a semi-logrithmic graph paper, where the values of t are plotted on the logarithmic scale and the values of s on the arithmetic scale. If the value of u becomes small say less then 0.01, the observed data should fall on a straight line. From this straight line t_1 and t_2 are arbitrarily chosen for which the corresponding values of s_1 and s_2 are read from the graph. Hence equation 4.7 can be solved for T. For convenience t_1 and t_2 are chosen over one log cycle apart so that

$$\log_{10} \frac{t_2}{t_1} = 1$$

and equation 4.7 is reduced to

$$T = \frac{264\ Q}{\Delta s} \quad \text{.. .. ..} \quad (4.8)$$

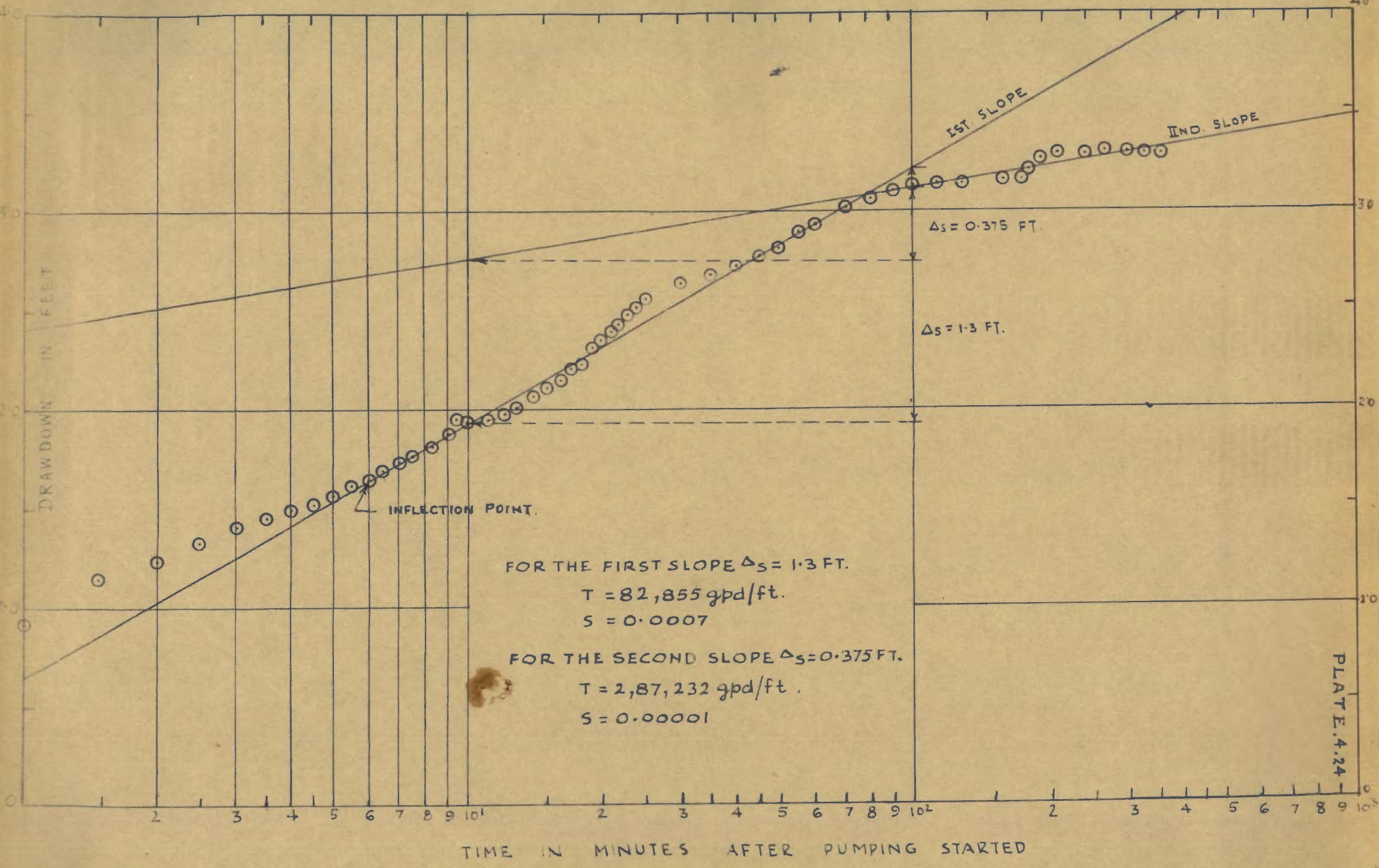
where s is the change, in feet, in the drawdown or recovery over one log cycle of time. The storage coefficient is also determined with the help of equation 4.9.

$$S = \frac{0.3\ T\ t_o}{r^2} \quad \text{.. .. ..} \quad (4.9)$$

where S, T and r are same as defined earlier and t_o is time intercept, in days, where the plotted straight line (time drawdown curve) intersects to zero drawdown axis.

The time drawdown curves for the observed data were plotted on semi-logsheets as shown in (Plates 4.24 to 4.38). The computed values of T and S by the above method are also given in these plates.

A perusal of these figures would indicate that the slope of the time-drawdown curves does not remain constant. Such a change can indicate different conditions. A decrease in the slope of the time drawdown curve can indicate either recharge boundary conditions or leaky confined conditions (Walton[35]). Simiiar effects will be seen if the well has partial penetration (Hantush[36] Singhal[37]). This leads to to the question as which part of the time-drawdown curve should be used for determining the aquifer constants? If there is a effect of recharge boundary conditions or leaky conditions



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 20 N.L

PLATE. 4.24

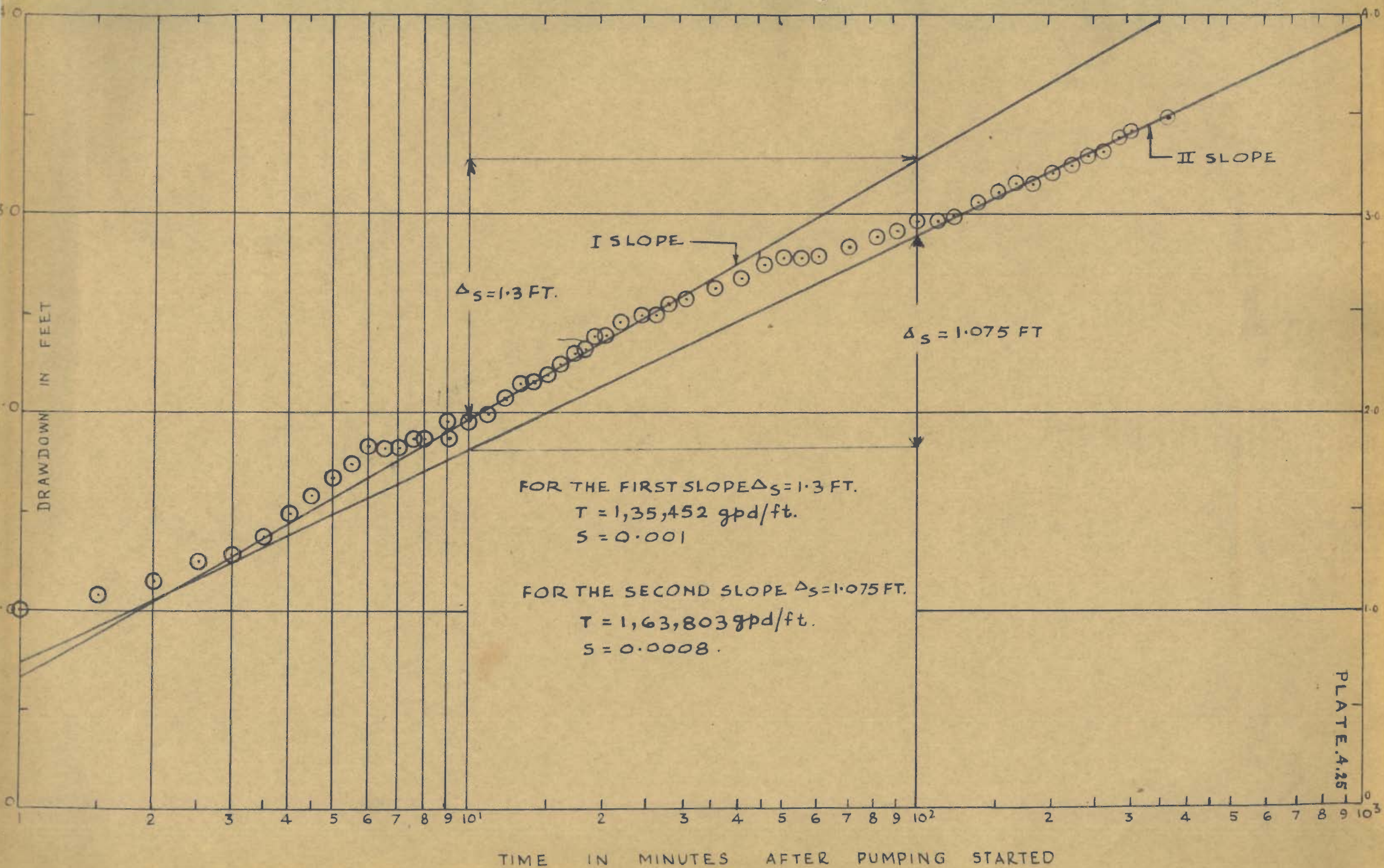
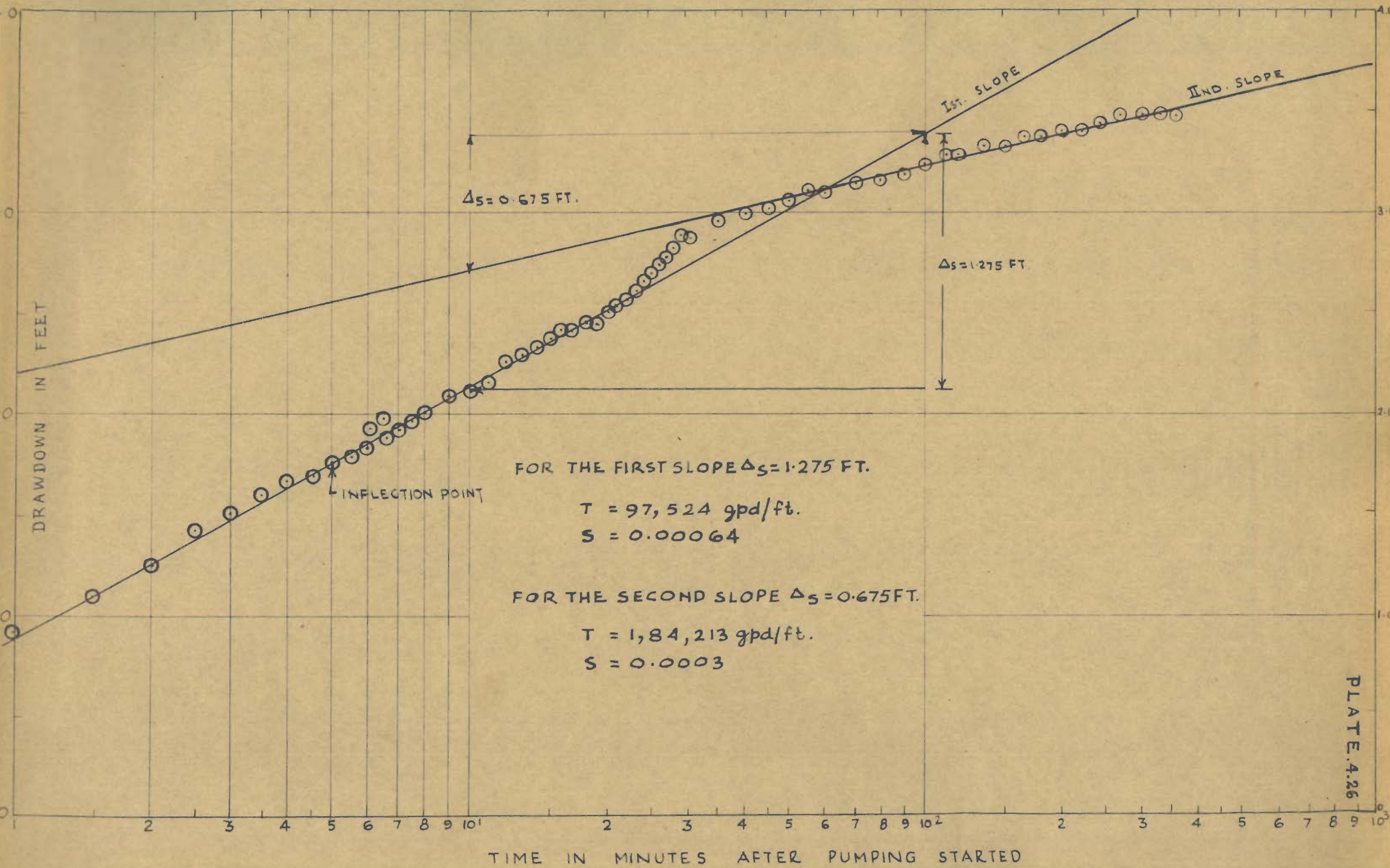

DRAWDOWN IN FEET
I SLOPE
II SLOPE
Δs = 1·3 FT.
Δs = 1·075 FT
FOR THE FIRST SLOPE Δs = 1·3 FT.
T = 1,35,452 gpd/ft.
S = 0·001
FOR THE SECOND SLOPE Δs = 1·075 FT.
T = 1,63,803 gpd/ft.
S = 0·0008.
TIME IN MINUTES AFTER PUMPING STARTED

PLATE.4.25



SEMILOG PLOT OF DRAWDOWN VERSES TIME FOR WELL No. 17 N.L.

PLATE. 4.26

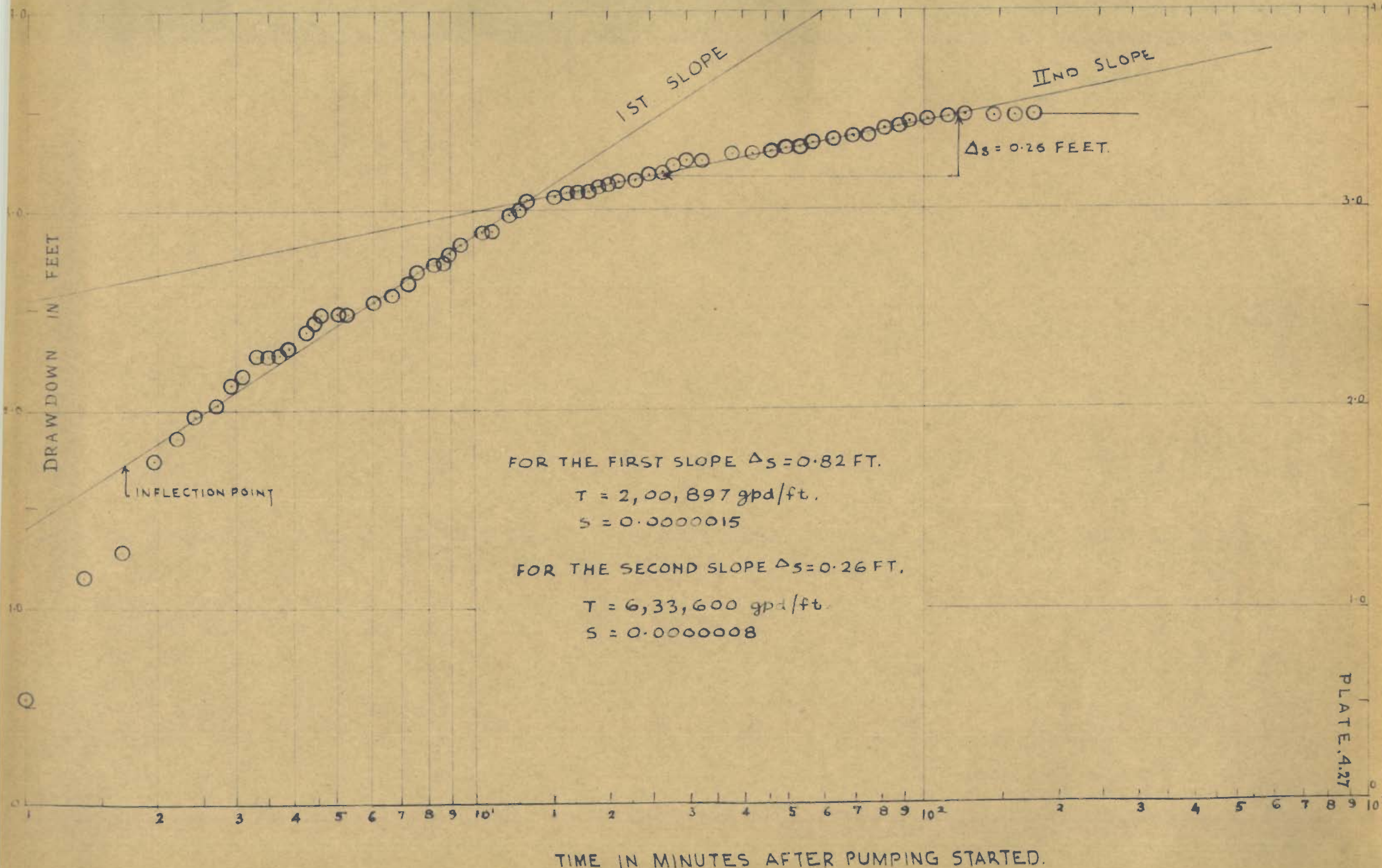
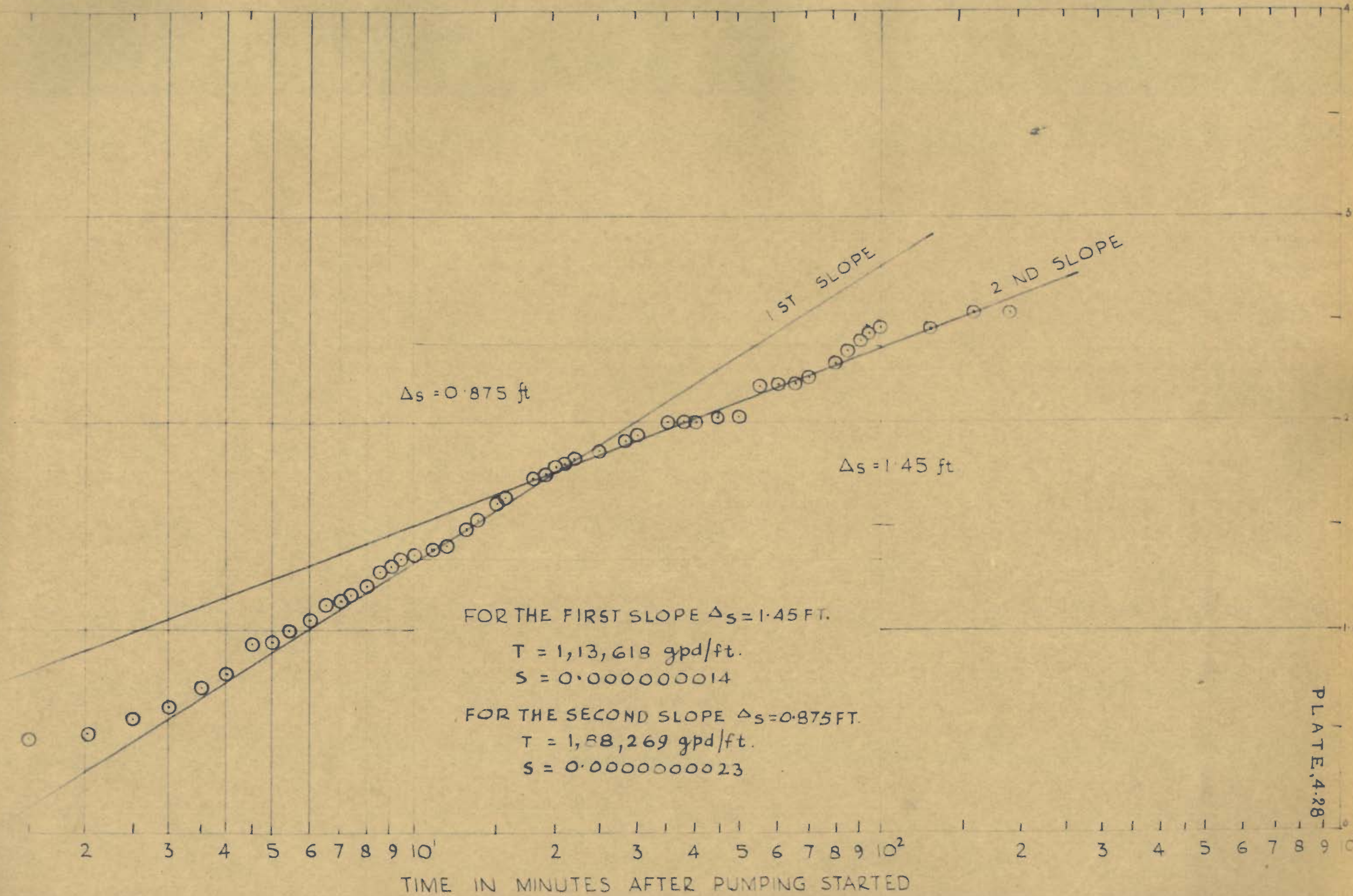


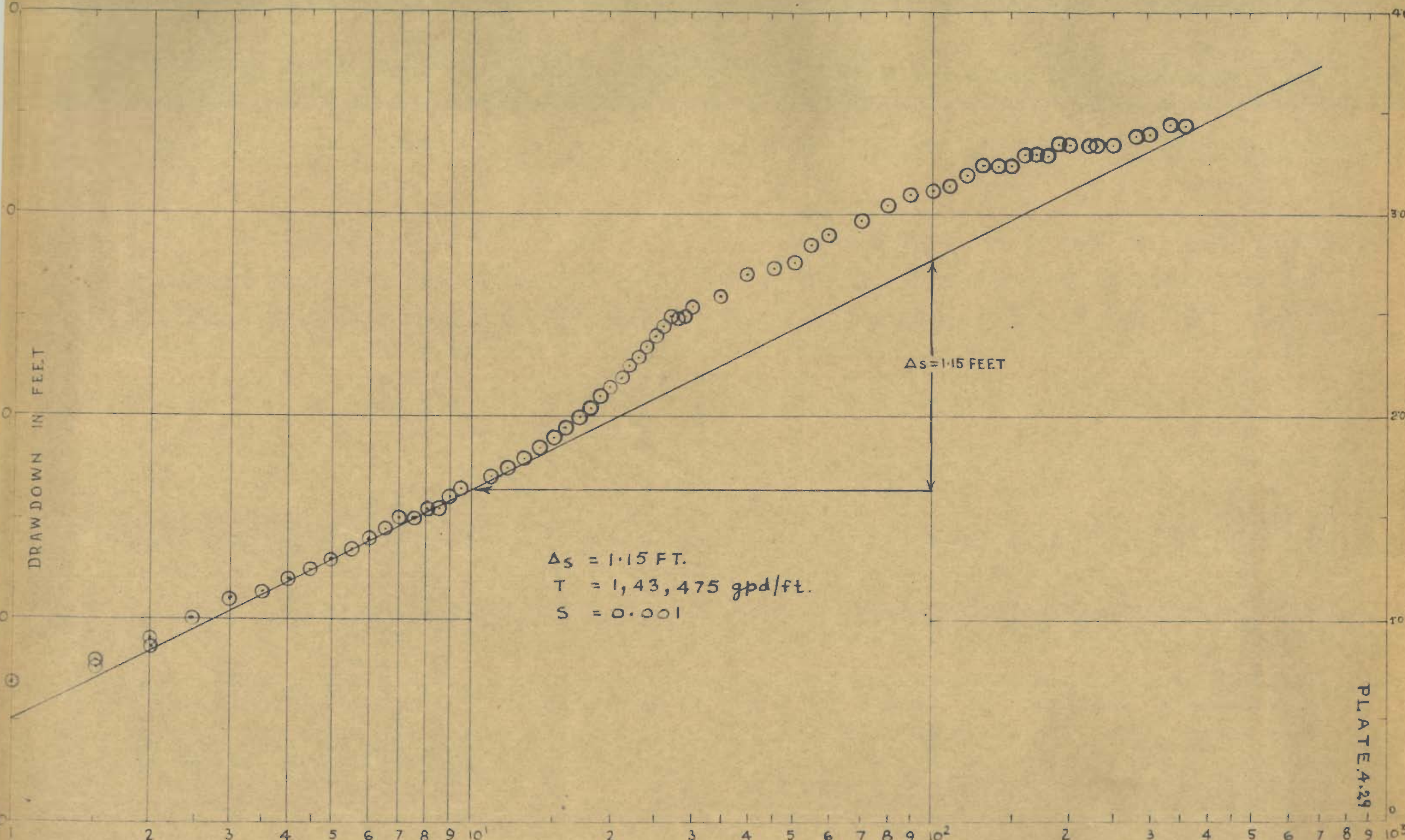
PLATE. 4.27

SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 13 N.L.



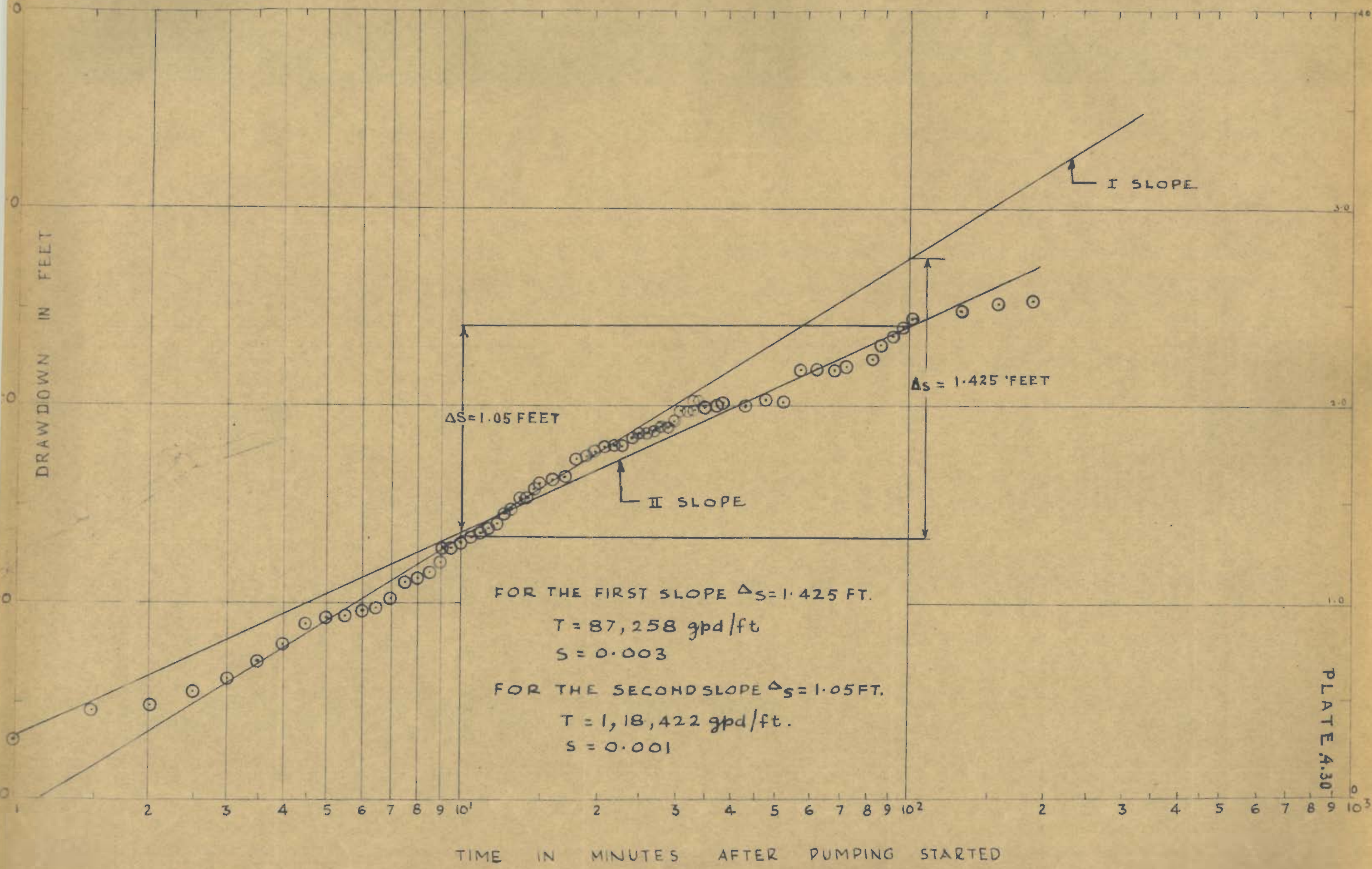
SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 12 N.L

PLATE, 4.28



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 22 N.L.

PLATE.4.29



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 2 S.L.

PLATE 4.30

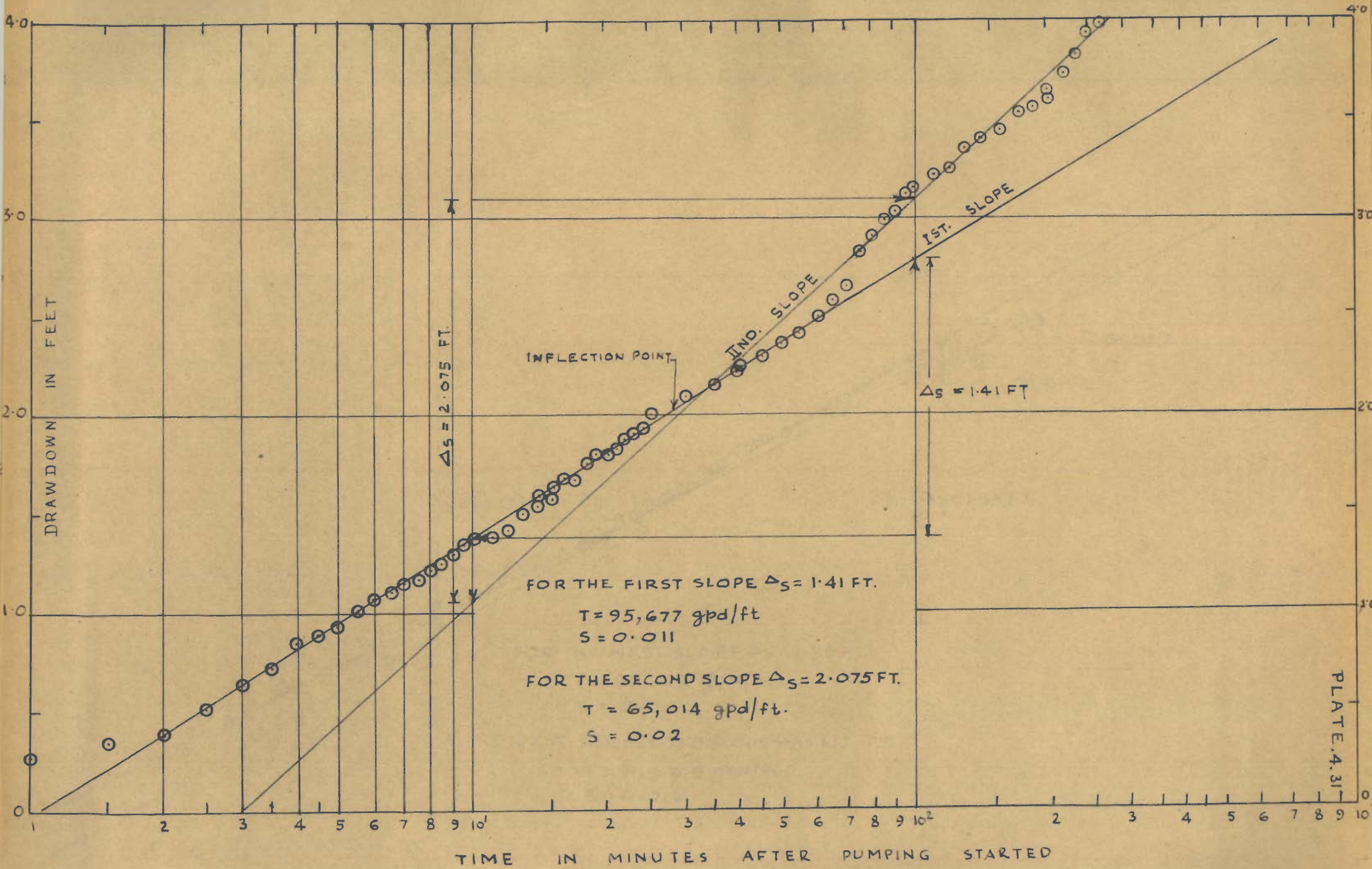
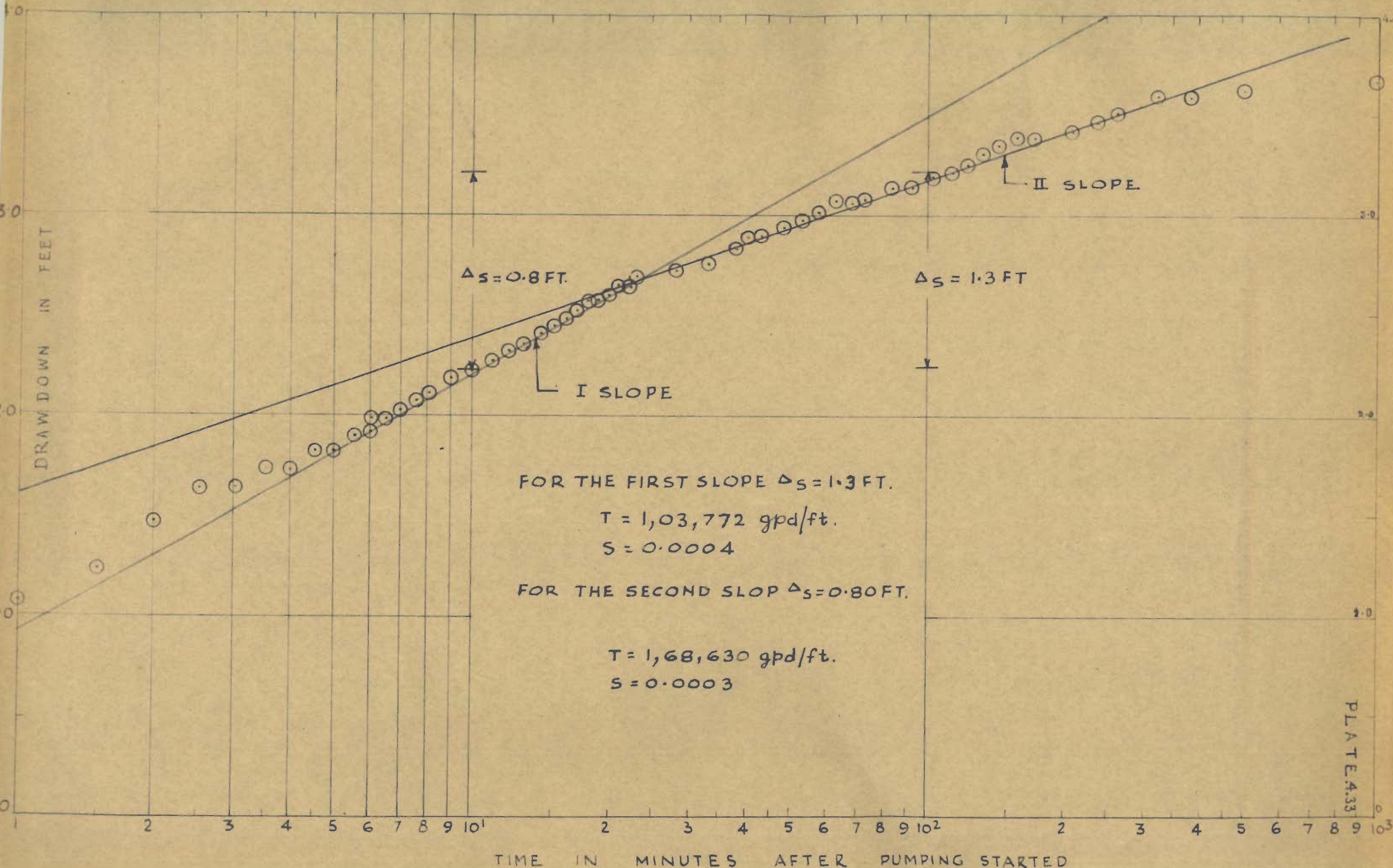


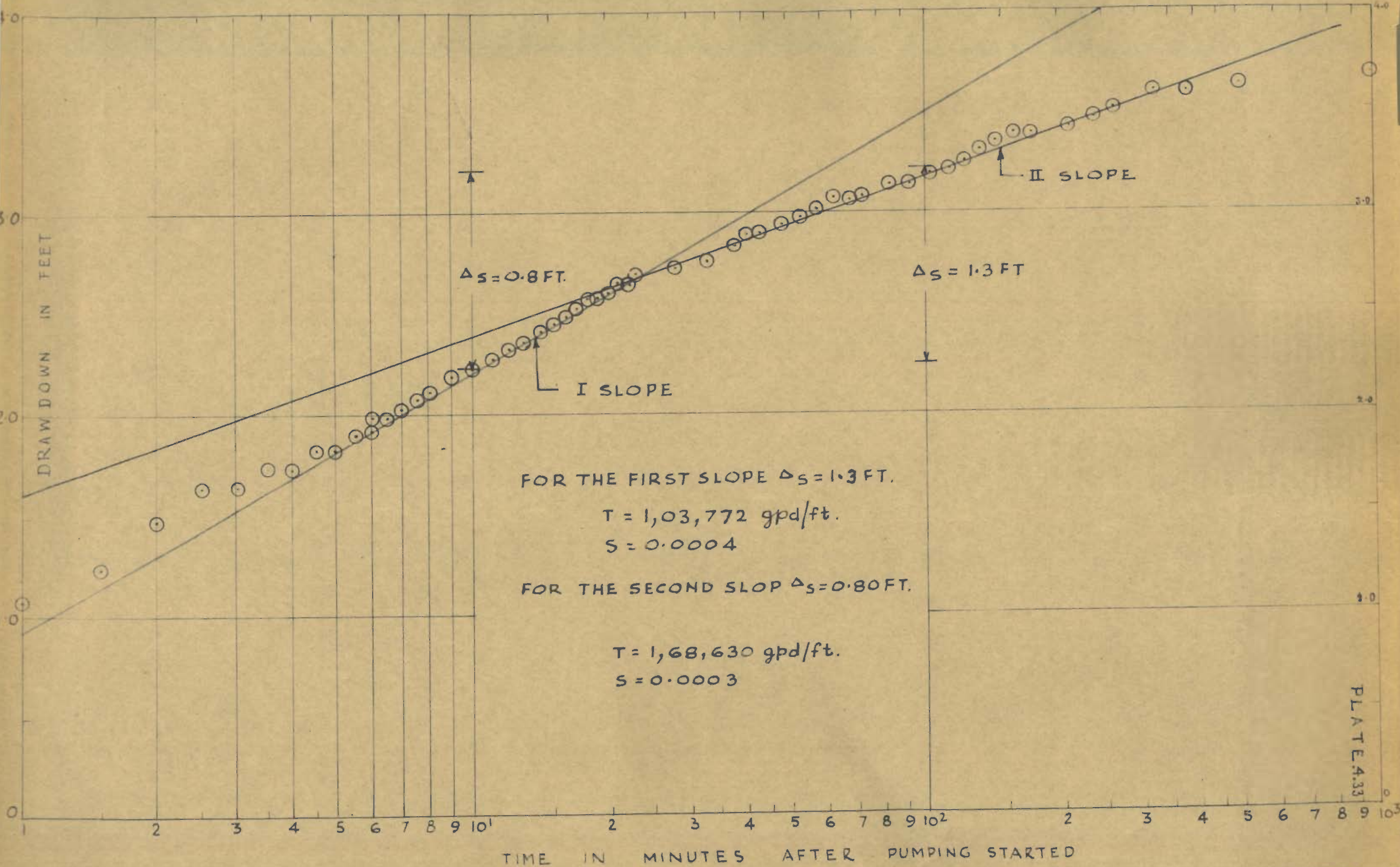
PLATE.4.31

SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 7 S.L



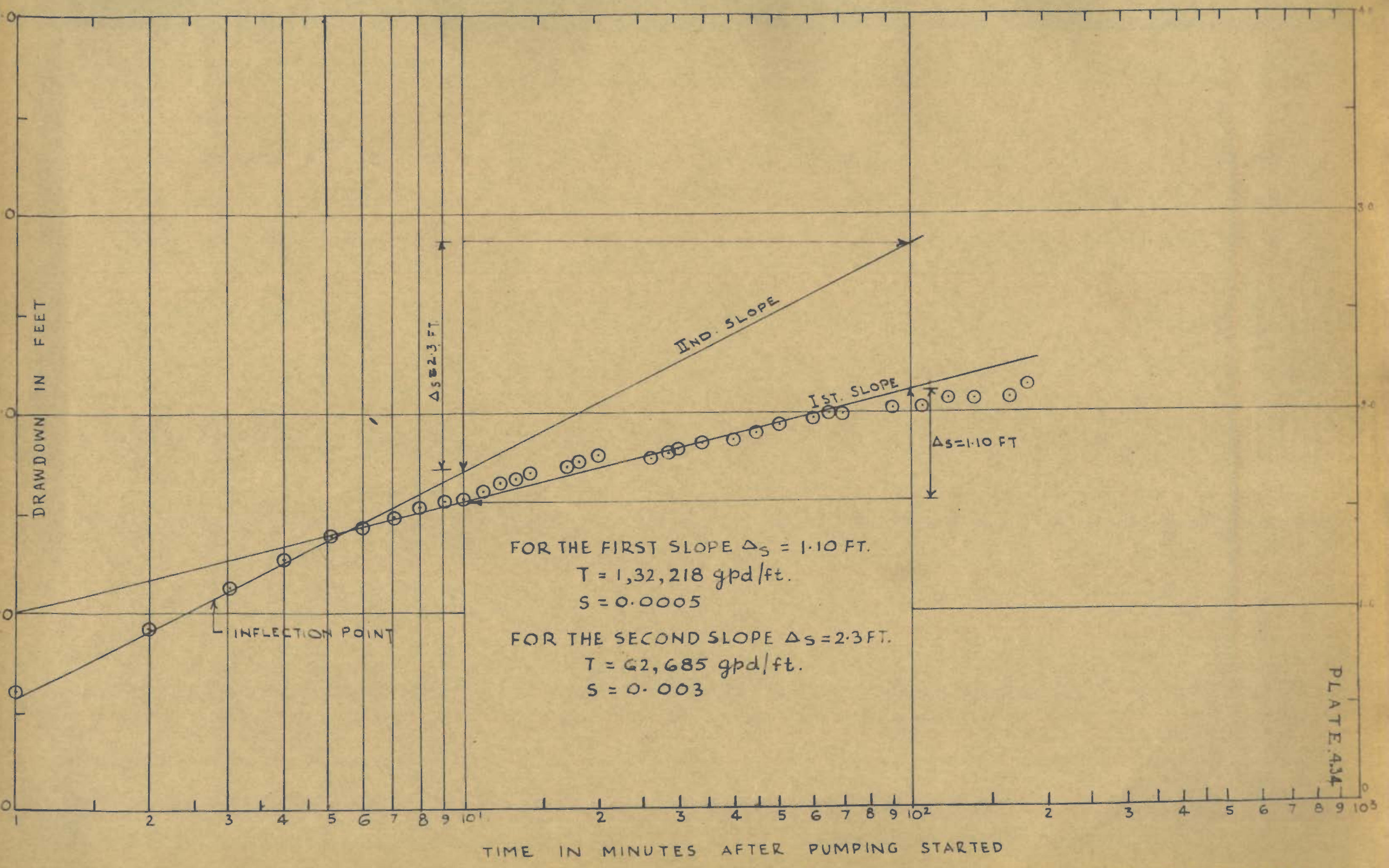
SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 17 S.L

PLATE.4.33



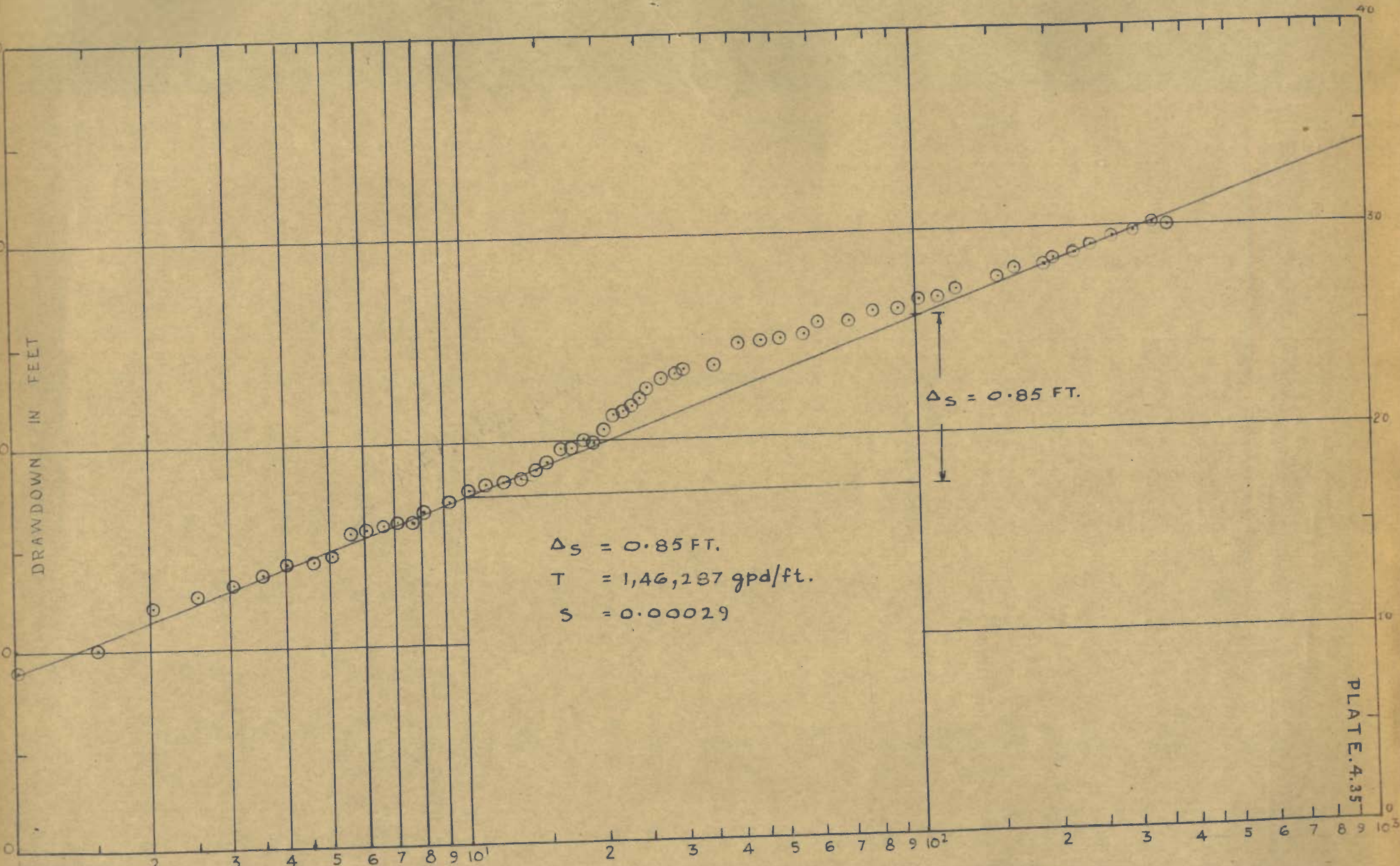
SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 17 S.L

PLATE 4.33

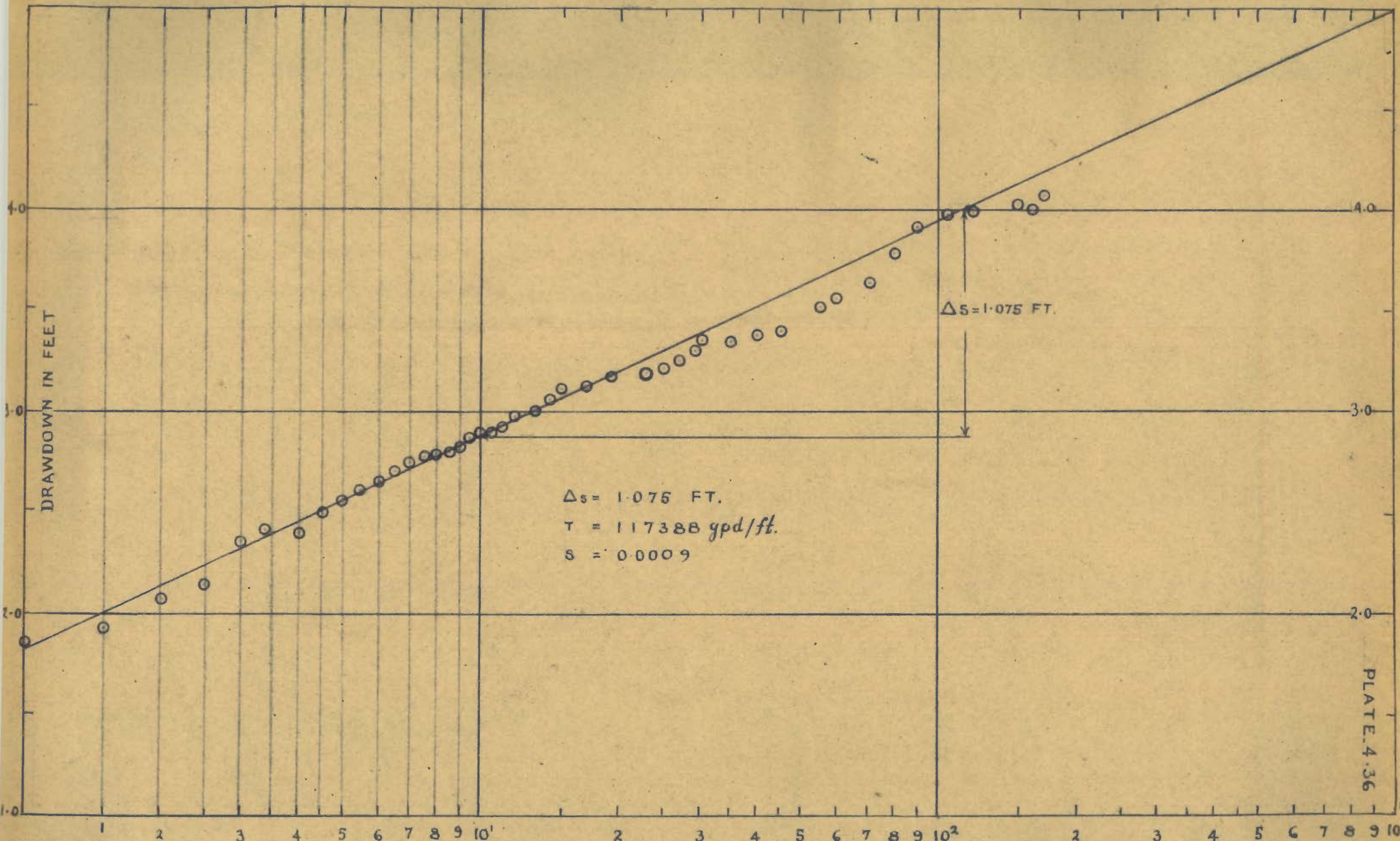


SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 20 S.L

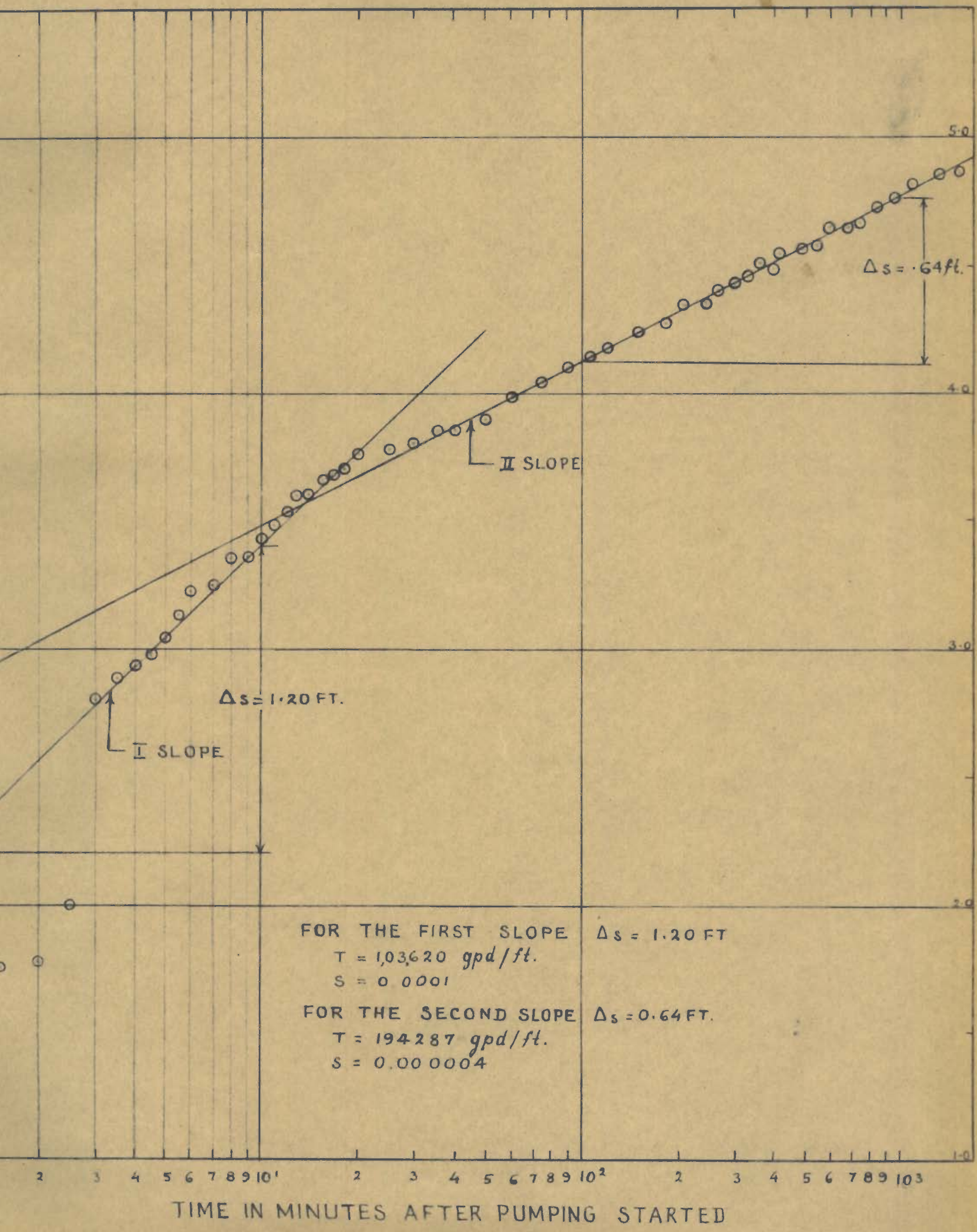
PLATE 4.34



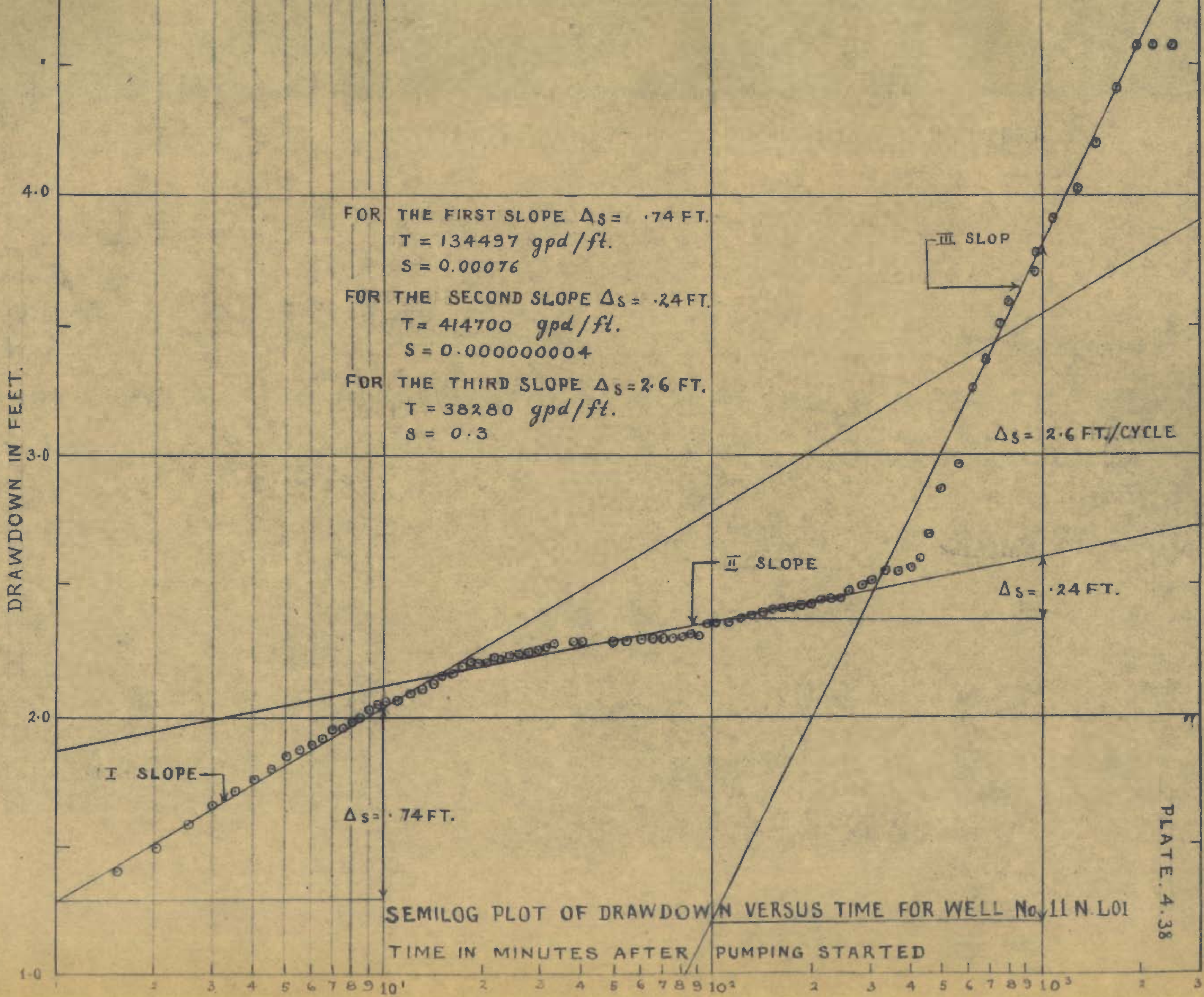
SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 10 A. KAKRA.



