PROJECT TECHNICAL REPORT NO. 61

Egypt Water Use & Management Project
Consortium for International Development

THE RELATION BETWEEN IRRIGATION WATER MANAGEMENT AND HIGH WATER TABLES IN EGYPT

By:

Kenneth E. Litwiller, Mona El-Kady,
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July - 1984

EGYPT WATER USE AND MANAGEMENT PROJECT

22 El Galaa St., Bulak, Cairo, Egypt

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Prepared under support of

WATER DISTRIBUTION RESEARCH INSTITUTE, WATER RESEARCH CENTER

MINISTRY OF IRRIGATION, GOVERNMENT OF EGYPT

Contracting agencies

Colorado State University
Engineering Research Center
Ft. Collins, Colorado 80521
USA

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ABSTRACT

High water table levels presenting hazards to crop growth were measured at field sites in upper, middle, and lower Egypt. Water table contribution to evapotranspiration was significant at each site. A water balance model of the water table aquifer was used to predict the effect of various interventions on water table levels. Desirable lower water table levels could not be maintained through on-farm irrigation efficiency improvement including lining of on-farm channels while using surface irrigation methods. Branch, distributary, and private canal lining would have negligible effect on water table levels. Increasing drainage outflows could maintain desirable water table levels. Corresponding increases in required water deliveries would be expected.

مستخلص

يشكل إرتفاع منسوب المياه الجوفيه خطراً على نمو المحاصيل الزراعيه ، وقد ظهر هذا بوضوح في المناطق التي قيس فيها هذا المنسوب بمناطق مصر العليا والوسطى والسفلى . وكان تأثير ارتفاع منسوب المياه الجوفيه على البخر نتح ملحوظاً في كل موقع . وكان لإستخدام نموذج الإتزان المائي للطبقات الحاملة للمياه الجوفيه أثر فعال في إمكانية تقدير تأثير العوامل المختلفة على منسوب المياه الجوفيه . ومن الصعب المحافظة على مناسيب مقبولة للمياه الجوفيه اثناء تطوير كفاءة الري الحقلي والتي تتضمن تبطين القنوات في حالة استخدام طرق الري السطحي . كما يمكن إهمال تأثير الفرعيات وقنوات التوزيع الصغيره والمساقي الخاصه على منسوب المياه الجوفيه . وبزيادة كفاءة الصرف يمكن المحافظة على مناسيب مقبولة للمياه الجوفيه ، ومن المتوقع أن يزيد معدل الإمداد بالمياه المطلوبه تبعاً لذلك .

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ACKNOWLEDGEMENTS

The authors wish to express their thanks and appreciation for the contributions made to this paper by the staff of the Egypt Water Use and Management Project, and to the field teams at Mansuriya, Kafr El Sheikh and El Minya.

The Project is funded jointly by the Arab Republic of Egypt, and by the United States Agency for International Development. The United States Agency for International Development in Egypt is under the directorship of Mr. Michael P. W. Stone. Mr. John Foster is the United States Agency for International Development Project Officer for the Egypt Water Use and Management Project.

The Egypt Water Use and Management Project is implemented under the auspices of the Ministry of Irrigation's Water Management and Irrigation Technologies Research Institute and in collaboration with both the Ministry of Irrigation and the Ministry of Agriculture through the Soil and Water Research Institute and the Agriculture Ecomomics Institute, which provide the Project with personnel and services.

The Consortium for International Development, with executive offices in Tucson, Arizona, is the United States Agency for International Development Contractor for the Project. American Project personnel are drawn from the faculties of Colorado State University, the lead American university taking part in the Project, Oregon State University, New Mexico State University, and Montana State University. The Project Director is Dr. Hassan Wahby and the Project Technical Director is Dr. Eugene Quenemoen. Dr. E. V. Richardson is the Campus Project Coordinator.

INTRODUCTION

High water table levels have been observed at Egypt Water Use and Management Project (EWUP) sites in the old lands of Egypt. Measurements at Abyuha, Beni Magdul, and Abu Raya have revealed that average water table levels vary between 0.2 and 2.0 m below the ground surface on a monthly basis (Helal et al., 1984). High water tables present hazards of water logging, salinity, and restricted crop root zone depth. As part of an effort to improve irrigation water management at the farm level, EWUP has conducted a study to describe the relation between irrigation water management and high water tables. Such a description would aid in understanding how a high water table affects the way water is managed and used on the farm. Also, it would aid in evaluating how improvements in irrigation water management might alter the high water table condition.

At Project sites in Abyuha, Beni Magdul, and Abu Raya, the water table is supported by a heterogeneous soil profile containing layers of clays, silts, and to a lesser extent, sands. This heterogeneous profile, referred to in this study as the clay-silt layer, forms a semi-confining cap over a lower aquifer of sand and gravel (Warner et al., 1984; Barber and Carr, 1981; Ministry of Irrigation, 1981).

At present, average water table levels at Project sites appear to be stable from year to year, neither rising nor falling on an annual basis. Storage change in the clay-silt layer containing the water table is negligible with inflow essentially equal to outflow (Helal et al., 1984). Lowering the water table requires a reduction in storage in the clay-silt layer or a condition where outflow exceeds inflow. If inflow is reduced or outflow increased for a sufficient period of time then the water table will be lowered. In order for a stable lower water table level to be maintained, a new equilibrium of inflow and outflow must be obtained which provides adequate water to meet crop consumptive use requirements. Interventions with potential for providing stable lower water table levels include improving on-farm irrigation efficiency and lining canals to reduce inflow to the water table as well as providing artificial drainage to increase outflow.

To describe the relation between irrigation water management and high water tables in Egypt, EWUP conducted a study with the following objectives:

1. Develop a conceptual water balance model of the water table in the clay-silt layer to include all components of inflow, outflow, and storage change and to describe the components in relation to parameters associated with irrigation water management,
2. Quantify the terms of the water balance model using data collected from Project field sites, and
3. Employ the model to investigate alternatives for establishing stable lower water table levels including improving on-farm irrigation efficiency, lining canals, and installing artificial drainage.

LITERATURE REVIEW

Moustafa, et al. (1977) conducted lysimeter experiments in which maize was grown on an Egyptian clay loam soil with various constant depths between 0.4 and 1.60 m to a saline water table (10,000 ppm $NaCl+CaCl_2$ 4:1). For water table depths of less than 1.30 m, significant yield decreases were observed. There was no significant difference in evapotranspiration for the various treatments. Water table contributions to evapotranspiration were 26.5%, 16.7%, 10.0%, 7.4%, and 4.8% for water table depths of 0.4, 0.7, 1.0, 1.3, and 1.6 m, respectively.

Similar experiments were conducted for cotton by Moustafa, et al. (1975). Yield increased with increasing water table depth. As compared to the yield with a water table depth of 1.6 m, yield reductions were 11%, 18%, 30%, and 54% for water table depths of 1.3, 1.0, 0.7, and 0.4 m, respectively. Water table contribution to evapotranspiration was 30.7%, 21.4%, 18.7%, 15.1% and 8.8% for water table depths of 0.4, 0.7, 1.0, 1.3, and 1.6 m, respectively.

A shallow water table can serve the useful purpose of supplying water to the crop root zone. However, in general, yield reductions increase as water table levels rise and simultaneously water table contribution to evapotranspiration increases. The above experimental results suggest that for clay loam soils in Egypt, average saline water table levels should be held below 1.3 m in order to avoid yield reductions. That is, water table levels should be maintained for which water table contribution to evapotranspiration is low.

Data on the quality of the shallow water table at Project sites indicates that salinity is typically moderate but occasionally severe (El Falaky et al., 1984). Measurements in the shallow water table at Abyuha showed a range of about 300 to about 1,700 ppm total dissolved salts. At Beni Magdul, the range was about 250 to about 4,000 ppm. At Abu Raya, the salinity problem was most severe with measurements of total dissolved salts ranging from about 300 to about 14,500 ppm.

Lowering the water table can reduce upward water movement to negligible levels. The optimal depth at which water levels should be maintained can be determined by considering such factors as the cost of artificial drainage (Hillel, 1971). In the present study the desired water table depth is assumed to be that for which upward flow contributes less than 5% of evapotranspiration.

SITE DESCRIPTION

The study was conducted in three small irrigated regions (Figure 1): Abyuha, near El Minya in Middle Egypt; Beni Magdul, near Cairo; and Abu Raya, near Kafr El-Sheikh in the northern Nile Delta. At each site on-farm and delivery system improvements were tested within an area served by a distributary canal and its mesqas (private canals) which deliver water to farms. These sites were selected by the Project as representative of irrigated agriculture in Egypt and because their features allowed relatively well-defined system boundaries: canals, drains and roads. Irrigation and drainage conditions throughout each distributary canal command area had to be considered when quantifying inflow and outflow components to the water table subsystem and identifying interventions with potential for lowering average water table levels.

The surface soils at each of the three sites are clays of the Vertisol soil order (Dotzenko, et al., 1979; Selim, et al., 1983a; Selim, et al., 1983b). These soils expand under wetting and crack upon drying leading to large on-farm conveyance losses and large water application depths (Litwiller, et al., 1984; Ley, 1983). The clay-silt layer which supports the water table aquifer varies in thickness, composition, and hydraulic conductivity from site to site (Warner, et al., 1984). The monthly average depth to the water table for each site is shown in Figure 2.

