GROUND WATER APPRAISAL OF THE GASH RIVER BASIN AT KASSALA, KASSALA PROVINCE, SUDAN

by

El Tayeb M. Saeed

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SIGNED: Eltayeb M. Saeed

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Jerome J. Wright
JEROME J. WRIGHT
Associate Professor Geology

June 12, 1968
Date

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ABSTRACT

The Gash River basin lies in the eastern part of Kassala Province, Sudan. The rock units in the area are the Basement Complex, Clays of the Plain, and the alluvial deposits of the Gash River.

The average annual precipitation is 13.4 inches. The mean seasonal runoff of the Gash River at Kassala town is about 381,000 acre-feet, and the mean average period of flow is 88 days per year.

The principal aquifer in the area is the alluvium. The aquifer is unconfined, and the average saturated thickness is 90 feet. The average transmissivity of the aquifer is 100,000 gallons per day/foot and the average specific yield is 13 per cent. The storage capacity of the ground water reservoir is about 484,000 acre-feet. The annual discharge from the reservoir for irrigation, domestic uses, and evapotranspiration is about 58,000 acre-feet. The aquifer is recharged seasonally from the Gash River during the rainy season by influent seepage and from direct precipitation over the basin.

The ground water supplies of the area have small amounts of dissolved solids. The ground water is of an excellent quality for irrigation and domestic purposes.

INTRODUCTION

Scope and Nature of Work

In the Kassala area ground water is used for irrigation and domestic uses. The development depends to a great extent upon the availability of sufficient amounts of ground water for irrigation.

This work is the first appraisal of ground water resources in the area. Its main purpose is to determine the quantity of the water available for development in the Gash River basin in the Kassala area.

Location and Extent of the Area

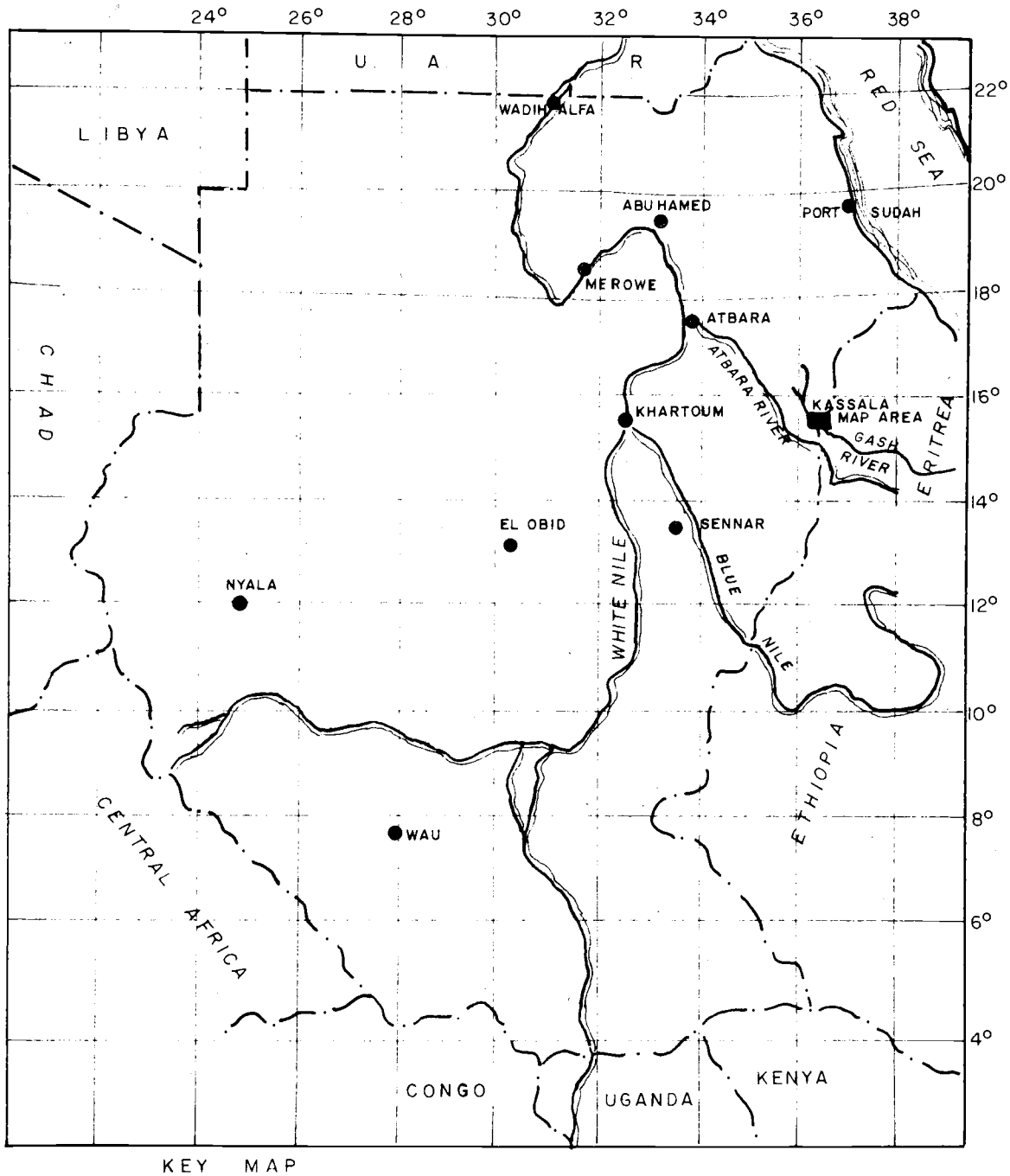
The area investigated lies near the International Boundary between Sudan and Ethiopia at the southern part of Kassala Province (Fig. 1). It is about 300 miles east of Khartoum.

Kassala town (lat. 15° 28', long. 36° 24'E), which is the administrative center of Kassala Province, lies within the study area. The area investigated is about 80 square miles or about 210 square kilometers.

Economic Development

Kassala town is the Capital of Kassala Province. The city has a population of about 65 thousand inhabitants.

The activities in the area depend upon the cultivation of the land by using ground water for irrigation. The agricultural products are mainly onions, bananas, and citrus which are sold to domestic



KEY MAP

SCALE : 14,000,000

0 100 200 500

KM

FIGURE 1 INDEX MAP OF SUDAN SHOWING LOCATION OF AREA OF STUDY

markets. Recently an onion processing plant was constructed in the area to prepare dry onions for foreign export.

Climate

The climate at Kassala is of tropical continental type. The winter between December and March is pleasantly cool. The mean minimum daily temperature in January is 16°C (60.8°F).

The summer is hot and dusty. During this period the area is subjected to local strong winds, usually accompanied by thick dust (Habub). Visibility is reduced during the Habub to a few meters and this condition continues for 2 to 3 hours. The mean maximum daily temperature in May is about 42°C (107°F).

The rainfall is confined to the summer and usually has a few thunder storms. This rainy period starts in July and continues to the end of September. The annual average rainfall in Kassala is 341 mm. (13.4 inches). There are usually no winter rains.

Topography and Drainage

The area is a plain which is covered by clays and dips gently toward the northwest. The average height of the plain is about 500 meters (1640 feet) above mean sea level. Rising above the clay plain and trending in a north-south direction are Jebel Kassala and Jebel Mokram. Jebel Kassala is the highest of these with an altitude of 1343 meters (4417 feet) above mean sea level.

The Gash River is an intermittent stream. It originates in the Eritrean highlands of eastern Sudan and Ethiopia and flows northwest

across the flat plain of northeastern Sudan until it disappears due to evaporation, infiltration into the ground, and irrigation before reaching the Atbara River.

Previous Work

No previous detailed study of the geologic and the ground water conditions of the Gash River area has been made. All earlier studies have been regional in nature.

Karkanis (1961) comments on the general ground water conditions in the area. In his report he has given some data on static water levels in a few wells at Kassala town.

Samuel (1962) described the geology of the area and classified the rock units as Basement Complex, Clay of the Plain, and Alluvial deposits. In his report he gives some static water levels for some wells in the area.

Present Investigation

The present study was started in October, 1962, and continued through October, 1964. In February, 1966, some pumping tests were carried out. The present report includes mapping and sampling of the major units in the area with special emphasis being placed upon the differentiation of the alluvial deposits.

The ground water investigation includes the data obtained from 42 test holes which were drilled to the basement rocks (Plate 1). The holes were drilled on a grid pattern which covered most of the area. Two-hundred and sixty determinations of electrical resistivity were

made in the area. The results of the resistivity survey and the test drilling were used to delineate the boundary and the thickness of the aquifer.

The fluctuations in the water table were observed for a period of 18 months in 12 observations wells. These data were used to determine the amounts of recharge and discharge and the general movement of the ground water.

The results of a pumping test utilizing one observation well, together with the recovery data, and the specific capacity of other pumping wells in the area were used to determine the aquifer coefficients.

Chemical analyses of some ground water samples were made to determine the suitability of ground water for irrigation and other purposes.

GEOLOGY

General Setting

In northeastern Sudan the general rock sequence, in descending order, consists of:

4. Quaternary Alluvial Deposits
3. The Tertiary?-Quaternary Deposits
2. The Paleozoic?-Mesozoic Nubian Sandstone Series
1. The Precambrian Basement Complex Rocks

The Precambrian Basement Complex Rocks

Since Precambrian time this part of Sudan has constituted part of the African Shield (sometimes called Ethiopian or Abyssinian Shield or Arabian Shield) and has been subjected mainly to uplift and erosion. It has generally been a stable region.

Ruxton (1956) distinguished a Lower, Middle, and Upper division of the Precambrian rocks in the northern Red Sea Hills.

Lower Precambrian Series or Primitive System

This division includes the most metamorphosed rocks and consists essentially of granitic gneisses, hornblende schists, schists, and slates. All of these rocks have been intruded by dolerite and granite dikes.

Middle Precambrian or Nafirdeib Series

These rocks rest unconformably on the lower Precambrian units and also are metamorphosed. The rock types are gneisses, quartzites, marbles, schists, and green andesite flows, all of which are cut by granite, gabbros, norites, and quartz veins.

Upper Precambrian or Awat Series

These units rest unconformably on the older rocks and are composed of lavas (ranging in composition from andesites to rhyolites), argilites, and conglomerates. This sequence shows little metamorphism.

The succession of the Basement Complex from the youngest to the oldest of the Sudan north of latitude 6°N was given by Andrew (1948, p. 95) as follows:

6. Soda granites (youngest)

5. Unfoliated granites

B. Folding of non-metamorphic succession

4. Unmetamorphosed greywackes and lavas (predominantly andesitic)

3. Plutonic intrusions: ultrabasic rocks (serpentines), gabbro-norite, granodiorite, granite, all more or less foliated.

A. Folding and regional metamorphism

2. Oldest plutonic orthogneisses

1. Regionally metamorphosed paraschists, containing many slightly metamorphosed bedded rocks, including lavas (oldest)

Kassala Area

In the Kassala area the Precambrian Basement Complex rocks are the oldest. Following their formation, the area was subjected to a period of prolonged erosion that reduced the whole area to a peneplain. Jeb. Kassala and Jeb. Mokram (Fig. 2), which rise above the plain, represent the main outcrops of the Basement Complex in the area. These outcrops are granitic biotite gneisses, pink to grey in color, and medium to coarse grained. The rocks are jointed in two sets vertically and horizontally.

The drill cuttings of the Basement Rocks are of a granitic nature; however, green schists and mica schists were observed in drill cuttings from some test holes.

Cross sections based upon test hole drillings show that along the line of section A-A' (Plate 2) the pre-alluvial topographic surface has little relief. Along section B-B' (Plate 3) there is a steep gradient of the surface of the Basement Rocks between test holes 7 and 20. This indicates the variation in the topography on the top of the Basement Rocks before the deposition of the alluvial sediments. Along section C-C (Plate 4) the profile of the surface of the Basement Rocks shows a gentle gradient from upstream to downstream, except in the extreme upstream area. At that point the gradient is steeper and indicates variation in the topography on the top of the Basement Rock due to erosion before the deposition of the post-Precambrian sediments.

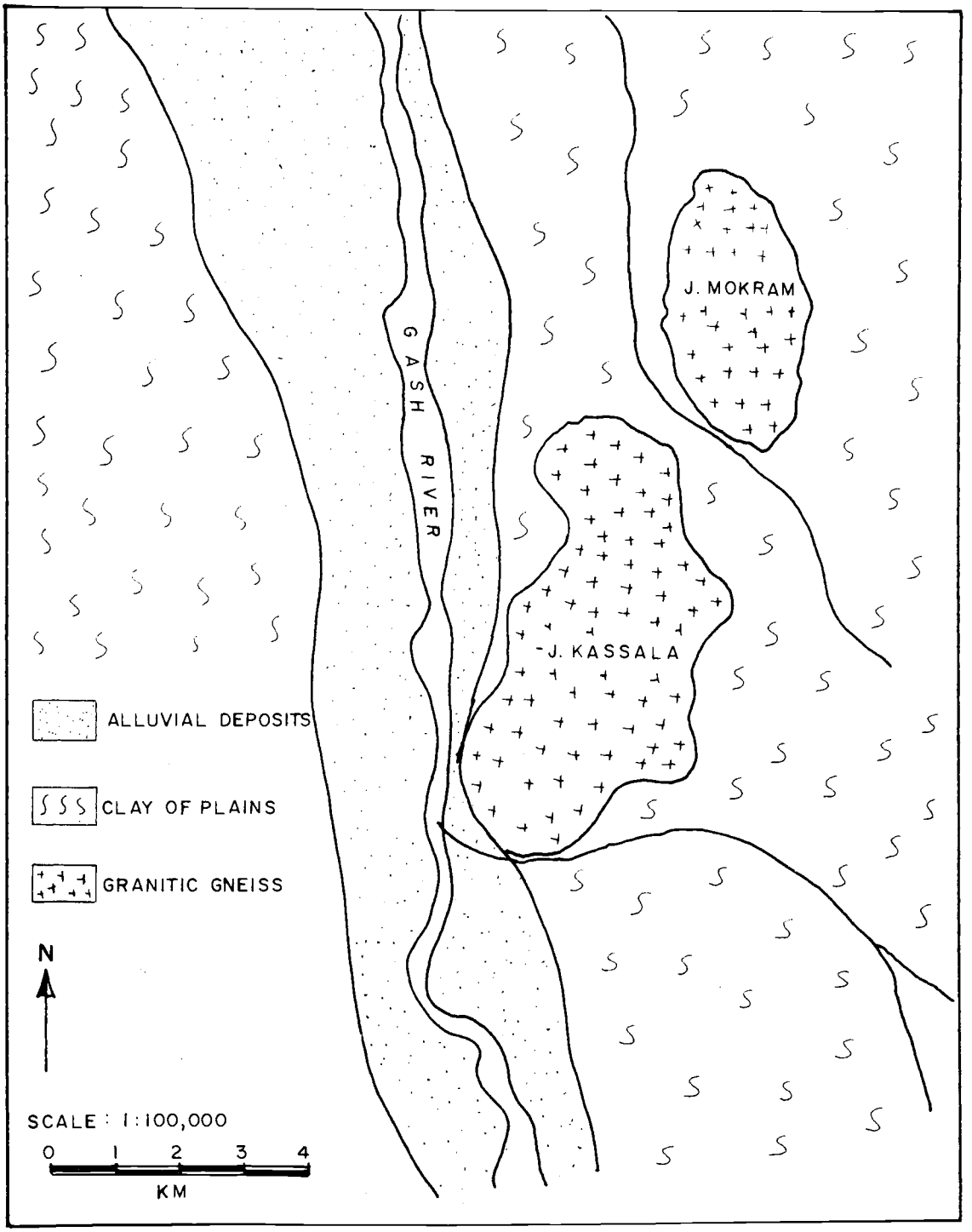


FIGURE 2 GEOLOGICAL MAP OF KASSALA AREA

Paleozoic?-Mesozoic Nubian Sandstone Series

The Nubian Sandstone Series is found in a very limited area in the northeastern part of Sudan. The age and the mode of deposition of the rocks of the Nubian Series are still in doubt. It lies nonconformably over the Basement Complex rocks.

The Nubian Sandstone Series includes several important economic aquifers in Sudan, especially in the western part of the country.

Stratigraphic Sequences

The Nubian Sandstone is a monotonous sequence of sandstones, often exhibiting current bedding, with occasional pebble beds and intercalated mudstones. The series is subdivided into three units: (1) the basal series, (2) the middle series, and (3) the upper series.

The basal series. This sequence consists of alternating brown, coarse grained silicified sandstone and conglomeratic beds. The components of the conglomerates are generally rounded quartz pebbles cemented with silica. When rocks of this series are exposed on the surface, they may occur as caps to the hills which are underlain by the Basement Complex.

The middle series. This series is composed of mudstone and sandstone, mudstone being the dominant lithology. Its color is white or grey with bentonitic clay being common. The sandstone is quartzitic in composition and is poorly cemented and friable.

The upper series. This unit is composed of brown and buff poorly-sorted sandstones which are poorly cemented and friable. The sand grains range in size from medium to fine sand, although silt and

clay sizes are present. The sandstone is quartzitic in composition.

Delany (1952) observed marine strata intercalated with the Nubian Sandstone in northeastern Sudan on el Bab which is located at Khor Langeb (17° 15'N, 36° 38'E). This is the only place at the present time in the Sudan where Nubian Sandstone and marine intercalation are observed.

The Nubian Sandstone sequence from the youngest to oldest below the basalt cap on el Bab is as follows:

5. White flinty mudstone, 25 m. thick; the flinty stratified beds are cherty; siliceous nodules give the rock a fossiliferous aspect.
4. Ferruginous sandstone, 10 m. thick.
3. Limestone, 2 m. thick; blue non-fossiliferous limestone horizon containing chert nodules; the overlying sandy marls form a transition to unit 4.
2. Sandstone, 4 m. thick; white and red in color and showing current cross bedding with occasional pebble beds.
1. Conglomerate of quartz pebbles, 1 m. thick; the components are subangular and embedded in loosely cemented sand.
0. Mica schist, unconformably overlain by the Nubian Sandstone succession.