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 9 DAHA



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 3 KAIRANA



SEMILOG PLOT OF DRAWDOWN VERSUS TIME FOR WELL No. 11 N L01

PLATE. 4.38

the first slope should be used to compute the aquifer properties but if it is due to partial penetration then the later slope should be considered.

The values of T and S for the various slopes of the time drawdown curves have been given in Table 4.3 . This table indicates that for the later slopes, which are flatten, the values of T are large and S is very small. The small value of S can be due to the fact that the zero drawdown intercept is poorly defined where the slope of the semi log plot is small. Intercepts often occur at points where the values of time are very small and minor deviations in extrapolating the straight line will result in large variations in computed values of the coefficient of storage. Therefore only those values of S which are determined from the earlier slopes are reliable.

(Table 4.3 on page 58)

Table 4.3 - VALUES OF T AND S BY JACOB-THEIS METHOD

S.No.	Well No.	Slope	T(g/day/ft)	S
1.	13 NL	1	200897	.0001
		2	633600	.0000008
2.	20 NL	1	82856	.0007
		2	287232	.00001
3.	3 Kairana	1	103620	.0001
		2	194287	.000004
4.	17 NL	1	97524	.00064
		2	184213	.0003
5.	7 SL	1	95677	.011
		2	65014	.02
6.	11 NL	1	134497	.00076
		2	414700	.000000004
		3	38280	.03
7.	10 SL	1	99929	.02
		2	119915	.016
8.	22 NL	1	143475	.001
9.	12 NL	1	113611	.00000001
		2.	188269	.000000002
10.	19 NL	1	135452	.001
		2	163803	.0008
11.	10A Kakra	1	146287	.00029
12.	17 SL	1	103772	.0004
		2	168630	.0003
13.	20 SL	1	131218	.0005
		2	62685	.003
14.	2 SL	1	87258	.003
		2	118422	.001
15.	9 Daha	1	117388	.0009

THEIS RECOVERY FORMULA

In the year 1935 Theis (Ferris et al[34]) evolved a formula for the analysis of data obtained from the recovery of a pumped well. If a well is pumped, or allowed to flow, for a known period of time and then shut down and allowed to recover, the residual drawdown at any instant will be the same as if the discharge of the well had been continued but a recharge well with the same flow had been introduced at the same point at the instant the discharge stopped. The residual drawdown at any time during the recovery period will be the difference between the observed water level and the non-pumping water level extrapolated from the observed trend before the pumping period. Therefore the residual drawdown, s' , at any instant will be

$$s' = \frac{114.6\ Q}{T}\left[\int_{1.87\ r^2 s/Tt}^{\infty} \frac{e^{-u}}{u}\,du - \int_{1.87\ r^2\ s/Tt'}^{\infty} \frac{e^{-u}}{u}\,du\right] \quad \text{.. .. (4.10)}$$

where Q, T, S and r are same as defined earlier, t is the time since pumping started and t' is the time since pumping stopped. The quantity $1.87\ r^2\ S/Tt'$ will be small when t' ceases to be small because r is very small and therefore the value of the integral will be given closely by the first two terms of the infinite series of equation (4.2) . The above equation therefore, can be re-written in modified form as

$$T = \frac{264\ Q}{s'} \log_{10} \frac{t}{t'} \quad \text{.. .. (4.11)}$$

Equation 4.11 is similar in form to, and is based on the same assumptions as, the modified formula developed by Jacob.

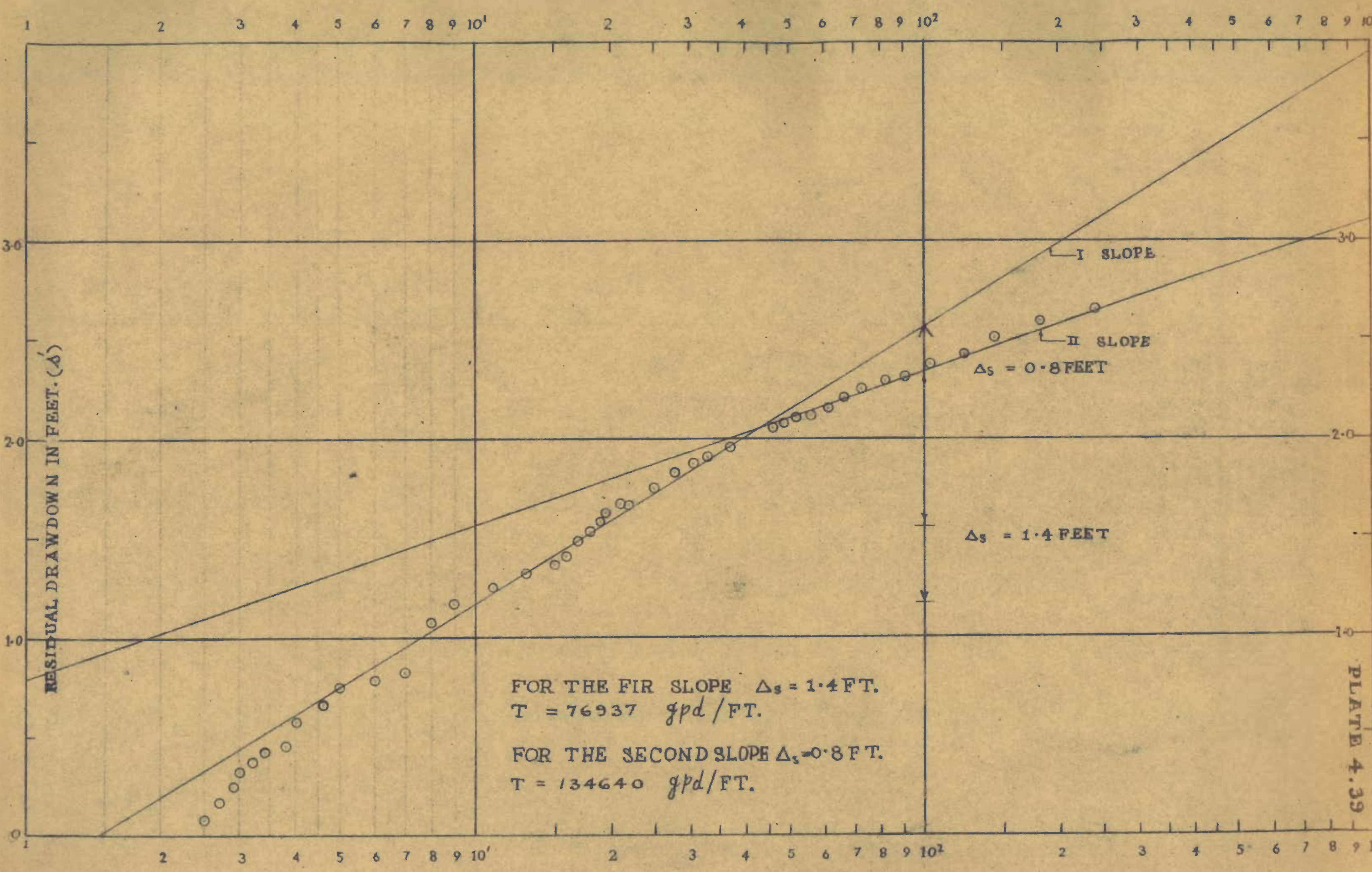
The recovery formula is applied in the same manner as the modified non-equilibrium formula. The convenient procedure is to plot the residual drawdown, s', against t/t' on a semilogrithmic paper, s' being plotted on the arithmetic scale and t/t'on the log scale. When the value of t' becomes sufficiently large, the observed data fall on a straight line. The slope of this line gives the value of the quantity $\log_{10} (t/t')/s'$ in equation 4.11. For convenience, the value of t/t' is generally chosen over one log cycle because its logarithm is then unity and then equation 4.11 can be written as

$$T = \frac{264\ Q}{\Delta s'} \quad .. \quad .. \quad .. \quad (4.12)$$

Where s' is the change in residual drawdown in feet, per log cycle of time. It is not possible to determine the coefficient of storage from the observation of the rate of recovery of a pumped well unless the effective radius rw is known.

The recovery data for the various tests were plotted on semi-logarithmic paper and the values of T were calculated. Only one such plotting is shown in Plate 4.39 and the others are not given here. However, values of T calculated on this basis from tests on different wells are given in Table 4.4.

(Table 4.4 on page61)



SEMILOG PLOT OF RESIDUAL DRAWDOWN Vs. t/t' FOR WELL NO. 20 N.L01.

Table 4.4 - VALUES OF T AS CALCULATED FROM RECOVERY DATA

Serial No.	Well No.	T in Gal/per day/ft
1	2	3
1	20 NL	134640
2	3 Kairana	98685
3	17 NL	108125
4	7 SL	114812
5	11 NL	134640
6	10 SL	103772
7	22 NL	146667
8	12 NL	205920
9	19 NL	117392
10	16 A Kakra	146827
11	17 SL	107923
12	13 NL	388570
13	20 SL	131218
14	2 SL	155430
15	9 Daha	112671

EVALUATION OF THE AQUIFER CONSTANTS

The above methods have indicated that the deeper aquifer in this area represent a complex condition and therefore, the conventional methods of analysis cannot be used directly. The reason is that the various assumptions which have been considered in the derivation of these formulae do not hold good in nature. The aquifers are usually anisotropic and there can also be possibilities of leakage from the overlying water table aquifer.

The values of S determined by the above methods show variation with time of pumping. However, all these values are indicative of the confined conditions of the aquifers. The time-drawdown curves for the tests under discussion have indicated flattening of the slope with increase in time of pumping. As mentioned earlier this would indicate either a recharge boundary condition or partial penetration of the well or water table condition or leaky condition.

Variation in the computed values of S with time of pumping indicates deviation from the assumption that groundwater is removed instanteneously from storage with decline in head. Ineson[38] has reported variation in T and S with time and space from confined aquifers. He has shown an increase in S with increase in time of pumping. Walton[39], Boulton[40] and Wenzel[29] have shown that variation in the computed values of S is indicative of slow draining of formations in the vicinity of a pumped well. In confined aquifers variation in S with time of pumping can be explained due to changes in the elasticity of the porous medium and of the overlying relatively impermeable beds. Therefore, it can be concluded at this place that a variation in the computed value of S can indicate both water table and confined conditions.

The deeper aquifers in the area under investigations do not show water table conditions. This has been concluded on the basis of the following observations:-

1. It has been observed that there is practically no effect of pumping from deeper aquifers on the adjacent shallow dug-wells. This indicates that the shallow and the deeper aquifers are not directly inter connected.

2. The test data were also analysed by Pricketts[41] method for water table aquifers and it was concluded that the tested aquifers have confined character (Appendix - I).

As the tested wells are not near to any surface source of recharge, possibilities of recharge boundary conditions are also rejected. The well assembly and the lithological logs have also shown that the wells have full penetration. Therefore, the test data are further analysed by Leaky Aquifer Methods as given below.

LEAKY AQUIFERS

In nature aquifers are not always perfectly confined between completely impervious strata. This becomes evident when the recharge conditions are studied for those aquifers which have larger yields than are available from the replenishment in the outcrop area. This percolation of water into and away from the main aquifer through the semiconfining strata is known as leakage. This phenomenon was analysed for the first time by Dutch hydrologists and engineers and later Jacob and Hantush worked on this problem (DeWiest[22]). From the year 1954 to 1964, Hantush in collaboration with Jacob and later by himself developed the theory of the leaky aquifer. Walton[42] has applied the theory of the leaky aquifer to some regional conditions in Illinois.

For the analysis of drawdown data from leaky confined aquifer conditions, both the type curve method of Walton[42] and the straight line method of Hantush[43] have been used as described below.

Hantush and Jacob (Walton[42]) have given the following equation for non-steady state drawdown in a leaky artesian aquifer:

$$s = \frac{Q}{4\pi T} \int_u^\infty (1/y) \exp(-y - r^2/4B^2 y)\, dy \quad .. \quad .. \quad (4.13)$$

$$= \frac{Q}{4\pi T} \left[2 K_0(r/B) - \int_q^\infty (1/y)\exp(-y - r^2/4B^2 y) \right] dy \quad (4.14)$$

$$= (Q/4\pi T)\, W \; (u, r/B) \quad .. \quad .. \quad .. \quad .. \; .. \quad (4.15)$$

The integral expression in equation 4.13 was written by Hantush[44] (Walton[42]) symbolically as W (u, r/B) and was termed the "Well function for leaky artesian aquifers".

$$s = \frac{Q}{4 \pi T} W (u, r B) \quad .. \quad .. \quad .. \quad (4.16)$$

where $u = r^2 S/4Tt$

Equation (4.16) can be written in the gallons/foot system of units as

$$s = \frac{114.6Q}{T} W(u, r/B) \quad .. \quad .. \quad (4.17)$$

where $u = \frac{2693r^2S}{Tt}$ .. .. .. (4.18)

and $r/B = \frac{r}{\sqrt{T/(P'/m')}}$ .. .. .. (4.19)

where t = time in minutes

P' = vertical permeability of confining bed, in gallons/day/sq.ft.

m' = thickness of the confining bed through which leakage occurs, in feet.

P'/m' = leakage coefficient of 'Leakance'.

NON-STEADY TIME DRAWDOWN TYPE CURVE METHOD

Hantush[43] has given values of W(u, r/B) in terms of u and r/B. Walton[42] has plotted value of W(u, r/B) against values of 1/u on logarithmic paper and a family of leaky artesian type curvés were constructed.

For the tests under discussion, values of s are plotted on logarithmic paper against values of t in minutes so that the time-drawdown field curves are obtained. These data curves are matched with one of the leaky-artesian type curves and a match point is selected for which values of W(u, r/B) and 1/u are read from the type curve sheet and the corresponding values of t and s are read from the data curve sheets (Plates 4.40 to 4.54) T has been calculated using equation (4.17) and S by equation (4.18) and P' by equation (4.19). Their values are given in Plates 4.40 to 4.54.

STRAIGHT LINE METHOD (HANTUSH'S METHOD)

Theory

Hantush[43] has shown that if the drawdown s is plotted against time t on semi-logarithmic paper, with t plotted in the logarithmic scale, then the slope m at any point is given by

$$m = \Delta s / \Delta \log_{10} t = (2.3Q/4\pi T)\exp(-u - r^2/4B^2u) \quad .. \quad (4.20)$$

The curves have an inflection point at which the following relation holds

$$u_1 = r^2 S/4Tt_1 = r/2B \quad .. \quad .. \quad .. \quad (4.21)$$

where the subscript 1 relates to values of the variables at the inflection point.

The slope of the curve m_1 at the inflection point is given by

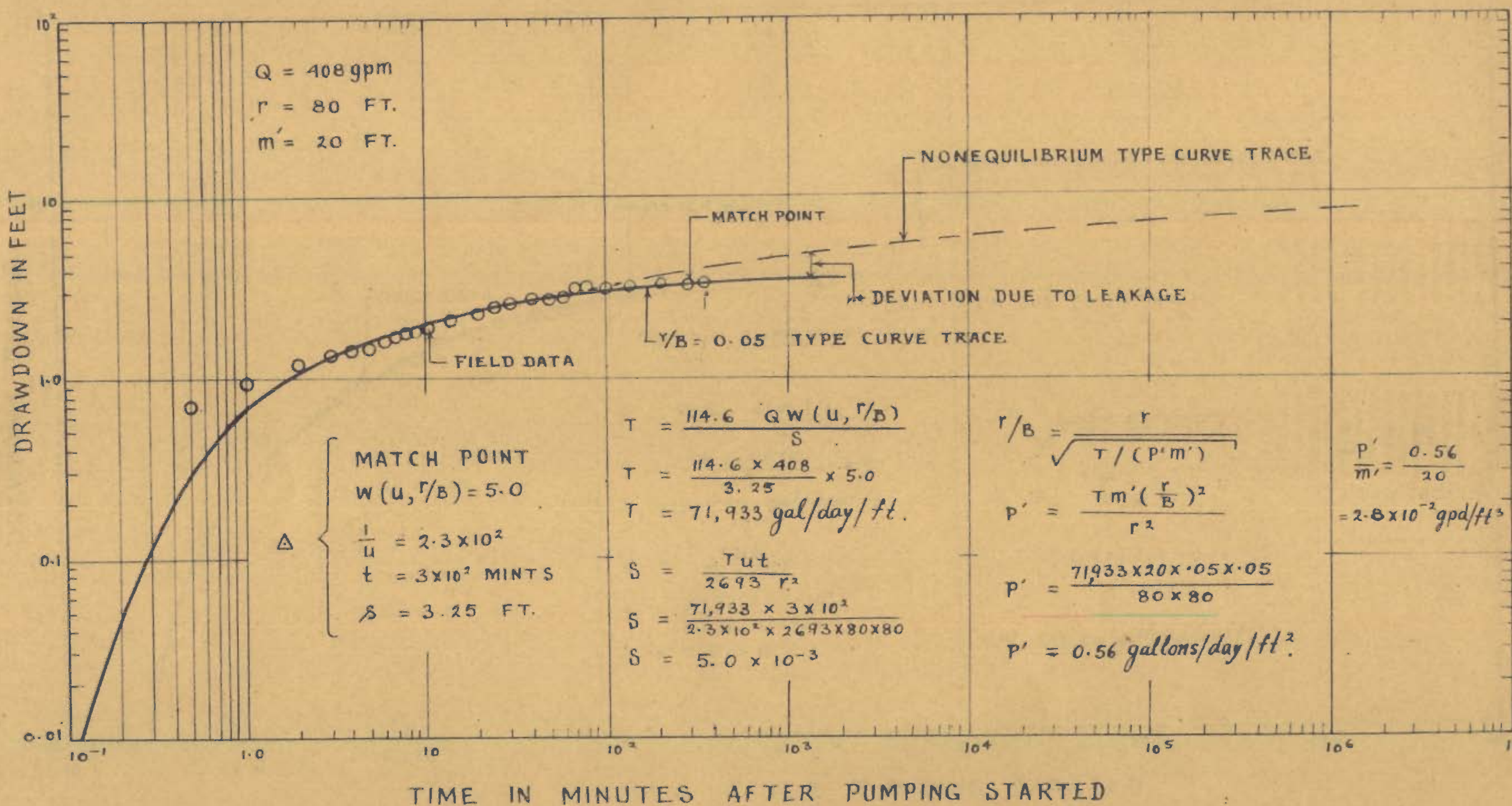
$$m_1 = (2.3Q/4\pi T)e^{-r/B} \quad .. \quad .. \quad .. \quad (4.22)$$

and the drawdown at the inflection/point s_1 is given by

$$s_1 = (Q/4\pi T)K_o(r/B) = (\tfrac{1}{2})\, Sm \quad .. \quad .. \quad (4.23)$$

The relation between the drawdown and the slope of the curve at the inflection point is given by

$$f(r/B) = e^{r/B} K_o(r/B) = 2.3\, s_1 / m_1 \quad .. \quad .. \quad (4.24)$$



TIME - DRAW - DOWN GRAPH FOR WELL No. 20 N. L01

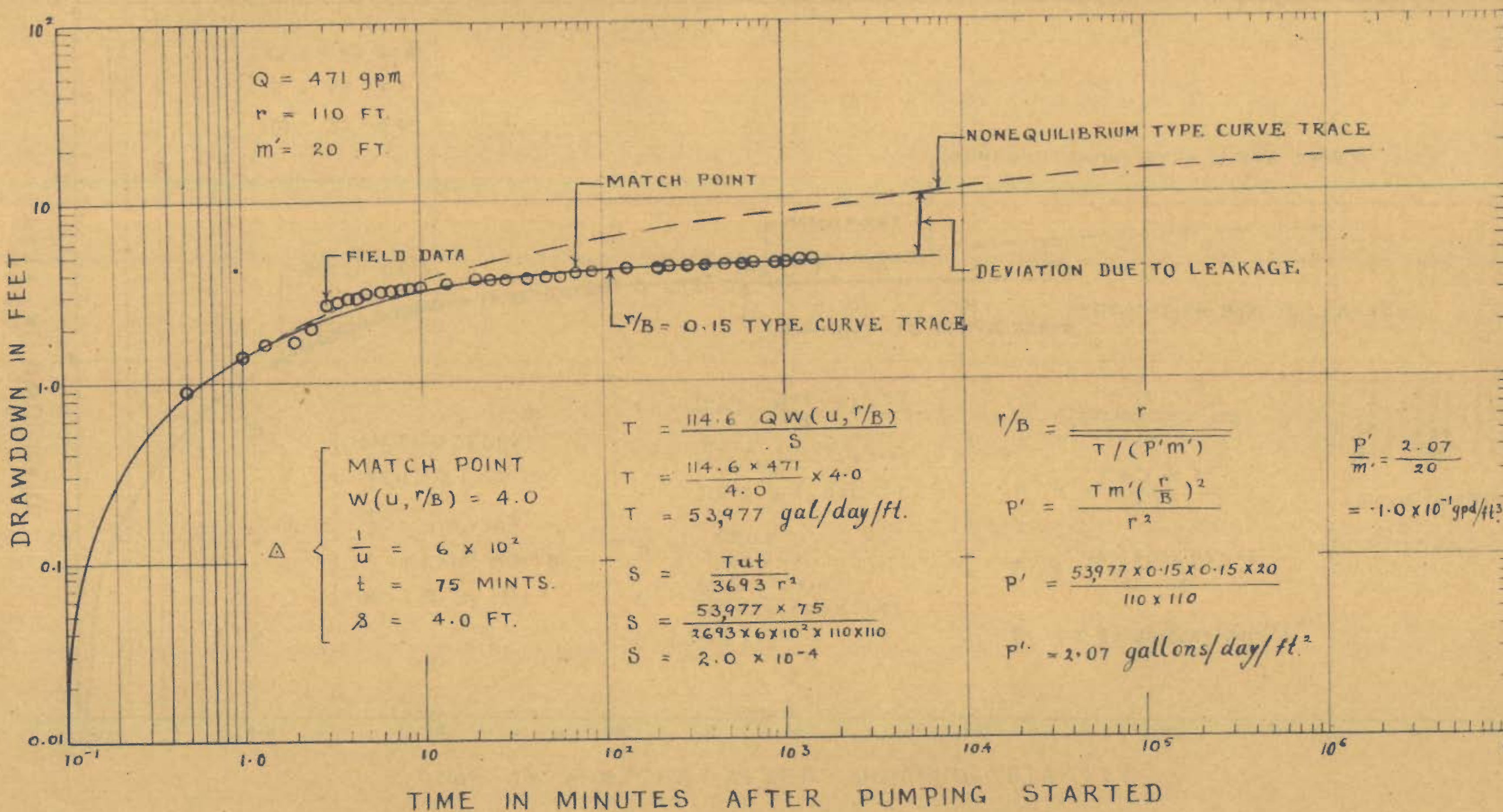
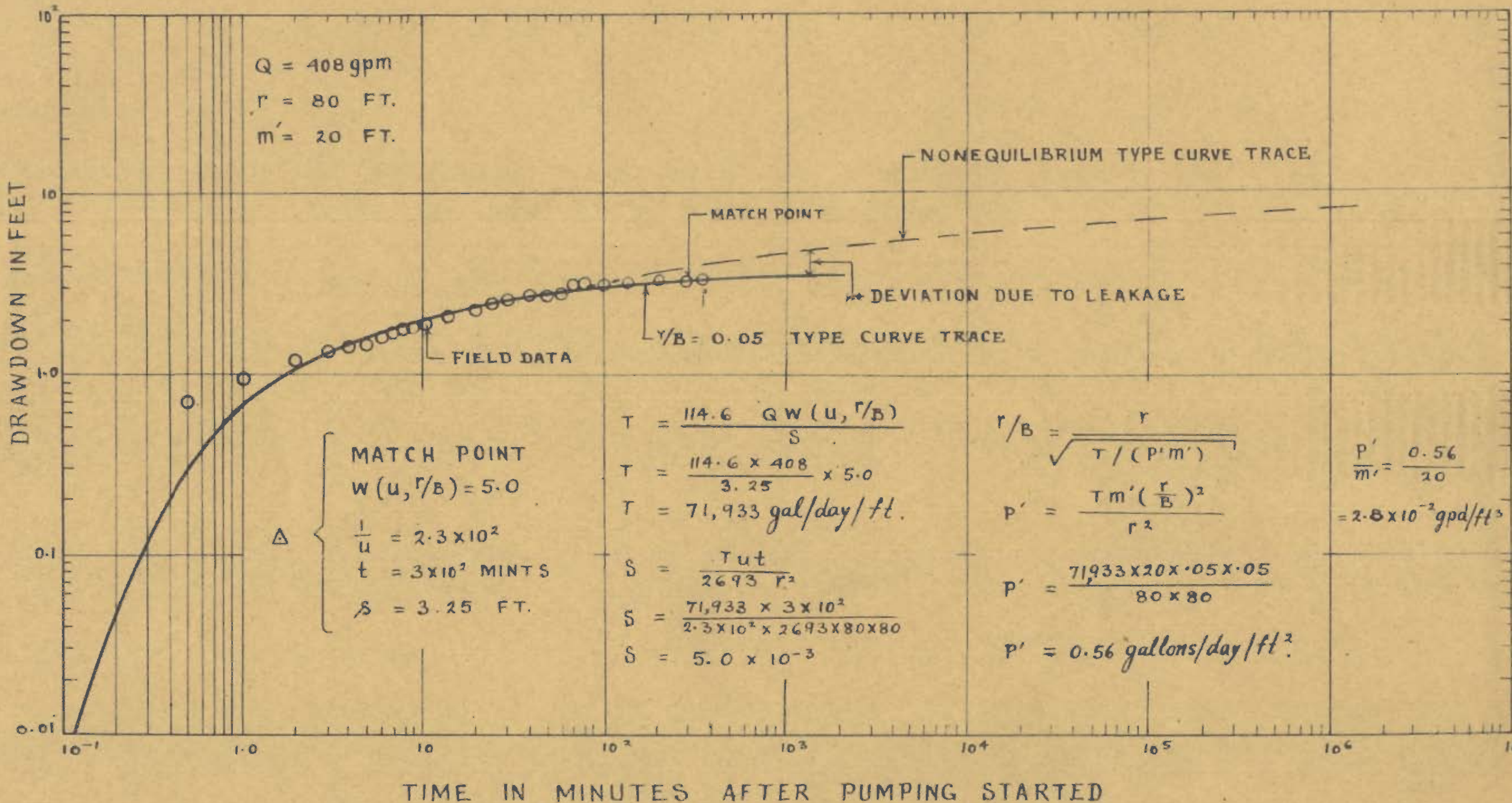
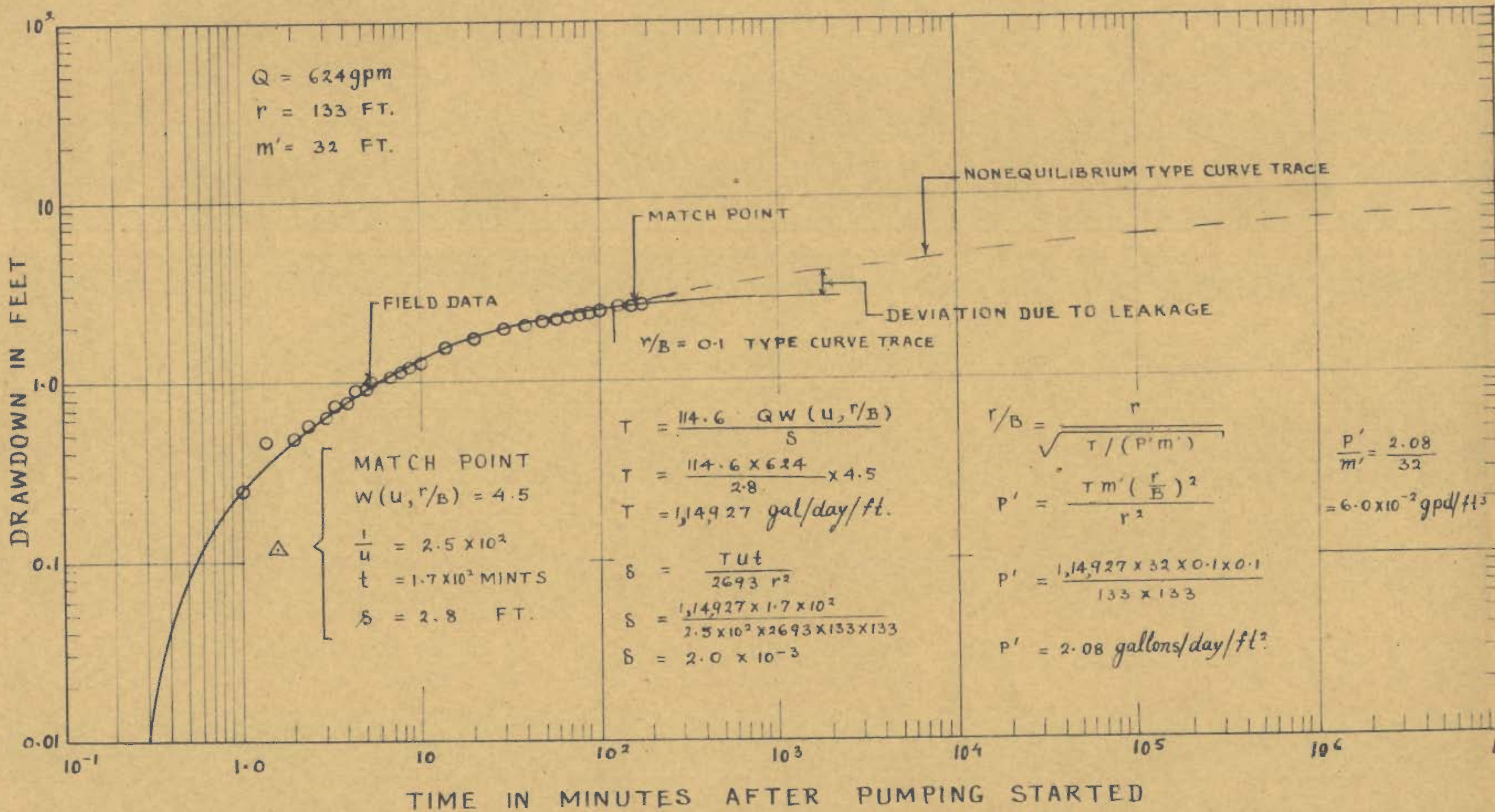


PLATE 4.48

TIME - DRAW - DOWN GRAPH FOR WELL NO. 3 KAIRANA

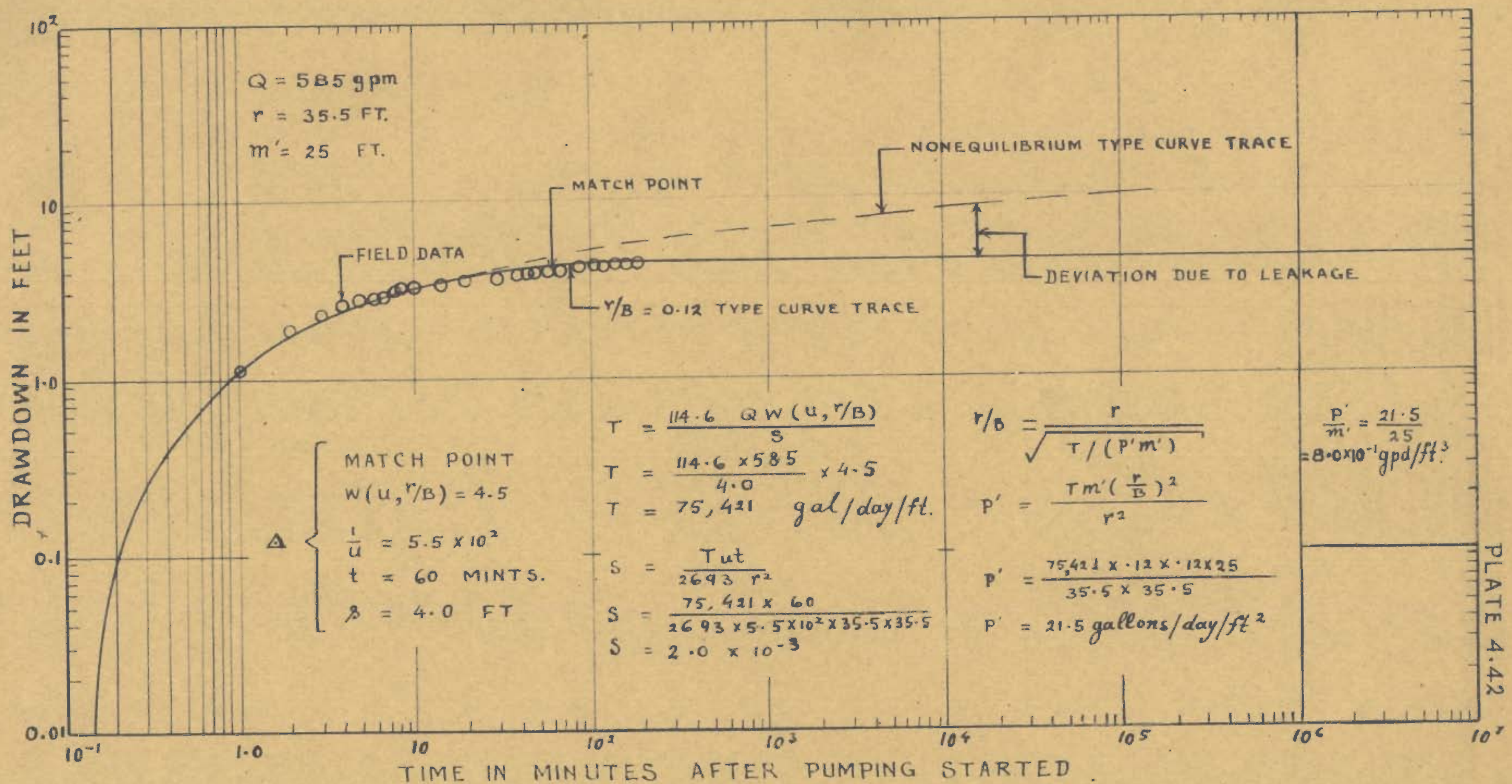


TIME - DRAW - DOWN GRAPH FOR WELL No. 20 N. L01

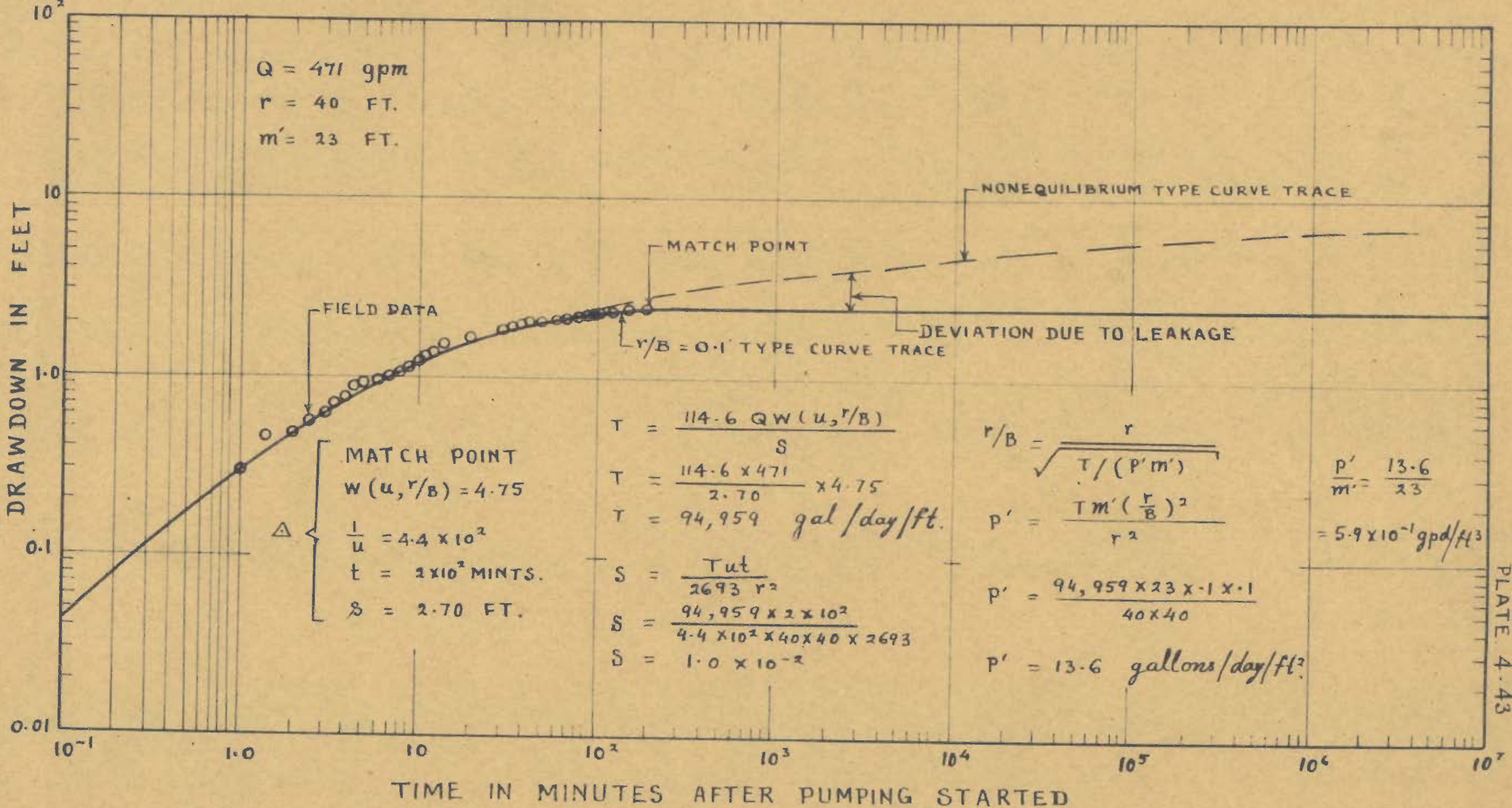


TIME-DRAW-DOWN GRAPH FOR WELL No. 12 N.L.O1

PLATE 4.41



TIME-DRAW-DOWN GRAPH FOR WELL No. 20. S.L01



TIME-DRAW-DOWN GRAPH FOR WELL No. 2 S.L01

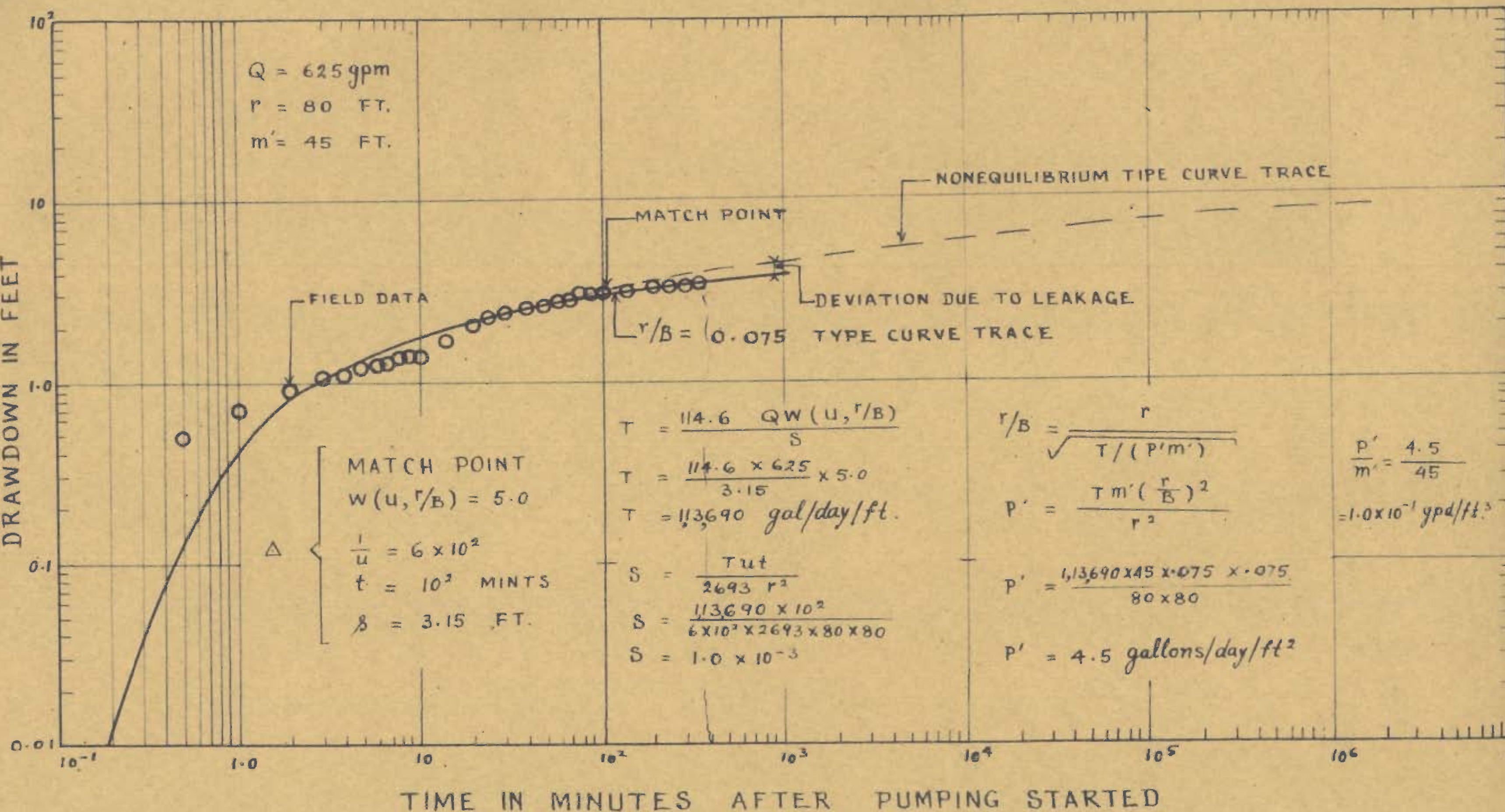


PLATE 4.44

TIME - DRAW - DOWN GRAPH FOR WELL No. 22 N. L01

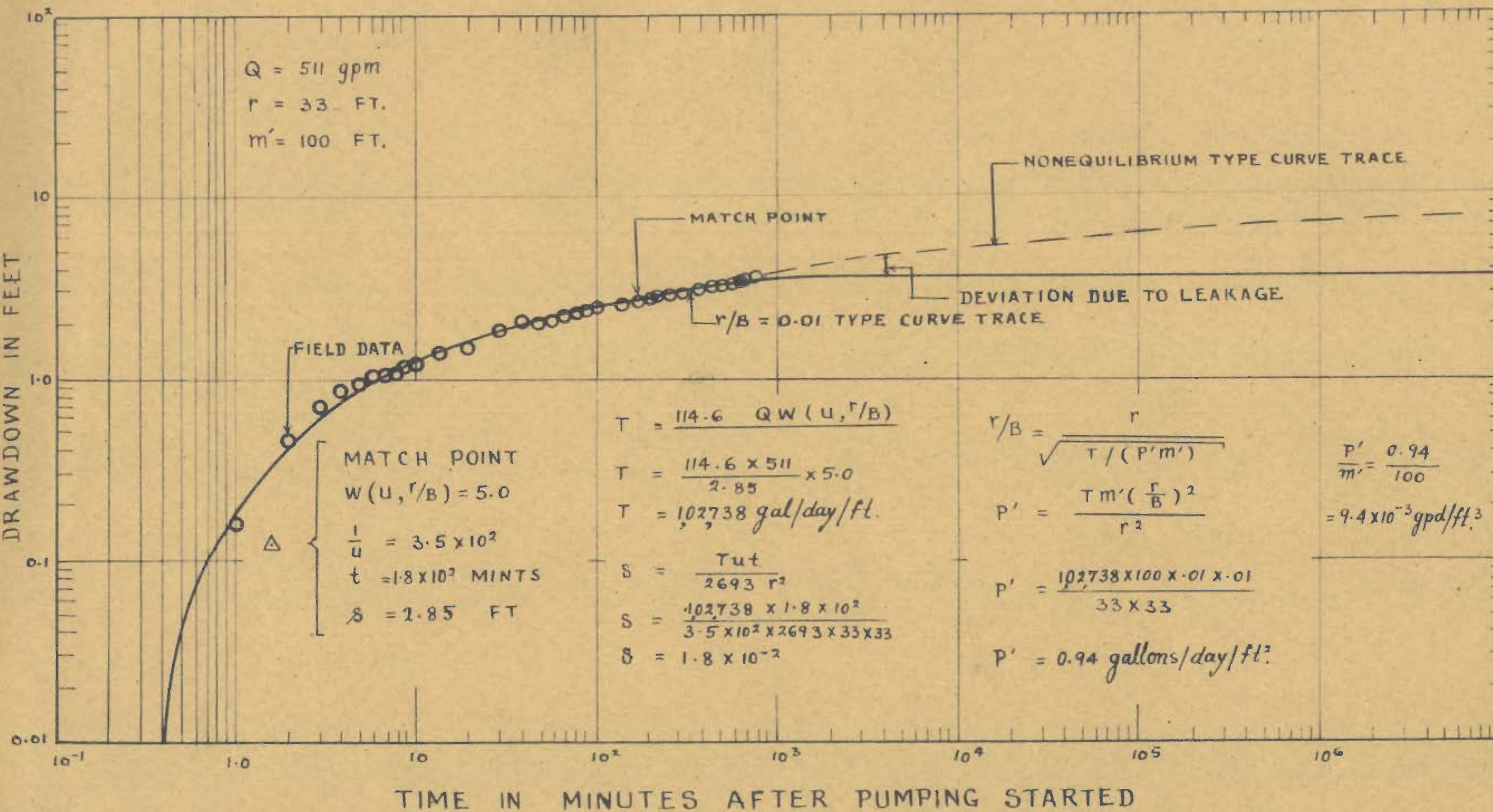
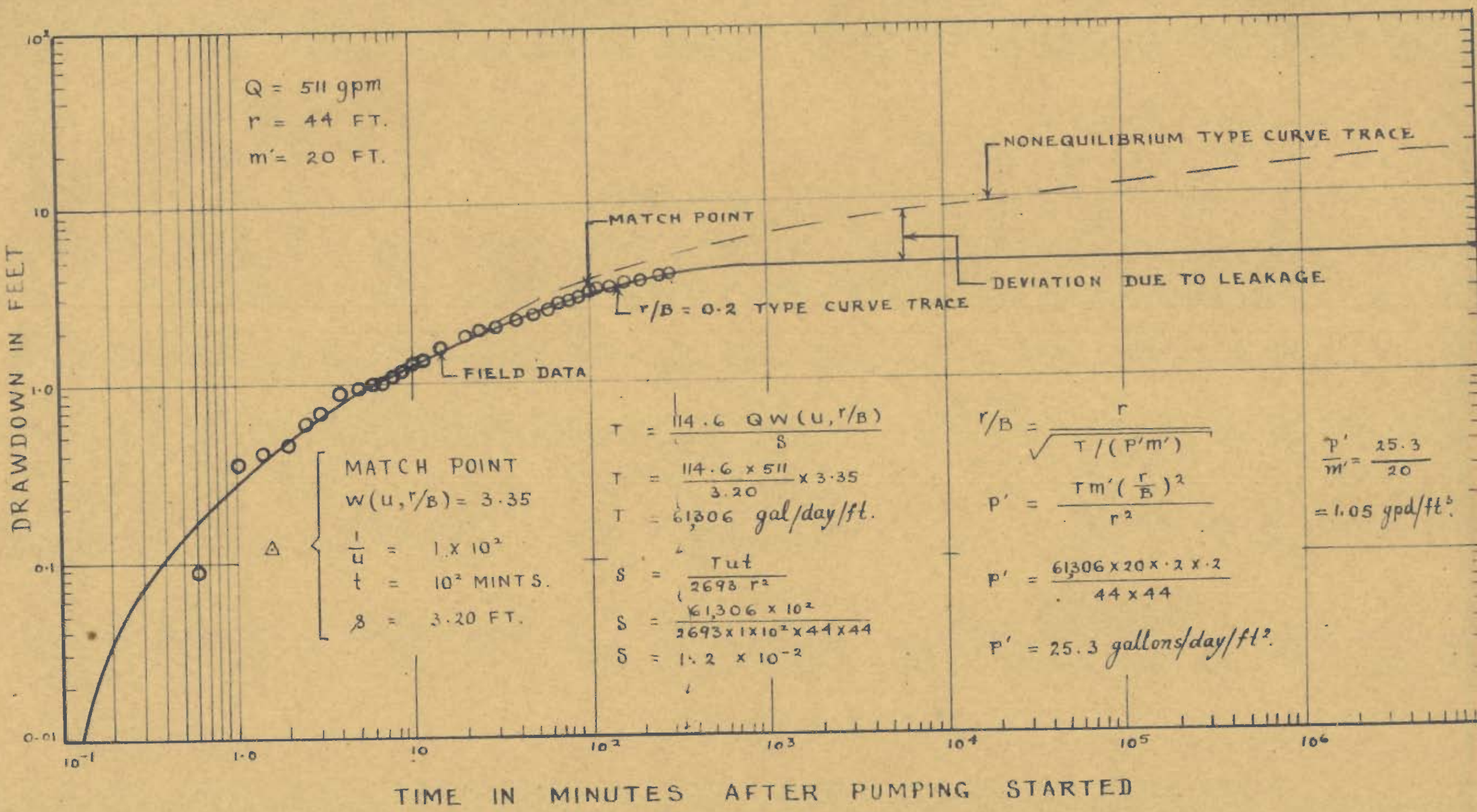


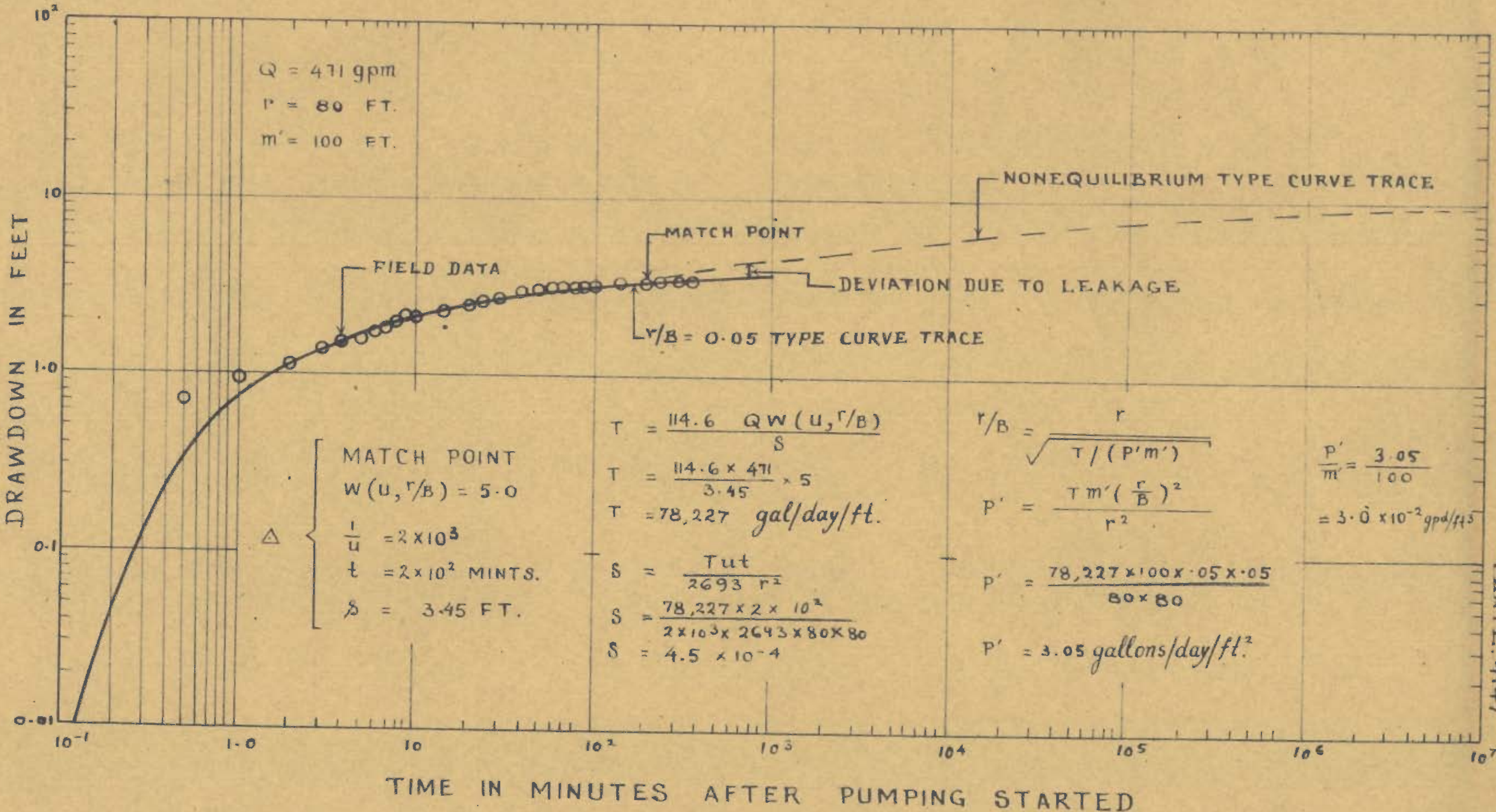
PLATE 4.45

TIME-DRAW-DOWN GRAPH FOR WELL No. 10 S.LOI

PLATE 4.46



TIME-DRAW-DOWN GRAPH FOR WELL No. 7 S. L01



TIME-DRAW-DOWN GRAPH FOR WELL No. 17 N. LOI.

