PROJECT TECHNICAL REPORT #60

HYDRAULIC CONDUCTIVITY AND VERTICAL LEAKAGE IN THE CLAY-SILT LAYER OF THE NILE ALLUVIUM IN EGYPT

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EGYPT WATER USE AND MANAGEMENT PROJECT

22 El Galaa St., Bulak, Cairo, Egypt

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ABSTRACT

Data were collected from three sites in Egypt's Nile Valley and Delta to determine saturated hydraulic conductivity in the clay-silt water table aquifer and vertical leakage to the underlying Nile River sands. Auger hole test results gave saturated horizontal hydraulic conductivities of 1103 mm/day for Abuyha in the middle Nile Valley, 197 mm/day for Beni Magdul near Cairo, and 103 mm/day for Abu Raya in the northern Delta. Auger hole, permeameter, and consolidation tests resulted in saturated vertical hydraulic conductivites of 0.03 to 4.9 mm/day for Abyuha, 0.03 to 0.87 mm/day for Beni Magdul, and 0.03 to 0.45 mm/day for Abu Raya. Several methods were used to determine vertical leakage: Darcy's law, water table decline, water budget, pumping test, and analytical solution. Average vertical leakage rates were very low for each site: 0.59 mm/day in Abyuha, 0.64 mm/day in Beni Magdul and 0.47 mm/day in Abu Raya. These results indicate poor natural drainage characteristics in the clay-silt layer which contribute to the high water table conditions observed throughout Egypt.

مستخلص

تقدم تجميع البيانات الخاصة بثلاث مواقع فى الدلتا ووادى النيل بمصر ، وذلك لتحديد درجة التوصيل الهيدروليكى المشبع فى طبقة الطمى السلتى الحاملة للمياه الجوفية ، وكذلك لتحديد التسرب الرأسى إلى طبقات الرمل السفلى تحت نهر النيل .

وقد أظهرت نتائج الاختبارات الحفر بالاوجر أن قيمة التوصيل الهيدروليكى المشبع الأفقى تبلغ ١١٫٣ م / يوم فى أبيوها بمنطقة وادى النيل الوسطى ، وتبلغ ١٩٧ م / يوم فى منطقة بنى مجدول قرب القاهرة ، وتبلغ ١٫٣ م / اليوم فى منطقة أبو دنيه فى شمال الدلتا . كما أظهرت نتائج إختبارات الحفر بالاوجر ، وجهاز النفاذية ، واختبارات معدل الهبوط أن نتائج درجة التوصيل الهيدروليكى الرأسى المشبع كالآتى : من ٠٫٠٣ إلى ٤٫٩ م / يوم لمنطقة أبيوها ، من ٠٫٠٣ إلى ٠٫١٧ م / يوم لمنطقة بنى مجدول ، من ٠٫٠٣ إلى ٤٫٩ م / يوم لمنطقة أبو دنيه .

وقد أتبعت طرق عديدة لتحديد التسرب الرأسى منها قاعدة دارسى ، وإنحدار سطح الماء الأرضى ، والميزانية الخاصة بالمياه ، وإختبارات الضخ ، وكذلك طريقة الحل التحليلى الرياضى . وقد أسفرت النتائج على أن متوسط معدل التسرب الرأسى كان منخفضا للغاية وتبلغ قيمته كالآتى : ٠٫٠٥٩ م / يوم لمنطقة أبيوها ، ٠٫٠٦٤ م / يوم لمنطقة بنى مجدول ، ٠٫٠٤٧ م / يوم لمنطقة أبو دنيه . وتدل هذه النتائج على مدى سوء خواص الصرف الطبيعى لطبقة الطمى السلتى (الطمى) والتى تؤثر بالتالى على مشروع إرتفاع الماء الأرضى الملاحظ وجوده فى معظم أراضى مصر الزراعية .

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HYDRAULIC CONDUCTIVITY AND VERTICAL LEAKAGE IN THE CLAY SILT LAYER OF THE NILE ALLUVIUM IN EGYPT

INTRODUCTION

Background

For over ten years Egypt has benefited from the change to perennial irrigation provided by the construction of the High Aswan Dam and the consequent control of the Nile's flow. However, this technological innovation has not come without adverse effects. Conditions have been created which pose serious constraints to potential crop production. If agriculture in Egypt is to advance to meet the demands of the increasing population, these problems must be effectively addressed.

Following the pattern of past civilizations which flourished under intense river valley irrigation (such as Mesopotamia), Egypt is beginning to suffer from the hazards of poor drainage. Before the High Dam, the lands in the Nile Valley and Delta were irrigated with the annual flood of the river. During this period the water table in the clay-silt soil rose due to downward flow of irrigation water. When the flood subsided and irrigation ceased, time was available for the water table to be lowered by natural drainage, which carried away harmful salts. Now, under perennial irrigation, constant recharge from overirrigation has created a very high water table. Associated with this high water table condition are problems of waterlogging and salinity in the plant root zone which can restrict crop growth and seriously affect agricultural production.

The problem of high water tables is widespread in Egypt, varying from region to region in severity. A better understanding is needed of the factors that effect this variation and how water may be best managed to control them. An important contribution to this understanding is a knowledge of the drainage characteristics of the clay-silt layer in which the water table is contained. Such knowledge is needed to determine the ability of this layer to naturally discharge its excess water and for designing artificial drainage systems. As part of farm-level hydrologic studies at selected sites in the Nile Valley and Delta, the Egypt Water Use and Management Project (EWUP) has sought to determine some of these characteristics.

Objectives

Studies of the clay-silt water table aquifer were conducted by EWUP at three sites: Abyuha, near El-Minya in Middle Egypt; Beni Magdul, near Cairo; and Abu Raya, near Kafr El-Sheikh in the northern Delta (Figure 1). The objectives of the studies were to determine: (1) the saturated hydraulic conductivity of the clay-silt layer in the horizontal and vertical directions and (2) the natural drainage presently occuring as vertical leakage from the clay-silt layer to the underlying Nile River sands.

Physical Setting

Between Aswan and Cairo (Figure 1), a distance of about 900 km, the Nile River has formed a long narrow valley. The width of the valley varies from between 2 km immediately below Aswan to a maximum width of about 20 km at El-Minya. The average width of the valley is approximately 14 km. The elevation of the Nile River along this stretch falls very gradually from about 90 m above mean sea level (MSL) at Aswan to about 20 m above MSL at Cairo.

The valley floor was created by the flood plain of the Nile River and is very flat. The lateral slope of the floor towards the Nile River is very slight. Except for that area occupied by buildings and roads, the entire valley floor is utilized essentially for irrigated agriculture. On both east and west flanks the edges of the valley are marked by steep erosion scarps which rise abruptly onto the adjacent desert plateaus.

Just downstream from Cairo, was created a large fan shaped delta plain as the Nile River flows northward into the Mediterranean Sea. As the river enters the delta, it splits into two major branches, the Damietta Branch and the Rosetta Branch. The northern, northeastern and northwestern boundaries of the delta are the Mediterranean Sea. The southwestern boundary is the Western Desert. The eastern boundary is the Suez Canal and the southeastern boundary is the Eastern Desert. The central part of the Nile Delta is heavily cultivated. Near the fringes of the desert and along the coast, less agricultural development has taken place. Like elsewhere in Egypt, most of the delta receives no significant rainfall (only about 2 cm a year). Along a narrow coastal belt in the north, however, annual rainfall of 15-20 cm is common. This small amount acts as a supplemental source of irrigation water in the northern delta and helps to recharge the lower aquifer.

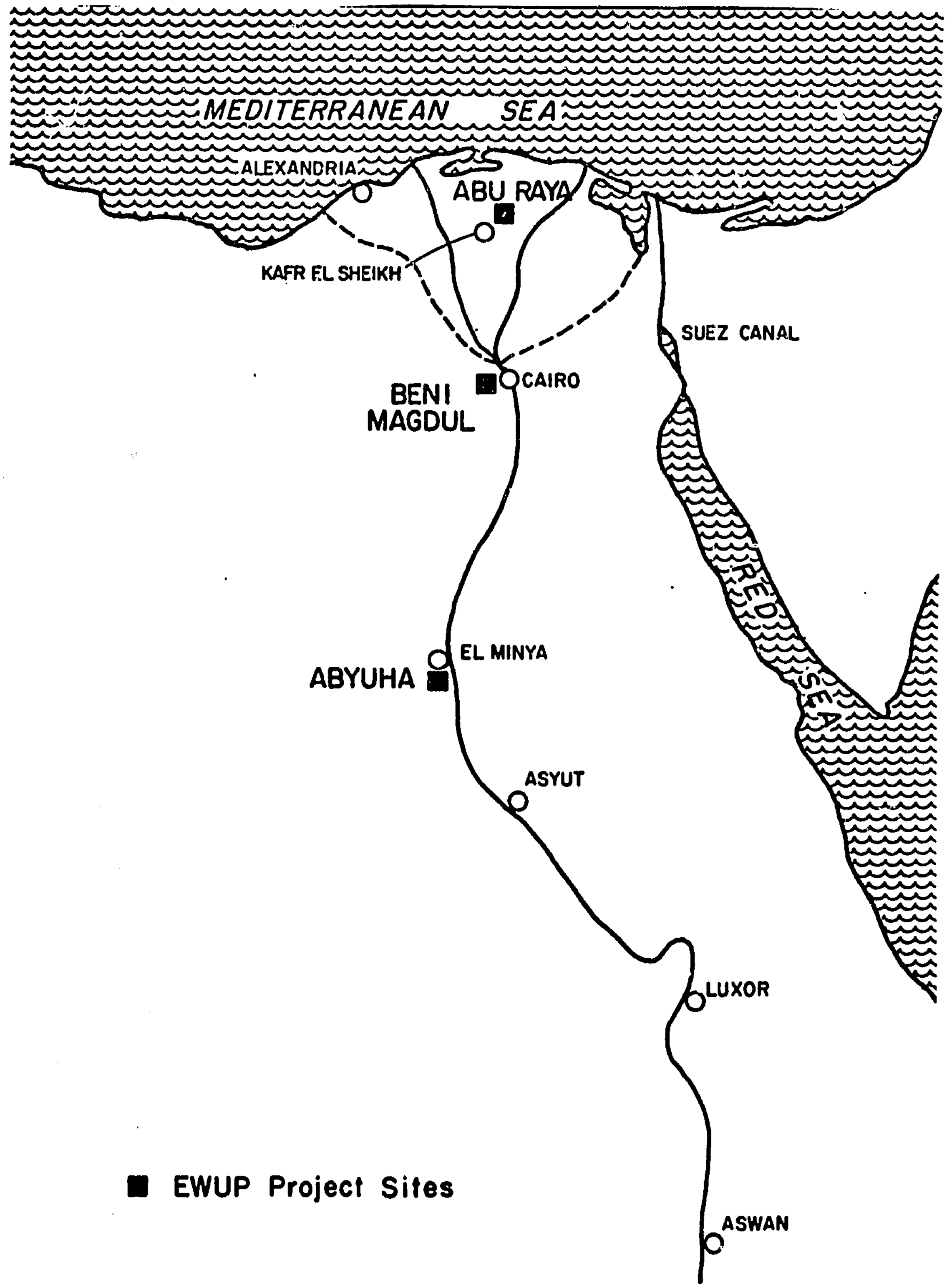

Figure 1 Location of EWUP Study Sites

Geology

The geology of the Nile River Valley and Delta may be broadly classified into two geologic units: the Nile River alluvium and the undifferentiated basement sediments. A brief description of the geology of the Nile Valley is presented here. For a more detailed discussion of the regional geology the reader is referred to MOI (1981) and Barber and Carr (1981).

Nile River Alluvium: The Nile River alluvium is composed of unconsolidated river channel deposits formed by the erosion of the basement complex and subsequent redeposition. Prior to the construction of the high Aswan Dam, the annual flood of the Blue Nile brought heavily sediment laden water to Egypt. The major source of this sediment was the upriver erosion of the Ethiopian high lands. The flood plain created by the Nile has resulted in thick alluvial deposits which are over 300 m thick in places. Since the construction of the High Aswan Dam, nearly all of this sediment has been trapped behind the dam and the depositional process has been halted. The Nile River alluvium is subdivided into two members: the Nile River sands and the clay-silt layer.

The Nile River sands member consists predominantly of beds of coarse and fine sands. The coarse sands are the more common, particularly in the deeper portion of the sequence. Laterally, the sands are typically thickest in the center of the valley and thinner near the escarpments which mark the lateral limits of the valley. The maximum thickness of the alluvium along a longitudinal section of the valley ranges from about 20 m just below Aswan to about 300 m downstream of El-Minya. The maximum thickness of the sands near Cairo is approximately 35 m. The Nile River sands are, for the most part, overlain by a near-surface clay-silt layer.

The clay-silt layer is predominantly composed of clay and silt with some beds of fine grained sands also present. The clay-silt layer is found on the surface over most of the valley floor. The average thickness of the clay-silt layer in the Nile Valley varies from about 4 to 14 m. Laterally, the clay-silt layer becomes thinner towards the fringes of the valley and may be locally absent.

The thickness of the alluvium in the Delta ranges from 100 to 900 m. The thickness of the clay-silt layer ranges from about 15 m near Cairo to about 80 m at the Mediterranean Sea.

Undifferentiated Basement Sediments: The Nile River Valley is carved out of a sequence of basement sediments consisting mostly of undifferentiated limestone and shales from the Tertiary and Cretaceous ages. The basement sediments include the Nubian sandstone which is a major aquifer unit in the Southwestern Desert.

An impermeable pliocene clay ranging from about 700 to 8000 m in thickness forms the base of the alluvium in the Nile Delta. (MOI, 1981)

Groundwater System

The Nile Valley alluvium represents the aquifer system in which groundwater flow takes place. The basement sediments from which the valley is carved are considered to be impermeable and represent the base and lateral boundaries of the system. This definition of the aquifer system is the generally accepted definition as given by Attia (1974) amd Attia and El Kateb (1975).

The Nile Valley aquifer system is composed of two hydrologically linked aquifers: (1) a water table aquifer formed by the clay-silt layer (which also acts as a confining cap on the underlying groundwater) and (2) a lower semi-confined aquifer formed by the Nile River sands (Attia and El Kateb, 1975; Barber and Carr, 1981). The water table aquifer in the clay-silt layer is recharged by infiltration of irrigation water and seepage from irrigation canals. Because of the extremely low rainfall over most of Egypt, almost no significant recharge occurs by infiltration of precipitation. The water table elevation is typically very high throughout the Nile Valley. The depth to the water table fluctuates in response to irrigation practices but is usually from 0.5 m to 2.0 m below the land surface. The principal components of discharge from the water table aquifer are evapotranspiration and vertical leakage to the underlying Nile River sands. Horizontal groundwater flow to surface drains appears to be a less significant component of discharge (Helal et al., 1984). Open drains primarily serve to remove surface drainage from farms and watercourses.

The Nile River is in direct hydrologic connection all along its course with the lower groundwater in the Nile River sands member. Under natural conditions before the construction of the High Aswan Dam, recharge to the groundwater in the lower aquifer occurred primarily during the flood period of the Nile River. During flood stage, the river elevation was above the groundwater level and water flowed from the river into the aquifer. When the river subsided to a lower level, reverse flow took place with groundwater flowing back into the river.

After construction of the High Aswan Dam, regulation of river discharge has resulted in the river elevation being lower than the groundwater level. As a result, the Nile River is now a permanent line sink for the groundwater along most of the reach of the river between Aswan and Cairo. The principal recharge source to the deep aquifer is presently thought to be from vertical leakage through the clay-silt layer (Barber and Carr, 1981; MOI, 1981).

The hydraulic conductivity of the Nile River sands is very high, ranging from about 35 to 100 m/day (Attia, 1974). The storage coefficient is on the order of 10^{-3} to 10^{-5}. The major groundwater discharge from the Nile River sands is through flow to the Nile River. Some groundwater discharge also occurs due to pumping by wells and as underflow parallel to the Nile River northward.

Shown in Figure 2 is a conceptual model of the groundwater flow system of the Nile River Valley. Recharge to the clay-silt layer occurs from infiltration of irrigation water and seepage from canals. Evapotranspiration from the shallow water table is a major discharge from the clay-silt layer Vertical leakage occurs from the clay-silt layer to the deeper Nile River sands. This vertical leakage has been thought to be the major source of recharge for the deeper aquifer (Barber and Carr, 1981). Groundwater flows laterally in the deeper aquifer towards the Nile River which is the major sink for the groundwater system. It should be noted that in the conceptual model of the groundwater system shown in Figure 2, the assumption is made that the numerous irrigation canals and drains that cross the valley floor are not deep enough to intersect the Nile River sands.

The Nile Delta aquifer system is very similar to that of the Nile River Valley. Nearly all of the recharge to the groundwater system is from infiltration of irrigaton water and seepage from canals with rainfall also contributing a small amount. Vertical leakage occurs from the clay-silt layer to the underlying sands. Because the clay-silt layer is in general much thicker in the Delta, one would expect that the vertical leakage is less there than in the Valley. The delta aquifer system is in direct hydrologic connection with the Mediteranean Sea. In general, groundwater in the Nile River sands member of the Delta, flows northward and is discharged into the

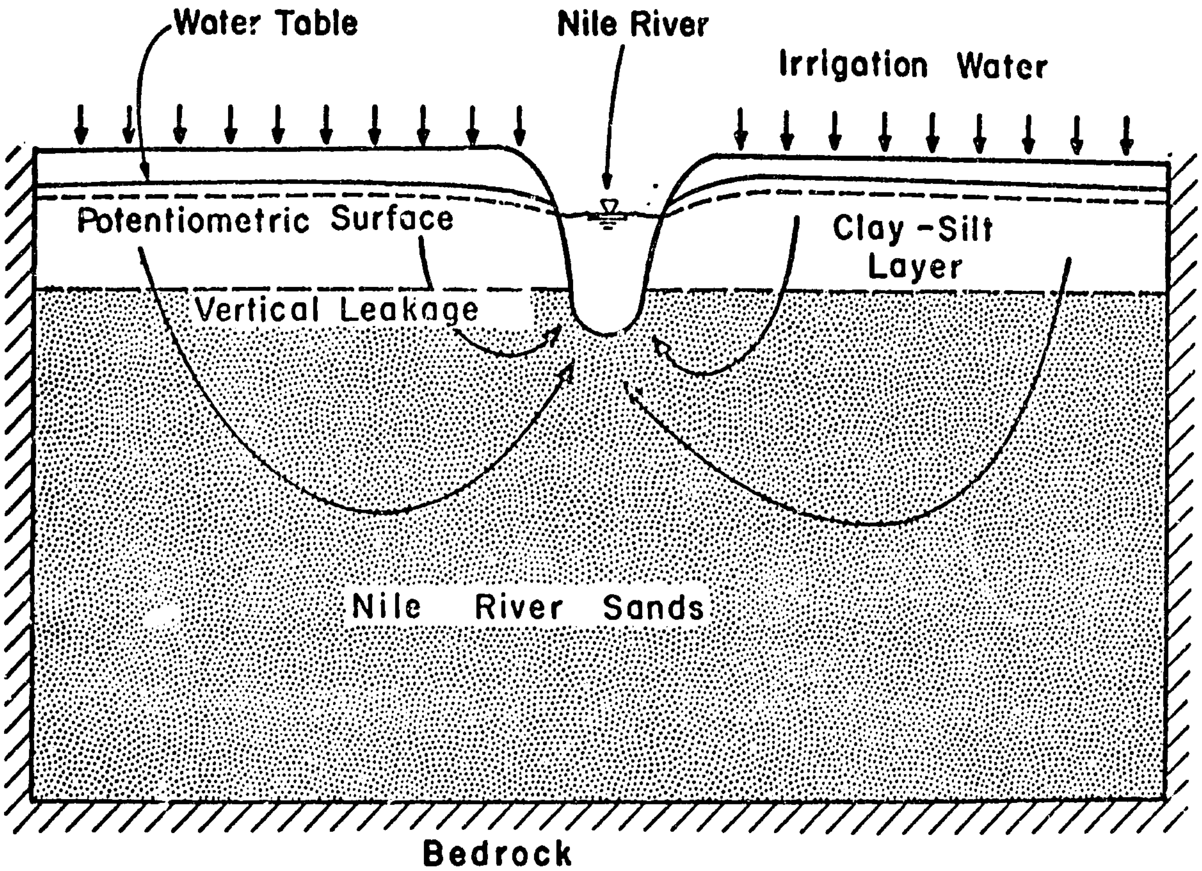

Figure 2. Conceptual Model of Groundwater Flow System of the Nile Valley (After Attia, 1974).

Mediterranean Sea. Near the coast, the hydraulic gradient is reversed between the clay-silt layer and the underlying sands and thus vertical flow is upwards. A huge saline wedge of seawater has intruded into the aquifer along the coast (MOI, 1981). Generally, the salinity increases with depth in the aquifer, gradually forming a transition zone between the fresh groundwater and the saline wedge. Along the fringes of the Delta beside the desert the clay-silt layer is often absent and groundwater in the Nile River sands is phreatic.