Environment of Deposition of the Nubian Sandstone

Much has been written on the mode of origin and environment of deposition of the Nubian Sandstone. Walther (1888) suggested an eolian

origin. Fourtau (1902) considered the formation to be a fossil desert that bordered the Paleozoic and Mesozoic seas. Cuvillier (1930) considered the whole formation, with the exception of the intercalated fossiliferous limestone, as of undoubted eolian origin. Hume (1906) considered the bedding, the presence of coarse conglomerates at the base of the formation in many localities, the extreme rounding of the quartz pebbles, the unbroken passage into marls containing marine faunas, and the presence of occasional marine shells, as evidence for a marine origin.

Shukri and Said (1944) inferred that the deposition of the Nubian Sandstone took place in a shallow sea on the fringe of a sinking peneplane. They regarded the non-fossiliferous sandstone as having been deposited under water in a beach or in a near-shore marine environment. They based this on the bedding exhibited by the Nubian Sandstone, on the presence of large pebbles, 65 per cent of which are disc-shaped, on the presence of ripple marks, on the indication of false-bedding, and on the well sorted sands composed of one chief ingredient.

Age

Edwards (1926) identified the following cretaceous plant fossils from a basal silicified sandstone capping Jebel Dirra east of el Fasher:

Frenelopsis hohenggeri

Weichselia reticulata

Dadoxylon aegyptiacum

Sandford (1935) concludes that the whole series is in all probability Mesozoic and may be of Cretaceous age.

Tectonic Activity

No important tectonic activity has affected the region since the deposition of the Nubian Series. The only movements are epeirogenic and consist of gentle warping with uplift, although outside of this area there is greater uplift, accompanied by faulting, which has formed the Red Sea Hills, the Abyssinian Plateau, and the Red Sea trough.

In the Kassala map area, there are no outcrops of the Nubian Sandstone Series.

Tertiary?-Quaternary Deposits

Clays of the Plain

The term Clays of the Plain has been applied by the geologists of Sudan to the dark grey to dark chocolate-colored clays that cover an extensive area between the White Nile and Ethiopia frontier. They overlie the Basement Complex, Nubian Series, and Tertiary lavas.

There is at the present time no satisfactory evidence of the age of the Clays of the Plain. Generally, they are considered to be of Tertiary to Quaternary age.

Kassala area. In the Kassala area the Clays of the Plain unit is found above the river flood plain east and west of the alluvial deposits. It is grey to dark grey in color and consists of laminated loosely to compacted clay, silt, sandy clay, and sandy silt. The clay is underlain by the Basement rocks. Its thickness ranges from a few feet to about 60 feet along the west side of the alluvial deposits.

Quaternary Alluvial Deposits

In the Kassala map area, the alluvial deposits were formed by the Gash River during the flood season. Annually, the Gash River flows during the period between June and September. It transports clay, sand, and gravel. According to the change of the velocity of the water in the stream, the coarse materials deposit upstream and the finer materials deposit downstream. The condition of transportation and deposition of the fragments vary with the carrying capacity of the stream which is directly related to the intensity of the storm causing the runoff. As a result an area covered with gravel or coarse sand, during one flood, may, after another storm, receive a deposit of silt or clay. Or an older deposit may be removed in whole or in part and be replaced by a new lithology. The end result of such widely fluctuating conditions is deposition of lens-shaped and finger-like units which change abruptly in texture and character, both horizontally and vertically, as shown in the cross sections A-A', B-B', and C-C' (Plates 2, 3, and 4).

The thickness of the alluvial deposits in the Kassala area range between 90 feet upstream near the south end of the map area to about 180 feet downstream or north end. As shown in the cross sections, the alluvial deposits are composed of intercalating beds of unconsolidated, coarse to fine-grained gravel, sand, silt, and clay. The fine materials such as silt and clay show a tendency to increase downstream.

The sand and gravel cover a wide range in both lithological composition and grain size. Lithologically, the gravel is composed mostly of angular to subangular quartz pebbles; however, volcanic, felspathic,

and granitic gravels are present. The gravel grain sizes range from 2 mm. to more than 10 mm. The sand is mostly well rounded and medium to coarse grained. Fine sand was found in several test holes. The sand is mostly composed of quartz; however, felspathic micaceous and volcanic sand are present.

The cross sections (Plates 2, 3, and 4) show that the surface of the ground is covered with a layer of silty clay or sandy clay which forms the fertile soil of Kassala. The thickness of this soil ranges from a few feet to more than 50 feet.

It is difficult to correlate the sediments in this area over long distances due to their deposition as lens-shaped and inter-fingering units and the abrupt changes in texture of the sediments.

Section A-A' (Plate 2) is a cross section at right angles to the Gash River. The grain size analyses in Tables 1 and 2 show that the dominant sizes are gravel, very coarse sand, and coarse sand. These constitute about 65 per cent of the sediments. Figures 3 and 4 are two histograms which represent the distribution of grain sizes of the entire bore hole in test holes Nos. 29 and 40.

Section B-B' (Plate 3) is a cross section in the downstream area of the Gash River. The analyses of the grain sizes are given in Tables 3 and 4. These indicate that the most abundant grain sizes are medium sand, fine sand, and clay. These comprise more than 65 per cent of the sediments in this section. Figures 5 and 6 are two histograms giving weight-size frequency in the entire bore hole in test holes Nos. 7 and 20.

Table 1. Grain Size Analyses[a] by Weight of the Samples from Test Hole No. 29

Depth Interval (in ft.)	Gravel	Sand					Silt & Clay
	Larger Than 2.38 mm.	Very Coarse Sand 2.38 to 1.19 mm.	Coarse 1.19 to 0.59 mm.	Medium 0.59 to 0.232 mm.	Fine 0.232 to 0.149 mm.	Very Fine 0.149 to 0.075 mm.	Less Than 0.075 mm.
00-15	-	1.27	1.24	3.35	5.36	31.30	57.42
15-21	2.90	2.42	11.28	40.82	28.84	12.42	1.20
21-26	1.30	26.60	2.93	3.75	25.18	28.20	35.83
26-31	2.90	20.04	40.82	25.00	4.70	3.42	2.46
31-40	16.36	31.16	35.86	11.56	1.90	1.12	1.96
40-97	57.24	23.84	16.90	1.56	0.22	0.06	0.08
Average (Per Cent of Total Bore Hole)	35.40	18.40	16.20	6.40	4.40	7.40	11.50

a. Sieves used were in a British sieve system, and definition of sizes is correlated as closely as possible with the Wentworth word designations. However, because of the different sieve system, the division of sizes does not have the same limits.

Table 2. Grain Size Analyses[a] by Weight of the Samples from Test Hole No. 40

Depth Interval (in ft.)	Gravel	Sand					Silt & Clay
	Larger Than 2.38 mm.	Very Coarse Sand 2.38 to 1.19 mm.	Coarse 1.19 to 0.59 mm.	Medium 0.59 to 0.232 mm.	Fine 0.232 to 0.149 mm.	Very Fine 0.149 to 0.075 mm.	Less Than 0.075 mm.
00-15	0.35	1.12	1.04	2.41	6.31	33.46	55.26
15-20	65.36	25.82	8.02	0.61	0.11	00.01	00.03
20-37	00.25	00.45	1.47	3.60	5.40	25.35	63.36
37-88	26.44	36.38	26.96	6.38	1.68	00.98	1.00
88-95	15.60	8.45	5.21	8.31	11.47	20.18	30.75
95-101	55.46	29.24	12.16	2.16	00.50	00.20	00.22
101-111	14.20	9.36	4.32	6.58	11.58	25.36	28.52
111-121	22.42	31.20	38.20	5.10	1.24	00.80	1.02
121-147	56.64	23.80	19.20	0.18	0.02	00.06	00.06
Average (Per Cent of Total Bore Hole)	27.40	22.20	16.80	4.20	3.00	9.50	16.80

a. See Table 1

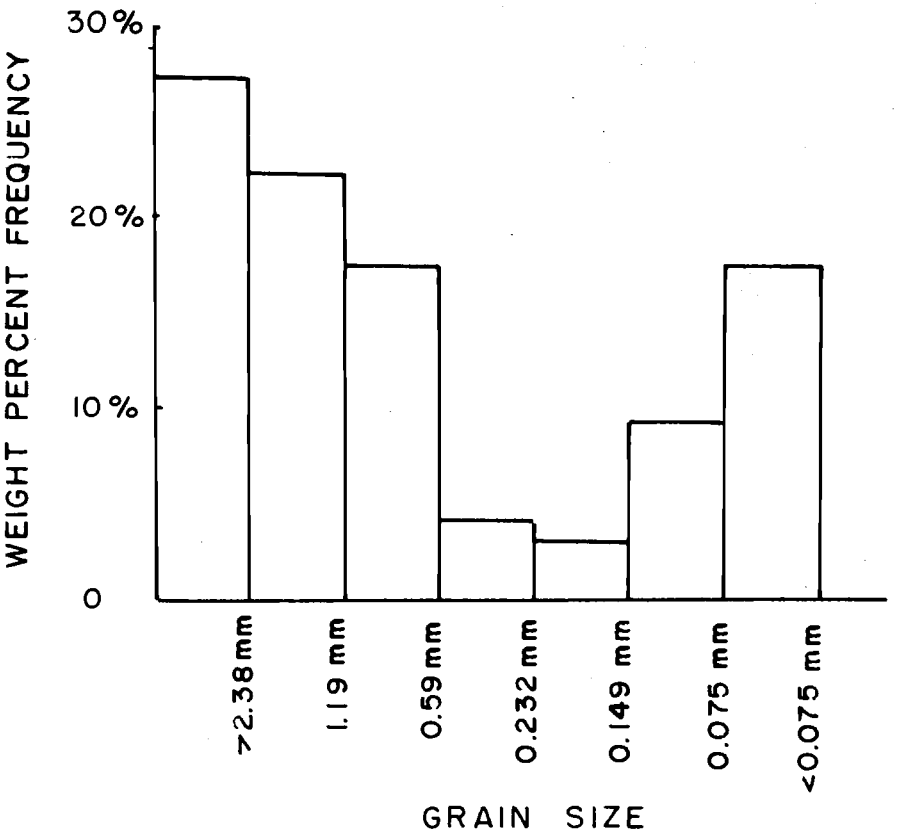


FIGURE 3 HISTOGRAM SHOWING THE DISTRIBUTION OF THE AVERAGE GRAIN SIZE OF THE ENTIRE BORE-HOLE AT THE WEST UP STREAM AREA IN TEST-HOLE NO.40

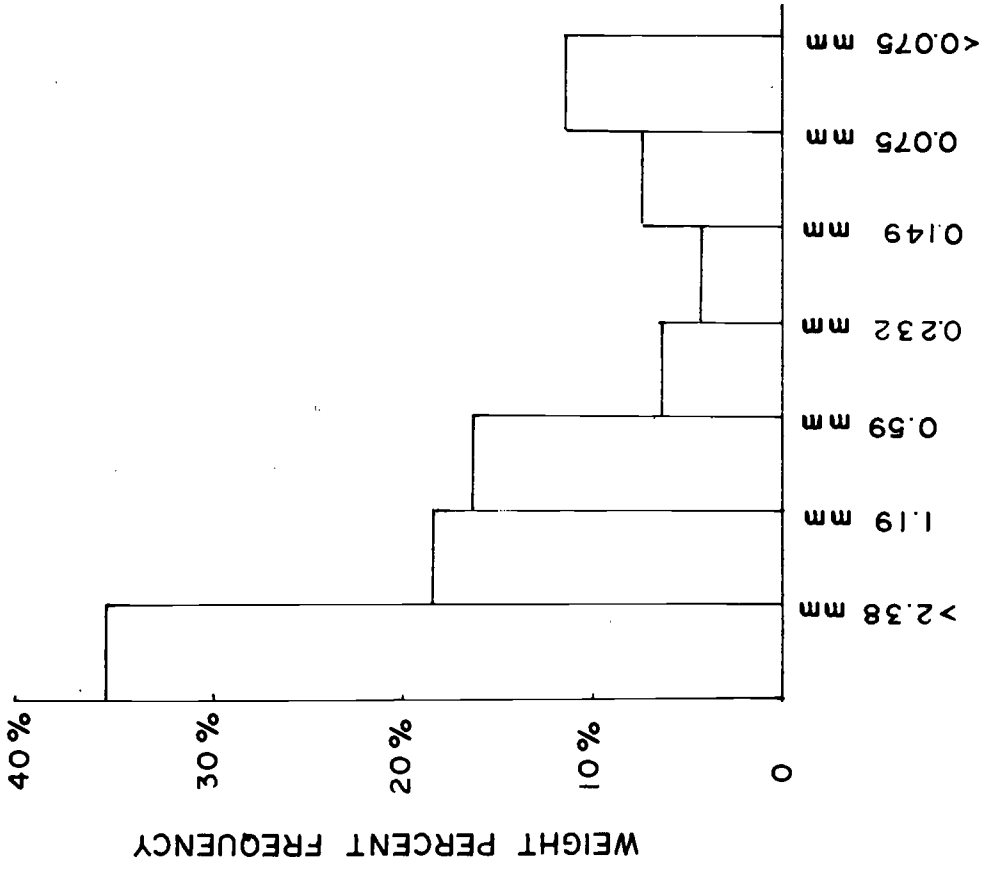


FIGURE 4 HISTOGRAM SHOWING THE DISTRIBUTION OF THE AVERAGE GRAIN SIZE OF THE ENTIRE BORE-HOLE AT THE EAST UP STREAM AREA IN TEST-HOLE NO.29

Table 3. Grain Size Analyses[a] by Weight of Samples from Test Hole No. 7

Depth Interval (in ft.)	Gravel	Sand					Silt & Clay
	Larger Than 2.38 mm.	Very Coarse Sand 2.38 to 1.19 mm.	Coarse 1.19 to 0.59 mm.	Medium 0.59 to 0.232 mm.	Fine 0.232 to 0.149 mm.	Very Fine 0.149 to 0.075 mm.	Less Than 0.075 mm.
0-6	-	-	1.12	4.65	8.56	23.31	62.26
6-25	0.02	10.60	41.50	38.20	7.20	1.50	00.20
25-43	-	5.60	7.20	11.60	14.70	25.85	35.70
43-58	-	-	5.40	10.50	13.90	26.50	53.50
58-76	5.30	6.20	6.50	7.10	8.32	30.60	38.80
76-82	16.20	47.00	26.50	5.32	1.60	1.66	1.62
82-88	-	1.80	5.20	5.50	7.75	13.95	65.70
88-96	22.00	44.00	30.80	1.60	0.40	00.38	00.60
96-123	1.80	45.40	50.70	0.92	0.30	00.36	00.64
Average (Per Cent of Total Bore Hole)	3.40	18.60	27.70	10.90	6.10	13.70	23.50

a. See Table 1.

Table 4. Grain Size Analyses[a] by Weight of the Samples from Test Hole No. 20

Depth Interval (in ft.)	Gravel	Sand					Silt & Clay
	Larger Than 2.38 mm.	Very Coarse Sand 2.38 to 1.19 mm.	Coarse 1.19 to 0.59 mm.	Medium 0.59 to 0.232 mm.	Fine 0.232 to 0.149 mm.	Very Fine 0.149 to 0.075 mm.	Less Than 0.075 mm.
00-13	0.40	1.90	2.55	2.85	3.30	25.75	63.10
13-32	1.90	2.08	13.30	25.70	45.60	10.06	1.20
32-41	0.90	1.40	1.60	6.65	12.30	22.09	45.03
41-56	0.00	0.00	0.40	0.75	2.15	13.50	83.15
56-65	0.00	2.40	8.10	4.10	18.80	17.30	49.02
65-106	0.00	0.38	0.90	1.45	7.20	22.60	67.40
106-120	2.86	25.46	58.80	11.40	0.58	0.26	0.42
121-175	8.80	34.40	49.06	5.86	0.50	0.24	0.84
Average (Per Cent of Total Bore Hole)	3.20	13.60	22.90	7.70	9.50	11.70	31.20

a. See Table 1.