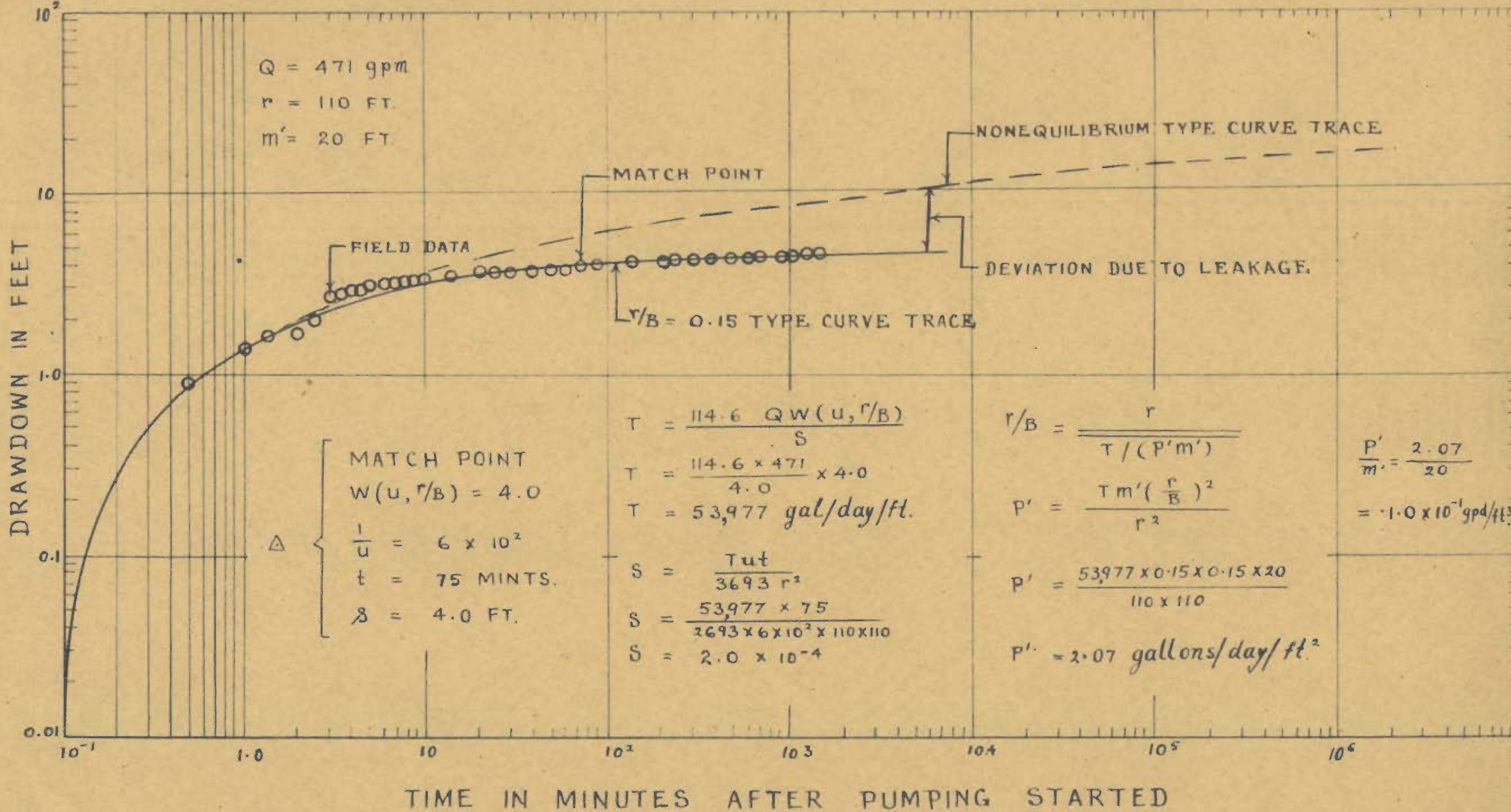


PLATE 4.48

TIME-DRAW-DOWN GRAPH FOR WELL NO. 3 KAIRANA

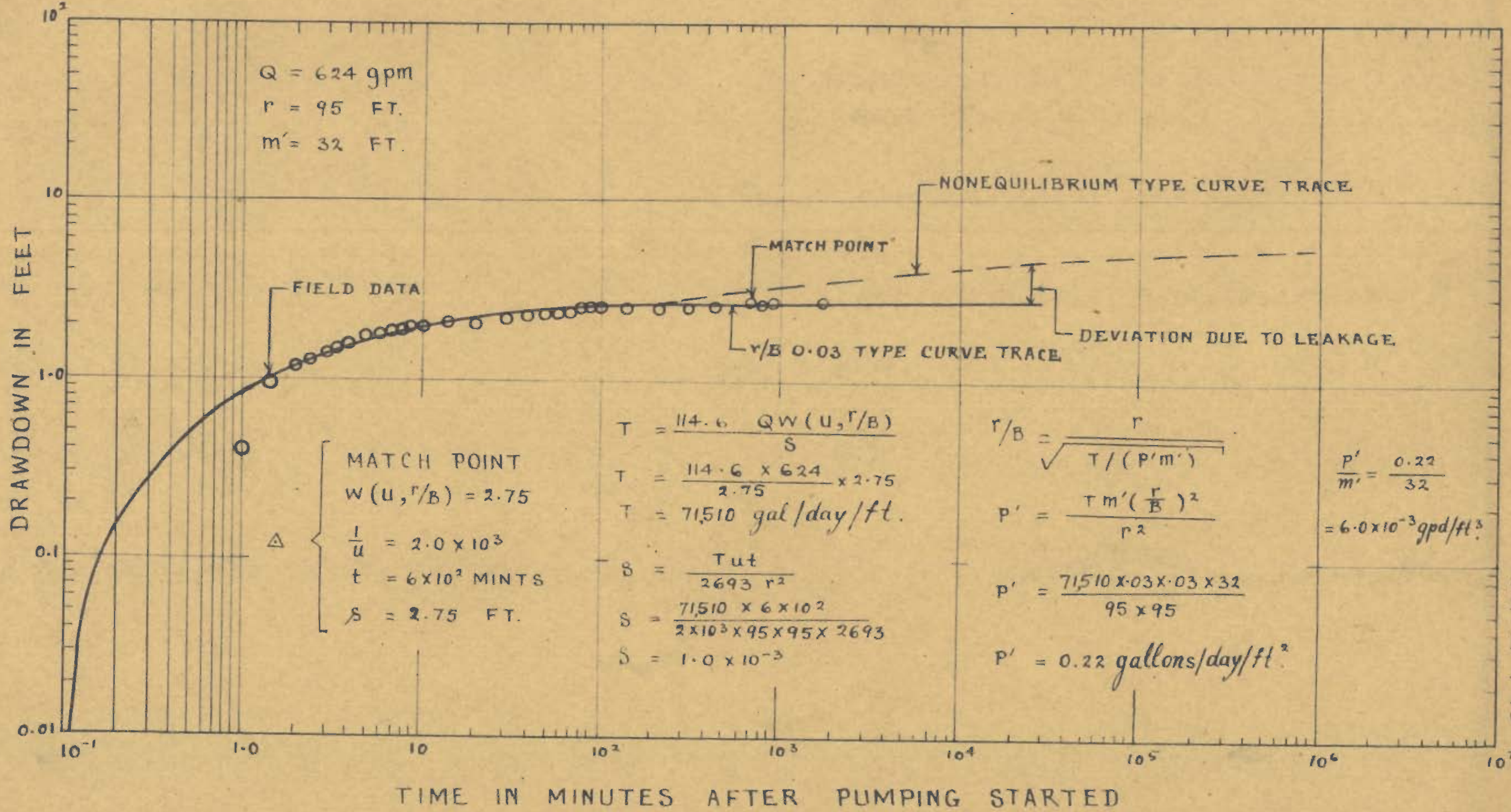


PLATE 4.49

TIME-DRAW-DOWN GRAPH FOR WELL No 13 N. L01.

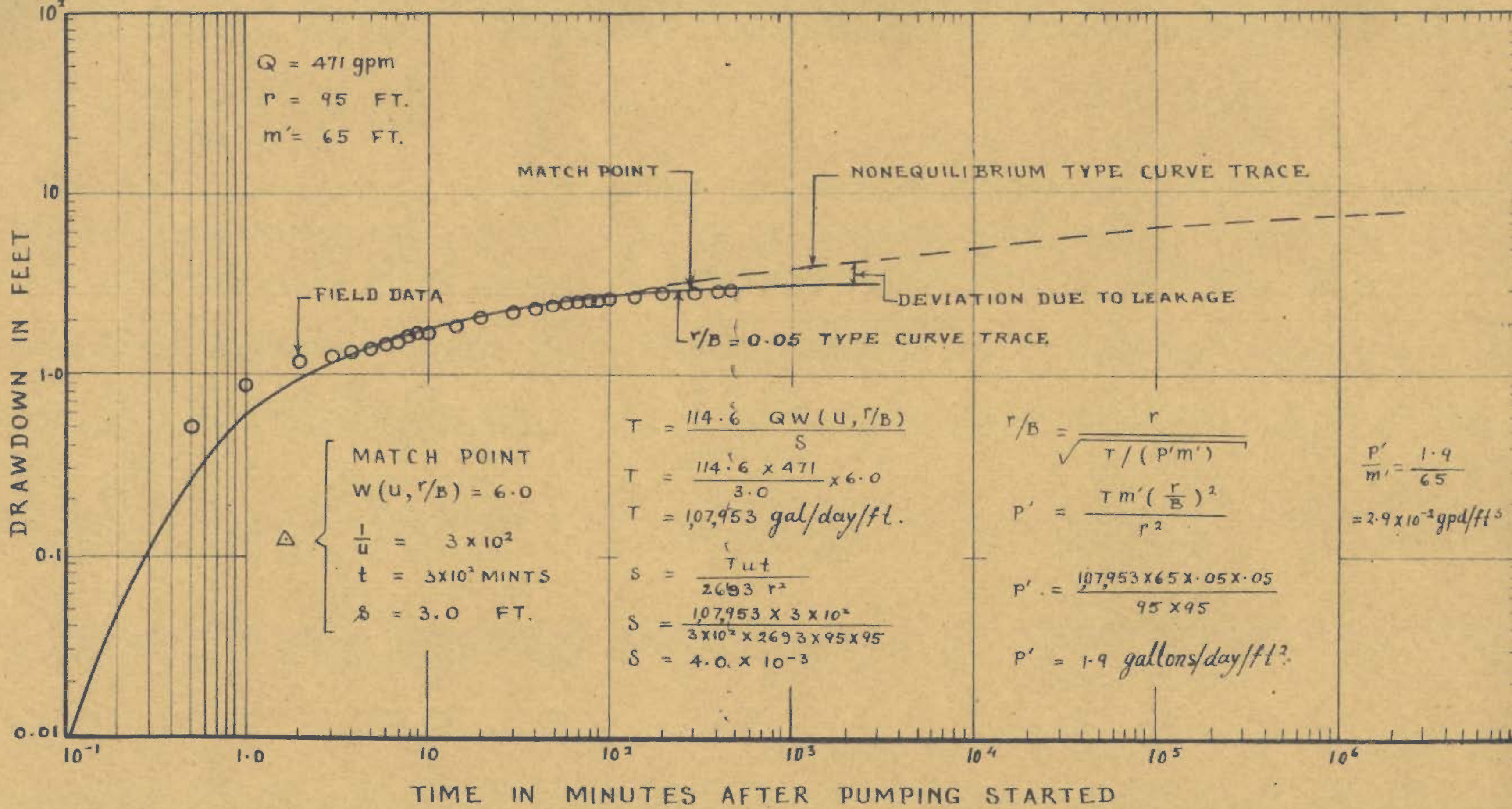
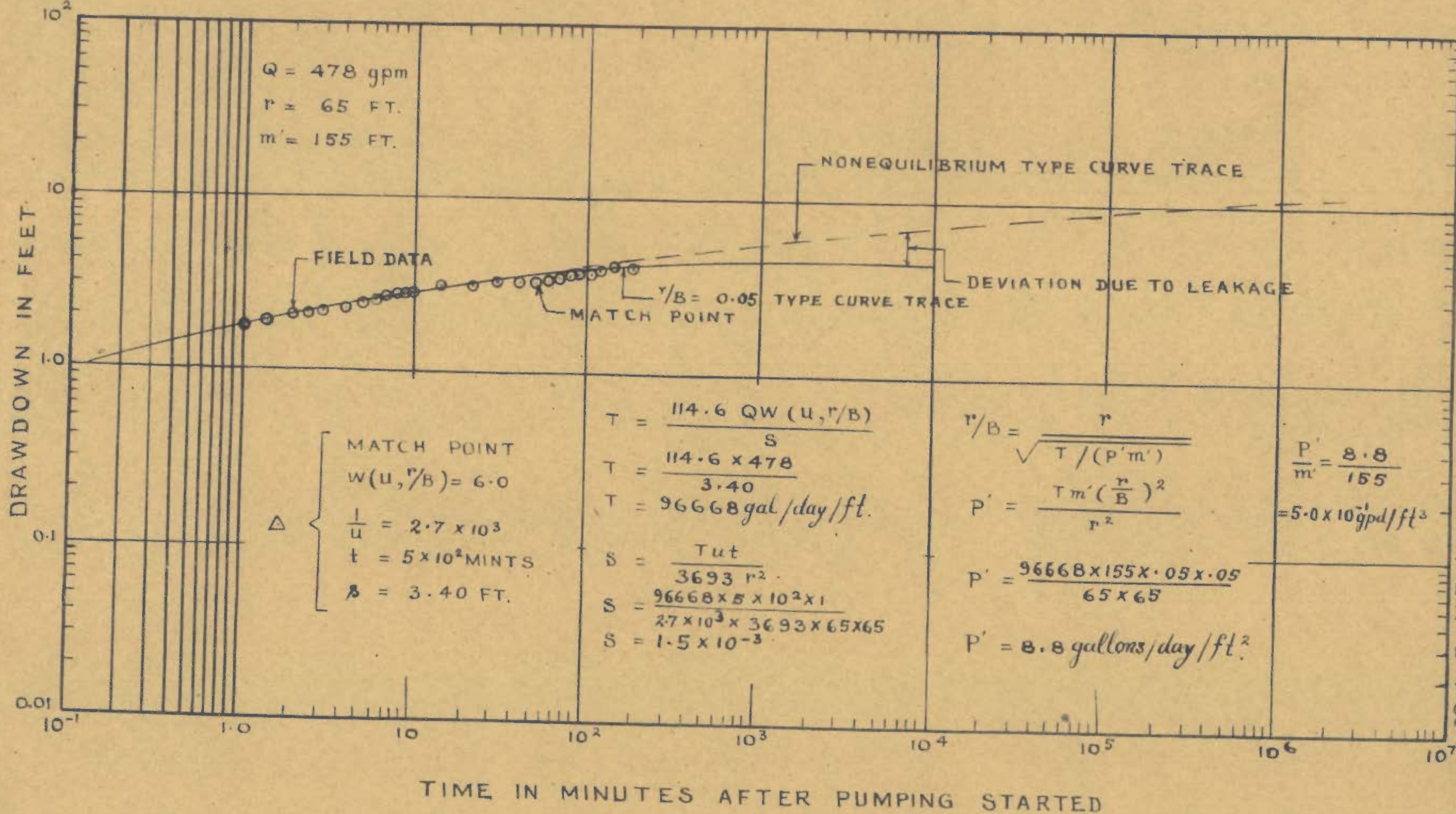
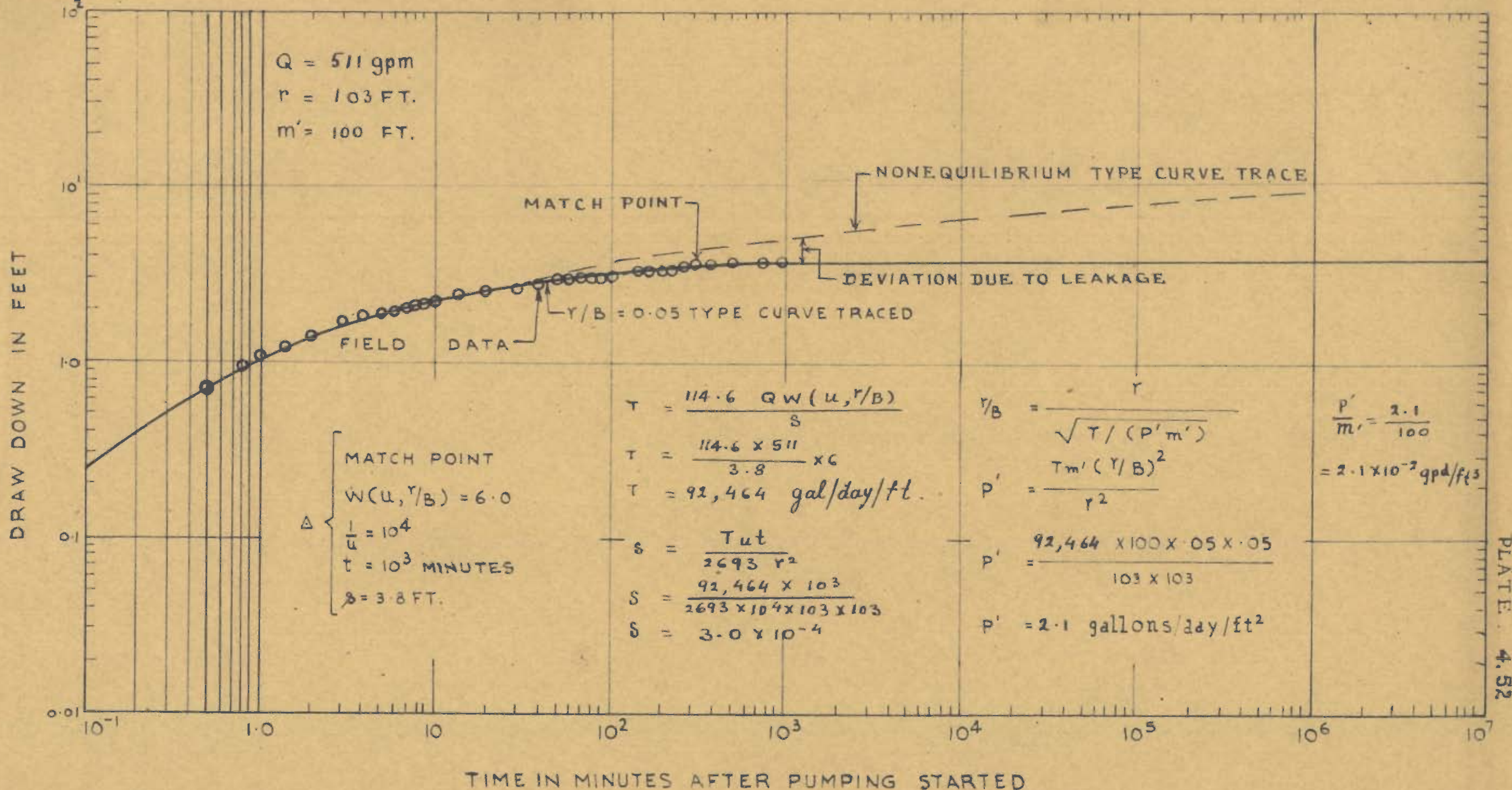


PLATE. 4.50

TIME-DRAW-DOWN GRAPH FOR WELL No. 10 A. KAKRA.



TIME-DRAW-DOWN GRAPH. FOR WELL No. 9 DAHA



TIME-DRAW-DOWN GRAPH FOR WELL No. 17 S. L01.

PLATE. 4.52

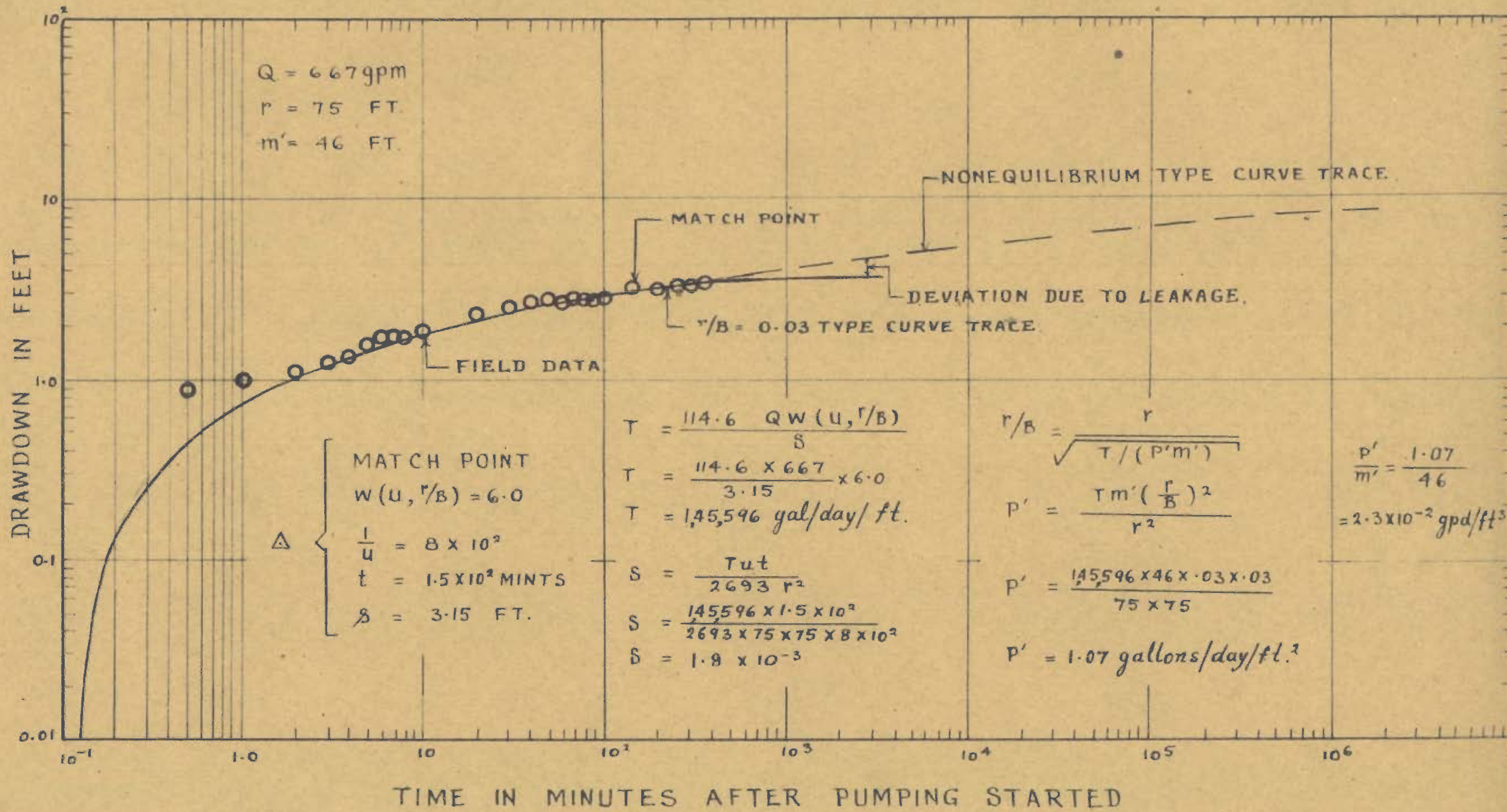


PLATE. 4. 53

TIME-DRAW-DOWN GRAPH FOR WELL No. 19 N. L01

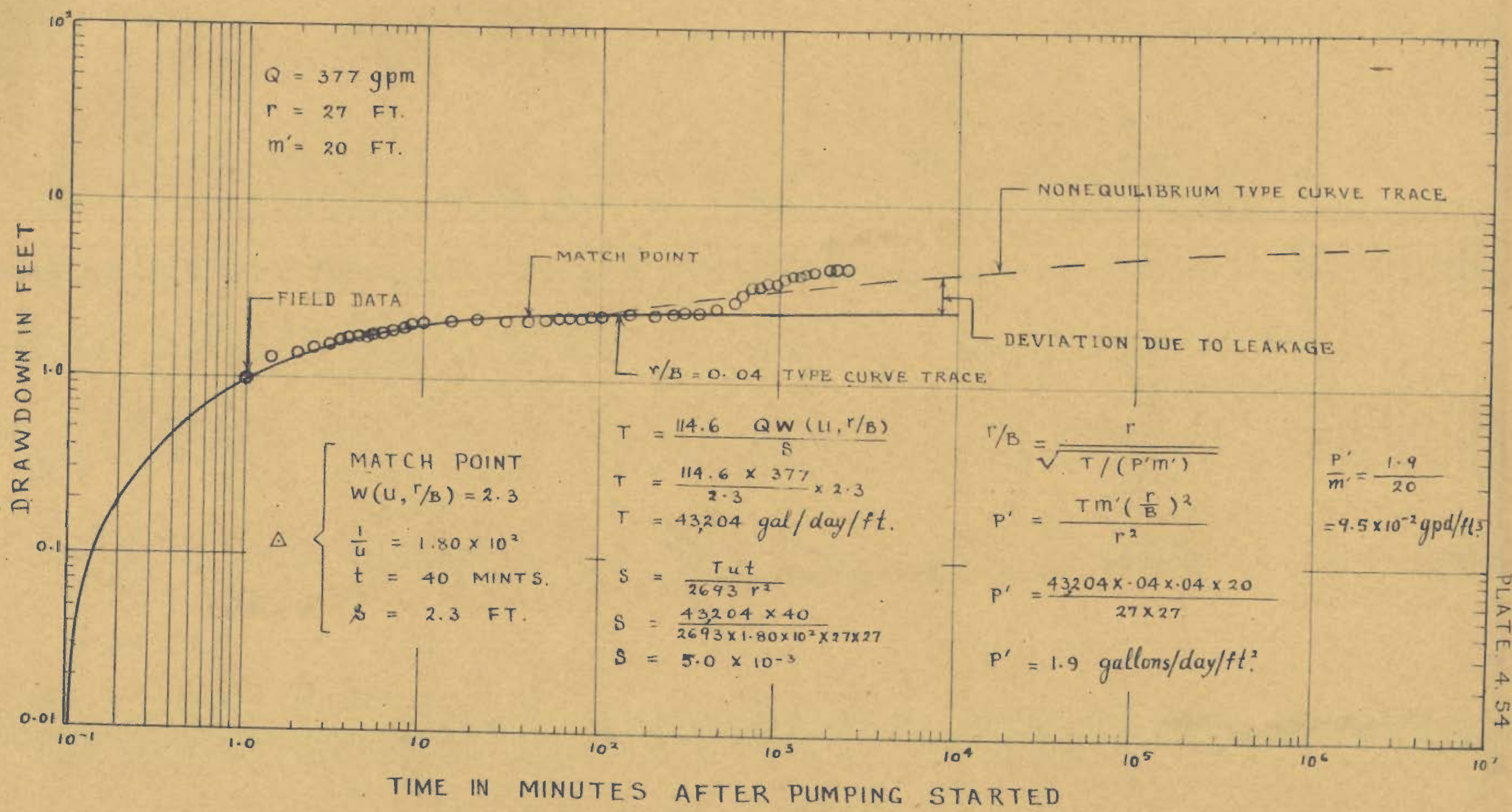


PLATE 4.54

TIME - DRAW - DOWN GRAPH FOR WELL No. 11 N. LOI.

In that part of the curve where it approaches asymptotically the maximum drawdown, the slope m at any point can be given by

$$m = (2.3\ Q/4\pi T)e^{-q} \quad \text{.. .. .. ..} \quad (4.25)$$

where $$q = Tt / sB^2 \quad \text{.. .. .. ..} \quad (4.26)$$

and the drawdown by

$$s = s_m - (Q/4\pi T)W(q) \quad \text{.. .. .. ..} \quad (4.27)$$

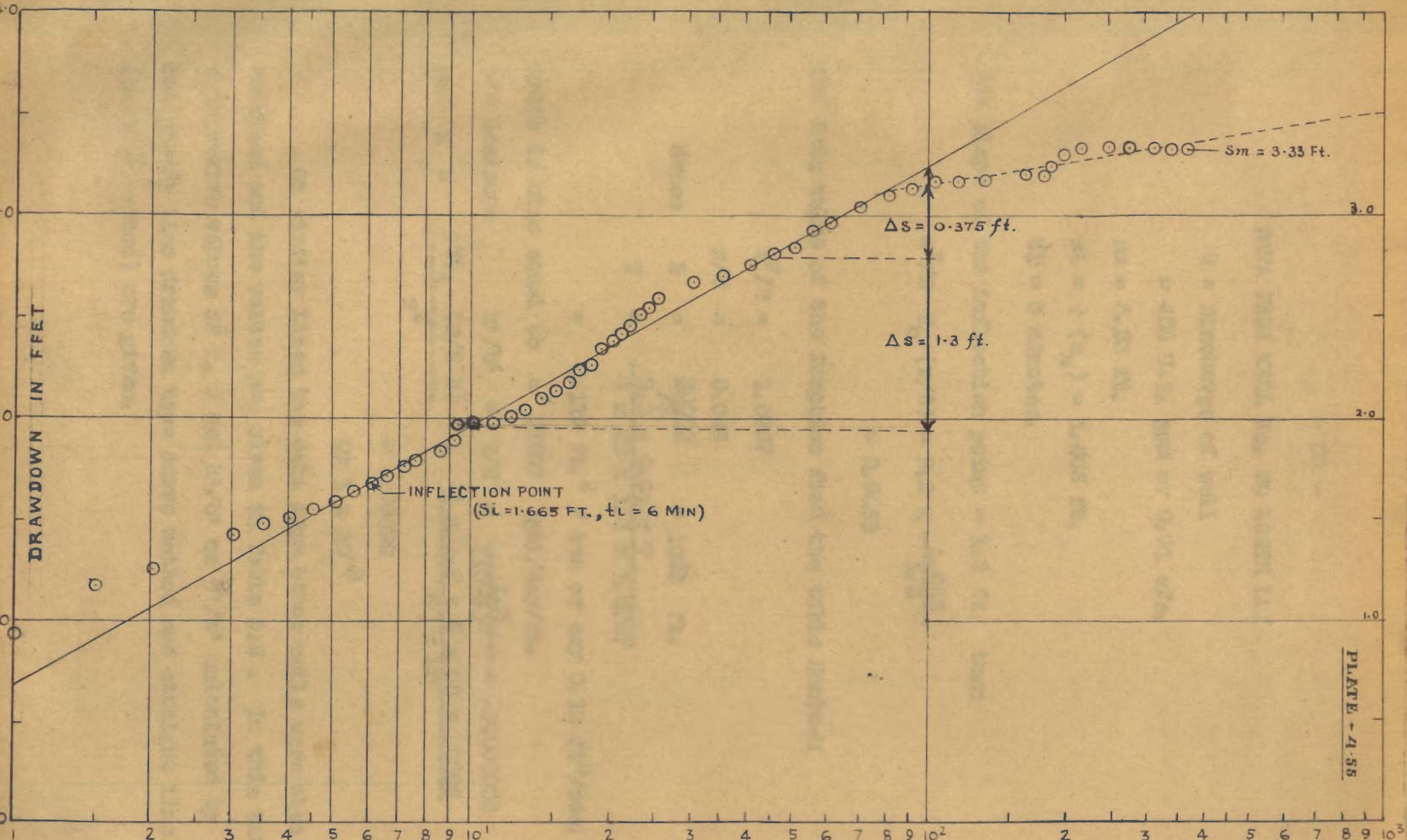
where W(q) is the exponential integral $-E_i(-q)$, which is known as the 'well function' in ground water hydrology. From equations (4.22), (4.23) and (4.24) the following relation is obtained.

$$f(q) = e^q W(q) = 2.3\ (s_m - s)/m \quad \text{.. ..} \quad (4.28)$$

Hantush[43] has tabulated the values of the functions used in the above equations.

This method also involves the measurement of drawdown in an observation well and plotting of a time-drawdown curve on a semilog graph so that the maximum drawdown (s_m) is found. The time drawdown curves (Plates 4.24 to 4.38) were utilised to determine the values of s_m, s_i, t_i and m. One such example is given in Plate 4.55.

Based on the above theory given by Hantush[43], the formation constants have been calculated. Following is the example of one such calculation for the data from well No.20 North Loi.



TIME-DRAW-DOWN GRAPH FOR WELL No. 20 N.LDI

A perusal of Table 4.5 would indicate that the values of T and S as determined by assuming leakage are more or less similar to those determined from the earlier drawdown data by Theis and Jacob-Theis methods. This has further supported the concept of leaky confined conditions for the deeper aquifers in the area.

DATA FROM WELL No. 20 NORTH LOI

Q = Discharge of well

= 408 U.S. gpm or 0.91 cfs.

sm = 3.33 ft.

si = $\frac{1}{2}(s_m)$ = 1.665 ft.

ti = 6 minutes.

The slope of the inflection point = 1.3 ft. then

$$e^r/B \; K_o (r/B) = 2.3 \times \frac{1.665}{1.3}$$

$$= 2.9458$$

for this value of the function from the table Hantush

e^r/B = 1.0757

r/B = 0.048

Hence B = $\frac{80000}{73}$ = 1096 ft.

$$T = \frac{2.3 \times 0.91 \times 7}{4 \times 22 \times 1.3 \times 1.0757}$$

= 0.119 ft.^{2} / sec or say 0.12 ft^2/séc.

which is also equal to = 77587 gal/day/ft.

and Leakance k'/b' = $T/B^2 = \frac{1.2}{(1096)^2}$ = .00000009

and $S = \frac{4Tt_i \; (r/2B)}{r^2} = \frac{4 \times 1.2 \times 6 \times 60 \times .0366}{80 \times 80}$

= .00099

or 1×10^{-3}

On similar lines the data from other wells were also analysed and the values are given in Table 4.5 . In this table comparative values of T, S and k'/b' or p'/m' calculated by non steady time drawdown type curve method and straight line method (Hantush method) are given.

Table 4.5 VALUES OF T, S AND P'/m' BY LEAKY TYPE CURVE AND STRAIGHT LINE METHOD

Well No.	T gpd / ft	S	P'/m' or K'/b'	
1	2	3	4	
20 North Loi	71933 / 75587	$5.0 \times 10^{-3}/1.0 \times 10^{-2}$	2.8×10^{-2} gpd/cft	$/1.0 \times 10^{-6}$ sec^{-1}
19 North Loi	145596 /103450	$1.8 \times 10^{-3}/1.4 \times 10^{-2}$	2.3×10^{-2} gpd/cft	$/1.0 \times 10^{-7}$ "
10 A Kakra	107953 /116380	$4.0 \times 10^{-3}/5.0 \times 10^{-6}$	2.9×10^{-2} gpd/cft	$/5.0 \times 10^{-2}$ "
13 North Loi	71510 /193967	$1.0 \times 10^{-3}/3.0 \times 10^{-6}$	6.0×10^{-3} gpd/cft	$/2.0 \times 10^{-8}$ "
3 Kairana	53977 /103450	$2.0 \times 10^{-4}/5.0 \times 10^{-4}$	1.0×10^{-1} gpd/cft	$/1.0 \times 10^{-8}$ "
17 North Loi	28227 / 90435	$4.5 \times 10^{-4}/7.0 \times 10^{-4}$	3.0×10^{-2} gpd/cft	$/7.0 \times 10^{-8}$ "
7 South Loi	61306 / 84036	$1.2 \times 10^{-2}/2.2 \times 10^{-2}$	1.05 gpd/cft	$/1.7 \times 10^{7}$ "

1	2	3	4	
10 South Loi	102738 /775870	1.8×10^{-2}/ 2.7×10^{-1}	9.4×10^{-3}gpd/cft	/2.7×10^{-5} sec^{-1}
22 North Loi	113690 /135277	1.0×10^{-3}/ 3.0×10^{-5}	1.0×10^{-1}gpd/cft	/ 5.0×10^{-8} "
12 North Loi	114927 / 90485	2.0×10^{-3}/ 1.0×10^{-3}	6.0×10^{-2}gpd/cft	/4.0×10^{-7} "
11 North Loi	43204/ 34936	5.0×10^{-3}/ 1.7×10^{-1}	9.0×10^{-2}gpd/cft	/3.6×10^{-6} "
2 South Loi	94959 / 58190	1.0×10^{-1}/ 3.4×10^{-3}	5.9×10^{-1}gpd/cft	/7.8×10^{-7} "
17 South Loi	92464 / 85347	3.0×10^{-4}/ 7.0×10^{-6}	2.1×10^{-2}gpd/cft	/3.0×10^{-8} "
20 South Loi	75421 / 77587	2.0×10^{-3}/3.0×10^{-2}	8.0×10^{-1}gpd/cft	/5.0×10^{-7} "
9 Daha	96668 / 90587	1.5×10^{-3}/2.0×10^{-2}	5.0×10^{-1}gpd/cft	/6.7×10^{-4} "

N.B. First values in each column is obtained by type curve method and the second value by the straight line method.

CONCLUSIONS

The hydrological character of the deeper aquifers in the Indo-Gangetic alluvium has been a matter of controversy. Taylor[8] while describing the ground water provinces of India has mentioned that in the Axial belt the deeper aquifers are under confined conditions, although the flowing well conditions are very rare. Chaturvedi and Pathak[17], on the basis of pump test data from Muzaffarnagar-Meerut regions have shown that the tubewells in this area tap water from water table aquifers. These conclusions were based on large values of S determined by these authors. Later, Chaturvedi and Pathak[16], while analysing data from Aligarh-Mathura district, which are also located in the Axial belt and are to the south of the present area, have shown that the deeper aquifers in the region are under leaky-confined conditions. They concluded that there are varying geohydrological conditions in the different parts of Uttar Pradesh.

Raghava Rao[14] had carried out the analysis of pump-test data from Roorkee area which lies about 20 miles to the north of Muzaffar-nagar town and he concluded that the deeper aquifers in Roorkee area show an average value of S which is of the order of 3.70×10^{-4} thereby indicating that the deeper aquifers in the area are under confined conditions.

Singhal and Gupta[15] have analysed pump test data from a well in Muzaffarnagar area (Appendix I). They also analysed the test data by Prickett's method and concluded that the deeper aquifers in the area are not under water table conditions but they show leaky confined characters.

The values of S have been taken to be indicative of the hydraulic characters of the aquifer by many workers. As mentioned earlier, Ferris et al[34] have indicated that for confined aquifers S varies from 0.00001 to 0.001 and for water table aquifers it varies from about 0.05 to 0.30.

A perusal of Table 4.2 and 4.3 would show that the value of S as determined by various methods comes to be well within the confined aquifer range and therefore, it indicates that the deeper aquifers in the area of investigation are under confined conditions. It does not mean that the overlying clayey formations have complete sealing effect, but as pumping from the deeper aquifer proceeds, water from the overlying water table aquifer leaks to the confined aquifers.

A perusal of Tables (4.2, 4.3 and 4.5) indicates that the values of T and S show variation with time of pumping. However, in most of the cases the values of T and S determined from the earlier parts of the time-drawdown curve, either by Theis - type curve method or by Jacob - Theis straight line method, are comparable with those determined by the leaky aquifer formulae. The later parts of the time-drawdown curves, which show flatter slope, cannot be utilised for determining the aquifer constants by the Jacob-Theis straight line method because the value of T and S are very different as compared with those which are determined by the leaky confined formulae. All these findings indicate that the aquifer under discussion behave during pumping as leaky confined aquifers.

The present study also indicates that for leaky aquifers the Theis and Theis-Jacob methods give dependable results only for the earlier data when there is practically no leakage to the tested aquifers from other horizons.

It should also be mentioned that during the above pump tests the water levels were above the top of the aquifer and the drawdown data were not measured in the pumping well itself. If drawdown is measured in the pumping well itself, the calculations for leaky aquifer conditions would be erroneous.

There is of course a possibility of interference between the various aquifers also because the wells tap more than one aquifer. However, their effect, if any, is difficult to determine quantitatively unless observation holes are put at every horizon.

It has been stated earlier in Chapter 2 that the aquifers in the area at places are of isolated character and there is interfingering of the formations which indicates that the aquifers are no homogeneous and isotropic. Such a hetrogenity will also be responsible for putting limitations on the applications of the above methods (Bruin and Hudson[45]).

The effect of draining of the semi-confining layer is also of importance in the interpretation of pump test data under such geological conditions. (Maxey[46]). However, as the saturated thickness of the tapped aquifer remained constant, there should not be any effect of draining on the pump test data under discussions.

Although in the present study it was not possible to determine the effect of either mutual interference of aquifers or their hetrogeneous character, however, it can be concluded that the deeper aquifers are under leaky confined conditions. The leakage becomes more as the drawdown becomes large and the cone of depression expands.

The average values of the various hydraulic parameters of the deeper aquifers in the area are:

T = 47,000 - 2,00,897 gallons per day per ft.

S = 1.0×10^{-4}

Pf = 800 gallons per day per sq.ft.

P'/m' or k'/b' = 5.0×10^{-8} sec^{-1}

CHAPTER 5

ANALYSIS OF HYDROLOGICAL DATA BY STATISTICAL METHODS

INTRODUCTION

Application of statistical methods to ground water hydrology helps in solving many complicated problems and as such their use to this field is many fold. Although these have not been used widely in this country but a start has been made by various workers to apply statistical methods in solving problems of ground water regime as is described in the following paragraph. The possible ways and parameters involved in statistical methods have been discussed in this chapter. The application of the correlation method of statistical analysis of the water level data helps in the determination of dependencies between the following variables: (1) Ground water levels in the preceding and in the following months (2) Water levels in rivers and the ground water levels (3) Atmospheric precipitation and shallow ground water levels. In the present area an attempt has been made to analyse the hydrological data collected for the shallow ground water reservoir during the year 1960-61 as well as for the period 1965-66. All the sites for which data have been used are shown in (Plate 5.1)

PLATE 5.1


LOCATION OF VARIOUS GEOHYDROLOGICAL STATIONS
N
SAHARANPUR.
MUZAFFAR NAGAR.
BIJNOR.
PUNJAB.
MEERUT.
MORADABAD.
EASTERN
KRISHNI NADI
HINDAN NADI
KALI NADI
GANGA CANAL
GANGA RIVER
YAMUNA RIVER
YAMUNA CANAL
ANUP SHAHR BRANCH
KALI NADI
SHAMLI
KAIRANA.
M. NAGAR.
DHANDAULI
PURBALIAN
BUDHANA
RAJPURA
BHAMBARA
GANGNAULI
NAGWA
BAMNAULI
BARAUT
MEERUT.
GARHMUKTESHWAR.
LEGEND:-
1. DISTRICT BOUNDARY
2. RIVER
3. ROADS
4. CANAL
SCALE 8 0 2 4 6 8 MILES

Altovsky[47] has described the methods of statistical correlation coefficient and applied the same to ground water regime data. He emphasised the importance of various artificial factors affecting one or the other element of underground water regime. Bhattacharya et al[5] have evolved an empirical formula for the infiltration of rain water to the ground water table for a few doabs of Western Uttar Pradesh lying in the main Ganga-Yamuna Doab. In (1962) Raghava Rao and Raju[48] attempted such studies along the upper Ganga Canal in Roorkee area. Later, Raghav Rao[14] established relationship between the various parameters affecting the ground water regime in parts of District Saharanpur, U.P.

In the present study, the data obtained for the various hydrological stations along the river Hindon, Krishni and Hindon-Kali have been tabulated in Table 5.1 to 5.8. This comprises of the water level data of shallow ground water reservoir observed by means of piezometric tubes installed transverse to these rivers. These data have been subjected to analysis by two linear correlation methods.

Table 5.1 HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG RIVERS HINDON & KRISHNI FOR THE PERIOD 1960-1961

GEO-HYDRO-LOGICAL STATTIONS.	NOV. 1960	DEC. 1960	JAN. 1961	FEB. 1961	MARCH 1961	APRIL 1961	MAY 1961	JUNE 1961
H2/2 (DATANA)	725.71	726.00	725.15	725.33	724.84	724.44	723.80	723.13
H4/2 (KHAP-RANA)	718.50	717.93	718.10	718.23	717.67	717.36	717.01	716.49
K1/4 (RAJPUR-GARHI)	744.66	744.55	743.81	743.47	734.08	742.67	742.35	742.06
K2/4 (BARNAWA-GHAT.)	738.35	740.43	739.92	739.93	739.04	738.57	738.25	738.00

	JULY 1961	AUG. 1961	SEPT. 1961	OCT. 1961	NOV. 1961
H2/2 (DATANA)	724.07	725.88	729.05	727.08	726.46
H4/2 (KHAPRANA)	717.40	719.12	420.97	720.38	719.70
K1/4 (RAJPURA-GARHI)	742.71	743.60	744.29	745.52	745.57
K2/4 (BARNAWA-GHAT)	739.50	740.76	740.33	740.35	740.60

Note: H2/2 = Piezometric pipe at a distance of 500 feet from the River Bank.

H4/2 = Piezometric pipe at a distance of 500 feet from the River Bank.

K1/4 = Piezometric pipe at a distance of 2400 feet from the River Bank.

K2/4 = Piezometric pipe at a distance of 2400 feet from the River Bank.

Table 5.2 HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG HINDON RIVER FOR THE PERIOD 1960 - 1961

GEO-HYDRO-LOGICAL STATIONS.	NOV. 1960	DEC. 1960	JAN. 1961	FEB. 1961	MARCH 1961	APRIL 1961	MAY 1961	JUNE 1961
H1/1 (BUDHANA)	734.10	734.92	735.23	735.38	734.60	734.39	734.02	733.57
H2/2 (DATANA)	725.71	725.00	725.15	725.33	724.94	724.44	723.80	723.13
H3/1 (NAGWA)	738.25	738.04	738.14	738.77	738.10	737.72	737.31	736.76
H4/2 (KHAPRANA)	718.50	717.93	718.10	718.23	717.67	717.36	717.01	716.49

	JULY 1961	AUG. 1961	SEPT. 1961	OCT. 1961	NOV. 1961
H1/1 (BUDHANA)	734.38	736.36	736.37	735.75	735.09
H2/2 (DATANA)	724.07	725.88	729.05	727.08	726.46
H3/1 (NAGWA)	738.01	739.41	739.27	738.23	737.81
H4/2 (KHAPRANA)	717.40	719.12	720.97	720.38	719.70

Note: All these stations are along river Hindon in Muzaffarnagar-Merrut district.

H/1 = Piezometric pipe at a distance of 100 feet from the river bank.

H/2 = Piezometric pipe at a distance of 500 feet from the river bank.

Table 5.3 HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG RIVER HINDON FOR DECLINING PERIOD (1966)

GEO-HYDRO-LOGI-CAL STA-TIONS.	JANUARY 1966	FEBRUARY 1966	MARCH 1966	APRIL 1966	MAY 1966	JUNE 1966
H1 (TATAVI)	770.30	770.35	770.50	770.40	770.00	770.00
H2 (TATAVI)	771.17	771.20	771.25	771.27	770.97	771.02
H1 (DANDHULI)	750.10	750.00	749.95	749.10	748.85	749.00
H2 (DANDAULI)	751.52	751.30	750.10	750.12	749.95	750.12
H1 (BUDHANA)	736.58	736.50	736.58	736.48	736.18	736.58
H2 (BUDHANA)	737.88	737.80	737.85	737.83	737.48	737.83

NOTE: H1/ 1 = Piezometric pipe at a distance of 100 feet from the river bank.

H2/2 = Piezometric pipe at a distance of 500 feet from the river bank.

Table 5.4 HEIGHT OF WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG KALI RIVER FOR THE ~~RISING~~ PERIOD 1965-1966.

Sl. No.	GEOHYDROLOGICAL STATIONS	JULY 1965	AUG. 1965	SEPT. 1965	OCT. 1965	NOV. 1965	DEC. 1965	JAN. 1966
1.	K1/1 (MUZAFFARNAGAR)	761.97	962.47	762.27	762.18	762.37	762.22	761.97
2.	K2/2 (MUZAFFARNAGAR)	763.21	764.11	763.61	763.48	763.66	763.54	763.21
3.	K1/1 (PURBALIAN)	751.02	751.62	750.32	751.20	751.32	751.24	751.12
4.	K2/2 (PURBALIAN)	751.51	752.21	751.31	751.69	751.76	751.72	751.31
5.	K1/1 (PURBALIAN)	724.16	724.96	724.68	724.54	724.58	724.58	724.33
6.	K2/2 (BANBANA)	725.23	726.13	725.79	725.67	725.77	725.82	726.57

Sl. No.	FEB. 1966	MARCH 1966	APRIL 1966	MAY 1966	JUNE 1966	JULY 1966	AUG. 1966	SEPT. 1966
1.	761.90	761.50	761.47	761.32	761.47	762.47	763.47	763.22
2.	763.70	763.00	762.84	762.66	762.81	762.84	765.17	765.19
3.	750.00	750.90	750.92	750.80	750.92	751.90	752.52	752.52
4.	751.20	751.51	751.41	751.33	751.46	751.80	752.21	753.26
5.	724.30	723.90	723.83	723.63	723.78	723.00	725.88	725.98
6.	725.60	725.00	724.44	724.77	724.92	723.12	727.09	727.14

Note: K1/1 Piezometeric pipe at a distance of 100 feet from the river bank.

K2/2 Piezometeric pipe at a distance of 500 feet fromthe river bank.