Previous Studies

Estimates of the vertical saturated hydraulic conductivity of the clay-silt layer and of vertical leakage rates have been made by other investigators. For the Nile Valley between Aswan and Cairo, Barber and Carr (1981) report a vertical hydraulic condicutivity for the clay-silt layer of from 30 to 110 mm/day based on auger-hole tests. They also report vertical leakage rates of from 1.8 to 8.4 mm/day, with an average of 4.5 mm/day, based on rate of water table declines. Attia (1974) reports a vertical hydraulic conductivity for the clay-silt layer in the Nile Valley of from 40 to 5000 mm/day with an average of 1300 mm/day based also on auger-hole tests.

For the Nile Delta, MOI (1981) reports an average vertical hydraulic conductivity for the clay-silt layer of 25 mm/day. The reported values for average vertical leakage rates for the Nile Delta are much smaller than for the Nile Valley. Farid (1980) using a water balance, estimated an average vertical leakage for the Nile Delta of 0.4 mm/day. Goode and Wilson (1981) using a numerical groundwater model estimated an average vertical leakage for the Nile Delta of 0.28 mm/day and a vertical hydraulic conductivity for the clay-silt layer of 6 mm/day.

DESCRIPTION OF STUDY SITES

Beni Magdul

The Beni Magdul site is located in the southern part of the Mansuriya Irrigation District about 20 km west of Cairo (Figure 3). The study site occupies an area of about 842 feddans (354 ha) of which about 810 feddans (340 ha) are under cultivation. The area is enclosed by the Beni Magdul, Lebini, and Nahia drains and also by the Mansuriya irrigation canal. Near the center of the study site is the Beni Magdul village.

To study the local aquifer system at the Beni Magdul site, 10 deep observation wells and 49 shallow observation wells were drilled. From well logs of the deep holes, the thickness of the clay-silt layer was found to vary from 7 m to 14 m with an average thickness of 11.5 m. The clay-silt layer at the Beni Magdul site consists mostly of dense clay interbedded with layers of fine sandy clay and clayey sand (Table 1).

TABLE 1. Textural Profile of Clay-Silt Layer and Nile River Sands in Beni Magdul

DEPTH (m)	CLASSIFICATION
0 - 1.5	clay
1.5 - 3	clayey sand/fine sand
3 - 8	clay/interbedded silty sand
8 - 14	sand/clay
14 - 15	fine sand
15 - 20	medium sand
20 - 26	sand/gravel
26 - 34	coarse sand/large gravel
34 - 45	fine sand
> 45	bedrock

The depth to the water-table in the clay-silt layer was measured in the shallow observation wells for about four years. On a daily basis the depth to water flucturated considerably in response to local irrigation practices. The

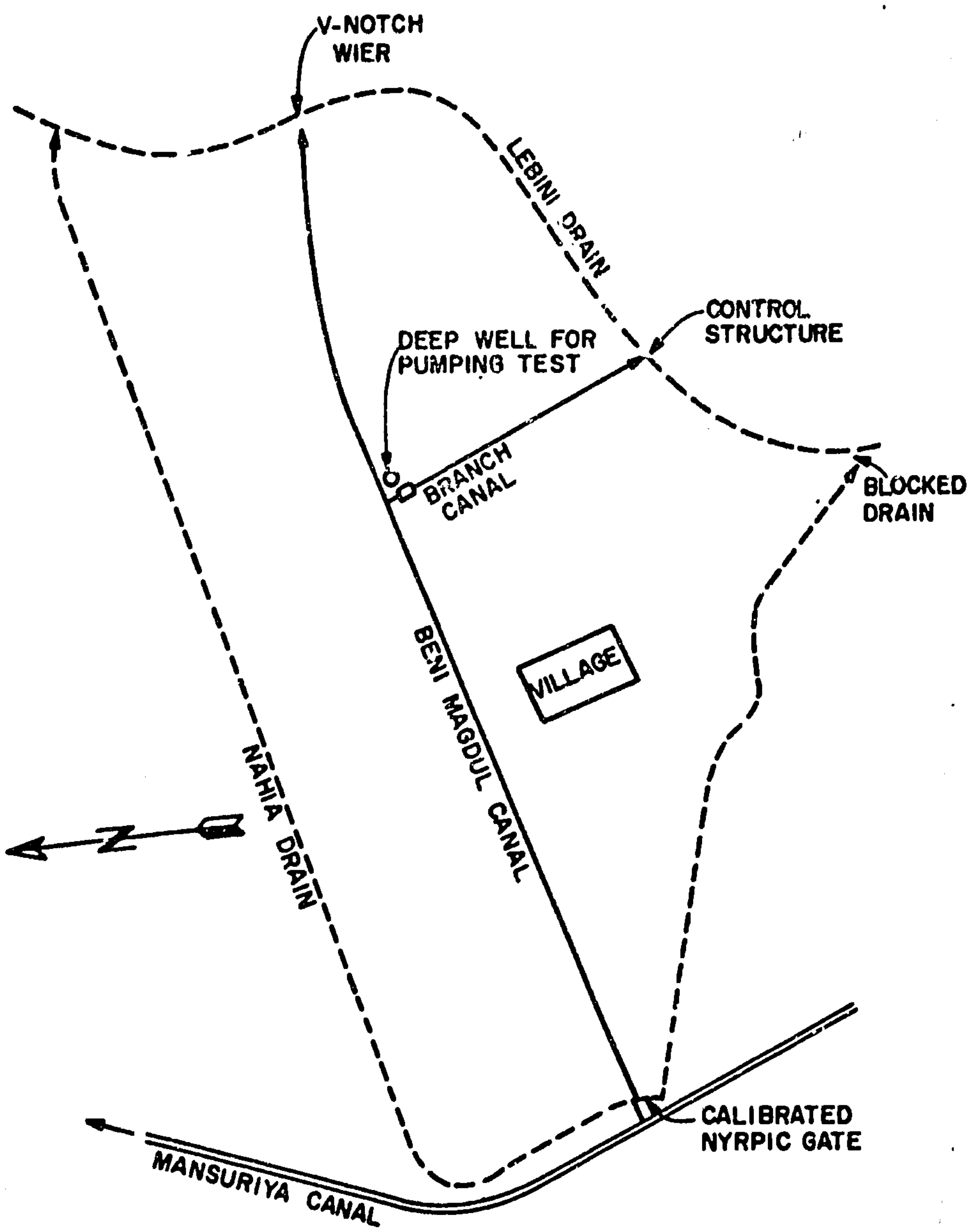

Figure 3 Beni Magdul Study Site

average monthly depth to the water table varied from between 0.65 m to 0.90 m as shown in Figure 4. This water-table depth data was plotted areally and contoured (not shown) afterwhich observation wells were installed along the boundaries of the site to determine if any horizontal components of flow existed in the clay-silt layer. It was determined that the horizontal flow components were negligible; thus, discharge from the clay-silt layer primarily must be due either to downward vertical leakage to the deeper aquifer or to upward movement of water caused by evapotranspiration.

The geology of the top 3.5 m of the clay-silt layer at the Beni Magdul site was mapped in detail during the drilling of the numerous shallow observation wells. The drilling indicated considerable fine sand in the upper part of the clay-silt layer. Apparently, this sand is discontinuous; otherwise, significant horizontal flow through the clay-silt layer towards the drains which form the boundaries of the Beni Magdul site would be expected.

The thickness of the deeper semi-confined aquifer formed by the underlying Nile River sands was estimated by Barber and Carr (1981) to be from 30 m to 50 m in this area. None of the deep observation wells which were drilled as part of the present study fully penetrated the entire thickness of the deep aquifer. The potentiometric surface in the deeper aquifer at the Beni Magdul site, as determined by water-level measurements made in the deep observation wells, shows a slight gradient of 0.5 m/km eastward, indicating flow towards the Nile River.

The groundwater system at the Beni Magdul site does not follow the classical system formulation (Figure 2) of the River Valley in which groundwater flow is uni-directional toward the Nile River. At Cairo the narrow Nile River Valley begins to fan out toward the broad Nile Delta. The Beni Magdul site is located at the transition from the Nile Valley to the Nile Delta. The Groundwater Research Institute of the Ministry of Irrigation monitors a large number of observation wells in the Cairo area. Shown on Figure 5 is a contour map of the potentiometric surface of the deep aquifer in the vicinity of the Beni Magdul site. As can be seen from the map, the regional groundwater flow pattern is generally towards the Nile River and also northward parrallel to the Nile River. Near the Beni Magdul site flow is greatly effected by great amounts of pumping from the deep aquifer near the Giza Pyramids. This pumping appears to cause a reversal in the natural pattern of groundwater flow in the vicinity of Beni Magdul.

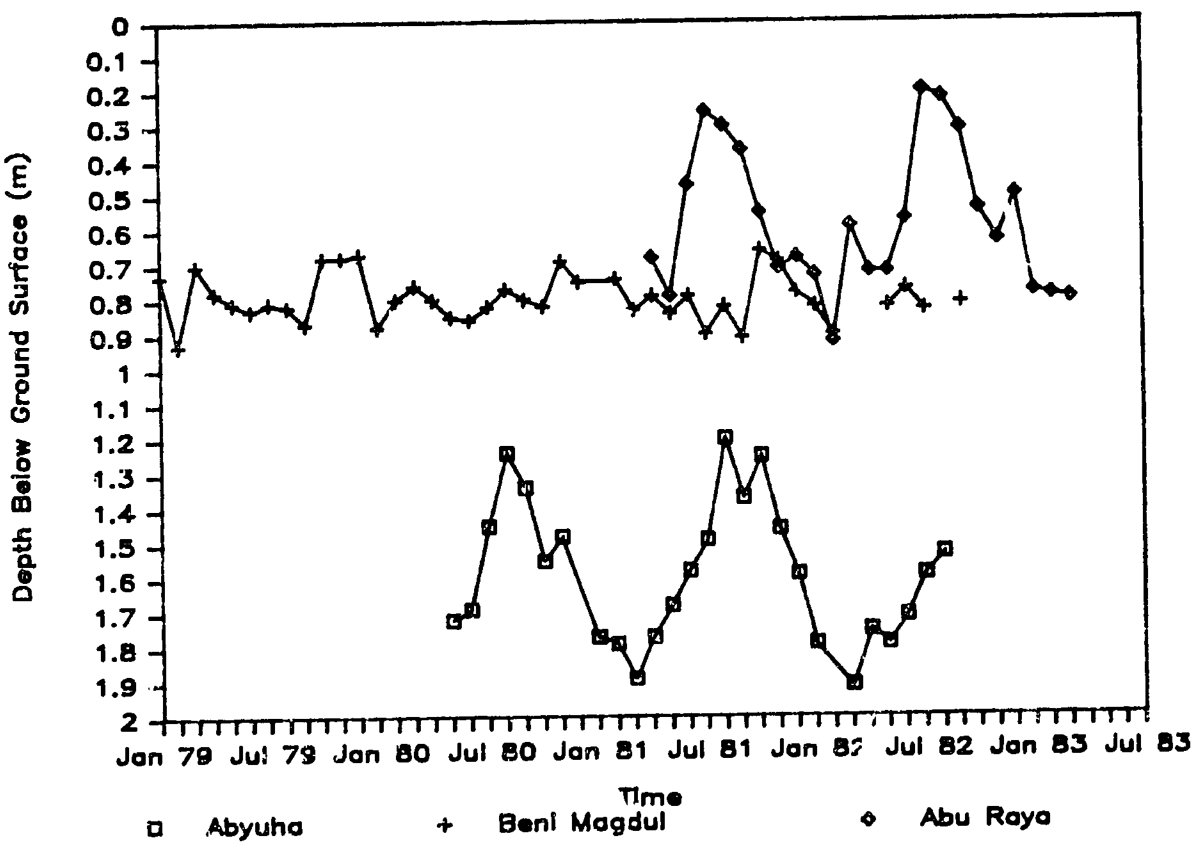

Figure 4 Monthly Average Water Table Depth at Study Sites

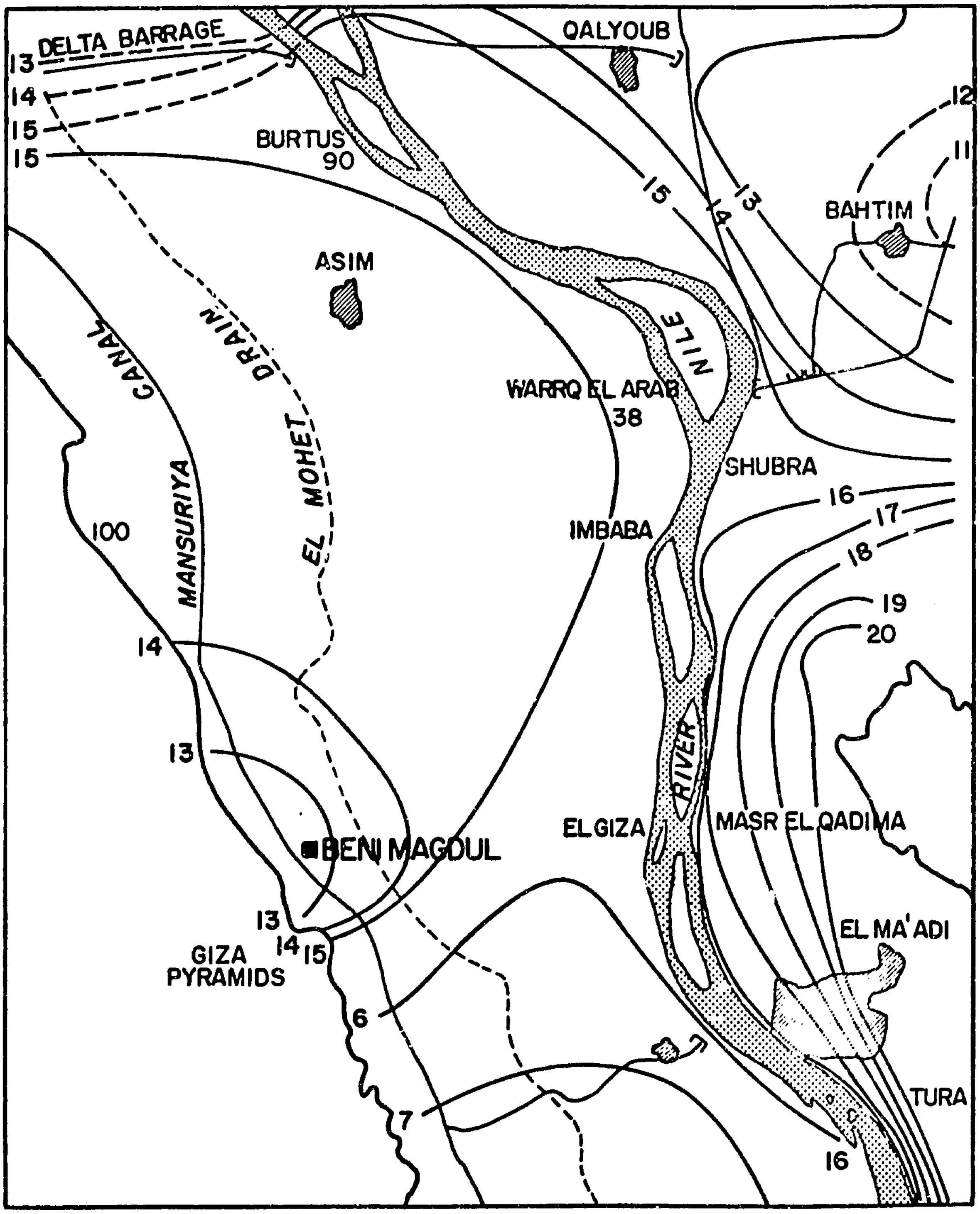

Figure 5. Contour Map of the Potentiometric Surface of the Deep Aquifer in the Vicinity of the Beni Magdul Site (February, 1982 Data from the Groundwater Research Institute, Water Research Center, Ministry of Irrigation)

Groundwater flow in the deep aquifer at the Beni Magdul site is also greatly effected by pumping from the wells at the Beni Magdul village. Water drawn from the Beni Magdul village wells is used as a public water supply for Beni Magdul and several other nearby villages.

Abyuha

The Abyuha site is located in Middle Egypt about 17 km south of the city of El-Minya (Figure 6). The study site occupies an area of about 1200 feddans (504 ha) of which about 1100 feddans (462 ha) are under cultivation. The area is enclosed by Ibrahimiya Canal, the Kom El Zoheir-El Mustagad and Kom El Zoheir-El Qadim drains, and mesqas 5 and 24. The village of Abyuha is located in the study area near the Ibrahimiya canal.

To study the local aquifer system at the Abyuha site, 4 deep observation wells and 41 shallow observation wells were drilled. From well logs of the deep wells, the thickness of the clay-silt layer was found to vary from 8 m to about 12 m with an average thickness of approximately 10 m. The clay-silt layer at the Abyuha site consists mostly of clay, silty clay loam and sandy loam (Table 2). The depth to the water-table was measured for about two years at the Abyuha site. The average monthly depth to water varied from approximately 1.20 m to 1.92 m below ground surface (Figure 4).

TABLE 2. Textural Profile of Clay-Silt Layer in Abyuha

DEPTH (m)	CLASSIFICATION
0 - 4	clay
4 - 6	silty clay loam/sandy loam
6 - 8	silt loam/sandy loam
8 - 10	silt loam/sandy clay loam
10 - 12	sandy loam/loamy sand

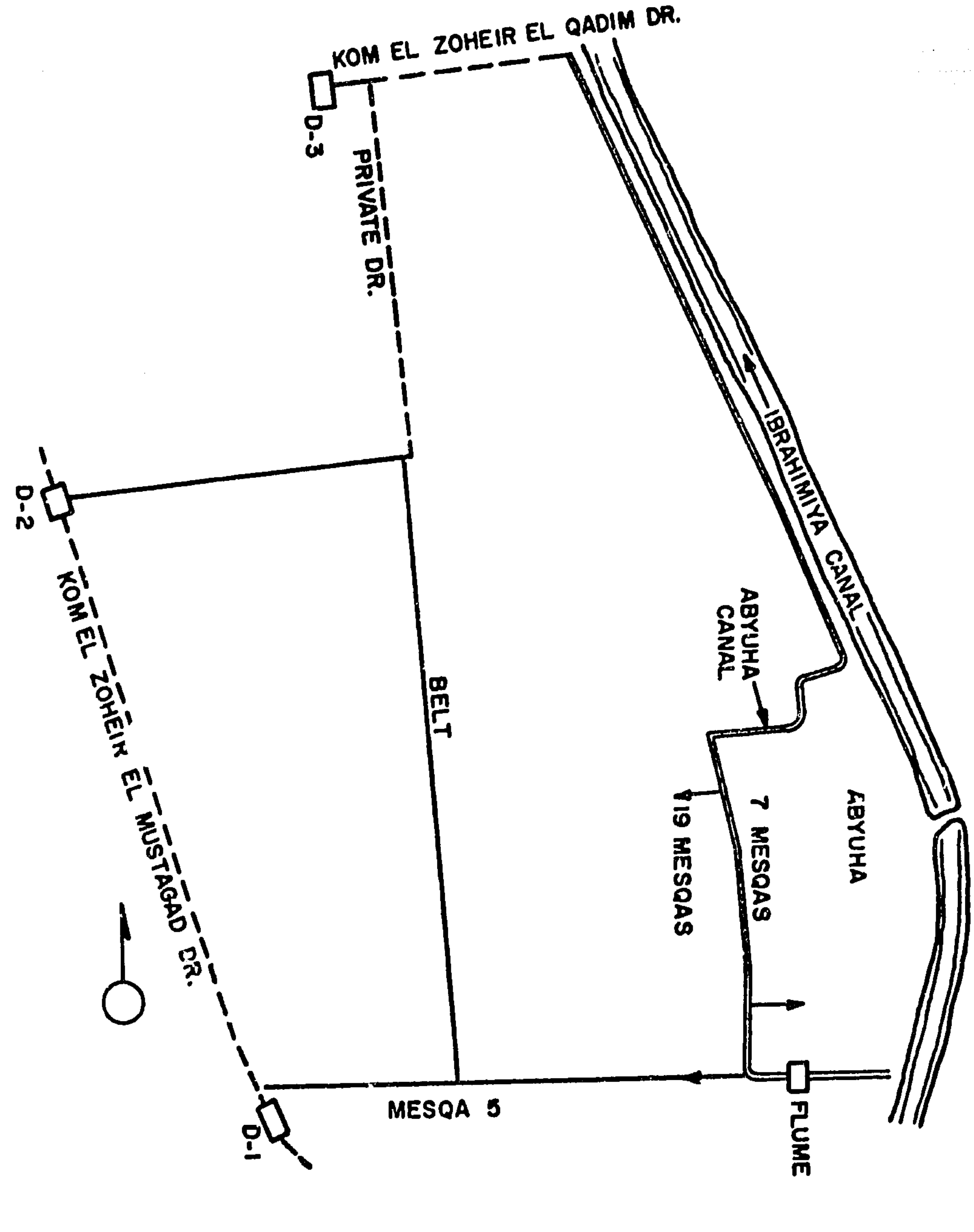

Figure 6 The Abyuha Study Site

The thickness of the deep aquifer at Abyuha is estimated to be 165 m by Attia and El Kateb (1975). There is no significant groundwater pumping in the vicinity of the Abyuha site that would alter the natural pattern of groundwater flow which follows the classical system formulation shown in Figure 2 for the Nile River Valley.