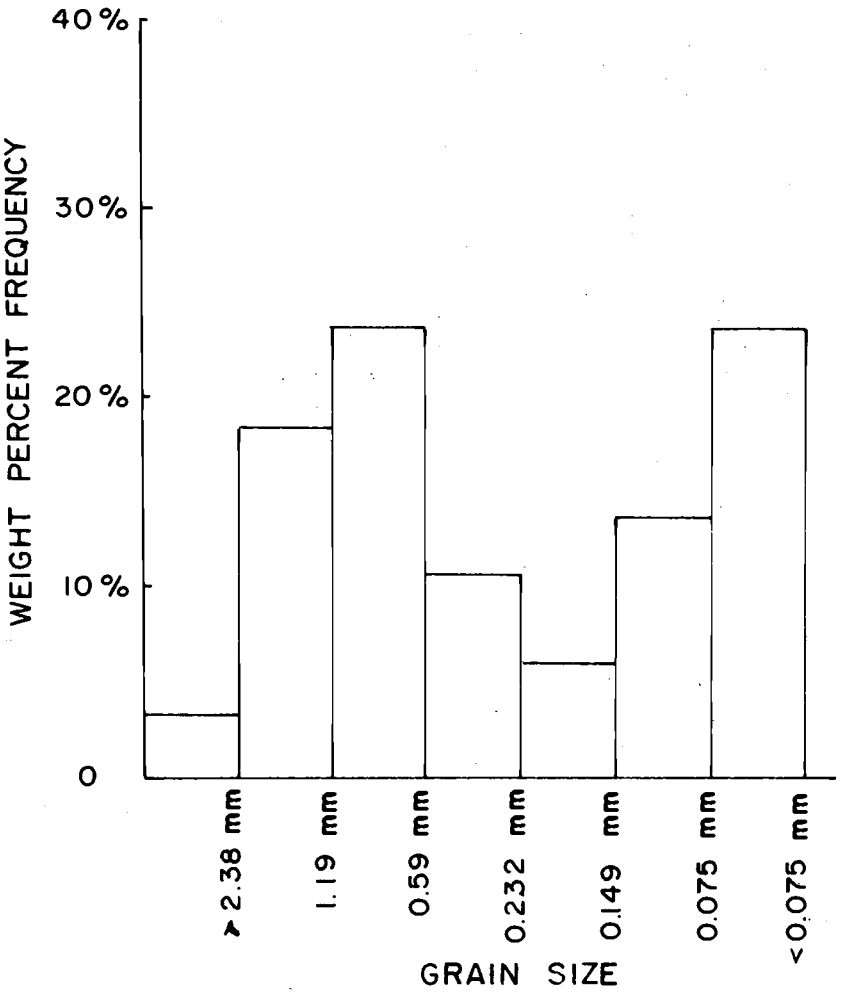


FIGURE 5 HISTOGRAM SHOWING THE DISTRIBUTION OF THE AVERAGE GRAIN SIZE OF THE ENTIRE BORE-HOLE AT THE EAST DOWN STREAM AREA IN TEST-HOLE NO.7

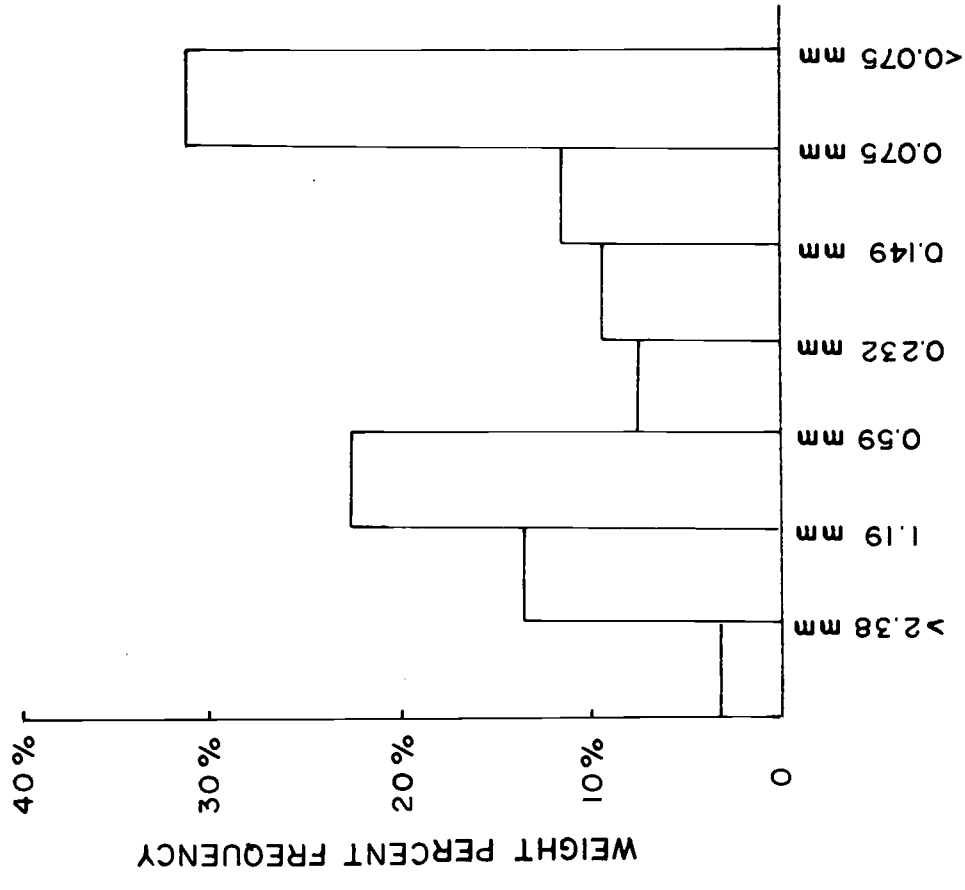


FIGURE 6 HISTOGRAM SHOWING THE DISTRIBUTION OF THE AVERAGE GRAIN SIZE OF THE ENTIRE BORE-HOLE AT THE WEST DOWN STREAM AREA IN TEST-HOLE NO.10

Section C-C' (Plate 4) is a cross section longitudinal to the stream. The analyses for size of grain show a tendency to decrease in grain size downstream. Clay and sandy clay layers or lenses extend horizontally downstream for long distances. The bottom of the section is composed mainly of sand and gravel and it can be correlated for a long distance.

Table 5 shows the summary of the lithology and water-bearing properties of the geological units in the Kassala area.

Table 5. Summary of the Lithology and Water-Bearing Properties of the Geological Units in the Kassala Area

Age	Formation	Thickness (ft.)	Lithology	Water-Bearing Properties
Quaternary	Alluvium	0 to 180	Unconsolidated beds of sand, gravel and clay	Aquifers occur in several horizons below the water table and are mainly composed of gravel, sand and pebbly sand.
Tertiary?-Quaternary	Clays of the Plain Deposits	0 to 60	Mostly clay, sandy clay, silt, and silty clay	Usually not water-bearing. Small quantity of water sometimes found in sandy pockets in the vicinity of the Gash River.
Precambrian	Basement Complex		Pink to grey coarse to medium grained, granitic biotite gneiss.	Impermeable. However, small amount of water found in joints, fractures, and in fault planes (spring issues from fault plane on the western side of Jeb. Kassala).

HYDROLOGY

Precipitation

The mean annual rainfall at Kassala town is 341 mm. (13.4 inches). The rainy season extends from late May to October. Over 90 per cent of the total precipitation falls during the period from June to September, and about 72 per cent of this amount falls during July and August. The average monthly distribution of rainfall in Kassala town over a period of 30 years is shown in Fig. 7.

Evapotranspiration

Evaporation losses from soil depend on the nature of the soil and the depth to the water table, provided that wind, air temperature, and relative humidity are the same. Evaporation of ground water from the land surface is not expected to be of great magnitude in the Gash basin, because the water table is relatively deep (the depth to the water table ranges from between 12 to 60 feet below the ground surface), but during the rainy season when the water table rises to within a few feet of the ground surface near the Gash River, evaporation losses will be high.

Evapotranspiration loss may be very high, particularly in the southern area, where the Dom (Hyphaene thebica Mort.) and Hashab (Acacia senegal) forests are found. The roots of these trees extend down to the top of the ground water reservoir and the result is a great amount of evapotranspiration of ground water.

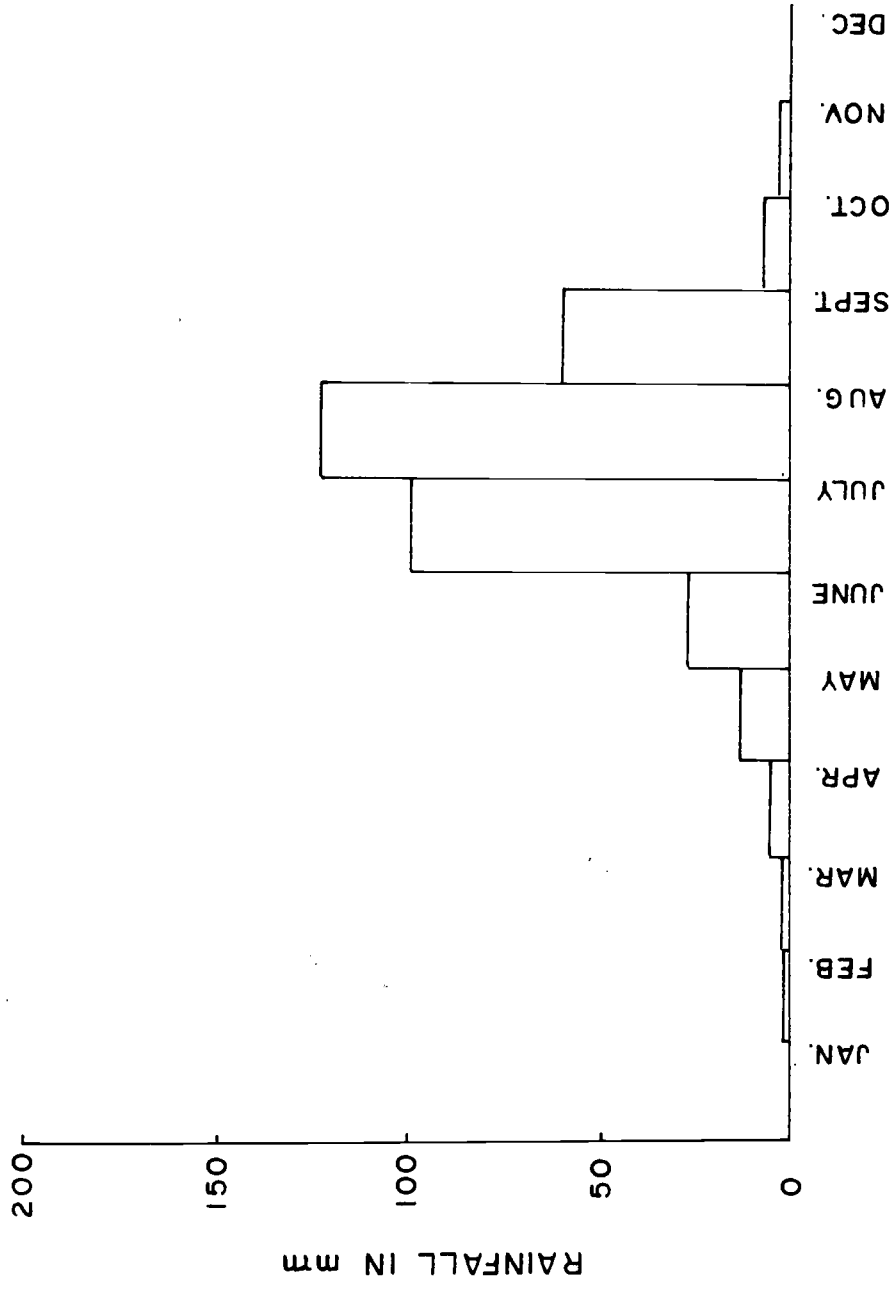


FIGURE 7 AVERAGE MONTHLY DISTRIBUTION OF RAINFALL IN KASSALA TOWN FOR THE PERIOD: 1930–1960

Runoff

The Gash River originates in the Eritrean highlands of Sudan and Ethiopia and flows northward across the area. It is an intermittent stream which flows for a period of about three months a year during or shortly after the rainy season.

Flow records taken at Kassala town during the period 1907 to 1940 are as follows:

Average period of flow - 88 days

Mean annual discharge - 483×10^6 cubic meters (3.81×10^5 acre-feet).

During the period 1955-1964 measurement for the Gash River discharge was taken at the gaging station north of the Magarda Canal, north of Kassala town. The annual discharge at this station over that period is shown in Table 6. The long term average of the annual discharge at that gaging station is 410×10^6 cubic meters (3.32×10^5 acre-feet) and the average period of flow is 87 days.

Table 6. Runoff at the Gaging Station North of the Magarda Canal, North Kassala Town

Years	Period	No. of Days	Amount of Runoff
1955	July 7 to Oct. 4	90	195 x $10^6 m^3$ (1.58 x 10^5 acre-feet)
1956	July 5 to Oct. 13	101	776 x $10^6 m^3$ (6.29 x 10^5 acre-feet)
1957	July 10 to Sept. 29	74	234 x $10^6 m^3$ (1.9 x 10^5 acre-feet)
1958	June 28 to Sept. 29	95	328 x $10^6 m^3$ (2.66 x 10^5 acre-feet)
1959	July 9 to Sept. 30	84	724 x $10^6 m^3$ (6 x 10^5 acre-feet)
1960	July 8 to Sept. 30	85	307 x $10^6 m^3$ (2.5 x 10^5 acre-feet)
1961	July 1 to Sept. 28	90	526 x $10^6 m^3$ (4.26 x 10^5 acre-feet)
1962	July 12 to Sept. 30	80	173 x $10^6 m^3$ (1.4 x 10^5 acre-feet)
1963	July 4 to Sept. 30	88	141 x $10^6 m^3$ (1.14 x 10^5 acre-feet)
1964	July 2 to Sept. 22	83	782 x $10^6 m^3$ (6.36 x 10^5 acre-feet)

GROUND WATER CONDITIONS

Occurrence of Ground Water

Ground water occupies the interstices or pore spaces of the rocks within the zone of saturation. A water-bearing formation is called an aquifer, which is defined as any geological formation or structure that transmits water in sufficient quantity to supply pumping wells or natural springs. The amount of water that can be stored in a rock material depends on the porosity of that rock and is expressed as the percentage of void space to the total volume of the mass. The pore space or interstices are affected by the size, shape, sorting and packing of the fragments forming the deposit, and by their cementation and compaction. The capacity of the rock to yield water is determined by its permeability or ability to transmit water through the pore space of the rock material under a given hydraulic gradient. Silt and clay have high porosity but they transmit water very slowly because their interstices are so small that the surface tension forces will hold the water.

Ground water generally occurs either under unconfined (water table) or confined (artesian) conditions. The unconfined condition prevails where the aquifer is in direct contact vertically with the atmosphere through open spaces in the overlying permeable material. Confined aquifers occur where ground water is under pressure greater than the atmosphere and is confined by an overlying relatively impermeable

strata. In a well penetrating such an aquifer, the water level will rise above the bottom of the confining bed.

The alluvial deposits of the Gash River basin are the principal sources of the ground water in the area. The aquifer is unconfined, so the water occurs under water table conditions. However, confined ground water occurs at a few places in the valley owing to the presence of a confining bed overlying the aquifer. This bed is somewhat permeable or leaky. The occurrence of the ground water under such conditions may be termed "semi-artesian." The water level in the wells drilled into this aquifer is approximately the same as the upper surface of the zone of saturation. With continued pumping the confining effect of the upper bed may be reduced and the entire saturated portion will function as a water table aquifer. Deeper aquifers in some areas may contain water under artesian pressure.

The Gash aquifer is composed of a heterogeneous sequence of beds which is dominated by coarse sand, gravel, clayey sand, and silt. The rock material has high porosity and permeability. Downstream at Tukrof west area, the average saturated thickness is more than 100 feet. At Tukrof east, Wad Shareefer, and el Sabil, the average saturated thickness is about 70 feet. The depth to the water table varies with the time and place, depending on the time of the year and the relative altitude of the ground surface. It ranges from a few feet below the surface near the Gash River to about 60 feet at the fringes of the aquifer.

Water Level Fluctuation

The water level in the Gash River basin fluctuates primarily in response to the variation in recharge and discharge. These fluctuations are reflected by the water level changes in wells which provide information on the change in the ground water storage.

The alluvial fill in the Gash Valley is recharged by infiltration of the Gash River when the stream flows during the flood season. However, there is also direct recharge by precipitation which infiltrates through the soil of the alluvial deposits and moves down to the water table.

The records of the water levels in the observation wells show that the ground water table starts to rise as precipitation and infiltration become greater during July, August, and September when the Gash River begins to flow. The water levels decline as the Gash River becomes dry. In the observation wells near the Gash River, there is an obvious drop in the water levels in November (Fig. 10). The water table reaches its lowest level in May and June. There is a sudden rise in the water levels in July, with a general high period from July to October while the river is flowing (Figs. 8, 9, and 10).

During the period 1963 to 1964 the maximum water level fluctuation in the observation wells was recorded in wells Nos. 11 and 13 (Fig. 10) and is equal to 28.5 feet. The minimum water level fluctuation for that period was recorded in wells Nos. 5 and 6 and is equal to 12.6 feet (Fig. 9). The annual average fluctuation within the area of the observation wells is about 20 feet.