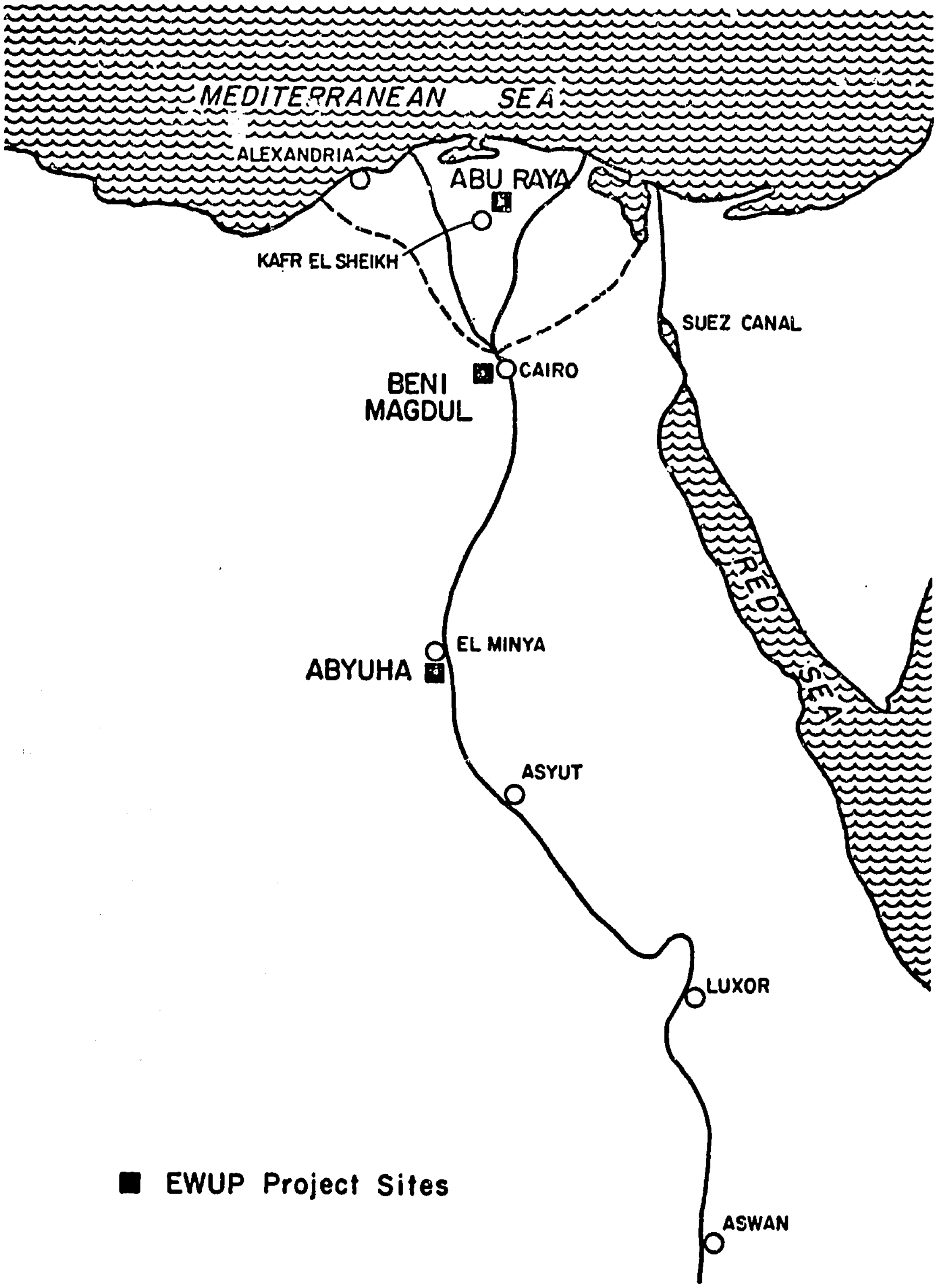

Figure 1 Location of Project Field Sites

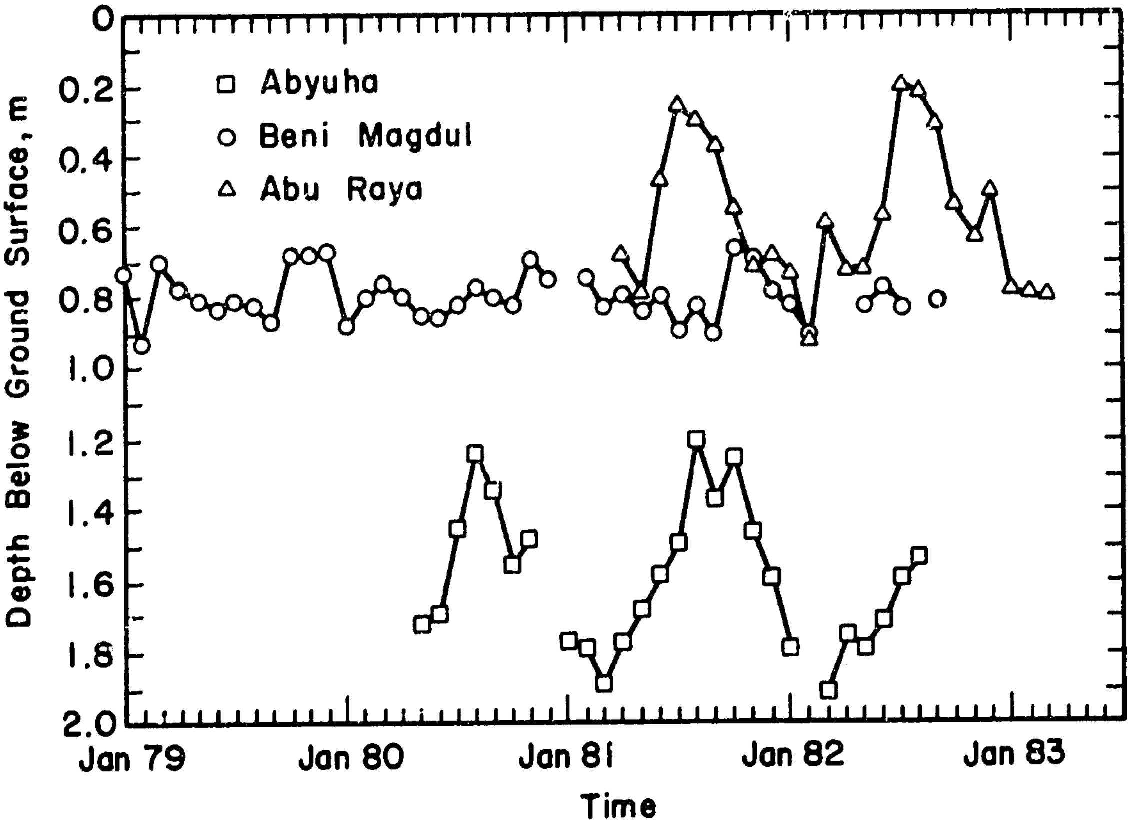

Figure 2 Monthly average water table depth at study sites.
(Helal et.al., 1984)

Figure 3 Abyuha field site.

Abyuha Site

Located in Middle Egypt about 17 km south of El Minya, the Abyuha site (Figure 3) encompasses a total area of approximately 1213 feddans (5604 hectares). Clover, beans, and wheat are the major crops grown in the winter season. In the summer, primary crops are maize, cotton, and soybeans. Sugar cane is grown throughout the year. The region is served by the Abyuha distributary canal which takes water from the Ibrahimiya branch canal and distributes it to the region's 30 mesqas. The clay-silt layer at Abyuha is about 12 m thick and consists of the following soils: clay, silty, clay loam, sandy loam, silt loam, and sandy clay loam. Horizontal saturated hydraulic conductivity was estimated to be about 1.10 m/day from 26 auger-hole tests. Data from 41 observation wells distributed throughout the region showed that over a period of two years the monthly average water table depth fluctuated between 1.20 m and 1.92 m below ground surface (Figure 2).

Beni Magdul Site

The Beni Magdul site (Figure 4) is located in the southern portion of El-Mansuriya Irrigation District of the Giza Governorate about 20 km west of Cairo. The site is comprised of approximately 842 feddans (354 hectares) of which about 810 feddans (340 hectares) are under cultivation. Clover wheat, and vegetables are the major corps grown in the winter season. Maize and vegetables are major summer crops. The Beni Magdul distributary canal, a branch of El-Mansuriya canal, supplies water to the region's 16 mesqas. A small amount of additional water is supplied by flow from adjacent regions, from deep aquifer pumping, and from pumping out of surface drains. The clay-silt layer at Beni Magdul (thickness, 14 m) consists of clay, sandy clay, clayey sand, and fine sand. Horizontal saturated hydraulic conductivity of the clay-silt layer was about 0.20 m/day (8 auger-hole tests). Observations from 30 wells over the past four years showed that the monthly average depth to water table ranged from about 0.65 m to 0.90 m (Figure 2).