Abu Raya

The Abu Raya site is located near the village of Abu Raya in the Kafr El-Sheikh governorate of the northern Delta. The study site occupies an area of about 260 feddans (109 ha) of which about 235 feddans (99 ha) are under cultivation. The area is enclosed by the Daqalt canal, the Hammad mesqa, the Gad-Alla drain, and the Om-Sen drain (Figure 7).

Thirty-five shallow observation wells were drilled at the Abu Raya site. The thickness of the clay-silt layer at this site is estimated by MOI (1981) to be approximately 35 m. Seven test holes drilled in the area revealed a dense clay depth of approximately 3.5 m. No deep observation wells were drilled at the Abu Raya site. The depth to water table in the shallow observation wells was measured for about two years with the monthly average depth to water varying from between 0.20 m to 0.80 m below ground surface (Figure 4).

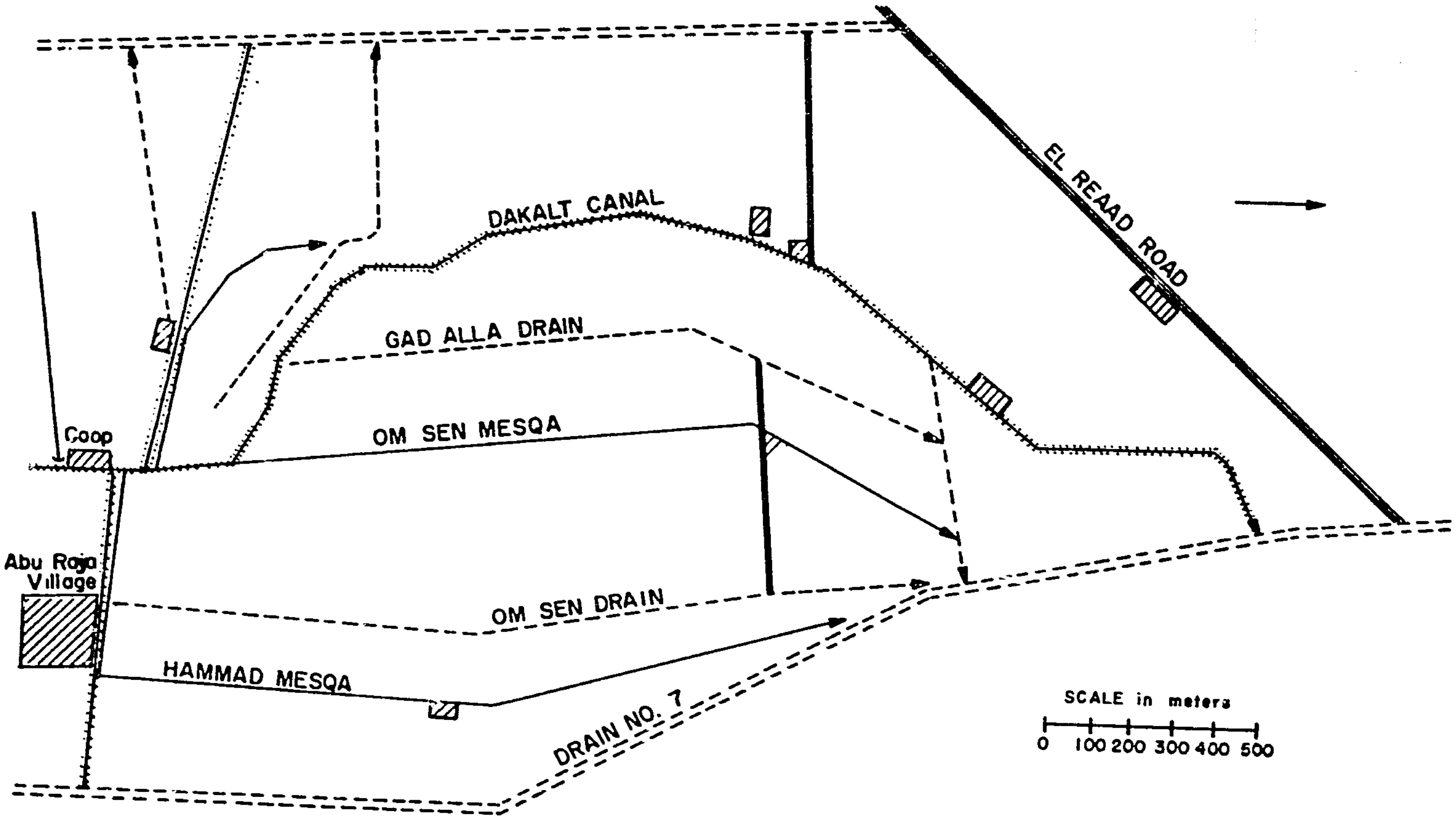

Figure 7 Layout of the Abu Raya Study Site

HYDRAULIC CONDUCTIVITY IN THE CLAY-SILT LAYER

The saturated hydraulic conductivity of the clay-silt layer was determined by three methods: (1) auger-hole test, (2) consolidation test, and (3) permeameter test. The resulting values of hydraulic conductivity were used to estimate the amount of vertical leakage from the clay-silt layer to the underlying Nile River sands. Only a brief description of the methodology of these tests is presented. The interested reader should refer to the appropriate references for a more detailed discussion.

Auger-Hole Test

The first method used to determine the hydraulic conductivity of the clay-silt layer was the auger-hole test. With this method, a hole is drilled to a depth of 1 to 2 meters below the water table. After the water level in the hole has reached equilibrium with the water table, it is then removed, usually by bailing. The groundwater then seeps back into the hole and the rate at which the water level rises in the hole is measured. The hydraulic conductivity of the soil can then be determined from the early part of the rate of rise data from the following equation (Todd, 1980):

$$K = C \frac{\Delta y}{\Delta t} \qquad (1)$$

where

K	=	hydraulic conductivity (m/day),
$\Delta y/\Delta t$	=	rate of rise (cm/s), and
C	=	dimensionless coefficient (determined from either a nomograph or by formula).

Ernst (1950) gave an empirical formula for estimating the dimensionless coefficient C:

$$C = \frac{4000\, r^2}{(H+20\, r)\left(2-\frac{y}{H}\right) y} \qquad (2)$$

where

r	=	radius of the auger-hole (cm),
H	=	depth of the hole below the water table (cm), and
y	=	distance between the water table and the average water level in the hole for the time interval Δt (cm).

These parameters are illustrated in Figure 8.

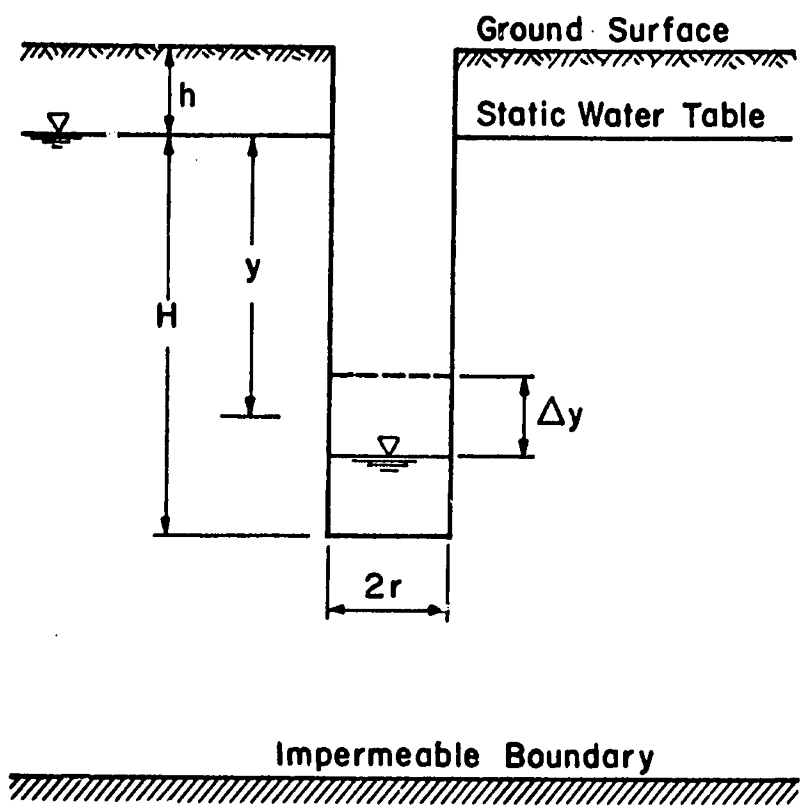

Figure 8. Definition Sketch of Auger-Hole Test
(See Appendix Tables A1-A3)

Use of the auger-hole method is limited to areas such as Egypt with high water tables. The method has the advantage that it can be quickly and easily performed in the field. Consequently, the hydraulic conductivity can be determined for a great many holes thereby providing a reasonably good estimate of spatial variability.

The results of the auger-hole tests at the study sites are summarized in Table 3 with the complete results given in Appendix A. The auger-hole method gives the horizontal saturated hydraulic conductivity of the soil within a 0.3 to 0.5 meter radius of the hole. The vertical saturated hydraulic conductivity may be estimated from this data.

TABLE 3 Hydraulic Conductivity From Auger-Hole Tests.

Study Site	No. of Holes	Horizontal Hydraulic Conductivity (mm/day)			Standard Deviation
		K_H max	K_H min	K_H mean	
Beni Magdul	8	637	30	197	217
Abyuha	26	2785	378	1103	607
Abu Raya	10	317	5	103	94

The auger-hole results (Appendix A) show considerable variation in the values of hydraulic conductivity of the clay-silt layer. This is reflected in the relatively large standard deviation and the large relative difference between the minimum and maximum values of K_H as seen in Table 3. The smaller values of hydraulic conductivity obtained from the auger-hole method are probably representative of soils with layers containing significant amounts of fine sand. The mean horizontal hydraulic conductivity for the three study sites ranged from 100 to 1100 mm/day. These results are similar to those reported for other auger-hole test data in Egypt. Tests performed by the Drainage Institute of the Ministry of Irrigation and reported in Barber and Carr (1981) showed a range of horizontal saturated hydraulic conductivity of between 200 to 800 mm/day from auger-hole tests at several sites in the Nile Valley. El-Mowelhi and Van Schifgaarde (1982) reported a value of 89 mm/day from field drainage experiments and 75 mm/day from auger-hole tests conducted at a site in the Nile Delta approximately 20 km north of Abu Raya.

To get vertical saturated hydraulic conductivity from the auger-hole data, a ratio of horizontal to vertical hydraulic conductivity must be estimated. This ratio is referred to as the ratio of anisotropy and typically ranges from 2 to 20 for alluvium although ratios of 100 or more can occur where clay layers are present. (Todd, 1980). Barber and Carr (1981) used a ratio of 7 for their auger-hole test data in Egypt. This assumes an essentially homogenous soil (i.e. only considers the effect on anisotropy of micro stratifiation of the soil). During the drilling of the auger-holes at the EWUP study sites, clay and silt interbeded with layers of fine sand were commonly encountered. A generalized auger-hole lithologic section is shown in Figure 9.

For a layered soil, the auger-hole method gives the average horizontal saturated hydraulic conductivity extending from the water table to the bottom of the hole. The average horizontal saturated hydraulic conductivity for a layered soil, with flow paralleled to the layers, is given by McWhorter and Sunada (1977) as:

$$K_H = \frac{\sum_{i=1}^{n} K_{Hi}\, b_i}{\sum_{i=1}^{n} b_i} \qquad (3)$$

where

b_i = thickness of layer i (mm),

K_{Hi} = horizontal saturated hydraulic conductivity of layer i (mm/day),

K_H = average horizontal saturated hydraulic conductivity as measured by the auger-hole test (mm/day), and

n = number of layers.

To use Equation (3), the relative hydraulic conductivity difference between the clay layers and the fine sand layers must be estimated. It was assumed that the hydraulic conductivity of the fine sand was two orders of magnitude, or one hundred times that of the clay.

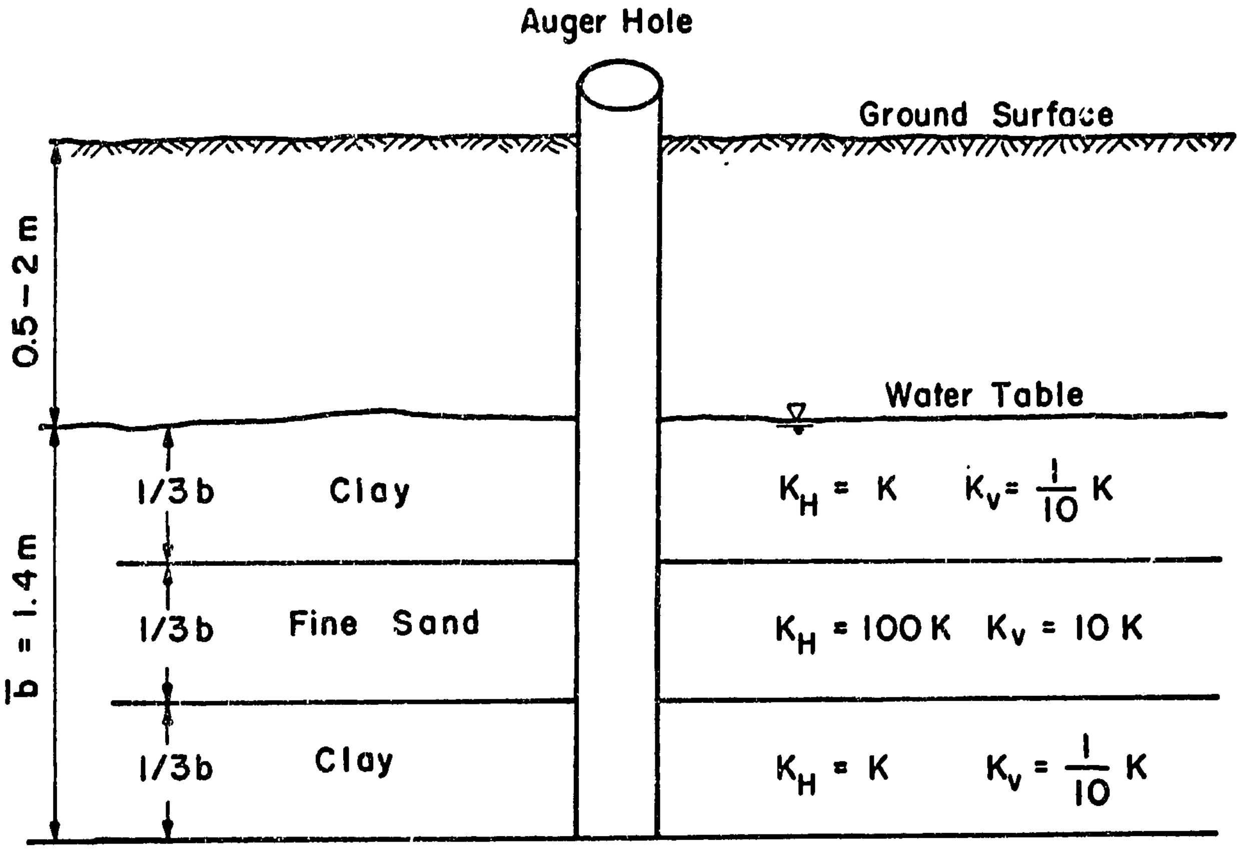

Figure 9. Generalized Lithologic Section of Auger-Hole

The average vertical saturated hydraulic conductivity for a layered soil, with flow perpendicular to the layers, is given by McWhorter and Sunada (1977) as:

$$K_V = \frac{\sum_{i=1}^{n} b_i}{\sum_{i=1}^{n} b_i/K_{Vi}} \qquad (4)$$

where

K_{Vi} = vertical saturated hydraulic conductivity of layer i (estimated that $K_{Vi} = 1/10\ K_{Hi}$ (mm/day), and

K_V = average vertical saturated hydraulic conductivity of clay-silt layer (mm/day).

To use Equation (4) the ratio of vertical to horizontal hydraulic conductivity within an individual layer must be estimated. This anisotropy is the result of micro-stratification within the individual layers and a ratio of one-tenth was thought to be a reasonable estimate.

Equations (3) and (4) were solved simultaneously to yield a ratio of horizontal to vertical permeability of

$$K_H/K_V = 227 \qquad (5)$$

This ratio includes the effects on anisotropy for a layered soil from both macro-stratification (large scale layering) and microstratification (small scale layering). An analysis was performed on the sensitivity of this ratio for various assumed geometries for the clay-silt layer (see Appendix B). The above ratio is thought to be a fairly conservative estimate of the ratio of anisotropy. Using this ratio (Equation 5) the vertical saturated hydraulic conductivity of the clay-silt layer was estimated from the auger-hole test results given in Table 3. The vertical saturated hydraulic conductivity calculated for Beni Magdul was 0.87 mm/day, for Abyuha was 4.9 mm/day, and for Abu Raya was 0.45 mm/day.

Consolidation Test

The second method used to determine the hydraulic conductivity of the clay-silt layer was the one-dimensional consolidation test. This test is only appropriate for determing the hydraulic conductivity of heavy soils such as clays. In the consolidation test a laterally confined saturated soil sample is subjected in the laboratory to a vertical load. When the load is first applied, the entire weight of the load is initially supported by the pore water pressure. Since the soil sample is not vertically confined, the water is free to flow out of the soil sample under pressure. Gradually, the weight of the load is tranferred from the pore water to the solid soil structure as the pore water is squeezed out of the voids. This results in a consolidation (a decrease in volume) of the soil sample. The amount of consolidation of the soil sample is then measured in the laboratory; thus, the amount of water that has escaped can be determined. The rate of consolidation is also measured. This rate of escape of the water depends on the saturated hydraulic conductivity of the soil. The governing equation for a consolidation test is Terzaghi's consolidation equation which can be written in the form of (Lambe and Whitman, 1969):

$$-\frac{\partial^2 P_e}{\partial Z^2} = \frac{\partial P_e}{\partial T} \qquad (6)$$

where

P_e = excess pore water pressure (kg/m^2);

Z = non-dimensional length defined as the ratio of elevation, Z, to one-half the height of the sample, H; and

T = non-dimensional time factor defined as:

$$T = Kt/\gamma_w m_v H^2 \qquad (7)$$

where

K = saturated hydraulic conductivity (m/day),

t = time of consolidation (days),

γ_w = unit weight of water (1000 kg/m^3),

H = one-half the initial height of the sample (m), and

m_v = coefficient of volume change (m^2/kg) which is measured during the consolidation test and is defined as the ratio of change in height, H, divided by initial height, 2H, to the vertical load per unit area applied to the sample (see Figure 10).

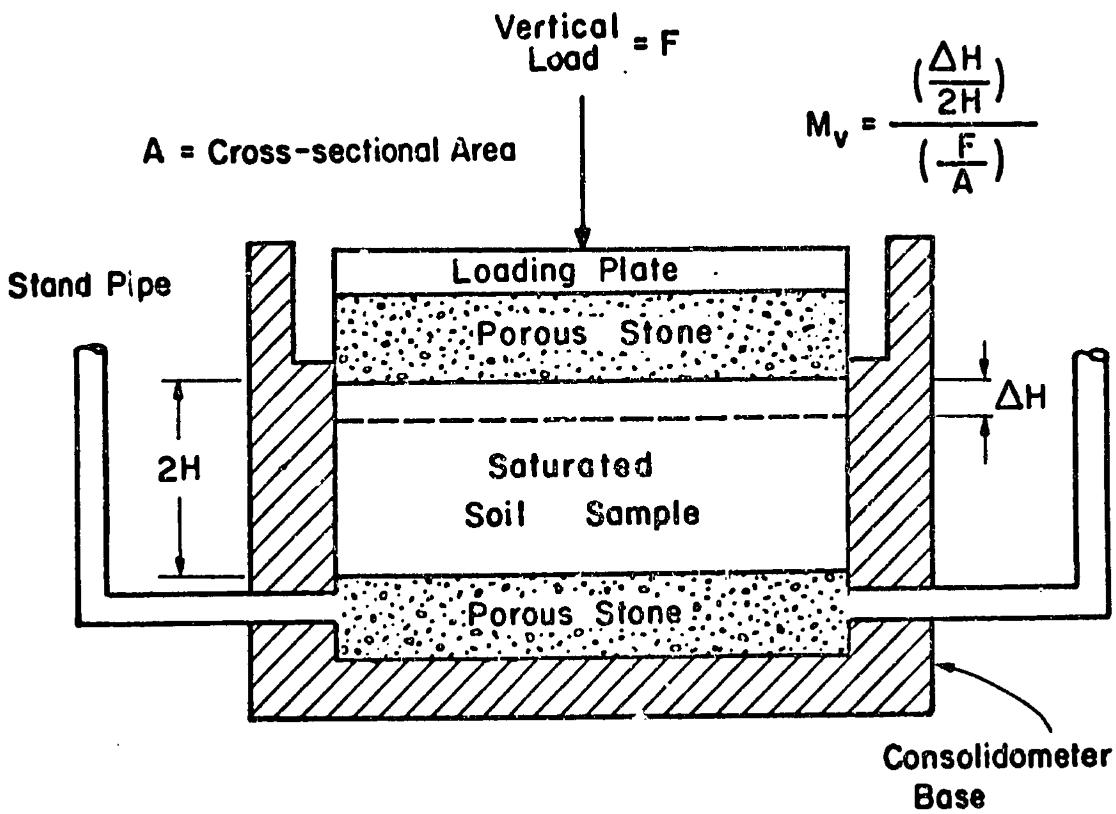

Figure 10. Definition Sketch for Consolidation Test

The solution to Equation (6) can be obtained analytically and is usually expressed with the non-dimensional time factor, T, given as a function of the consolidation ratio, U_z, defined as $1 - P_e/P_o$ where P_e is the excess pore water pressure and P_o is the initial pore pressure. The solution can also be given in graphical form (Lambe and Whitman, 1969) as a plot of the non-dimensional time factor, T, versus the percent consolidation, U (defined as the ratio of consolidation at time T to 100 percent consolidation). Using Equation (7) ,the hydraulic conductivity of the soil can then be determined.