Table 5.5 - HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG RIVER KALI F O R RISING PERIOD(1965)

Sl. No.	GEOHYDRO-LOGICAL STATIONS	JULY 1965	AUG. 1965	SEPT. 1965	OCT. 1965	NOV. 1965	DEC. 1965
1.	K1/1 (M.NAGAR.)	761.97	762.47	762.27	762.18	762.37	762.22
2.	K2/2 (M.NAGAR.)	763.21	764.11	763.61	763.48	763.66	763.54
3.	K1/1 (PURBALIAN)	751.02	751.62	750.32	751.20	751.32	751.24
4.	K2/2 (PURBALIAN)	751.51	752.21	751.31	751.69	751.76	751.72
5.	K1/1 (BANBANA)	724.16	724.96	724.68	724.54	724.58	724.58
6.	K2/2 (BANBANA)	725.23	726.13	725.79	725.67	725.77	725.82

NOTE:

1. K/1 piezometric pipe at a distance of 100 feet from the river Bank.
2. K/2 piezometric pipe at a distance of 500 feet from the river bank.

Table 5.6 - HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG RIVER KALI F O R DECLINING PERIOD(1966)

Sl. No.	GEOHYDROLOGICAL STATIONS.	JAN. 1966	FEB. 1966	MARCH 1966	APRIL 1966	MAY 1966	JUNE 1966
1.	K1/1 (M.NAGAR)	761.97	761.90	761.50	761.47	761.32	761.47
2.	K2/2 (M.NAGAR)	763.21	763.70	763.00	762.84	762.66	762.81
3.	K1/1 (PURBALIAN)	751.12	751.00	750.90	750.92	750.80	750.92
4.	K2/2 (PURBALIAN)	751.31	751.20	751.51	751.41	751.32	751.46
5.	K1/1 (BANBANA)	724.33	724.30	723.90	723.83	723.63	723.78
6.	K2/2 (BANBANA)	725.57	725.50	725.00	724.94	724.77	724.92

NOTE:

K1/1 piezometric pipe at a distance of 100 feet from River bank.

K2/2 piezometric pipe at a distance of 500 feet from the River bank.

Table 5.7 HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEA LEVEL ALONG RIVER HINDON FOR RISING PERIOD (1965)

Sl. No.	GEOHYDROLOGICAL STATIONS.	JULY 1965	AUG. 1965	SEPT. 1965	OCT. 1965	NOV. 1965	DEC 1965
1.	H1/1	770.60	771.20	770.50	770.40	770.50	770.60
2.	H2/2	771.72	772.27	771.57	771.47	771.62	771.62
3.	H1/1	750.10	750.90	750.35	750.22	750.45	750.35
4.	H2/2	751.07	752.07	751.70	751.60	751.85	751.70
5.	H1/1	737.48	738.68	737.00	736.90	736.98	736.88
6.	H2/2	738.73	738.98	738.29	738.24	738.33	738.23

NOTE:

H1/1 piezometric pipe at a distance of 100 feet from the River bank.

H2/2 piezometric pipe at a distance of 500 feet from the River bank.

Table 5.8 HEIGHT OF THE WATER TABLE IN FEET ABOVE MEAN SEALEVEL IN THE PRECEDING MONTHS & HEIGHT OF RIVER WATER LEVEL IN THE FOLLOWING MONTHS ALONG HINDON RIVER IN MUZAFFARNAGAR DISTRICT FOR THE PERIOD - 1965 - 1966.

Sl. No.	GEOHYDROLOGICAL STATIONS.	JULY 1965	AUG. 1965	SEPT. 1965	OCT. 1965	NOV. 1965	DEC. 1965
1.	Tatavi site	770.82	772.27	770.52	771.47	770.52	771.62
2.	Dandauli Site	748.06	752.07	747.66	751.60	747.66	751.70
3.	Budhana Site	736.06	739.98	735.66	738.24	735.66	738.23

	JAN. 1966	FEB. 1966	MARCH 1966	APR. 1966	MAY 1966	JUNE 1966	JULY 1966	AUG. 1966	SEPT. 1966
1.	770.12	771.20	770.12	771.27	769.92	771.02	771.00	772.72	771.60
2.	747.16	751.25	747.15	750.12	746.66	750.12	747.32	752.97	747.43
3.	735.66	737.80	735.35	737.83	734.86	737.83	735.92	739.28	737.30

===

The basic formula for the linear correlation coefficient (r) which has been used in this study was given by Pearson (Kapur and Saxena[49]).

Correlation coefficient 'r' between the two variables x and y has been defined as

$$r = \frac{\sum_{i=1}^{N} (x_i - x_m)(y_i - y_m)}{\sqrt{\sum_{i=1}^{N} (x_i - x_m)^2} \sqrt{\sum_{i=1}^{N} (y_i - y_m)^2}} \quad \ldots \ldots (5.1)$$

The equation (5.1) can be written as

$$r = \frac{\sum_{i=1}^{N} x_i \cdot y_i}{\sqrt{\left(\frac{\sum_{i=1}^{N} x_i^2}{N}\right)\left(\frac{\sum_{i=1}^{N} y_i^2}{N}\right)}} \quad \ldots \ldots (5.2)$$

where
$x_i = X_i - X_m$
$y_i = Y_i - Y_m$

The Equation (5.2) is changed to the following form in the case of bivariate frequency distributions i.e. in the case in which two variables say x_1 , y_1 occur with frequency where i = 1, 2 .... N

$$r = \frac{\sum_{i=1}^{N} \frac{n_{xy} - X_i Y_i}{\Sigma n} - V_1 V_2}{\sqrt{\frac{\Sigma x_i (n_x \cdot x_i)}{N} - u_1^2} \sqrt{\frac{\Sigma y_i (n_y \cdot y_i)}{N} - u_2^2}} \quad \ldots \ldots (5.3)$$

Where x_1 and y_1 are the two variables changed to arbitrary origin,

n_x , n_y are the frequencies of points contained in the intervals of x and y respectively.

n_{xy} is the frequency in cell at the intersection of a row and column represented by variables x and y respectively

and $v_1 = \frac{\Sigma nx.x_1}{N}$ and $V_2 = \frac{\Sigma ny.y_1}{N}$

Where $X = x_1, x_2 \ldots\ldots x_n$ and $y = y_1, y_2, \ldots\ldots y_n$

and $X_m = \sum_{i=1}^{N} \frac{x_i}{N}$ and $Y_m = \frac{\sum_{i=1}^{N^a} y_i}{N}$

ANALYSIS BY THE PEARSON'S LINEAR CORRELATION METHOD

The Pearson's Linear correlation coefficient, given earlier, has been widely used by various workers. In the present study, the analysis has been carried out under two broad heads viz. (1) Analysis of regional data and (2) of individual stations.

Analysis of Regional Data

This method allows to determine the level of ground water in a forth coming month on the basis of its average position during a preceding month. Altovsky[47] writes that this problem may not be solved for all the 12 months of the year. For the regions in USSR, which are devoid of a stable snow cover, recharge is achieved during the autumn and winter period by atmospheric precipitation. Under such circumstances the rise in the level of ground waters during this period assumes a more or less gradual character. As such the year, in these parts of USSR, may be splitted up into two periods, corresponding to a drop and a rise in level. Therefore, it is possible to compile two correlated dependencies; One for the period of decline and the other for the period of rise in the ground water level.

In the present area of study the year may be divided into two parts viz. summers and the winters and for the sake of ground water levels it can be divided into pre-monsoon and post-monsoon i.e. period upto May can be classified as pre-monsoon and that of October and beyond as post-monsoon. As such the month of May indicates the lowest ground water levels while that of October the maximum ground water levels because the main recharge is obtained by rainfall during the month of July to October. The variable X and Y in the present problem are represented by the ground water level data for preceding and the following months.

In order to analyse the data on a regional basis, the same have been grouped in the form of bivariate frequency distribution. Hence formula (5.3) which has also been used by Altovsky[47], has been utilised in the present case.

The above method of correlation not only makes it possible to arrive at a correlated dependency, but is helpful in determining the basic factor influencing any given element of the water regime. Correlated dependencies may thus be found between the level of underground waters and any other natural or artificial factors. For example, a relation may be established between amount of precipitation, water levels in rivers, reservoirs and canals, evaporation losses etc.

In the present study, data collected for 1960-61 and 1965-66 have been subjected to analysis for the following dependencies:

(1) Shallow ground water level for the preceding and the following months.

(2) Rise and decline of water levels in preceding and the following months separately.

(3) Shallow ground water levels and the river water levels.

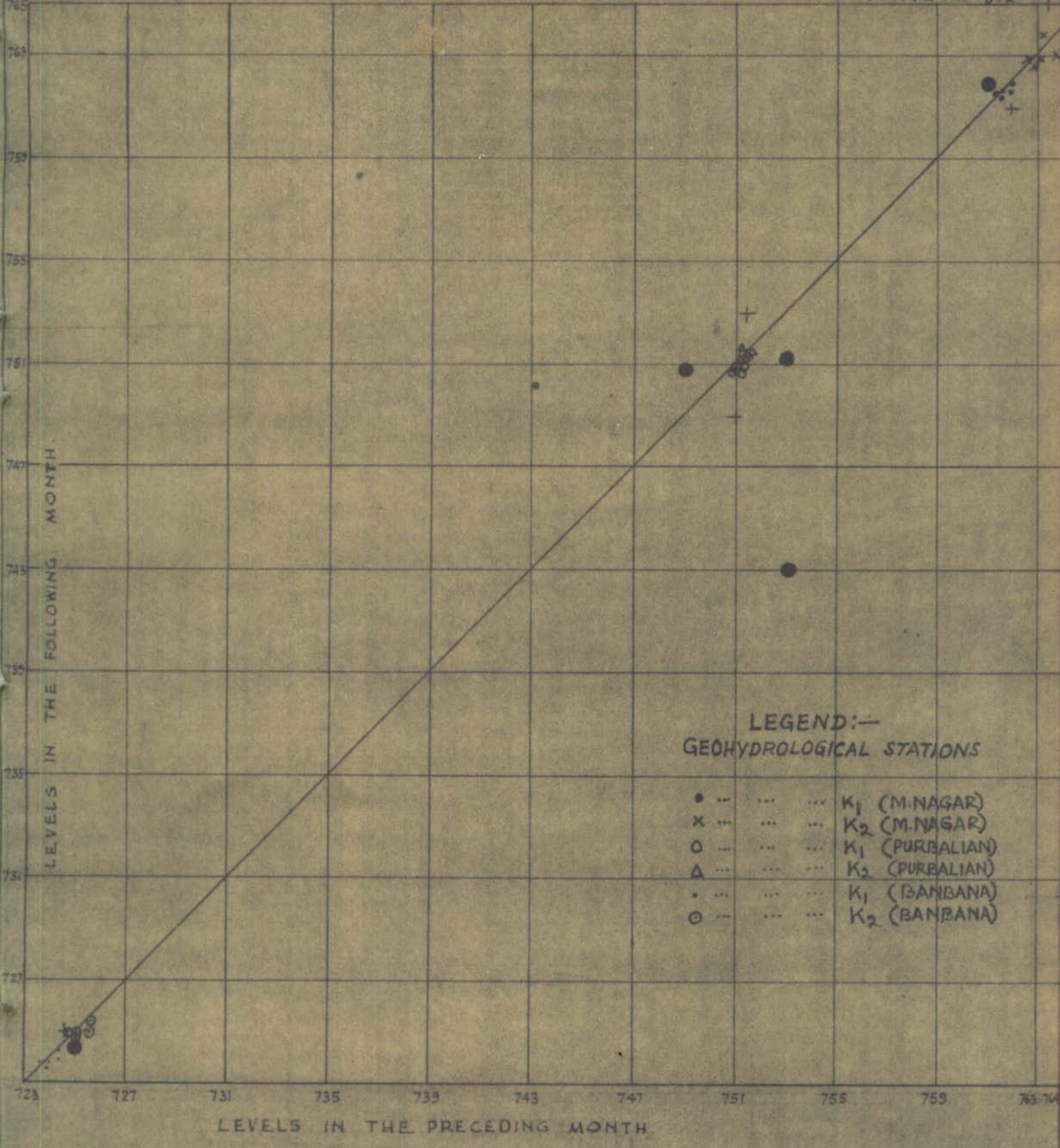
Shallow ground water levels for the preceding & the following months:

In order to evaluate the accuracy of the relation between the levels of a preceding and following months and to establish a correlated dependency between them; x denotes the levels of ground waters for a preceding month and y for the following month. The values of x and y have been determined from the data in (Table 5.1 to 5.8) and their relation is shown graphically in (Plates 5.2 to 5.7). The construction of such a line graph involves marking off levels intervals on the axis of abscissa for the preceding month and on the axis of the ordinate, the ground water levels for the forthcoming month.

The relation between x and y has been calculated by dividing the line graph into vertical bands which include equal intervals of the value of x, and into horizontal bands which include equal intervals of the value of y.

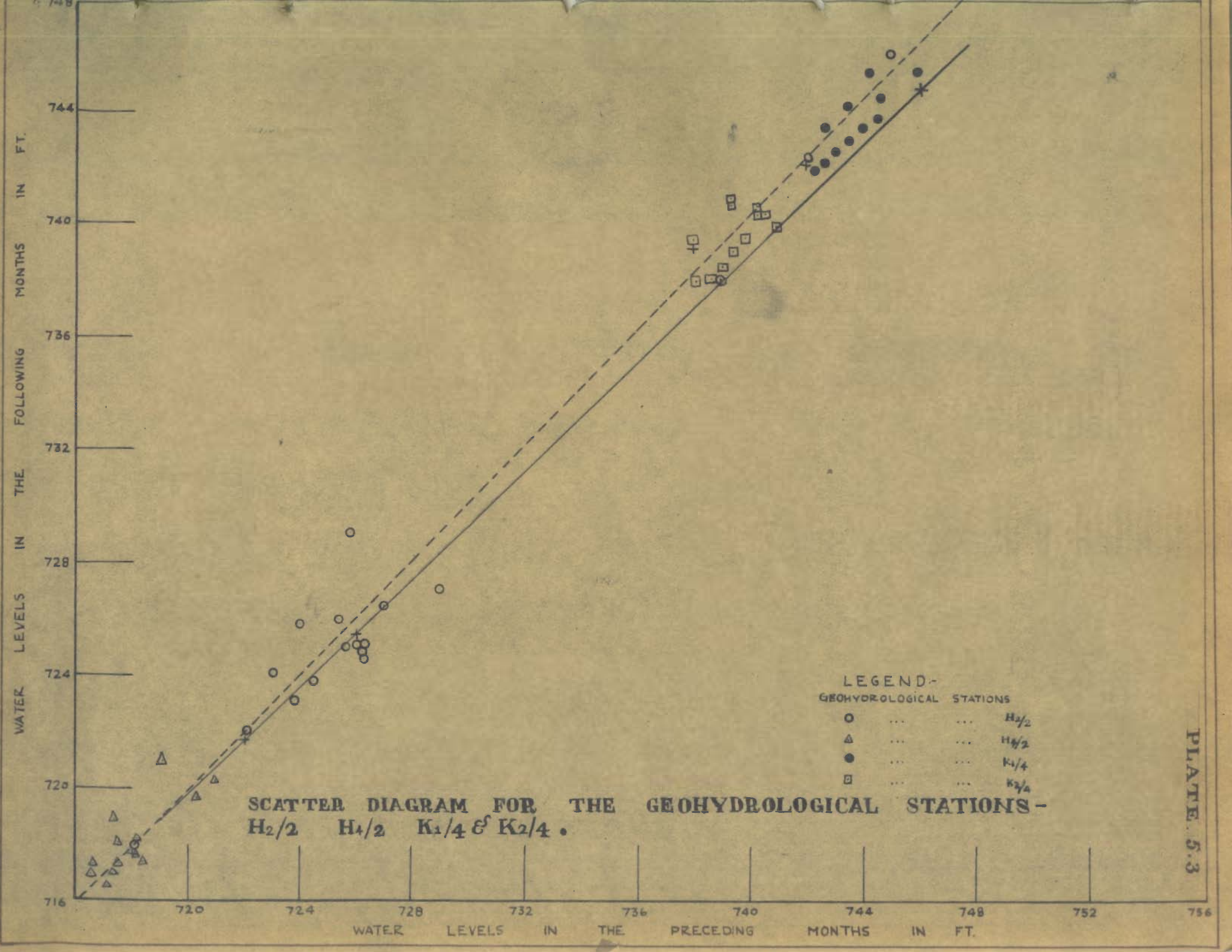
On the basis of the above mean value of x_o and y_o separately for each vertical and horizontal band, as an arithmetical mean of all values for the level of ground water included in any particular band, has been determined in Table 5.9 and these points have been plotted in (Plates 5.2 to 5.7).

PLATE No. 5.2



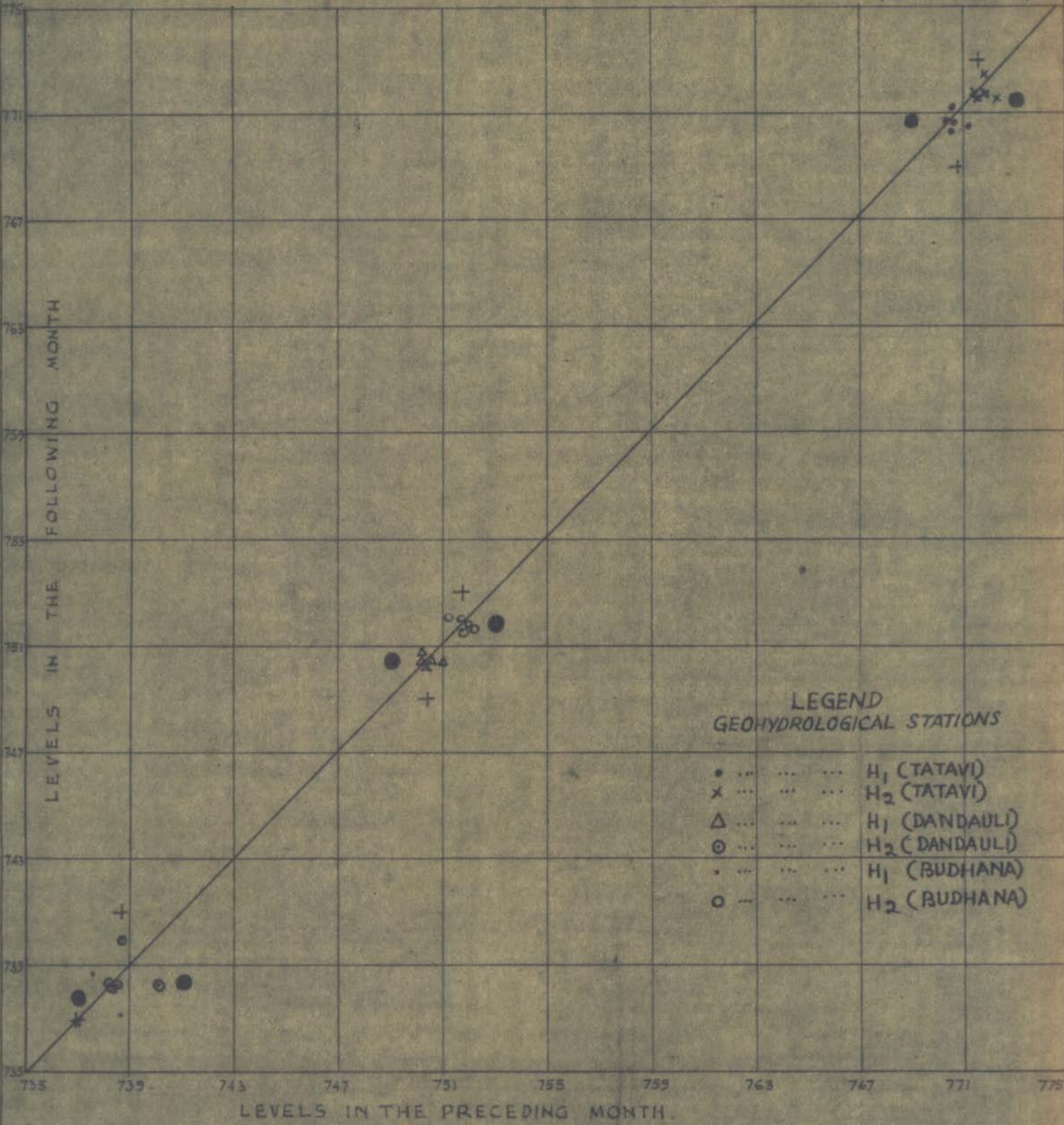
SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS

ALONG KALI RIVER (1965-1966) (DECLINING PERIOD)



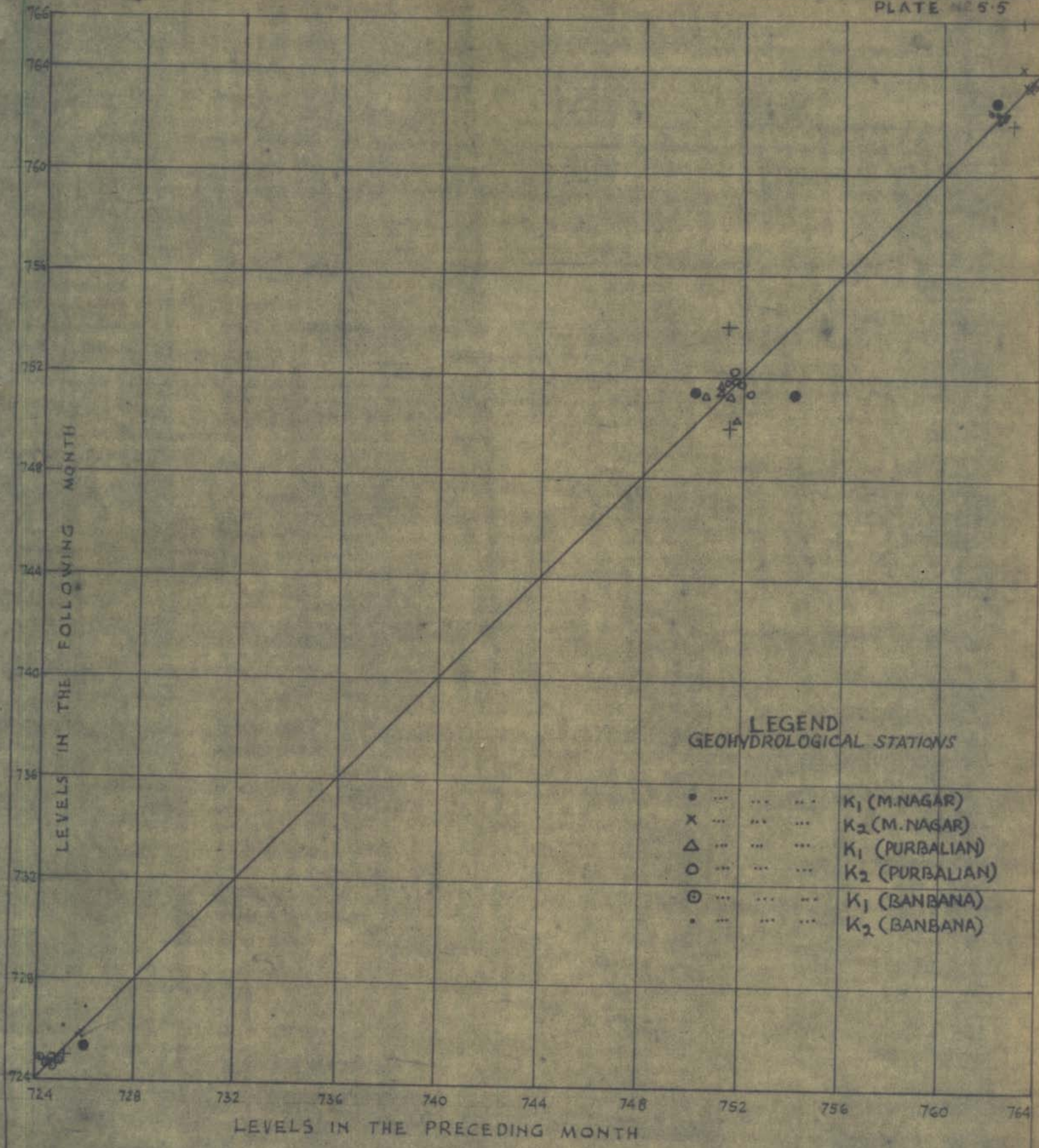
SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS-
$H_2/2$ $H_4/2$ $K_1/4$ & $K_2/4$.

PLATE. 5.3

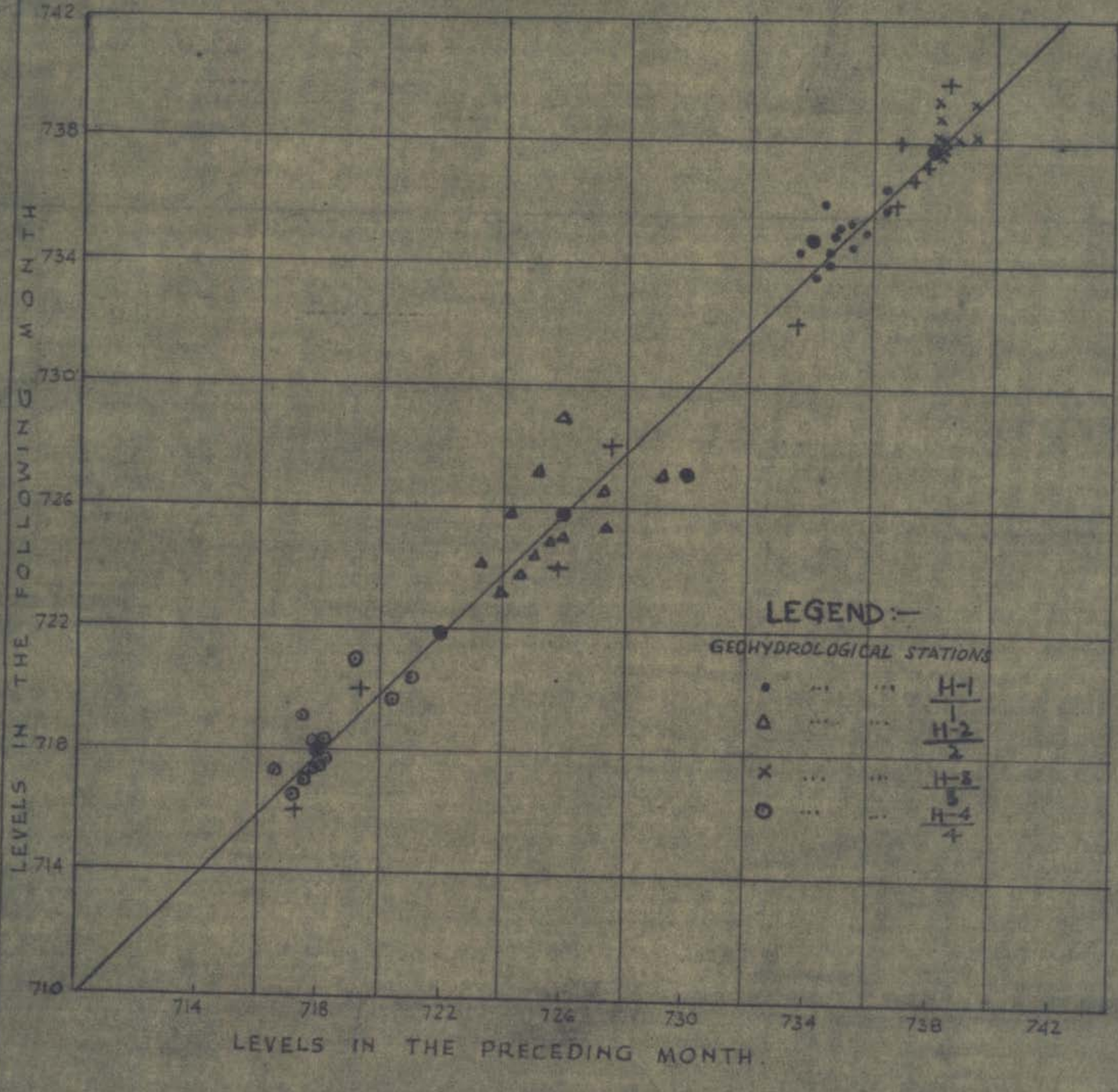


SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS ALONG HINDON RIVER (RISING PERIOD)

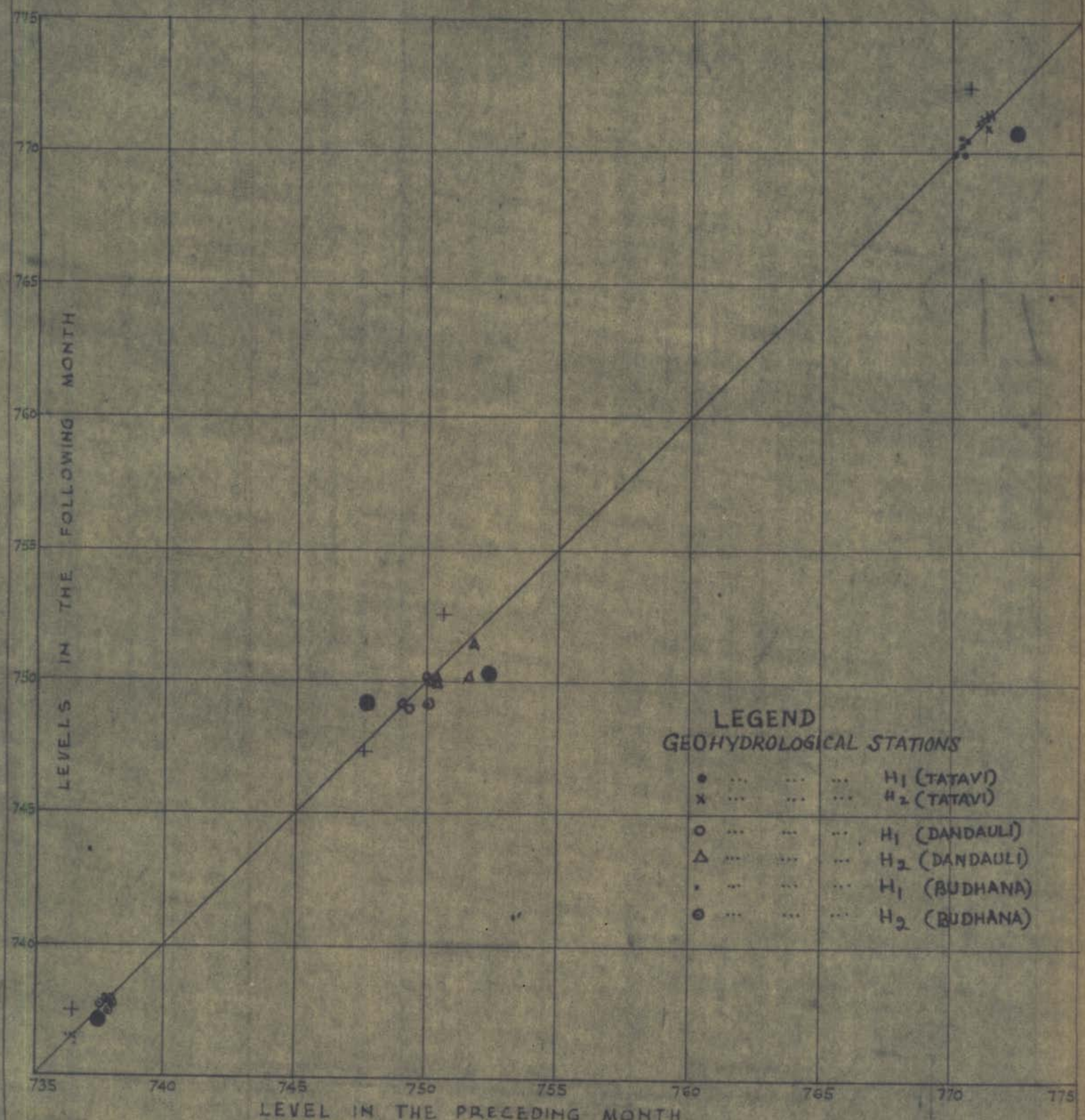
PLATE № 5·5



SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS K_1 & K_2 (M.NAGAR), K_1 & K_2 (PURBALIAN), K_1 & K_2 (BANBANA)



SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS $H_1/1$, $H_2/2$, $H_3/3$ AND $H_4/2$.



SCATTER DIAGRAM FOR THE GEOHYDROLOGICAL STATIONS H_1 & H_2 (TATAVI), H_1 & H_2 (DANDAULI), H_1 & H_2 (BUDHANA)

Table 5.9 MEAN VALUES OF x_o AND y_o FOR THE GEOHYDROLOGICAL STATIONS IN FEET ABOVE MEAN SEA LEVEL

Mean value of the interval x (level for the preceding month)	Mean value of y_o in the given interval x (Mean value of level for the following month.)	Mean value of the interval y (level for following month)	Mean value of x_o in the given interval y (level for the preceding month)
1	2	3	4
1. GEOHYDROLOGICAL STATIONS H2/2, H4/2, K1/4 AND K2/4.			
746.00	744.86	718.00	718.14
742.00	742.18	722.00	722.07
738.00	739.22	726.00	725.36
726.00	725.45	738.00	738.96
722.00	721.82	742.00	742.02
718.00	717.93	746.00	744.98
2. ALONG HINDON RIVER FOR H1/1, H2/2, H3/1 AND H4/2			
738.00	737.8	740.0	738.5
734.0	734.8	736.0	735.7
730.0	727.1	732.0	733.6
726.0	725.8	728.0	727.5
722.0	721.8	724.0	725.8
718.0	718.0	720.0	719.4
-	-	716.0	717.3
3. FOR HINDON RIVER DECLINING PERIOD.			
737.5	737.1	737.5	736.5
747.5	749.2	747.5	749.6
752.5	750.7	752.5	750.7
772.5	770.7	772.5	770.7
4. GEOHYDROLOGICAL STATIONS ALONG KALI RIVER AT MUZAFFARNAGAR PURBALIAN AND BANBANA FOR 1965-1966.			
725.0	724.5	725.0	724.8
729.0	727.1	729.0	725.1
749.0	751.1	749.0	750.9
753.0	753.9	753.0	751.5
761.0	762.4	761.0	762.3
765.0	763.8	765.0	763.5

(Table 5.9 contd.)

1	2	3	4
5. FOR KALI RIVER RISING PERIOD.			
726.0	725.4	726.0	725.2
750.0	751.4	750.0	751.4
754.0	751.3	754.0	751.5
762.0	762.9	762.0	762.9
766.0	763.6	766.0	763.2
6. FOR K1/1, K2/2, K1/1 AND K2/2 ALONG RIVER KALI FOR DECLINING PERIOD 1966.			
725.0	724.5	725.0	724.6
749.0	750.8	749.0	751.0
753.0	751.3	753.0	751.4
761.0	761.9	761.0	762.1
765.0	763.2	765.0	763.5
7. ALONG HINDON RIVER FOR RISING PERIOD 1965			
737.0	737.9	737.0	736.9
741.0	738.3	741.0	738.7
749.0	750.4	749.0	750.4
753.0	751.8	753.0	751.7
769.0	770.7	769.0	770.7
773.0	771.5	773.0	771.6
8. ALONG HINDON RIVER FOR TAPAVI, DANDULI & BUDHANA SITE.			
733.0	737.6	733.0	737.9
737.0	737.2	737.0	737.1
741.0	736.4	741.0	736.0
745.0	750.2	745.0	750.2
749.0	750.5	749.0	750.4
753.0	747.3	753.0	747.5
769.0	771.5	769.0	771.6
773.0	770.8	773.0	770.7

Through these points straight lines are drawn. Such a diagram is known a scatter diagram which is based on the principle that the graphical fitted straight line minimizes deviations on both the sides. Thus two linear relations y_0 from x and x_0 from y have been obtained i.e., mean values for the level of ground waters for the forthcoming month obtained from its given values in the preceding month and mean values of the preceding months from the given values in the following months.

Most of the scatter diagrams, thus obtained, reveal that the points are distributed regularly along a definite diagonal band and that a definite value of y fluctuating in the proximity of a certain mean value corresponds to each value of x. Since both the straight lines are more or less parallel to each other (Plate 5.3) it is indicative of an almost exact dependency between the various factors governing the ground water regime i.e. in the present case between the water levels in the preceding and the following months.

The correlation coefficient 'r' for the above data has been calculated in the manner given as below from their data in (Plates 5.8 to 5.13).

$$v_1 = \frac{\Sigma n_x x_1}{\Sigma n} = -\frac{27}{48} = -0.563$$

and $$v_2 = \frac{\Sigma n_y y_1}{\Sigma n} = \frac{22}{48} = +0.458$$

$\Sigma n = N =$ 48 (i.e. the sum of column I).

$\Sigma n_y \cdot y_1 = +22$ (i.e. the sum of column III line 3)

$\Sigma n_x \cdot x_1 = -27$ (i.e. the sum of row 3)

$\Sigma y_1 (n_y \cdot y_1) = +324$ (i.e. the sum of column IV)

STATISTICAL CORRELATION TABLE ; MUZAFFARNAGAR AREA FOR GEOHYDROLOGICAL STATIONS $H_2/2$, $H_4/2$, $K_1/4$ AND $K_2/4$

Y ↓ \ X →	716-720	720-724	724-728	728-732	732-736	736-740	740-744	744-748	748-752	I hy	II y_1	III $hy-y_1$	IV $Y_1[hy-y_1]$	V ΣY_1	VI $Y_1[\Sigma Y_1]$
748-744							●	●●●		4	+4	16	64	11	44
744-740						⊡⊡	⊡⊡⊡ ●●●● ●●●	●		13	+3	39	117	25	75
740-736						⊡⊡⊡ ⊡⊡⊡	⊡			7	+2	14	28	8	16
736-732										0	+1	0	0	0	0
732-728			◉							1	0	0	0	-2	0
728-724		◉	●●●● ●●●	◉						9	-1	-9	9	-18	18
724-720	△	△◉	◉							4	-2	-8	16	-12	24
720-716	△△△△ △△△ △△	△								10	-3	-30	90	-39	117
I hx	10	4	9	1	0	8	-12	4	0	48	—	+22	324	—	294
II x_1	-4	-3	-2	-1	0	+1	+2	+3	+4	—					
III $hx-x_1$	-40	-12	-18	-1	0	8	24	12	0	-27					
IV $x_1[hx-x_1]$	160	36	36	1	0	8	48	36	0	325					
V Σx_1	-29	-8	-9	-1	0	18	36	15	0	—					
VI $x_1[\Sigma x_1]$	116	24	18	1	0	18	72	45	0	294					

LEGEND

X :- WATER LEVEL IN PRECEDING MONTHS.

Y :- WATER LEVEL IN FOLLOWING MONTHS.

PLATE. 5.8

GEOHYDROLOGICAL STATIONS, ALONG KALI RIVER (1965-1966) (DECLINING PERIOD)

y \ x	723-727	727-731	731-735	735-739	739-743	743-747	747-751	751-755	755-759	759-763	763-767	I hy	II y_1	III $hy.y_1$	IV $y_1[hy.y_1]$	V $[\Sigma y_1]$	VI $y_1[\Sigma y]$
763-767											+ +	2	+5	10	50	+10	50
759-763										●●●● ● + + +		8	+4	32	128	+32	128
755-759												0	+3	0	0	0	0
751-755								⊙ △△△ △△				6	+2	12	24	+12	24
747-751							○○○	⊙				4	+1	4	4	+5	5
743-747												0	0	0	0	0	0
739-743												0	-1	0	0	0	0
735-739												0	-2	0	0	0	0
731-735												0	-3	0	0	0	0
727-731												0	-4	0	0	0	0
723-727	⊙⊙⊙⊙ ⊙											10	-5	-50	250	-50	250
I hx	10	0	0	0	0	0	3	7	0	8	2	30		+8	456		457
II x_1	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5						
III $x_1.hx$	-50	0	0	0	0	0	3	14	0	32	10	+9					
IV $x_1[hx.x_1]$	250	0	0	0	0	0	3	28	0	128	50	459					
V $[\Sigma x_1]$	-50	0	0	0	0	0	3	13	0	32	10						
VI $x_1[\Sigma x_1]$	250	0	0	0	0	0	3	26	0	128	50	457					

LEGEND

X = SHALLOW GROUND WATER LEVEL IN FT. FOR PRECEDING MONTHS.

Y = SHALLOW GROUND WATER LEVEL IN FT. FOR FOLLOWING MONTHS.

PLATE. 5.9

STATISTICAL CORRELATION TABLE MUZAFFARNAGAR-MEERUT AREA FOR THE GEOHYDROLOGICAL STATIONS, ALONG HINDON RIVER (RISING PERIOD)

y ↓ \ x →	735-739	739-743	743-747	747-751	751-755	755-759	759-763	763-767	767-771	771-775	I n_y	II y_1	III $y_1 . n_y$	IV $y_1[n_y . y_1]$	V $[\Sigma y_1]$	VI $y_1[\Sigma y_1]$
771-775									●	+ + + + +	6	+4	24	96	+23	92
767-771									● ● ●	●	4	+3	12	36	+13	39
763-767											0	+2	0	0	0	0
759-763											0	+1	0	0	0	0
755-759											0	0	0	0	0	0
751-755					⊙ ⊙ ⊙ ⊙ ⊙						5	−1	−5	5	−5	5
747-751				△ △ △ △ △							5	−2	−10	20	−10	20
743-747											0	−3	0	0	0	0
739-743	⊙										1	−4	−4	16	−5	20
735-739	• • • • • o o o	⊙									9	−5	−45	225	−44	220
I n_x	9	1	0	5	5	0	0	0	4	6	30		−28	398		396
II x_1	−5	−4	−3	−2	−1	0	+1	+2	+3	+4						
III $x_1 . n_x$	−45	−4	0	−10	−5	0	0	0	12	24	−28					
IV $x_1[n_x . x_1]$	225	16	0	20	5	0	0	0	36	96	398					
V $[\Sigma x_1]$	−44	−5	0	−10	−5	0	0	0	13	23	–					
VI $x_1[\Sigma x_1]$	220	20	0	20	5	0	0	0	39	92	396					

LEGEND.

X = SHALLOW GROUND WATER LEVEL IN FT. FOR PRECEDING MONTHS

Y = SHALLOW GROUND WATER LEVEL IN FT. FOR FOLLOWING MONTHS.

PLATE.5.10

PLATE. 5.II

STATISTICAL CORRELATION TABLE MUZAFFARNAGAR - MEERUT AREA FOR THE GEOHYDROLOGICAL STATIONS, K1/1 AND K2/2 (M.NAGAR), K1 AND K2 (PURBALIAN), K1 AND K2 (BANBANA)

y ↓ \ x →	724-728	728-732	732-736	736-740	740-744	744-748	748-752	752-756	756-760	760-764	764-768	I n_y	II y_1	III $n_y \cdot y_1$	IV $y_1[n_y \cdot y_1]$	V $[\Sigma y_1]$	VI $y_1[\Sigma y]$
764-768										+		1	+5	5	25	+4	20
760-764										●●●● +++●	+	9	+4	36	144	+37	148
756-760												0	+3	0	0	0	0
752-756							○					1	+2	2	4	+1	2
748-752							△△△ △△○○ ○	○				9	+1	9	9	+10	10
744-748												0	0	0	0	0	0
740-744												0	-1	0	0	0	0
736-740												0	-2	0	0	0	0
732-736												0	-3	0	0	0	0
728-732	○○○○ ○.....											0	-4	0	0	0	0
724-728												10	-5	-50	250	-50	250
I n_x	10	0	0	0	0	0	9	1	0	9	1	30		+2	+432		+430
II x_1	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5						
III $n_x \cdot x_1$	-50	0	0	0	0	0	+9	+2	0	+36	+5	+2					
IV $x_1[n_x \cdot x_1]$	250	0	0	0	0	0	+9	+4	0	+144	+25	+432					
V $[\Sigma x_1]$	-50	0	0	0	0	0	+10	+1	0	+37	+4						
VI $x_1[\Sigma x_1]$	+250	0	0	0	0	0	+10	+2	0	+148	+20	430					

LEGEND

X = SHALLOW GROUND WATER LEVEL IN FT. FOR PRECEDING MONTHS

Y = SHALLOW GROUND WATER LEVEL IN FT. FOR FOLLOWING MONTHS

STATISTICAL CORRELATION TABLE MUZAFFAR-NAGAR - MEERUT AREA FOR THE GEOHYDROLOGICAL STATIONS, $H_1/1$, $H_2/2$, $H_3/1$ AND $H_4/2$

y ↓ \ x →	716-720	720-724	724-728	728-732	732-736	736-740	I n_{y_1}	II y_1	III $n_{y_1}y_1$	IV $y_1[n_{y_1}y_1]$	V Σy_1	VI $y_1[\Sigma y_1]$
742-738						+ + + + + + +	7	+3	21	63	14	+42
738-734					● ● ● ● ● ● ● ● ● ●	+ + + + +	15	+2	30	60	20	+40
734-730					●		1	+1	1	1	1	+1
730-726			△ △	△			3	0	0	0	-2	0
726-722		△ △	△ △ △ △ △ △ △				9	-1	-9	9	-11	+11
722-718	⊙ ⊙	⊙ ⊙					4	-2	-8	16	-10	+20
718-714	⊙ ⊙ ⊙ ⊙ ⊙ ⊙ ⊙ ⊙						8	-3	-24	72	-24	+72
I n_x	10	4	9	1	11	12	47		+11	221		+186
II x_1	-3	-2	-1	0	+1	+2						
III $n_x.x_1$	-30	-8	-9	0	11	24	-12					
IV $x_1[n_x x_1]$	90	16	9	0	11	48	174					
V Σx_1	-28	-6	-7	0	21	31						
VI $x_1[\Sigma x_1]$	+84	+12	+7	0	+21	+62	+186					

LEGEND

X = SHALLOW GROUND WATER LEVEL IN FT. FOR PRECEDING MONTHS

Y = SHALLOW GROUND WATER LEVEL IN FT. FOR FOLLOWING MONTHS

PLATE.5.12

STATISTICAL CORRELATION TABLE MUZAFFARNAGAR-MEERUT AREA FOR THE GEOHYDROLOGICAL STATIONS H_1 & H_2 (TATAVI), H_1 & H_2 (DANDAULI), H_1 & H_2 (BUDHANA)

Y ↓ \ X →	735-740	740-745	745-750	750-755	755-760	760-765	765-770	770-775	I n_y	II y_1	III $n_y.y_1$	IV $y_1[n_y.y_1]$	V $[\Sigma y_1]$	VI $y_1[\Sigma y_1]$
770-775								● ● ● ● + + + + +	9	+3	27	81	27	81
765-770							●		1	+2	2	4	2	4
760-765									0	+1	0	0	0	0
755-760									0	0	0	0	0	0
750-755			△	○ △ △ △			•		5	-1	-5	5	-6	6
745-750				○ ○ ○ ○ △					5	-2	-10	20	-5	10
740-745									0	-3	0	0	0	0
735-740	• • • • • ○ ○ ○ ○ ○								10	-4	-40	160	-40	160
I n_x	10	0	1	9	0	0	1	9	30		-26	270	0	261
II x_1	-4	-3	-2	-1	0	+1	+2	+3						
III $n_x.x_1$	-40	0	-2	-9	0	0	2	27	-22					
IV $x_1[n_x.x_1]$	160	0	4	9	0	0	4	81	258					
V $[\Sigma x_1]$	-40	0	-1	-14	0	0	+2	+27						
VI $x_1[\Sigma x_1]$	160	0	2	14	0	0	4	81	261					

LEGEND

X = SHALLOW GROUND WATER LEVEL IN FT. FOR PRECEDING MONTHS

Y = SHALLOW GROUND WATER LEVEL IN FT. FOR FOLLOWING MONTHS

PLATE.5.13

$\Sigma x_1(n_x x_1)$ = +325 (i.e. the sum of row IV)

$\Sigma n_{xy} x_1 \cdot y_1$ = 294 (i.e. the sum of column 6 = sum of row 6)

$$r = \frac{\Sigma n_{xy} x_1 \cdot y_1 / \Sigma n - v_1 v_2}{\delta x \cdot \delta y} \quad \ldots \ldots \ldots (5.4)$$

where $$\delta x = \sqrt{\frac{\Sigma x_1 (n_x x_1)}{\Sigma n} - v_1^2} \quad \ldots \ldots \ldots (5.5)$$

and $$\delta y = \sqrt{\frac{\Sigma y_1 (n_y y_1)}{\Sigma n} - v_2^2} \quad \ldots \ldots \ldots (5.6)$$

substituting the above values in the above formulae (5.5 & 5.6)

$$\delta x = \sqrt{\frac{325}{48} - (-0.563)^2}$$

$$= 2.52$$

similarly $$\delta y = \sqrt{\frac{324}{48} - (0.458)^2}$$

$$= 2.56$$

$$\therefore \quad r = \frac{\frac{294}{48} - (-0.563)(0.458)}{2.52 \times 2.56}$$

$$= \frac{6.125 + 0.258}{6.4512}$$

$$= \frac{6.383}{6.4512}$$

$$\cong + 0.989$$

The above is only one such calculation and to keep the size of the Chapter to a minimum the results of other calculations have been tabulated in Table 6.10).

On the basis of the correlation coefficient being positive and almost approaching to unity in value, it is inferred that there is a direct and definite relation between the water levels in the preceding and the following months. As such, an attempt has been made to predict the water levels by computing the linear correlated dependencies. Since the prediction of water levels in the following month depending on the preceding month (yx) is desirable, the linear correlated dependency for the same has been calculated as follows

(a) For a dependence of the mean value $\bar{y}$ upon x

$$y - \bar{y} = b_y \ (x - \bar{x}) \quad .. \ .. \ .. \ (5.7)$$

(b) For a dependence of the mean value $\bar{x}$ upon y

$$x - \bar{x} = b_y \ (y - \bar{y}) \quad .. \ .. \ .. \ (5.8)$$

In these equations b_y and b_x represent angular coefficient of straight lines drawn to the axis of the coordinates and is computed according to the following formulae.

$$b_x = \frac{r \, \delta x}{y} \quad .. \ .. \ .. \ (5.9)$$

$$b_y = \frac{r \, \delta y}{x} \quad .. \ .. \ .. \ (5.10)$$

where r = the correlation coefficient equal to + 0.989 as calculated above.

δx = root-mean square deviation of the variable x;

δy = root-mean square deviation of the variable y.

In computing $\delta x, \delta y$ and b_x and b_y the values found from the correlation table in conventional limits for $\bar{x}$, $\bar{y}$ should be converted so as to acquire their true values.

The true value of δx is equal to its conventional value (in this case 2.56) multiplied by the capacity of the interval (K - 4) of value δy.

$$\delta y = 2.56 \times 4$$

$$= 10.24$$

The true mean value of x is equal to the mean value x_o of the interval of values x, which later is equal to zero (in this case the zero interval of the values for x lies within a range from 732 to 736 with the mean value equal to 734) plus the product of the capacity of the interval (4 ft.) by the value v_1.

$$\bar{x} = x_o + K\ v_1 \qquad \dots \dots \dots (5.11)$$
$$= 734 + 4 \times (-0.563)$$
$$= 734 - 2.252$$
$$= 731.748$$

Similarly, the mean value $\bar{y}$ is equal to the mean value y_o of the interval of the y_1 values accepted as zero (in this case equal to the zero interval of the value for y which lies within a range of from 728-732 and at a mean value equal to 730) plus the product of the interval (4 ft.) by the value v_2.

$$\bar{y} = y_o + K\ v_2 \qquad \dots \dots \dots (5.12)$$
$$= 730 + 4 \times (0.458)$$
$$= 730 + 1.832$$
$$= 731.832$$

Hence

$$b_x = \frac{0.989 \times 10.08}{10.24} = 0.973$$

$$b_y = \frac{0.989 \times 10.24}{10.08} = 1.004$$

Consequently, the desired linear correlated dependencies will be as follows:

$$x - \bar{x} = bx\ (y - \bar{y}) \qquad \dots \dots \dots (5.13)$$

By substituting the values of $\bar{x}$, b_x and $\bar{y}$ as given above in the equation(5.13).

$$(x - 731.748) = 0.973 (y-731.832)$$

or $$x = 731.748 + 0.973 (y-731.832)$$

or $$x = 19.68 + 0.97 y \qquad .. \quad .. \quad .. \quad (5.14)$$

Similarly

$$y = 731.832 = 1.004 (x - 731.748)$$

$$= 1.004 x - 2.863$$

$$= - 2.863 + 1.004 x$$

In the forescasting of ground water levels, only the second of these two dependencies will be of interest since it will enable to determine the mean value of the level of ground waters for a forthcoming month (Y) depending upon its position in the preceding month (X).

For checking the accuracy of this method, assume that in December thelevel of ground waters was at a height of 732 ft. above sea level. Then according to the obtained correlated dependency, in January it should be at a height of

$$Y = - 2.863 + 1.004 \times 732$$

$$= 732.065 \text{ ft.}$$

During the following months, possible deviations of the calculated mean values of ground water level from actual deviations will be equal to

$$\Delta y = \delta y \sqrt{1-r^2} \qquad .. \quad .. \quad .. \quad (5.15)$$

and for the dependence of x yupon y

$$\Delta x = \delta x \sqrt{1-r^2} \qquad \text{.. .. ..} \quad (5.16)$$

In this connection it should be noted that a single value of Δy or Δx will ensure a 68% probability or reliability of the value of Y obtained in accordance with the correlated dependency; in other words, 32% of the levels of ground waters might have other values from that of $Y \pm \Delta Y$ a double value of ΔY ensures a 95% probability, i.e. the levels of ground waters will be within the limits of $Y \pm 2\Delta Y$ and finally, a triple value will make reliability certain in 99 cases out of hundred. In our example ΔY is equal to

$$\Delta y = \delta y \sqrt{1-r^2} = 10.24\sqrt{1-(0.99)^2} = \pm 1.4336 \text{ ft.} \quad (5.17)$$

Hence the level of ground waters will be found within the limits of 732.065 ± 1.4336, that is, from 733.4986 to 730.6314 ft. in 68 cases out of a hundred. Accuracy of calculations based on the correlated dependency will be considerably increased if the forecast will be given not only for one, but for a group of wells according to the following formula:

$$\Delta n = \frac{\Delta Y}{\sqrt{n}} \qquad \text{.. .. ..} \quad (5.18)$$

where n - number of wells.