Abu Raya Site

The Abu Raya site (Figure 5) is located near Abu Raya village, about 35 km northeast of the city of Kafr El-Sheikh. The site it comprised of a total of about 6,300 feddans (2,646 hectares). In the winter season,

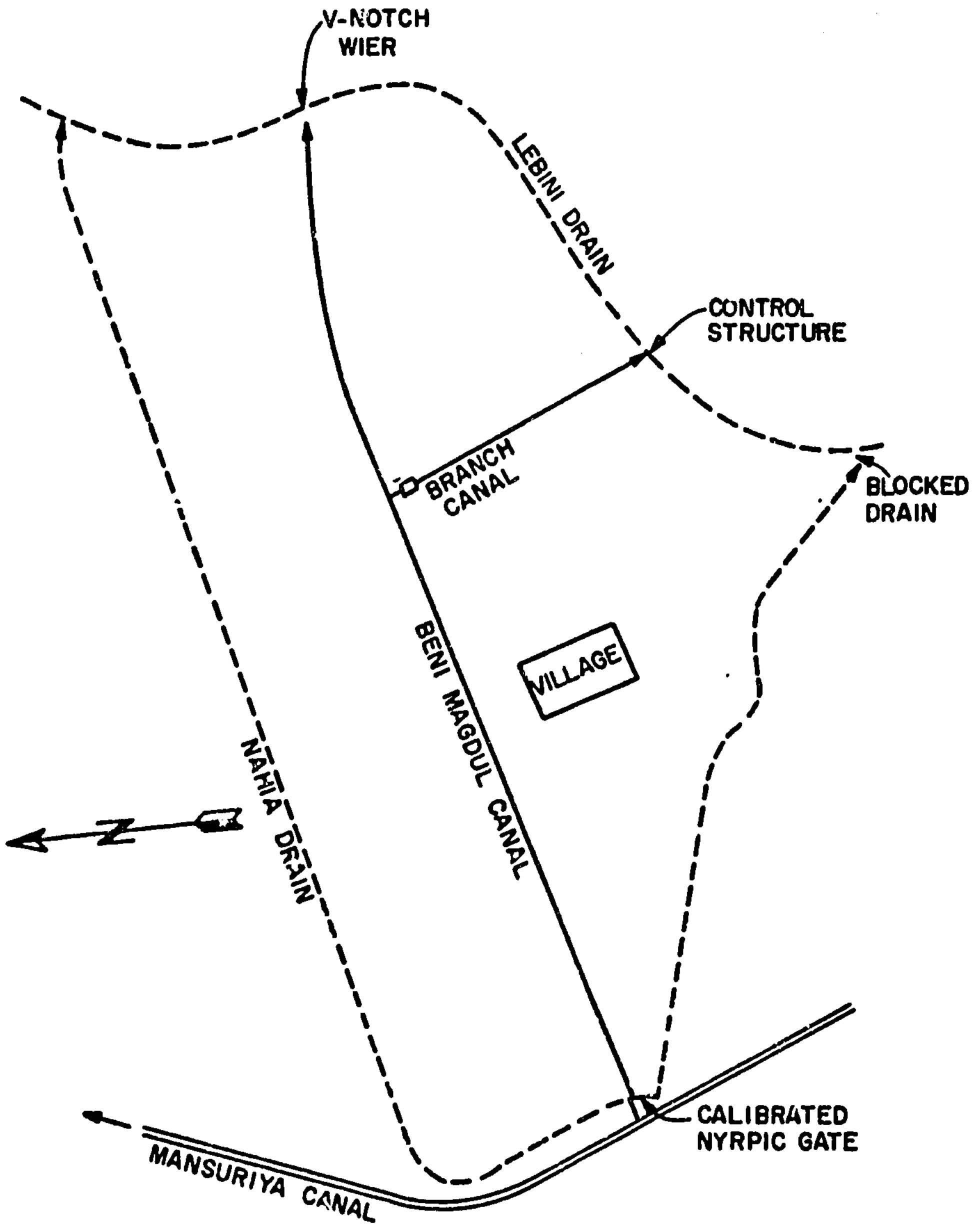

Figure 4 Beni Magdul field site

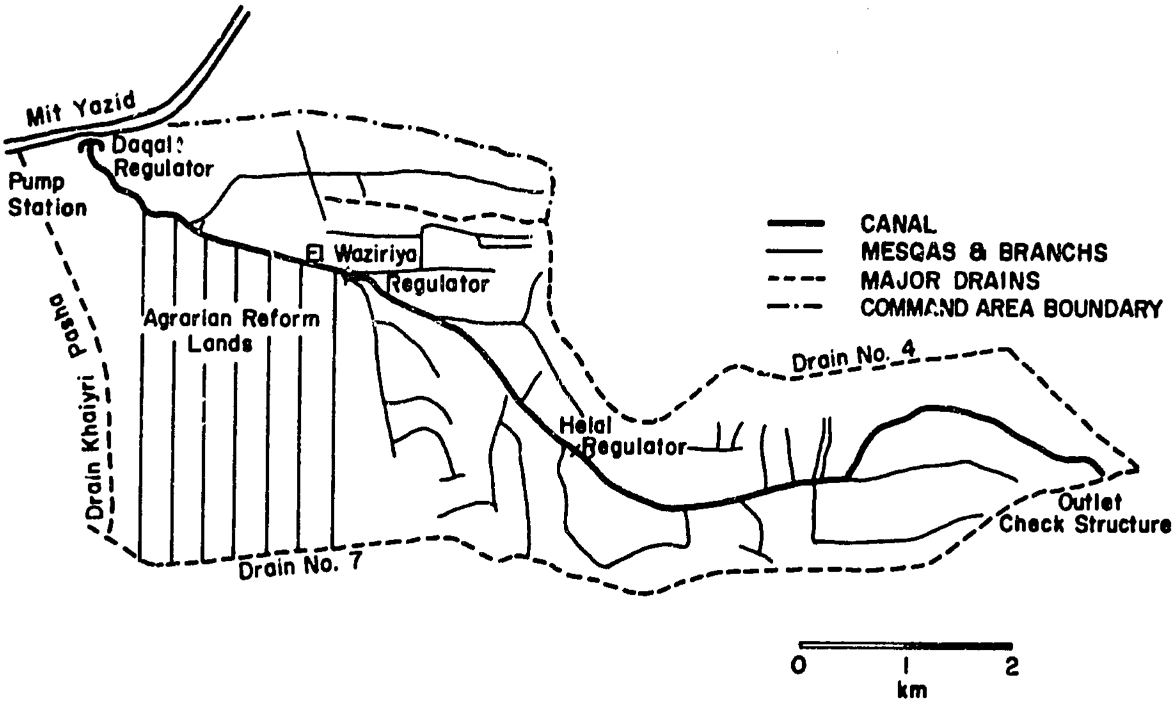

Figure 5 Abu Raya field site

clover, wheat, and sugar beets are the primary crops grown. The major summer crops are rice, cotton and maize. The Daqalt distributary canal takes its water from the Mett Yazeed branch canal and distributes it to the region's 23 mesqas. Most of the Project's work in the area was concentrated along the third reach of the Daqalt on command areas served by three mesqas which consisted of a total of about 700 feddans (294 hectares). Data collected from 35 observation wells over a period of two years in an area of 246 feddans (102 hectares) served by one of these mesqas showed that the monthly average depth to the water table was 0.20 m to 0.80 m (Figure 2). The clay-silt layer at Abu Raya extends to a depth of about 35 m (Ministry of Irrigation, 1981). The saturated horizontal hydraulic conductivity was about 0.10 m/day (10 auger-hole tests).

Rice cultivation represents a specific condition with direct impact on water table levels in Abu Raya. During rice cultivation, water is ponded continuously above the ground surface representing a water table level above the mean field elevation. The specific conditions of rice cultivation were not considered in the present study.

The Irrigation System

The irrigation system studied at each of the sites consisted of the irrigated land served by a distributary canal, the canal itself, and the network of private canals (mesqas) delivering water to the land. The system was defined by the following boundaries:

1. The inlet from the branch canal tc the distributary canal,
2. The interface between the cropped area and the branch canal,
3. The interface between the cropped are and the surface drains within and surrounding the region,
4. The vertical extension of boundaries which define the horizontal extent of the irrigation system, that is, canals and/or drains surrounding the region,
5. The interface between the bottom of the clay-silt layer containing the water table aquifer and the underlying sands, and
6. The interface between the atmosphere and soil, plant, or water surfaces within the system.

Figure 5 shows an example of the first three boundaries for the Daqalt distributary canal system at Abu Raya. Public drains enclose the area. Private drains which parallel private canals (*mesqas*) are not illustrated.