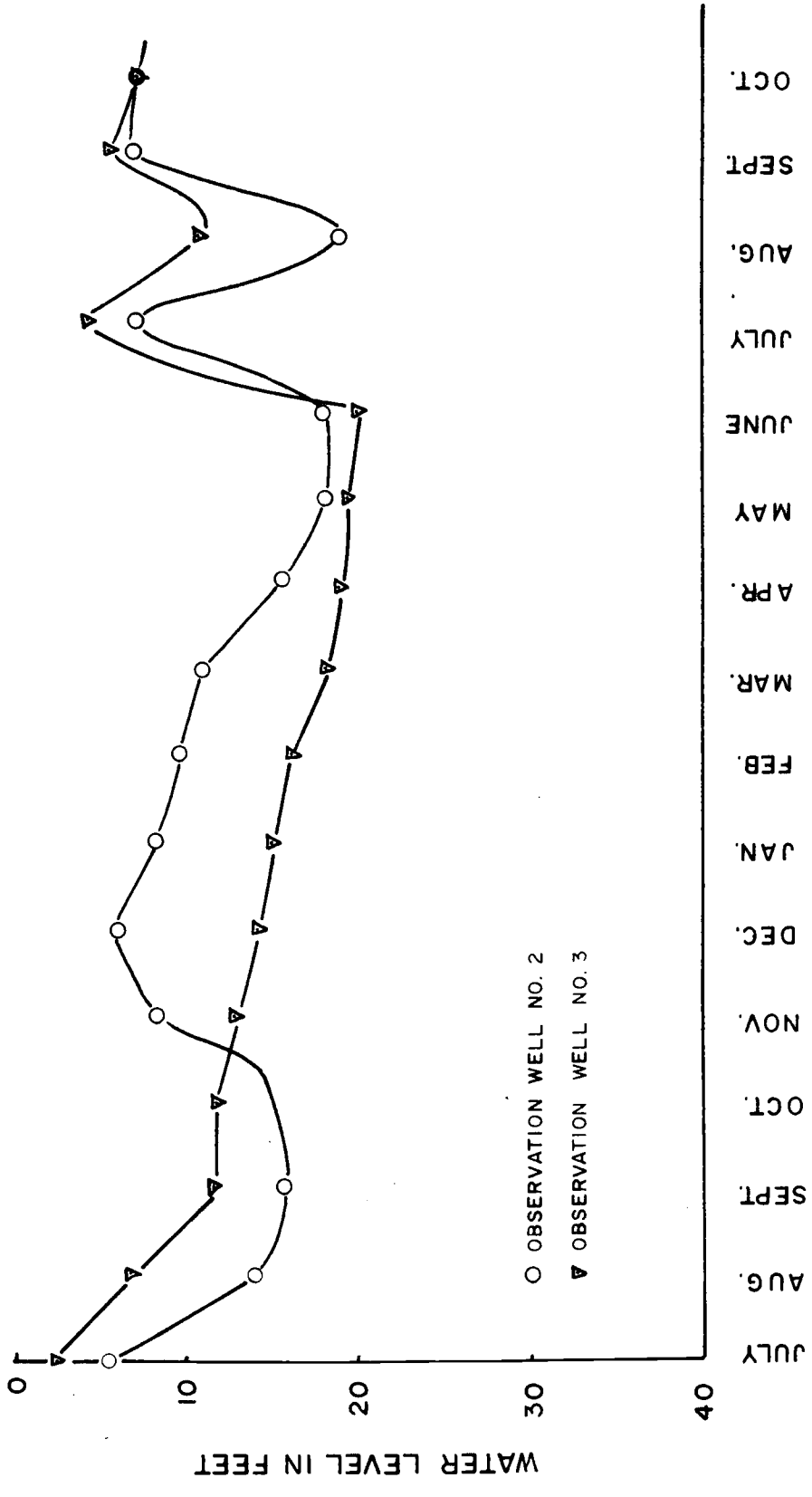


FIGURE 8 WATER LEVEL FLUCTUATION IN OBSERVATION WELLS NOS. 2 AND 3

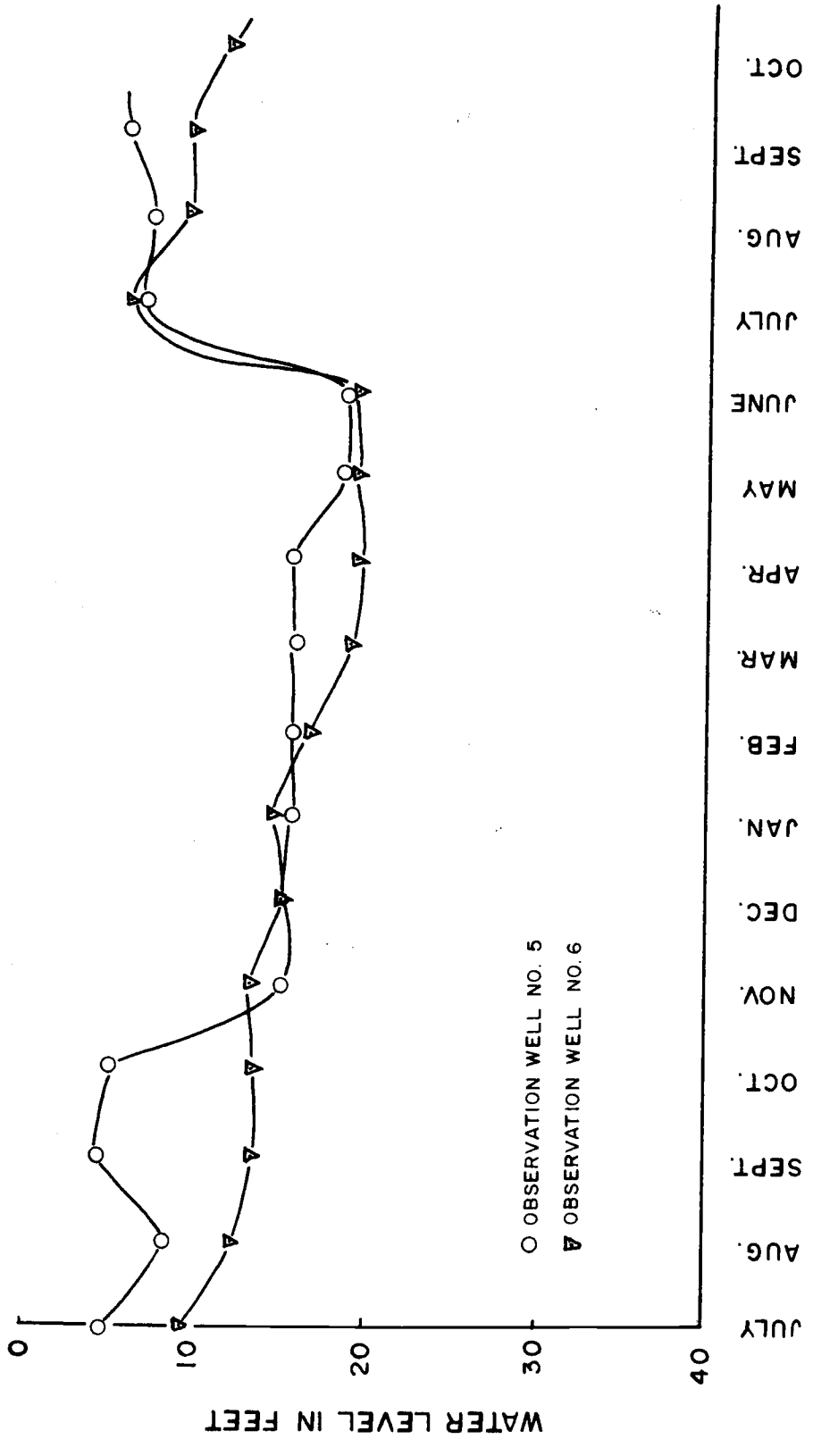


FIGURE 9 WATER LEVEL FLUCTUATION IN OBSERVATION WELLS NOS. 5 AND 6

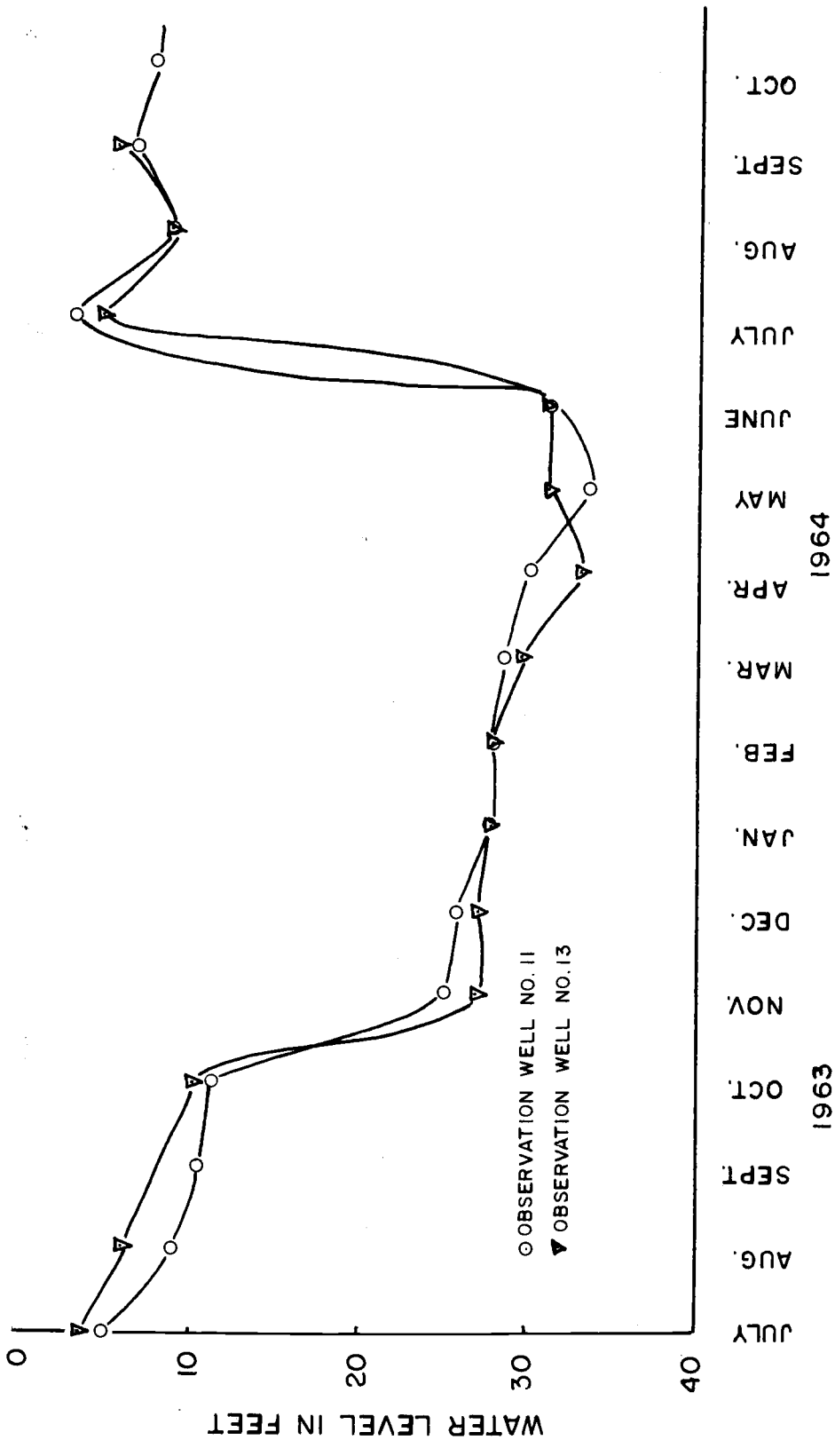


FIGURE 10 WATER LEVEL FLUCTUATION IN OBSERVATION WELLS NOS. 11 AND 13

The water level measurements in the Mudiriya Garden well (Fig. 11) reflects the long term water level fluctuation in that area from 1909-1966. Dates of observations and water levels are shown in Fig. 12. Figure 12 shows that there is no overall decline in the water table at that location through the past 57 years.

Movement of Ground Water

The movement of ground water is determined by the rock permeability and the general configuration of the hydrologic boundaries. The rate of the movement may vary from a few feet per year to several feet per day depending on permeability and hydraulic gradient.

At Kassala the ground water moves toward the northwest. The elevation of the water table in February, 1964, varied between 505 meters (1626 feet) above mean sea level in the south to 486 meters (1587 feet) in the north (Plate 5). The average hydraulic gradient is 2 meters per kilometer (10 feet per mile).

The elevation of the water table in September, 1964, varied between 512 meters (1680 feet) above mean sea level in the south to 496 meters (1628 feet) above sea level in the north (Plate 6). The average hydraulic gradient is 1.6 meters per kilometer (8 feet per mile).

The difference in the water table elevation between February, 1964, and September of the same year is due to the effect of the Gash River which generally starts to flood between July and September of each year.

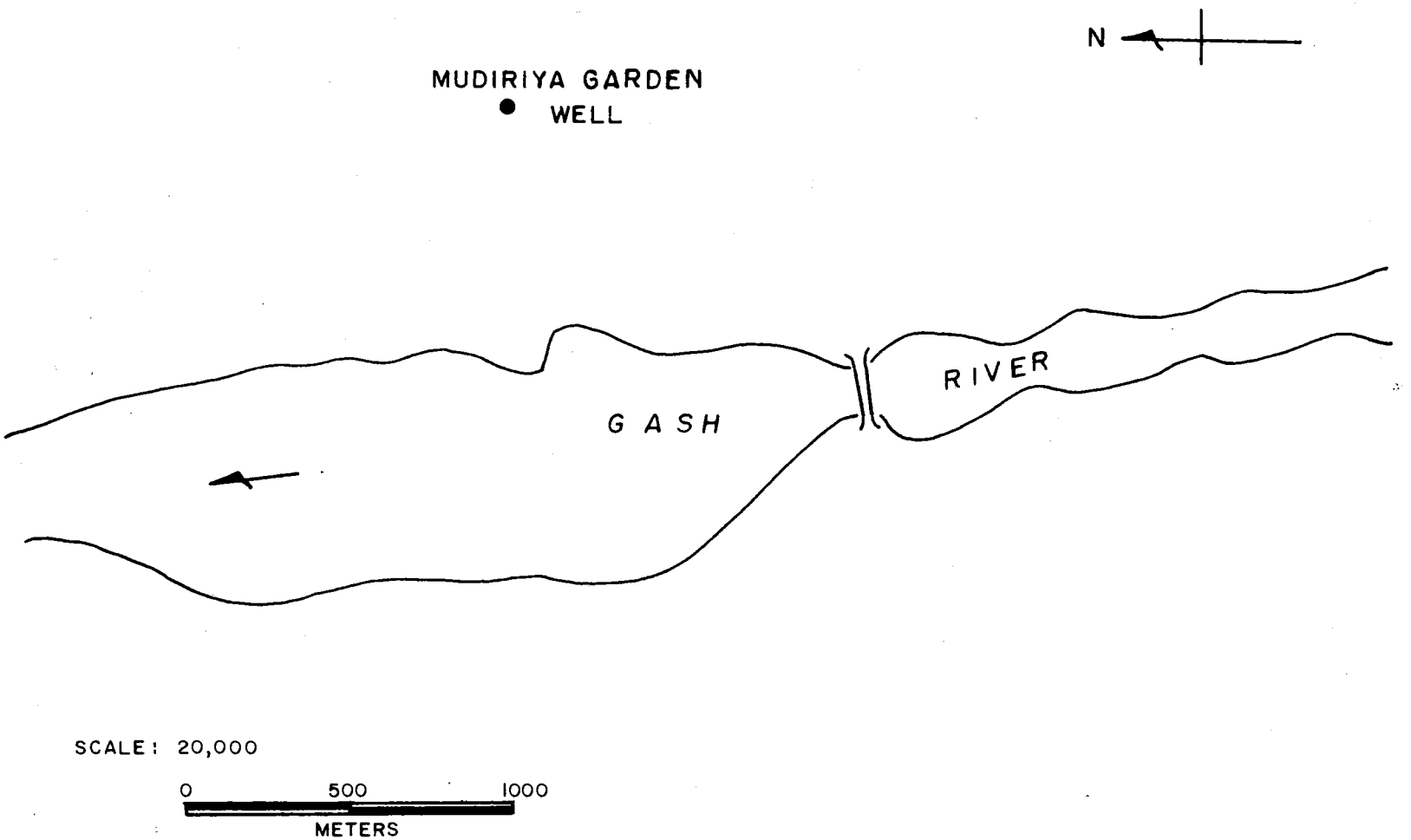


FIGURE 11 MAP SHOWING THE LOCATION OF MUDIRIYA GARDEN WELL AT KASSALA TOWN

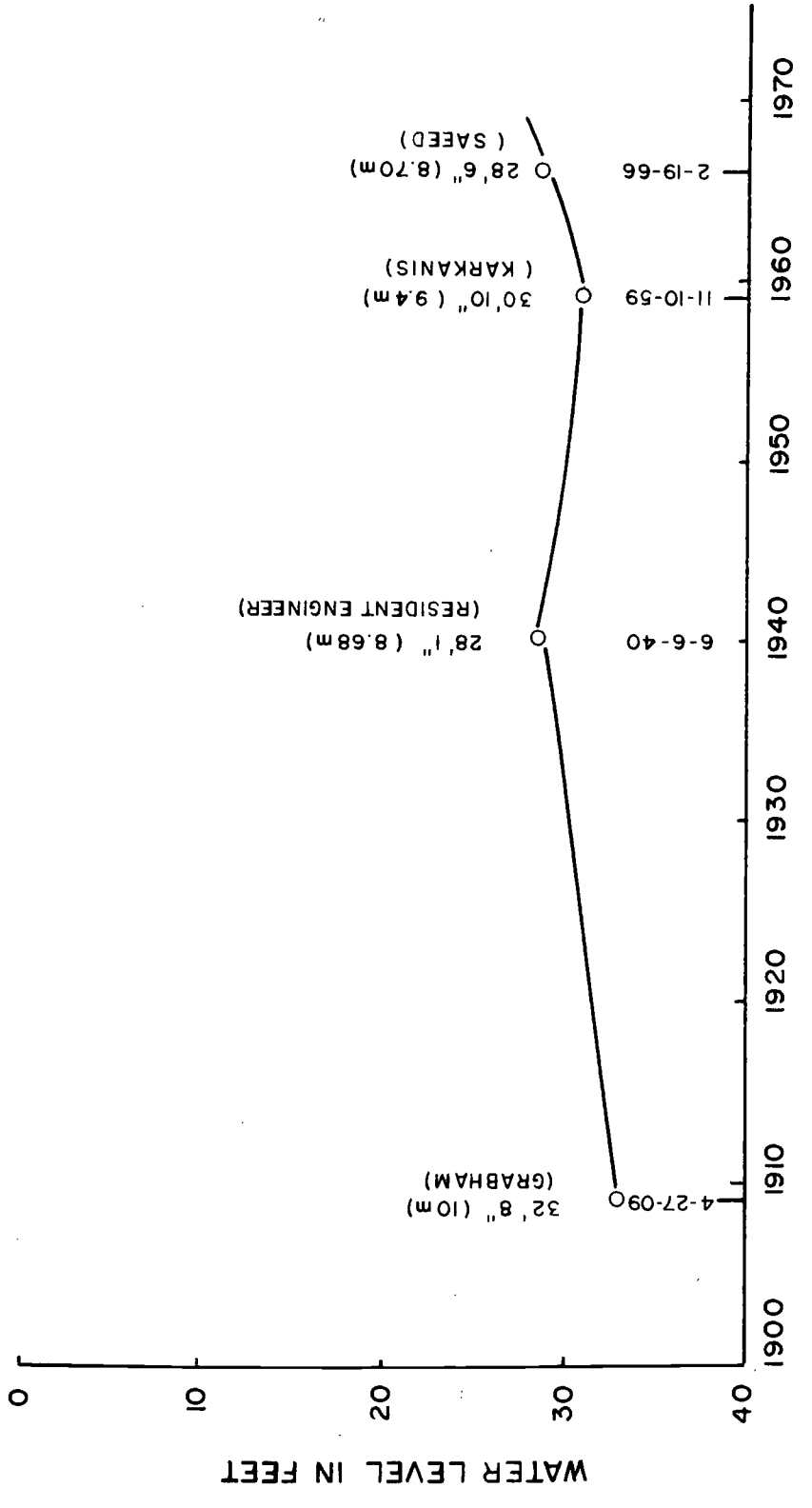


FIGURE 12 WATER LEVEL FLUCTUATIONS FOR 57 YEARS IN MUDIRIYA GARDEN WELL

GROUND WATER APPRAISAL

Hydrologic Properties of the Aquifer

The amount of water that can be pumped from an aquifer perennially depends primarily on the capacity of the aquifer to transmit water from areas of recharge to areas of discharge, the amount of water available for recharge, and the amount of water in storage in the aquifer. To estimate accurately the amount of water that can be pumped perennially, the hydraulic characteristics of the aquifer must be known. Aquifer performance or pumping tests are the best method of determining the hydraulic characteristics. These characteristics are permeability, transmissivity, and storage.