This method has the advantage that it directly gives the vertical saturated hydraulic conductivity of the soil sample. The soil sample used in the test must be undisturbed and must also be saturated. This requires careful collection of the sample in the field and very careful sample preparation in the laboratory. The consolidation test takes about 24 hours to run in the laboratory. The major disadvantage of the method is that the entire process, from field collection and laboratory testing to analyzing the results in the office, requires a considerable amount of time and effort. Nevertheless, for clay soils this method is one of the most accurate laboratory methods for determining hydraulic conductivity.

The results of the consolidation tests are summarized in Table 4 with the complete results given in Appendix C. The vertical hydraulic conductivity determined for Beni Magdul was 0.33 mm/day, for Abyuha was 0.32 mm/day and for Abu Raya was 0.30 mm/day. Most of the samples analyzed by the consolidation test method were either clay or sandy clay. The results of the consolidation test indicate that the hydraulic conductivity of the clay is very similar at all three study sites. The values obtained for the clay are extremely low, much lower than other values of hydraulic conductivity reported in the literature for the clay-silt layer in Egypt.

TABLE 4. Hydraulic Conductivity From Consolidation Tests.

Study Site	No. of Holes	Vertical Hydraulic Conductivity (mm/day)			Standard Deviation
		K_V max	K_V min	K_V mean	
Beni Magdul	14	0.0586	0.0060	0.0329	0.0205
Abyuha	9	0.0672	0.0083	0.0318	0.0190
Abu Raya	4	0.0647	0.0100	0.0296	0.0258

The consolidation test directly gives the vertical saturated hydraulic conductivity of a homogeneous soil. However, based on the drilling of the deep observation wells and the drilling of the auger-holes, the clay-silt layer consists of mostly clay and silt interbedded with lenses of fine sand. As such, the clay-silt layer should properly be treated as a layered soil. For a layered soil, the average vertical saturated hydraulic conductivity in the direction perpendicular to the layers (i.e. the vertical direction) is given by Equation (4). The average vertical saturated hydraulic conductivity is dependent primarily on the vertical hydraulic conducitivity of the least permeable layers. In the case of the clay-silt layer, the clay layers are the least permeable. If the generalized lithology of the clay-silt layer is assumed to be represented as shown in Figure 9, then from Equation (4), the average vertical hydraulic conductivity of the clay-silt layer for the consolidation test data is 0.049 mm/day at Beni Magdul, 0.047 mm/day at Abyuha and 0.044 mm/day at Abu Raya. Thus, the presence of the more permeable sand lenses appears to have little effect on the average vertical hydraulic conductivity of the clay-silt layer. These more permeable sand lenses do, however, significantly increase the average horizontal hydraulic conductivity of the clay-silt layer (see auger-hole test results).

Permeameter Test

The permeameter test was the third method by which the hydraulic conductivity of the clay-silt layer was estimated. The permeameter test is the most common laboratory method used by groundwater hydrologists to determine hydraulic conductivity. There are two types of permeameter tests: the constant head test and the falling head test. The constant head test is most appropriate for low permeability soils such as fine sands and silts. With either type of permeameter test an undisturbed soil sample is placed in a cylindrical chamber and water is allowed to flow through the sample. The rate of flow through the permeameter and the head drop across the sample are measured during the test. Applying Darcy's Law to the permeameter, the hydraulic conductivity of the soil sample can then be calculated (McWhorter and Sunada, 1977). The falling head permeameter test was run on the samples collected from the three study sites.

With a falling head permeameter (Figure 11), the head at the inflow end or the sample is allowed to drop during the test. This is accomplished by letting the water level drop in a standpipe that is of a much smaller diameter

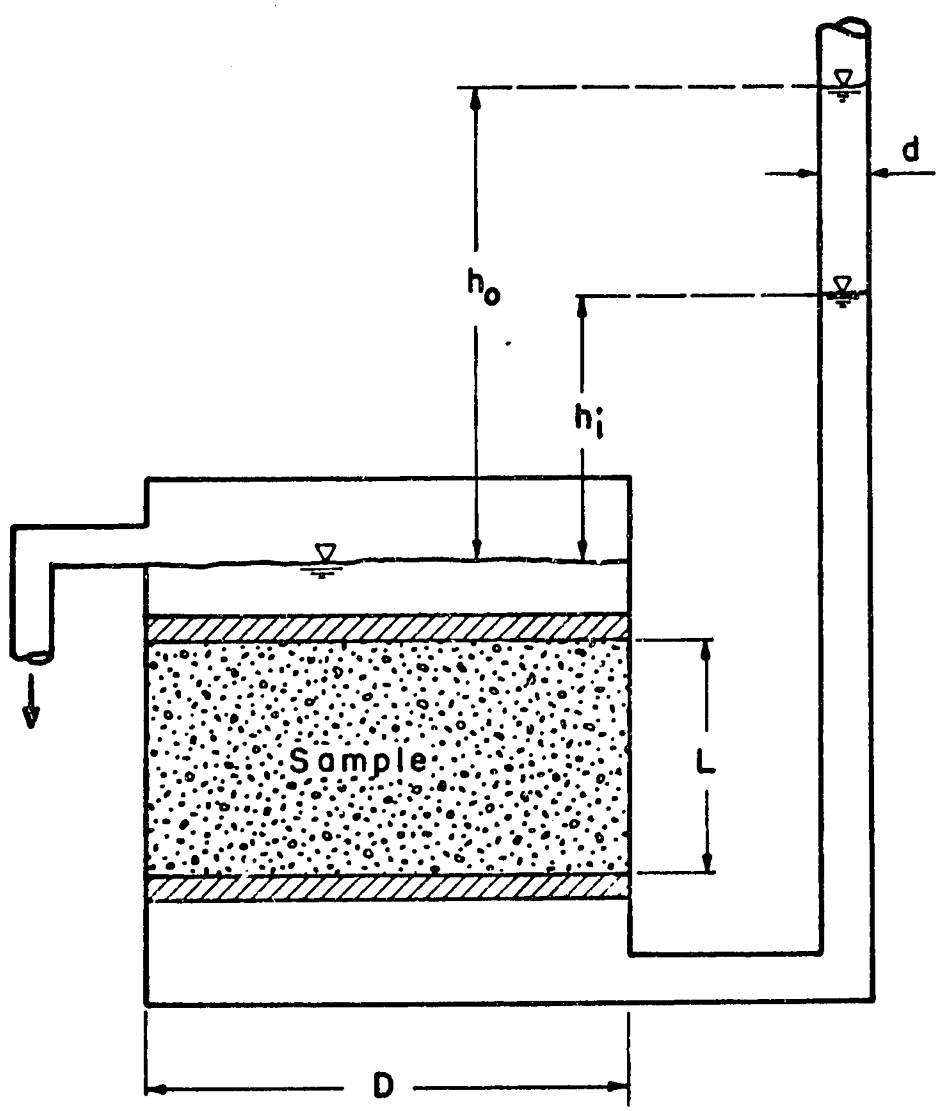

Figure 11. Falling Head Permeameter

than the sample. For the falling head permeameter, the volume rate of flow, Q, can be expressed as the product of the cross-sectional area of the standpipe and the rate of fall of the water level in the standpipe. The volume flow rate can also be expressed in terms of Darcy's law. Equating the two expressions for Q, integrating and solving for the saturated hydraulic conductivity, K, yields (Bouwer, 1978):

$$K = \frac{d^2 L}{D^2 t} \ln \frac{h_o}{h_i} \qquad (8)$$

where

- K = saturated hydraulic conductivity (m/day),
- L = height of the sample (m),
- D = sample diameter (m),
- d = standpipe diameter (m),
- h_o = initial head (m), and
- h_i = head (m) at time, t (days). Both h_o and h_i are measured as the vertical distance from the water level in the outflow reservoir to the water level in the standpipe at the beginning and end of the test.

Like the consolidation test, the permeameter test has the advantage that it directly gives the vertical saturated hydraulic conductivity of the soil. This method has the additional advantage that it requires much less time and effort to perform than does the consolidation test. For soils such as silt and some sandy clays, the permeameter test is more accurate than the consolidation test.

For very low permeability soils, such as many clays, the permeameter test is less accurate than the consolidation test. One difficulty with the permeameter test is that some leakage may occur between the soil and the permeameter chamber wall. For relatively permeable soils this leakage is not significant but for soils of very low hydraulic conductivity this source of error can be significant. Other sources of error which may be significant for very low permeability soils are evaporation of water from the standpipe and entrappment of air in the flow path. All of these errors tend to over estimate the hydraulic conductivity of the soil.

The results of the permeameter tests are summarized in Table 5 with the complete results given in Appendix D. The mean vertical saturated hydraulic conducitivity determined for the clay at Beni Magdul was 0.073 mm/day, at Abyuha was 0.147 mm/day and at Abu Raya was 0.071 mm/day. The results of the permeameter test are in close agreement with the results of the consolidation test. The difference in results is within the expected range of error associated with the two methods. The slightly larger mean value of hydraulic conductivity from the permeameter test could possibly be due to the previously discussed measurement errors for permeameter tests in clay soils. Applying Equation (4) for the same generalized lithology of the clay-silt layer as was used for the auger-hole and consolidation tests (Figure 9) gives average vertical hydraulic conductivities of the clay-silt layer from the permeameter test data of 0.11 mm/day at Beni Magdul, 0.22 mm/day at Abyuha and 0.11 mm/day at Abu Raya.

TABLE 5 Hydraulic Conductivity from Permeameter Tests

Study Site	No. of Holes	Vertical Hydraulic Conductivity (mm/day)			Standard Deviation
		K_V max	K_V min	K_V mean	
Beni Magdul	11	0.2523	0.0131	0.0728	0.0646
Abyuha	8	0.4130	0.0350	0.1467	0.1574
Abu Raya	4	0.1419	0.0218	0.0714	0.0514

Comparison Of Methods

Each method for determining hydraulic conductivity has both its advantages and disadvantages. The auger-hole method has the advantage that it is an *in situ* test. It is easily performed in the field with essentially no disturbance of the soil. The consolidation and permeameter tests require that an undisturbed soil sample be collected and taken back to the laboratory for testing. Truly undisturbed samples of sub-surface soils are difficult, if not impossible, to obtain and some disturbance is a natural consequence. This will have some effect on the values of hydraulic conductivity determined by the consolidation and permeameter tests.

Both the consolidation and permeameter tests have the advantage that they give the vertical saturated hydraulic conductivity of the soil sample directly. The auger-hole method gives the horizontal saturated hydraulic conductivity of the soil from which the vertical saturated hydraulic conductivity must be estimated. For a layered soil the average horizontal saturated conductivity is primarily dependent on the hydraulic conductivity of the most permeable layers, which for the clay-silt layer are the sand lenses. The average vertical hydraulic conductivity is primarily dependent on the hydraulic conductivity of the least permeable layer which for the clay-silt layer is the clay. This is demonstrated in Appendix B for the sensitivity analysis of the average vertical and horizontal hydraulic conductivity versus the assumed geometry of the clay-silt layer.

The consolidation and permeameter tests gave very similar results for vertical hydraulic conductivity of the clay-silt layer in the range of 0.03 to 0.15 mm/day. The auger-hole method gave a larger range of vertical hydraulic conductivity of 0.4 to 5 mm/day. Considering the basic differences in the underlying assumptions of the three methods, the results are in relatively good agreement. All methods indicated a very small value for the vertical saturated hydraulic conductivity of the clay-silt layer. These values are extremely low, much lower than any other values reported in the literature for the clay-silt layer in Egypt.

VERTICAL LEAKAGE FROM THE CLAY-SILT LAYER

Vertical leakage from the clay-silt layer represents the only major source of recharge for the deeper Nile River sands and is thought to be an important component in the dynamics of the groundwater flow system (Barber and Carr, 1981; MOI, 1981). In this study, the vertical leakage from the clay-silt layer was determined using five methods: (1) calculation from Darcy's law, (2) water table decline during closure, (3) water budgets, (4) pumping test, and (5) analytical solution.

Calculation From Darcy's Law

The equation upon which much of the theory of groundwater hydrology is based is Darcy's law. This equation relates the volume rate of flow through the aquifer to the hydraulic gradient. In its simplist form Darcy's law can be written as:

$$q = - K \Delta H/L \qquad (9)$$

where

q	=	volume flux per unit area (m^3/day/m^2), also known as the Darcy velocity since it has units of velocity (m/day),
ΔH	=	head drop between two points on the flow path (m),
L	=	length of flow path between the two points (m), (the hydraulic gradient is defined as $\Delta H/L$), and
K	=	hydraulic conductivity (m/day).

The negative sign in Equation (9) indicates that flow is in the direction of decreasing head. Darcy's law may be applied to both horizontal flow as well as to vertical leakage. Implicit in Darcy's law is that whenever there is a head drop in any direction throughout an aquifer, there is a corresponding component of groundwater flow in the same direction.

Historical groundwater data from most areas in Egypt indicate a head drop between the water table elevation of the clay-silt layer (measured as the water level elevation in shallow observation wells) and the potentiometric surface elevation of the underlying Nile River sands (measured as the water level elevation in deep observation wells). This condition is illustrated in Figure 12 and is an indication that vertical leakage occurs from the clay-silt layer to the underlying Nile River sands. Matched pairs of deep and shallow observation wells were drilled at the Beni Magdul and Abyuha study sites. At Beni Magdul the water level elevation in the upper clay-silt layer was on the average 1.2 meters above the potentiometric surface elevation of the lower Nile River sands (Figure 13). At Abyuha the difference was about 0.15 meters (Figure 14). No deep observation wells were drilled at the Abu Raya site.

In addition to the head drop, the length of the flow path and the vertical hydraulic conductivity of the clay-silt layer are also needed in applying Darcy's law to determine vertical leakage (Figure 12). The length of the flow path for vertical leakage is the saturated thickness of the clay-silt layer. This was calculated as the difference between the total thickness of the clay-silt layer as determined from inspection of the lithologic logs for the deep observation wells and the average depth to the water table as measured in shallow wells. The average saturated thickness of the clay-silt layer was 11.6 meters at Beni Magdul and 8.4 meters at Abyuha. The Ministry of Irrigation reported that in 1981 the thickness of the clay-silt layer in the delta region near Abu Raya may be as great as 30 m. The vertical saturated hydraulic conductivity of the clay-silt layer was determined in the previous section of the report by three methods: auger-hole test, consolidation test and permeameter test. The hydraulic conductivity determined by each of these three methods was substituted into the Darcy's equation to give a range of estimates for vertical leakage for the Beni Magdul and Abyuha sites (Table 6).

The estimates of vertical leakage given in Table (6) range from 0.0008 mm/day to 0.09 mm/day for the sites studied. These values are extremely low and indicate that vertical leakage from the clay-silt layer in these areas is very small . They reflect the dense nature of the clay-silt cap and it's correspondingly small vertical saturated hydraulic conductivity.

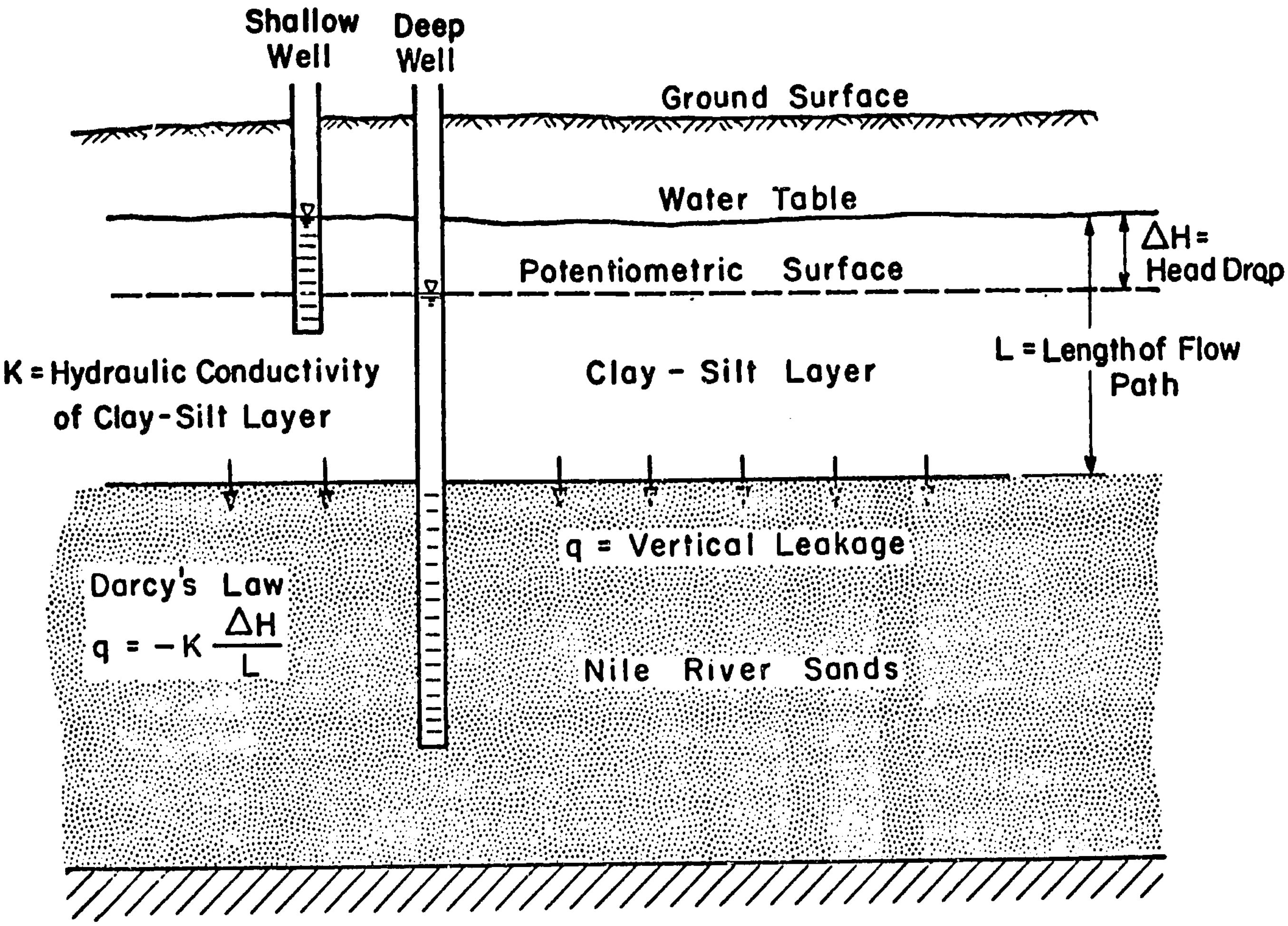

Figure 12. Vertical Leakage from the Clay-Silt Layer as Calculated From Darcy's Law