The irrigation system was divided into the following subsystems for purpose of analysis: the water delivery subsystem which includes the distributary canal and *mesqas* (Figure A1 of Appendix A), the on-farm conveyance subsystem which includes all on-farm channels (*marwas*) used for distribution of water to fields (Figure A1), the field surface water subsystem which contains the crop stand above the ground surface (Figure A2 of Appendix A), the soil water subsystem which contains the soil profile down to the water table and includes the crop root zone (Figure A2), and the water table subsystem which contains the soil profile from the water table to the bottom of the clay-silt layer (Figure 6). The various subsystems interact by means of water that flows across the boundaries of one subsystem into another. The water table subsystem, which is the focus of this report, is described below. The functions and boundaries of the other subsystems are described in detail in Appendix A.

WATER BALANCE MODEL

The water table subsystem of the irrigation system is defined by the following boundaries (Figure 6):

1. The water table (which fluctuates with time),
2. The bottom of the clay-silt layer,
3. Interfaces with canals or drains intersecting the water table, and
4. The vertical extension of canals and/or drains surrounding the region.

A water balance equation for the water table subsystem was developed from the general principle of continuity for a fluid. This principle states that for a specific period of time the total inflow to a system minus the total outflow from the system is equal to the change in storage within the system. The total inflow to the water table subsystem is composed of water that enters as lateral drainage and as deep percolation which includes downward drainage from the soil water subsystem and percolation from canals or drains intersecting the

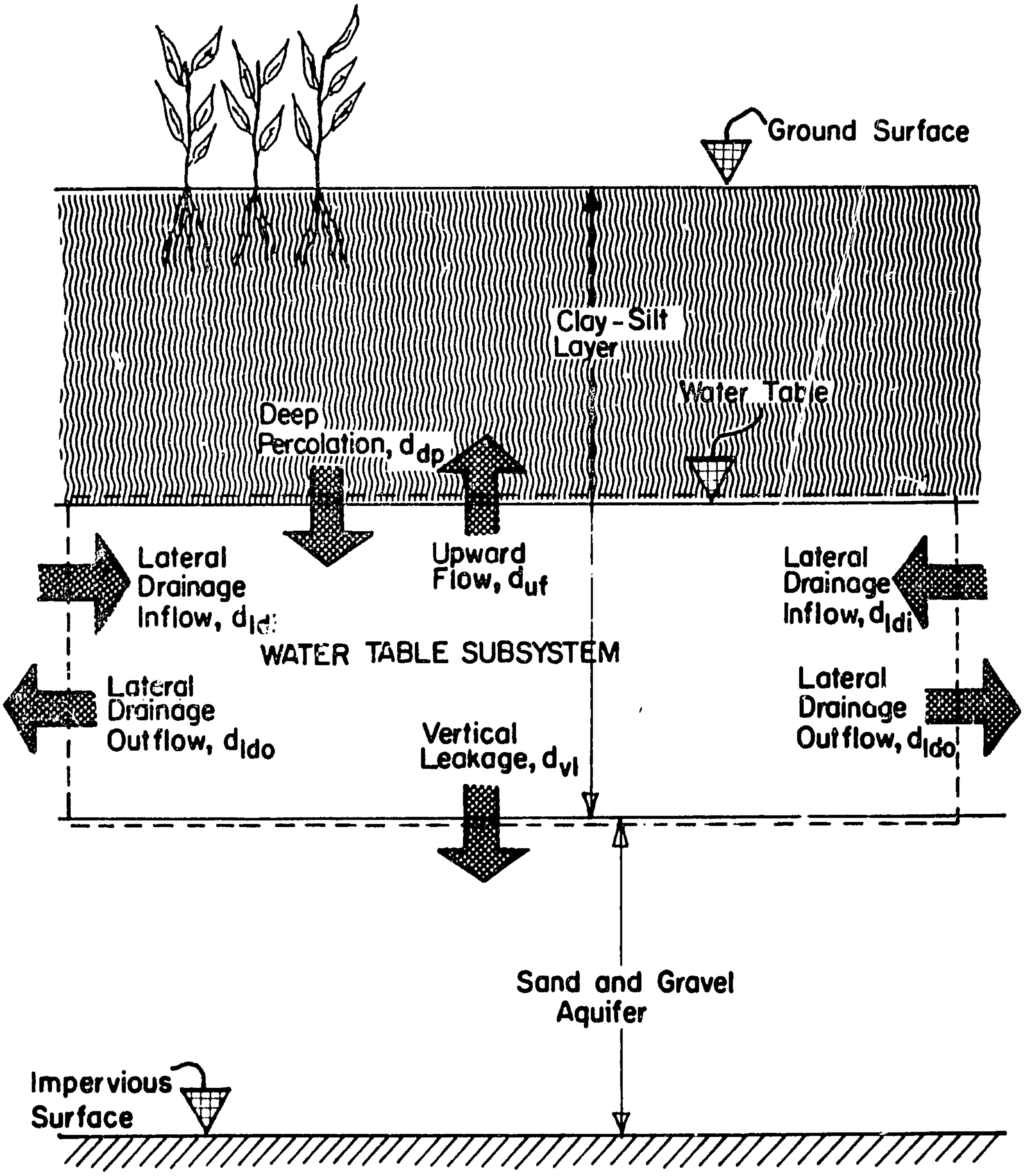

Figure 6 Water table subsystem

water table. Total outflow is composed of vertical leakage to the lower aquifer, upward flow to the soil water subsystem, and lateral drainage outflow. Changes in water stored in the subsystem occur as the water table rises and falls. Thus, for a specific period of time the following equation describes the water balance in the water table subsystem [terms are expressed in units of volume rates per unit land area, or depth per time [$(mm^3/day)/mm^2 = mm/day$]:

$$(d_{dp} + d_{ldi}) - (d_{uf} + d_{ldo} + d_{vl}) = S_{wt} \qquad (1)$$

Where: d_{dp} = inflow as deep percolation (mm/day),
d_{ldi} = inflow as lateral drainage (mm/day),
d_{uf} = outflow as upward flow from the water table (mm/day),
d_{ldo} = outflow as lateral drainage (mm/day),
d_{vl} = outflow as vertical leakage (mm/day), and
S_{wt} = storage change within the water table subsystem (mm/day).

A condition of water table equilibrium, or no seasonal storage change within the subsystem was considered. The components of Equation (1) were expressed in terms of components of water balance equations for other subsystems and in terms of several irrigation water management evaluation parameters resulting in the following balance equation for the water table subsystem:

$$(1/e_a - 1)\,(d_{et} - d_{uf})a + (1/e_{cf} - 1)\,(d_{et} - d_{uf})\,(1/e_a)$$
$$+ d_{dpwd} = d_{uf} + d_{ldo} + d_{vl} \qquad (2)$$

Where e_a = application efficiency (decimal),
e_{cf} = on-farm conveyance efficiency (decimal),
d_{et} = outflow from the soil water subsystem as evapotranspiration (mm/day),
d_{dpwd} = outflow from the water delivery subsystem as deep percolation (mm/day), and
a = the fraction of loss of applied water that occurs as deep percolation losses from the soil water subsystem to the water table subsystem (decimal).

The detailed development of Equation (2) is presented in Appendix A (Equation (A21)).

For given soil profile characteristics and soil water content in the root zone, upward flow can be expressed as a function of the depth to the water table [i.e., $d_{uf} = f\ (y_{wt})$ where y_{wt} is the depth to the water table] (Doorenbos and Pruitt, 1977). When the relation between water table depth and upward flow is known, Equation (2) may be used as a water balance model to describe the relation between commonly used parameters associated with irrigation water management and the depth to the water table. For a known or assumed set of irrigation water management conditions, Equation (2) may be used to compute the resulting stable water table depth. Equation (2) may also be used to investigate the combinations of irrigation water management conditions required to produce a desired stable depth to water table.

DATA COLLECTION AND DISCUSSION

Data were collected at each of the Project sites for use in employing the model of Equation (2). Water budget studies at the regional level and studies of on-farm irrigation supplied data on the existing and potential values of the parameters e_a, e_{cf}, and a and of the flow and storage components of the various subsystems. Studies of water table fluctuation at the sites and a review of the literature provided estimated relations between depth to water table and upward flow.

Parameters and Subsystem Components

The flow components d_{et}, d_{dpwd}, d_{ldo}, d_{uf}, and d_{vl} and the parameters e_a, e_{cf}, and a of Equation (2) were quantified from data collected in the field. The flow components d_{et}, d_{dpwd}, d_{ldo}, and d_{vl} of Equation (2) were estimated by means of water budget studies conducted for several agricultural seasons at each of the Project sites (Helal, et al., 1984). The parameters e_a, e_{cf}, and a were estimated from studies of on-farm irrigation under conventional practices and under improved practices introduced by EWUP (Ley, 1983; Ley, et al., 1984). The flow component, d_{uf}, was determined as a function of depth to the water table, y_{wt}, for existing soil conditions from field data on water table decline during summer and winter cropping seasons.

For Beni Magdul and Abu Raya, complete climatic data were collected from Project weather stations and crop surveys were conducted for use in computing d_{et} by means of the FAO modified form of the Blaney-Criddle equation (Doorenbos and Pruitt, 1977; Helal, et al., 1984). For Abyuha, d_{et} was calculated using values of evapotranspiration for Middle Egypt reported in Nabawy (1981) and crop surveys in the region. Average summer season and winter season values of d_{et} for each of the sites are summarized in Table 1.