The coefficient of permeability was defined by Meinzer (1923) as the rate of flow of water in gallons per day through a cross sectional area of one square foot under a hydraulic gradient of foot per foot at 60°F. Theis (1935) introduced the term coefficient of transmissivity T, which is expressed as the rate of flow of water, at the prevailing temperature, in gallons per day, through a vertical strip of the aquifer one foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 per cent. Ferris, Knowles, Brown, and Stallman (1962) defined the coefficient of storage, S, of an aquifer as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to the surface.

In order to determine the hydraulic characteristics of the Gash basin at Kassala, the following methods were used:

1. Non-equilibrium method using Theis matching curve for estimating the coefficient of transmissivity and coefficient of storage.

2. Modified non-equilibrium for estimating the coefficient of transmissivity and the coefficient of the storage.

3. Theis recovery method for estimating the coefficient of transmissivity.

4. Specific capacity of some well for estimating the coefficient of transmissivity.

Non-Equilibrium Method

In order to determine the coefficient of the transmissivity and the coefficient of the storage, an aquifer test was run during February 17 and 18, 1966, at the Horticulture farm. The pumping well has a diameter of 8-5/8 inches. The rate of discharge was 100 gpm. and continued for a period of 40 hours. The drawdown was measured by a steel tape in the observation well located 95 feet south of the pumping well. Table 7 shows the results of the pumping test.

Using the non-equilibrium formula developed by Theis (1935)

$$T = \frac{114.6Q}{s} \int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u}\, du$$

Table 7. Calculated Data of the Observation Well

Time, t, in Minutes	Drawdown in Feet	Time in Days	r^2/t
90	0.02	6.25×10^{-2}	1.40×10^{5}
120	0.04	8.33×10^{-2}	1.10×10^{5}
240	0.07	1.67×10^{-1}	5.40×10^{4}
360	0.09	2.50×10^{-1}	3.60×10^{4}
480	0.14	3.33×10^{-1}	2.70×10^{4}
600	0.17	4.17×10^{-1}	2.20×10^{4}
900	0.22	6.25×10^{-1}	1.40×10^{4}
1200	0.24	8.33×10^{-1}	1.10×10^{4}
1500	0.27	1.06×10^{0}	8.70×10^{3}
1800	0.31	1.25×10^{0}	7.20×10^{3}
2400	0.34	1.67×10^{0}	5.40×10^{3}

where T = Coefficient of transmissivity in gpd per foot

Q = The discharge of the pumped well in gpm

s = The drawdown in feet

r = The distance from the pumped to the point of observation in feet

S = The coefficient of storage expressed as decimal fraction

t = Time in days since pumping started

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

The part of the equation that lies to the right of the integral sign is not directly integrable, but it can be evaluated as a series:

$$\int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u}\,du = W(u) = -0.577216 - \log u + \frac{u-u^2}{2.21} + \frac{u^3}{3.31}$$

In the simplest form, the non-equilibrium formula may be written:

$$T = \frac{114.6QW(u)}{s}$$

where W(u) is a symbol used to represent the series that evaluates the exponential integral and is generally read "well function" and as already indicated, $u = \frac{1.87r^2S}{Tt}$.

The data from the observation well (Table 7) were plotted as s versus r^2/t on log/log paper as shown in Fig. 13. The observed-data plots of $W(u)$ versus u were made on a log/log paper of the same scale. The following results were obtained:

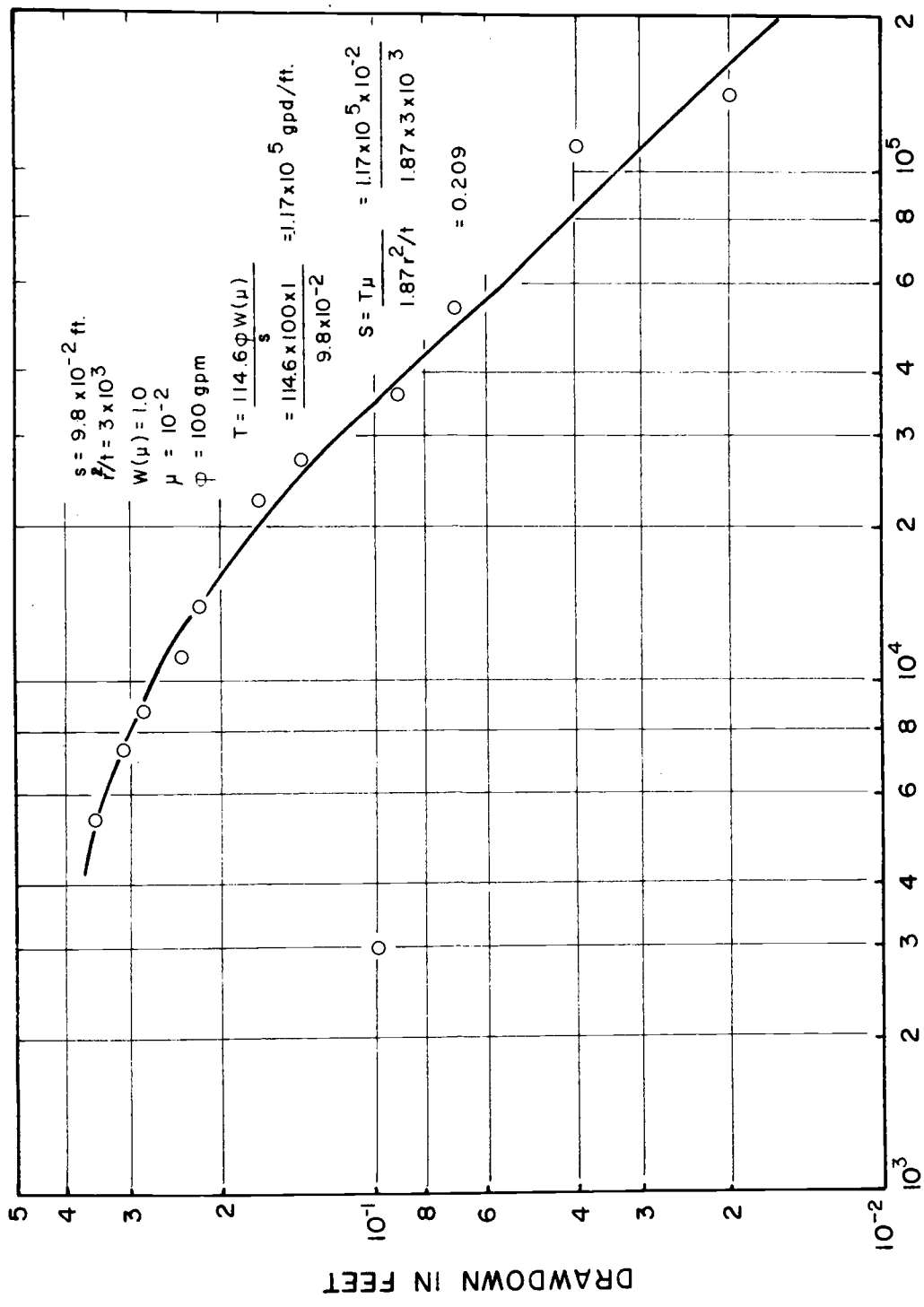


FIGURE 13 GRAPH SHOWING CURVE OBTAINED BY PLOTTING LOG OF DRAWDOWN AGAINST LOG r^2/t FOR THE OBSERVATION WELL

$$s = 9.8 \times 10^{-2} \text{ feet}$$

$$r^2/t = 3 \times 10^3$$

$$W(u) = 1.0$$

$$u = 10^{-2}$$

$$Q = 100 \text{ gpm}$$

$$T = \frac{114.6QW(u)}{s}$$

$$= \frac{114.6 \times 100 \times 1}{9.8 \times 10^{-2}} = 1.17 \times 10^5 \text{ gpd/foot}$$

$$S = \frac{Tu}{1.87r^2/t}$$

$$= \frac{11.7 \times 10^5 \times 10^{-2}}{1.87 \times 3 \times 10^3} = 0.209$$

Modified Non-Equilibrium Formula

In working with the Theis formula, Jacob (1950) pointed out that when the value of u is sufficiently small (generally less than 0.01) and the value of time, t, becomes great, the non-equilibrium formula can be modified to the following form without significant error:

$$s = \frac{Q}{4\pi T} \frac{(\log_e 2.25Tt)}{r^2S}$$

For the drawdown in the observation well, the distance r will be constant, and at two different times, t_1 and t_2, T could be calculated as follows:

$$T = \frac{264Q (\log t_2/t_1)}{(s_2 - s_1)}$$

where s_1 and s_2 are drawdowns corresponding to t_1 and t_2.

The data of Table 7 are shown in Fig. 14 using semilogarithmic papers and plotting the value of t on the logarithmic scale and the value of s on the arithmetic scale as in Fig. 14. Crossing one log cycle then

$$\log t_2/t_1 = 1$$

and

$$T = \frac{264Q}{s}$$

$$Q = 100 \text{ gpm}$$

$$s = 0.26$$

$$T = \frac{264 \times 100}{0.26} = 100.000 \text{ gpd per foot}$$

The coefficient of the storage, S, can be calculated from Fig. 14 by taking the value of the time, t_o, at which the straight line intercepts with the zero-drawdown.

$$S = \frac{0.3\ Tt_o}{r^2}$$

$$t_o = 1.2 \times 10^2$$

$$= \frac{0.3 \times 100.000 \times 1.2 \times 10^2}{(95)^2 \times 144} = 0.277$$

Theis Recovery Method

Theis recovery formula can be applied to determine the transmissivity of the aquifer in the same manner as the modified non-equilibrium formula is used:

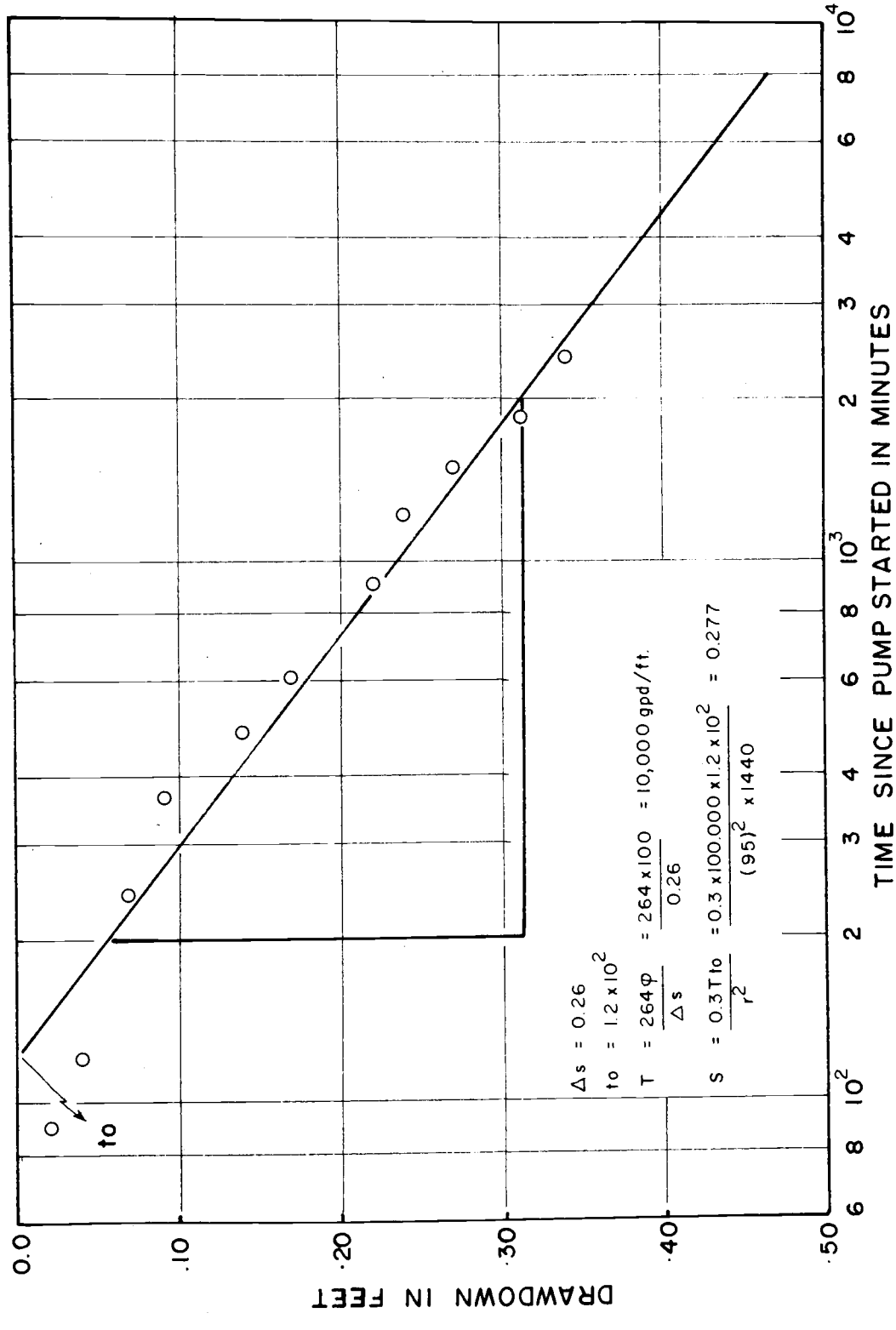


FIGURE 14 GRAPH SHOWING CURVE OBTAINED BY PLOTTING THE DRAWDOWN s AGAINST LOG TIME t FOR THE OBSERVATION WELL

$$T = \frac{264Q}{s'} \log_{10} t/t'$$

where

t = time since pumping started

t' = time since pumping stopped

s' = the residual drawdown

The residual drawdown is defined as the difference between the original static water level and the depth to the water at a given instant during the recovery period.

The residual drawdown s' versus the time ratio t/t' in Table 8 is plotted on semilogarithmic paper, s' on the arithmetic scale and ratio t/t' on a logarithmic scale as is shown in Fig. 15. Choosing one log cycle, the following results were obtained:

$s' = 0.55$ feet

$Q = 250$ gpm

$$T = \frac{264Q}{s'}$$

$$= \frac{264 \times 250}{0.55} = 1.2 \times 10^5 \text{ gpd/foot}$$

By plotting the recovery data in Table 8 (s - s') versus the time, t' (time since pump test stopped) on semilogarithmic paper, in the same way as in the residual drawdown, and crossing one log cycle as in Fig. 16, the following results were obtained:

Table 8. Residual Drawdown and Recovery Data for the Well No. 1834

Time Since Pump Test Started (t min.)	Time Since Pump Test Stopped (t' min.)	Ratio t/t'	Depth to Water Level (in ft.)	Residual Drawdown (s') (in ft.)	Calculated Recovery (s-s') (in ft.)	Remarks
600	0	0.00	32.50	4.03	0.00	Static water level is 28.47 ft. Q = 250 gpm.
601	1	601	29.58	1.11	2.92	
602	2	301	29.35	0.88	3.15	
604	4	150	29.18	0.71	3.32	
607	7	86.70	29.14	0.67	3.36	
610	10	61.00	29.09	0.62	3.41	
613	13	47.15	29.00	0.53	3.50	
618	18	34.30	28.93	0.46	3.57	
623	23	27.08	28.83	0.36	3.67	
631	31	20.35	28.68	0.21	3.82	
640	40	16.00	28.64	0.17	3.86	
645	45	14.10	28.60	0.13	3.90	
650	50	13.00	28.57	0.10	3.93	
660	60	11.00	28.54	0.07	3.96	
670	70	9.60	28.51	0.04	3.99	
680	80	8.50	28.49	0.02	4.01	