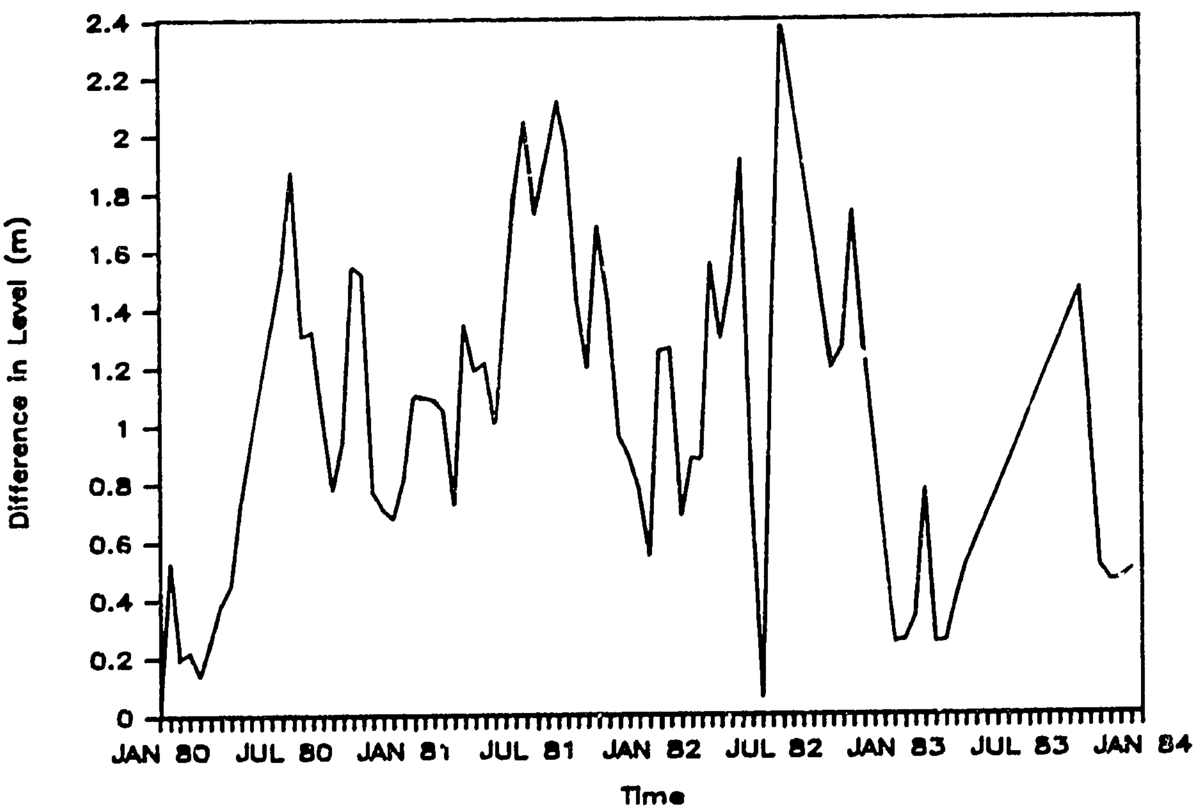

Figure 13. Difference Between Water Table Level in Clay-Silt Layer and Level of Potentiometric Surface in Deep Sands at Beni Magdul

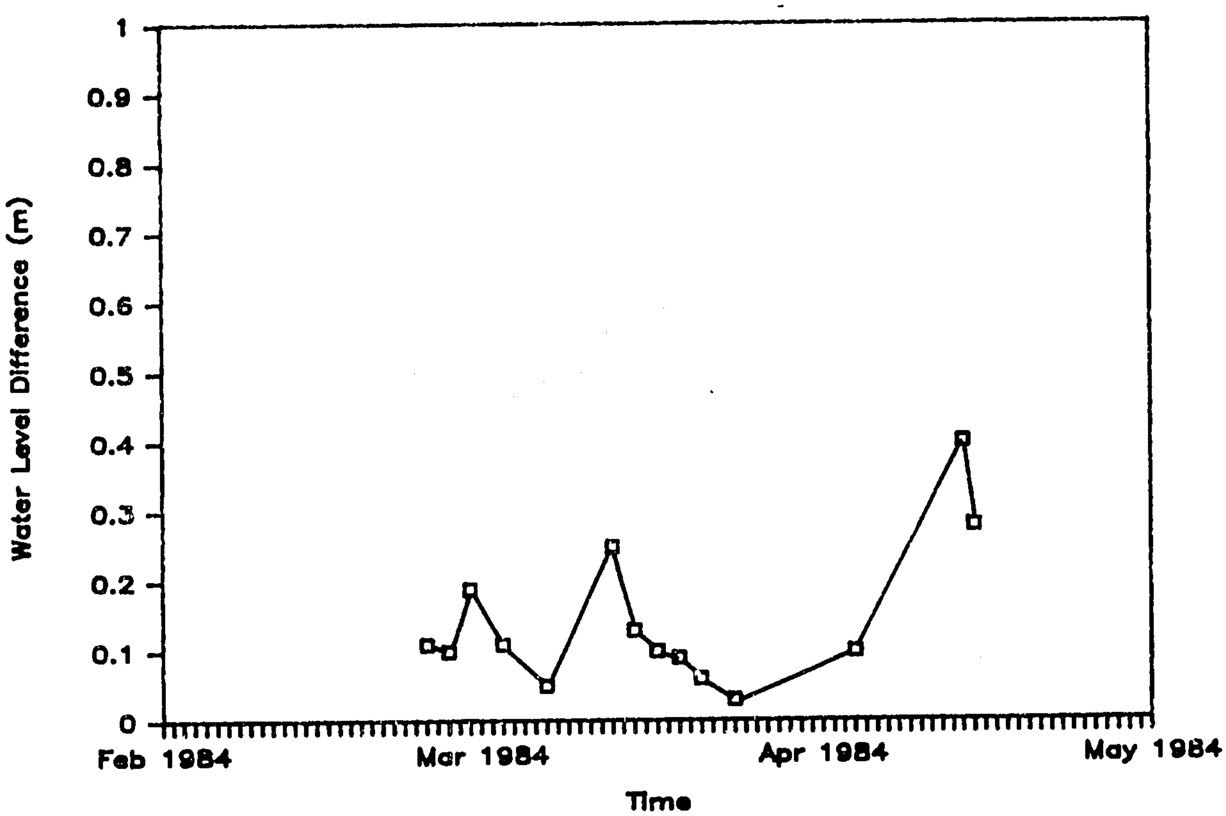

Figure 14. Difference Between Water Table Level in Clay-Silt Layer and Level of Potentiometric Surface in Deep Sands at Abyuha

TABLE 6 Vertical Leakage from Darcy Equation

Study Site	Auger Hole K_V mm/day	Auger Hole q mm/day	Consolidation K_V mm/day	Consolidation q mm/day	Permeameter K_V mm/day	Permeameter q mm/day
Beni Magdul	0.87	0.090	0.049	0.005	0.11	0.011
Abyuha	4.90	0.088	0.047	0.008	0.22	0.004

Water Table Decline During Closure

Normally during the months of January and February each year, flow in Egypt's irrigation canals is significantly reduced in an orderly sequence to allow maintenance of hydraulic structures and cleaning of canals. During this period of time, referred to as the closure period, essentially all irrigation is halted. As a result, the water table in the clay-silt layer declines approximately .5 to 1 meter during the closure period.

This water table decline in the clay-silt layer was measured in 41 shallow observation wells for three years (1979, 1980 and 1982) at Beni Magdul (Figure 15), in 46 shallow wells for two years (1981 and 1982) at Abyuha (Figure 16) and in 35 shallow wells for two years (1982 and 1983) at Abu Raya (Figure 17). An estimate of the vertical leakage from the clay-silt layer can be determined from these water table declines during the closure period.

The decline of the water table during closure is due primarily to downward movement of the water by vertical leakage and upward movement through evapotranspiration. At the start of the closure period the upward movement of the water due to evapotranspiration is at a maximum and should represent a significant part of the water table decline. Toward the end of the closure period the evapotranpiration loss is at a minimum and should represent a smaller part of the water table decline. Thus, analysis of the rate of water table decline at the end of closure should provide an estimate of vertical leakage from the clay silt layer to the underlying Nile River sands.

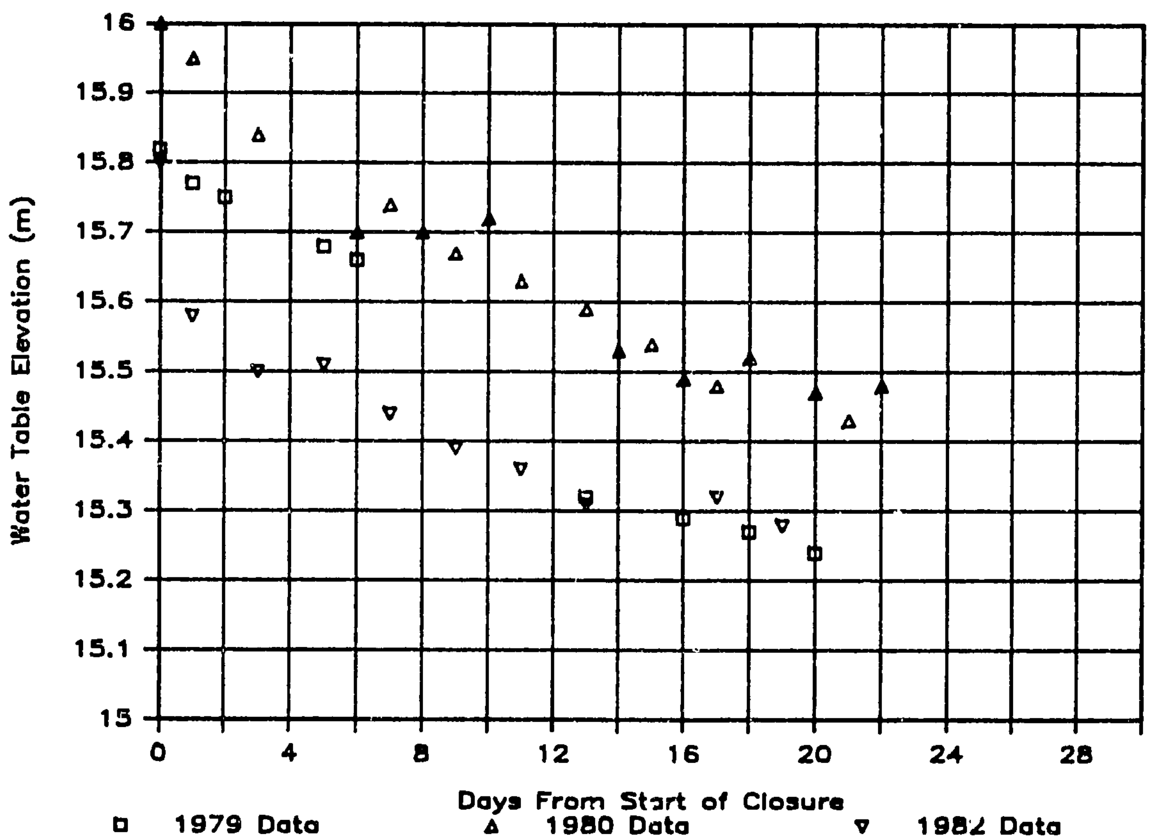

Figure 15. Decline of water table during the closure period at Beni Magdul.

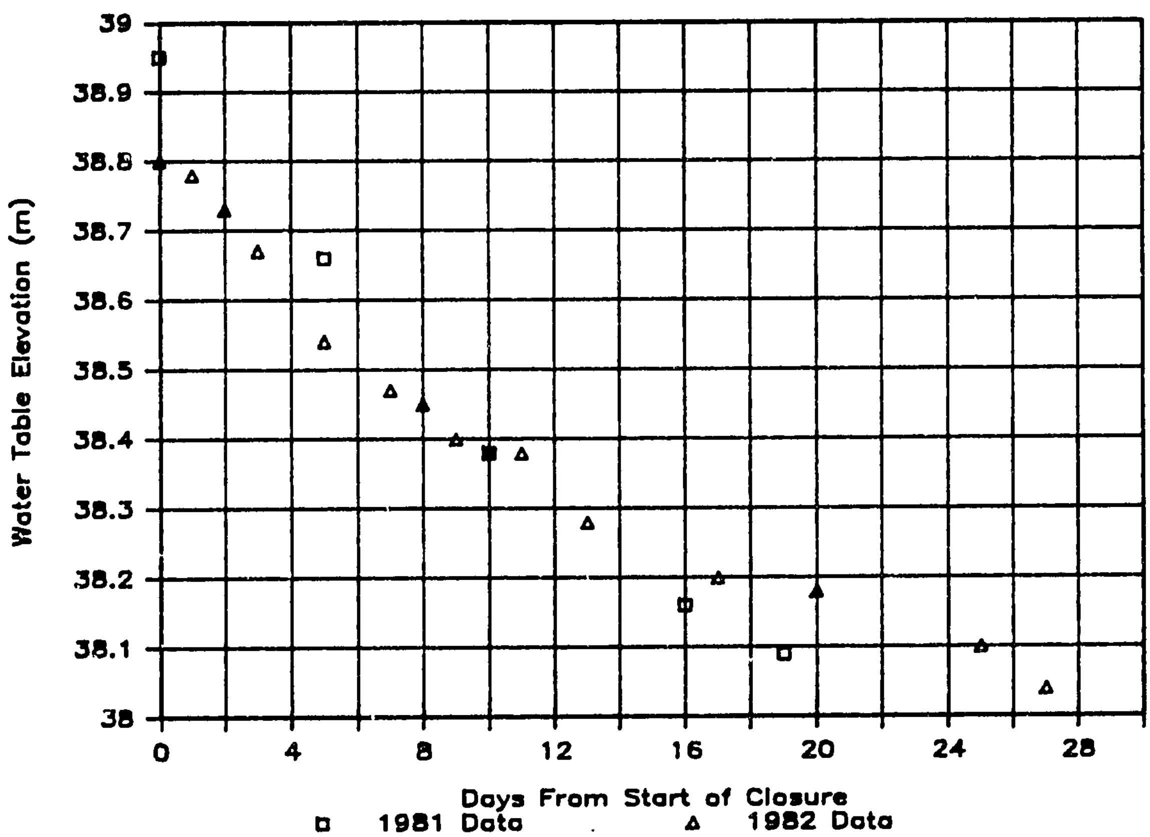

Figure 16. Decline of water table during the closure period at Abyuha.

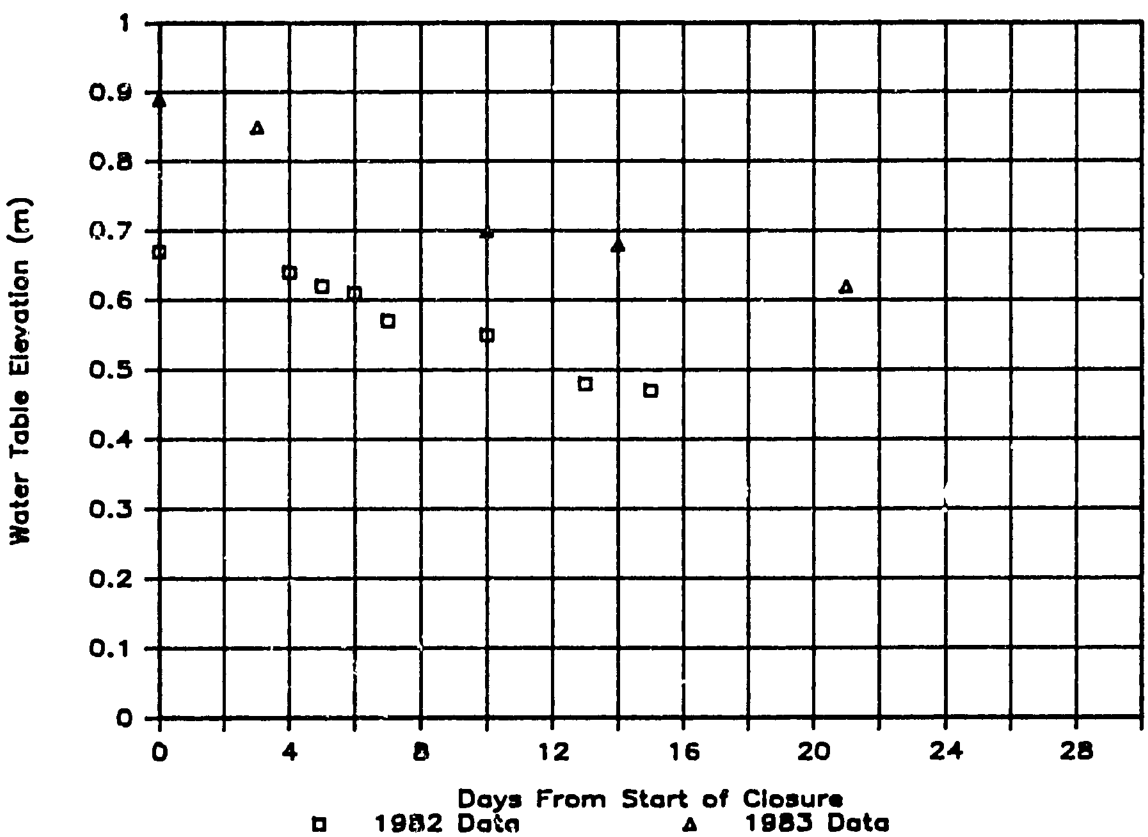

Figure 17. Decline of water table during the closure period at Abu Raya.

The rate of vertical leakage during closure is approximately constant. The water table decline in the clay-silt layer during closure is accompanied by a corresponding parallel decline in the potentiometric surface elevation of the underlying Nile River sands. This is shown on Figure (18) for a shallow well and a deep well at the Beni Magdul site. Since the declines in the upper and lower aquifers are nearly parallel, the head difference between the two aquifers remains nearly constant. This head drop is the driving force behind the vertical leakage. From Darcy's law (Equation 9), if the head drop is constant (in essence the hydraulic gradient is assumed constant), then the vertical leakage is a constant.

The fact that water level fluctuations in deep and shallow observation wells are commonly observed to be parallel may lead one to conclude that there is close hydrologic connection between the deep and shallow aquifers. The assumption implicit in such reasoning is that a decline in the water table elevation causes a reduction in the vertical leakage and a corresponding drop in the potentiometric surface elevation of the underlying Nile River sands. Similarly, a rise in the water table elevation causes an increase in the vertical leakage and a corresponding rise in the potentiometric surface elevation of the deeper aquifer. However, the error in this reasoning is that since the water level fluctuations are nearly parallel in magnitude, the head difference is nearly constant, and, from Darcy's law it follows that the vertical leakage is nearly constant.

A more probable explanation for the water level fluctuations of the two aquifers being parallel is that the lower aquifer is merely reflecting a change in overburden stress caused by changes in storage in the clay-silt layer. The overburden weight, caused by the weight of the solid material composing the clay-silt layer as well as the water in storage in the clay-silt is supported in part by the water pressure in the lower aquifer and in part by the solid aquifer skeleton of the lower aquifer (McWhorter and Sunada, 1977). Any changes in the overburden weight (due to changes in water storage in the clay-silt layer) would initially be supported by changes in water pressure in the deep aquifer. Since the water in the lower aquifer is free to flow laterally to and from the Nile River, eventually any change in overburden weight would gradually be transferred to the solid aquifer skeleton. This transfer takes place slowly and since typical observed water level fluctuations are usually short term, changes in storage within the clay-silt layer as measured in shallow wells is reflected most generally by a similar change in the potentiometric surface elevation of the lower aquifer as measured in the deep wells.

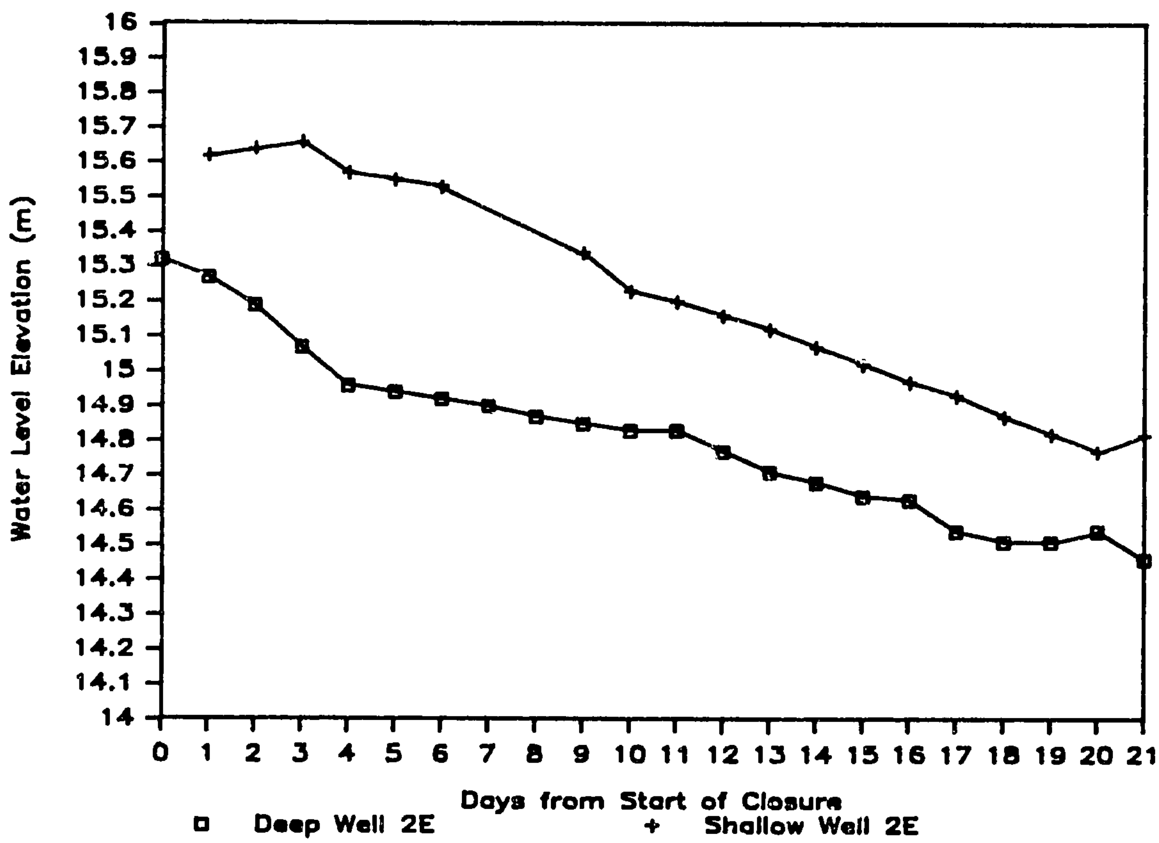

Figure 18. Water level elevation in the deep and shallow aquifer during the closure period at Beni Magdul.