For example, if there are 4 wells the value of a possible deviation will be equal to

$$\Delta n = \frac{1.4336}{\sqrt{4}} = 0.71 \text{ ft.} \qquad \text{.. .. ..} \quad (5.19)$$

Hence the level of ground water, found here has a 68%

probability and equal to 732.065 ft. for 4 wells will actually be within the limits of 732.065 ± 0.71 ft., those with a probability of 95% will be within the limits of 732.065 ± 1.42 and those with a 99% probability will be within the limits of 732.065 ± 2.13 ft.

The results of correlation coefficient 'r' for the various geohydrological stations as obtained by the above method have been given in (Table 5.10).

Table 5.10 - SUMMARISED RESULTS OF CORRELATION COEFFICIENT 'r' BETWEEN THE WATER LEVELS FOR THE PRECEDING AND FOLLOWING MONTHS FOR VARIOUS GEOHYDROLOGICAL STATIONS.

S. No.	Name of Geohydrological stations	Correlation Coefficient 'r'
1.	$\frac{H-2}{2}$, $\frac{H-4}{2}$, $\frac{K-1}{4}$, $\frac{K-2}{4}$ (For Hindon & Krishni river)	+ 0.989
2.	$\frac{H-1}{1}$, $\frac{H-2}{2}$, $\frac{H-3}{1}$, $\frac{H-4}{2}$ (For Hindon River)	+ 0.98
3.	Declining Period for Hindon River.	+ 0.992
4.	Along Kali River at M.Nagar, Purbalian and Banbana.	+ 0.999
5.	Rising period for Kali River.	+ 0.99
6.	$\frac{K-1}{1}$, $\frac{K-2}{2}$, $\frac{K-1}{1}$ and $\frac{K-2}{2}$ (For Kali River)	+ 0.996
7.	Rising period for Hindon River 1965.	+ 0.95
8.	Along Hindon River for Tatavi, Dandauli and Budhana.	+ 0.97

Analysis of Data from individual stations

The method described earlier is useful for determining the correlation coefficient only when there is huge group data. As the correlation coefficient for the water levels versus rainfall or river flow and between the water level of preceding and following months have to be established with a set of limited data for each hydrological station, the following linear correlation method has also been adopted:

$$r = \frac{\Sigma x_i y_i}{\sqrt{(\sum_{i=1}^{N} x_i^2/N)(\sum_{i=1}^{N} y_i^2/N)}} \quad .. \quad .. \quad .. \quad .. \quad (5.20)$$

or it may be written as

$$r = \frac{p}{\sigma_x \sigma_y} \quad .. \quad .. \quad .. \quad .. \quad (5.21)$$

where X and Y are the two variables between which the correlation is sought

X_m = the average obtained from the values of x

Y_m = the average obtained from the values of y

where x and y are deviation values i.e. (from mean values) as shown in the following(Tables 5.11 to 5.14).

Table 5.11 - TOTAL RAINFALL AND WATER LEVEL DATA FOR A FEW GEOHYDROLOGICAL STATIONS

...

Geohydrological stations	X Rainfall in ft.	Y Water level in the following months (in ft.) below ground surface.	$X-X_m$ (x)= X-XM	$Y-Y_m$ (y)= Y-YM	x^2	y^2	xy
1	2	3	4	5	6	7	8
H 3/1 (NAGWA)	0.200	8.30	-0.031	0.115	0.001	0.013	-0.004
	0.000	7.57	-0.231	-0.615	0.053	0.378	+0.142
	0.025	8.62	-0.206	0.535	0.042	0.286	-0.110
	0.850	9.58	+0.619	1.395	0.383	1.946	+0.864
	0.310	6.93	+0.079	-1.255	0.006	1.575	-0.099
	0.000	8.11	-0.231	-0.075	0.053	0.006	+0.017
H3/2 (NAGWA)	0.06	8.42	-0.25	+0.88	0.062	0.774	-0.22
	0.00	12.09	-0.30	4.55	0.090	0.302	-1.37
	0.00	6.89	-0.30	-0.65	0.090	0.422	0.20
	1.50	7.85	1 .20	0.31	1.444	0.106	0.10
	0.26	5.11	-0.04	-2.43	0.002	5.904	0.10
	0.00	5.09	-0.30	-2.45	0.090	5.002	0.74
K1/1 (RAJPUR-GARHI)	0.08	11.94	-0.17	-0.067	0.029	0.004	+0.011
	0.22	12.54	-0.03	0.533	0.001	0.284	-0.016
	0.00	12.82	-0.25	0.813	0.063	0.661	-0.203
	0.11	13.65	-0.14	1.643	0.020	2.699	-0.230
	1.20	12.49	+0.95	0.483	0.903	0.233	+0.459
	0.07	10.18	-0.18	-1.827	0.032	3.338	+0.329
	0.06	10.43	-0.19	-1.577	0.036	2.487	+0.300
H1/1 (BUDHANA)	0.14	6 .02	-0.075	0.18	0.006	0.032	-0.014
	0.00	5.66	-0.215	0.32	0.046	0.010	-0.069
	0.00	6.55	-0.215	0.67	0.046	0.449	-0.143
	0.90	7.37	0.685	1.49	0.469	2.120	+0.920
	0.30	4.58	0.085	1.30	0.007	1.690	+0.110
	0.00	5.19	-0.215	6.69	0.046	0.476	-0.148
H1/2 (BUDHANA)	0.00	6.91	-0.183	-0.466	0.034	0.217	+0.085
	0.00	6.52	-0.183	-0.856	0.034	0.733	+0.156
	0.09	7.34	-0.093	-0.036	0.009	0.001	+0.003
	0.90	8.39	+0.717	1.014	0.514	1.028	+0.727
	0.11	5.47	-0.073	-1.906	0.005	3.633	+0.139
	0.00	9.63	-0.183	2.254	0.034	5.080	-0.413

NOTE:

H1 or H 3/1	piezometric pipe at a distance of 100 feet from the bank of river Hindon.
H/2 or H 3/3	piezometric pipe at a distance of 500 feet from the bank of river.
K/1 or H 3/2	piezometric pipe at a distance of 100 feet from the bank of river Krishni.

Correlation coefficient for hydrological station H3/1

$$r = \frac{D}{\sigma x \, . \, \sigma y}$$

$$X_m = \frac{\Sigma x}{N} = \frac{1.385}{6} = 0.231$$

$$Y_m = \frac{\Sigma x}{N} = \frac{49.11}{6} = 8.185$$

$$P = \frac{\Sigma xy}{N} = \frac{0.809925}{6} = 0.135$$

$$x = \sqrt{\frac{\Sigma x^2}{N}} = \sqrt{\frac{0.539521}{6}} = 0.299$$

$$y = \sqrt{\frac{\Sigma y^2}{N}} = \sqrt{\frac{4.204050}{6}} = 0.837$$

$$r = \frac{D}{\sigma x \, . \, \sigma y} = \frac{0.135}{.299 \times .837} = + 0.539$$

say $= + 0.54$

Table 5.12 RELATION BETWEEN DISCHARGE OF RIVER KALI AND SHALLOW GROUND WATER LEVEL IN FEET BELOW GROUND SURFACE FOR MUZAFFARNAGAR DISTRICT FOR THE YEAR 1965

Geohydrological station	X Discharge in cusecs	Y Water level in ft.	$X-X_m$ (x)	$Y-Y_m$ (y)	x^2	y^2	xy
K-1 (MUZAFFAR-NAGAR.)	222	7.50	9.5	0.29	90.25	0.0841	2.755
	292	7.70	89.5	0.49	8010.30	0.2401	43.855
	240	6.70	27.5	-0.51	756.25	0.2601	-14.025
	212	7.25	- 0.5	0.04	0.25	0.0016	- 0.020
	169	7.12	-43.5	-0.09	1892.30	0.0081	3.115
	140	7.00	-72.5	-0.21	5256.30	0.0441	15.225

Correlation coefficient

$$X_m = \frac{x}{N} = \frac{1275}{6} = 212.5$$

$$Y_m = \frac{y}{N} = \frac{43.27}{6} = 7.21$$

$$\sigma x = \sqrt{\frac{\Sigma x^2}{N}} = \frac{16005.65}{6} = 51.6$$

$$\sigma y = \sqrt{\frac{\Sigma y^2}{N}} = \frac{0.6381}{6} = 0.32$$

$$P = \frac{\Sigma xy}{N} = 8.48$$

$$r = \frac{8.48}{0.32 \times 51.6}$$

$$= + 0.5$$

Table 5.13 RELATION BETWEEN THE GROUND WATER LEVEL IN THE PRECEDING AND IN THE FOLLOWING MONTHS FOR THE PERIOD 1960-1961

Geohydro-logical station.	Water level (X) in the preceding month ft.	Water level (Y) in following month ft.	$X-X_m$ (x)	$Y-Y_m$ (y)	x^2	y^2	xy
H2/2 (DATANA)	725.71	725.00	+0.29	-0.14	0.08	0.02	-0.04
	725.15	725.33	-0.27	+0.19	0.07	0.04	-0.05
	724.84	724.44	-0.58	-0.70	0.34	0.49	+0.41
	723.80	723.13	-1.62	-2.01	2.62	4.04	+3.26
	724.07	725.88	-1.35	0.74	1.82	0.55	-0.99
	729.05	727.08	3.63	1.94	13.18	3.76	+7.04

Note : H2/2 piezometric pipe at a distance of 500 feet from the bank of river Hindon.

Correlation coefficient $r = P/ \sigma x. \sigma y$

$$X_m = \frac{\Sigma X}{N} = \frac{4352.62}{6} = 725.42$$

$$Y_m = \frac{\Sigma Y}{N} = \frac{4350.86}{6} = 725.14$$

$$P = \frac{\Sigma xy}{N} = \frac{9.6135}{6} = 1.6023$$

$$\sigma x = \sqrt{\frac{\Sigma x^2}{N}} = \frac{18.1173}{6}$$

$$= 1.737$$

$$\sigma y = \sqrt{\frac{\Sigma y^2}{N}} = \frac{8.8970}{6}$$

$$= 1.57$$

$$r = \frac{D}{\sigma x \cdot \sigma y} = \frac{1.6023}{1.737 \times 157} = \frac{1.6023}{2.72709}$$

$$= + 0.6$$

Based on this method the correlation coefficient for establishing the relationship between (I) rain-fall and water levels and (II) River flow and water levels have been computed for all the geohydrological stations and the summarised results are given below in (Table 5.14).

Table 5.14 CORRELATION COEFFICIENTS BASED ON LINEAR CORRELATION FOR MUZAFFARNAGAR AND MEERUT AREA.

Geohydro-logical stations.	Rainfall versus shallow ground water table.	Shallow ground water level in River Discharge in cfs.	Shallow water level in the preceding months and following months.
$\frac{H-1}{1}$(NAGWA)	+ 0.54	-	-
K-1(M.NAGAR)	-	+ 0.5	-
$\frac{H-2}{2}$(DATANA)	-	-	+0.6
$\frac{H-3}{2}$(NAGWA)	+ 4.40	-	-
$\frac{K-1}{1}$(RAJPURGARHI)	+ 0.43	-	-
$\frac{H-1}{1}$(BUDHANA)	+ 0.43	-	-
$\frac{H-1}{2}$(BUDHANA)	+ 0.20	-	-

CONCLUSIONS

On the basis of correlation coefficient using Linear Correlation Method of Altovsky the following results have been derived.

From the various scatter diagrams drawn for the geohydrological data of shallow ground water body it can be definitely inferred that they have a definite dependency on one another i.e.

1) The shallow ground water is closely related with river water level.
2) The shallow ground water level for the preceding and the following months are inter-related i.e. one is dependent on the other.

The coefficient of correlation obtained between the various factors i.e. shallow ground water level for the preceding and the following months, rise and decline of water levels in preceding and following months and the shallow ground water levels and the river water levels varies from + 0.95 to 0.999 which is almost equal to + 1.0 and hence the relationship is 'exact' and definite.

According to the second method i.e. by the analysis of data from individual stations, the following results have been obtained:

1) Although there is a relationship between the rainfall and the level of shallow ground water body, it is not very high (correlation factor is + 0.53 or 0.54)

2) Similarly, the relation between the river discharge and shallow ground water reservoir is also low (correlation factor + 0.5).

3) A third relation attempted by this method was between the level of shallow ground water reservoir for preceding and following months for a particular station. The correlation factor 'r' comes to be + 0.6.

The above results (correlation factors) obtained by the above statistical methods are not very similar. The difference is due to the nature of the data which have been subjected to analysis. As mentioned earlier in the Altovsky's method huge group data have been analysed while in the other method data from individual stations have been considered.

JACOB's METHOD OF STATISTICAL ANALYSIS

Introduction

In the earlier part a correlation was attempted between the various hydrological factors such as spring level, river water level and precipitation affecting the ground water regime. Here an attempt has been made to determine the relation of precipitation with that of shallow ground water table by means of Jacob's[50] method. This study is based on the data collected from the various Irrigation Divisions of Meerut and Muzaffarnagar Districts in respects of precipitation and water level in the shallow ground water reservoir.

In the correlation of precipitation data with records of ground water level the usual procedure has been to cumulate departures of the precipitation from the normal or mean ~~precipi-~~

precipitation. In recent years progressive averages have also been used. In this the aim has been to use the cumulative departure from progressive averages for correlating precipitation with ground water levels.

Jacob[50] has shown that by multiplying the cumulative departures from progressive averages by a pre-determined coefficient and adding each in turn to a constant, the value of the "effective average rate of precipitation" may be determined. By the "effective average rate of precipitation" at any given time is meant that "the rate of precipitation which had it been maintained uniterrupted throughout the past, would have been effective in producing the same water profile as actually existed at that particular time".

Two assumptions have been made by Jacob[51] i.e.
1) Uniform recharge over the area by means of rainfall and
2) the total saturated thickness to be constant so that the equation for steady state profile of water level can be expanded in the simplest form.

Muzaffarnagar and Meerut districts which are parts of the Ganga Yamuna Doab represent an important field area for such investigations. This area is an infinite strip of land with uniform width and also satisfies the above two assumptions.

The following equations as derived by Jacob[50] have been used to compute various tables involved in this method:

$$\bar{R}_n = R_{(n-K+1)} + \sum_{i=1}^{(K-1)} c_{(n-i)} R_{(n-i+1)} - R_{(n-i)}) \quad .. \; .. (5.22)$$

$$C_{(n-i)} = \left[2\, i\, K - i\, (i - 1) \right] / \left[K (K + 1) \right] .. \quad .. (5.23)$$

$$\bar{R}_n = \sum_{i=1}^{K} R_{(n - i + 1)}\, 2 (K - i + 1) / K (K + 1) \; .. (5.24)$$

$$\bar{R}_p = \sum_{i=1}^{K} R_{(p - i + 1)}{}^2 (K - i + 1) / K (K + 1) \quad .. (5.25)$$

$$\bar{R}_n = \left[2 / (K + 1) \right] (1/K) \left[K' R_m - \sum_{j=1}^{K} R_{(m-j)} \right] + \bar{R}_p (5.26$$

where:

R = Precipitation rate in a particular year

$\bar{R}$ = The effective average rate of precipitation in a particular year.

K = Period in years = 10 years

i = A number having values as 0,1,2,3,4,5,6,7,8,9

$\bar{R}_p$ = Initial value of effective average rate of precipitation.

The computed values of the effective average rate of precipitation for Meerut-Muzaffarnagar are given in (Table 5.15 and 5.16). A value of 10 has been assigned to K. Table (5.15) gives two equivalent methods of computing the ten year effective average rate of precipitation at the end of the year 1965. First the long method has been given using equation (5.22) in which infinite increment in the rate of precipitation have been multiplied by the appropriate coefficients:

$C_{n-i} = \left[10i - i (i - 1) / 2 \right] / 55$ and then summed and added to the value of R for the (n-9)th year(the year 1956). The short method, following equation (5.23) is nearly summing up products of rates of precipitation and appropriate differences between successive coefficients:

$$C_{(n-i)} - C_{(n-i+1)} = (11 - i) / 55 \quad .. \quad (5.27)$$

Table 5.16 gives the 10 years effective average rates of precipitation at the end of the year, 1928. By the help of above equations values of the ten year effective average rate of precipitation at the end of succeeding years have been computed. First values of ten-year progressive average precipipation have been determined and thereafter the departures of the actual annual rates of precipitation from the progressive average have been determined. The cumulated departures have thereafter been multiplied by $[2/(k+1)] = (2/11)$ and added to the effective average for 1928 ($\bar{R}_{oo}$) and these are given in (Table 5.16).

It is seen that the effective average rate of precipitation at the end of 1965 determined by different procedures, is 28.60 inches per year (Tables 5.15 and 5.16) which has been calculated, from the past records of precipitation.

Table 5.15 - TEN YEAR EFFECTIVE AVERAGE RATE OF PRECIPITATION AT THE END OF THE YEAR 1965, COMPUTED BY MEANS OF EQUATION(5.22) AND THEN BY MEANS OF EQUATION (5.23) BASED ON RECORDS OF PRECIPITATION AT MUZAFFARNAGER AND MEERUT.

S.No.	Year (n-1)	(i)	Rn-i in/yr.	Long method using equation(5.22) (Rn-i+1-Rn-i)Cn-i	Short method using equation(5.23) (Rn-i+1)(ii-i)/55.
1.	1955	10 = K	--	---	36.60(1/55) = 0.67
2.	1956	9	36.60	-1.2 (54/55)=(-)1.18	35.40(2/55) = 1.28
3.	1957	8	35.40	-6.90(52/55)=(-)6.52	28.50(3/55) = 1.56
4.	1958	7	28.50	1.20(49/55)= 1.07	29.70(4/55) = 2.16
5.	1959	6	29.70	2.70(45/55)= 2.21	32.40(5/55) = 2.95
6.	1960	5	32.40	-1.80(40/55)=(-)1.32	30.60(6/55) = 3.34
7.	1961	4	30.60	-1.80(34/55)=(-)1.11	28.80(7/55) = 3.66
8.	1962	3	28.80	1.50(27/55)= 0.73	30.30(8/55) = 4.41
9.	1963	2	30.30	-3.50(19/55)=(-)1.21	26.80(9/55) = 4.37
10.	1964	1	26.80	-3.70(10/55)=(-)0.67	23.10(10/55)=4.30
11.	1965	0	23.10	---	---
Σ			-----	-----------=(-)8.00	----- = 28.60

R̄o 9 = 36.60 - 8.00 = 28.60 = R̄o 9

Table 5.16 - TEN YEAR EFFECTIVE AVERAGE RATE OF PRECIPITATION AT THE END OF THE YEAR 1928, COMPUTED BY MEANS OF EQUATION(5.25) AND AT THE END OF EACH SUCEDING YEAR UPTO 1965, COMPUTED BY MEANS OF EQUATION (5.24) BASED ON RECORDS OF PRECIPITATION AT MUZAFFARNAGAR-MEERUT AREA.

Year (p-i)	(i)	R_p-i in/yr.	Using Equation (5.25) R_p-i+1) (11-i)/55
1918	10(=K)	-	28.70 (1/55) = 0.52
1919	9	28.70	29.30 (2/55) = 1.07
1920	8	29.30	31.66 (3/55) = 1.73
1921	7	31.66	30.80 (4/55) = 2.24
1922	6	30.80	34.82 (5/55) = 3.17
1923	5	34.82	40.10 (6/55) = 4.37
1924	4	40.10	38.76 (7/55) = 4.93
1925	3	38.76	32.51 (8/55) = 4.73
1926	2	32.51	33.15 (9/55) = 5.42
1927	1	33.15	28.20(10/55) = 5.12
Σ	-	-	- Roo = 33.30

Year (n)	(i) Rate of precipi-tation.	10 Yr. progre-ssive average.	Depar-ture from prog. aver-age.		Commu-lative depar-ture.		Cum. Dep. x.2/11	Effective average rate of precipi-tation, (R_n) in/year
1 2	3	4		5		6	7	8
1928	28.20	--		--		--	--	33.30
1929	38.53	32.68		4.73		4.73	0.86	34.16
1930	34.24	33.68		0.56		5.29	0.96	34.26
1931	29.61	34.18	(-)	4.57	(+)	0.72(+)	0.13	33.43
1932	28.70	33.97	(-)	5.27	(-)	4.55(-)	0.83	32.47
1933	33.50	33.76	(-)	0.26	(-)	4.81 -	0.88	32.42
1934	30.34	33.63	(-)	3.29	-	8.10 -	1.47	31.83
1935	31.95	32.65	-	0.70	-	8.80 -	1.60	31.70
1936	36.50	31.98		4.52	-	4.28 -	0.78	32.52
1937	35.22	32.37		2.85	-	1.43 -	0.26	33.04

- contd. - - - -

(Table 5.16 contd.)

1	2	3	4	5	6	7	8
1938		29.70	32.58	- 2.88	- 4.31	- 0.78	32.52
1939		30.50	32.73	- 2.23	- 6.54	- 1.19	32.11
1940		33.65	32.03	1.62	- 4.92	- 0.89	32.41
1941		28.85	31.97	- 3.12	- 8.04	- 1.46	31.84
1942		39.66	31.89	7.77	- 0.27	- 0.05	33.25
1943		34.24	32.99	1.25	0.98	+ 0.18	33.48
1944		32.10	33.06	- 0.96	0.02	0.004	33.30
1945		40.40	33.24	7.16	7.18	1.31	34.61
1946		36.32	34.08	+ 2.24	9.42	1.71	35.01
1947		34.76	34.06	+ 0.70	10.12	1.84	35.14
1948		32.94	34.02	- 1.08	9.04	1.64	34.94
1949		30.76	34.34	- 3.58	5.46	0.99	34.29
1950		32.58	34.37	- 1.79	3.67	0.67	33.97
1951		29.76	34.26	- 4.50	- 0.83	- 0.15	33.15
1952		31.25	34.35	- 3.10	- 3.93	- 0.71	32.59
1953		29.37	33.51	- 4.14	- 8.07	- 1.47	31.83
1954		30.90	33.02	- 21.12	- 10.19	- 1.85	31.45
1955		38.40	32.90	- 5.50	- 4.69	- 0.85	32.45
1956		36.60	32.70	3.90	- 0.79	- 0.14	33.16
1957		35.40	32.73	2.67	1.88	0.34	32.96
1958		28.50	32.80	- 4.30	- 2.42	- 0.44	32.86
1959		29.70	32.35	- 2.65	- 5.07	- 0.92	32.38
1960		32.40	32.25	0.15	- 4.92	- 0.89	32.41
1961		30.60	32.23	- 1.63	- 6.55	- 1.20	32.10
1962		28.80	32.31	- 3.51	- 10.06	- 1.83	31.47
1963		30.30	32.07	- 1.77	- 11.83	- 2.15	31.15
1964		26.80	32.16	- 5.36	- 17.19	- 3.13	30.17
1965		23.10	31.75	- 8.65	- 25.84	- 4.70	28.60

Water level data for the open wells which are being analysed in this study have been chosen on account of their availability for fairly long period and also because the shallow wells from which the data is analysed have a more or less uniform distribution in the area. Table 5.17 gives pertinent data of such 20 wells and their location is given in (Plates 3.1 to 3.8).

All these observation wells on whose records the present study is based are all sufficiently distant from the centre of pumpage so that the effect of pumping on their water levels can be neglected. It has also been shown earlier that the shallow ground water reservoir is not interconnected with the deeper aquifer's, except when pumping is large and leakage takes place.

Table 5.17 - DATA REGARDING 20 SHALLOW (OPEN) WELLS IN GANGA - YAMUNA DOAB IN MEERUT-MUZAFFARNAGAR DISTRICTS (1954 - 1963)

Well Nos.	Locality	Ratio 20 Well-average to elevation water-level in well (1954-1964) (6)[a]	Approximate depth to water level in ft. below ground surface in (1964)	Elevation mean water level for 1954 ft.	Remarks
1	2	3	4	5	6
9 B	Morna, Muzaffarnagar,	0.9578	36.78 = 37	775.32	
6 B	Jat Mayhera, Muzaffarnagar.	0.9241	6.47 = 6	803.73	
2	Qumaruddin Nagar, Muzaffarnagar.	0.9402	10.20 = 10	789.92	
6	Banat, Muzaffarnagar.	0.95	11.89 = 12	781.98	
11	Panjit, Muzaffarnagar.	0.98	10.51 = 11	755.72	
12	Titwana, Muzaffarnagar	0.94	16.82 = 17	766.18	
2	Kandhla, Muzaffarnagar	0.95	9.32 = 9	771.90	
18	Budhana, Muzaffarnagar	1.005	32.58 = 33	738.14	
5	Satheri, Muzaffarnagar.	0.96	4.76 = 5	770.04	
10	Mirzapur, Muzaffarnagar.	0.98	23.30 = 23	758.08	
17	Daha, Meerut	1.03	46.05 = 46	719.91	
7	Kutana, Meerut	1.02	26,44 = 26	725.46	
1	Binauli, Meerut	1.05	43.01 = 43	707.29	

Contd.-

(Table 5.17 contd..)

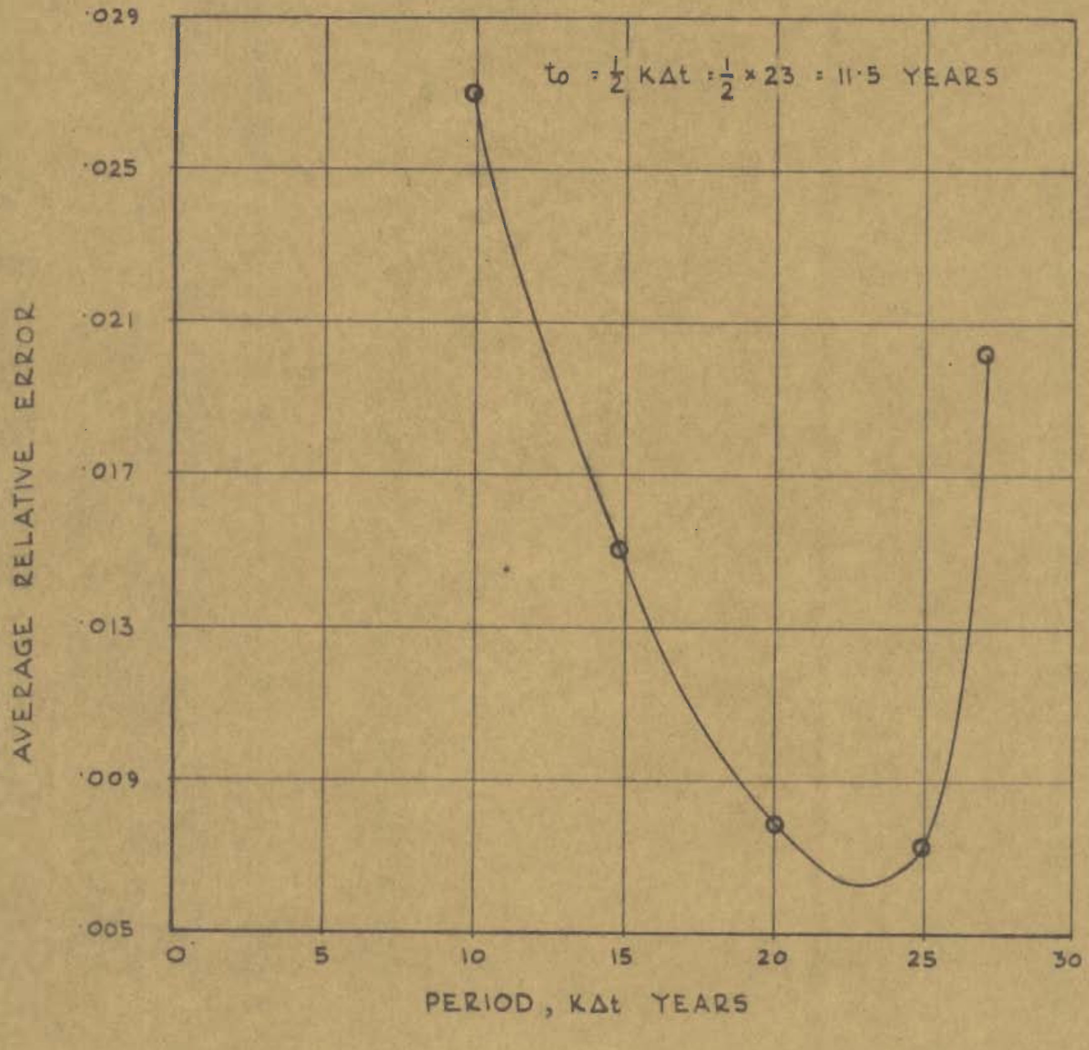
1	2	3	4	5	6
20/4	Meerut-Prichhat Garh Road, M 2-0-15	1.04	14.13 = 14	712.13	
9	Along Meerut-Miranpur Road.	1.003	11.05 = 11	739.99	
9	Baghpat, Meerut.	1.057	28.56 = 29	702.04	
1	Bakri Meerut	1.07	14.78 = 15	694.97	
12	Meerut-Baghpat Road, Meerut	1.03	8.89 = 9	723.89	
23/9	Meerut-Parichhat garh road, Meerut.	1.051	23.43 = 23	706.35	
27/18	Meerut-Parichhat garh road, Meerut.	1.044	16.19 = 16	711.47	
	Agerage for all 20 wells		22.10 say 22	742.72 say 743.	

(C)[a] = Average of the ratios (for the year 1954 to 1964) of (average altitude of mean annual water-levels in 20 wells) to (altitude of mean annual water-level in the given well).

Tables (5.18 to 5.22) give the "composite average water levels" and effective average rate of precipitation" for the years 1955-1964. The yearly values of composite average water level have been computed from annual mean water-levels. The number of wells for which there is sufficient record to determine an annual mean water level for a given year is as in column 3 of (Table 5.18 to 5.22). If the number of wells (for which complete records are available) are n, then the composite average water level for a given year can be calculated by

$$\frac{\text{(Average water-level in 20 wells for 1955-64)}}{\text{(Average water-level in n wells for 1955-64)}} \times \text{(Average water level in n well for the given years.)}$$

Values of 25 years effective average rate of precipitation have been computed and are given in (Table 5.18). Effective average rates of precipitation have also been determined on the basis of 10, 15, 20 and 27 year periods of adjustment from the same rainfall data. It has been found that the values of the effective average rate of precipitation can be correlated with composite average water levels. The best correlation has been obtained with the 25 year effective average which shows a fair agreement with mean annual water level. This has been shown in (Plate 5.14) in which values of average relative error is



GRAPH OF AVERAGE RELATIVE ERROR OF LINEAR CORRELATION BETWEEN EFFECTIVE AVERAGE RATES OF PRECIPITATION AT MUZAFFARNAGAR AND MEERUT AREA AND COMPOSITE AVERAGE WATER-LEVEL OF THE SAME AREA.

Table 5.18 - COMPARISON BETWEEN COMPOSITE AVERAGE WATER LEVEL AND EFFECTIVE AVERAGE RATE OF PRECIPITATION IN MUZAFFARNAGAR-MEERUT DISTRICTS.

Year	Elevation composite average water-level $\bar{h}$ (in ft)	No. of wells.	Effective rate of precipitation	
			25 Year $\bar{R}$ in/yr	a in/yr
1955	727.80	9	33.03	9.43
1956	727.95	9	33.02	9.06
1957	730.03	9	33.04	7.42
1958	741.94	11	33.06	- 4.04
1959	740.80	11	33.08	- 2.45
1960	739.94	11	33.10	- 1.14
1961	740.45	11	33.09	- 1.88
1962	740.18	11	33.03	- 2.92
1963	741.03	11	32.97	- 5.13
1964	742.72	20	32.89	- 9.62
Mean	737.28		33.03	- 5.309

Average Relative Error = .0072

Table 5.19 - COMPARISON BETWEEN COMPOSITE AVERAGE WATER LEVEL AND EFFECTIVE AVERAGE OF PRECIPITATION

Year	($\bar{h}$)	No. of wells.	Effective rate of precipitation	
			10 Year (R) in/year	a in/yr.
1955	727.80	9	32.45	27.25
1956	727.95	9	33.16	33.40
1957	730.95	9	32.96	26.73
1958	742.94	11	32.86	12.53
1959	740.80	11	32.38	0.64
1960	739.94	11	32.41	4.19
1961	740.45	11	32.10	- 3.43
1962	740.18	11	31.47	- 17.63
1963	741.03	11	31.15	- 24.83
1964	742.72	20	30.17	- 24.83
Mean	737.28		32.11	20.065

Average relative error = .027

Table 5.20 - COMPARISON BETWEEN COMPOSITE AVERAGE WATER LEVEL & EFFECTIVE AVERAGE RATE OF PRECIPITATION.

Year	$\bar{h}$	No. of wells.	Effective rate of precipitation	
			15 year ($\bar{R}$) in/year	a in/yr.
1955	727.80	9	33.42	16.13
1956	727.95	9	33.51	17.98
1957	730.03	9	33.49	15.46
1958	741.94	11	33.45	- 4.02
1959	740.80	11	33.38	1.24
1960	739.94	11	33.24	- 0.02
1961	740.45	11	33.04	- 4-98
1962	740.18	11	32.80	- 10.05
1963	741.03	11	32.55	- 16.47
1964	742.72	20	32.27	- 24.39
Mean	737.28	-	33.12	11.074

Average relative error = .015

Table 5.21 - COMPARISON BETWEEN COMPOSITE AVERAGE WATER LEVEL AND EFFECTIVE AVERAGE RATE OF PRECI - PITATION.

Year	h̄	No. of wells.	Effective rate of precipitation 20 Year (R̄) in/yr	a in/year
1955	727.80	9	33.20	9.90
1956	727.95	9	33.23	10.42
1957	730.03	9	33.22	8.12
1958	741.94	11	33.25	- 3.57
1959	740.80	11	33.25	- 1.93
1960	739.94	11	33.25	- 1.12
1961	740.45	11	33.27	- 1.19
1962	740.18	11	33.18	- 2.92
1963	741.03	11	33.06	- 6.44
1964	742.72	20	32.90	- 11.63
Mean	737.28	-	33.18	5.734

Average relative error = .0078

Table 5.22 - COMPARISON BETWEEN COMPOSITE AVERAGE WATER LEVEL AND EFFECTIVE AVERAGE RATE OF PRECI - PITATION.

Year	Elevation composite average water level. h̄ (in ft.)	No. of wells	Effective rate of precipitation 27 years R̄ (in ft)	a in/year
1955	727.80	9	33.48	22.82
1956	727.95	9	33.81	30.07
1957	730.03	9	33.53	22.83
1958	741.94	11	32.99	- 2.31
1959	740.80	11	32.66	- 8.56
1960	739.94	11	32.45	- 12.41
1961	740.45	11	32.21	- 18.30
1962	740.18	11	32.92	- 13.32
1963	741.03	11	32.84	- 4.76
1964	742.72	20	32.51	- 13.85
Mean	737.28		32.89	Mean 14.923

Relative average error = .0202

is plotted against the period of adjustment, $k\Delta t$. The average elevation of the composite average water level ($\bar{h}$) for the 10 years of record in 737.28 ft. The average value of the 25 years effective average rate of precipitation ($\bar{R}$) for the same 10 years is 23.60 inches per year. On the basis of the above assumptions there should be direct proportion of $\bar{h}$ and $\bar{R}$ of constant value 737.28 ft/28.60 in/yr. The average absolute values of the residuals in this case is 5.309 in/yr. and the average relative error in this case has been determined to be (5.309/737.28) = 0.0072.

If we take effective average precipitation rate to be about 28.6 in/year or $\bar{R}$ = 0.0065 feet/day. Then the rate of accretion to the water table is about 21.5 % of the average rate of precipitation.

This value of 21.5 % is very much comparable with those obtained by using the empirical formula earlier evolved by Bhattacharya et al[5] according to which

$$R_p = 1.35\,(R - 14)^{\frac{1}{2}} \qquad \ldots\ \ldots\ (5.28)$$

where R_p = Rain penetration in inches

R = Rainfall in inches

By substituting the value of R obtained from Table 5.16 in the above equation (5.28) we get the rate of accretion to ground water as 18.1% or say 18%. This is comparable to the value of 21.5 % as determined by Jacob's method.

CONCLUSIONS

1. The results obtained by the application of the above method can be very useful in computing the ground water recharge of the area.

2. The results obtained for the accreation of water table by Jacob's Method are comparable to those obtained emperically by Bhattacharya et al[5].

3. This method may bridge the gap between the present understanding of infiltration and of run-off.

CHAPTER 6

CHEMICAL QUALITY OF GROUND WATERS

INTRODUCTION

During the past few decades ground water studies were only aimed towards establishment of subsurface water resources but at present these are considered incomplete unless the chemical quality of water is assured to be satisfactory. Besides this, water is never found in its pure state in nature, as essentially all waters contain substances derived from natural environments or from the waste products of human beings. These constituents are basic criteria in the determination of water quality. In view of this, the geochemistry of ground water is very important and has to be studied with special reference to the need for which the water is put to maxiumum use in any region. As the present area of study is very important from agricultural point of view it becomes ever more significant to study the suitability of water for irrigational purposes.

As already discussed in Chapter 4 the deeper aquifers in the area are under confined conditions while the shallow aquifers are under water table conditions. It, therefore, becomes essential to clearly bring out the differences, if any, between the chemical quality of waters from these two geohydrological units. However, a greater emphasis is given to the water from deeper aquifers. Thus the chemical quality of ground water has been dealt under two broad heads i.e. (i) the chemical quality of ground water from shallow reservoir and (ii) from deeper aquifers. Such a division is regarded desirable because the geochemical evolution of water under these different hydrological conditions may differ to some extent.

COLLECTION OF WATER SAMPLES

Water samples from the deeper aquifers were collected from the state tubewells directly from the discharge pipe while they were being run for watering the fields. These samples were collected in the year 1964 and 1965 during the months of October and June respectively, so that seasonal variation, if any, may also be determined. Twenty water samples from dug-wells, which tap the shallow water table aquifer, were collected during the month of October 1965. One hundred water samples were collected from tubewells which tap the deeper confined aquifers. The water samples from the deeper aquifers have been chosen in such a manner that they represent the entire area on a regional basis.

METHOD OF ANALYSIS

The commonly determined constituents in water analysis are expressed as ions and include the cations (positively charged ions) i.e. Calcium, Magnesium, Sodium and Potassium and the anions (negatively charged ions) i.e. Sulphate, Chloride, Carbonate and Bi-carbonate.

There are various methods in vogue for the water analysis which include gravimetric, volumetric, spectrophotometric and Flame photometric procedures (Rainwater and Thatcher[52]). The gravimetric technique in water analysis is tedious and time consuming because of usual necessity for precipitation, filtration, washing, ignition and weighing, whereas the volumetric analysis is more rapid and sensitive. Recent developments have made available precision instruments such as Spectrophotometer and Flame Photometer which are very useful in water analysis.

The water sample collected during October 1964, June 1965 and October 1965 were analysed in the Chemical Laboratory of U.P. Irrigation Research Institute, Roorkee, and the Chemistry Department of the University of Roorkee, Roorkee. Na^{1+} and K^{1+} were determined by Flame Photometer while the other cations as Ca^{2+} , Mg^{2+} and anions Cl^{1-} , SO_4^{2-} , CO_3^{2-} and HCO_3^{1-} were determined by gravimetric or volumetric methods. pH was determined by a pH meter and electrical conductivity by conductivity meter bridge. Total dissolved solids (TDS) have been calculated from the electrical conductivity measurements of the water samples.

METHOD OF EXPRESSING ANALYSIS

As the total amount of dissolved constituents form only a small fraction of the total weight of water samples, the analyses are expressed in parts per million (ppm). Parts per million and miligrams per litre are numbrically almost the same if the concentration of dissolved solids is low and the specific gravity of water is nearly 1.0.

A better unit useful for geochemical studies is equivalents per million (epm), or more exactly milligram equivalents per Kilogram. Equivalents per million are calculated by dividing parts per million by the equivalent weight of the ion under consideration. Inasmuch as the total equivalent weights of cations and anions in a solution must be the same, the sum of the equivalents per million can be used to check the accuracy and completeness of chemical analyses (Davis and DeWiest [32]).

CHEMICAL QUALITY OF WATER FROM SHALLOW AQUIFERS

The chemical characteristics of water from shallow aquifers are not discussed in detail because the water from this horizon is mainly used locally for drinking purposes only. The range of the important constituents have been given in Table 6.1.

TABLE 6.1 RANGE OF CHEMICAL COMPOSITION OF GROUND WATER IN THE SHALLOW AQUIFERS IN MUZAFFARNAGAR - MEERUT DISTRICT

Sl.No.	Constituents	Concentration
1	Bicarbonates ..	140 - 250 ppm
2	Sulphate ..	100 - 300 ppm
3	Chloride ..	5 - 25 ppm
4	Total dissolved solids..	140 - 400 ppm
5	pH ..	6.8 - 7.5
6	Electrical Conductivity. ($EC \times 10^6$).	176 - 600

The above table indicates that the water is of good quality from drinking standards which is also indicated from the bacterial analysis data which were made available by the Municipal Boards of Meerut and Muzaffarnagar districts. The chemical data from shallow ground water reservoir indicate that primarily, the water is of bicarbonate-sulphate type. The higher concentration of SO_4 in these waters can be explained due to the presence of organic material, and also due to the presence of SO_4 in the soil in the form of '<u>reh</u>' as has been stated in chapter 2.

CHEMICAL QUALITY OF WATER FROM DEEPER AQUIFERS

The results of chemical analysis of waters from deeper (confined) aquifers for the month of October 1964 are given in Table 6.2 and for June 1965 in Table 6.3. The concentration of various constitutents is expresed in parts per million (ppm) and for principal cations and anions concentration in equivalents per million (epm) is also given.

TABLE 6.2 CHEMICAL ANALYSIS DATA OF GROUND WATER FROM MEERUT-MUZAFFARNAGAR DISTRICTS - OCTOBER, 1 9 6 4

Tubewell Nos.	19A		53		54		15A	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	6.5	-	4.6	-	18.6	-	9.3	-
Iron	-	-	-	-	-	-	-	-
Calcium(Ca)	74.3	3.707	40.0	1.996	74.2	3.707	35.7	1.781
Magnesium(Mg)	9.6	0.789	24.0	1.973	16.8	1.386	30.0	2.280
Sodium(Na) + Potassium(K)	17.7	0.769	13.3	0.578	6.0	0.261	7.8	0.339
Carbonate(CO_3)	18.0	0.599	12.0	0.399	-	-	12.0	0.399
Bicarbonate(HCO_3)	292.8	4.798	170.8	2.799	146.4	2.399	219.6	3.599
Sulphate(SO_4)	66.5	0.34	48.6	1.001	48.8	1.016	20.6	0.428
Chloride(Cl)	14.0	0.40	42.6	1.213	79.9	2.253	7.1	0.200
Dissolved solids calculated	330	-	310	-	300	-	200	-
Specific conductance (Micromhos at 25°C)	504.0	-	441.0	-	504.0	-	409.5	-
pH		7.8		7.2		7.3	7.8	

(Table 6.2 Contd.)

Tubewell Nos.	43		48		59		3	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	7.0	-	14.0	-	13.0	-	18.2	-
Iron	-	-	-	-	-	-	-	-
Calcium(Ca)	5.3	1.427	74.3	3.707	85.7	4.276	170.0	8.483
Magnesium(Mg.)	9.6	0.789	9.6	0.789	7.2	0.592	75.6	6.217
Sodium(Na) + Potassaium(K)	6.3	0.274	19.7	0.856	25.2	1.096	38.6	1.679
Carbonate(CO_3)	-	-	36.0	1.199	-	-	60.0	1.999
Bicarbonate(HCO_3)	195.2	3.199	292.8	4.798	146.4	2.390	536.8	8.792
Sulphate(SO_4)	14.8	0.308	18.1	0.376	86.5	1.800	169.3	3.524
Chloride(Cl)	9.9	0.279	8.5	0.239	66.7	1.880	161.9	4.565
Dissolved solids calculated.	214	-	272	-	384	-	1020	-
Specific conductance (micromhos) at 25°C)	315.0	-	535.5	-	598.5	.	1701.1	-
pH	7.7		7.9		7.7		8.0	

(Table 6.2 Contd.)

Tubewell Nos.	13		21		22		29	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	5.2	-	-	-	13,5	-	8.86	-
Iron	4.2	-	-	-	-	-	-	-
Calcium(Ca)	127.1	6.344	44.28	2.70	107.1	5.34	44.3	2.21
Magnesium(Mg.)	34.8	2.861	43.0	3.52	114.0	9.37	27.6	2.26
Sodium(Na) + Potassium(K)	20.4	0.887	22.0	0.900	95.6	4.15	16.5	0.71
Carbonate(CO_3)	-	-	12.0	0.389	-	-	-	-
Bicarbonate(HCO_3)	439.2	7.192	254.2	4.179	683.2	11.19	341.6	5.89
Sulphate(SO_4)	79.5	1.655	70.0	1.45	210.5	4.38	37.5	0.78
Chloride(Cl)	78.1	2.202	43.0	1.21	225.8	6.36	7.1	0.20
Dissolved solids calculated.	665	-	1412.0	-	1246.0	-	374.0	-
Specific conductance (micromhos) at 25°C)	1071	-	2268	-	1953.0	-	535.0	-
pH	7.6		7.8		7.6		7.2	

(Table 6.2 Contd.)

Tubewell Nos.	19		18		22		30	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	6.06	-	22.4	-	9.3	-	4.66	-
Iron	-	-	2.8	-	-	-	-	-
Calcium(Ca)	35.7	1.78	42.86	2.13	30.0	1.49	51.4	2.56
Magnesium(Mg.)	9.6	0.78	48.0	3.94	39.6	3.25	33.6	2.76
Sodium(Na) + Potassium(K)	22.0	0.95	16.5	0. 71	38.6	1.67	40.8	1.77
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	219.6	3.59	219.6	3.59	268.4	4.39	414.8	6.79
Sulphate(SO_4)	21.8	0.45	70.6	1.12	21. 6	0.45	27.0	0.56
Chloride(Cl)	8.52	0.24	41.1	1.16	42.6	1.21	17.64	0.49
Dissolved solids calculated.	250.0	-	414.0	-	332.0	-	456.0	-
Specific conductance (micromhos) at 25°C)	378.0	-	630.0	-	504.0	-	693.0	-
pH	7.1		7.6		8.2		7.5	

(Table 6.2 Contd.)

Tubewell Nos.	10		26		32		36	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	9.33	-	2.33	-	5.6	-	2.8	-
Iron	-	-	5.6	-	-	-	2.8	-
Calcium(Ca)	42.85	2.13	80.0	3.99	74.7	3.73	102.8	5.13
Magnesium(Mg.)	19.2	1.57	45.6	3.75	43.2	3.55	19.20	1.57
Sodium(Na) + Potassium(K)	7.86	0.34	9.04	0.39	11.79	0.59	2.36	0.10
Carbonate(CO_3)	36.0	1.19	-	-	12.0	0.33	60.0	1.99
Bicarbonate(HCO_3)	146.4	2.39	488.0	7.99	365.0	5.98	268.4	4.39
Sulphate(SO_4)	37.08	0.77	32.9	0.68	42.85	0.89	35.43	0.73
Chloride(Cl)	35.5	1.06	26.9	0.76	34.08	0.96	15.62	0.44
Dissolved solids calculated.	260.0	-	540.0	-	480.0	-	368.0	-
Specific conductance (micromhos) at 25°C)	441.0	-	819.0	-	756.0	-	567.0	-
pH	8.0		7.9		8.0		7.8	

(Table 6.2 Contd.)

Tubewell Nos.	37		38		50		53	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	18.8	-	1.87	-	12.6	-	-	-
Iron	-	-	4.2	-	4.2	-	2.8	-
Calcium(Ca)	68.57	3.42	45.7	2.28	41.42	2.56	47.14	2.48
Magnesium(Mg.)	31.2	2.56	10.8	0.88	15.6	2.28	34.8	2.86
Sodium(Na) + Potassium(K)	40.87	1.77	-	-	38.6	1.67	10.8	0.88
Carbonate(CO_3)	-	-	-	-	36.0	1.19	-	-
Bicarbonate(HCO_3)	449.2	7.36	146.4	2.39	268.4	4.39	341.6	5.59
Sulphate(SO_4)	30.49	0.63	24.72	0.51	18.54	0.38	20.18	0.42
Chloride(Cl)	24.14	0.68	14.2	0.40	9.23	0.26	14.91	0.42
Dissolved solids calculated.	478.0	-	200.0	-	300.0	-	364.0	-
Specific conductance (micromhos) at 25°C)	724.5	-	283.5	-	472.0	-	567.0	-
pH	7.9		8.4		7.6		7.4	

(Table 6.2 Contd.)

Tubewell Nos.	24A		36A		39		50	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	4.7	-	5.0	-	12.2	-	5.6	-
Iron	-	-	16.5	-	8.1	-	-	-
Calcium(Ca)	61.4	3.06	89.7	4.47	35.8	1.78	38.3	1.91
Magnesium(Mg.)	26.4	2.17	14.6	1.20	14.2	1.16	16.6	1.36
Sodium(Na) + Potassium(K)	29.1	1.26	7.5	0.32	1.6	0.66	2.4	0.10
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	390.4	6.39	390.4	6.39	268.4	4.38	219.6	3.56
Sulphate(SO_4)	27.2	0.56	14 .3	0.29	9.6	0.17	10.2	0.21
Chloride(Cl)	7.8	0.21	18.5	0.52	8.5	0.23	12.8	0.30
Dissolved solids claculated.	418.0	-	490	-	276.0	-	338.0	-
Specific conductance (micromhos) at 25°C)	661.50	-	756.0	-	409.5	-	520.5	-
pH	5.95		8.5		8.8		8.5	

(Table 6.2 Contd.)

Tubewell Nos.	30		59		50		5	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	2.5	-	4.0	-	15.86	-	31.7	-
Iron	-	-	-	-	-	-	-	-
Calcium(Ca)	95.0	4.74	120.0	5.99	87.14	4.34	100.0	4.99
Magnesium(Mg.)	8.4	0.69	20.6	1.69	22.80	1.87	34.80	2.86
Sodium(Na) + Potassium(K)	1.6	0.07	3.5	0.15	3.14	0.13	9.4	0.40
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	292.8	4.79	180.0	5.99	366.0	5.99	414.8	6.86
Sulphate(SO_4)	18.2	0.37	20.5	0.42	14.0	0.29	49.4	1.02
Chloride(Cl)	7.2	0.20	9.5	0.26	7.1	0.20	24.14	0.68
Dissolved solids calculated.	340.0	-	445.0	-	314.0	-	418.0	-
Specific conductance (micromhos at 25°C)	526.0	-	663.0	-	504.0	-	693.0	-
pH	7.2		7.5		8.4		8.5	

(Table 6.2 Contd.)

Tubewell Nos.	1		13		12		36	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	1.4	-	0.8	-	7.83	-	2.8	-
Iron	-	-	6.2	-	12.32	-	-	-
Calcium(Ca)	28.6	1.42	64.0	3.19	34.0	1.69	80.0	3.99
Magnesium(Mg.)	12.0	0.98	23.8	1.95	25.2	2.07	14.0	1.35
Sodium(Na) + Potassium(K)	62.9	2.73	17.3	0.75	7.0	0.30	1.2	0.52
Carbonate(CO_3)	-	-	-	-	24.0	0.79	-	-
Bicrbonate(HCO_3)	336.0	5.50	292.8	4.78	219.6	3.599	292.8	4.78
Sulphate(SO_4)	8.3	0.17	35.8	0.74	15.16	0.31	16.0	0.33
Chloride(Cl)	5.7	0.16	9.9	0.27	8.52	0.24	7.2	0.20
Dissolved solids calculated.	350.0	-	310.0	-	340.0	-	335.0	-
Specific conductance(micromhos) at 25°C)	567.0	-	504.0	-	459.90	-	526.0	-
pH	5.7		7.3		8.4		7.3	

(Table 6.2 Contd.)

Tubewell Nos.	9		3A		4		28	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	-	-	4.2	-	1.9	-	5.6	-
Iron	2.8	-	--	-	7.0	-	12.6	-
Calcium(Ca)	90.0	4.49	92.5	4.61	54.3	2.70	32.8	1.63
Magnesium(Mg.)	8.5	0.69	10.0	0.82	28.8	2.36	19.2	1.57
Sodium(Na) + Potassium(K)	3.4	0.14	2.8	0.12	2.3	0.10	25.9	1.12
Carbonate(CO_3)	12.0	0.399	24.0	0.79	-	-	-	-
Bicarbonate(HCO_3)	292.0	4.788	256.0	4.19	244.0	3.99	244.0	3.99
Sulphate(SO_4)	2.4	0.05	8.0	0.16	32.5	0.67	10.0	0.20
Chloride(Cl)	4.1	0.11	6.8	0.19	34.1	0.96	7.1	0.20
Dissolved solids calculated	350.0	-	370.0	-	408.0	-	356.0	-
Specific conductance (micromhos) at 25°C)	520.0	-	560.0	-	630.0	-	567.0	-
pH	8.5		8.4		8.8		9.1	

(Table 6.2 Contd.)

Tubewell Nos.	14		10		11		1	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	4.1	-	-	-	4.2	-	7.5	-
Iron	-	-	-	-	15.4	-	9.8	-
Calcium(Ca)	29.7	1.48	57.1	2.84	41.4	2.06	30.0	1.49
Magnesium(Mg.)	23.7	1.94	3.4	0.27	42.0	3.45	20.4	1.69
Sodium(Na) + Potassium(K)	13.7	0.59	21.9	1.26	14.9	0.64	8.6	0.37
Carbonate(CO_3)	-	-	-	-	-	-	12.0	0.39
Bicarbonate(HCO_3)	256.2	4.19	158.7	2.60	244.0	3.99	146.4	2.39
Sulphate(SO_4)	10.2	0.21	17.3	0.36	58.1	1.20	12.8	0.26
Chloride(Cl)	8.5	0.23	8.8	0.24	39.8	1.12	8.5	0.23
Dissolved solids calculated.	264.0	-	195.0	-	472.0	-	304.0	-
Specific conductance (micromhos) at 25°C)	390.6	-	304.1	-	693-0	-	472.5	-
pH	8.6		7.3		9.1		9.0	

(Table 6.2 Contd.)