The components d_{dpwd} and d_{ldo} were calculated from the Darcy equation for groundwater flow using measured values of water table surface elevation from boundary observation wells and average measured values of saturated horizontal hydraulic conductivity (Mc Whorter and Sunada, 1977; Warner, et al., 1984). A more detailed description of the method used is given in Appendix B. Vertical leakage, d_{vl}, at Project sites was determined by a combination of methods (Warner, et al., 1984). A summary of the estimated values for d_{dpwd}, d_{ldo}, and d_{vl} for each of the sites is given in Table 2.

Data were collected by EWUP on selected farms at each of the Project sites to characterize conventional irrigation water management practices and to evaluate improved methods introduced by the Project. Application efficiency, e_a, was calculated for conventional and improved practices by measuring the amount of water applied to fields with small flumes and the amount stored in the soil profile by soil sampling. Seepage tests by the inflow-outflow and ponding methods were conducted for calculating the on-farm conveyance efficiency, e_{cf}. The fraction of loss of applied water occurring as deep percolation from the soil water subsystem, a, was computed as follows:

$$a = (d_a - d_s - d_{rowd} - d_{rod})/(d_a - d_s) \qquad (3)$$

Where d_a = the amount applied to the field (mm/day),
d_s = the amount stored in the soil water subsystem (mm/day),
d_{rowd} = the amount of runoff from the field that re-entered the water delivery channels (mm/day),
d_{rod} = the amount of runoff from the field that entered surface drains (mm/day).

The components d_{rowd} and d_{rod} were usually negligible in Abyuha and Beni Magdul since there was seldom surface runoff from fields, even under conventional practices. Consequently, the value of a was

Table 1. Average evapotranspiration at Project sites for summer and winter seasons (from Helal, et al., 1984).

Site	d_{et} (mm/day)	
	Summer	Winter
Abyuha	4.5	2.2
Beni Magdul	3.9	2.3
Abu Raya	3.8	1.9

Table 2. Water delivery deep percolation losses, lateral drainage outflow, and vertical leakage at Project sites.

Inflow or Outflow Components	Description	Estimated Value (mm/day)		
		Abyuha	Beni Magdul	Abu Raya
d_{dpwd}	deep percolation losses from branch canals, distributary canals and private canals (*mesqas*).	0.058	0.038	0.020
d_{ldo}	lateral subsurface drainage outflow from the area to public and private drains.	0.001	0.002	0.001
d_{vl}	Vertical leakage from the clay-silt layer to the underlying sands.	0.60	0.60	0.50

estimated as 1.0 for Abyuha and Beni Magdul. In Abu Raya, surface runoff from fields to canals and/or drains under conventional practices was significant. The fraction α was estimated to be 0.75 for conventional layouts. For improved practices little or no runoff occurred and α was taken as 1.0. The estimates of e_a, e_{cf}, and α for both conventional and improved practices at each site are summarized in Table 3. Higher values of e_a and e_{cf} represent water savings, reduced irrigation time, and reduced labor and water lifting costs (Ley et al., 1984).

Dependence of Mass Balance Components on Water Table Level

In defining the conditions required to maintain the water table at a desired level, the dependence of inflow and outflow components on water table level must be known. Warner, et al. (1984) presented data indicating that in the old lands of Egypt, the vertical leakage rate from the water table aquifer in the clay-silt layer to the lower sands is relatively independent of water table level. Darcy's Law predicts that lateral drainage inflow or outflow is directly proportional to the differential head between the water table and the source (canal) or sink (drain). Deep percolation losses are primarily dependent on irrigation practices, not water table depth. Upward flow from the water table due to capillary forces is dependent on water table depth. The relation is complex and some background information is useful in predicting the significance of upward flow under irrigated conditions in the old lands of Egypt.

Relation Between Depth to Water Table and Upward Flow

Water is held in the soil above the water table at negative pressure due to capillary forces. An increment of soil above the water table is practically saturated and is referred to as the capillary fringe. The capillary fringe may have a thickness as great as one meter in clay soils. Far above the water table, gravitational water drains until the moisture content approaches field capacity. The pressure corresponding to this moisture content is about - 1/3 bar (McWhorter and Sunada, 1977). The pressure continues to decrease as plants extract water from the soil for evapotranspiration.

Table 3. On-farm efficiency parameters under conventional and improved water management practices.

Site	Conditions/Practices			e_{cf}	e_a	e_{if}	a
	PLL[1/]	Conveyance Channels	Field Basins				
Abyuha	No	None	Conventional	1.00	0.65	0.65	1.0
	Yes	None	Redesigned	1.00	0.80	0.80	1.0
Beni Magdul	No	Unimproved	Conventional	0.80	0.65	0.52	1.0
	Yes	Reshaped	Redesigned	0.90	0.80	0.72	1.0
	Yes	Lined	Redesigned	1.00	0.80	0.80	1.0
Abu Raya	No	Unimproved	Conventional	0.60	0.65	0.39	0.75
	Yes	Reshaped	Redesigned	0.80	0.80	0.64	1.0
	Yes	Lined	Redesigned	1.00	0.80	0.80	1.0

1/ PLL - Precision land leveling of fields.

Plants are also able to use water at pressures above that corresponding to field capacity due to high water table conditions. Non-agricultural plants known as phreatophytes take water directly from the saturated zone represented by the capillary fringe and water table. These plants can cause dramatic day/night water table fluctuations (Bouwer, 1978; McWhorter and Sunada, 1977). Agricultural crops can take water from the unsaturated zone above the capillary fringe (Manor, 1974). Removal of this water by plant roots creates a pressure head gradient resulting in upward flow from the water table. Subject to the effect of other inflow and outflow components from the water table subsystem, upward flow from the water table would result in a lowering of the water table. Conversely, a lowering of the water table could be used to estimate the amount of upward flow if all other inflow and outflow components are known.

When the water table is close to a bare soil surface, the unsaturated hydraulic conductivity of the soil may be sufficient to allow upward flow due to an evaporative demand at the surface. The maximum upward flow rate cannot exceed the potential evaporative demand due to meteorogical conditions (Bouwer, 1978). Similarly, when agricultural crops are cultivated above a high water table, the upward flow would be limited by the total demand represented by evapotranspiration (Manor, 1974). As water table levels decline, potential upward movement also decreases until a water table level is reached where potential evaporative flow can no longer be sustained (Bouwer, 1978). For water table depths below this particular level, upward water movement from the water table will be less than evaporative demand. Figure 7 shows a graphical representation of the above discussion.

The rate of upward water movement from the water table is primarily dependent on the following:

1. Water table depth below the ground surface,
2. Capillary and conductive soil properties (a function of soil texture and structure), and
3. Soil water content in the root zone or upper soil layers (Doorenbos and Pruitt, 1977; Manor, 1974).

Doorenbos and Pruitt (1977) presented various data on water table contribution to the root zone (Figure 8). Soil water pressure in the