Equation (10) gives the of vertical leakage from the decline of the water table during the end of closure:

$$q = S_{ya}\, dh/dt \qquad (10)$$

where

q = vertical leakage (mm/day)

S_{ya} = apparent specific yield (dimensionless), and

dh/dt = rate of water table decline during the end of closure (mm/day).

The apparent specific yield used in Equation (10) is defined as the ratio of the volume of water drained to the bulk volume of the aquifer for a resultant lowering of the water table elevation. From this definition, the apparant specific yield was obtained as the ratio of the shaded area (Figure 19) between the ground surface and the water retention curve for two successive depths to the water table to the corresponding change in depth. Using data from Moustafa and Tinsley (1984), the apparent specific yield obtained by this method was 0.038 for the Abyuha study site. This value is in close agreement with that reported by El-Mowelhi and Van Schilfgaarde (1982) from field drainage experiments in Egypt. In their work they reported an apparent specific yield of 0.041 for the Sakha area in the delta. A constant apparent specific yield of 0.04 was used in Equation (10) for all study sites.

To determine the rate of the water table decline, a straight line was fitted to the tail end of the data for the water table decline curves given in Figures 15, 16 and 17. The rate of decline for each site and also the corresponding estimate of the upper limit of vertical leakage is given in Table (7). The range in vertical leakage calculated by this method is between 0.33 mm/day at Abu-Raya and 0.752 mm/day at Abyuha.

TABLE 7 Vertical Leakage for Water Table Decline During Closure.

Study Site	S_{ya}	dh/dt (mm/day)	q_u (mm/day)
Beni Magdul	0.04	11.4	0.456
Abyuha	0.04	18.8	0.752
Abu Raya	0.04	8.3	0.332

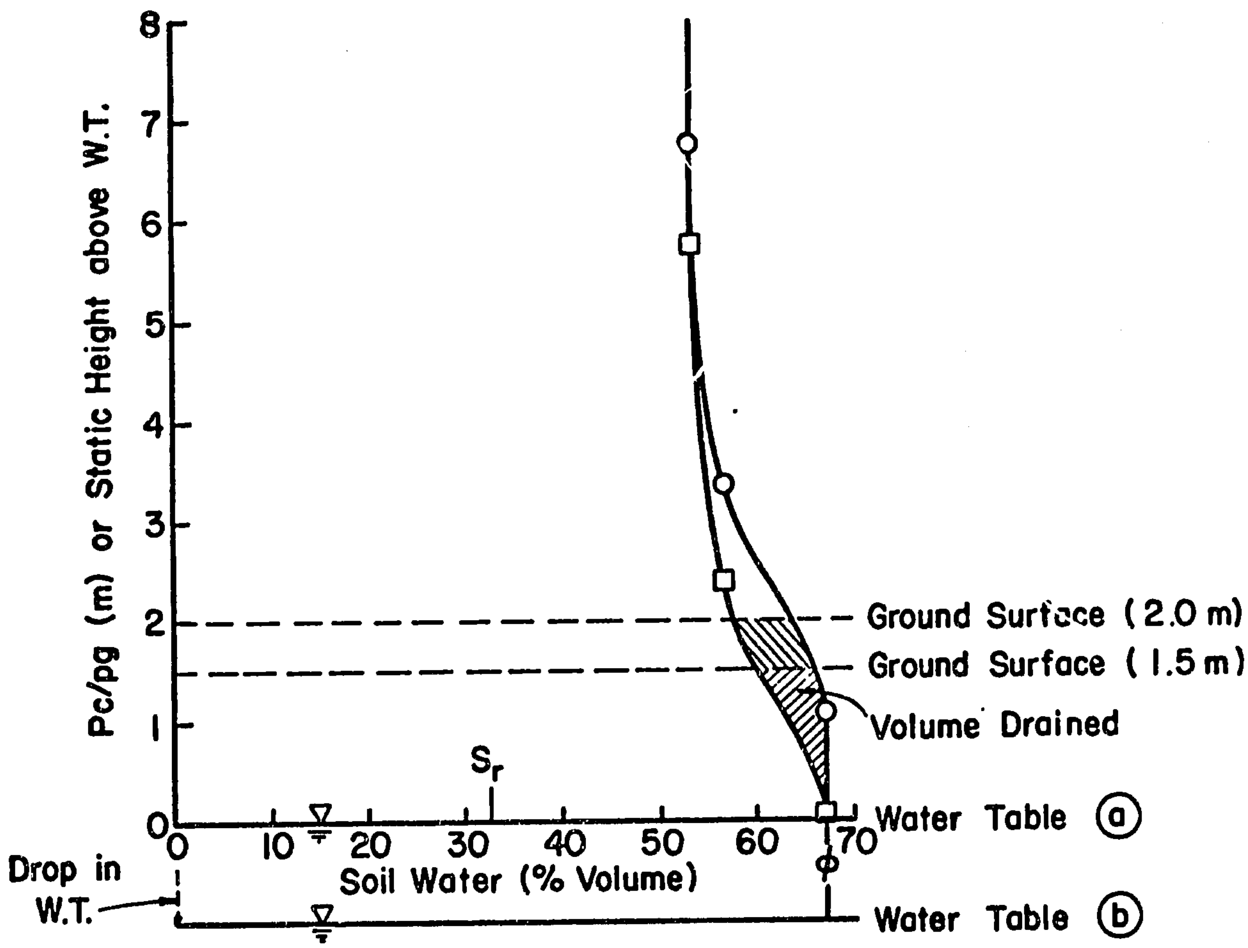

Figure 19. Calculation of Apparent Specific Yield From the Soil Water Retention Curve for Abyuha (After Moustafa and Tinsley, 1984).

Water Budgets

The third method used to estimate vertical leakage was by water budgets. A water budget is an account of all water that enters, exits and is stored in a specified region during a given time period. A detailed water budget was performed for the clay-silt layer of each of the three study sites. The details of these water budget studies are presented in Helal et al. (1984). Only a very brief description of the results of the water budgets is presented in this report. One of the components of the water budget for the clay-silt layer is vertical leakage. By solving for all other components in the water budget, the vertical leakage from the clay-silt layer was estimated as the dependent component in the budget.

The basis for any water budget study is the equation of continuity which can be written as:

$$I - O = \Delta S \qquad (11)$$

where

I = total inflow volume of water entering the specified region during a given time period (m^3)

O = total outflow volume of water leaving the specified region during a given time period (m^3)

ΔS = total change in the volume of water stored within the specified region during a given time period (m^3).

For the clay-silt layer, the major source of inflow in the water budget is applied irrigation water as measured by surface water delivered in the irrigation canals. Minor amounts of inflow occur as horizontal subsurface inflow and from infiltration of precipitation. The major outflows are surface discharge to the drains and crop consumptive use. Minor amounts of outflow occur as surface outflow to other irrigated areas, as horizontal subsurface outflow and as vertical leakage. Except during and immediately after the closure period, the clay-silt layer can be considered to be in a state of dynamic equilibrium with only small changes occuring in the volume of subsurface water in storage.

Summarized in Table 8 are the results of the water budget studies for the three study sites. Vertical leakage was calculated by solving for all other components and then setting the unaccounted-for water in the water budget equal to the vertical leakage. The resulting average calculated vertical leakage was 0.90 mm/day for Beni Magdul, 1.10 mm/day for Abyuha and 0.60 mm/day for Abu Raya.

Because of measurement errors, the sum of the inflow components minus the sum of the outflow components never exactly equals the change in storage. Significant error can be introduced into the estimate of vertical leakage as the result of even the smallest measurement errors of the major components in the water budget calculation. The water budget method only gives approximate estimates of vertical leakage but does confirm the results obtained by the other methods that the vertical leakage from the clay-silt layer is very small.

Leaky Aquifer Pumping Test

With the previous three methods, calculation of vertical leakage was determined from consideration of only the clay-silt layer. The classical method of determining vertical leakage is through a leaky aquifer pumping test on the lower semi-confined aquifer, which in this case is the underlying Nile River sands. By analyzing the drawdown response of the semi-confined aquifer for a constant pumping stress, it is possible to determine if the aquifer is being recharged by vertical leakage. The setup for a leaky aquifer test is shown in Figure 20. With this method, a deep well, perforated only in the lower Nile River sands aquifer, is pumped at a constant rate. The drawdown response is monitored at a series of nearby observation wells.

For a leaky aquifer the theoretical drawdown response is given by Walton (1970) as:

$$s = \frac{Q}{4\pi T} W(u, r/B) \tag{12}$$

TABLE 8 Water Balance Components From Study Sites With Vertical Leakage Computed As Dependent Variable (from Helal, et. al., 1984)

		INFLOW (mm/day)			STORAGE CHANGE (mm/day)		OUTFLOW (mm/day)					
Site	Period	I(A)	I(B)	I(C)	dS(A)	dS(B)	O(A1)	O(A2)	O(B2)	O(C)	O(D)	O(B1)
Abyuha	W80	5.742	0.100	0.000	0.000	0.071	2.588	0.443	0.000	1.956	0.019	0.906
	S81	9.308	0.085	0.000	0.000	0.180	3.056	0.703	0.000	4.188	0.044	1.582
	W81-82	5.490	0.100	0.000	0.000	-0.042	2.553	0.166	0.000	2.015	0.017	0.798
											Average =	1.095
Beni Magdul	W79-80	3.363	0.077	0.036	0.000	0.022	0.463	0.061	0.000	2.119	0.009	0.846
	S80	5.258	0.118	0.000	0.000	-0.064	0.503	0.095	0.000	4.031	0.019	0.665
	W80-81	3.638	0.082	0.030	0.000	0.037	0.476	0.066	0.000	2.443	0.009	0.794
	S81	5.284	0.119	0.005	0.000	0.018	0.503	0.095	0.000	3.876	0.020	0.933
	W81-82	3.977	0.080	0.043	0.000	0.026	0.460	0.072	0.000	2.060	0.009	1.534
	S82	4.508	0.101	0.000	0.000	-0.033	0.503	0.077	0.000	3.333	0.020	0.644
											Average =	0.903
Abu Raya	S82	8.052	0.000	0.000	0.000	0.044	4.670	0.000	0.000	3.438	0.052	-0.064
	W81-83	5.779	0.000	0.201	0.000	-0.126	2.669	0.000	0.000	1.685	0.236	1.263
											Average =	0.599

"W" indicates winter agricultural season
"S" indicates summer agricultural season

I(A) = total surface inflow
I(B) = total subsurface inflow
I(C) = total precipitation
O(AI) = total surface outflow in drains
O(A2) = total surface outflow to irrigate adjacent areas

O(B1) = total vertical leakage subsurface outflow
O(B2) = total horizontal subsurface outflow
O(C) = total crop consumptive use
O(D) = total outflow as evaporation from free water surface
dS(A) = total storage change in surface water
dS(B) = total storage change in subsurface water

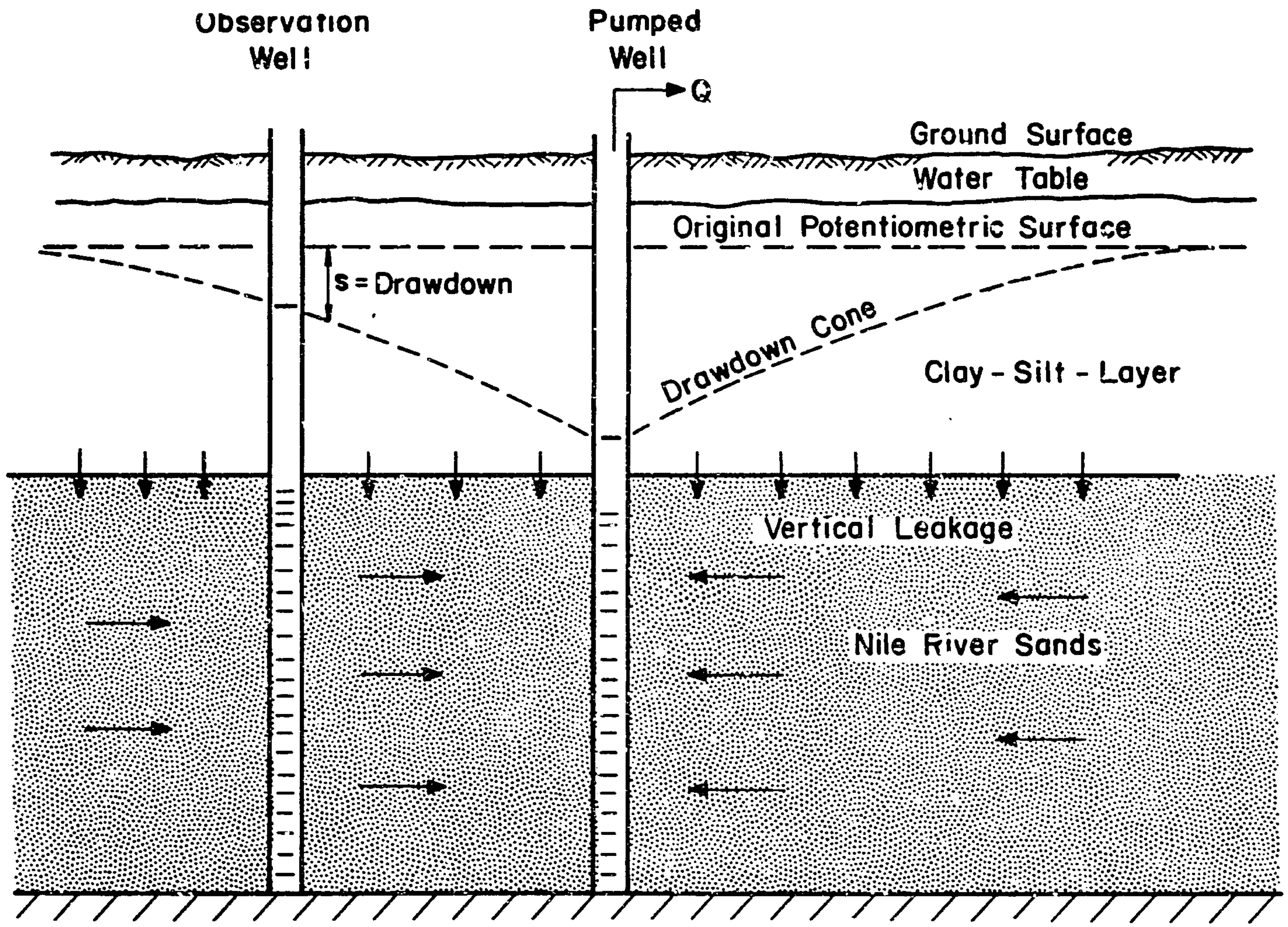

Figure 20 Schematic of Leaky Aquifer Pumping Test

where

s	=	drawdown at a distance r (m) at time t (days) from the pumped well (m),
Q	=	constant pumping rate (m^3/day),
T	=	transmissivity of the semi-confined aquifer which, in this case, is the underlying Nile River sands (m^2/day),
$W(u,r/B)$	=	leaky well function, the value of which is tabulated in most standard groundwater text books (Bouwer 1978),
u	=	Boltzman variable (dimensionless) defined as:

$$u = r^2S/4Tt \qquad (13)$$

S	=	storage coefficient of the semi-confined aquifer (dimensionless)
r/B	=	hydraulic resistance (dimensionless) where:

$$B^2 = T/(K'/b') \qquad (14)$$

K'	=	vertical hydraulic conductivity of the semi-confining layer which in this case is the clay-silt layer (m/day), and
b'	=	saturated thickness of the semi-confining layer (m).

The quantity (K'/b') is referred to as the leakance which is to be solved for through the leaky aquifer pumping test.

The transmissivity and storage coefficient for a leaky aquifer, and the leakance of the overlying leaky confining layer may be determined by use of a type-curve graphical matching procedure developed by Walton (1970). With this method, values of $W(u,r/B)$ are plotted versus $1/u$ on log-log paper and a family of leaky type curves (one curve for each value of r/B used (see Todd, 1980)) are generated. From the field data, values of drawdowns measured for each observation well are then plotted against time, t, on log-log paper of the same scale as was used for the type curves. The type curves are super-imposed over the plot of the time-drawdown data measured in the field and a match point is then determined. The transmissivity, T, of the aquifer is determined from Equation (12), the storage coefficient, S, or of the aquifer is determined from Equation (13) and the leakance (K'/b') of the confining layer is determined from Equation (14). The vertical leakage from the clay-silt layer can then be determined by applying Darcy's law:

$$q = (K'/b')\, \Delta H \qquad (15)$$

where

q	=	vertical leakage ($m^3/day/m^2$) and
ΔH	=	head difference between the water table elevation in the clay-silt layer and the potentiometric surface elevation of the Nile River sands (m).

A leaky aquifer test was preformed in August, 1982 on a deep well at the Beni Magdul site. A well was pumped at a constant rate of about 25.8 L/s for 48 hours. During the test the aquifer response to pumping was measured in 12 observation wells, (6 deep observation wells in the Nile River sands and 6 shallow observation wells in the clay-silt layer). These 12 observation wells were clustered in sets of 6 with each set represented by a shallow and a deep observation well at essentially the same location. The six sets of observation wells were spaced 5, 10, 15, 25, 75 and 100 m from the pumped well.

The location of observation wells is very critical for a leaky aquifer test. As a general rule, the observation wells should be located at a distance of at least 1.5 times the thickness of the aquifer from the pumped well to avoid the effects of partial penetration of the wells. Additionally, with the observation wells too close to the pumped well, the time drawdown data follows the flat internal part of the type curves, which makes it difficult to obtain a relatively good match. An earlier pump test was performed at the Beni Magdul site in December, 1979. In this attempt, no definite conclusions could be made regarding the existence of leakage. The main difficulty with the previous test was that the observation wells were located too close to the pumped well thus making it impossible to obtain a good match. Consequently, two outer sets of observation wells (75 m and 100 m) were drilled for the later test. There is a tradeoff between increasing the distance of the observation wells from the pumped well to avoid the forementioned difficulties and still being able to measure the aquifer response to pumping. For conditions in Egypt similar to those at Beni Magdul, one or more of the observation wells should be located 75 to 100 meters from the pumped well.

The time-drawdown data from the Beni Magdul aquifer test for the two most distant observation wells is shown in Figures 21 and 22. Analysis of these data yielded the following results:

Transmissivity of deep sands	T	=	6120 m^2/day
Storage coefficient of deep sands	S	=	6.80×10^{-4}
Leakance of clay-silt layer	K'/b'	=	0.985 (m/day)/(m)

Using an average head difference of 1.2 m between the water table in the clay-silt layer and the potentiometric surface of the underlying Nile River sands, the vertical leakage was computed from Equation (15) to be about 1.18 mm/day. For a leaky aquifer pumping test this is a very low value of vertical leakage and is nearly the practical lower limit of the test. This method is better suited and gives more reliable results for a higher value of leakage. The problem is that when leakage is small, the Walton leaky type curve approaches the Theis non-leaky type curve. Thus, the test needs to be run for a longer time period at a higher pumping rate with the observation wells located farther from the pumping well in order to differentiate between the two type curves.

Also, the leaky aquifer test does not differentiate between sources of recharge. There is the implicit assumption in this method that vertical leakage is the only source of recharge for the underlying Nile River sands. The Beni Magdul aquifer test site is probably typical of most sites in Egypt in that several irrigation canals and drains are in close proximity of the site. It was assumed that none of these canals or drains are deep enough to intersect the deep sands.

It is possible, however, that all or part of the leakage determined by the aquifer test may be due to recharge sources other than vertical leakage. The estimated vertical leakage of 1.18 mm/day at Beni Magdul determined by the aquifer test represents a maximum amount of actual vertical leakage occurring.