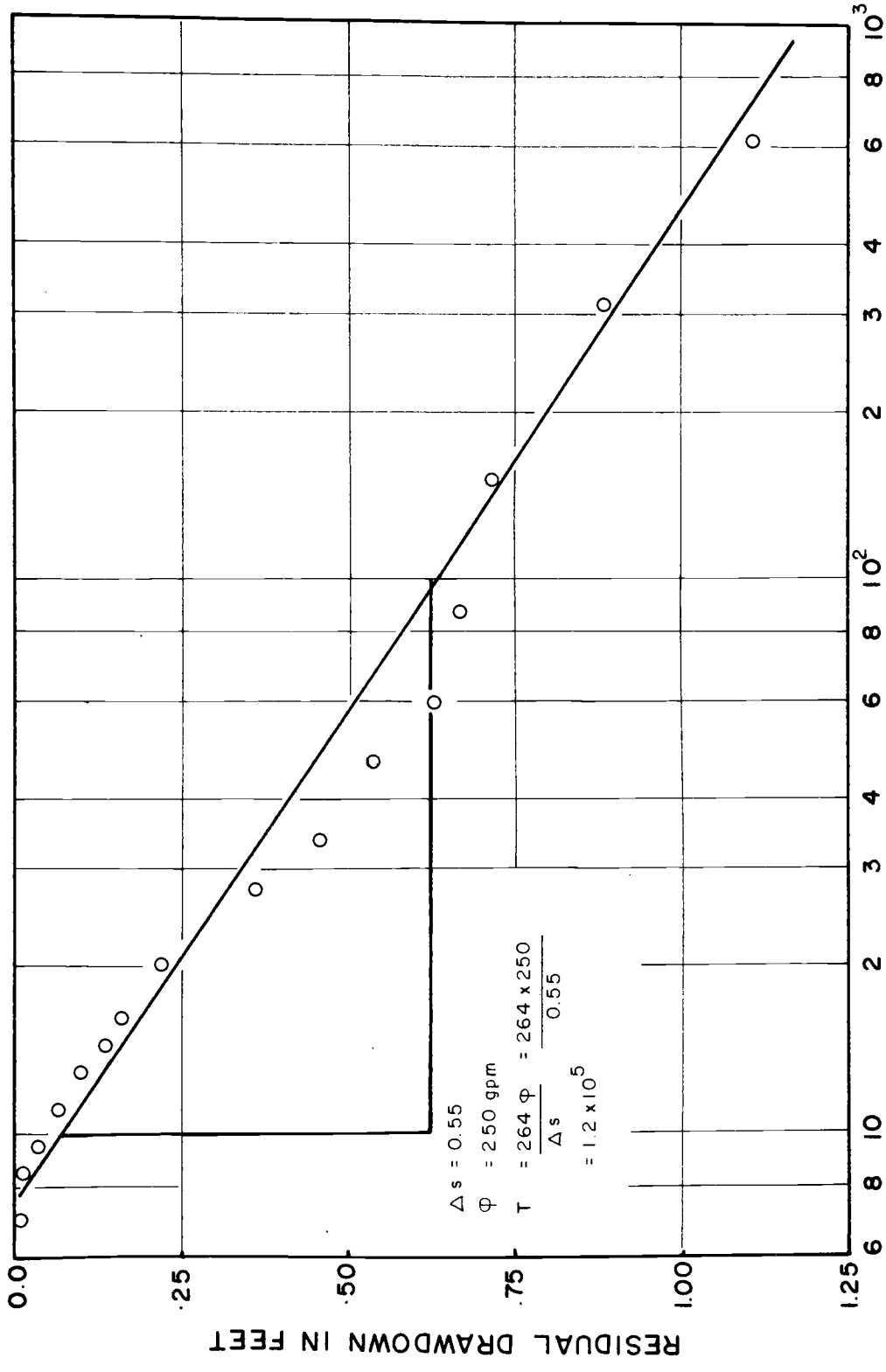


FIGURE 15 GRAPH SHOWING CURVE OBTAINED BY PLOTTING RESIDUAL DRAWDOWN AGAINST LOG (t/t') FOR WELL NO. 1834

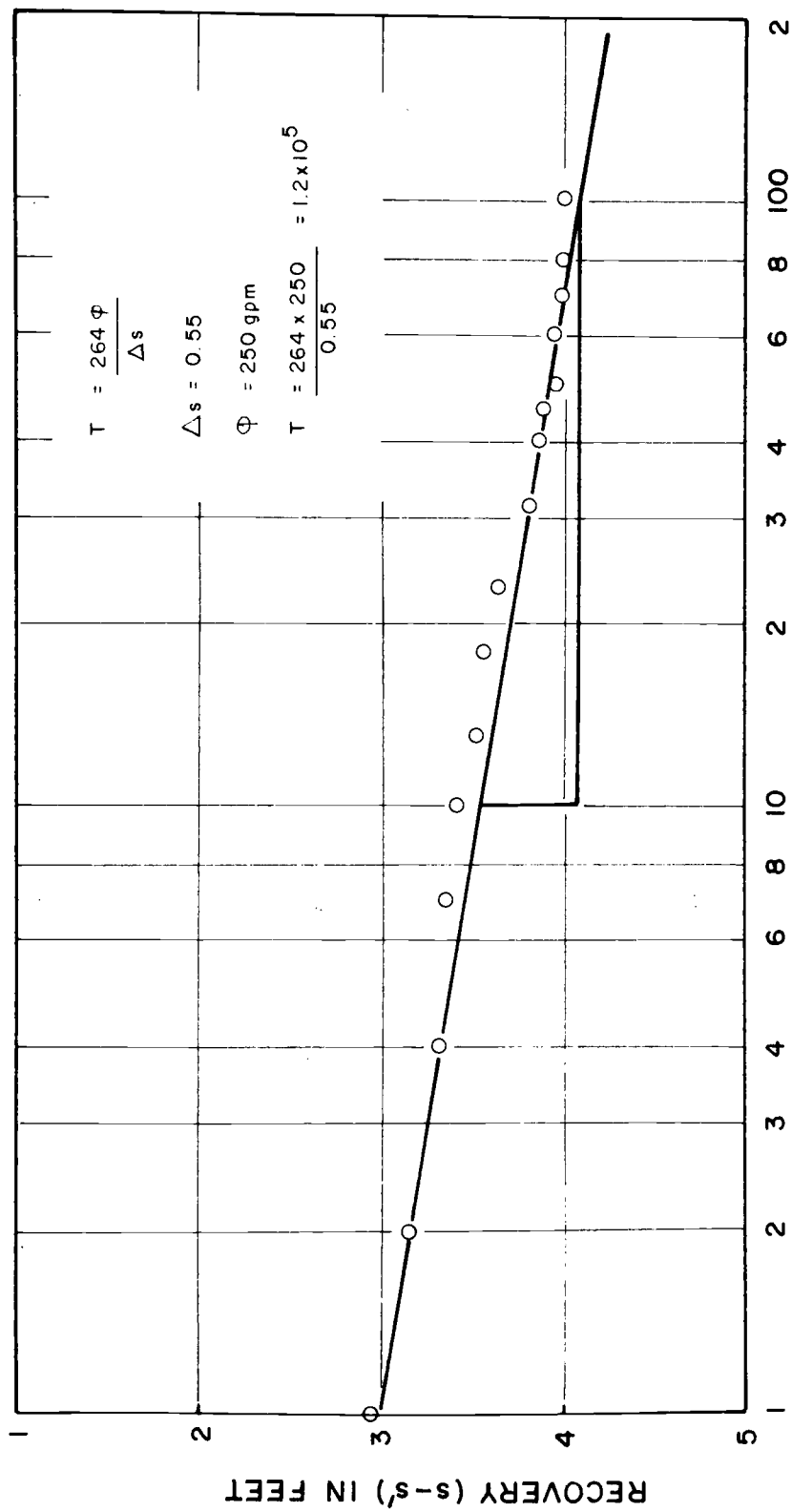


FIGURE 16 GRAPH SHOWING THE TIME RECOVERY FOR THE WELL NO. 1834

$$s = 0.55 \text{ feet}$$

$$Q = 250 \text{ gpm}$$

$$T = \frac{264Q}{s}$$

$$= \frac{264 \times 250}{0.55} = 1.2 \times 10^5 \text{ gpd/foot}$$

Specific Capacities of Wells

Specific capacity of a well is its yield per unit of drawdown. It is expressed as gallons per minute per foot of drawdown. For the steady state condition, T can be calculated from the following equation:

$$T = \frac{527.7Q \log_{10} r_2/r_1}{s}$$

$$\frac{Q}{s} = \text{specific capacity} = Cs$$

$$T = 527.7 \times Cs \log r_2/r_1$$

If the pumping well has a radius of one foot and the r_2 is 10,000, then

$$T = 527.7 \times Cs \times 4.0$$

$$= 2000 \times Cs$$

Table 9 shows the specific capacities of some wells in the study area. From the table, the transmissivity ranges between 2.4×10^4 to 2.1×10^5 gpd per foot.

Ground Water Storage Capacity

The ground water storage capacity is defined as the volume of water that can be drained by gravity or can be pumped from materials

Table 9. Specific Capacities of Some Wells

Location Area	Owner	Discharge (gpm)	Drawdown Feet	Specific Capacity (gpm/ft.) of draw-down	Transmis-sivity = Cs x 2000 gpm/ft.
Garb El Gash B. H.No. 1834	Municipality	250	4.03	61	122,000
Garb El Gash B. H. No. 1834	Municipality	250	4.50	55.55	111,000
Tukrof West	Mohamed Kider Dunbalab B. H. No. A	210	2.00	105	210,000
"	Mohamed Kider Dunbalab B. H. No. B	200	5.00	40.00	80,000
"	Mohed. Osman Wagie	192	16.00	12.00	24,000
"	Abdel Rahim Mahgoub	192	10.00	19.20	38,400
Tukrof	Ibrahim Fad El Mola	192	2.00	96	192,000
"	Mohed. Babiker Atta	180	10.00	18	36,000

underlying a designated ground water unit. It may be defined also as volume of water required to resaturate the deposits after they are drained. To estimate the storage capacity of the Gash aquifer at Kassala, the following procedure was used, employing the indicated successive steps:

1. Subdivision of the Gash aquifer into four subareas,

2. Estimation of the average saturated thickness of the aquifer underlying each subarea,

3. Grouping the materials described in the test-hole logs into six classes,

4. Assignment of specific yield to each class,

5. Calculating average thickness of each class in the subarea,

6. Calculating specific yield for each subarea, and

7. Computation of ground storage in each subarea.

Subdivision of the Gash Aquifer into Subareas

The aquifer in the study area has been subdivided into four subareas as shown in Plate 1. The subareas are:

A.	Tukrof east, with an area of	8,100	acres
B.	Tukrof west "	9,300	acres
C.	Kassala town "	13,500	acres
D.	Wad Shareefei and el Sabil	9,400	acres
	Total Area	40,300	acres

Estimation of the Average Saturated Thickness of the Aquifer Underlying Each Subarea

The average saturated thickness of the aquifer underlying each subarea was computed as follows:

1. The static water level in the wells found in each subarea was measured in February, 1966. The average static water level in each subarea was found to be

Tukrof east = 30 feet below the ground surface

Tukrof west = 40 " " " " "

Kassala town = 35 " " " " "

Wad Shareefei and el Sabil = 35 " " " " "

2. The average static water level in each subarea was subtracted from the total depth of each test hole in the subarea (each test hole was drilled to the Basement rock) to give the average saturated thickness in the test holes in each subarea. Table 10 shows the computed average saturated thickness in each subarea.

Table 10. Average Saturated Thickness in Each Subarea

Subarea	Average Saturated Thickness
A. Tukrof east	70 feet
B. Tukrof west	106 feet
C. Kassala town	100 feet
D. Wad Shareefei and el Sabil	71 feet

Grouping the Materials Described in the Logs

The materials described in the test-hole logs were grouped into six classes. The classifications were based on hand specimen identification with the help of some sieve analyses. However, the samples were collected from rotary drilled wells and, consequently, it is very possible that some of the fine materials were washed out of the samples. The six classes are as follows:

Class No.	Material Logged
I	Gravel, very coarse sand with gravel and pebbles
II	Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand
III	Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel
IV	Fine sand, clayey sand
V	Sandy clay, silt, silty clay, gravelly clay
VI	Clay (plastic)

Assignment of Specific Yields to the Water-Bearing Materials

Meinzer (1923, p. 28) defined the specific yield of a rock or a soil, with respect to the water, as the ratio of the volume of water that will drain by gravity from a saturated rock to the total volume of the rock, this ratio usually being expressed as a percentage.

The specific retention of a rock or a soil has been defined by Meinzer (1923, pp. 28-29) as the ratio of the volume of water that will be retained against gravity drainage from a saturated rock to total volume of the rock. It usually is expressed as a percentage.

Johnson (1967) presents a table (Table 11) which summarizes values of specific yield obtained during many previous investigations. The table shows a specific yield averaged from all values reported for each texture of rock or soil material. The data presented in Table 11 (see page 57) are taken as a guide for the estimation of the specific yield of the different materials of the Gash aquifers. The specific yield values which were assigned to the six classes of material in the test-hole logs are presented in Table 12.

Table 12. Classes of the Water-Bearing Material and Their Approximate Assigned Specific Yield

Class No.	Material Logged	Assigned Specific Yield
I	Gravel, very coarse sand with gravel, etc.	25
II	Coarse sand, coarse sand with pebbles, etc.	25
III	Medium sand, medium and coarse sand, etc.	20
IV	Fine sand, clayey sand	10
V	Sandy clay, silt, silty clay, gravelly clay	5
VI	Clay (plastic)	1

Table 11. Compilation of Specific Yields for Various Materials[a]

(All values rounded off to nearest whole percentage)

Material	Valley fill, California (Bekis, 1934)	Mokelumne area, California (Piper and others, 1939)	Santa Ynez River basin, California (Upson and Thomasson, 1951)	Sacramento Valley, Calif. (Poland and others, 1949)	Smith River plain, California (Back, 1957)	Ventura County, Calif. (Calif. Water Resources Board, 1956)	Santa Margarita Valley, Calif. (Calif. Dept. Public Works, 1936)	Tia Juana Basin, Calif. (Calif. Water Rights Board, 1957)	San Luis Obispo County, Calif. (Calif. Water Resources Board, 1958)	San Joaquin Valley, Calif. (Davis and others, 1959)	Eureka area, California (Evenson, 1959)	Santa Ynez Basin, Calif. (Wilson, 1959)	Reelma Doab, Pakistan (Kazmi, 1961)	Napa-Sonoma Valleys, Calif. (Kunkel and Upson, 1960)	Humboldt River Valley, Nev. (Cohen, 1963)	Unconsolidated alluvium (Preuss and Todd, 1963)	Little Bighorn River valley, Montana (Moulder and Others, 1960)	Average specific yield
Clay	1	4	2	3	1	0	1	1	3	3	3	5	3	3	1			2
Silt	10	4	12	3	5	3	10	10	5	5	10	5	5	5	19	4	17	8
Sandy clay	10	4	12	3	5	5	5	5	5	5	10			10				7
Fine sand	21	26	12	10	10	25	28	25	25	10	20	20	27	20	26	33	32	21
Medium sand	31	26	30	20	15	25	28	30	25	25	20	30	28	20	28	28	32	26
Coarse sand	31	35	35	20	25	25	28	32	25	25	20	30	23	20	27	28	32	27
Gravelly sand	32	35	35	20	25	22	28	28	21	25	20		23	20		27	32	25
Fine gravel	27	35	35	25	25	22	26	26	21	25	25	25	23	25	19	23	25	25
Medium gravel	21			25	25	22	23	23	21	25	25	25	23	25		23	25	23
Coarse gravel	14			25	25	22	22	18	21	25	25	25	23	25		23		23

a. From A. J. Johnson, U.S.G.S. Water-Supply Paper 1662-D, 1967, p. 70.

Calculating Average Thickness of Each Class in the Subareas

The average thickness (per cent) for each of the six classes in the subareas was estimated and is recorded in the Appendix. Table 13 shows the per cent thickness of each class in the subareas within the saturated zone of the aquifer.

Table 13. Per Cent Thickness of the Six Classes in the Subareas

Subarea	Average Thickness (per cent)					
	Class I	Class II	Class III	Class IV	Class V	Class VI
Tukrof east	6.30	3.70	14.40	19.10	40.00	16.50
Tukrof west	12.00	5.00	6.10	10.70	63.00	3.20
Kassala town	18.40	35.20	4.60	6.20	27.60	8.00
Wad Shareefei and el Sabil	37.30	9.80	8.90	23.00	21.00	-

Calculating Specific Yield for Each Subarea

The specific yield for each subarea was estimated as follows:

1. The assigned specific yield for each class of the material logged in the test holes was multiplied by the per cent thickness of each class in the subarea to give the specific yield for each class in the subarea.

2. The total specific yield for each subarea was obtained by combining the specific yield values of the six classes in the subarea. Table 14 summarizes the calculation of the specific yield in Tukrof east, Tukrof west, Kassala town, Wad Shareefei, and el Sabil subareas.

Table 14. Calculation of the Specific Yield in Each Subarea

Class No.	Material Logged	Assgnd. Spec. Yield for Each Class	Thickness (per cent)	Spec. Yield for the Subarea
	A. Tukrof East			
I	Gravel, very coarse sand with gravel and pebbles	25	6.30	1.575
II	Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand	25	3.70	0.925
III	Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel	20	14.40	2.880
IV	Fine sand, clayey sand	10	19.10	1.910
V	Sandy clay, silt, silty clay, gravelly clay	5	40.00	2.000
VI	Clay	1	16.50	0.165
	Total		100.00	9.455
	B. Tukrof West			
I	Gravel, very coarse sand with gravel and pebbles	25	12.00	3.000
II	Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand	25	5.00	1.000
III	Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel	20	6.10	1.220
IV	Fine sand, clayey sand	10	10.70	1.070

Table 14.--Continued

Class No.	Material Logged	Assgnd. Spec. Yield for Each Class	Thickness (per cent)	Spec. Yield for the Subarea
V	Sandy clay, silt, silty clay, gravelly clay	5	63.00	3.150
VI	Clay	1	3.20	0.032
	Total		100.00	9.722
		C. Kassala Town		
I	Gravel, very coarse sand with gravel and pebbles	25	18.40	4.600
II	Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand	25	35.20	8.800
III	Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel	20	4.60	0.920
IV	Fine sand, clayey sand	10	6.20	0.620
V	Sandy clay, silt, silty clay, gravelly clay	5	27.60	1.380
VI	Clay	1	8.00	0.000
	Total		100.00	16.400
		D. Wad Shareefei and El Sabil		
I	Gravel, very coarse sand with gravel and pebbles	25	37.30	9.325
II	Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand	25	9.80	2.450

Table 14.--Continued

Class No.	Material Logged	Assgnd. Spec. Yield for Each Class	Thickness (per cent)	Spec. Yield for the Subarea
III	Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel	20	8.90	1.780
IV	Fine sand, clayey sand	10	23.00	2.300
V	Sandy clay, silt, silty clay, gravelly clay	5	21.00	1.050
VI	Clay	1	-	-
	Total		100.00	16.905

Computation of the Storage Capacity

The storage capacity of the Gash basin aquifer was estimated as follows:

1. The ground storage in each subarea was computed as: area x average saturated thickness x estimated specific yield.

2. The estimated storage in the four subareas was combined to give the total storage capacity in the Gash River aquifer. Table 15 summarizes the estimates of ground water storage capacity in the Gash River basin at Kassala. The table indicates that the water available for pumping in the reservoir is about 4.84×10^5 acre-feet (approximately 600×10^6 cubic meters).