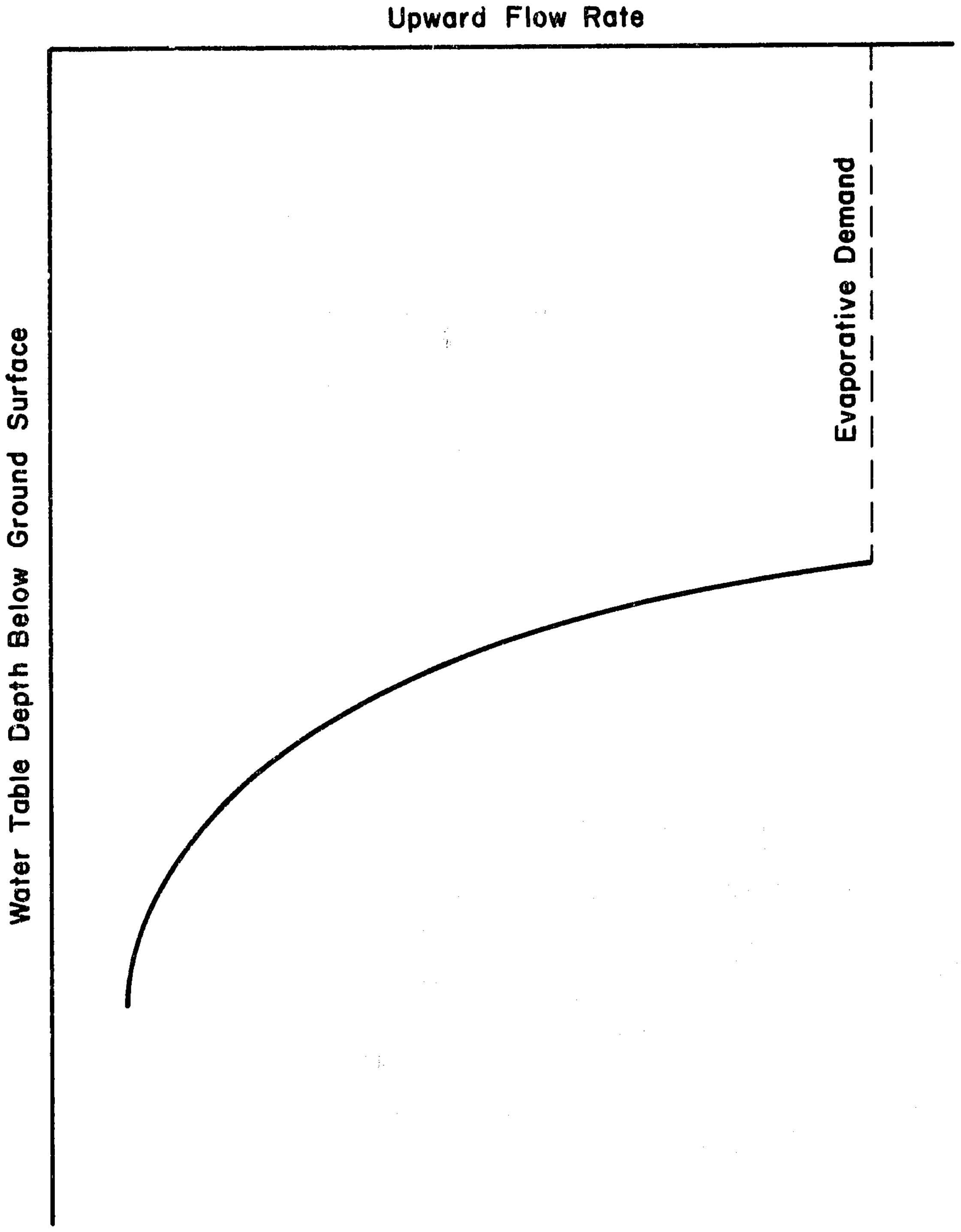

Figure 7 General upward flow response to an evaporative demand at the soil surface (Bouwer, 1978).

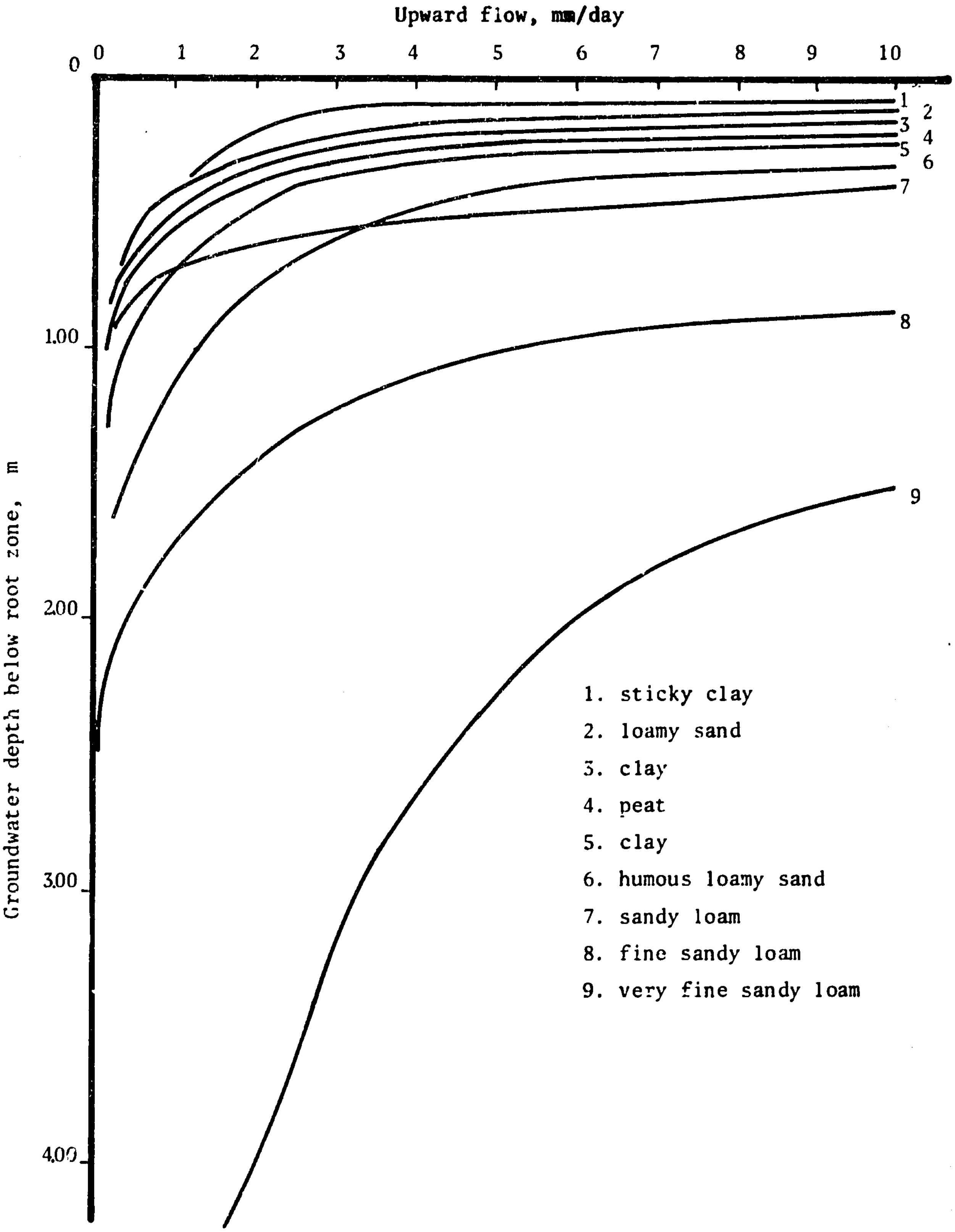

Figure 8 Water table contribution to the root zone for various soils (from Doorenbos & Pruitt, 1977).

root zone was assumed to be about -0.5 bar. For clay soils, water table contribution to the root zone can be significant for water table depths below the root zone of less than one meter.

Continuous water level recorders were installed in shallow observation wells at Beni Magdul and Abu Raya to monitor water table fluctuation. Water table levels rose sharply immediately following irrigation and fell gradually between irrigations (see Figure C1 in Appendix C). A marked difference was observed between water table decline during daylight hours and nighttime hours. An example of the pattern of water table decline is shown in Figure 9 for the drying out period following the last irrigation of cotton in Abu Raya. The flatter portions of the curve occur during the night and the steeper portions occur during the day. The difference between the rate of decline during the day and at night was considered to be due to upward flow of water from the water table contributing to evapotranspiration during the day. The decline at night was considered to represent the combination of vertical leakage, d_{vl}, and local lateral drainage outflow to adjacent fields with upward flow being negligible. At lower water table levels the rate of decline during day and night became equal. It was assumed that at this level upward flow during the day had become negligible and the entire decline was due to vertical leakage and lateral drainage outflow.

Records of water table decline were analyzed to determine the relation between upward flow, d_{uf}, and depth to the water table, y_{wt}. This method of analysis used is described in Appendix C. Resulting data of upward flow versus depth to the water table are plotted in Figures C2a, C2b, C3a, and C3b of Appendix C for Abu Raya and Beni Magdul. Curves were drawn by hand based on expected shape for upward flow versus water table depth curves (Doorenbos and Pruitt, 1977). From these plots the relation between d_{uf} and y_{wt} may be determined for summer and winter conditions. Upward flow during the winter season when the evapotranspiration rate is low is considerably less than during summer season. The data are compared with those from the literature in Figure 10. At Abyuha, the evapotranspiration rate is greater and the soils are more permeable than at Beni Magdul or Abu Raya (Warner et al., 1984). The upward flow versus water table depth