Tubewell Nos.	2		15					
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	5.6	-	11.57	-				
Iron	5.6	-	-	-				
Calcium(Ca)	41.4	2.06	25.43	1.26				
Magnesium(Mg.)	25.2	2.07	10.56	0.87				
Sodium(Na) + Potassium(K)	11.0	0.47	7.0	0.29				
Carbonate(CO_3)	-	-	-	-				
Bicarbonate(HCO_3)	244.0	3.99	146.4	2.39				
Sulphate(SO_4)	18.5	0.38	9.39	0.19				
Chloride(Cl)	11.4	0.34	9.94	0.28				
Dissolved solids calculated.	359.0	-	220.0	-				
Specific conductance (micromhos) at 25°C)	535.0	-	434.70	-				
pH	9.1		8.1					

TABLE 6.3 CHEMICAL ANALYSIS DATA OF GROUND WATER FROM MEERUT- MUZAFFARNAGAR DISTRICTS - J U N E, 1 9 6 5

Tubewell Nos.	10		53		64		43	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	-	-	6.36	-	13.6	-	-	-
Iron	-	-	-	-	-	-	1.8	-
Calcium(ca)	28.57	1.42	40.0	1.99	69.3	3.45	80.0	4.0
Magnesium(Mg.)	28.0	2.30	32.4	2.66	14.4	1.18	13.2	1.06
Sodium (Na) + Potassium(K)	0.23	0.10	5.53	0.24	-	-	2.90	0.12
Carbonate(CO_3)	-	-	-	-	15.0	0.49	24.0	0.8
Bicarbonate(HCO_3)	195.20	3.19	219.6	3.59	185.8	3.04	317.2	5.2
Sulphate(SO_4)	7.42	0.15	14.8	0.30	17.0	0.35	17.0	0.35
Chloride(Cl)	14.2	0.40	14.2	0.40	14.2	0.40	14.2	0.42
Dissolved solids calculated.	198.0	-	236.0	-	301.0	-	460.0	-
Specific conductance (micromhos) at 25°C)	359.1	-	409.50	- -	456.0	-	129.9	-
pH	8.0		7.8		7.3		7.1	

(Table 6.3 Contd.)

Tubewell Nos.	48		59		30		22	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	-	-	-	-	-	-	20.53	-
Iron	2.5	-	-	-	10.6	-	19.6	-
Calcium(Ca)	128.0	6.4	66.0	3.2	38.57	1.92	37.1	1.85
Magnesium(Mg.)	15.7	1.26	7.2	0.58	28.8	2.36	18.0	1.48
Sodium (Na) + Potassium(K)	1.95	0.08	0.48	0.02	0.22	0.009	3.37	0.006
Carbonate(CO_3)	24.1	0.80	36.0	1.19	-	-	-	-
Bicarbonate(HCO_3)	439.2	7.03	122.0	2.00	268.4	4.399	195.2	3.19
Sulphate(SO_4)	22.5	0.47	14.6	0.30	18.5	0.38	5.68	0.16
Chloride(Cl)	21.4	0.63	25.56	0.76	8.5	0.24	17.30	0.36
Dissolved solids calculated.	480.0	-	290.0	-	270.0	-	258.0	-
Specific conductance (micromhos) at 25°C)	811.3	-	486.6	-	415.80	-	396.90	-
pH	7.4		7.7		8.2		8.2	

(Table 6.3 Contd.)

Tubewell Nos.	21		13		29		22	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	8.40	-	8.4	-	10.26	-	21.0	-
Iron	-	-	-	-	-	-	12.6	-
Calcium(Ca)	60.0	3.0	50.0	2.49	38.5	1.92	34.2	1.91
Magnesium(Mg.)	38.4	3.07	31.2	2.56	26.4	2.17	81.6	6.71
Sodium(Na) + Potassium(K)	0.25	0.01	9.87	0.42	9.0	0.39	0.22	0.009
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	341.6	5.6	268.4	4.39	244.0	3.99	439.20	7.19
Sulphate(SO_4)	9.99	0.20	74.2	0.15	10.71	0.22	34.61	0.72
Chloride(Cl)	12.8	0.38	14.2	0.40	11.36	0.32	12.78	0.36
Dissolved solids calculated.	260.0	-	244.0	-	276.0	-	448.0	-
Specific conductance (micromhos) at 25°C)	459.9	-	441.0	-	422.1	-	693.0	-
pH		8.8		7.8		7.8		8.3

(Table 6.3 Contd.)

Tubewell Nos.	29		10		26		38	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	18.1	-	29.8	-	11.2	-	39.2	-
Iron	-	-	11.2	-	19.6	-	25.2	-
Calcium(ca)	34.28	1.91	37.1	1.85	31.4	1.56	102.8	5.13
Magnesium(Mg.)	51.6	4.24	64.8	5.32	45.6	3,75	45.6	3.75
Sodium(Na) + Potassium(K)	-	-	2.9	0.12	0.4	0.01	0.13	0.006
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	317.2	5.19	366.0	5.99	317.2	5.19	463.60	7.57
Sulphate(SO_4)	28.8	0.60	73.3	1.62	6.59	0.13	71.69	1.59
Chloride(Cl)	15.6	0.44	21.3	0.60	15.62	0.44	25.5	0.72
Dissolved Solids calculated.	384.0	-	490.0	-	394.0	-	488.0	-
Specific conductance (micromhos) at 25°C)	567.0	-	756.0	-	604.0	-	756.0	-
pH	8.5		8.8		8.4		9.0	

(Table 6.3 Contd.)

Tubewell Nos.	32		2		11		D_6	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	4.6	-	21.0	-	15.8	-	15.85	-
Iron	-	-	8.4	-	19.6	-	2.3	-
Calcium(Ca)	80.0	4.0	17.71	3.84	60.0	2.99	50.0	2.49
Magnesium(Mg.)	40.8	3,27	43.2	3.55	43.2	3.55	21.6	1.77
Sodium(Na) + Potassium(K)	0.39	0.02	0.3	0.13	0.35	0.01	8.8	0.38
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	366.0	6.0	341.6	5.59	268.4	4.39	244.00	3.99
Sulphate(SO_4)	35.43	0.74	24.72	0.51	43.6	0.90	15.66	0.32
Chloride(Cl)	25.56	0.76	28.2	0.79	7.10	0.20	8.52	0.36
Dissolved solids calculated.	408.0	-	450.0	-	295.0	-	265.0	-
Specific conductance (micromhos) at 25°C)	612.0	-	693.0	-	459.90	-	409.50	-
pH	9.0		8.1		7.8		8.3	

(Table 6.3 Contd.)

Tubewell Nos.	D_1		D_3		63		6	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	4.24	-	-	-	11.2	-	15.8	-
Iron	14.0	-	-	-	-	-	-	-
Calcium(Ca)	42.85	2.13	31.4	1.56	11.42	0.57	75.7	3.77
Magnesium(Mg.)	45.6	3.75	33.6	2.76	24.0	1.97	21.6	1.77
Sodium(Na) + Potassium(K)	0.35	0.01	0.65	0.02	11.8	0.51	-	-
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	292.3	4.79	244.0	3.99	146.4	2.39	317.2	5.19
Sulphate(SO_4)	14.42	0.30	8.24	0.17	23.07	0.48	27.2	0.56
Chloride(Cl)	19.88	0.56	12.78	0.36	11.35	0.32	15.6	0.44
Dissolved solids calculated.	335.0	-	280.0	-	206.0	-	300.0	-
Specific conductance (micromhos) at 25°C)	541.80	-	415.80	-	189.0	-	504.0	-
pH		7.7		7.6		7.7		7.6

(Table 6.3 Contd.)

Tubewell Nos.	14		23		52		50	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	11.18	-	25.66	-	24.26	-	4.06	-
Iron	-	-	2.8	-	-	-	-	-
Calcium(Ca)	35.7	1.78	27.1	1.85	57.14	2.85	54.28	2.70
Magnesium(Mg.)	16.8	1.38	25.2	1.89	19.2	1.57	14.4	1.18
Sodium(Na) + Potassium(K)	-	-	3.7	0.006	11.0	0.47	-	-
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	195.7	3.18	195.2	3.19	244.0	3.99	219.6	3.59
Sulphate(SO_4)	-	-	14.01	0.29	16.5	0.46	7.88	0.20
Chloride(Cl)	14.2	0.40	7.10	0.20	14.2	0.40	11.36	0.32
Dissolved solids calculated.	240.0	-	280.0	-	310.0	-	305.0	-
Specific conductance (micromhos) at 25°C)	378.0	-	428.4	-	472.5	-	434.6	-
pH	8.6		8;7		8.0		8.2	

(Table 6.3 Contd.)

Tubewell Nos.	36A		19		1		8	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	7.40	-	22.8	-	-	-	-	-
Iron	2.12	-	16.8	-	2.8	-	2.8	-
Calcium(Ca)	45.7	2.28	105.71	5.27	116.0	5.78	115.0	5.73
Magnesium(Mg.)	14.4	1.18	50.4	4.14	31.2	2.56	36.0	2.96
Sodium(Na) + Potassium(K)	-	-	37.04	1.61	2.0	0.08	2.4	0.104
Carbonate(CO_3)	-	-	-	-	12.0	0.79	-	-
Bicarbonate(HCO_3)	196.0	3.19	366.0	5.09	388.2	6.30	414.8	6.86
Sulphate(SO_4)	6.5	0.13	230.7	4.80	21.2	0.44	226.6	0.47
Chloride(Cl)	7.1	0.20	11.3	0.32	17.04	0.48	17.0	0.48
Dissolved solids calculated.	285.0	-	414.0	-	510.0	-	520.0	-
Specific conductance (micromhos at 25°C)	365.0	-	567.0	-	634.7	-	662.9	-
pH		8.8		7.8		7.2		7.5

(Table 6.3 Contd.)

Tubewell Nos.	9		12		16		6	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	1.4	-	1.4	-	-	-	18.46	-
Iron	-	-	-	-	2.0	-	5.6	-
Calcium(Ca)	108.0	5.38	115.0	5.73	80.0	3.99	41.4	2.06
Magnesium(Mg.)	30.0	2.46	25.0	2.05	40.00	3.28	25.2	2.01
Sodium(Na) + Potassium(K)	2.6	0.11	4.8	0.20	2.6	0.11	-	-
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	414.8	6.86	390.4	6.39	366.0	5.99	146.40	2.39
Sulphate(SO_4)	19.8	0.41	20.6	0.43	22.5	0.47	26.7	0.54
Chloride(Cl)	21.3	0.60	15.02	0.42	11.36	0.32	19.8	0.56
Dissolved solids calculated.	490.0	-	495.0	-	464.0	-	426.0	-
Specific conductance (micromhos) at 25°D)	608.2	-	608.2	-	584.0	-	630.0	-
pH	7.0		8.2		7.3		8.5	

(Table 6.3 Contd.)

Tubewell Nos.	24		31		42		29	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	-	-	3.26	-	4.6	-	4.6	-
Iron	8.4	-	-	-	2.8	-	-	-
Calcium(Ca)	12.8	0.64	28.5	1.42	54.3	2.71	31.4	1.53
Magnessium(Mg.)	30.0	2.46	3.6	0.29	24.0	1.97	26.4	2.17
Sodium(Na) + Potassium(K)	4.33	0.18	19.6	0.85	9.4	0.41	11.4	0.49
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	219.6	3.59	146.4	2.39	317.2	5.19	268.4	4.39
Sulphate(SO_4)	6.59	0.13	33.1	0.68	37.8	0.78	11.5	0.24
Chloride(Cl)	8.82	0.24	8.5	0.22	4.3	0.12	5.7	0.13
Dissolved solids calculated.	198.0	-	186.0	-	360.0	-	294.0	-
Specific conductance (micromhos) at 25°C)	340.0	-	270.9	-	567.0	-	453.0	-
pH	8.9		8.2		7.5		7.7	

(Table 6.3 Contd.)

Tubewell Nos.	14		9		20		13	
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	8.4	-	19.6	-	11.2	-	11.6	-
Iron	-	-	16.8	-	5.6	-	-	-
Calcium(Ca)	28.5	1.43	111.4	5.57	45.7	2.28	25.7	1.28
Magnesium(Mg.)	33.6	2.69	26.4	2.17	16.8	1.38	10.8	0.88
Sodium(Na) + Potassium(K)	-	-	0.33	0.01	0.15	0.006	6.29	0.29
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	195.2	3.20	366.0	5.99	195.2	3.20	146.4	2.39
Sulphate(SO_4)	23.07	0.48	28.8	0;60	23.8	0.49	9.47	0.19
Chloride(Cl)	8.9	0.27	9.90	0.28	5.68	0.16	9.94	0.28
Dissolved solids calculated.	256.0	-	260.0	-	160.0	-	220.0	-
Specific conductance(micromhos) at 25°C)	441.0	-	403.0	-	258.3	-	352.8	-
pH	8.4		8.0		8.1		8.3	

(Table 6.3 Contd.)

Tubewell Nos.	18		29					
Constituents	ppm	epm	ppm	epm	ppm	epm	ppm	epm
Silica	6.53	-	12.6	-	-	-	-	-
Iron	-	-	-	-	-	-	-	-
Calcium(Ca)	22.8	1.14	57.1	2.85	-	-	-	-
Magnesium(Mg.)	12.0	0.98	19.2	1.57	--	-	-	-
Sodium(Na) + Potassium(K)	-	-	11.0	0.47	-	-	-	-
Carbonate(CO_3)	-	-	-	-	-	-	-	-
Bicarbonate(HCO_3)	146.0	2.39	268.4	4.39	-	-	-	-
Sulphate(SO_4)	2.47	0.05	14.4	0.29	-	-	-	-
Chloride(Cl)	2.84	0.08	7.1	0.20	-	-	-	-
Dissolved solids calculated.	136.0	-	400.0	-	-	-	-	-
Specific conductance (micromhos at 25°C)	264.6	-	384.30	-	-	-	-	-
PH	7.2		8.2					

GRAPHICAL REPRESENTATION OF WATER ANALYSIS DATA

There are many methods of graphic representation of water analysis which are very useful in the study of the chemical quality of water. In this chapter the following graphical methods of representation are used:

BAR PATTERN OR PERCENTAGE COMPOSITION DIAGRAM

Collins [53] first introduced the graphical presentation of analysis data in the form of bar diagrams. Under this system, the analysis is represented by a vertical bar graph whose total height is proportional to the total concentration of anions or cations. The bar is divided into segments to show the concentrations of the cations and anions which make up the total. Usually these are divided into six sub-divisions. Cations are plotted on the left half of the vertical bar and anions on the right.

The bar diagrams in plate 6.1 show the chemical data for the ground water from a few of the representative wells tapping the deeper aquifers of the area.

A comparison of the water analysis data for the months of June and October indicates that the concentration of Na^{1+} and K^{1+} is more in October than in June while Mg^{2+} and HCO_3^{1-} are less in June as compared with October. These seasonal changes in the quality of water can be explained either due to cation exchange or changes in ground water regime. It is difficult to establish the influence of cation exchange as the chemical changes in the sediments are not known. However, excessive recharge due to rain, which falls from June to October, will influence the chemical character of ground water. Greater concentration of Na^{1+} + K^{1+} and HCO_3^{1-} indicate that it is due to the leaching of the overlying alluvial formations in the recharge area.

PIPER'S DIAGRAM

This system of plotting was suggested by Piper[54] and represents a trilinear plotting system. The relative concentrations of constitutents is expressed as a percentage of total reacting value and the essential chemical character of water is indicated graphically by a single point plotting of cations and anions on trilinear coordinates. For convenience, the sub-total of all cations and anions reacting values is taken as 100 percent for computing seperately percentage reacting values of the several cation and anion variables. This procedure balances analytical errors automatically.

Piper's diagram combines three distinct fields for plotting, two triangular fields at the lower left and lower right respectively, and an intervening diamond-shaped field. All the three fields have scales reading in 100 parts (Plate 6.2 and 6.3). In the triangular field at the lower left, the percentage reacting value of the three cation groups (Ca^{2+}, Mg^{2+}, Na^{1+} + K^{1+}) are plotted as a single point according to conventional trilinear coordinates. Likewise the three anion groups (HCO_3^{1-} + CO_3^{2-}, SO_4^{2-}, Cl^{1-}) are plotted in the triangular field at the lower right.

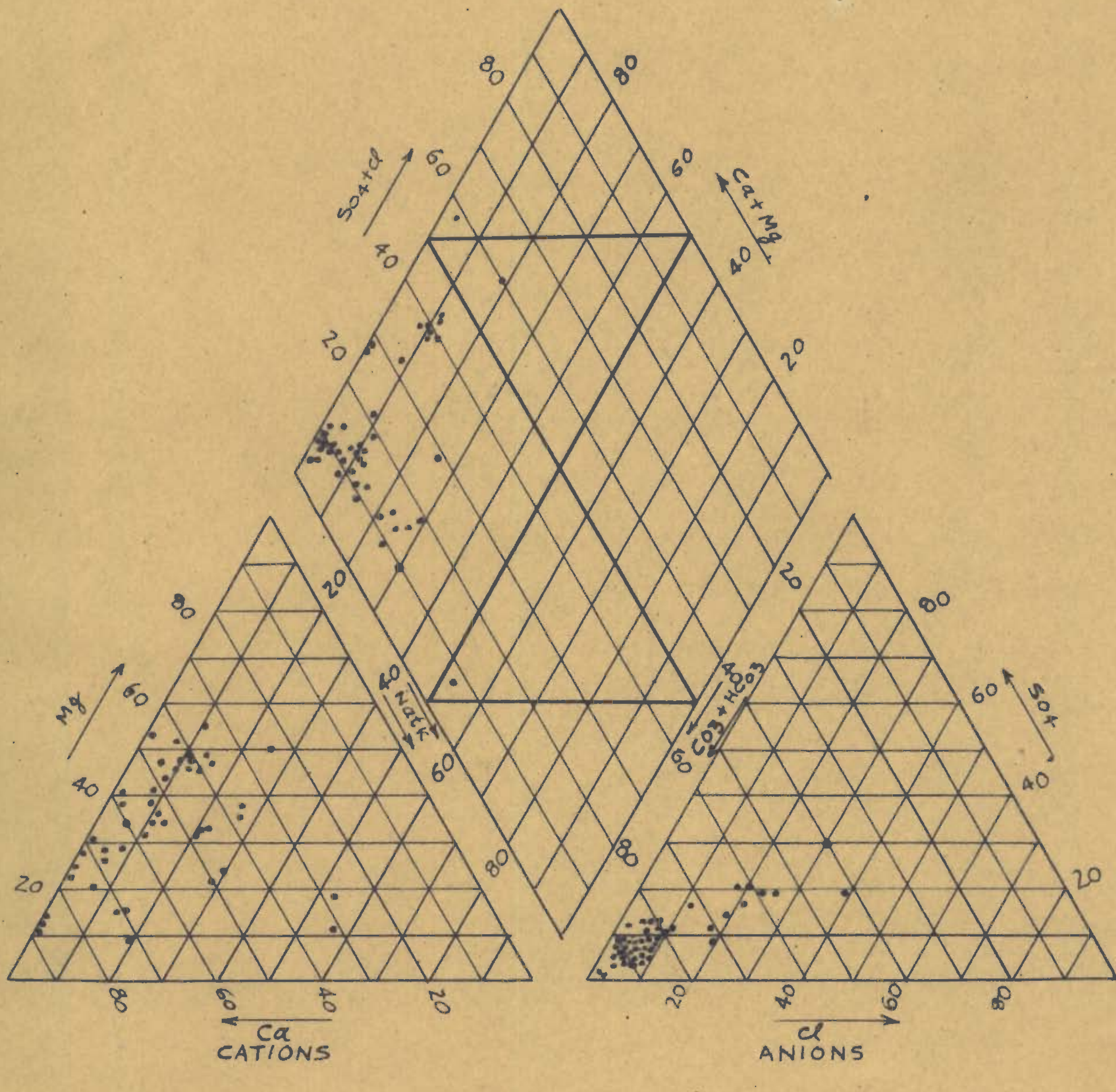
Thus, two points on the diagram, one in each of the two triangular fields, indicate the relative concentrations of the several dissolved constituents of a natural water.

The Central diamond shaped field is used to represent the overall chemical character of water by a third single-point plotting. A few features of the chemical quality of natural waters can not be explained by the Piper diagram, e.g. waters having different total solid contents but the same percentage of cations and anions fall at the same point within the diagram. The plottings in these diagrams show the chemical character of water according to the relative concentration of its constituents but not according to the absolute concentration. Piper suggested that the absolute concentration can be indicated by drawing circle around the plotting in the central field so that the area of this circle is proportional to the total concentration. Such a method is not convenient in the present study because the plottings are so close to each other, that one circle will overlap the other and hence the total solid contents have been tabulted separately (Table 6.2 and 6.3).

The diamond shaped field has been divided into several zones, according to which it becomes easy to discriminate quality of water by their plottings in certain sub-areas of the diamond shaped field.

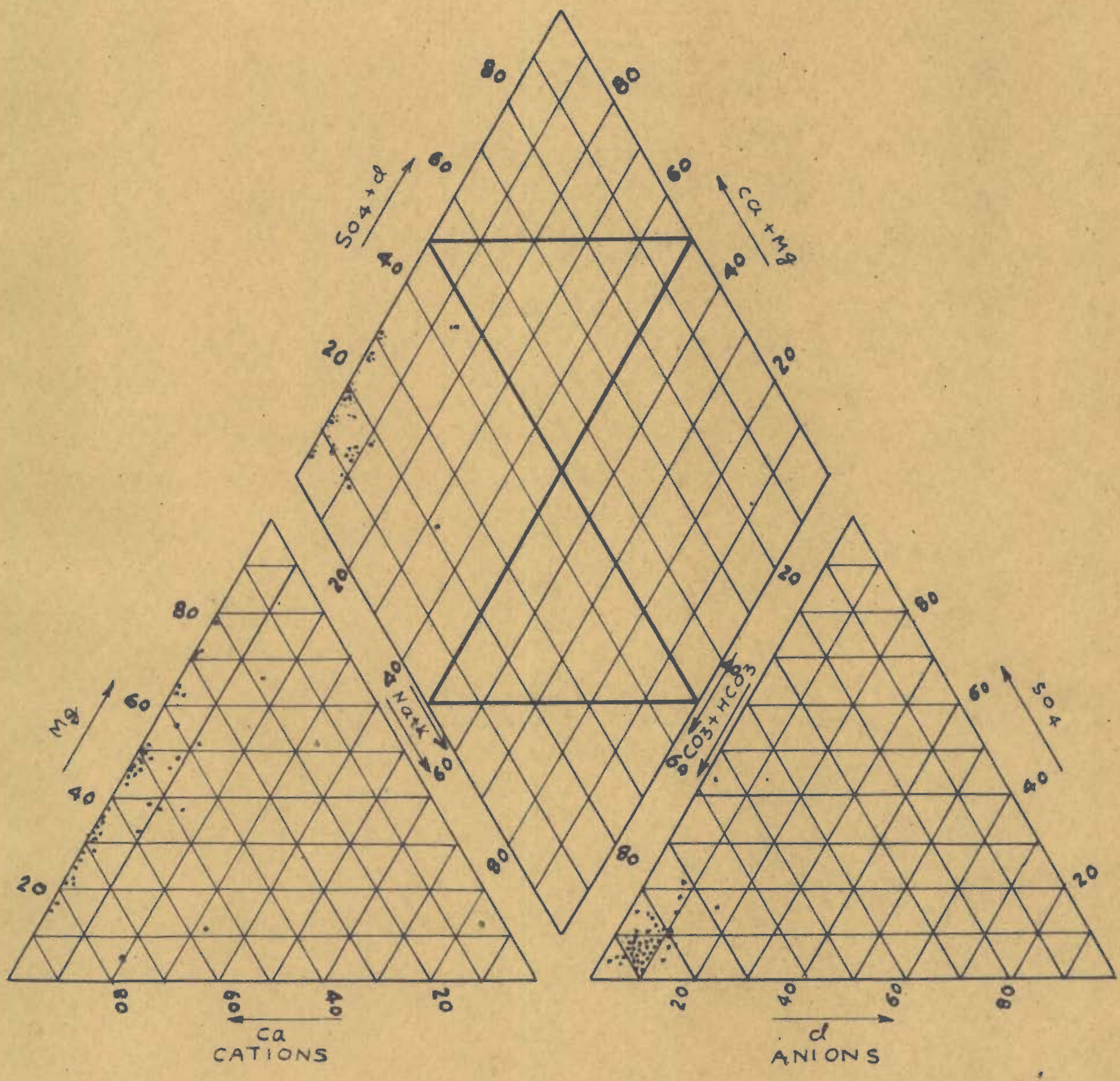
The plots of ground water samples for the months of October and June are shown in Plate 6.2 and 6.3. Each water sample is represented by a point in the central diamond shaped field. The plottings (both for October and May June) indicate that the water sample are

PLATE 6.2



PLOTTINGS OF WATER ANALYSIS DATA FOR OCTOBER 1964 IN PIPER'S DIAGRAM.

PLATE 6.3



PLOTTINGS OF WATER ANALYSIS DATA FOR SUMMER, (May-June) 1965 IN PIPER'S DIAGRAM.

dominated by alkaline earths and weak acids. Such a type will be included under the "Secondary alkalinity" class of Palmer[55].

DUROV'S DIAGRAM

Durov's diagram (Chillingar[56]) is a double triangular diagram. In one triangle the composition of water is expressed in terms of HCO_3^{1-}, SO_4^{2-} and Cl^{1-} anions and in the other in terms of Ca^{2+}, Mg^{2+} and Na^{1+} cations. The amount of these ions are expressed in percent milligram equivalents as in Piper's diagram. In this plotting CO_3^{2-} is added with HCO_3^{1-} and K^{1+} with Na^{1+}.

In order to obtain points inside the square, perpendiculars are drawn from the corresponding points plotted in the triangles and extended until they intersect.

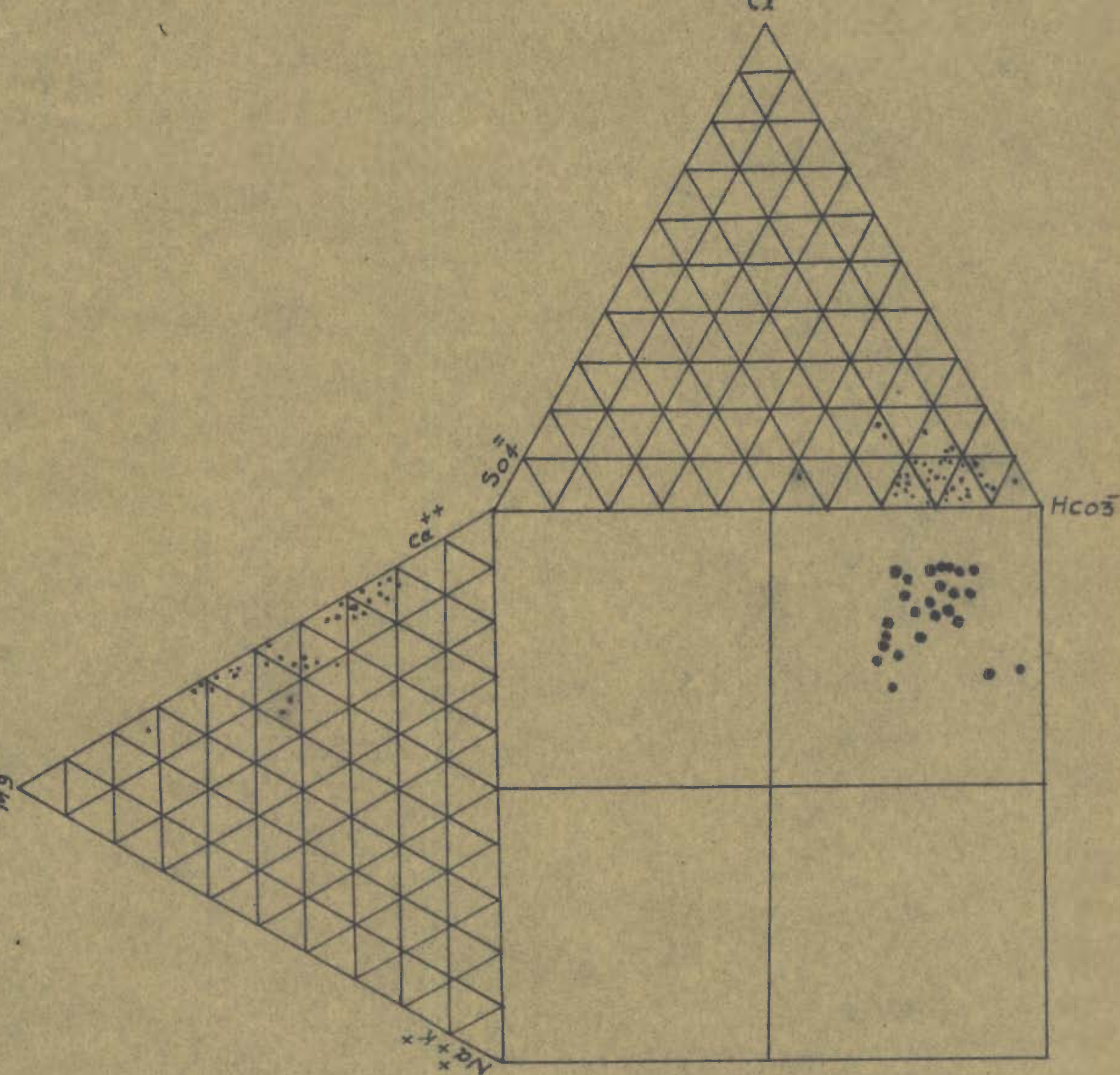
In Plate 6.4 the waters from the investigated area fall in the upper right corner, representing, Durov's Class I (Primary waters). These are classified as simple waters and formed as a result of the action of atmospheric precipitation falling on the Earth's surface.

WATER QUALITY MAPS

A useful procedure in the study of water quality data is to plot the results on the map. Such maps are mostly utilized, in the study of ground water in a single aquifer.

Generally a water quality map is prepared by entering numbers or symbols at well locations to represent the concentration of total

PLATE 6.4



PLOTTINGS OF WATER SAMPLE DATA FOR SUMMER (MAY-JUNE) 1965 IN DUROV'S DIAGRAM dissolved solids or of individual constituents in absolute values, or as ratios. The areal distribution of the water of various kinds can thus be observed on the map in a general way (Hem[57]). It has been indicated earlier that the deeper aquifers in the area form one single hydraulic unit and they in turn are distinguished from the shallow aquifer. The Chemical data from the deeper aquifer have been used for the preparation of such maps. These types of maps extrapolate data between sampling points and show the areal characteristics more clearly than any other procedure.

ISOCONE MAPS

The technique of mapping water quality characteristics by drawing lines of equal concentration of dissolved solids or single ions in ppm has been used in the present discussion. On this basis lines showing equal chloride concentrations (Isochlors) have been drawn as shown in Plates 6.5, 6.6 and Isosulphate maps are given in Plates 6.7 and 6.8.

RATIO MAPS

The study of the variation in the values of rSO_4/rCl, rMg/rCa etc. gives a clear picture of the chemical characteristics of a ground water reservoir (Schoeller [58]). Such maps are of help for the study of variation in the chemical quality of water in the direction of flow (The symbol r indicates that the elements before which it is placed are expressed in milliequivalents). Keeping this

PLATE 6.5

ISOCHLOR MAP FOR DEEPER AQUIFERS MAY-JUNE 1965.

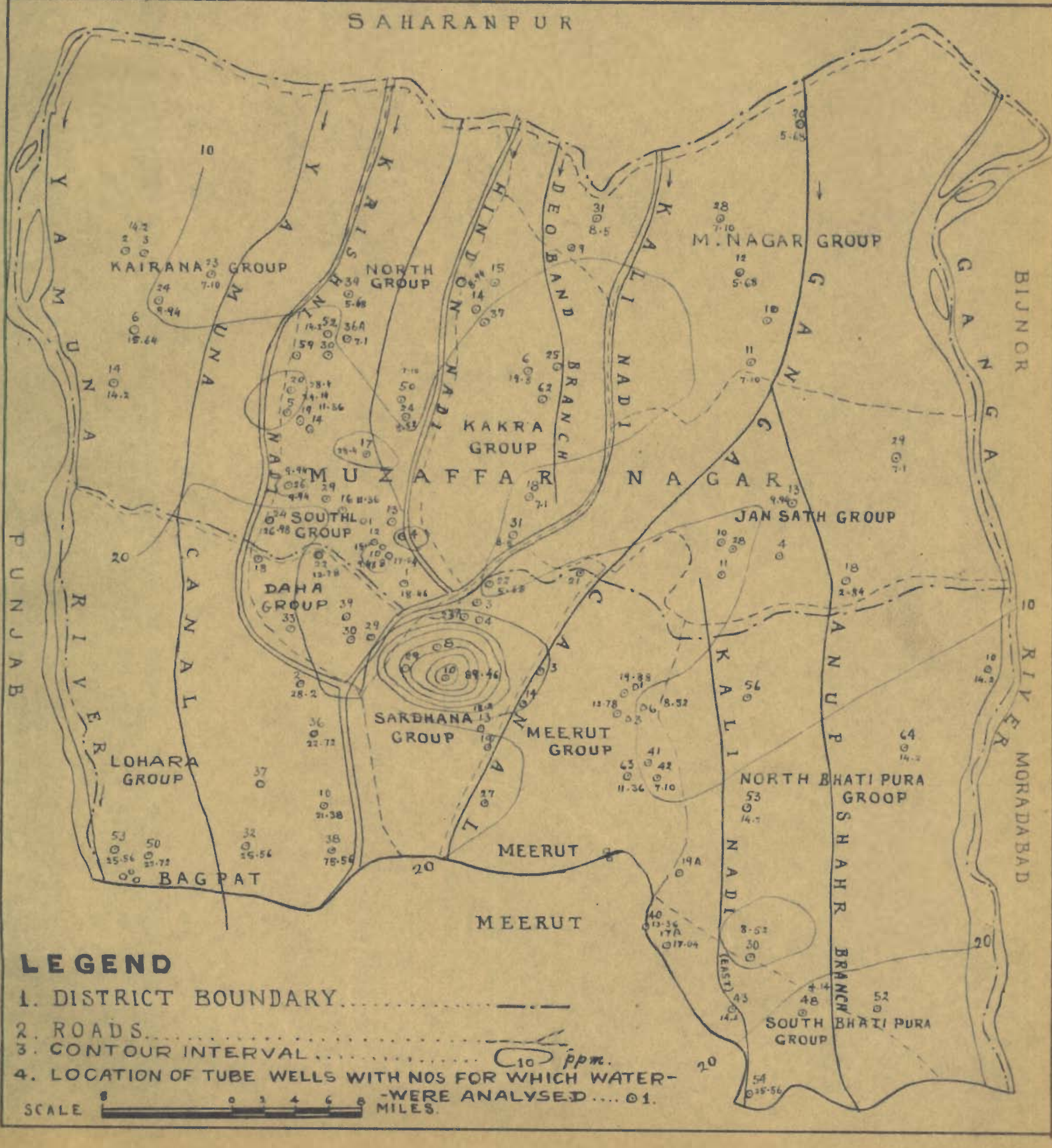
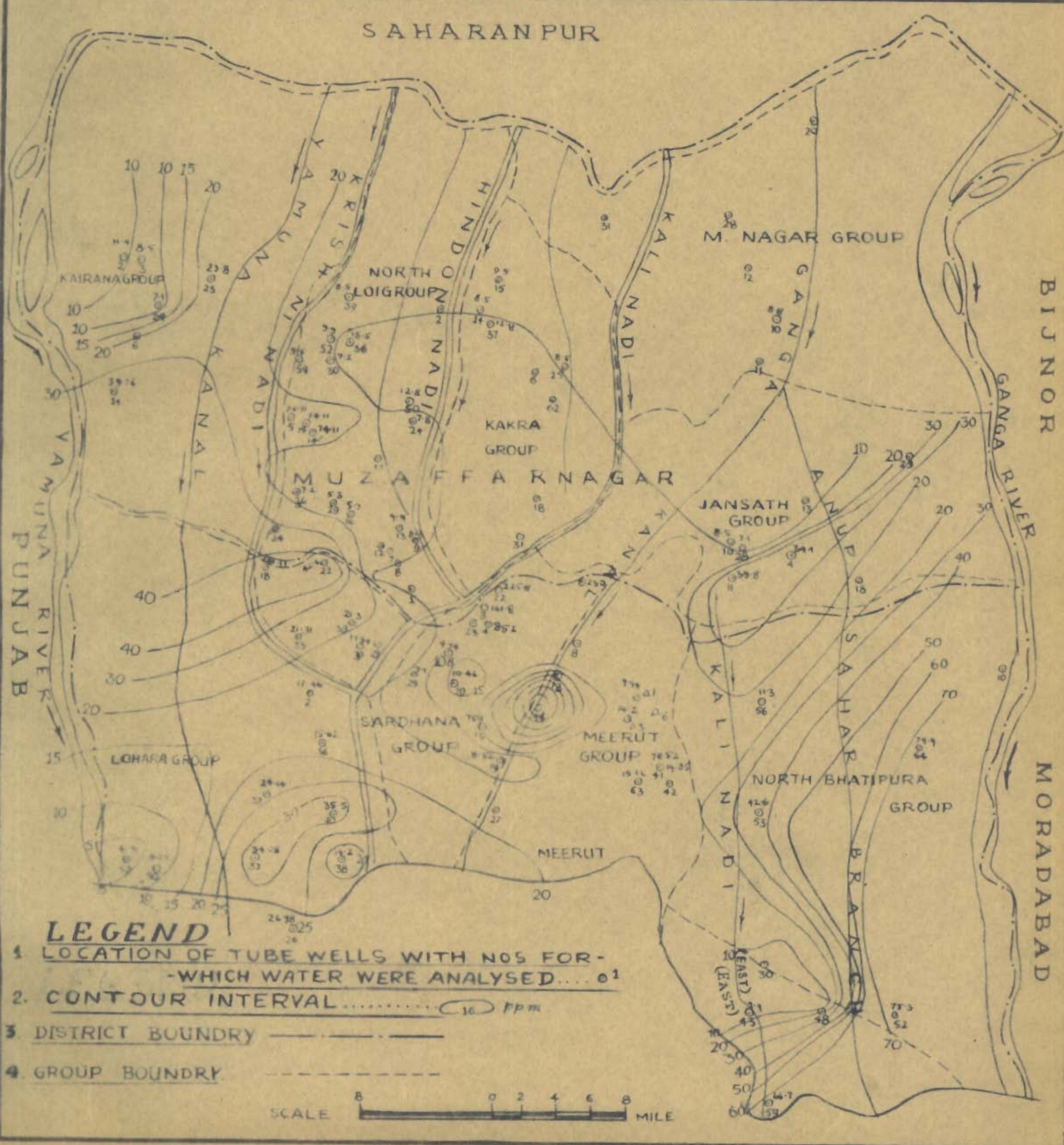


PLATE 6.6

ISOCHLOR MAP FOR DEEP AQUIFERS OCT. 1964.



LEGEND

1. LOCATION OF TUBE WELLS WITH NOS FOR -WHICH WATER WERE ANALYSED.... o[1]
2. CONTOUR INTERVAL .... (10) ppm
3. DISTRICT BOUNDRY — · — · —
4. GROUP BOUNDRY - - - - - - -

SCALE 8 0 2 4 6 8 MILE

PLATE 6.7

ISO-SULPHATE MAP FOR DEEP AQUIFERS, MAY-JUNE 1965.

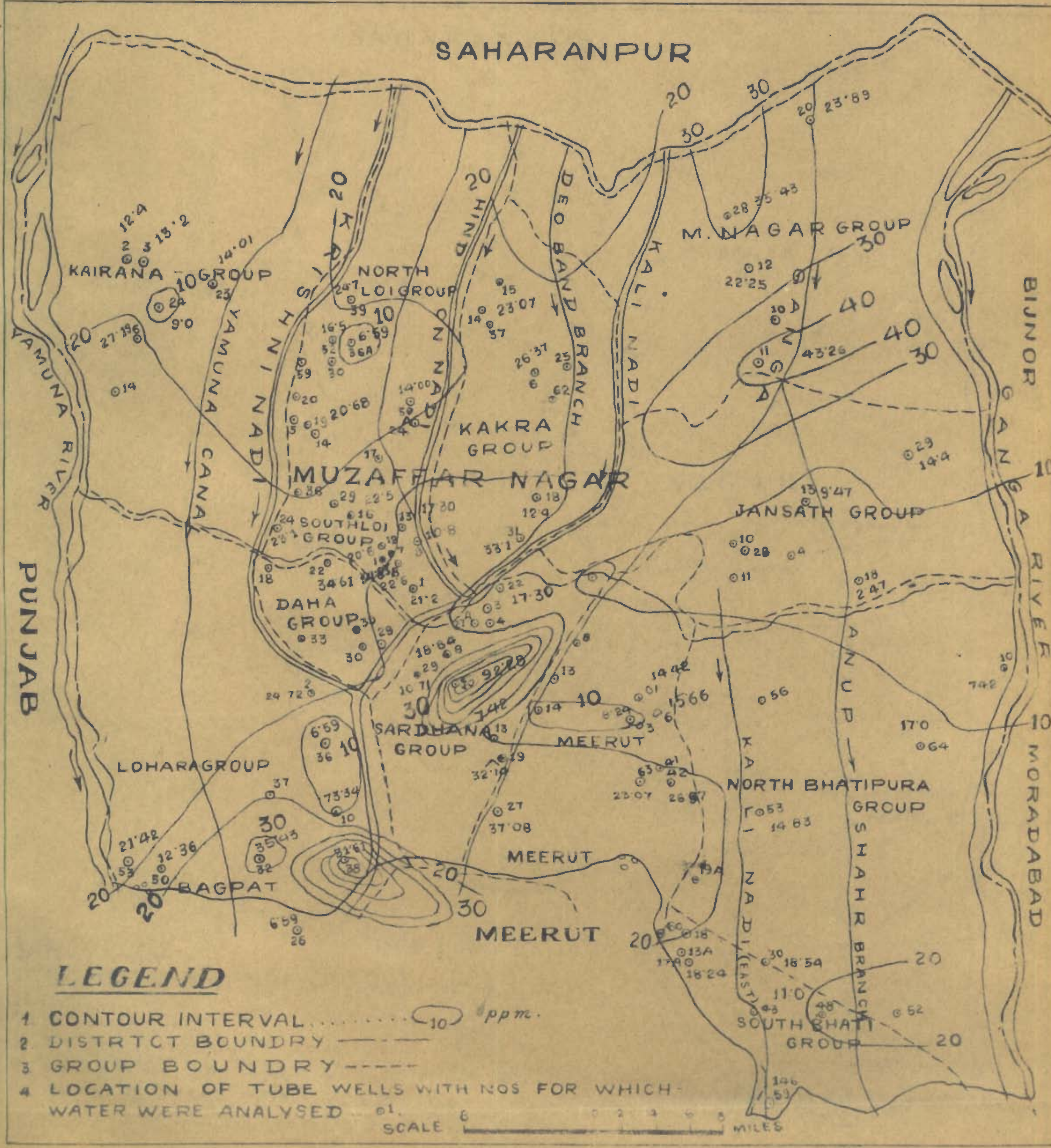


PLATE 6.8

ISO-SULPHATE MAP FOR DEEP AQUIFER OCT. 1964.

in view, rSO_4 /rCl and rMg /rCa ratios are determined for the water samples and these are plotted in the ratio maps (Plates 6.9 to 6.12). Based on these values, contours of equal ratio values were drawn. These ratio maps indicate that the rSO_4 /rCl and rMg/rCa ratio decreases in general from north to south.i.e. in the direction of ground water flow. This is in confirmity with the views of Schoeller [58] according to whom, "the chemical composition of water in a ground water reservoir does not remain constant from the point of entry to the point of exit. Broadly speaking, the ratio rSO_4 /rCl and rMg/rCa decreases from the area of recharge to the area of discharge."

SUITABILITY OF WATER FROM DEEPER AQUIFERS FOR DRINKING PURPOSES

This study is of importance because in the investigated area, water is mainly used for domestic and irrigational purposes.

In Table 6.4 given the permissible limits of various constituents with respect to the use of water for different purposes.

PLATE .6.9

rSO_4/rCl RATIO MAP FOR WATER FROM DEEP AQUIFERS, MAY-JUNE 1965.

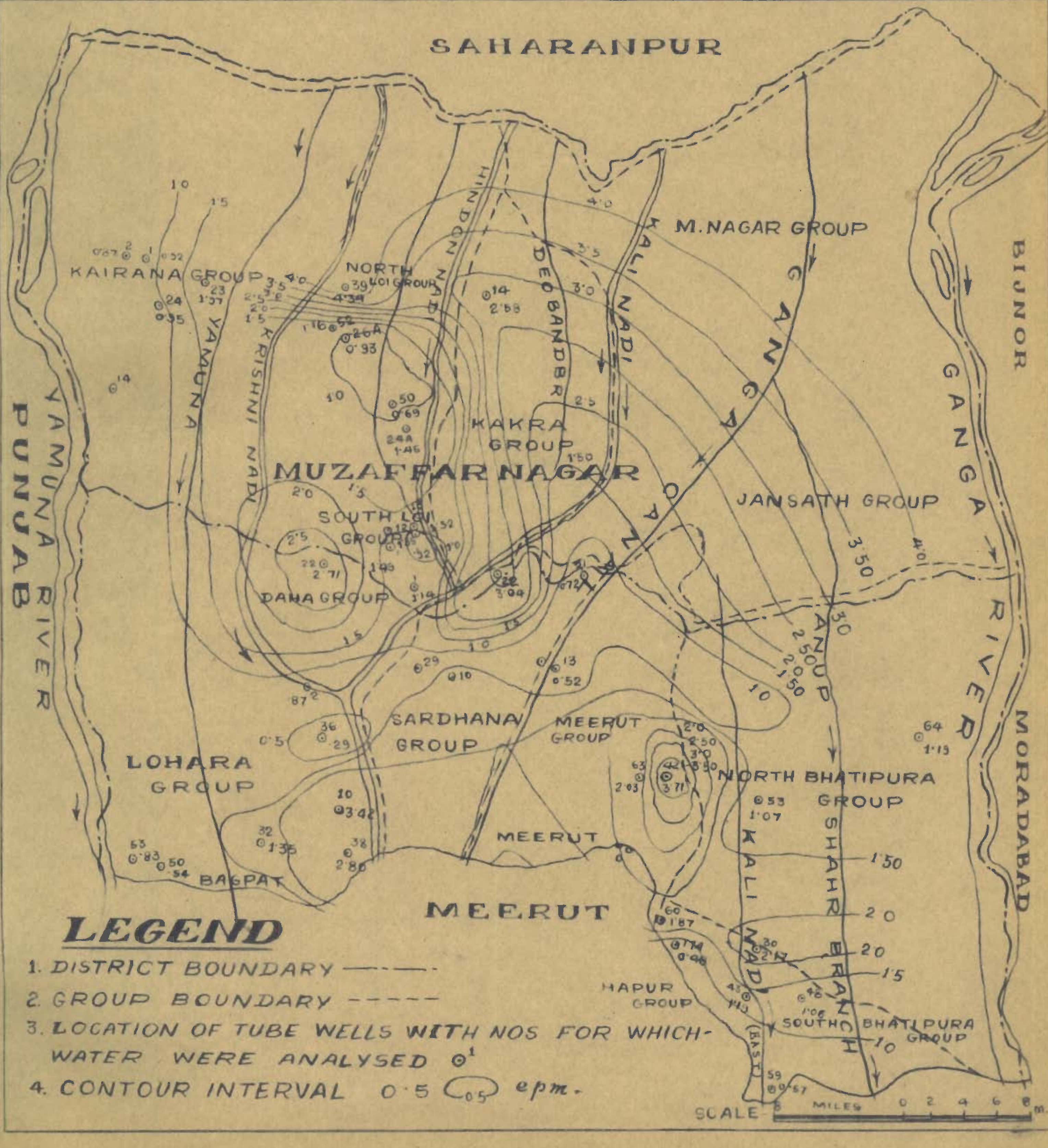
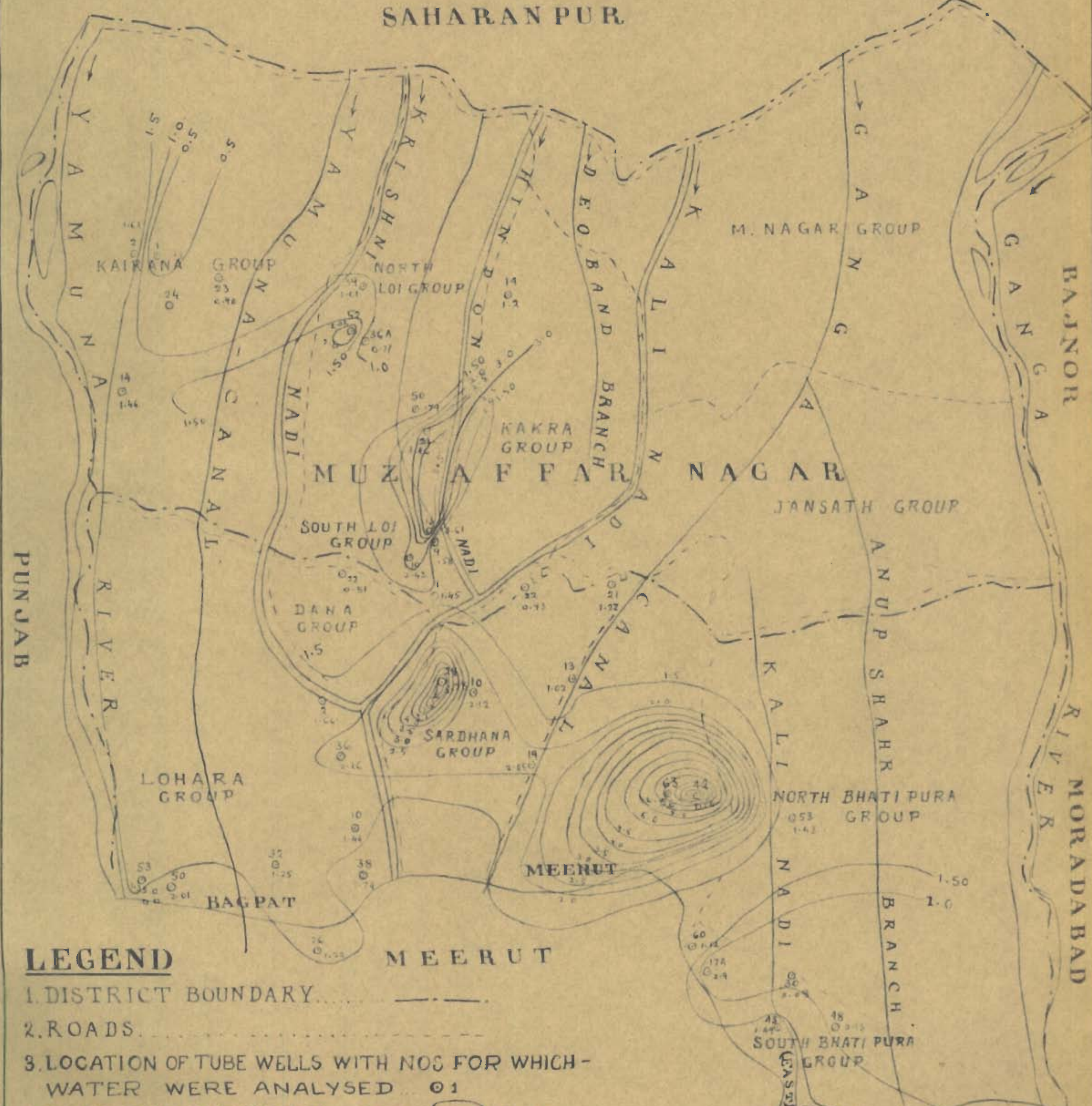


PLATE 6.10

rSO4/rCl RATIO MAP FOR WATER FROM DEEP AQUIFERS, OCT. 1964



LEGEND

1. DISTRICT BOUNDARY ...... —·—
2. ROADS .... - - - -
3. LOCATION OF TUBE WELLS WITH NOS FOR WHICH WATER WERE ANALYSED ... ⊙1
4. CONTOUR INTERVAL 0·5 epm.

SCALE 0 2 4 6 8 MILES.

PLATE 6.11

rMg/rCa RATIO MAP FOR WATER FROM DEEP AQUIFERS, MAY JUNE 1965.