Table 15. Estimates of Ground Water Storage Capacity of the Gash River Basin at Kassala

Subarea	Surface Area (acres)	Specific Yield for the Subarea (per cent)	Saturated Thickness (in feet)	Estimated Storage (acres-feet)
Tukrof east	8,100	9.500	70	53,865
Tukrof west	9,300	9.700	106	95,623
Kassala town	13,500	16.400	100	221,400
Wad Shareefei and el Sabil	9,400	16.900	71	112,791
Total	40,300	-	-	483,693

Annual Discharge From the Reservoir

The annual amount of water used by Kassala town in 1965 was estimated as 1080 acre-feet (1,334,000 cubic meters). No previous

estimation has been made for the amount of the water used for irrigation. Therefore, the following estimate of the amount of water required annually for irrigation in the study area has been prepared.

The total cultivated land at Kassala amounts to 5,342 acres. The distribution of these acres is as follows:

Bananas	2,462 acres
Onions	1,227 "
Vegetables	743 "
Grapefruit	150 "
Oranges	130 "
Tangerines	23 "
Lemons	245 "
Mango	275 "
Guava	87 "
Total	5,342 acres

Erie, French, and Harris (1965) estimated the consumptive use of water by some crops in Arizona. Table 16 shows their results for some crops cultivated in Arizona which are similar to some crops cultivated in Kassala area.

Table 16. Seasonal Consumptive Use of Water by Some Crops in Arizona

Crop	Consumptive Use in Inches	Station
Grapefruit	47.9	Phoenix
Oranges (Navel)	39.1	Phoenix
Vegetables		
Onions (dry)	23.3	Mesa
Onions (green)	17.5	"
Potatoes	24.3	"
Lettuce	8.5	"
Carrots	16.6	"
Cauliflower	18.6	"

Simmonds (1959, p. 186) gives a table which shows the recommended range for the amount of water required for irrigation of bananas in different countries. The following countries have been chosen as examples:

Egypt	8 inches per month
India	10 " " "
Jamaica	10 " " "
Honduras	12 " " "

Higgins (1906) states that the annual range of water requirements for mango irrigation in Hawaii is from 50 to 70 inches.

The results obtained in Arizona by Erie et al. (1965) for grapefruit, oranges, onions, and vegetables, using India as an example for bananas, and the Higgins experiment in Hawaii for mango, will be taken as guides to estimate the amounts of water required annually to irrigate the cultivated crops in the study area. The consumption of water by oranges will be used for oranges, tangerines, lemons, and guava. As a safety measure 50 per cent will be added to the water consumption of each crop to account for losses during the irrigation process and the difference in evapotranspiration rates. Table 17 shows that the calculated amount of water that must be pumped annually from the aquifer for irrigation purposes is about 48,365 acre-feet (about 60×10^6 cubic meters).

Table 17. Calculated Amount of Water Used Annually for Irrigation at Kassala

Crop	Cultivated Area in Acre	Consumptive Use of Water in feet/year	Amount of Water Required in acre-feet
Bananas	2,462	15	36,930
Onions	1,227	3	3,681
Vegetables	743	3	2,229
Mango	275	8	2,200
Grapefruit	150	6	900
Oranges	130	5	650
Lemons	245	5	1,225
Tangerines	23	5	115
Guava	87	5	435
Total	5,342		48,365

In the southern part of the study area there is an area of about 3,000 acres which is covered by Dom (Hyphaene thebica), Hashab (Acacia senegal), and Sidr (Ziziphus spinachristi) forests. These forests are concentrated along the Gash channel at el Sabil and Wad Shareefei subareas and have a volume density which may reach 100 per cent.

Gatewood, Robinson, Colby, Hem, and Halpenny (1950) found that the total water used during 12 months by phreatophytes common to the lower Safford Valley, Arizona, computed for a growth of 100 per cent volume density was saltcedar, 7.2; bacchair, 4.7; mesquite, 3.3, in acre-feet per acre.

In the Kassala area a value of 3 acre-feet per acre as annual consumption of water can be assigned to the plants that grow in the forest area. The area of the forests is about 3,000 acres; therefore, the estimated discharge through evapotranspiration is about 9,000 acre-feet (about 11 x 10^6 cubic meters).

The total estimated annual discharge from the Gash River basin at Kassala is about 58,000 acre-feet (approximately 73 x 10^6 cubic meters), which is the summation of discharge for domestic purpose, irrigation, and evapotranspiration. This amount of water forms about 12 per cent of the total storage of the ground water reservoir of the Gash River basin at Kassala.

Storage Changes

From the water level fluctuation in the observation wells (Figs. 8-10), it was found that the annual average fluctuation within

the area of the observation wells is about 20 feet. Assuming an average water level fluctuation of 11 feet for the entire area of the aquifer, the storage change is equal to

$$11 \times 13.16 \times 40,300 = 58,300 \text{ acre-feet}$$

where 13.16 percent = the average specific yield of the aquifer and 40,300 acres = the total area of the aquifer.

Assuming that the subsurface inflow equals the subsurface outflow, the above amount of water will account for the water discharged annually from the aquifer for irrigation, domestic uses, and evapotranspiration. However, some of this loss may be due to excess outflow over inflow, but the amount of this excess cannot be determined.

QUALITY OF WATER

The ground water in the study area is of excellent quality. The total dissolved solids average about 230 parts per million. The analyses of the ground water samples were made by Wellcome Chemical Laboratory of the Sudan Ministry of Health. Table 18 shows the chemical analyses for water from some selected wells in the study area.

Hydrogen-ion Concentration (pH)

The hydrogen-ion concentration of a solution is a measure of its acidity and is recorded in pH units. The pH unit is defined as the negative logarithm of the concentration of the hydrogen ions in moles per liter. A value of 7.0 is neutral. In the study area the ground water has a pH ranging from 7.4 to 8.3; therefore, the ground water is slightly alkaline.

Total Dissolved Solids

The total concentration of dissolved material is determined from the weight of the dry residue after the evaporation of the water sample at 180°C. This solid residue does not completely coincide with the dissolved material which was originally in the solution since dissolved gases are lost and bicarbonate is converted to carbonate with the loss of CO_2.

In the area of study the total dissolved solids reported range from 180 to 260 ppm. The distribution of the total solids does not follow any pattern in the aquifer.

Table 18. Chemical Analyses of Some Ground Water Samples from the Study Area

Well No.	Location	pH	Total Dissolved Solids ppm.	Hardness as $CaCO_3$ ppm.	Calcium Ca^{++} ppm.	Magnesium Mg^{++} ppm.	Sodium Na^{+} ppm.	Silicate as SiO_2 ppm.	Sulphate ppm.	Nitrate ppm.	Chloride ppm.	Fluoride ppm.
277	Police Garage	7.8	228	90	36	20	-	25	25	2.4	25	-
292	Halab Area	7.8	222	100	26	17	-	-	nil	2.7	23	-
497	Gash Board Water Yard	7.5	260	90	36	24	40	35	18	2.0	14	0.24
602	Halab Area	8.3	220	80	20	10	50	30	10	nil	20	0.60
606	Halanga Area	8.0	180	130	35	10	30	-	nil	nil	10	0.50
644	Halab Area	7.6	260	150	40	12	50	40	nil	0.58	20	0.40
1095	Nersery	8.2	220	156	30	20	36	20	10	1.8	12	0.40
1135	Nersery	8.3	196	92	21	10	35	18	10	1.6	10	0.52
1834	Garb El Gash	7.4	220	130	35	10	50	20	50	nil	25	0.64
1836	El Gash East	8.3	200	90	25	10	40	10	35	nil	25	0.32

Total Hardness

The total hardness is a measure of calcium and magnesium content and is generally expressed as equivalent amounts of calcium carbonates. In the Gash aquifer the hardness ranges from 60 to 160 ppm.

Ions and Compounds in Solution

Calcium, magnesium, sodium, silica, sulphate, nitrate, chloride, and fluoride are the main ions and compounds found in the Gash aquifer water. Since no indurated sedimentary rocks are present in the area, these materials in solution are dissolved from various igneous and metamorphic minerals in the Basement Complex and in the Tertiary and Quaternary alluvial deposits across and through which the water has flowed. The low concentration of ions is due to the fact that most of these minerals are relatively insoluble and that the water is mainly derived from recently fallen rains; that is, it is mainly runoff. Table 18 shows that

Calcium (Ca^{++})	ranges from	20 to 40 ppm
Magnesium (Mg^{++})	" "	10 to 30 ppm
Sodium (Na^{+})	" "	20 to 50 ppm
Silica (SiO_2)	" "	10 to 40 ppm
Sulphate (SO_4^{--})	" "	0.00 to 40 ppm
Nitrate (NO_3^{-})	" "	0.00 to 2.7 ppm
Chloride (Cl^{-})	" "	10 to 30 ppm
Fluoride (Fl^{-})	is less than	1 ppm

Suitability of Ground Water for Irrigation

The suitability of ground water for irrigation is dependent upon the effects of the mineral constituents of the water on both plants and soil. Salts may harm the growth of plants physically and chemically and cause low aeration. Sodium concentration is important in classifying irrigation water because sodium reacts with soil and reduces its permeability, and causes hardening of the soil. Sodium adsorption ratio (SAR), which is recommended by the Salinity Laboratory Staff of the U. S. Department of Agriculture (1954), is one of the most important factors in evaluating irrigation water. It is defined by

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

where the concentration of the constituents are expressed in equivalents per million. (Equivalents per million "epm" are calculated by dividing parts per million by the equivalent weight of the ion under consideration.) The recommended water classification for SAR follows:

SAR	Water Class
10	Excellent
10 - 18	Good
10 - 26	Fair
26	Poor

Table 19 indicates that, based upon this index, the ground water quality in the Gash River basin is excellent for irrigation.

Table 19. SAR of Some Ground Water Samples in the Area of the Study

Well No.	SAR
602	2.28
606	1.24
644	1.60
1095	1.20
1135	1.57
1834	1.91
1836	1.70

DISCUSSION

The pumping test at Kassala town subarea gives a transmissivity of 120,000 gallons per day/foot and a coefficient of storage of about 0.2. These values do not represent the hydrological properties of the entire aquifer because there is a variation in the textural materials in each subarea. Therefore, it is possible to get different values for the transmissivity and storage coefficient of the aquifer. This fact can be recognized from the geological cross sections, grain size analyses, and from the estimation of the specific yield of each subarea.

The estimated values for the specific yields range from 9 per cent to 17 per cent, with an average of 13 per cent for the entire aquifer. The variation of the specific yield values is due to the changing texture of the alluvial sediments in each subarea. The coarse-textured materials such as sand and gravel have a high specific yield and low specific retention, while the fine-textured materials such as silt and clay have a high specific retention and low specific yield. The coarse-textured materials are found at Wad Shareefei, el Sabil, and Kassala town subareas. Therefore, these subareas have high specific yield as compared with Tukrof east and Tukrof west subareas, which have low specific yield due to the presence of the fine-textured materials.

At the Tukrof west subarea the transmissivity coefficients which were measured from the specific capacity of the wells (Table 8)

show a wide variation in values. This variation is due to both the geological conditions and to the development of the wells ("development" means the overall effectiveness of the completion of the well). Geologically, the aquifer shows lateral and vertical variations in lithology. Wells which have been drilled in a formation with a high percentage of coarse materials, such as sand and gravel, will have specific capacities higher than those that have been drilled in a formation which has a high percentage of fine materials, such as silt and clay. The development of the wells affects to a great extent the specific capacity of the wells and the variation may be due to one or more factors such as the position of the screen, the length and size of the screen casing, the depth of the wells, the presence or absence of gravel packing, and the minimization of formation damage due to drilling of the well.

The estimated amount of recoverable water in the ground storage is about 484,000 acre-feet. This amount of water may be higher or lower than the amount of recoverable water which actually is in the reservoir, because the specific yield values assigned to the different layers of the aquifer are based on estimates from other areas. However, the average specific value of 13 per cent, which was obtained from the four subareas, is quite reasonable for the Gash basin aquifer. Therefore, the estimated storage capacity seems to be reasonable.

The annual discharge from storage was estimated to be 58,000 acre-feet. This amount constitutes about 12 per cent of the total storage of the aquifer. Although this amount of water is high, if compared

to the total amount of water in the reservoir, the storage does not show a significant decline in the water level through a period of 57 years, as indicated in the record of the Mudiriya Garden well. This observation well indicates that there is an overall recharge to the ground reservoir, since there is no serious decline in the water level over the 57 years. There is a balance in the aquifer between the water discharged from the reservoir for irrigation, domestic uses, evapotranspiration, and water recharge from the Gash River by influent seepage and direct precipitation. This balance is over a period of years and depends to a great extent upon the amount and duration of the rainfall and flood of the Gash River.

In the future more water can be taken from the reservoir (about 10 per cent of the present annual discharge) without making a serious decline in the water table level, because there is a great possibility that this amount of water discharged from the aquifer will be recharged by the Gash River during the flood seasons.

SUMMARY AND CONCLUSION

1. The geological units in the Kassala area are the Basement Complex of Precambrian age, the Clays of the Plain of Tertiary?-Quaternary age, and the alluvial deposits of Pleistocene to Recent age.

2. The annual precipitation over the area is about 341 mm. (about 13.4 inches) and mainly falls in a three-month period from July to September. The average period for the Gash River flow is about 88 days, and the mean annual discharge is about 381,000 acre-feet.

3. The principal aquifer in the Gash basin is the valley alluvium. The average saturated thickness is about 90 feet. The general movement of the ground water is toward the northwest. The average gradient ranges from 8 to 10 feet per mile. The water table reaches its maximum elevation during the flood season (July to September). During the dry season the water table declines. The average annual water level fluctuation within the observation well area is about 20 feet.

4. The transmissivity of the aquifer as estimated from the pumping test is about 120,000 gallons per day/foot, and the coefficient of storage is about 0.2. The average of the specific yield through the entire basin is about 13 per cent.

5. The storage of the ground water in the reservoir, in February, 1966, was about 484,000 acre-feet (approximately 600 x 10^6 cubic meters). The annual discharge from the basin for irrigation, domestic

uses, and evapotranspiration is about 58,000 acre-feet (approximately 73×10^6 cubic meters). This constitutes about 12 per cent of the storage capacity of the Gash basin reservoir.

6. The annual loss of ground water due to irrigation, domestic uses, and evapotranspiration is recharged by the Gash River during the rainfall season by influent seepage and by direct precipitation over the basin.

7. The ground water of the Gash basin at Kassala is of an excellent quality and can be used safely for irrigation and domestic uses.

APPENDIX

AVERAGE PER CENT OF MATERIAL LOGGED IN THE TEST HOLES WITHIN THE SATURATED ZONE OF THE AQUIFER

APPENDIX

AVERAGE PER CENT OF MATERIAL LOGGED IN THE TEST HOLES WITHIN THE SATURATED ZONE OF THE AQUIFER

A. Tukrof East

Test Hole No.	Classes of Material Logged - Per Cent of Saturated Thickness						Total Thickness of Aquifer
	Class I[a]	Class II[b]	Class III[c]	Class IV[d]	Class V[e]	Class VI[f]	
1	8	-	-	-	92	-	118
5	-	-	56	13	-	31	35
6	-	-	33	-	17	50	89
7	42	-	-	2	40	16	93
8	-	-	-	-	40	60	56
9	-	-	8	53	-	39	103
10	-	18	10	34	38	-	107
11	-	-	67	-	6	27	78
12	6	-	-	49	31	41	65
13	1	24	-	38	26	11	87
14	-	-	42	26	32	-	71
15	-	13	-	47	40	-	35
16	-	-	-	24	76	-	53
17	24	-	-	-	76	-	46
18	14	-	-	-	86	-	34
Average Per Cent	6.30	3.70	14.40	19.10	40.00	16.50	

a. Class I: Gravel, very coarse sand with gravel and pebbles; b. Class II: Coarse sand, coarse sand with pebbles, very coarse sand to coarse sand; c. Class III: Medium sand, medium and coarse sand, medium sand with gravel, medium to coarse sand with gravel; d. Class IV: Fine sand, clayey sand; e. Class V: Sandy clay, silt, silty clay, gravelly clay; f. Class VI: Clay (plastic).

Appendix--Continued

Test Hole No.	Class I[a]	Class II[b]	Class III[c]	Class IV[d]	Class V[e]	Class VI[f]	Total Thickness of Aquifer
			B. Tukrof West				
20	47	4	-	4	45	-	135
21	-	24	-	-	76	-	63
22	-	-	20	7	73	-	41
23	27	10	-	18	45	-	97
24	-	7	-	13	80	-	122
25	2	-	16	17	42	23	133
26	12	-	-	12	70	6	125
27	-	-	20	-	80	-	116
28	21	-	-	25	54	-	110
Average Per Cent	12	5	6.1	10.7	63	3.2	
			C. Kassala Town				
B.H. 1834	37	17	-	4	42	-	120
B.H. 1835	30	70	-	-	-	-	120
B.H. 1836	25	75	-	-	-	-	125
T.H. 38	-	-	23	27	50	-	107
T.H. 39	-	14	-	-	46	40	112
Average Per Cent	18.4	35.2	4.6	6.2	27.6	8	

a, b, c, d, e, f. See page 79.