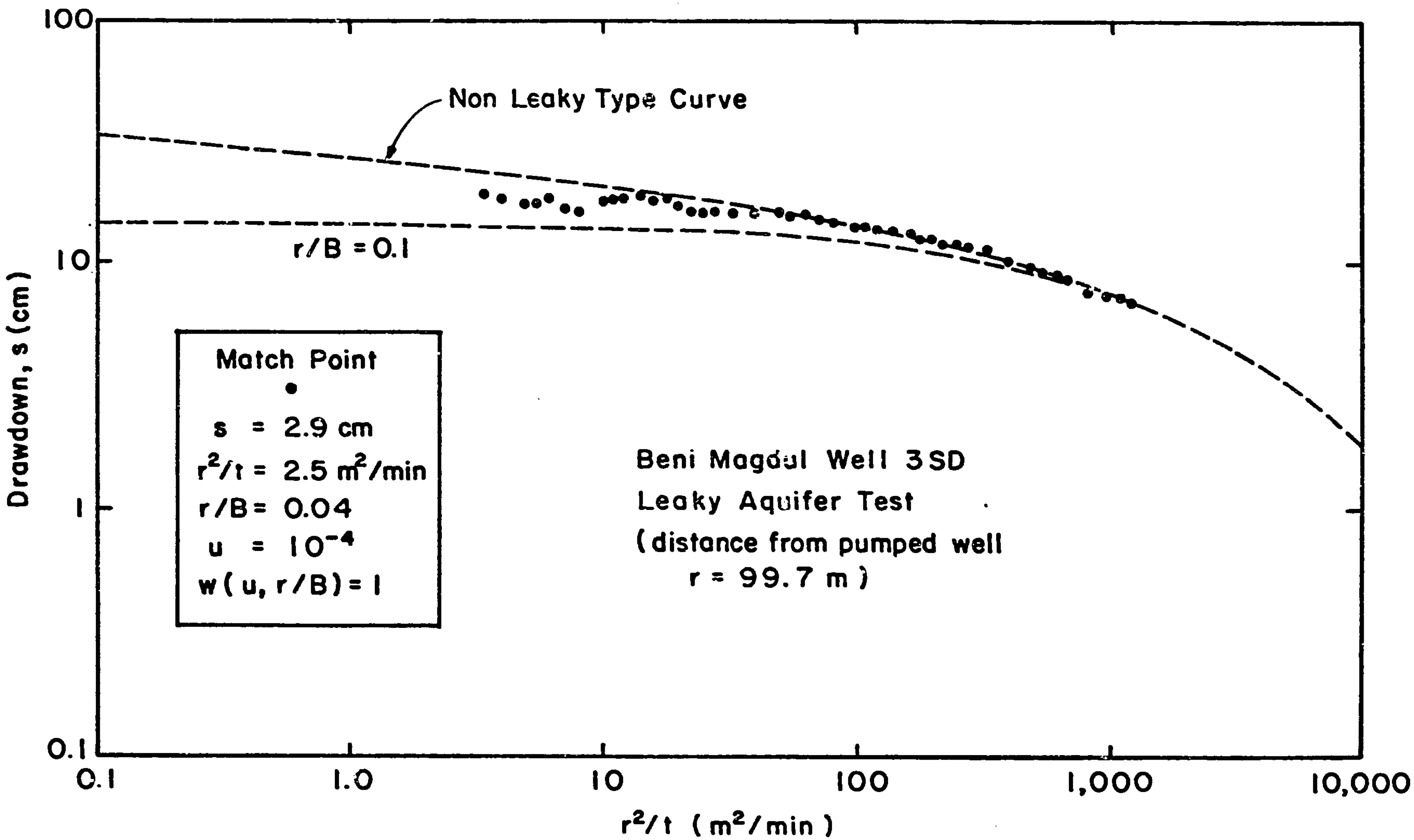

Figure 21 Time-Drawdown Data From Beni Magdul Leaky Aquifer Test For Well 3SD

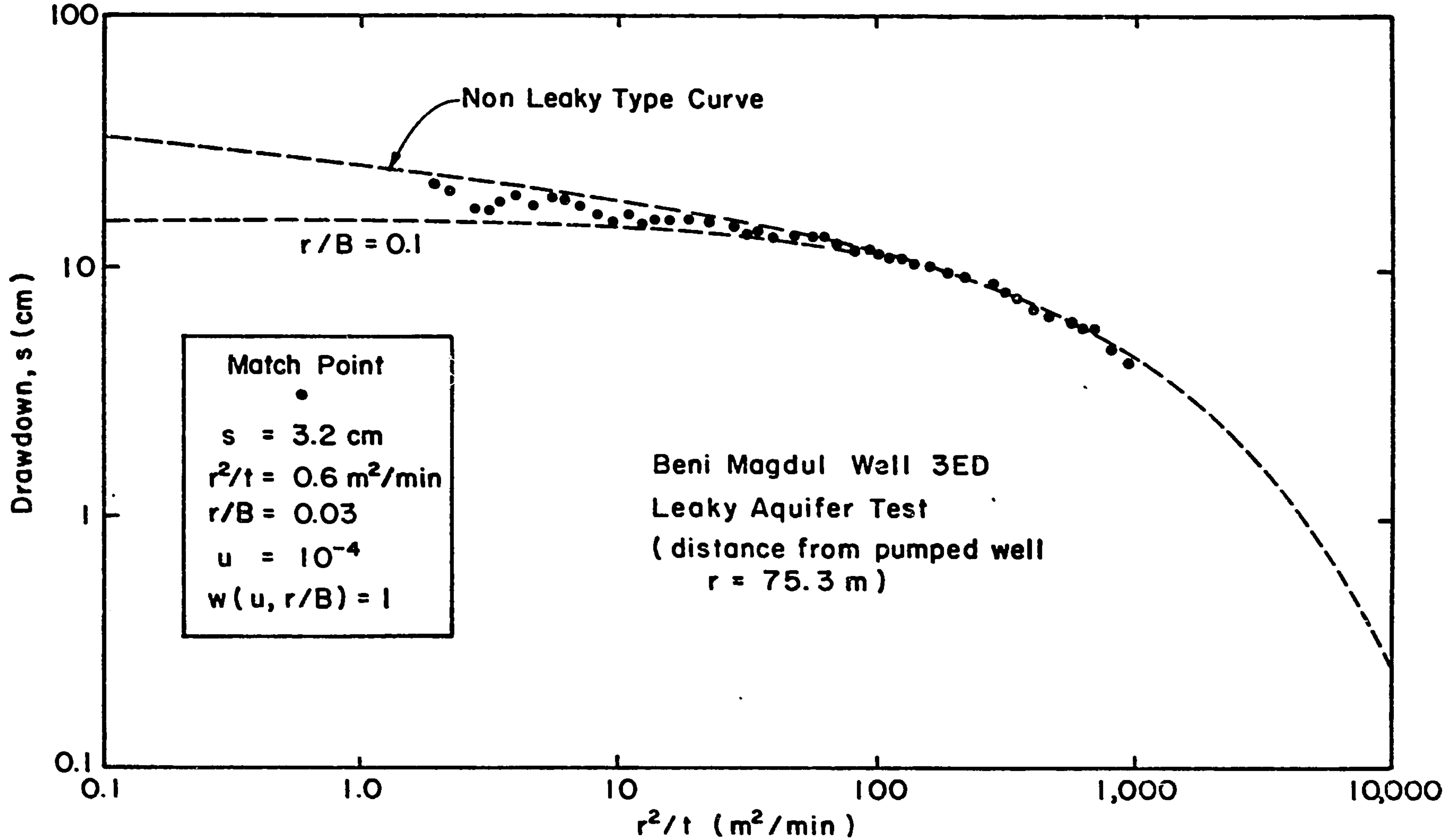

Figure 22 Time-Drawdown Data From Beni Magdul Leaky Aquifer Test For Well 3ED

Analytical Solution

Like the aquifer test, this method uses the behavior of the underlying Nile River sands to estimate the vertical leakage from the clay-silt layer. Using the conceptual model of the groundwater system shown on Figure 2, the vertical leakage can be estimated through use of the following analytical solution:

$$q = \frac{2T\,(h-h_r)}{(a^2 - (a-x)^2)} \quad (1000) \qquad (16)$$

where

q = vertical leakage (mm/day),

T = transmissivity of Nile River sands (m^2/day),

a = distance from Nile River to the edge of the river valley flank (m),

h_r = water surface elevation of the Nile River sands at a distance of x meters from the Nile River, and

h = water surface elevation in the Nile River (m).

Equation (16) from Todd (1980) has been modified for the case of a semi-confined aquifer. The above analytical solution is valid only for one-dimensional groundwater flow towards the Nile. In the vicinity of the Beni Magdul site, local groundwater flow patterns are effected by pumping near Giza and the conceptual model of the groundwater flow system shown on Figure 2 is not valid for this site. However, in the vicinity of Abyuha the groundwater flow pattern is, in general, toward the Nile River. There is a component of groundwater flow parallel to the Nile River but is small compared to the component of groundwater flow directly towards the Nile. Thus, the anlytical solution given in Equation (16) should be reasonably applicable for the Abyuha study site. In the delta area, a major component of the groundwater flow is toward the Mediterranaen Sea and parallel to the Nile River, thus Equation (16) is not applicable to the Abu Raya site.

To apply Equation (16), the transmissivity of the Nile River sands and the head difference between the Nile River and the groundwater are needed. The Groundwater Research Institute of the Ministry of Irrigation has performed an aquifer test to determine the transmissivity of the deep aquifer for well 6g, which is very near the Abyuha site (Figure 24). They obtained a transmissivity of 12,375 m^2/day for this site (Barber and Carr, 1981). The head difference between the Nile River and the groundwater fluctuates over the year (Figure 23). An average head difference was determined for each of three wells (Figure 24). The vertical leakage at Abyuha estimated from Equation (16) was about 0.5 mm/day (Table 9). This result compares very well the vertical leakage determined by the other methods.

TABLE 9 Vertical Leakage Calculated by Analytical Solution

Study Site	Well No.	a Distance from Nile River to Valley Flank (m)	x Distance from Nile River to Well (m)	$h-h_r$ Average Head Difference between River and Groundwater (m)	q Vertical Leakage (mm/day)
Abyuha	40	14,900	10,500	3.72	0.441
	43	14,800	12,300	3.43	0.387
	5G	15,400	4,400	2.93	0.605
Mean					0.476

Comparison of Methods

In comparing the five methods (Darcy's law, water table declines during closure, water budget, aquifer tests and analytical solution), it must be realized that each method is subject to measurement errors and is based on some fundamental underlying assumptions. The magnitude of these measurement errors and how well these underlying assumptions agree with the actual field conditions, determine for a large part the reliability of an individual method.

In estimating vertical leakage by Darcy's law, the variables subject to measurement error are the vertical saturated hydraulic conductivity of the clay-silt layer, the head differences between the two aquifers, and the length of the flow path. The errors involved in determining the vertical saturated hydraulic conductivity of the clay-silt layer were discussed in the previous section of the report. The measured values of vertical saturated hydraulic conductivity are thought to be fairly reliable. The head differences and the flow path length are easily measured in the field and should also be fairly reliable. The major underlying assumption for this method is that the fine sand lenses found in the clay-silt layer

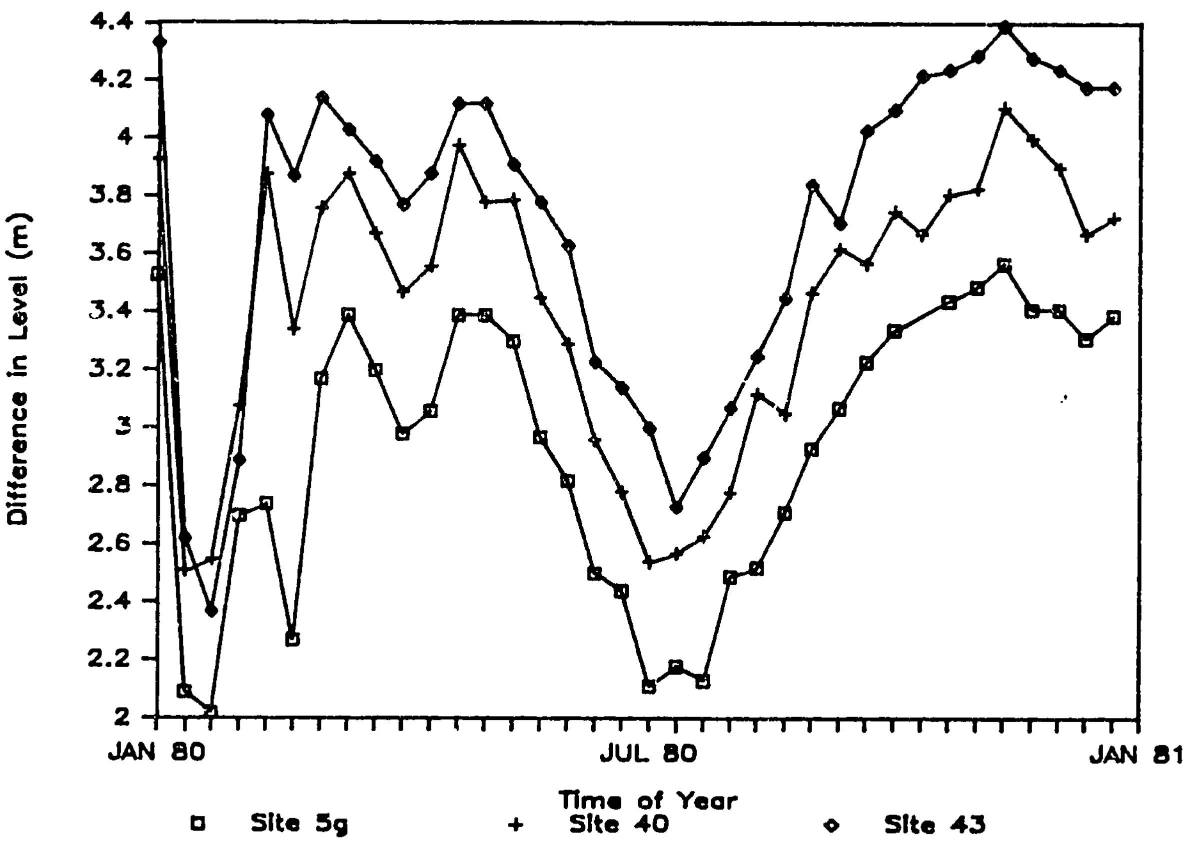

Figure 23. Difference between the level of the potentiometric surface in the Nile River sands and the wter level in the Nile River near Abyuha.

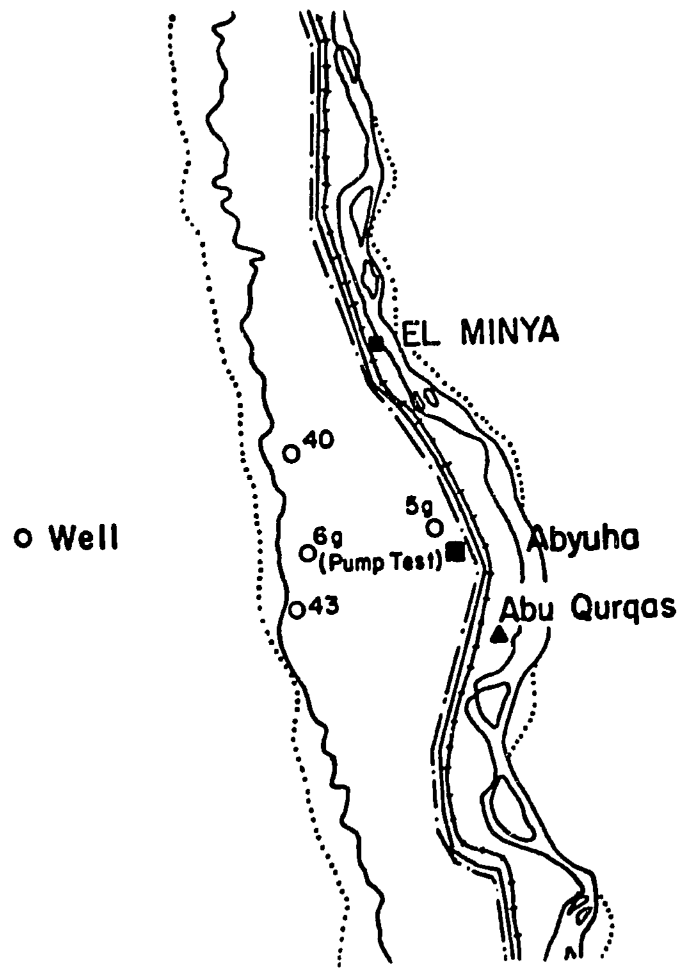

Figure 24 Location of Wells Near Abyuha Used for Determination of Vertical Leakage by Analytical Solution

are discontinuous in the vertical direction. This then requires that the downward vertical leakage must occur through the clay layers. The vertical leakage as determined by Darcy's law was smaller than that determined by the other methods. This could indirectly indicate the existence of continuous fine sand lenses which would then act as conduits for downward flow. Estimates of vertical leakage by this method should be considered a minimum.

In determining vertical leakage by measuring the rate of water table decline during closure, the variables subject to measurement errors are the specific yield and the rate of decline in the observation wells. It is thought that fairly reliable measurements were made for both of these variables. Some of the vertical leakage as determined by this method included losses due to evapotranspiration. This evapotranspiration component is thought to be negligible but the vertical leakage as determined by this method should be considered an upper range estimate.

In using a water budget calculation to estimate vertical leakage, measurement errors are a major problem. Vertical leakage is a fairly small component of the water budget and is calculated as the difference between some fairly large components. Even small measurement errors for the major components in the water budget calculations can introduce significant errors in the estimate of vertical leakage. The water budgets for all three project sites do show missing water, which in essence indicates the existence of vertical leakage. If the measurement errors are considered random (unbiased), then over a large number of components, and over a large number of water budgets (as many as six separate water budgets were performed for different periods of time for individual study sites) their cumulative effects should be offsetting and their overall effect much smaller.

In estimating vertical leakage using a leaky aquifer test, the vertical leakage through the clay-silt layer is so small as to be near the practical lower limits of determination by this method. For the estimated range of vertical leakage, it is very difficult to differentiate between the Theis nonleaky type curve and the Hantush leaky type curve. In essence, the test must be conducted for an extended period of time, and there can be no changes in external hydrologic stresses during the time of the test. The Nile River valley is an extremely active hydrologic region subject to almost continual changes in hydrologic stresses. Also, the leaky aquifer test does not differentiate between sources of recharge. There is the implicit assumption in the method that vertical leakage is the only source of recharge for the deeper sand aquifer. It is assumed that leakage from the numerous canals or drains that cross the valley are not deep enough to intersect the deep sands and therefore are not a source of recharge. If this is not a valid assumption, then vertical leakage estimates made by this method will be too high. The aquifer test analysis yielded the highest estimate for vertical leakage of all the methods.

All of the the variables in the analytical solution (valley width, distance from Nile River, average head difference between the groundwater and the Nile River, and aquifer transmissivity) are fairly easy to measure and the measurement error involved in this method is thought to be small. The analytical solution method is based on the conceptual model of the groundwater flow system shown on Figure 2. The extent to which actual conditions resemble the assumed conditions is indicative of the accuracy of this method. The method was only applied at the Abyuha site and yielded reasonable estimates of vertical leakage. Its applicability to other sites needs to be determined.

Each of the methods used for determining vertical leakage has its advantages and disadvantages. None of the methods is clearly better or worse than the other methods. The largest estimate of vertical leakage was 1.18 mm/day at the Beni Magdul site using the leaky aquifer pumping test data. The smallest estimate was 0.03 mm/day at the Abyuha site using the Darcy's law approach. Considering the basic differences in the underlying assumptions for each method, the results are in relatively good agreement and tend to support each other. If an average of all five methods is used then the vertical leakage at Beni Magdul is about 0.644 mm/day, at Abuyha is about 0.588 mm/day and at Abu Raya is about 0.466 mm/day. For the Beni Magdul and Abyuha sites, these estimated values of vertical leakage are much lower than any other values reported in the literature for the Nile River Valley. For the Abu Raya site, the estimated leakage is in fairly close agreement with other estimates reported in the literature for the Nile Delta.

SUMMARY AND CONCLUSIONS

Studies of the clay-silt water table aquifer were conducted at three sites in Egypt's Nile Valley and Delta to determine saturated hydraulic conductivity and vertical leakage occurring to the underlying Nile River Sands. Results of tests for horizontal and vertical saturated hydraulic conductivity are summarized in Table 10. Results for vertical leakage rates are summarized in Table 11. Though varying with the method of analysis employed, the results indicate that both hydraulic conductivity and vertical leakage are very small at each of the three sites.

The vertical leakage rate is an indicator of the natural drainage characteristics of the clay-silt layer. The rate at which excess irrigation water moves downward through the saturated region of the soil profile influences the water table level and, consequently, the crop growth environment. Any attempt to maintain lower water table levels in Egypt must take into account the very low rate at which vertical drainage occurs.