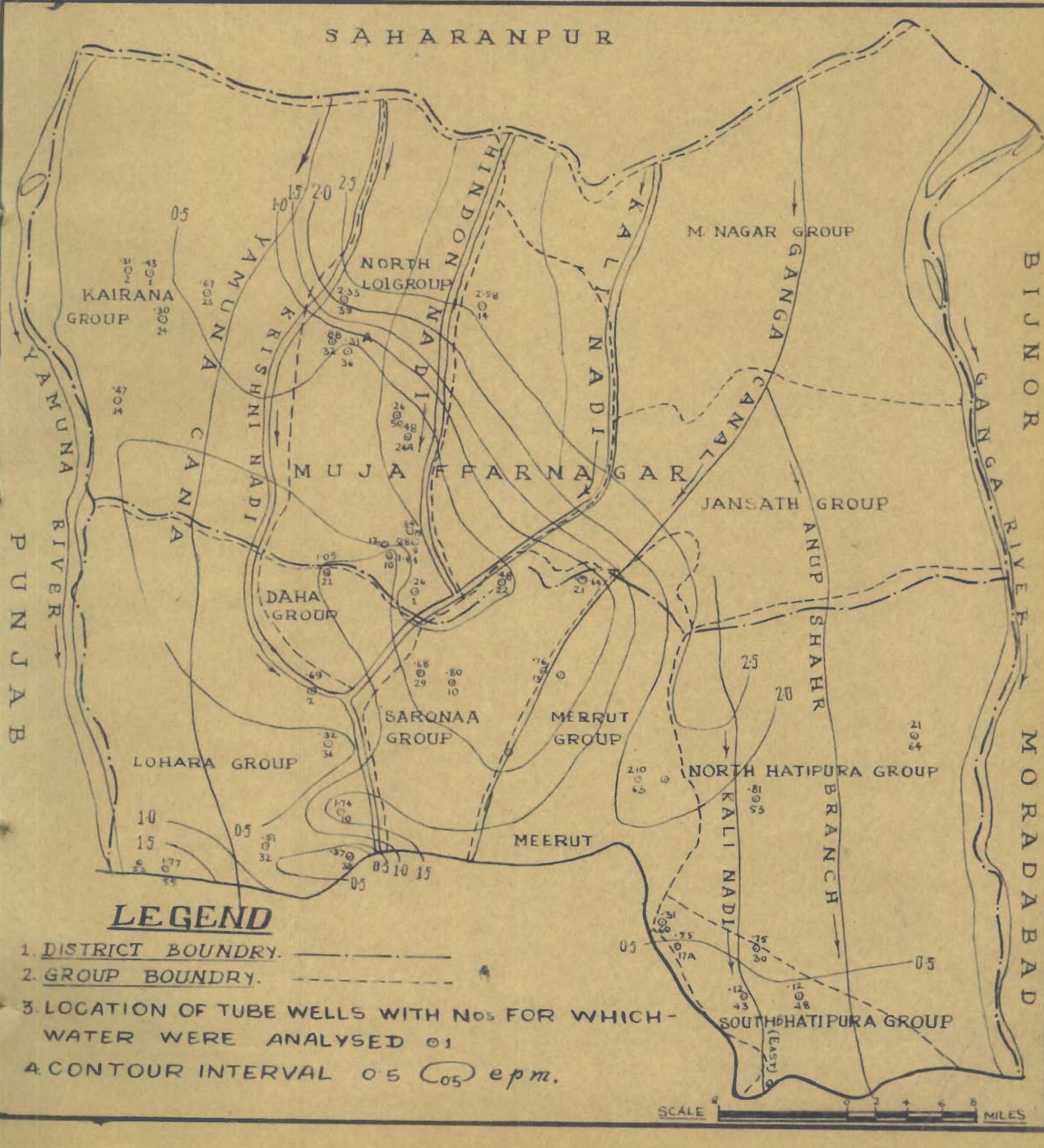


PLATE 6.12

rMg/rCa RATIO MAP FOR WATER FROM DEEP AQUIFERS, OCT.-1964.

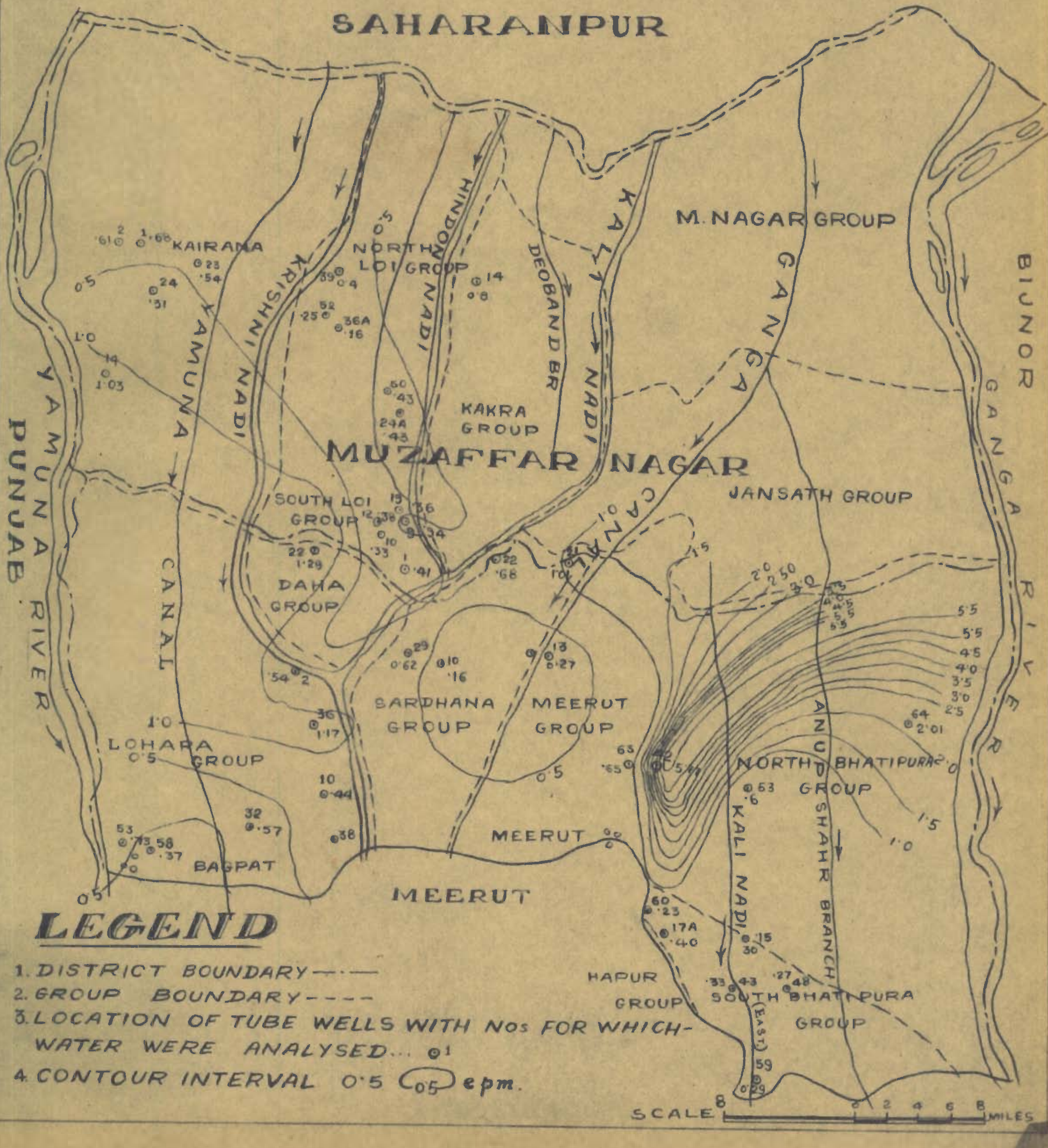


TABLE 6.4 QUALITY CRITERIA FOR VARIOUS USES. NUMBERS ARE MAXIMUM RECOMMENDED CONCENTRATIONS IN PARTS PER MILLION (AFTER Davis AND DeWiest[32])

	Drinking	General house-hold use. Good	General house-hold use. Poor	Irrigation Good	Irrigation Poor	Food Processing	Bioler water High pressure	Bioler water Low pressure.
Antimony	0.05	-	-	-	-	0.05	-	-
Arsenic	0.05[a]	-	-	-	-	0.05	-	-
Barium	1.00[a]	-	-	-	-	1.00	-	-
Bicarbonate	500	150	500	200	500	300	5	50
Boron	20	-	-	0.3	3.0	-	-	-
Cadmium	0.01[a]	-	-	-	-	0.01	-	-
Calcium	200	40	100	-	-	80	1	40
Chloride	250	-	-	100	300	300	-	-
Chromium	0.05[a]	-	-	-	-	0.05	-	-
Copper	1.0	0.5	3.0	-	-	3.0	-	-
Cyanide	0.2[a]	-	-	-	-	0.2	-	-
Fluoride	1.5	-	-	-	-	1.5	-	-
Hydrogen-Sulfide	1.0	0.05	2.0	-	-	0.5	0	5
Iron	1.0	0.2	0.5	-	-	0.2	-	-
Lead	0.05[a]	-	-	-	-	0.05	-	-
Magnesium	125	20	100	-	-	40	1	20
Manganese	0.05	0.05	0.3	-	-	0.1	-	-
Nitrate	20	-	-	-	-	20	-	-
Phenol	0.001	-	-	-	-	0.001	-	-
Selinium	0.01[a]	-	-	-	-	0.01	-	-
Silica	-	10	50	-	-	[illegible]	1	30
Silver	0.05[a]	-	-	-	-	0.05	-	-
Sodium	200	100	300	50	300	300	-	50
Sulphate	250	100	300	200	500	-	-	-
Synthetic-detergents	0.5	0.2	1.0	-	-	0.5	0	0
Total solid	1500	300	2000	500	3000	1000	100	2000
Zinc	5	-	-	-	-	5	-	-

Note: [a] Mandatory limits of the U.S. Public Health Service for water used in Inter-state Public transportation facilities.

SUITABILITY OF WATER FROM DEEPER AQUIFERS FOR IRRIGATIONAL PURPOSES

The suitability of ground water for irrigation is contingent upon the effects of the mineral constituents of water of both the plant and soil. Wilcox [59] has classified the suitability of irrigation waters on the basis of electtical conductivity, sodium percentage and boron concentration in ppm (Table 6.5). Sodium percentage (also known as percent sodium) is defined by $\% Na = \frac{(Na+K)100}{Ca+Mg+Na+K}$ where all ionic concentrations are expressed in milliequivalents per litre.

TABLE 6.5 QUALITY CLASSIFICATION OF WATER FOR IRRIGATION (AFTER WILCOX [59])

Water class	Percent sodium.	Electrical conductivity $EC \times 10^6$	Boron ppm.
Excellent	< 20	< 250	< 0.67
Good	20 - 40	250 - 750	0.67 - 1.33
Permissible	40 - 60	750 - 2000	1.33 - 2.00
Doubtful	60 - 80	2000 - 3000	2.00 - 2.50
Unsuitable	> 80	> 3000	> 2.50

The sodium percentage and electrical conductivity of the water samples from the area under study are given in Tables 6.6 and 6.7. On the basis of the percentage sodium and electrical conductivity, the author is of the opinion that almost all water from the deeper aquifess fall under the class of "Good waters" which can be used for irrigation purposes without any harm.

TABLE 6.6 SODIUM PERCENTAGE AND ELECTRICAL CONDUCTIVITY IN WATER SAMPLES FOR OCTOBER - 1964

Constituents	TUBEWELL NUMBERS							
	19A	53	64	17A	43	48	59	3
Sodium Percentage.	14.6	12.1	4.8	7.7	10.8	15.3	19.3	12.3
Electrical conductivity. ($EC \times 10^6$)	504.0	441.0	504.0	409.5	315.0	535.5	598.5	1701.0

Constituents	TUBEWELL NUMBERS							
	21	22	29	19	18	22	30	10
Sodium Percentage.	12.70	22.10	12.9	27.1	10.6	26.1	25.01	8.4
Electrical conductivity. ($EC \times 10^6$)	2268.0	1953.0	535.0	378.0	630.0	504.0	693.0	441.0

Constituents	TUBEWELL NUMBERS							
	32	36	37	38	50	53	24A	36A
Sodium Percentage.	7.5	1.5	22.90	-	30.32	14.0	19.5	5.5
Electrical conductivity. ($EC \times 10^6$)	756.5	567.0	724.5	283.5	472.5	567.0	661.50	756.0

Constituents	TUBEWELL NUMBERS							
	50	30	59	50	5	1	13	12
Sodium Percentage.	3.0	1.26	2.0	2.14	4.94	53.1	12.74	7.53
Electrical conductivity. ($EC \times 10^6$)	520.51	526.0	663.0	504.0	693.0	567.0	504.0	459.90

(Table 6.6 Contd.)

Constituents	TUBEWELL NUMBERS 13	26	39	36	9	3A	4	28
Sodium Percentage.	8.7	5.0	2.28	0.93	1.97	2.18	1.93	25.94
Electrical conductivity. ($EC \times 10^6$)	1071.0	819.0	409.50	526.0	520.0	560.0	630.0	567.0

Constituents	TUBEWELL NUMBERS 14	10	11	1	2	15
Sodium Percentage.	14.86	28.86	10.30	10.49	10.3	12.1
Electrical conductivity. ($EC \times 10^6$)	390.6	661.50	693.0	472.5	535.5	315.2

TABLE 6.7 SHOWING SODIUM PERCENTAGE AND ELECTRICAL CONDUCTIVITY IN WATER SAMPLES FOR JUNE - 1965.

Constituents	TUBEWELL NUMBERS							
	10	53	64	43	48	59	30	22
Sodium Percentage.	0.30	4.9	-	2.4	1.2	0.5	0.2	0.2
Electrical Conductivity. ($EC \times 10^6$)	359.10	409.50	456.0	729.9	811.3	486.6	415.80	396.90

Constituents	TUBEWELL NUMBERS							
	21	13	29	22	29	10	26	38
Sodium Percentage.	0.2	7.8	8.7	0.1	-	1.6	0.3	0.1
Electrical conductivity. ($EC \times 10^6$)	459.90	441.00	422.10	693.0	567.0	756.0	604.80	756.0

Constituents	TUBEWELL NUMBERS							
	32	2	11	D6	D1	D3	63	6
Sodium Percentage.	0.2	1.7	0.3	8.2	0.3	0.7	16.5	-
Electrical conductivity. ($EC \times 10^6$)	612.20	693.0	459.90	409.5	541.8	415.8	189.0	504.0

Constituents	TUBEWELL NUMBERS							
	23	14	52	50	36A	19	1	8
Sodium Percentage.	0.1	-	9.5	-	-	14.8	1.2	1.3
Electrical conductividy. ($EC \times 10^6$)	428.4	378.0	384.3	434.6	365.0	567.0	634.7	662.9

(Table 6.7 Contd.)

Constituents	TUBEWELL NUMBERS							
	9	12	16	6	24	31	42	29
Sodium Percentage.	1.5	2.7	1.7	-	4.8	33.2	7.5	11.7
Electrical conductivity. (EC x 10^6)	608.2	608.2	584.0	630.0	340.2	270.90	567.0	453.6

Constituents	TUBEWELL NUMBERS					
	14	9	20	13	18	29
Sodium Percentage.	-	0.14	0.3	11.2	-	9.6
Electrical conductivity. (EC x 10^6)	441.0	403.2	258.3	352.8	264.6	384.30

According to the classification by the U.S. Salinity Laboratory (Todd[60]), the suitability of water for irrigation purposes is based on Sodium Adsorption Ratio (SAR) and electrical conductivity. The Sodium Adsorption Ratio (SAR) is defined by

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

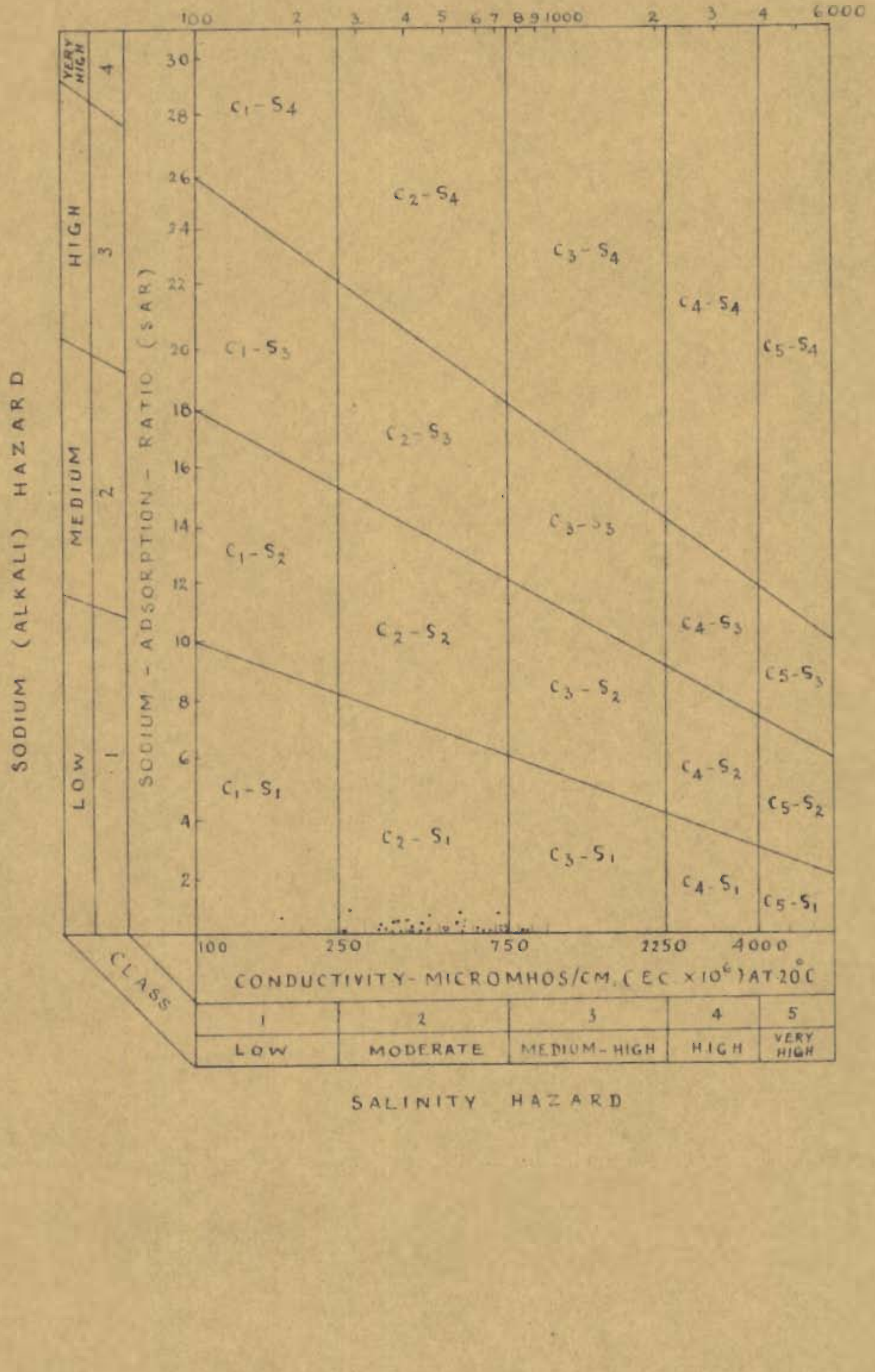
where the concentrations of the constituents are expressed in milliequivalents per litre.

Direct indication of the salinity and alkalinity hazards can be obtained by locating the points for a particular irrigation water in the classification diagram with electrical conductivity and SAR as coordinates (Plate 6.13, 6.14). The figure is binomial and C_1, C_2, C_3, C_4 and C_5 represent water classes with increasing hazards from total salt concentrations and S_1, S_2, S_3 and S_4 represent water classes for increasing hazards of exchangeable sodium accumulation in irrigated soils.

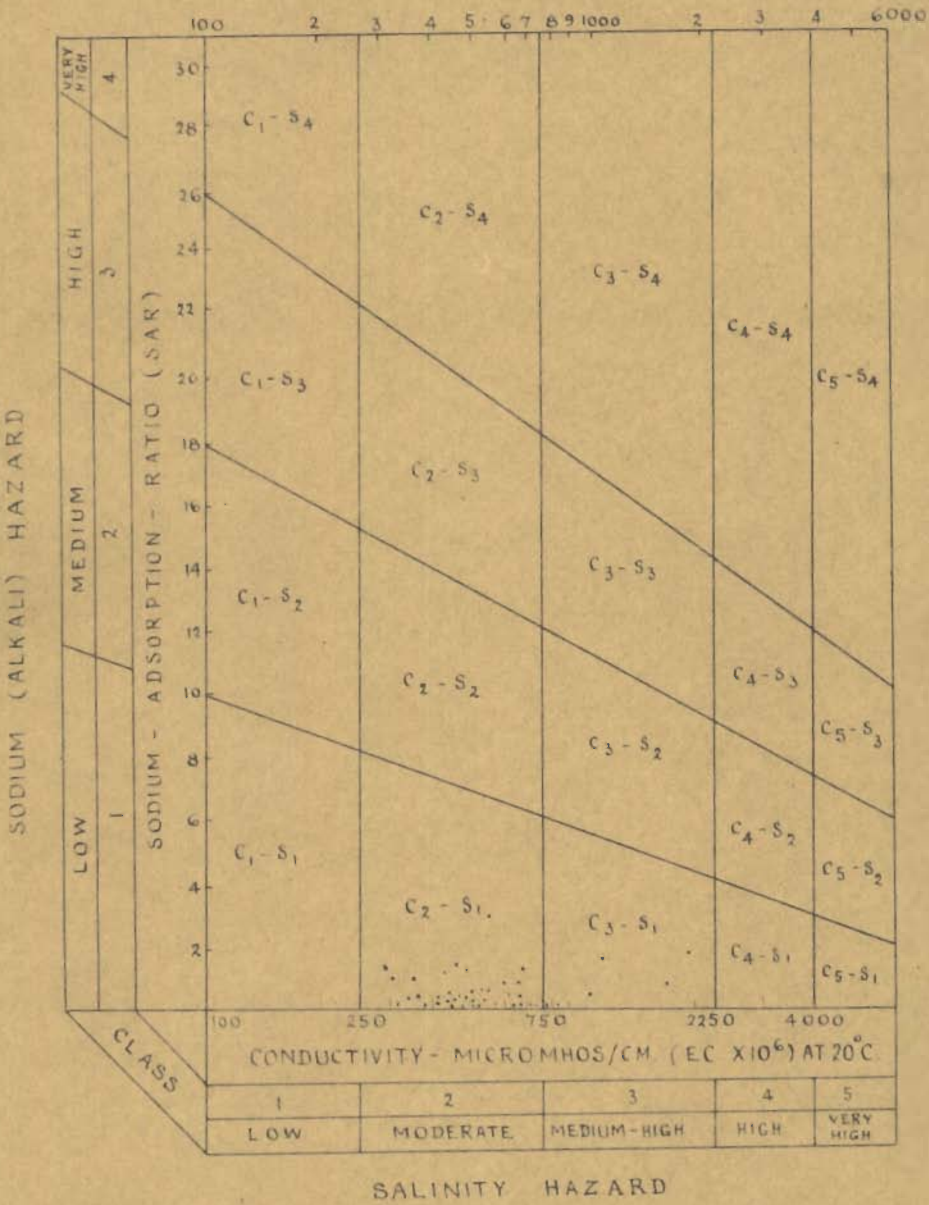
The SAR values are determined from the chemical data and these are tabulated along with electrical conductivity in Table 6.8 and 6.9. These data are plotted in the Salinity Diagram (Plates 6.13 and 6.14).

Such a plotting indicates that almost all waters from the area fall within $C_2 - S_1$ class and, therefore, are suitable for irrigational purposes.

PLATE. 6.13



PLOTTINGS OF WATER ANALYSIS DATA FOR-
MAY- JUNE (1965)
IN U.S. SALINITY DIAGRAM.



PLOTTINGS OF WATER ANALYSIS DATA FOR OCT. (1964) IN U.S. SALINITY DIAGRAM.

TABLE 6.8 SODIUM ADSORPTION RATIO (SAR) AND ELECTRICAL CONDUCTIVITY FOR WATER SAMPLES - WINTER - 1964

Constituents	TUBEWELL NUMBERS							
	19A	53	64	17A	43	48	59	3
SAR	0.50	0.41	0.08	0.27	.261	0.62	0.7	0.61
Electrical conductivity. ($EC \times 10^6$)	504.0	441.0	504.0	409.5	315.0	535.5	598.5	1701.0

Constituents	TUBEWELL NUMBERS							
	13	21	22	29	19	18	22	30
SAR	0.41	4.27	1.53	0.47	0;88	0.5	0.28	1.08
Electrical conductivity. ($EC \times 10^6$)	1071.0	2268.0	1953.0	535.0	378.0	630.0	504.0	693.0

Constituents	TUBEWELL NUMBERS							
	10	26	32	36	37	38	50	53
SAR	0.25	0.19	0.22	0.05	1.0	1.5	1.2	0.55
Electrical conductivity. ($EC \times 10^6$)	441.0	819.0	756.0	567.0	724.5	283.5	472.5	567.0

Constituents	TUBEWELL NUMBERS							
	24A	36A	39	50	30	59	5	
SAR	0.78	0.11	0.05	0.08	0.01	0.02	0.08	-
Electrical conductivity. ($EC \times 10^6$)	661.5	756.0	409.5	520.51	526.0	663. 0	504.0	893.0

(Table 6.8 Contd.)

Constituents	TUBEWELL NUMBERS 1	13	12	36	9	3A	4	28
SAR	2.48	0.47	0.08	0.01	0.066	0.075	0.06	0.89
Electrical conductivity. ($EC \times 10^6$)	567.0	504,0	459.90	526.0	520.0	560.0	630.0	567.0

Constituents	TUBEWELL NUMBERS 14	10	11	1	2	15
SAR	0.45	1.01	0.39	0.28	0.33	0.85
Electrical conductivity. ($EC \times 10^6$)	390.6	304.14	693.0	472.5	533.5	315.0

TABLE 6.9 SODIUM ADSORPTION RATIO (SAR) AND ELECTRICAL CONDUCTIVITY FOR WATER SAMPLES JUNE - 1965

Constituents	TUBEWELL NUMBERS						
	10	53	43	48	59	30	22
SAR	0.083	1.16	0.8	0.4	0.01	0.006	0.003
Electrical Conductivity, ($EC \times 10^6$)	359.10	409.50	729.99	811.3	486.6	415.80	396.90

Constituents	TUBEWELL NUMBERS						
	21	13	29	22	10	26	38
SAR	0.005	0.262	0.278=	0.03	0.066	0.01	0.002
Electrical conductivity. ($EC \times 10^6$)	459.90	441.0	422.10	693.0	756.0	604.8	756.0

Constituents	TUBEWELL NUMBERS						
	2	D-1	D-3	63	23	52	19
SAR	0.004	0.008	0.019	0.40	0.003	0.315	0.766
Electrical Conductivity. ($EC \times 10^6$)	693.0	541.8	415.8	189.0	428.4	384.3	567.0

Constituents	TUBEWELL NUMBERS						
	1	8	9	12	16	24	31
SAR	0.042	0.047	0.055	0.106	0.057	0.05	0.90
Electrical conductivity. ($EC \times 10^6$)	634.7	662.9	608.2	608.2	584.0	340-2	270.9

(Table 6.9 Contd.)

Constituents	TUBEWELL NUMBERS							
	42	29	14	9	20	13	29	D-6
SAR	0.27	0.37	0.014	0.008	0.004	0.12	0.315	0.50
Electrical conductivity. ($EC \times 10^6$)	567.0	453.6	440.0	403.2	258.3	352.8	384.3	409.5

CONCLUSIONS

1. The chemical analysis of water samples from dug wells and from deeper tubewells has shown that these waters are of somewhat different chemical quality. The waters in the shallow aquifers are comparatively rich in sulphate while those from confined aquifers are rich in bicarbonate. This difference has again indicated that the shallow and the deep aquifers in this area are not hydraulically interconnected.

2. There are some seasonal differences in the chemical character of waters from deeper aquifers. In October the water is relatively righ in Sodium, Potassium and Bicarbonate while in June it gets rich in Magnessium. Such a difference in the quality of water can be explained by either the effect of leaching of alkaline soils during the recharge or by cation exchange.

3. The water from deeper aquifers can be classified as "Secondary alkaline" water according to Palmer's classification (Palmer 55). It can also be classified as 'Primary' water according to Durov's classification and therefore is regarded to be of meteoric origin.

According to Piper's classification it is characterised by the predominance of alkaline earths and weak acids.

4. The study of the variation in the quality of water by the help of ratio maps has indicated that the rSO_4 /rCl and rMg /rCa ratios decrease from north to sourth which is also the

direction of groundwater flow. Such a variation can be explained by the greater solubility of Cl and Ca in water.

5. The water from deeper aquifers is found suitable for irrigational purposes as has been concluded by the study of electrical conductivity, SAR and percent sodium values.

6. Although it has been shown from pump test data in chapter 4 that minor amount of leakage from shallow aquifer to the deeper confined aquifer takes place during pumping, however, no appreciable difference in the chemical quality of water with pumping from deeper aquifers was observed.

CHAPTER 7

QUANTITATIVE ASSESSMENT OF GROUND WATER

Introduction

Water is a renewable resource. In this respect it is like soil and plant and animal life. Rain periodically replanishes the natural supply of water on the earth's surface and in the subsurface formations which are tapped by wells and springs. This natural supply of water, like that of other renewable resources, is usually limited in time and space. In recent years, the use from this limited source, about which we know very little has grown enormously. This lack of knowledge has hampered its effective development as well as its use and conservation.

The imperative need in ground water development, past and future, is to know what we are doing. This knowledge comes from probing into the methods by which nature puts water into the ground and takes it out again, as well as the changes that man makes by his activities.

The ultimate goal of quantitative hydrologic assessment is to determine addition of water to the ground water reservoir of the area under investigation from all sources (ground water increment) and discharge of every kind from the ground water body (ground water decrement). The balancing of the one against the other is known as the ground water inventory. The general equation of hydrologic equilibrium provides a quantitative statement of this balance.

The aim of such investigations will be (a) to determine the amount of recharge and its fluctuations (b) to determine the amount of storage in the aquifers (c) to determine the rate of present ground water withdrawal and its effect on the available supply, (d) to determine the amount of natural drainage and (e) to estimate the amount of salvage from such inflows and out-flows for optimum development of the ground water basin.

Precise establishment of such relationships is very time consuming and more so for ground water basins which have been put to use by way of development for short period. The main aim in the present study is to formulate a basis for evaluating quantitatively such relationships. From the observations of shallow wells in the area it is concluded that the dug-wells are constructed only down to a maximum depth of 80 ft. (24.4 metres) below ground surface and draw water from the water bearing sand horizons encountered within this depth only. From the sub-surface correlation charts it has been observed that in this region the clay beds separating the shallow aquifers with that of the deeper aquifers below 100 ft. depth(30.5 metres) are of considerable thickness. As mentioned earlier in Chapter 4 the deeper aquifers are under semi-confined or leaky confined conditions and as such it will be reasonable to believe that the effect of rainfall and subsurface drainage to the rivers are more effective on the shallow ground water reservoir rather than on deeper aquifers. With this in view it would be reasonable to deal ground water assessment in the present area under the two broad heads viz: (i) shallow ground water reservoir and (ii) of semi-confined ground water reservoir. The shallow ground water reservoir is defined as a group of aquifers met above the first effective and well defined aquiclude in the depth zone between 80-100 ft. (24.4 - 30.5 metres). The quantitative estimates have been made for the years 1962 and 1965. Such a study involves, an accurate quantitative analysis of the ground water storage based on the ground water equation.

Previous work

Earlier attempts on the quantitative ground water studies in Gangetic alluvium dates back to the early thirties when Mackenzie-Taylor[3] initiated such studies before starting the Ganges valley state-tubewell scheme. These investigations were again revived in the year 1957 when the Research Committee of the Central Board of Irrigation and Power accepted the necessity of undertaking systematic observations of water table conditions in the country. Earlier attempts in this direction were made by Dwivedi and Gupta[11] and Daya Prakash et al[12]. Similar studies have also been attempted in parts of Aligarh, Etah and Bulandshahar by Raghava Rao et al[61] and in parts of Saharanpur district in western Uttar Pradesh by Raghava Rao[14].

For the area under description there has been no attempt in the past to carry out such studies.

COLLECTION OF DATA

Rainfall data for more than 30 rain-gauge stations of Meerut and Muzaffarnagar region for the years 1958 to 1965 were collected from the various departments. Estimates of pumpage hour were available for each state tubewell for the entire period of study from the various Tubewell divisions of the Irrigation Department. Water levels (for May and October) in the open wells were partly measured and partly collected from the Irrigation Divisions. Information regarding the discharges of rivers were also made available by the various Irrigation Divisions.

GROUND WATER STORAGE IN THE SHALLOW RESERVOIR

A study of the various lithological charts indicates that the average thickness of the clay bed within 100 feet (30.5 metres) depth of shallow aquifers works out to be approximately 35 ft. (10.70 metres). Therefore the thickness of the group of aquifers in the shallow reservoir is approximately 45 feet (13.71 metres) whereas the average water level in the shallow aquifers is about 20 feet (6.09 metres). Hence the average saturated thickness of aquifer will be (45-20 ft = 25 ft. i.e. 7.62 metres)

∴ The area under study is = 2838 sq.miles
Volume of the saturated aquifer
= 2838 x 640 x 25 Acre ft.
= 45408,000 Acre ft.
= 45408 thousand Acres ft.

Bhattacharya et al[62] has inferred that, on an average, the specific yield of the alluvial aquifer in this part of Gangetic Valley is 17 %.

Hence

Ground water storage $= \frac{45408}{100} \times 17$

= 7719.36

= say 7719 thousand acre ft.

Leaving 50% of the ground water storage as permanent reserve and other contingencies for drought seasons

Ground water storage available for use	=	3859.8
or say	=	3860 thousand acre ft.

An accurate method for the determination of ground water balance depends on the general hydrological equation (Wisler and Brater[63]) which may be written as:

$$F + R_S + R_U + R_L + R_W = E + D_S + D_U + D_L + D_W \pm S \quad .. (7.1)$$

where F = recharge from infiltration

R_S = recharge from surface bodies of water

R_U = recharge from lateral underflow

R_L = recharge by leakage through an aquiclude

R_W = recharge by wells, trenches, or other infiltration devices

and

E = discharge by evapo-transpiration

D_S = discharge to surface bodies of water

D_U = discharge by lateral underflow

D_L = discharge by leakage through an aquiclude

D_W = discharge by wells

$\pm \Delta S$ = increase or decrease in storage volume

Each of the above mentioned factors have been evaluated separately as below, before they could be balanced out to give the value of ΔS.

Recharge from Infiltration F

The precipitation reaching ground surface becomes either surface run off or infiltration accordingly as rain intensity exceeds or falls short of infiltration capacity. The latter term, infiltration capacity, is defined as the maximum rate at which a soil in any given condition is capable of absorbing water. Bhattacharya et al[5] on the basis of study from the western districts of Ganga-Yamuna Doab have given the following empirical formula for computing the rainfall penetration:

$$R_p = 1.35 \ (R - 14)^{\frac{1}{2}} \qquad \text{.. .. .. (7.2)}$$

where R_p = Rainfall penetration, in inches.

R = Annual Rainfall in inches.

Therefore the total amount of rain water infiltered into the area is $\frac{R_p}{12}$ A x 640 sq acres ft. .. .. .. (7.3)

Where A is the area in sq.miles.

However, part of this water will be lost through evapotranspiration and subsurface drainage. Such losses are considered as 50% of the total rainfall infiltration.

Rainfall infiltration figures for the period under study i.e. (1958-65) as computed from equations (7.2) and &(7.3) have been tabulated in Table (7.1)

Table 7.1 RAINFALL INFILTRATION FIGURES FOR MUZAFFARNAGAR AND MEERUT AREA

Year	Rainfall (inches)	R_p (inches)	Amount of rainfall infiltration (Acre ft/yr)	Recharge due to Rain fall infiltration after deducting 50% as evapotranspiration and subsurface flow. (Acre feet/yr.)
1958	28.50	5.14	777384.96	388692.48
1960	32.40	5.79	868200.96	434100.48
1962	28.80	5.19	785538.40	392779.20
1964	26.80	4.83	731068.80	365534.40
1965	23.10	4.07	616089.74	308044.87
	Average		755660	377830

The amount of recharge to ground water varies from year to year which depends on the annual precipitation and as such an average value has been incorporated while compiling the ground water balance.

Recharge from Surface Bodies of Water - R_S

This includes (a) recharge from such bodies of water as reservoirs, lakes, ponds, irrigation channels and irrigation areas and (b) recharge from bounding rivers. However the class (a) has been dealt under the factor R_W, and the class (b) alone under the factor R_S .

The main drainage courses in the area are of effluent nature and as such the amount of influent drainage is taken as negligible.

Recharge from Lateral Under Flow - R_U

The water table contour map for the shallow aquifer (Plate 3.1 to 3.8) depicts a hydraulic gradient of about 3.0 ft. per mile in the northern and southern regions.

As mentioned earlier the saturated thickness of the shallow aquifer within 80 ft. thickness of the alluvium is 25 ft. in the northern part of the area. The average permeability of the shallow aquifer can be taken to be the same as that of the deeper aquifer because the grain size parameters of the two are more or less the same. Therefore, for computational purposes the permeability of the shallow aquifer is taken to be 800 gallons per day per sq. ft.

$$\therefore T = 800 \times 25 = 20{,}000 \text{ gpd/ft.}$$

The inflow to the area = T i L

Where T = Transmissibility of shallow aquifer

i = Hydraulic gradient

L = width of the cross section through which ground water enters the area i.e. about 55 miles.

$\therefore R_U$ = 20000 x 55 x 3 gallons/day

= 3300000 gallons/day

= 3697.82 Acre ft./ year

= or say 3700 Acre ft/year

Recharge by Leakage - R_L

The water level in the dug-wells which tap the shallow aquifer is usually the same as in the deeper confined aquifers. Therefore there will be no recharge of the shallow aquifer due to the upward leakage from the confined aquifers.

Recharge by Wells Trenches or Other Infiltration Devices - R_W

Under this factor direct feed to ground water reservoir from lakes, ponds trenches, irrigation channels and irrigated areas have been accounted for. There are three major canals passing through the area namely Ganga Canal, Lower Eastern Yamuna Canal and Anupshahar Branch. Mathur[64] has shown that influent seepage from these canals is insignificant and as such this assumption holds good for the present area of study also. The total infiltration F is computed as

$$F = f\ A.\ t.$$

where f is the infiltration capacity, A is the area under these surface bodies of water and t is the duration for for which water stands over the area A. Thus R_W is given by

$$R_W = F = f. A. T.$$

Irrigated areas do not materially add anything to the ground water reservoir as the water mostly evaporates or is consumed in replenishing soil moisture defficiency.

Discharge by Evapotranspiration - E

All water losses are classified as

1. Interception
2. Evapotation from water surfaces.
3. Plant transpiration
4. Soil or land evaporation and
5. Water shed leakage.

As it is difficult to determine these loses accurately, they are taken to be 50% of the total recharge by infiltration.

Discharge to Surface Bodies of Water - D_S

Here are included losses to surface water bodies e.g. rivers etc. There are many drainage courses in the area such as the Yamuna, the Ganga, the Hindon, the Krishni and the Kali Nadi (East and West). Their effluent character in the area has been established by the study of water table maps (Plates 3.1 to 3.8) and the profiles accross the river courses. The profiles are also used to determine the amount of hydraulic gradient (Table 7.2). The water level data have been given in ft. above M.S.L.

Table 7.2 DATA OF GROUND WATER GRADIENT ALONG THE VARIOUS CROSS SECTIONS

Yamuna River

Section 1

Covers well No. 12 and 11

Distance between well No. 12 and 11 = 2.80 miles

Year	Water level in well No. 12	Water level in well No. 11	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
	May				
1958	740.67	761.50	20.83	(+)20.83	(+) 7.44
1962	750.00	770.00	20.00		
1965	751.80	773.46	21.66		
	October				
1958	749.67	766.05	16.38	(+)12.92	(+) 4.61
1962	760.31	770.05	9.74		
1965	761.66	774.30	12.64		

Section 2

Covers well No. 9 and 8

Distance between Well No. 9 and 8 = 1.00 mile

Year	Water level in well No. 9	Water level in well No. 8	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
	May				
1958	707.19	714.16	6.97	(+)10.82	(+)10.82
1962	701.77	716.92	15.15		
1965	702.07	712.42	10.35		
	October				
1958	703.32	719.17	15.85	(+)17.30	(+)17.30
1962	700.27	717.82	17.55		
1965	700.02	718.52	18.50		

Average hydraulic gradient = (+) 10.04 ft/mile

Ganga River

Section 1

Covers well No. 10 and 9

Distance between 10 and 9 = 3.60 miles.

Year	Water level in well No.10	Water level in well No.9	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
			May		
1958	751.05	778.34	27.29	(+) 27.46	(+) 7.63
1962	745.33	772.34	27.01		
1965	748.20	736.30	28.10		
			October		
1958	756.33	782.84	26.51	(+) 26.27	(+) 7.30
1962	747.33	772.84	25.51		
1965	748.53	775.33	26.80		

Section 2

Covers well No. 21/16 and 19/12

Distance between well No.21/16 & 19/12 = 2.08 miles.

Year	Water level in well No.21/16	Water level in well No.19/12	Difference inf water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile.
			May		
1958	642.12	686.18	44.06	(+) 44.19	(+) 21.24
1962	648.22	687.33	39.11		
1965	647.60	685.00	37.40		
			October		
1958	649.72	691.48	41.76	(+) 39.09	(+) 18.79
1962	649.22	687.33	38.21		
1965	646.80	684.10	37.30		

Average hydraulic gradient = (+) 13.74 ft/mile

Krishni River

Section 1

Covers well No. 4 and 5

Distance between well No. 4 and 5 = 1.6 miles

Year	Water level in well No.4	Water level in well No.5	Difference in water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft/mile
	May				
1958	779.40	772.75	(+) 6.65	(+) 6.03	(+) 3.77
1962	776.22	770.91	(+) 5.31		
1965	776.32	770.20	(+) 6.12		
	October				
1958	782.69	786.62	3.93	(+) 5.22	(+) 3.26
1962	773.81	776.13	2.32		
1965	770.61	780.03	9.42		

Section 2

Covers well No. 4 and 1

Distance between well No. 4 and 1 = 1.6 miles

Year	Water level in well No.4	Water level in well No.1	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
	May				
1958	752.65	771.28	18.61	(+) 18.76	(+) 11.72
1962	751.42	770.20	18.78		
1965	751.54	770.44	18.90		
	October				
1958	758.85	-	-	(+) 3.82	(+) 2.38
1962	774.21	778.03	3.82		
1965	773.21	777.03	3.82		

Section 3

Covers well No. 7 and 1

Distance between well No. 7 and 1 = 1.6 miles

Year	Water level in well No.7	Water level in well No.1	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile.
			May		
1958	718.56	723.50	4.94		
1962	718.06	720.83	2.77	(+) 2.98	(+) 1.86
1965	718.75	720.00	1.25		
			October		
1958	720.81	725.92	5.11		
1962	719.96	724.34	4.38	(+) 4.74	(+) 2.96
1965	720.00	724.74	4.74		

Average hydraulic gradient = 4.33 ft./mile

Hindon River

Section 1

Covers well No. 2 and 3

Distance between well No. 2 and 3 = 1.6 miles.

Year	Water level in well No.2	Water level in well No.3	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
			May		
1958	789.59	812.02	22.43		
1962	812.87	814.02	1.15	(+) 8.22	(+) 5.14
1965	812.51	813.61	1.10		
			October		
1958	813.10	815.34	2.24		
1962	-	-	-	(+) 2.07	(+) 1.29
1965	815.91	817.81	1.90		

Section 2

Covers well No. 1 and 2

Distance between well Nol 1 and 2 = 1.6 miles

Year	Water level in well No. 1	Water level in well No. 2	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile.
			May		
1958	706.72	719.22	12.50		
1962	705.14	718.00	12.86	(+) 12.35	(+) 7.72
1965	706.10	717.80	11.70		
			October		
1958	714.18	723.18	9.00		
1962	706.72	718.72	12.00	(+)11.06	(+) 6.91
1965	707.72	719.92	12.20		

Section 3

Covers well No. 5 and 1

Distance between well No. 5 and 1 = 1.00 miles.

Year	Water level in well No.5	Water level in well No. 1	Difference in water level in ft.	Average difference in water level in ft.	Average hydraulic gradient in ft./mile
			May		
1958	692.03	693.28	1.25		
1962	691.90	693.65	1.75	(+) 2.16	(+) 2.16
1965	690.24	693.72	3.48		
			October		
1958	696.10	695.97	0. 13		
1962	697.65	694.72	2.93	(+) 1.53	(+) 1.53
1965	697.00	695.47	1.53		

Average hydraulic gradient = 4.13 ft. /mile

Kali River West

Section 1

Covers well No. 3 and 4

Distance between well No. 3 and 4 = 1.6 miles.

Year	Water level in well No. 3	Water level in well No. 4	Difference of water level in ft.	Average diff. in water level in ft.	Average Hydraulic gradient in ft-/mile.
		May			
1958	788.30	798.00	9.70		
1962	789.09	792.81	3.72	(+) 4.96	(+) 3.10
1965	790.34	791.81	1.47		
		October			
1958	790.59	800.71	10.12		
1962	789.09	797.81	8.72	(+)7.25	(+) 4.53
1965	789.54	792.46	2.92		

Section 2

Covers well No. 3 and 4

Distance between well No. 3 and 4 = 2.20 miles.

Year	Water level In well No. 3	Water level in Well No. 4	Difference of water level in ft.	Average diff. in water level in ft.	Average hydraulic gradient in ft./mile.
		May			
1958	725.02	750.35	25.33		
1962	724.52	761-20	36.68	(+)33.00	(+)15.00
1965	723.93	760.94	37.01		
		October			
1958	724.52	762.19	37.67		
1962	725.56	761.00	35.44	(+)36.43	(+)16.51
1965	725.00	761.19	36.19		

Average hydraulic gradient = 9.79 ft/mile.

Kali Nadi East

Section 1

Covers well No. 13 and 7

Distance between well No. 13 and 7 = 0.8 miles

Year	Water level in well No.13	Water level in well No.7	Difference of water level in ft.	Average difference in water level in ft.	Average hydraulic gradinnt in ft/mile
	May				
1958	708.20	713.00	4.80		
1962	708.87	713.62	4.75	(+) 4.65	(+) 5.81
1965	712.00	716.40	4.40		
	October				
1968	714.10	719.81	5.71		
1962	713.81	717.20	3.39	(+) 5.03	(+) 6.29
1965	716.24	722.24	6.00		

Section 2

Covers well No. 1 and 2

Distance between well No. 1 and 2 = 0.60 miles.

Year	Water level in well No. 1	Water level in well No.2	Difference of water level in ft.	Average difference in water levdl in ft.	Average hydraulic gradient in ft./mile.
	May				
1958	720.83	724.20	3.37		
1962	716.91	720.91	4.00	(+) 3.81	(+) 6.35
1965	716.42	720.50	4.08		
	October				
1958	728.08	734.45	6.37		
1962	725.74	727.52	1.78	(+) 4.74	(+)7.9
1965	724.75	730.81	6.06		

Average hydraulic gradient = 6.58 ft./mile

Taking into account that the thickness of the strata through which percolation takes place is 20 ft. and the average permeability of the formations is 800 gpd/ft.^{2}, the amount of effluent drainage works out to be as given in Table (7.3).

Table 7.3 STATEMENT OF EFFLUENT DRAINAGE DUE TO NATURAL HYDRAULIC GRADIENT IN MUZAFFARNAGAR AND MEERUT AREA

Name of the River	Length of the River in Miles.	Coefficient of transmissibility T = Pf x m = gpd/ft.	Average hydraulic gradient ft./miles.	Effluent drainage (L T I)in gpd.
1. Yamuna River	60	16,000	10.04	96,38,400
2. Ganga River	68	16,000	13.74	1,49,49,120
3. Hindon River	64	16,000	4.13	42,29,120 x 2
4. Krishni River	48	16,000	4.33	33,23,440 x 2
5. Kali River(West)	44	16,000	9.79	68,92,160 x 2
6. Kali River(East)	36	16,000	6.58	37,87,200 x 2

Total Effluent drainage due to natural hydraulic gradient. = 6,10,55,360 Gal/day

=22,28,52,06,400 Gal/year

= 68,411 Acre ft/yr.

Note: As the Rivers Hindon, Krishni, Kali (West) and Kali(East) flow through the central parts of the area, effluent drainage to these rivers has been taken to be twice. =

Discharge by Lateral Under Flow - D_U

From the water table map for the shallow aquifer (Plate 3.1 to 3.8) it is inferred that the hydraulic gradient on an average is about 32 feet per mile in the north to about 2.8 feet per mile in the South. The saturated part of the aquifer material within 80 feet thickness of the alluvium in the southern portion of the area is of the order of 45 feet. The average permeability is 800 gpd/ft.^{2}

The out flow from the area due to continuous ground water movement will be equal to the product of transmissibility, hydraulic gradient, and the width of the cross section through which flow takes place.

Hence

$$D_U = T\ I\ L$$

where T = transmissibility , 36,000 gpd/ft.

I = hydraulic gradient 3 ft./mile.

L = width of cross section through which flow take place i.e. 55 miles.

= 36,000 x 3 x 55 gallons/day.

= 2,16,81,00,000 gallons/year

= 6656.067 Acre ft/year

= 6660 Acre ft./year.

Discharge by Leakage Through the Aquiclude (AQUITARD) - D_L

In the present area for the shallow aquifers the leakage can be calculated by the following formula given by Hantush[65].

$$Q \frac{T}{B^2} \quad A \Delta h$$

Where

Q = amount of leakage through a vertical column of the semiconfining bed of area A

$\frac{T}{B^2}$ = Leakance

Δh = the difference between the water levels in the confined and shallow aquifer in the area.

On the basis of the actual pump-test the average leakance for the area works out to be 1.66×10^{-6} Acre ft/day, while the value of Δh been computed by substracting the altitude of the water levels in the shallow aquifer from the altitudes of the water levels in the semi-confined aquifer which is approximately 2 feet. Therefore, the loss due to leakage is equal to

$\frac{T}{B^2}$ = 1.66×10^{-6} Acre ft./day.

A = 2838 sq.miles

Δh = 2 ft.

Q = $1.66 \times 10^{-6} \times 2838 \times 640 \times 2$ Acre ft/day

= 6.03 acre ft./day

= 2200.95 Acre ft/year

Discharge by Open Wells - D_W

There are many open wells which have not been put to full use as was noticed from the various transverses taken in the area. However, on the basis of data taken from various agencies such as Revenue records, Irrigation records and others, the draft by means of open wells may safely be taken as 60,000 Acre ft.

BALANCE SHEET OF SHALLOW GROUND WATER RESERVOIR
FOR THE YEAR 1965.

1.	Recharge from infiltration	:	6,16,100 Acre ft.
2.	Recharge from surface bodies of water.	:	Nil
3.	Recharge from lateral underflow	:	3,700 Acre ft.
4.	Recharge by leakage through aquiclude.	:	Nil
5.	Recharge by wells trenches and other infiltration devices.	:	Nil
6.	Total Recharge for the shallow ground water reservoir (1+2+3+4+5)	:	6,19,800 Acre ft.
7.	Discharge by evapotranspiration	:	3,77,830 Acre ft.
8.	Discharge to surface bodies of water.	:	68,411 Acre ft.
9.	Discharge by lateral underflow	:	6,660 Acre ft.
10.	Discharge by leakage through aquiclude	:	2,000 Acre ft.
11.	Discharge by open-wells	:	60,000 Acre ft.
12.	Total discharge from the area in the shallow ground water reservoir (7+8+9+10+11)	:	4,45,321 Acre ft.
13.	Ground water balance i.e. increment. (6 - 12)	:	1,74,479 Acre ft.

After the balance of ground water equation it is inferred that the net increase in the shallow groundwater reservoir is

1,74,479 Acre. Ft. which can be further utilized for various irrigation and allied purposes without depleting the permanent ground water storage which is calculated as 3,860,000 Acre ft.

Computations on similar lines have been made for the year 1958 and 1962 and the results are given in Table 7.4 and 7.5 .

Table 7.4 NET CHANGE IN THE GROUND WATER STORAGE OF THE SHALLOW GROUND WATER RESERVOIR FOR THE INVESTIGATED AREA
1958

Sl. No.	R (Recharging factors)	Depth in inches	D(Discharging factors)	Depth in inches
1.	Recharge from Infiltration ..	22.64	Discharge by .. evapotranspiration	1400
2.	Recharge from surface bodies of waters ..	Nil	Discharge to .. surface bodies of water.	0.28
3.	Recharge from lateral under flow. ..	0.03	Discharge by .. lateral underflow.	0.027
4.	Recharge by leakage through an aquiclude. ..	Nil	Discharge by .. leakage through an aquiclude.	0.012
5.	Recharge by wells and trenches. ..	Nil	Discharge by well trenches.	3.20
	Total:	22.67		17.519

Net change in shallow ground water storage in the area for the year 1958 .. = 22.67 - 17.519

= 5.151 inches.

TABLE 7.5 SHOWING NET CHANGE IN GROUND WATER STORAGE IN SHALLOW GROUND WATER RESERVOIR IN THE AREA FOR THE YEAR 1 9 6 2.

S.No.	R(Recharging factor)	Amount inches depth.	D(Discharging factor)	Amount inches depth.
1.	Recharge from infiltration:	25.47	Discharge by evapotranspiration	15.20
2.	Recharge from surface bodies of waters.	Nil	Discharge from surface bodies of water	0.26
3.	Recharge from lateral underflow.	0.18	Discharge from lateral underflow	0.16
4.	Recharge by leakage through aquiclude.	nil	Discharge by leakage through aquiclude	0.02
5.	Recharge by wells and trenches.	nil	Discharge by wells	3.40
	Total:	25.65		19.04

Net change in shallow groundwater storage in the area for the year 1962.

= 25.65 - 19.04

= 6.61 inches depth of water.

CONFINED GROUND WATER RESERVOIR

There are many difficulties in preparing a ground water budget for the confined group of aquifers in this region which is due to the complex geohydrological conditions. The recharge which takes place due to rainfall is difficult to assess as the recharge area is not well demarcated. However, it has been shown earlier in this chapter that approximate recharge due to leakage from the overlying water table aquifer is of the order of 2,000 acre feet per year.

In the following paragraphs an attempt has been made to find out the total draft due to pumpage from the deeper aquifers and the fluctuations of the observed water levels in wells which tap these aquifers.

(i). Draft due to Pumpage through Tubewells.

The total amount of withdrawal of ground water from the area by means of tubewells was calculated by summing up the total discharge figures after multiplying with their running hours for each year. The total draft due to pumpage from 1958-59 to 1964-65 is given in Table 7.6.