Appendix--Continued

D. Wad Shareefei and El Sabil

Test Hole No.	Class I[a]	Class II[b]	Class III[c]	Class IV[d]	Class V[e]	Class VI[f]	Total Thickness of Aquifer
29	92	8	-	-	-	-	65
30	10	80	-	-	10	-	65
32	16	4	20	-	60	-	63
33	64	-	-	18	18	-	84
34	27	-	-	66	7	-	75
35	84	16	-	-	-	-	51
36	22	-	19	19	40	-	37
37	7	-	50	17	26	-	83
40	74	-	9	-	17	-	112
41	14	-	-	50	36	-	70
42	-	-	-	82	18	-	55
Average Per Cent	37.3	9.8	8.9	23	21	-	

a, b, c, d, e, f. See page 79.

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TUKROF WEST SUBAREA

TUKROF EAST SUBAREA

KASSALA SUB AREA

TOWN

ELSABIL AND WAD SHAREEFEI SUBAREA

J. MOKRAM

J. KASSALA

GASH RIVER

TH

OBSERVATION WELL

A

A'

B

B'

C

C'

N

EXPLANATION

TEST HOLE

WELL

AQUIFER BOUNDARY

SUBAQUIFER BOUNDARY

CROSS SECTION

SCALE: 1:80,000

0 2 4 6 8

KM

SAEED 1968

FIGURE 17

PLATE I

MAP OF KASSALA AREA SHOWING THE SUBAREAS OF THE AQUIFER AND LOCATION OF THE TEST HOLES AND SOME WELLS

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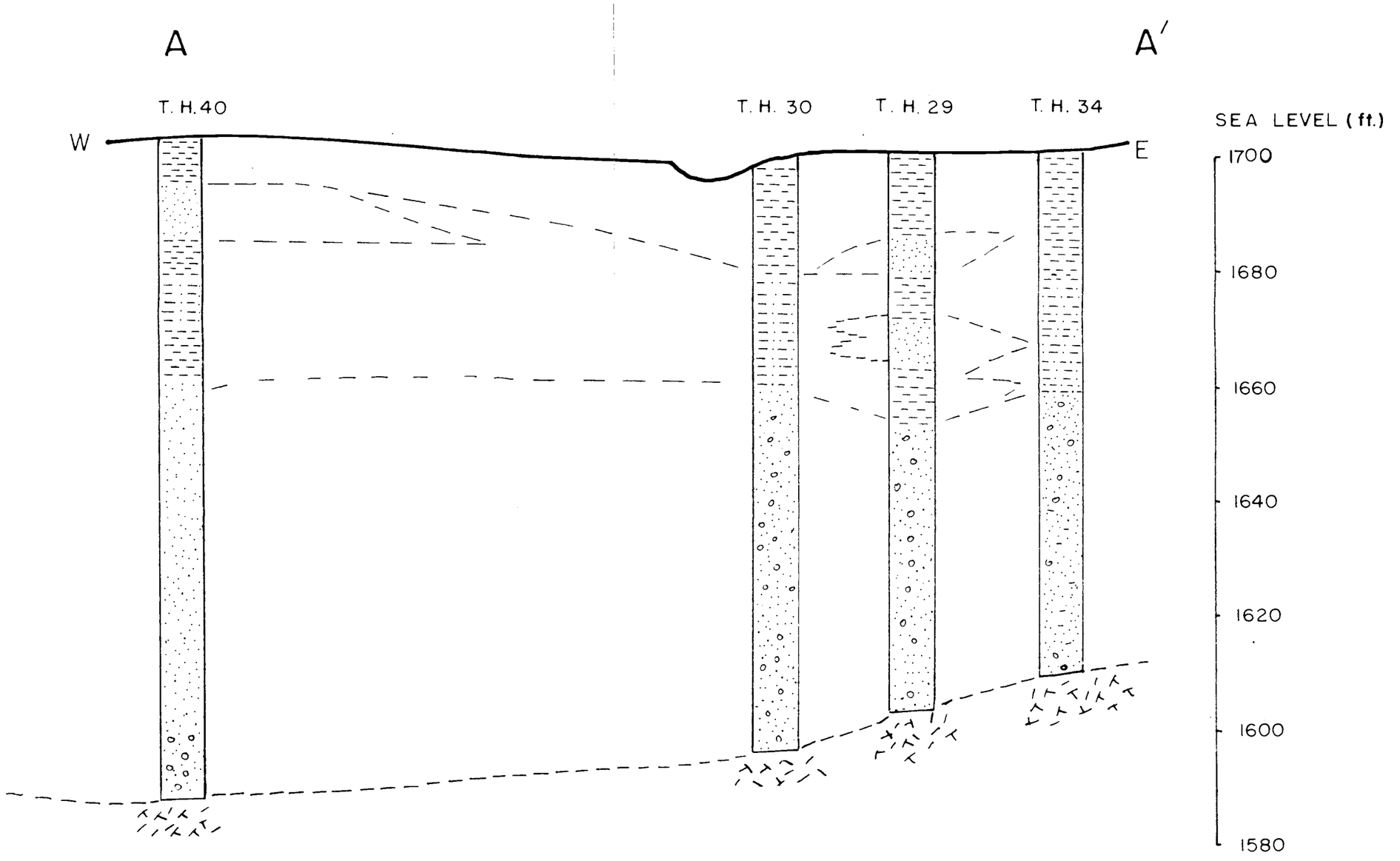

EXPLANATION

- CLAY
- SANDY CLAY
- SAND
- SAND AND GRAVEL
- BASEMENT ROCKS
- T.H. TEST HOLE

FIGURE 18

PLATE 2

KASSALA

GEOLOGICAL CROSS SECTION A–A′

VERT. SCALE: 1" = 20'

HORIZ. SCALE: 1 = 20,000

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B

B′

NW

SE

SEA LEVEL (ft.)

T.H. 25
T.H. 26
T.H. 20
T.H. 10
T.H. 7
T.H. 5

1650
1630
1610
1590
1550
1530
1510
1490
1470
1450
1430

EXPLANATION

- CLAY
- SANDY CLAY
- CLAY AND SAND
- SAND
- SAND AND GRAVEL
- GRAVEL
- BASEMENT ROCKS
- T.H. TEST HOLE

FIGURE 19

PLATE 3

KASSALA AREA

GEOLOGICAL CROSS SECTION B-B′

HORIZ. SCALE : 1:20,000

VERT. SCALE : 1" = 20 ft.

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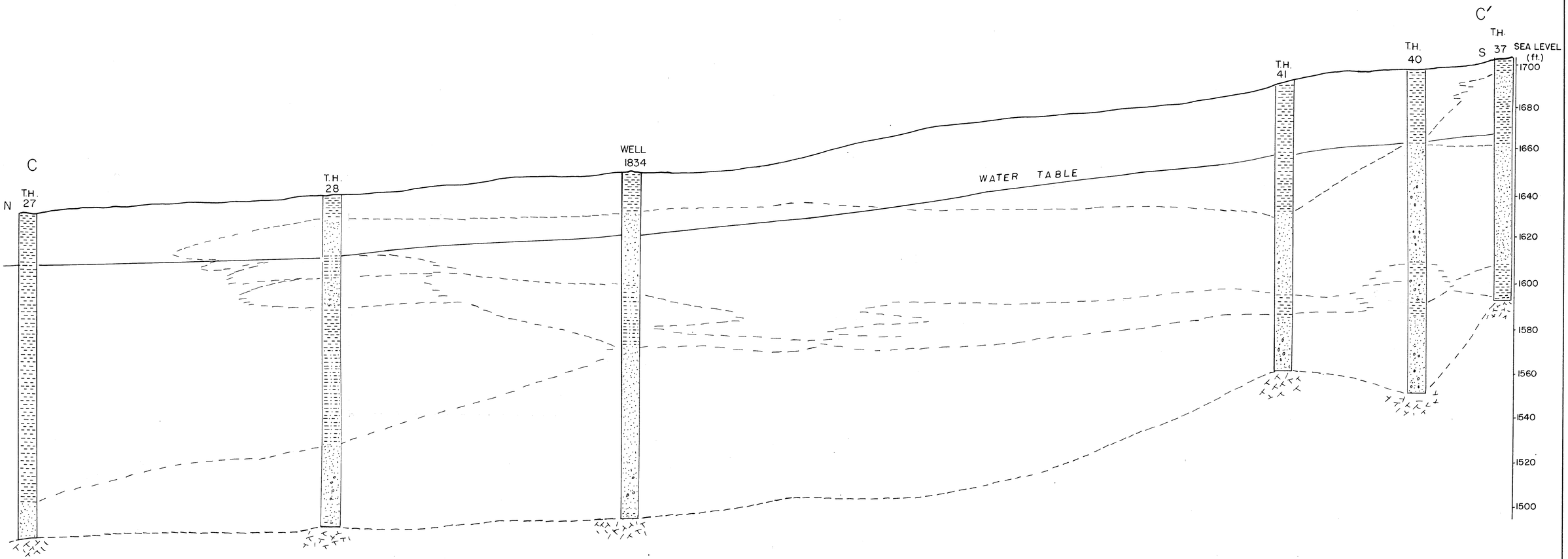

FIGURE 20

PLATE 4

KASSALA

GEOLOGICAL CROSS SECTION C-C'

HORIZ. SCALE : 1: 20,000

VERT. SCALE : 1" = 20 ft.

SAEED 1968

EXPLANATION

- CLAY
- SANDY CLAY
- SAND
- SAND AND GRAVEL
- BASEMENT ROCKS
- T.H. TEST HOLE

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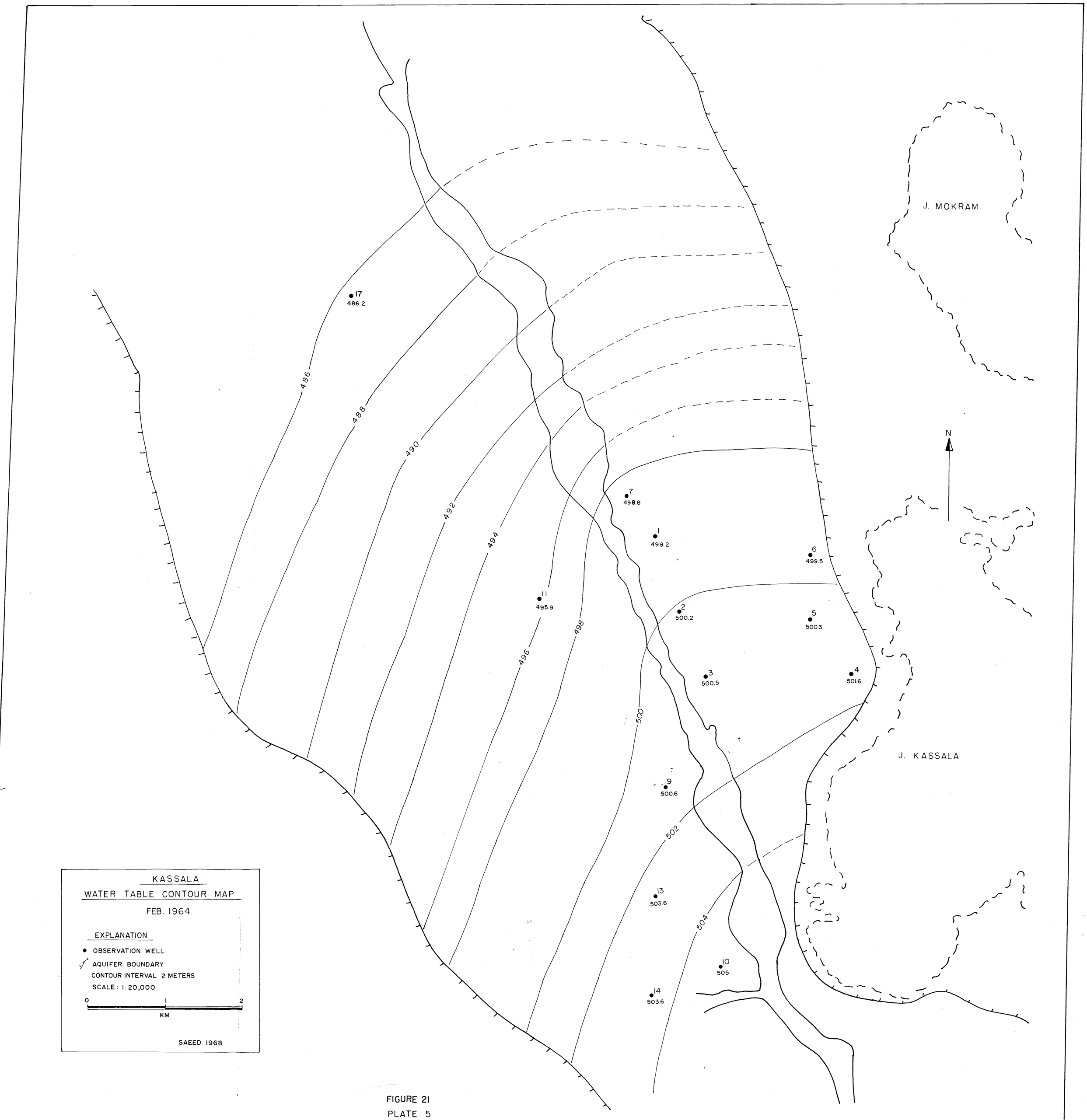

FIGURE 21
PLATE 5

MAP OF KASSALA AREA SHOWING CONTOUR OF THE WATER TABLE —— FEB. 1964

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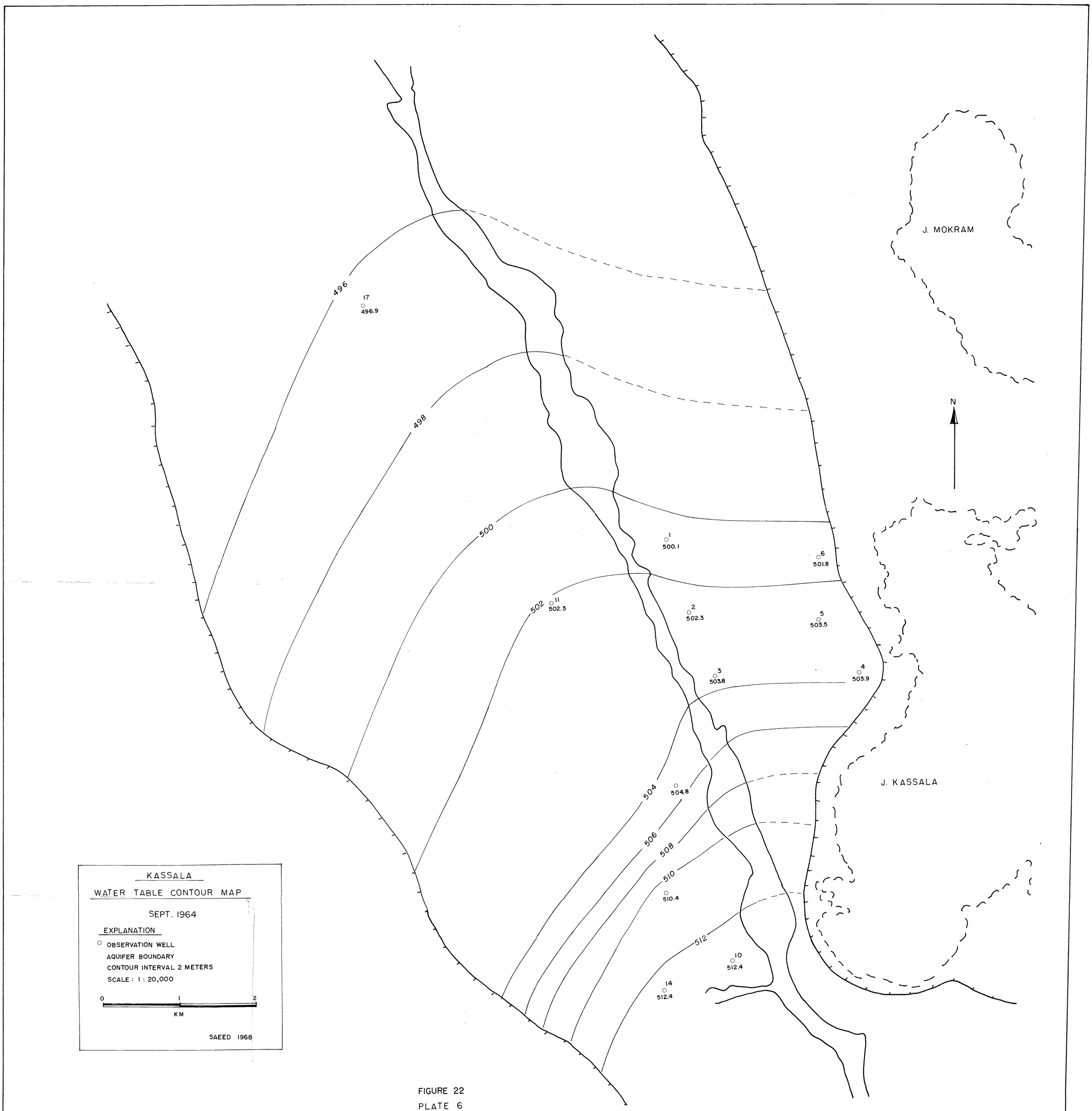

KASSALA

WATER TABLE CONTOUR MAP

SEPT. 1964

EXPLANATION

○ OBSERVATION WELL

AQUIFER BOUNDARY

CONTOUR INTERVAL 2 METERS

SCALE : 1 : 20,000

0 1 2

KM

SAEED 1968

FIGURE 22

PLATE 6

MAP OF KASSALA AREA SHOWING CONTOUR OF THE WATER TABLE —— SEPT. 1964