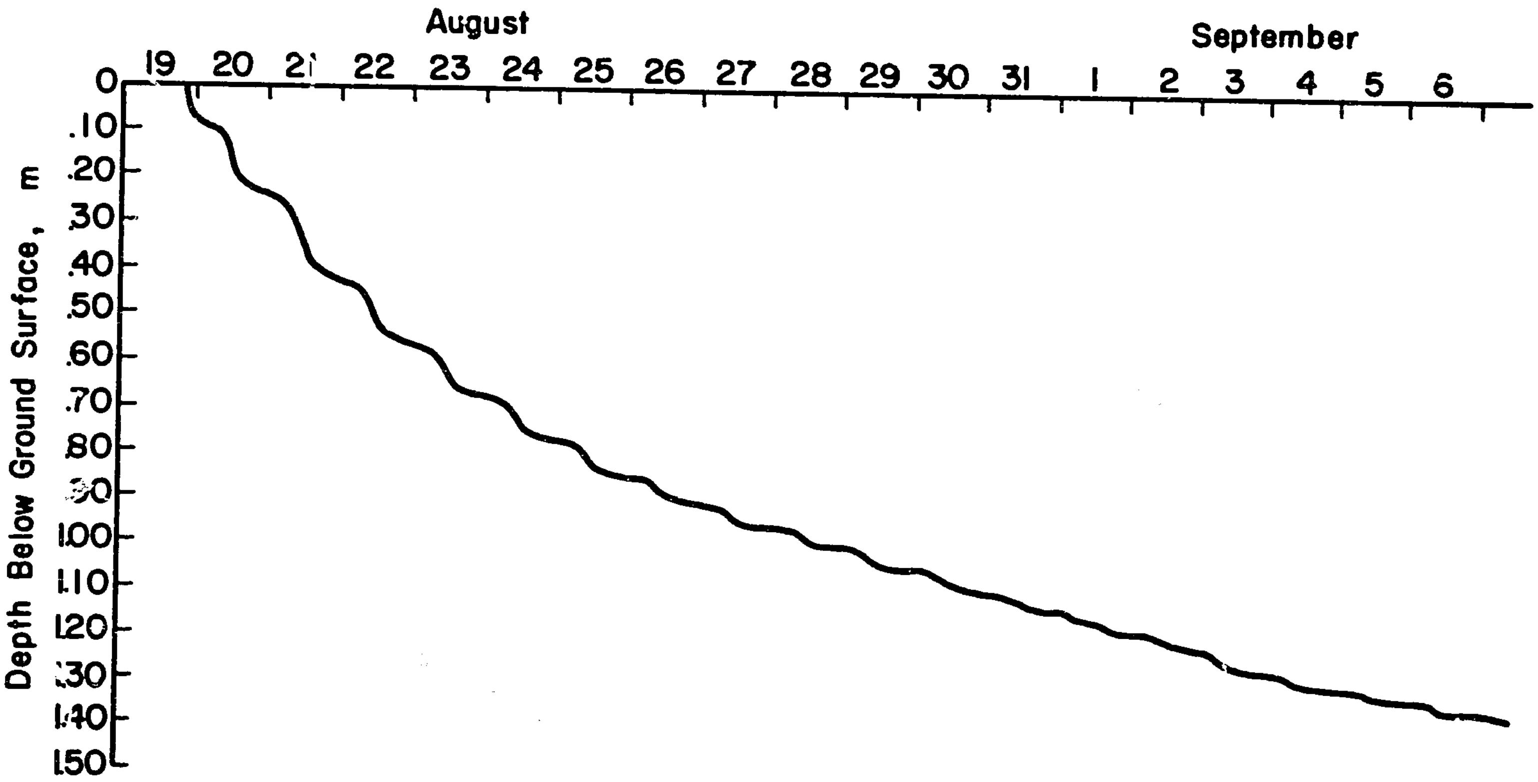

Figure 9 Water table decline following the last irrigation of cotton at Abu Raya.

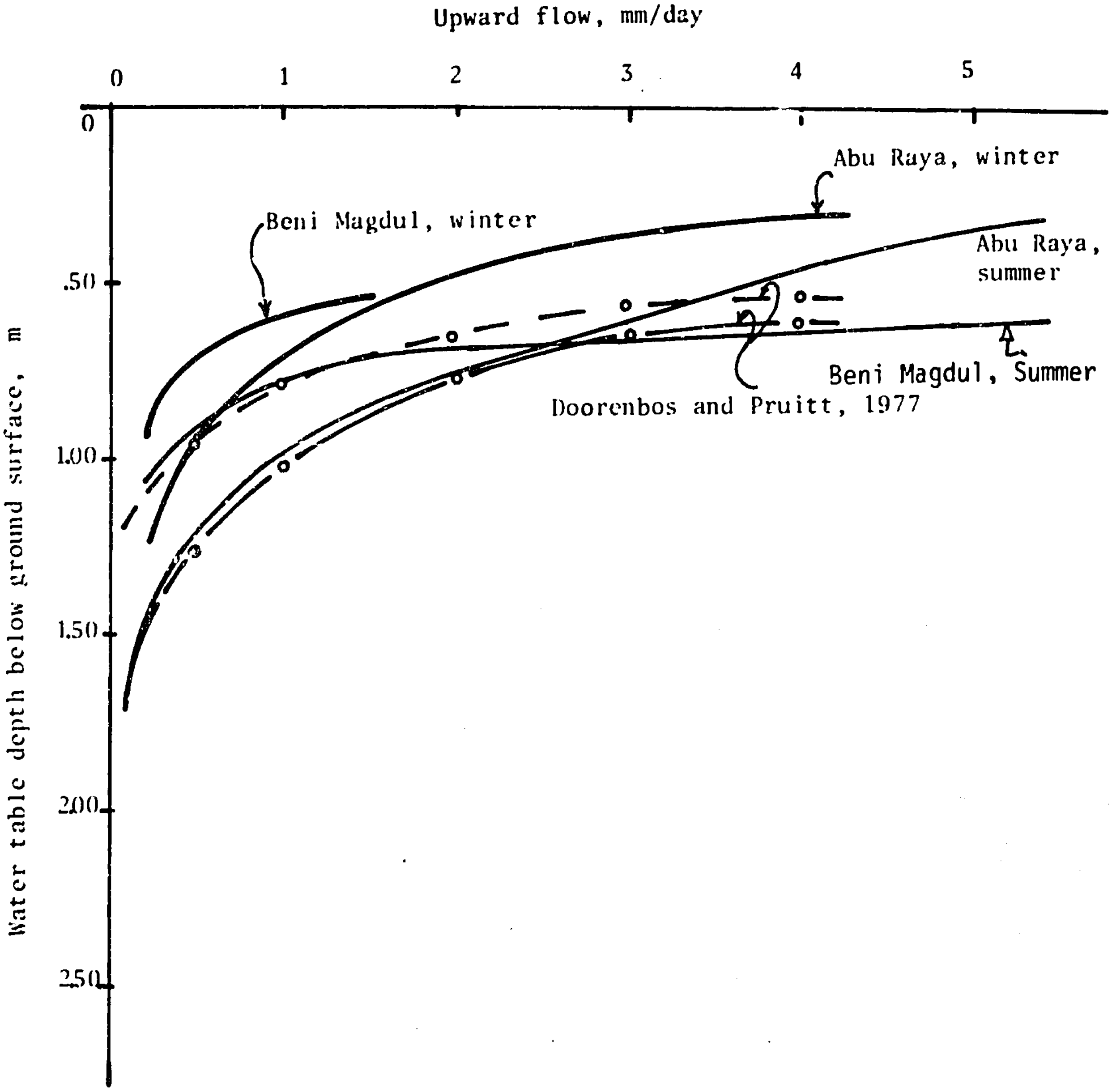

Figure 10 Upward flow for clay soils at Project Sites and from the literature.

curves for Abyuha would thus be expected to lie below those for Beni Magdul and Abu Raya.

ANALYSIS AND RESULTS

Interventions in the irrigation system have potential for maintaining stable lower water tables. When left for a short period of time without irrigation (such as during the period of canal closure in the winter), water table levels in Egypt fall rather rapidly due to upward flow and natural drainage. (Warner et al, 1984). Maintaining a lower water table level throughout the year requires changes in irrigation and drainage practices to produce a new system equilibrium. The water table level could theoretically be maintained at a lower level by increasing vertical leakage or lateral drainage outflow to the drain. Alternatively, net surface recharge could be decreased by decreasing deep percolation losses from fields, on-farm channels, and canals. Deep percolation losses from on-farm channels and fields could be decreased by improving on-farm water management. Losses from canals could be reduced by lining.

Rice cultivation at Abu Raya represents a special case where water levels must be maintained above the ground surface during an entire summer season. The interventions chosen for lowering the water table for other summer crops in adjacent fields must allow for ponded water in rice paddies. In addition, conditions must exist for lowering the water table to desired levels following rice cultivation.

The data collected from the field sites were used to employ the model of Equation (2) to predict the depth to water table for traditional and improved practices of irrigation water management on the farm. The model was then used to predict what conditions of irrigation water management would have to be present in order to maintain the water table at a depth where upward flow would not exceed 5% of evapotranspiration. Alternatives of improve on-farm irrigation efficiency, canal lining, and artificial drainage were considered separately. Water table levels for which upward flow contributes 5% of evapotranspiration are shown in Table 4. Water table levels at or

Table 4. Water table levels for which upward flow contributes five percent of evapotranspiration at Project sites for summer and winter seasons.

Site	Summer			Winter		
	d_{et} (mm/day)	0.05 d_{et} (mm/day)	y_{wt} (m)	d_{et} (mm/day)	0.05 d_{et} (mm/day)	y_{wt} (m)
Abyuha	4.5	0.23	>1.50	2.2	0.11	>1.70
Beni Magdul	3.9	0.20	1.15	2.3	0.12	0.95
Abu Raya	3.8	0.19	1.45	1.9	0.10	1.15

below those shown in Table 4 were considered desirable in this study.

Conventional Practices and Water Table Depth

The values of parameters and components characterizing conventional irrigation practices are summarized in Tables 5, 6, and 7 for Abyuha, Beni Magdul, and Abu Raya, respectively. These values were entered in Equation (2) to calculate values of upward flow, d_{uf}, and fraction of evapotranspiration contributed by upward flow, d_{uf}/d_{et}. Corresponding values of y_{wt} were then determined from Figure 10 for the given values of d_{et}. The resulting solution (summarized in Tables 5, 6, and 7) showed that the percent of evapotranspiration contributed by upward flow was 27%, 40%, and 53% for the summer season and 19%, 35%, and 48% for the winter season for Abyuha, Beni Magdul, and Abu Raya, respectively. For Abu Raya, the water table fluctuation study revealed that water table contribution to evapotranspiration may range between 30% to 41% (Table C2 of Appendix C). The corresponding average depth to water table predicted by the analysis was 0.70 m and 0.75 m for the summer season and 0.60 m and 0.75 m for the winter season for Beni Magdul and Abu Raya, respectively. These results compare well with the range of measured water table depths at the three sites as summarized in Table 8.