Table 7.6 TOTAL ANNUAL DRAFT FROM TUBEWELLS IN THE AREA UNDER STUDY

Year	No. of tubewells commissioned.	Annual draft in Acre ft.
1958-59	462	137102
1959-60	469	191463
1960-61	482	150913
1961-62	495	127293
1962-63	545	188430
1963-64	600	199550
1964-65	643	203991

The draft for the year 1964-65 for state tubewells works out to be of the order of 2,04,000 Acre ft. Taking an assumption of 1,000 private tubewells in the present area of study the total draft due to pumpage can safely be taken as 4,00,000 Acre ft/year.

(ii). Changes in the Piezometric Head.

According to the piezometric observations in the tubewells of the Muzaffarnagar District it has been determined that for the year 1964-65, at an average, there is a rise of 1.5 ft (Table 7.7).

However, for parts of Meerut District which are also included in the present work, for the same period i.e. 1964-65, it has been determined, according to piezometric observations, that there is a net decline of 2.31 ft in the piezometric surface.

From the above it can be concluded that more tubewells can be constructed in the Muzaffarnagar area while in the Meerut area additional tubewells would further lower the piezometric surface.

Table 7.7 PIEZOMETRIC OBSERVATIONS IN MUZZAFARNAGAR DISTRICT.

Sl.No.	Tubewell Nos.	Water level above mean sea level in ft. for the state tubewells. Summers (1965)	Winters (1964.)	Rise or fall
1.	10 South Loi	41	38	+ 3
2.	16 "	39	38	+ 1
3.	18 "	46	42	+ 4
4.	25 "	37	36	+ 1
5.	27 "	35	34	+ 1
6.	30 "	40	38	+ 2
7.	32 "	40	38	+ 2
8.	10 Kairana	35	34	+ 1
9.	11 "	22	24.5	- 2.5
10.	14 "	24	24	00
11.	21 "	19	18	+ 1
12.	26 "	23	23	00
13.	27 "	21	20	+ 1
14.	28 "	23	20	+ 3
15.	31 "	20	22	- 2
16.	5 "	26	24	+ 2
17.	2 North Loi	39	38	+ 1
18.	4 "	25	23	+ 2
19.	5 "	32	30	+ 2
20.	6 "	33	32	+ 1
21.	12 A "	33.0	35	- 2
22.	14 "	29	28	+ 1
23.	17 Kairana	25	20	+ 5
24.	14 A North Loi	30	25	+ 5
25.	15 "	26	25	+ 1
26.	27 "	32	28	+ 4
27.	29 "	25	25	00
28.	31 "	27	22	+ 5

Net change 42.5 ft.

Therefore average rise = 1.5 ft.

CONCLUSIONS

An attempt has been made in this Chapter to assess quantitatively the ground water potential in an area of about 2,838 sq.miles in shallow as well as in deep confined aquifers.

ii). The net ground water storage for the shallow aquifers comes out to be 38,60,000 Acre feet. This excess of ground water for the reservoir indicate an excess water source of the order of 1,74,479 Acre ft. due to recharge. This potential could be further utilised.

iii). The ground water budget for the confined aquifers could not be prepared due to complex geohydrological conditions. However, the fluctuations in the piezometric surface has shown the possibilities of further ground water development in Muzaffarnagar area.

CHAPTER 8

SUMMARY

Systematic studies of the ground water conditions in the Indo-Gangetic alluvium covering approximately 7265 sq.km. in Muzaffarnagar and parts of Meerut districts were started by the author in the month of August 1964. The importance of such investigations were felt when the author was associated with the U.P. Irrigation Research Institute, Roorkee.

In Chapter 1 of the thesis a review of the previous work carried out by several workers has been given. It may be worth mentioning at this place that although large scale tubewell irrigation is practised in this part of the country since long, no systematic hydrogeological studies were carried out by the earlier workers.

In Chapter 2 an attempt has been made to describe the geomorphology and the geology of the area. The area under description represents parts of Ganga-Yamuna Doab. It is also drained by a number of other rivers all of which are of perennial character. The drainage characteristics of the area in terms of quantitative parameters i.e. drainage density and bifurcation ratio have been given. The computed drainage density comes to be 0.77 miles/sq.miles which is indicative of high permeability of the surface formations. The changes in the courses of the

river Ganga and Yamuna, as evidenced by the presence of ox-bow lakes and point bars, have also been described. The ground surface is more or less flat with a gentle slope of 1 to 2 ft. per mile from north to south.

Geologically the area is comprised of alluvial formations i.e. gravel, sand, clay and kankar. The complete thickness of the alluvial fill is not known but it may be of the order of 7000-8000 ft. or even more. In the present work, however, an attempt has been made to describe the geology of the area upto a depth of 300 to 350 ft. as has been observed from the lithological logs. In alluvial formations the various lithological units, usually, do not extend laterally to long distances. The various formations may show interfingering or lensoid characters. The sand samples from various horizons within the depth range of 115-350 ft. were subjected to mechanical analysis and the various grain size parameters have been determined i.e. Median, Sorting Coefficient, Effective size and Uniformity Coefficient. It has been observed that the sands which form the aquifers are well sorted and the grain size decreases from north to south. In order to determine the sedimentation conditions CM pattern was also drawn and it is concluded that most of the sand was deposited by the activity of tractive currents.

In Chapter 3 ground water conditions of the area have been described. Broadly speaking two types of aquifers have been delineated i.e. the shallow aquifer (with depth range of 80 ft.) and deeper aquifers (100-350 ft.). The second hydraulic unit (Deeper aquifers) is not composed of one single aquifer but of a number of aquifers interconnected with each other. The above two hydraulic units are separated by a thick clay layers intermixed with silt and Kankar which behaves as an aquitard. The shallow aquifer is under water table conditions while the deeper aquifers have been identified as of leaky confined character.

Periodic measurements of depth to water level in shallow wells which tap the shallow aquifers and the tubewells which tap the deeper aquifers were carried out. This was necessary in order to establish the ground water movement in the two hydraulic units and also to depict seasonal fluctuations of water level. It is inferred that the main source of recharge for the aquifers is the rainfall.

In Chapter 4, hydraulic characteristics, of the aquifers i.e. Coefficient of Transmissibility and Coefficient of Storage, as determined by the pump tests, have been given. It was quite interesting to find that the conventional Theis-nonequilibrium method could not be applied as such under the hydrogeological conditions which exists in this part of the country. In this chapter a thorough analysis of the aquifer characteristics have been made based on recent development in ground water hydrology and it has been concluded that in all probability the deeper aquifers of the area represent leaky confined character. In establishing this the vertical permeability and the leakance of aquitard have also been determined. There are of course still some querries which have to be answered.one of these is the effect of vertical draining of the aquifers. It is worth suggesting that in alluvial areas, in general, it is necessary to have a number of observation holes tapping different horizons in order to determine the interconnections between different aquifers. The author feels that this will be a correct approach to distinguish between the water table conditions and leaky conditions in such regions.

In Chapter 5 some of the important statistical correlation methods have been utilised to describe the ground water regime of the area. Use has been made of the methods suggested by Altovsky, Jacob and others.

These analyses were necessary to determine the basic factors which influence the ground water conditions in the present area. In order to do this rainfall and ground water level data from the year 1961-1965 have been used and the correlation coefficients by the Linear Correlation Method between the various variables have been determined. Jacobs' method has been utilised to determine the amount of accretion to the ground water reservoir by rainfall. In doing so rainfall data from 1918 to 1965 have been taken into consideration and it has been concluded that the rainfall penetration is 21.5 %.

In Chapter 6 chemical characteristics of the ground water have been described both form the shallow aquifers and also from the deeper aquifers. However, a greater emphasis has been laid on the chemical characteristics of ground water from the deeper aquifers as this horison is tapped by all the tubewells and is most developed. The water has been classified as of calcium bi-carbonate type which is suitable for irrigational and domestic purposes. Variation in the chemical quality of water in the direction of flow has been indicated by preparing r SO_4/r Cl and r Mg/r Ca ratio Maps.

In Chapter 7 quantitative ground water assessment has been made. The aim of such studies is to determine the total quantity of ground water which can be put to use without depleting the ground water reservoir permanently. Ground water assessment of the shallow aquifer and the deeper aquifers have been made separately by determining the various factors of the general ground water equation. Quantititive assessment of the shallow aquifers have been made for the year 1958, 1962 and 1965. From this analysis it has been concluded that for the year 1965 there was an additional amount of 174479 acre ft. of water which could have been further utilised without depleting the permanent storage of the shallow ground water reservoir which is 3860000 acre ft.

Due to complex geohydrological conditions, ground water budget for the deeper aquifers could not be finalised. However possibilities of further ground water development in Muzaffarnagar area have been indicated.

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ANALYSIS OF PUMPING TEST DATA FROM A WELL IN THE INDO-GANGETIC ALLUVIUM OF INDIA AND ITS BEARING ON THE AQUIFER CHARACTERISTICS

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Abstract: Draw-down data collected during a pumping test on a well in the Indo-Gangetic alluvium of India are subjected to detailed analysis in order to determine the hydrologic properties of the aquifer and the aquiclude. The coefficient of transmissibility T and the coefficient of storage S were determined by assuming that the aquifer fulfils all the assumptions for the application of the Theis and Theis-Jacob non-steady state methods, but it was found that the values of T and S did not remain constant with the time of pumping. This result led to the conclusion that there were deviations from the conditions which are assumed in the derivation and application of the Theis non-equilibrium equation. By taking into consideration the various possibilities it was concluded that the aquifer behaved as a leaky confined aquifer.

1. Previous work on the geology and hydrology of the area

The well investigated is situated within the Indo-Gangetic alluvium, which forms a wide tract extending in an E–W direction south of the Himalayas (Fig. 1). Thickness of the alluvium is variable, with a maximum exceeding 8 000 or even 9 000 ft. The Indo-Gangetic plain is divided into three roughly parallel belts which are known from north to south as the Bhabar, Tarai and Axial Belts (Taylor[1]). The well tested lies in the district of Muzaffarnagar, Uttar Pradesh, within the Axial Belt and between the two well-known rivers of India i.e. the Ganges and the Yamuna.

Some earlier investigations have been carried out on the ground-water conditions of the Indo-Gangetic plains. B. D. Pathak[2]) has described the ground-water conditions in the alluvium and he is of the opinion that shallow aquifers are under water-table conditions while the deeper aquifers are under confined conditions. Mehta and Adyalkar[3]) have described the potentialities of ground-water reservoirs from the Tarai and Bhabar zones. Chaturvedi and Pathak[4]) after analysing pump-test data from certain areas of the Indo-Gangetic plains have suggested varying geohydrological conditions, and such a conclusion is also drawn by Pandey *et al.*[5]) from independent studies in the Indo-Gangetic plains.

The Indo-Gangetic plains are made up of unconsolidated fluviatile formations comprising sand, silt, clay and Kankar (a nodular formation high in $CaCO_3$), with occasional beds of gravel. The beds are variable in lateral extent and in thickness. Cut-outs and interfingering between different units is a common feature which imparts an anisotropic character to both the aquifers and the confining formations.

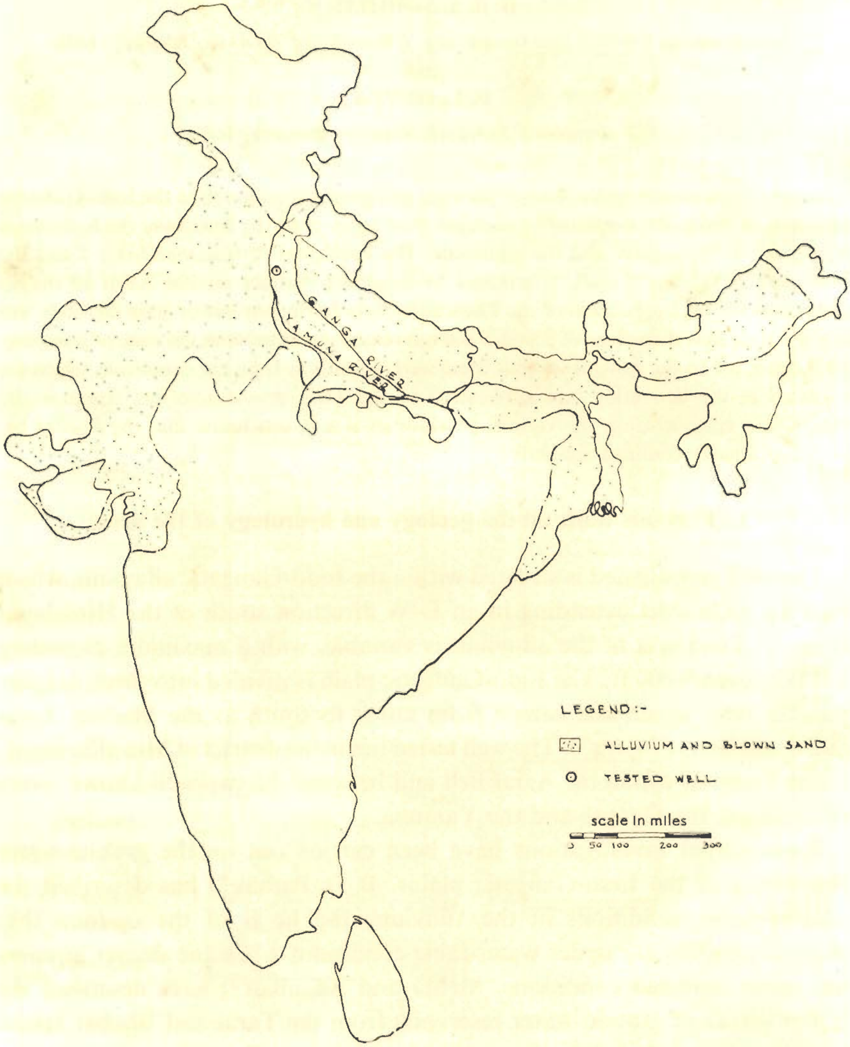


Fig. 1. Map of India showing alluvium and the location of tested well.

2. Description of the tested well and local geology

The lithological log and the position of the strainers in the pumped well and the observation well are shown in Fig. 2. The observation well is situated at a distance of 103 ft from the pumped well.

From the lithological log it can be seen that both the pumping well and the observation well are tapping water from the aquifers which are overlain

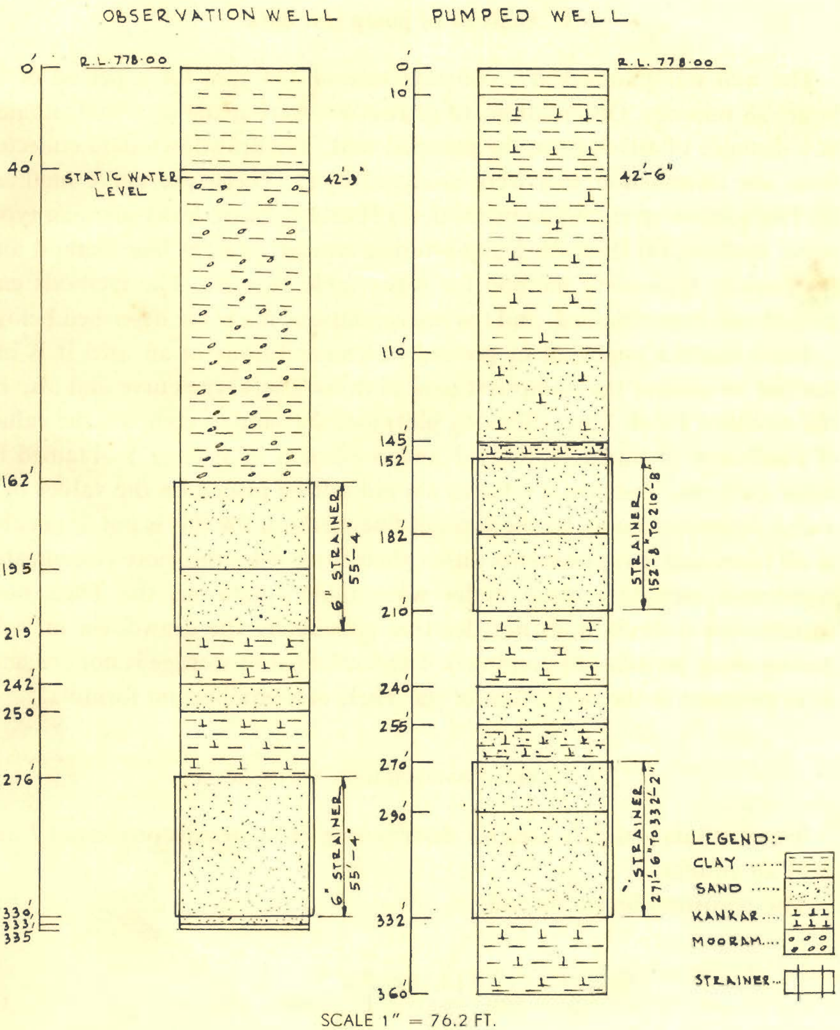


Fig. 2. Lithoogical logs of the pumped well and the observation well. Observation well is 103 ft from pumped well.

by comparatively impermeable clay formations intercalated with mooram* and kankar. These comparatively impermeable units represent the formations through which leakage occurs during pumping as shown by the analysis of pump-test data in the following text.

Fig. 3 (pp. 128/129) shows the nature of the lithological formations on a regional scale which indicates that the overlying confining layers are laterally extensive.

3. Analysis of pump test data

The well was pumped at a constant rate of 424 gpm for a period of 16 hours 38 minutes. Observations of drawdown were made in a well situated at a distance of 103 ft from the pumped well. The drawdown data collected from the observation well were analyzed by (1) Theis-type curve method, (2) Theis-Jacob straight-line method, (3) Hantush-Jacob leaky-artesian type-curve method, (4) Hantush leaky-artesian aquifer straight line method and (5) Prickett type-curve method for water-table aquifers. The methods employed, the data obtained, and the interpretations made are described below.

For a correct appraisal of ground-water conditions in an area it is important to analyse the pump-test data both by Theis type curve and also by the modified Jacob-Theis (Semilog plot) methods and to compare the values of coefficient of transmissibility T and coefficient of storage S obtained by these methods. Too much reliance should not be placed on the values of T and S determined only by the straight-line method, for this is not applicable in all cases and it supplements rather than supersedes the more complicated type-curve method[6]). Also under water-table conditions the Theis non-equilibrium formula does not describe completely the drawdown in wells during short periods of pumping[6]). The coefficient of storage is not constant as is assumed in the derivation of the Theis non-equilibrium formula.

3.1. THEIS NON-EQUILIBRIUM FORMULA

This formula is widely used for determining the hydraulic properties T and S of an aquifer.

The non-equilibrium formula is

$$s = \frac{114.16\,Q}{T} \int_{u}^{\infty} \frac{e^{-u}}{u}\, du \tag{1}$$

* Local term for red gravelly soil.

where

$$u = \frac{1.87\, r^2 S}{Tt} \tag{2}$$

s = drawdown in feet, at any point of observation in the vicinity of a well discharging at a constant rate

Q = discharge of a well in gallons per minute

T = Transmissibility, in gallons per day per ft

r = distance in feet from the discharging well to the point of observation

S = coefficient of storage, expressed as a decimal fraction

t = time in days since pumping started.

The integral expression in Eq. (1) cannot be integrated directly, but its value is given by the series.

$$\int_{1.87 r^2 S/Tt}^{\infty} \frac{e^{-u}\,du}{u} = W(u) = -0.5\,77216 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} \tag{3}$$

where

$$u = \frac{1.87\, r^2 S}{Tt}.$$

Hence Eq. (1) can be written as

$$s = \frac{114.6\, Q}{T} W(u). \tag{4}$$

Two methods are used in the applications of this formula i.e. (1) The type curve method and (2) The straight line method.

3.1.1. *Type curve method*

In this method a type curve is plotted on logarithmic coordinate paper from the values of $W(u)$ and u given in Ferris *et al.*[7]). On another logarithmic paper r^2/t is plotted against s to obtain the data curve. The two are superposed and a match point is obtained for which values of r^2/t and s are read from the data curve sheet and $W(u)$ and u from the type curve sheet.

T and S can be determined from these data by rewriting Eqs. (4) and (2) as

$$T = \frac{114.6\, Q}{s} W(u) \tag{5}$$

and

$$S = \frac{Tu}{1.87\, r^2/t}. \tag{6}$$

In the present case (Fig. 4) the field data do not match completely with the type curve, but parts of the two curves match. Three match points are determined as 1, 2 and 3 (Fig. 4). Point 1 is for the earlier part of the pumping and point 3 for the later part while point 2 is for the intermediate time. Values of T and S are determined from these three match points as given below:

For match point 1,

$$W(u) = 3.3$$
$$u = 1.8 \times 10^{-2}$$
$$r^2/t = 3.4 \times 10^6$$
$$s = 1.9 \quad .$$

Substituting these values in Eqs. (5) and (6):

$$T = 84\,394 \text{ gallons/day/ft}$$

and

$$S = 2 \times 10^{-4}.$$

Similarly for match point 2

$$T = 66\,083 \text{ gallons/day/ft}$$
$$S = 6 \times 10^{-4}$$

and for match point 3

$$T = 57\,701 \text{ gallons/day/ft}$$

and

$$S = 2 \times 10^{-3}.$$

TABLE 1

Variation in T and S with time

	T	S
Earlier	84 394 gpd/ft	2×10^{-4}
Middle	66 083 gpd/ft	6×10^{-4}
Later	57 701 gpd/ft	2×10^{-3}

These values of T and S indicate that they are not consistent but they change with time of pumping. The question arises as to which part of the time-draw-down data should be given more emphasis and can be regarded as representative of the aquifer. If we assume that this decrease is due to some boundary conditions, then the early draw-down data have to be

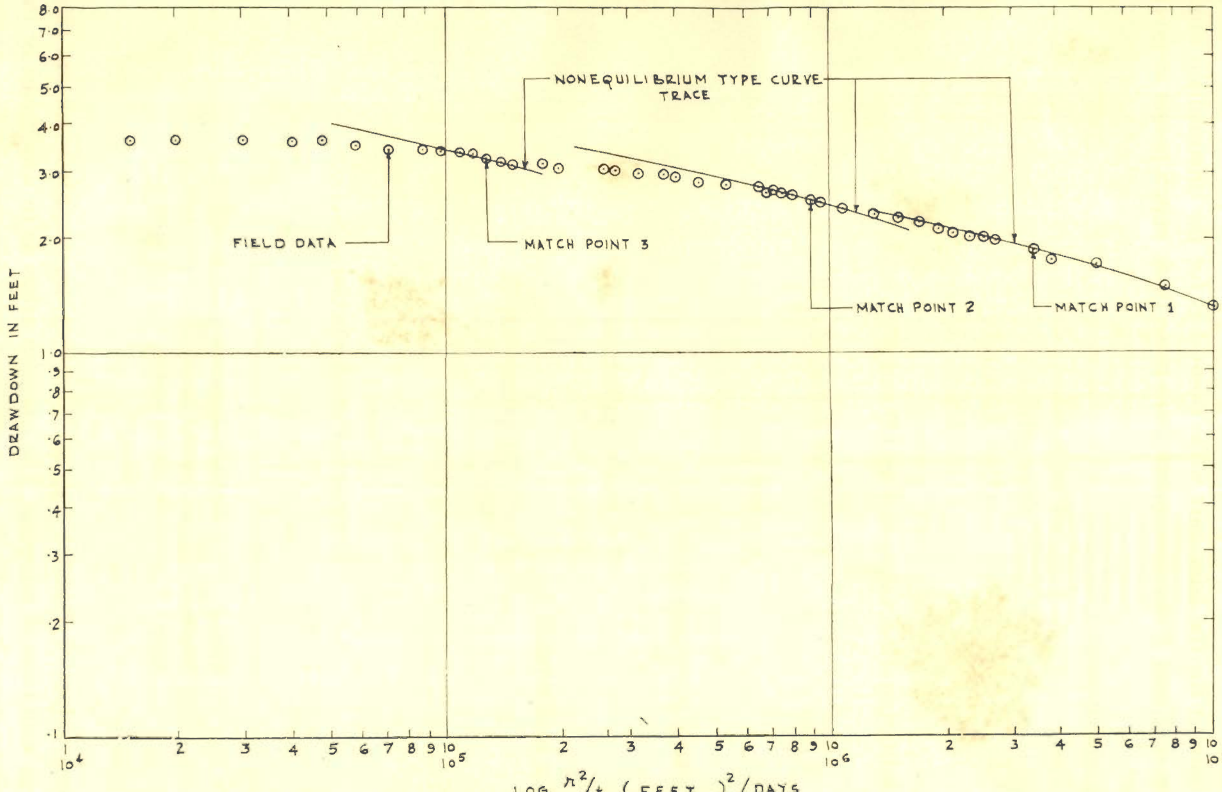


Fig. 4. Time-draw-down graph.

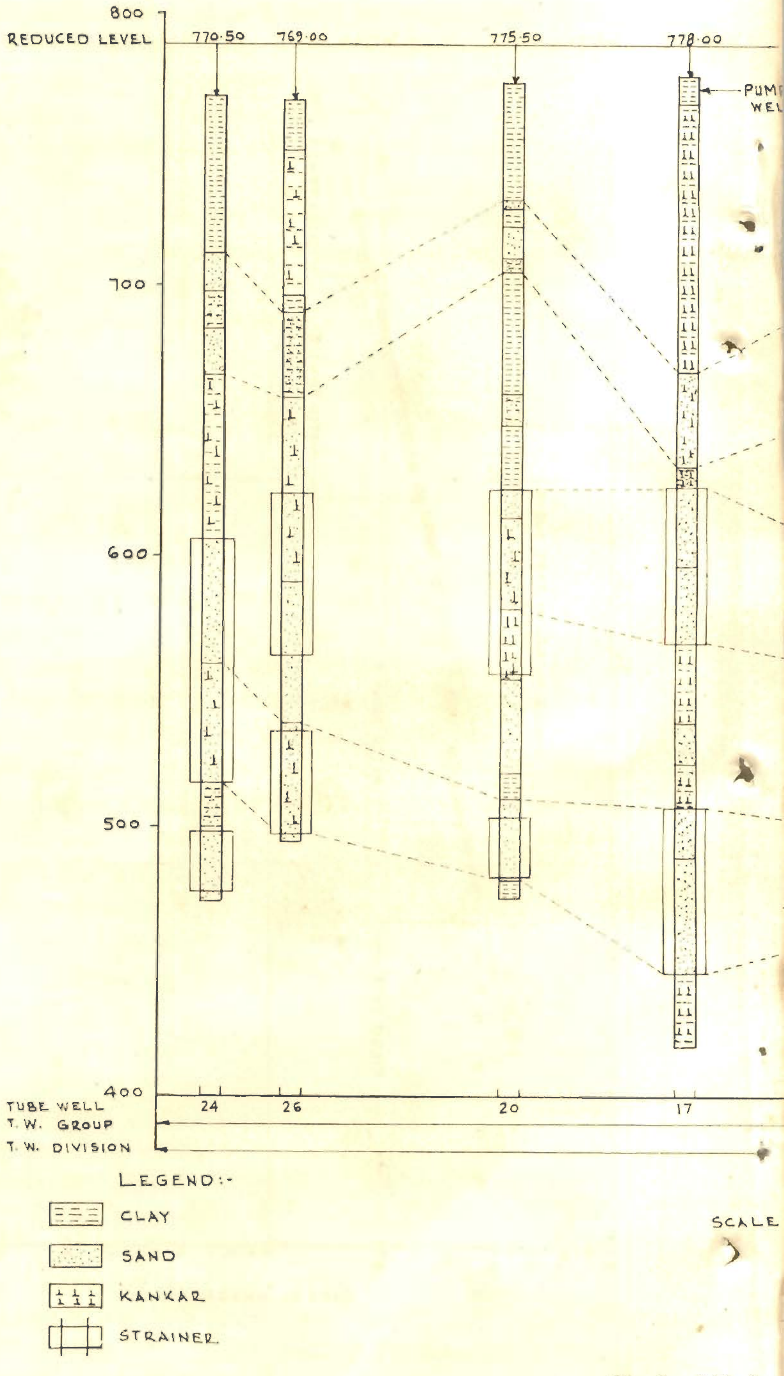
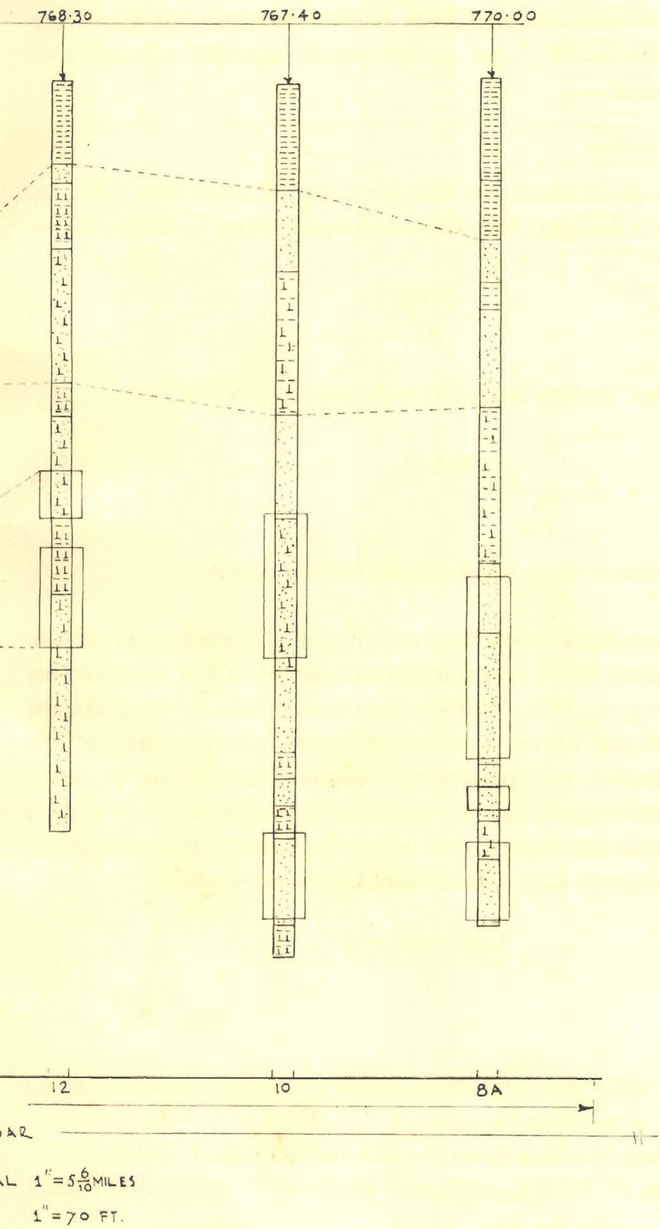


Fig. 3. Litholog



nap.

accepted but if this variation is due to water-table conditions then the later data should be taken into account. Even if the later data are used from which the value of S is 2×10^{-3}, the aquifer can be regarded as under confined aquifer conditions.

3.1.2. *Straight line method*

Jacob (in Ferris *et al.*[7]) has shown that for values of u less than 0.01, i.e. when r is small and t is large, the Theis non-equilibrium formula can be written as

$$T = \frac{264\,Q}{\Delta s} \tag{7}$$

where Δs is the change in drawdown (ft) over one log cycle of time, and

$$S = \frac{0.3\,T t_0}{r^2} \tag{8}$$

where

t_0 = time in days when the drawdown is zero.

In this method time-draw-down data are plotted on semilog coordinate paper (t on the log scale and s on the arithmetic scale). If the observations fulfil the conditions i.e. $u<0.01$, then the data plot should lie on a straight line. It is often found that all the data do not lie on a straight line and this is sometimes interpreted as representing boundary conditions or leaky aquifer conditions, although it may also be due to large values of u. Walton[6]) has shown that the time that must elapse before the straight line method can be applied to pumping-test data is determined from the equation:

$$t_{sl} = \frac{1.35\times10^5\,r^2 S}{T} \tag{9}$$

where

t_{sl} = time in minutes, after pumping starts before a semilog time-draw-down plot will yield a straight line graph.

Substituting the data obtained from the type curve method (Table 1), it is found that if we take $T=84\,394$ gpd/ft and $S=2\times10^{-4}$ and $r=103$ ft then

$t_{sl} = 3$ minutes

and for

$T = 57\,701$, $S = 2\times10^{-3}$ and $r = 103$ ft

$t_{sl} = 49$ minutes.

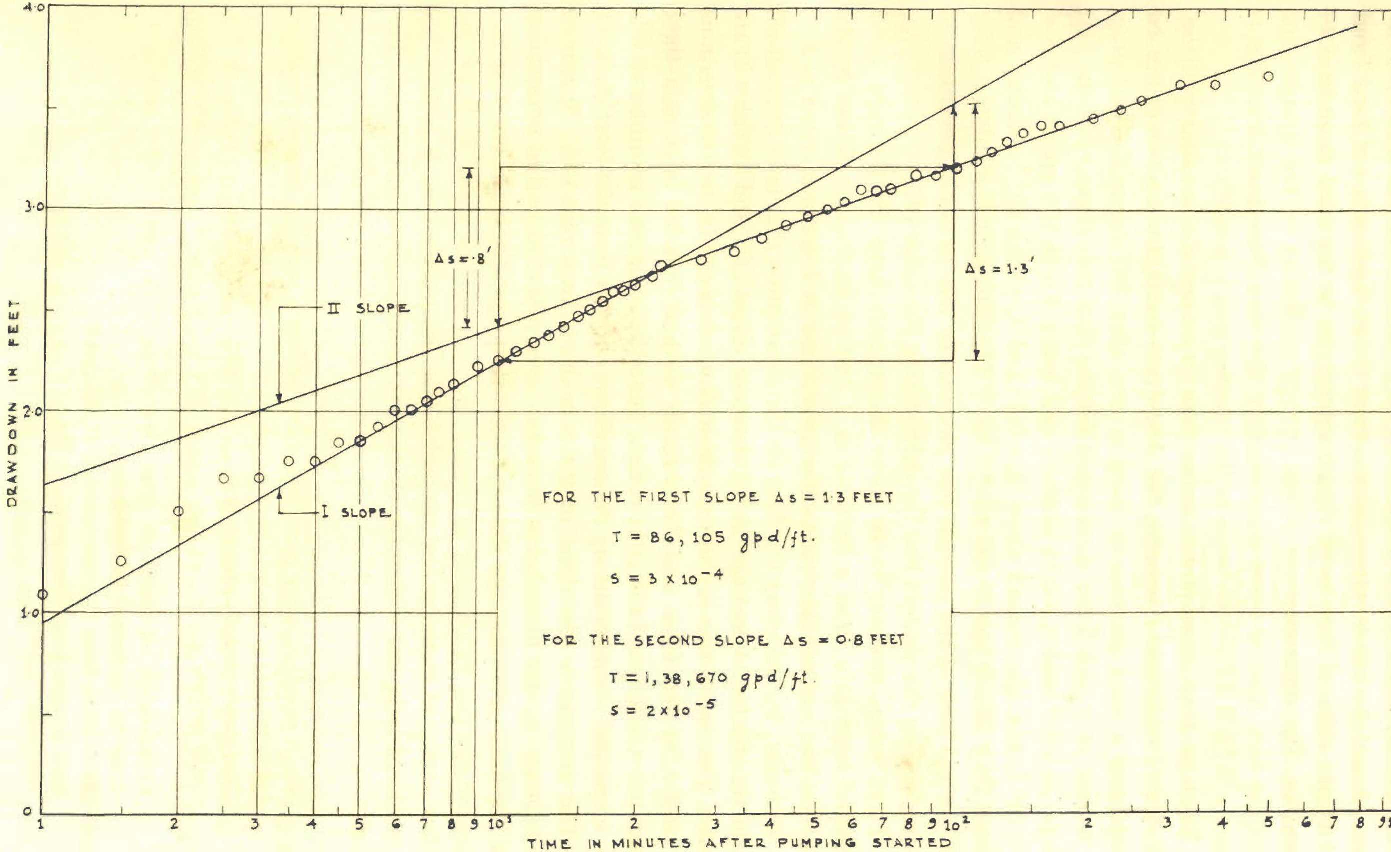


Fig. 5. Semilog plot of drawdown versus time.

It indicates for the test under discussion that part of the semilog time-draw-down plot can be taken to be correct for the application of Eqs. 7 and 8, when values of t are more than 3 minutes or at the most more than 49 minutes. The determination of the storage coefficient by the straight line method may involve some error because the zero-draw-down intercept is poorly defined where the slope of the semilog plot is small[6]).

The time-draw-down plot from the observation well shows two slopes (Fig. 5). After 25 minutes of pumping the time-draw-down plot shows a decreased slope and a third decrease in slope is seen after 300 minutes of pumping.

Values of T and S are determined for the first two slopes. For the first slope $\Delta s = 1.3'$ and $t_0 = 0.18$ minutes and hence $T = 86\,105$ gpd/ft and $S = 3 \times 10^{-4}$. For the second slope $\Delta s = 0.8'$ and $t_0 = 0.6 \times 10^{-5}$ minutes and hence $T = 1\,38\,670$ gpd/ft and $S = 2 \times 10^{-5}$. The extremely low value of S for the second part of the straight line plot can be due to minor deviations in extrapolating the straight line for determining the value of t_0.

There seems however to be some discrepancy here. By the type curve method later data show a decrease in T and an increase in S, but by the straight-line method later data show an increase in T and a decrease in S.

However, by analysing the data on the assumption that later draw-down data are affected by leakage fairly consistent values of T and S (Table 2) are given. This means that earlier time-draw-down data can be used to determine T and S by the Theis and Theis-Jacob method, but for later data these methods would give erroneous values; hence leaky-aquifer formulas should be employed for determining the aquifer properties from the later data.

The decrease in the slope of the time-draw-down plot (Fig. 5) can be interpreted as due to recharge boundary conditions, to partial penetration of the well, or to leakage through the overlying aquiclude. The first two possibilities can be rejected as there is no near-surface water body or any other source of recharge and the wells have full penetration. It is therefore considered to be due to leakage through the overlying confining layers. This

TABLE 2

Sl. No.	Type of method	T	S	K'/b' or P'/m'
1	Non-steady time-draw-down type curve method	76 706 gpd/ft	2.9×10^{-4}	1.8×10^{-3} gpd/cft or 2.6×10^{-10} sec^{-1}
2	Extrapolation of maximum draw-down by constructing a time-draw-down curve from the observational data on semi-logarithmic paper (Hantush's method)	0.12 ft^2/sec or 77 587 gpd/ft	3×10^{-4}	2×10^{-8} sec^{-1}

is confirmed as shown below because the value of T and S determined by the leaky-aquifer formula from the later part of the draw-down data tally with those determined by the Theis formula from the earlier parts of the draw-down data.

4. Analysis of data by assuming leaky confined aquifer conditions

For the analysis of draw-down data from leaky confined aquifer conditions, both the type curve method (Walton[8]) and the straight line method (Hantush[9]) can be used as described below.

4.1. THEORY

Hantush and Jacob (Walton[8]) have given the following equation for non-steady state drawdown in a leaky artesian aquifer

$$s = \frac{Q}{4\pi T}\int_u^\infty \left(\frac{1}{Y}\right) \exp\left(-y - r^2/4B^2 y\right) \mathrm{d}y \tag{10}$$

$$= \frac{Q}{4\pi T}\left[2K_0(r/B) - \int_q^\infty (1/y)\exp\left(-y - r^2/4B^2 y\right)\right]\mathrm{d}y \tag{11}$$

$$= (Q/4\pi T)\, W(u, r/B). \tag{12}$$

The integral expression was written by Hantush (Walton[8]) symbolically as $W(u, r/B)$ and was termed the "Well function for leaky artesian aquifers". Hence,

$$s = \frac{Q}{4\pi T} W(u, rB) \tag{13}$$

where

$$u = r^2 S/4Tt\,.$$

Eq. (13) can be written in the gallons/foot system of units as

$$s = \frac{114.6\,Q}{T} W(u, r/B) \tag{14}$$

where

$$u = \frac{2693\, r^2 S}{Tt} \tag{15}$$

and

$$r/B = \frac{r}{\sqrt{T/(P'/m')}} \tag{16}$$

where t = time in minutes
P' = vertical permeability of confining bed, in gallons/day/sq.ft
m' = thickness of confining bed through which leakage occurs, in feet.
P'/m' = leakage coefficient or "leakance".

4.1.1. *Non-Steady time-draw-down type curve method*

Hantush[9]) has given values of $W(u, r/B)$ in terms of u and r/B. Walton[8]) has plotted values of $W(u, r/B)$ against values of $1/u$ on logarithmic paper and a family of leaky artesian type curves was constructed.

From the test under discussion values of s are plotted on logarithmic paper against values of t in minutes so that a time-draw-down field curve is obtained. This data curve is matched with one of the leaky-artesian type curves and a match point is selected for which values of $W(u, r/B)$ and $1/u$ are read from the type curve sheet and corresponding values of t and s are read from the data curve sheet (Fig. 6).

In Fig. 6 is shown the trace of the type curve of value $r/B = 0.05$ with which the data from the test under discussion show the best matching, and the coordinates of the match point are also given in this figure. T is calculated using Eq. (14), S by Eq. (15) and P' by Eq. (16). Their values are given in Fig. 6 and Table 2.

4.1.2. *Straight-line method (Hantush method)*

In this method the drawdown measured in feet in an observation well during pumping is plotted versus time in minutes on semi-logarithmic paper and the data is extrapolated until the maximum drawdown (s_m) is found. The inflection point (s_i) is located on the draw-down curve by taking $s_i = \frac{1}{2}\, s_m$ where s_i is the drawdown at the inflection point. The slope m_i of the draw-down curve at the inflection point is determined graphically and t_i is read corresponding to the inflection point.

Hantush[9]) has shown that if the drawdown s is plotted against the time t on semi-logarithmic paper, with t plotted in the logarithmic scale, then the slope m at any point is given by

$$m = \Delta s/\Delta \log_{10} t = (2.3Q/4\pi T) \exp\left(-u - r^2/4B^2u\right). \tag{17}$$

The curve has an inflection point at which the following relations hold

$$u_i = r^2 S/4Tt_i = r/2B \tag{18}$$

where the subscript i relates to values of the variables at the inflection point.

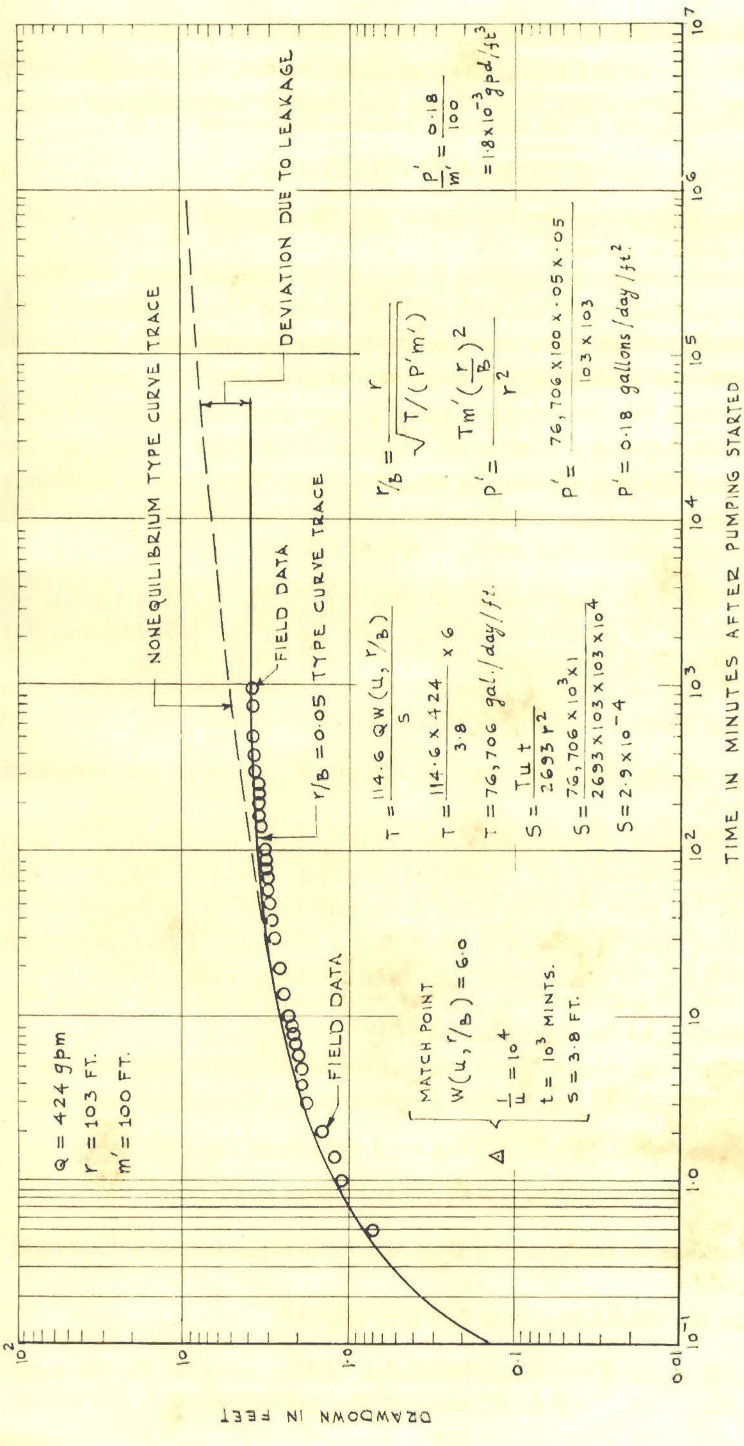


Fig. 6. Time-draw-down graph.

The slope of the curve m_i at the inflection point is given by

$$m_i = (2.3Q/4\pi T)\,e^{-r/B} \tag{19}$$

and the drawdown at the inflection point s_i is given by

$$s_i = (Q/4\pi T)\,K_0(r/B) = (\tfrac{1}{2})s_m\,. \tag{20}$$

The relation between the drawdown and the slope of the curve at the inflection point is given by

$$f(r/B) = e^{r/B}K_0(r/B) = 2.3\,s_i/m_i\,. \tag{21}$$

In that part of the curve where it approaches asymptotically the maximum drawdown, the slope m at any point can be given by

$$m = (2.3Q/4\pi T)e^{-q} \tag{22}$$

where

$$q = Tt/sB^2 \tag{23}$$

and the drawdown by

$$s = s_m - (Q/4\pi T)\,W(q) \tag{24}$$

where $W(q)$ is the exponential integral $-E_i(-q)$, which is known as the 'well function' in ground-water hydrology. From Eqs. (19), (20) and (21) the following relation is obtained:

$$f(q) = e^q W(q) = 2.3(s_m - s)/m. \tag{25}$$

Values of the functions used in the above equations are tabulated by Hantush[9]).

The following procedure of extrapolation of maximum drawdown is adopted to determine the formation constants based on the above theory.

In Fig. 7 is given the time-draw-down plot based on the drawdown in the observation well. Discharge of the well was 424 gpm = 1 cfs (approximately) and r (distance of observation well from pumping well) = 103 ft

$$s_m = 3.75 \text{ ft}$$
$$s_i = \tfrac{1}{2}(s_m) = 1.87 \text{ ft}$$
$$t_i = 6 \text{ minutes.}$$

If the slope of the inflection point = 1.3 then from Eq. (21)

$$e^{r/B}K_0(r/B) = 2.3 \times 1.87/1.3 = 3.3\,.$$

For this value of the function from the table (Hantush[9])) $e^{r/B} = 1.0492$ and $r/B = 0.048$.

Hence $B = 103/0.048 = 2148$ ft. From Eq. (19)

$$T = 2.3 \times 1/4\pi \times 1.3 \times 1.049$$
$$= 0.12 \text{ ft}^2/\text{sec} = 77\,587 \text{ gallons/day/ft.}$$

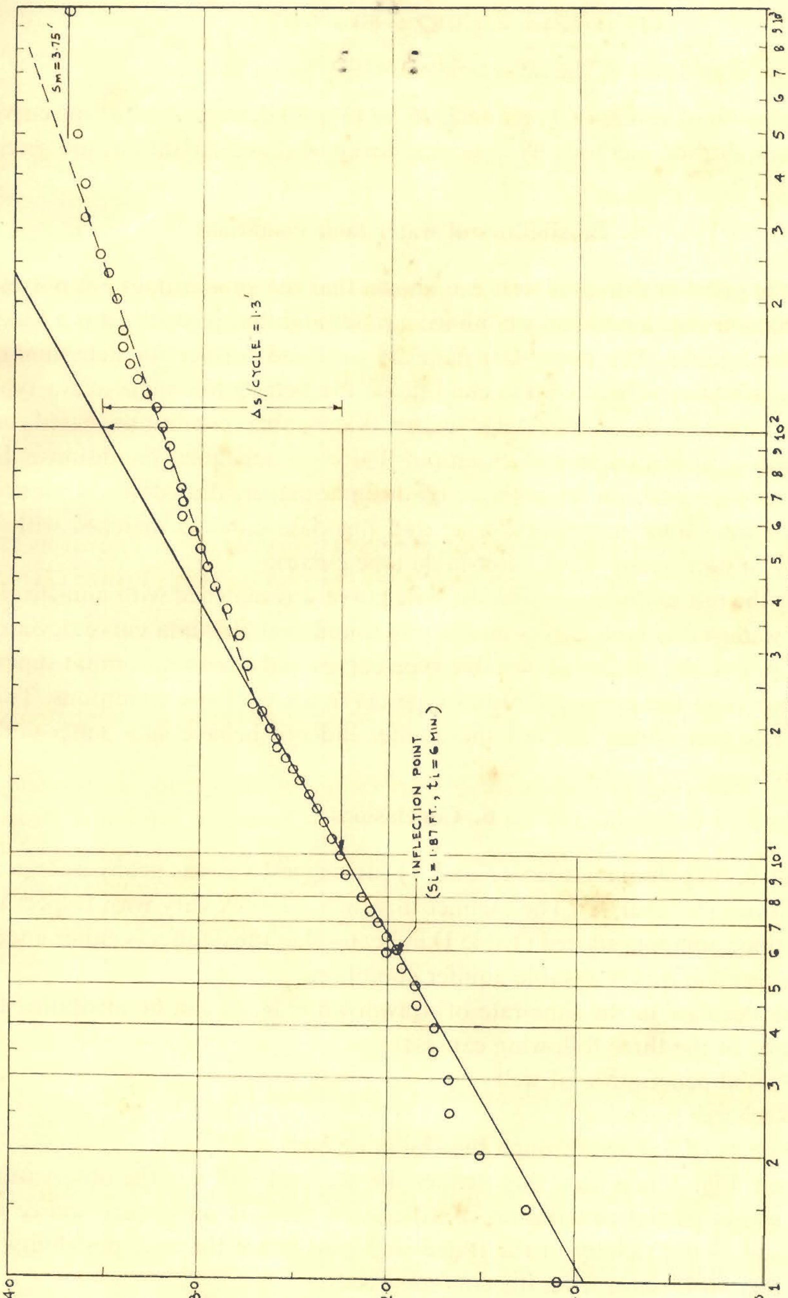


Fig. 7. Time-draw-down graph.

Leakance or $K'/b' = T/B^2 = 0.12/(2148)^2 = 2 \times 10^{-8}$ sec^{-1}. From Eq. (18)

$$S = \frac{4Tt_i(r/2B)}{r^2} = \frac{4 \times 0.12 \times 60 \times 0.02}{103 \times 103} = 3 \times 10^{-4}.$$

Comparison of values of T, S and K'/b' or (P'/m') determined by type curve and straight line methods by assuming leaky confined conditions are given in Table 2.

5. Possibilities of water table conditions

In the preceding discussion it was shown that the aquifer does not possess the characters of a non-leaky confined aquifer and that probably it is a leaky artesian aquifer. The pump-test data are analyzed further for determining the possibilities of water-table conditions. Prickett[10]) has suggested a type curve solution to aquifer tests under water-table conditions based on Boulton's non-equilibrium equation[11]) for water-table conditions. In Prickett's method, on logarithmic co-ordinate paper, drawdown is plotted against time since pumping started and this data curve is matched with a family of non-steady state water-table type curves.

For the test under discussion the data curve was matched with non-steady state water-table type curves and it was found that the data curve deviates from practically all the water-table type curves and shows maximum superposition with the non-equilibrium type curve for confined conditions. This indicates that during the test the aquifer did not behave as a water-table aquifer.

6. Conclusions

The aquifer characteristics (T and S) can suggest various geohydrological conditions (Singhal[12])). The manner in which T and S vary with respect to time since pumping started (Table 1) indicates that the aquifer is either under leaky artesian or water-table aquifer condition.

The decrease in the time-rate of drawdown (Fig. 5) can be attributed to any one of the three following causes:

(1) Partial penetration of well
(2) Recharge boundary
(3) Effects of leakage through the confining bed.

From Fig. 2, it is seen that neither the pumped well nor the observation well shows partial penetration. Furthermore there is no surface source of recharge in the vicinity of the tested well, and hence the only possibility is that there is leakage from the confining beds.

From Table 2 it is seen that the values of T, P'/m' or K'/b' and S are comparable if the two leaky-artesian aquifer methods are applied to the present case. Furthermore, the values of T and S determined by these methods are similar to those determined for the earlier data by the Theis and Theis-Jacob methods. All these findings indicate that the aquifer under discussion is a leaky artesian aquifer.

The present study also indicates that for leaky aquifers the Theis and Theis-Jacob methods give dependable results only for earlier data when there is practically no leakage to the tested aquifer from other horizons. It should also be mentioned that during the test the water levels were above the top of the aquifer and the draw-down data were not measured in the pumping well itself. If draw-down data are measured in the pumping well itself, the calculations for leaky aquifer conditions would be erroneous. The lowest pumping piezometric surface was 105.7 ft above the top of the aquifer.

Hence it may be concluded that the tested aquifer has behaved as a leaky artesian aquifer, and possibly this is a common characteristic of the deeper aquifers in the Indo-Gangetic alluvial plains.

7. Acknowledgements

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