TABLE 10 Horizontal and Vertical Saturated Hydraulic Conductivity At The Study Sites

Site	Method	K_H (mm/day	K_V (mm/day)
Beni Magdul	Auger Hole	197	0.87
	Consolidation	-	0.0329
	Permeameter	-	0.0728
Abuyha	Auger Hole	1197	4.9
	Consolidation	-	0.0318
	Permeameter	-	0.1467
Aby Raya	Auger Hole	103	0.45
	Consolidation	-	0.0296
	Permeameter	-	0.0714

TABLE 11 Vertical Leakage Rates At The Study Sites

Site	Method	Vertical Leakage (mm/day)
Beni Magdul	A. Darcy's Law	
	1. Auger Hole	0.09
	2. Consolidation	0.005
	3. Permeameter	0.011
	4. Average (A1, A2, A3)	0.035
	B. Water Table Decline	0.456
	C. Water Budget	0.903
	D. Pumping Test	1.18
	Average (A4, B, C, D)	0.644
Abyuha	A. Darcy's Law	
	1. Auger Hole	0.088
	2. Consolidation	0.0008
	3. Permeameter	0.004
	4. Average (A1, A2, A3,)	0.031
	B. Water Table Decline	0.752
	C. Water Budget	1.095
	D. Analytical Solution	0.476
	Average (A4, B, C, D)	0.588
Abu Raya	A. Water Table Decline	0.332
	B. Water Budget	0.599
	Average (A, B)	0.466

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APPENDICES

APPENDIX A

AUGER HOLE TEST DATA

TABLE A1 Horizontal Hydraulic Conductivity and Parameters Used in Ernst (1950) Equation for Auger Holes at Beni Magdul.

Auger Hole No.	r (cm)	H (cm)	y (cm)	$y/\Delta t$	K_H (mm/day)
611	2.54	98.0	15.1	0.005	30
612	2.54	91.0	64.0	0.030	66
617	2.54	158.0	54.6	0.303	415
A	5.00	141.0	72.7	0.041	157
B	5.00	65.0	56.5	0.017	158
C	5.00	151.0	119.5	0.231	637
D	5.00	260.0	255.5	0.074	80
E	5.00	311.0	275.5	0.041	33
Mean					197

TABLE A2 Horizontal Hydraulic Conductivity and Parameters Used in Ernst (1950) Equation for Auger Holes at Abyuha.

Auger Hole No.	r (cm)	H (cm)	y (cm)	y/Δt	K_H (mm/day)
3	2.54	174.0	20.0	0.15	468
6	2.54	161.0	29.8	0.45	1006
8	2.54	145.0	67.4	1.46	1857
10	2.54	120.0	65.1	0.79	1251
11	2.54	108.0	77.8	0.34	550
11'	2.54	138.0	48.9	1.04	1767
12	2.54	141.0	52.7	0.77	1200
13	2.54	185.0	13.8	0.16	638
13A	2.54	100.0	22.4	0.27	1159
13B	2.54	92.0	7.5	0.03	378
13'	2.54	167.0	53.2	0.39	521
14	2.54	170.0	65.5	0.82	908
15	2.54	140.0	58.3	1.33	1953
17	2.54	139.0	53.2	0.69	1094
24	2.54	121.0	38.9	1.21	2785
26	2.54	129.0	75.9	0.73	979
27	2.54	141.0	84.0	0.50	570
28	2.54	180.0	80.4	0.63	568
A	2.54	136.0	62.5	0.61	869
C	2.54	107.0	27.4	0.11	387
C'	2.54	151.0	15.3	0.13	550
F	2.54	168.0	66.8	0.01	1108
J'	2.54	160.0	82.5	1.00	1000
L	2.54	155.0	49.8	1.36	2041
O'	2.54	136.0	67.6	1.26	1716
Q'	2.54	102.0	38.3	0.50	1359
Mean					1103

TABLE A3 Horizontal Hydraulic Conductivity and Parameters Used in Ernst (1950) Equation for Auger Holes at Abyuha.

Auger Hole No.	r (cm)	H (cm)	y (cm)	y/Δt	K_H (mm/day)
32	2.54	36.0	14.0	0.006	74
33	2.54	120.5	23.8	0.057	199
A	3.81	74.0	33.8	0.008	63
B	3.81	96.0	18.7	0.013	130
C	3.81	120.0	54.7	0.010	35
D	3.81	105.0	56.6	0.016	62
E	3.81	145.0	51.4	0.009	28
F	3.81	160.0	44.5	0.036	115
G	3.81	150.0	48.7	0.101	317
H	3.81	133.0	39.4	0.001	5
Mean					103

APPENDIX 8

SENSITIVITY ANALYSIS FOR K_H/K_V

TABLE B1 Sensitivity Analysis for K_H/K_V for Various Assumed Geometries of Clay-Silt Layer and Relative Magnitudes of Hydraulic Conductivities of Clay and Sand.

Case No.	Thickness		Horizontal		Vertical		K_H	K_V	Ratio K_H/K_V
	Clay	Sand	Clay	Sand	Clay	Sand			
1	2/3 b	1/3 b	K	100 K	K/10	10 K	34K	.149 K	227.8
2	2/3 b	1/3 b	K	250 K	K/10	25 K	84 K	.150 K	561.1
3	2/3 b	1/3 b	K	500 K	K/10	50 K	167.3K	.150 K	1116.7
4	2/3 b	1/3 b	K	1000 K	K/10	100 K	334 K	.150 K	2227.8
5	3/4 b	1/4 b	K	100 K	K/10	10 K	25.75 K	.133 K	193.8
6	3/4 b	1/4 b	K	250 K	K/10	25 K	63.25 K	.133 K	478.8
7	3/4 b	1/4 b	K	500 K	K/10	50 K	125.75 K	.133 K	943.8
8	3/4 b	1/4 b	K	1000 K	K/10	100 K	250.75 K	.133 K	1881.3
9	4/5 b	1/5 b	K	100 K	K/10	10 K	20.8 K	.125 K	166.8
10	4/5 b	1/5 b	K	250 K	K/10	25 K	50.8 K	.125 K	406.8
11	4/5 b	1/5 b	K	500 K	K/10	50 K	100.8 K	.125 K	806.8
12	4.5 b	1/5 b	K	1000 K	K/10	100 K	200.8 K	.125 K	1606.8
13	2/3 b	1/3 b	K	100 K	K/20	10 K	34 K	.075 K	454.5
14	2/3 b	1/3 b	K	100 K	K/10	5 K	34 K	.150 K	227.2

b = total thickness of clay-silt layer

APPENDIX C

CONSOLIDATION TEST DATA

TABLE C1 Vertical Hydraulic Conductivity for Consolidation Tests at Beni Magdul

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
1	1	Clay	0.0135	
	2	Clay	0.0058	
	3	Clay	0.0122	0.0105
2	1	Clay	0.0068	
	2	Clay	0.0051	0.0060
3	1	Sandy Clay	0.0085	
	2	Sandy Clay	0.0246	
	3	Sandy Clay	0.0137	0.0156
4	2	Clay	0.0341	
	3	Clay	0.0620	0.0481
5	1	Clay	0.0141	
	3	Clay	0.1027	0.0584
7	1	Very Sandy Clay	0.1599	
	2	Clay	0.0035	
	3	Clay	0.0074	0.0569
9	1	Clay	0.0050	
	2	Clay	0.0203	
	3	Clay	0.0025	
	4	Clay	0.0015	0.0073
10	5	Clay with Sand	0.0341	0.0341
11	1	Clay	0.0091	
	2	Clay	0.0254	
	3	Clay with Sand	0.1130	0.0492
12	4	Clay	0.0586	0.0586
13	1	Clay	0.1210	
	2	Clay	0.0057	
	3	Clay	0.0713	
	4	Clay	0.0138	0.0530
14	1	Clay	0.0132	
	2	Clay	0.0136	
	4	Clay	0.0351	0.0206

TABLE C1 (Cont.) Vertical Hydraulic Conductivity for Consolidation Tests at Beni Magdul

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
15	1	Sandy Clay	0.0036	
	2	Sandy Clay	0.0200	
	3	Sandy Clay	0.0805	
	4	Sandy Clay	0.0030	0.0268
16	1	Clay	0.0084	
	2	Sandy Clay	0.0097	
	3	Clay	0.0125	
	4	Clay	0.0315	0.0155
Mean				0.0329

TABLE C2 Vertical Hydraulic Conductivity for Consolidation Tests at Abyuha

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
1	1	Sandy Clay	0.0152	
	2	Sandy Clay	0.0350	
	3	Sandy Clay	0.0695	0.0399
2	4	Sandy Clay	0.0672	0.0672
3	2	Clay	0.0255	
	3	Clay	0.0592	
	4	Clay	0.0269	0.0372
4	1	Sandy Clay	0.0412	0.0412
5	1	Clay with Sand	0.0393	0.0393
7	2	Clay	0.0102	0.0102
8	1	Clay	0.0173	
	2	Clay	0.0435	0.0304
9	1	Clay	0.0089	
	2	Clay	0.0080	
	3	Silty Clay	0.0199	0.0123
10	1	Clay	0.00827	0.00827
Mean				0.0318

TABLE C3 Vertical Hydraulic Conductivity for Consolidation Tests at Abu Raya

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
2	1	Clay	0.0085	
	2	Clay	0.0114	0.0100
3	1	Clay	0.0315	
	2	Clay	0.0147	
	3	Clay	0.0358	0.0273
5	1	Sandy Clay	0.0944	
	2	Sandy Clay	0.0580	
	3	Sandy Clay	0.0129	
	4	Sandy Clay	0.0933	0.0647
6	1	Clay	0.0248	
	2	Clay	0.0055	
	3	Clay	0.0188	
	4	Clay	0.0162	0.0163
Mean				0.0296

APPENDIX D

PERMEAMETER TEST DATA

TABLE D1 Vertical Hydraulic Conductivity for Permeameter Tests at Beni Magdul

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
3	2	Sandy Clay	0.1035	0.1035
4	2	Clay	0.0455	
	3	Clay	0.1107	
	4	Clay	0.0131	0.0564
7	2	Clay	0.0131	0.0131
8	1	Sand	0.3085	
	2	Sand	0.8091	0.5581
9	1	Clay	0.0193	
	2	Clay	0.1114	
	4	Clay	0.0935	0.0747
10a	1	Sand with Clay	6.4480	
	2	Sand	0.8940	
	3	Sand	5.2419	
	6	Sand	3.2190	3.9507
10b	5	Clay with Sand	0.0735	0.0735
11	1	Clay	0.0120	
	2	Clay	0.0327	
	4	Clay with Sand	0.1554	0.0667
12a	2	Sand with Clay	5.2419	
	3	Sand with Clay	4.2680	4.7550
12b	4	Clay	0.0427	0.0427
13	1	Clay	0.2947	
	2	Clay	0.1164	
	3	Clay	0.5517	
	4	Clay	0.0464	0.2523
14	1	Clay	0.0556	
	2	Clay	0.0763	
	3	Clay	5.8571*	
	4	Clay	0.0956	0.0529
15	1	Sandy Clay	0.0140	
	2	Sandy Clay	0.0547	
	3	Sandy Clay	0.5305*	
	4	Sandy Clay	0.0556	0.0414

TABLE D1 (Cont.) Vertical Hydraulic Conductivity for Permeameter Tests at Beni Magdul

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
16	1	Clay	0.0264	
	2	Sandy Clay	0.0273	
	3	Clay	0.0158	
	4	Clay	0.1854*	0.0232
17	1	Sand	0.4147	
	2	Sand with Clay	0.7121	
	3	Sand	0.4544	0.5271
Mean	(Sites 8, 10a, 12a, 17)		Sand with Clay	2.4477
	(Sites 3, 4, 7, 9, 10b, 11, 12b, 13, 14, 15, 16)		Clay	0.0728

* Outlier - Not used in data analysis

TABLE D2 Vertical Hydraulic Conductivity for Permeameter Tests at Abyuha

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
1	1	Sandy Clay	0.0395	
	2	Sandy Clay	1.424*	
	3	Sandy Clay	1.553*	0.0395
2	4	Sandy Clay	0.4130	0.4130
3	2	Clay	0.0663	
	3	Clay	0.0262	
	4	Clay	0.0607	0.0511
4a	2	Clay and Sand	1.477	
	3	Clay and Sand	2.581	
	4	Clay and Sand	3.178	2.412
4b	1	Sandy Clay	0.358	0.358
5a	2	Sand with Clay	1.549	
	3	Sand and Silt	4.77	
	4	Sand and Silt	3.16	3.160
5b	1	Clay with Sand	2.066*	2.066*
6	2	Silt with Sand	0.521	
	3	Silt with Sand	0.206	
	4	Sand and Silt	1.09	0.6057
7	2	Clay	0.0350	0.0350
8a	3	Clay and Sand	2.365	
	4	Clay and Sand	4.548	3.457
8b	1	Clay	0.0570	
	2	Clay	0.3320	0.1945
9a	4	Sand and Silt	6.24	6.24
9b	1	Clay	0.0340	
	2	Clay	0.0273	
	3	Silty Clay	0.0460	0.0358
10a	3	Sand with Silt	15.7	
	4	Silt with Sand	0.1428	7.921
10b	1	Clay	0.0464	0.0464

TABLE D2 (Cont.) Vertical Hydraulic Conductivity for Permeameter Tests at Abyuha

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
11	1	Silt with Sand	0.1428	
	2	Silt with Sand	0.5958	
	3	Silt with Gravel	2.880	1.2062
Mean	(Sites 4a, 5a, 6, 8a, 9a, 10a, 11)		Sand with Clay	3.572
	(Sites 1, 2, 3, 4b, 5b, 7, 8b, 9b, 10b)		Clay	0.1467

* Outlier - Data not used in analysis

TABLE D3 Vertical Hydraulic Conductivity for Permeameter Tests at Abu Raya

Site No.	Sample No.	Description	K_V (mm/day)	Mean K_V (mm/day)
1	1	Sand with Clay	9.10	
	2	Sand with Clay	8.30	8.70
2	1	Clay	0.0174	
	2	Clay	0.0262	0.0218
3	1	Clay	0.0910	
	2	Clay	0.0528	
	3	Clay	0.0740	0.0726
4	1	Clayey Sand	0.8954	0.8954
5	2	Sandy Clay	0.2391	
	3	Sandy Clay	0.0446	
	4	Sandy Clay	1.1714*	0.1419
6	1	Clay	0.0538	
	2	Clay	0.0193	
	3	Clay	0.0622	
	4	Clay	0.0612	0.0491
Mean	(Sites 1, 4)		Sand with Clay	4.798
	(Sites 2, 3, 5, 6)		Clay	0.0714

* Outlier - Not used in data analysis

AMERICAN EQUIVALENTS OF EGYPTIAN ARABIC TERMS AND MEASURES COMMONLY USED IN IRRIGATION WORK

LAND AREA	IN SQ METERS	IN ACRES	IN FEDDANS	IN HECTARES
1 acre	4,046.856	1.000	0.963	0.405
1 feddan	4,200.833	1.038	1.000	0.420
1 hectare (ha)	10,000.000	2.471	2.380	1.000
1 sq. kilometer	100×10^4	247.105	238.048	100.000
1 sq. mile	259×10^6	640.000	616.400	259.000

WATER MEASUREMENTS	FEDDAN-CM	ACRE-FEET	ACRE-INCHES
1 billion m^3	23,809,000.000	810,710.000	
1,000 m^3	23.809	0.811	9.728
1,000 m^3 /Feddan (= 238 mm rainfall)	23.809	0.781	9.372
420 m^3 /Feddan (= 100 mm rainfall)	10.00	0.328	3.936

OTHER CONVERSION		METRIC	U.S.
1 ardab	=	198 liters	5.62 bushels
1 ardab/feddan	=		5.41 bushels/acre
1 kg/feddan	=		2.12 lb/acre
1 donkey load	=	100 kg	
1 camel load	=	250 kg	
1 donkey load of manure	=	0.1 m^3	
1 camel load of manure	=	0.25 m^3	

EGYPTIAN UNITS OF FIELD CROPS

CROP	EG. UNIT	IN KG	IN LBS	IN BUSHELS
Lentils	ardeb	160.0	352.42	5.87
Clover	ardeb	157.0	345.81	5.76
Broadbeans	ardeb	155.0	341.41	6.10
Wheat	ardeb	150.0	330.40	5.51
Maize, Sorghum	ardeb	140.0	308.37	5.51
Barley	ardeb	120.0	264.32	5.51
Cottonseed	ardeb	120.0	264.32	8.26
Sesame	ardeb	120.0	264.32	
Groundnut	ardeb	75.0	165.20	7.51
Rice	dariba	945.0	2081.50	46.26
Chick-peas	ardeb	150.0	330.40	
Lupine	ardeb	150.0	330.40	
Linseed	ardeb	122.0	268.72	
Fenugreek	ardeb	155.0	341.41	
Cotton (unginned)	metric qintar	157.5	346.92	
Cotton (lint or ginned)	metric qintar	50.0	110.13	

EGYPTIAN FARMING AND IRRIGATION TERMS

fara = branch
marwa = small distributor, irrigation ditch
masraf = field drain
mesqa = small canal feeding from 10 to 40 farms
qirat = cf. English "karat", A land measure of 1/24 feddan, 175.03 m^2
qaria = village
sahm = 1/24th of a qirat, 7.29 m^2
saqia = animal powered water wheel
sarf = drain (vb.), or drainage. See also masraf, (n.)

EGYPT WATER USE AND MANAGEMENT PROJECT

PROJECT TECHNICAL REPORTS

NO.	TITLE	AUTHOR
PTR#1	Problem Identification Report for Mansuriya Study Area, 10/77 to 10/78.	Egyptian and American Field Teams.
PTR#2	Preliminary Soil Survey Report for the Beni Magdul and El-Hammami Areas.	A. D. Dotzenko, M. Zanati, A. A. Abdel Wahed, & A. M. Keleg.
PTR#3	Preliminary Evaluation of Mansuriya Canal System, Giza Governorate, Egypt.	American and Egyptian Field Teams.
PTR#4	On-farm Irrigation Practices in Mansuriya District, Egypt.	M. El-Kady, W. Clyma & M. Abu-Zeid
PTR#5	Economic Costs of Water Shortage Along Branch Canals.	A. El Shinnawi M. Skold & M. Nasr
PTR#6	Problem Identification Report For Kafr El-Sheikh Study Area.	Egyptian and American Field Teams.
PTR#7	A Procedure for Evaluating the Cost of Lifting Water for Irrigation in Egypt.	H. Wahby, G. Quenemoen & M. Helal
PTR#8	Farm Record Summary and Analysis for Study Cases at Abu Raya and Mansuriya Sites, 1978/1979.	F. Abdel Al & M. Skold
PTR#9	Irrigation & Production of Rice in Abu Raya, Kafr El-Sheikh Governorate.	Kafr El-Sheikh Team as Compiled by T. W. Ley & R. L. Tinsley
PTR#10	Soil Fertility Survey in Kafr El-Sheikh, El Mansuriya and El-Minya Sites.	M. Zanati, P. N. Soltanpour, A.T.A. Mostafa, & A. Keleg.
PTR#11	Kafr El-Sheikh Farm Management Survey Crop Enterprise Budgets and Profitability Analysis.	M. Haider & F. Abdel Al
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PTR#16B	Irrigation System Improvement By Simulation and Optimization: 1. Application.	J. Mohan Reddy & W. Clyma
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PTR#21	El-Hammami Pipeline Design.	Fort Collins Staff Team
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PTR#57	Infiltration Studies on Egyptian Vertisols.	K. Litwiller, R. L. Tinsley H. Deweeb, & T. W. Ley
PTR#58*	Cotton Field Trials, Summer, 1980 Abu Raya.	Kafr El-Sheikh Team as compiled by M. Awad & A. El-Kayal
PTR#59*	Management Plan for a Distributary Canal System	A. Saber, E. Wafik, T. K. Gates, & J. Layton
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PTR#75	Abyuha Farm Record Summary 1979-1983	EWUP Field Team
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PTR#78	Beni Magdul Farm Record Summary	EWUP Field Team
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NO.	TITLE	AUTHOR
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MAN.#2	Programs for the HP Computer Model 9825 for EWUP Operations.	By: M. Helal, D. Sunada, J. Loftis, M. Quenemoen, W. Ree, R. McConnen, R. King, A. Nazr and R. Stalford.
MAN.#5	Precison Land Leveling Data Analysis Program for HP9825 Desktop Calculator	T. W. Ley
MAN.#8	Thirty Steps to Precison Land Leveling	A. Bayoumi, S. Boctor & N. Dimick
MAN.#9	Alphabetical List of Some Crops and Plants with Their English, Egyptian, Botanical & Arabic Names and Vocabulary of Agricultural and other Terms Commonly Used.	G. Ayad
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