EWUP Improved Practices and Water Table Depth

A similar analysis was conducted to predict what effect the large scale adoption of improved irrigation practices would have on water table depth and upward flow at Project sites. Two conditions of improved practices were considered: (1) improvement of application efficiency alone and (2) improvement of application efficiency along with improvement of on-farm conveyance efficiency achieved by lining on-farm channels (*marwas*). A summary of values of parameters and components associated with these two conditions is given in Tables 5, 6, and 7 along with the resulting solutions for d_{uf} and y_{wt}.

At Abyuha, on-farm improvements such as those tested by EWUP could lower the water table and reduce water table contribution to evapotranspiration. Upward flow could be reduced to 10% evapotranspiration during summer season. During winter season upward flow could be eliminated (Table 5).

Table 5. Upward flow from the water table and stable water table depths for conventional and improved on-farm irrigation systems at Abyuha.

Component		Conventional On-Farm System		Improved On-Farm System	
		Summer	Winter	Summer	Winter
d_{et}	(mm/day)	4.5	2.2	4.5	2.2
d_{dpwd}	(mm/day)	0.058	0.058	0.058	0.058
d_{ldo}	(mm/day)	0.001	0.001	0.001	0.001
d_{vl}	(mm/day)	0.6	0.6	0.6	0.6
e_{cf}	(decimal)	1.0	1.0	1.0	1.0
e_a	(decimal)	0.65	0.65	0.80	0.80
α	(decimal)	1.0	1.0	1.0	1.0
d_{uf}	(mm/day)	1.22	0.42	0.47	0.01
d_{uf}/d_{et}	(decimal)[1]	0.27	0.19	0.10	0
Water table depth, y_{wt}	(m)	>1.00	>1.30	>1.30	>1.70

[1] Fraction of evapotranspiration that is contributed by upward flow.

Table 6. Upward flow from the water table and stable water table depths for conventional and improved on-farm irrigation systems at Beni Magdul.

Component	Conventional On-Farm System		Improved On-Farm System (no lining)		Improved On-Farm System (*Marwa* lining)	
	Summer	Winter	Summer	Winter	Summer	Winter
d_{et} (mm/day)	3.9	2.3	3.9	2.3	3.9	2.3
d_{dpwd} (mm/day)	0.038	0.038	0.038	0.038	0.038	0.038
d_{lpo} (mm/day)	0.002	0.002	0.002	0.002	0.002	0.002
d_{vl} (mm/day)	0.6	0.6	0.6	0.6	0.6	0.6
e_{cf} (decimal)	0.80	0.80	0.90	0.90	1.00	1.00
e_a (decimal)	0.65	0.65	0.80	0.80	0.80	0.80
α (decimal)	1.0	1.0	1.0	1.0	1.0	1.0
d_{uf} (mm/day)	1.58	0.81	0.69	0.24	0.33	0.01
d_{uf}/d_{et} (decimal)[1]	0.40	0.35	0.18	0.10	0.08	0
Water table depth, y_{wt} (m)	0.70	0.60	0.85	0.90	1.10	>0.90

[1] Fraction of evapotranspiration that is contributed by upward flow.

Table 7. Upward flow from the water table and stable water table depths for conventional and improved on-farm irrigation systems at Abu Raya.

Component	Conventional On-Farm System		Improved On-Farm System (no lining)		Improved On-Farm System (*Marwa* lining)	
	Summer	Winter	Summer	Winter	Summer	Winter
d_{et} (mm/day)	3.8	1.9	3.8	1.9	3.8	1.9
d_{dpwd} (mm/day)	0.020	0.020	0.020	0.020	0.020	0.020
d_{lpo} (mm/day)	0.001	0.001	0.001	0.001	0.001	0.001
d_{vl} (mm/day)	0.50	0.50	0.50	0.50	0.50	0.50
e_{cf} (decimal)	0.65	0.65	0.80	0.80	1.00	1.00
e_a (decimal)	0.60	0.60	0.80	0.80	0.80	0.80
α (decimal)	0.75	0.75	1.00	1.00	1.00	1.00
d_{uf} (mm/day)	2.01	0.91	1.06	0.38	0.38	0
d_{uf}/d_{et} (decimal)[1/]	0.53	0.48	0.28	0.20	0.10	0
Water table depth, y_{wt} (m)	0.75	0.75	1.00	1.05	1.25	>1.25

[1/] Fraction of evapotranspiration that is contributed by upward flow.

Table 8. Monthly average depth to water table measured at Project sites.

Site	Monthly Average Depth to Water Table (m)			
	Summer Season		Winter Season	
	Range	Mean	Range	Mean
Abyuha	1.20-1.79	1.56	1.25-1.91	1.65
Beni Magdul	0.77-0.91	0.82	0.77-0.91	0.76
Abu Raya	*	*	0.50-0.92	0.69

* Summer season values for Abu Raya are not reported due to the influence of rice cultivation in the area.

At Beni Magdul, improvement in on-farm water management without marwa lining could reduce upward flow to 10-18% of evapotranspiration. With marwa lining upward flow from the water table could be reduced to 0-8% of evapotranspiration. (Table 6)

At Abu Raya, area-wide improved on-farm water management without marwa lining would result in a decrease in water table contribution to evapotranspiration to 20-28%. The water table level would be lowered by about 0.25 m. Area-wide on-farm water management improvements with marwa lining would have a greater impact on lowering the water table contribution to evapotranspiration to 0-10% and the water table level to about 1.25 m below the ground surface. (Table 7)

On-Farm Irrigation Efficiency for Stable Low Water Table

The model of Equation (2) was used to calculate the application efficiency, e_a, that would be required to maintain the water table at a depth for which upward flow contributed less than 5% of evapotranspiration (d_{uf}/d_{ef} 0.05) $<$ 0.05) for various conditions of improved on-farm conveyance efficiency, e_{cf}. Results are presented in Table 9.

At Abyuha, application efficiency would need to exceed 85% to maintain a desirable water table level. It would be difficult to obtain this efficiency with prevailing surface irrigation methods.

At Beni Magdul, it is infeasible to lower the water table to desired levels through improving application efficiency with conventional unlined channels. For improved but unlined channels, application efficiency would need to exceed 90%. For lined marwas, an application efficiency of about 85% would be required. These application efficiencies cannot practically be attained with surface irrigation methods under conditions of cracking clay soils.

At Abu Raya, for conventional on-farm channels and reshaped on-farm channels without lining, it is not possible to reduce water table upward flow to desired rates through application efficiency improvements alone. For lined on-farm channels, an application efficiency exceeding 80% would be required. It would be very difficult to sustain this high application efficiency with cracking clay soils and surface irrigation methods.

Table 9. Upward flow as a fraction of evapotranspiration for various values of on-farm efficiencies.

e_a	d_{uf}/d_{et}						
	Abyuha[1]	Beni Magdul[2]			Abu Raya[3]		
	$e_{cf}=1.0$	$e_{cf}=0.8$	$e_{cf}=0.9$	$e_{cf}=1.0$	$e_{cf}=0.6$	$e_{cf}=0.8$	$e_{cf}=1.0$
50	0.44	0.54	0.48	0.43	0.63	0.50	0.36
60	0.33	0.45	0.38	0.31	0.57	0.41	0.25
70	0.22	0.36	0.28	0.20	0.50	0.33	0.15
80	0.10	0.27	0.18	0.08	0.44	0.25	0.05
85	0.05	0.22	0.12	0.03	0.41	0.21	0.01
90	0	0.18	0.07	-	0.38	0.17	-
95	-	0.13	0.02	-	0.35	0.14	-
100	-	0.08	-	-	0.32	0.10	-

[1] For Abyuha d_{et} = 4.5 mm/day, d_{dpwd} = 0.058 mm/day, d_{ldo} = 0.001 mm/day, and d_{vl} = 0.60 mm/day, a = 1.0

[2] For Beni Magdul d_{et} = 3.9 mm/day, d_{dpwd} = 0.038 mm/day, d_{ldo} = 0.002 mm/day, and d_{vl} = 0.60 mm/day. a = 1.0

[3] For Abu Raya d_{et} = 3.8 mm/day, d_{dpwd} = 0.020 mm/day, d_{ldo} = 0.001 mm/day, and d_{vl} = 0.50 mm/day. a = 0.75

Canal Improvements for Stable Low Water Table

Deep percolation due to seepage from branch canals, distributary canals, and <u>mesqas</u>, d_{dpwd}, was found to be quite small at Project sites, ranging from 0.02 mm/day to 0.06 mm/day on an area wide basis (Table 2). The model was employed to investigate what effect canal improvements such as lining or use of buried pipelines alone would have on water table depth and upward flow. The results shown in Table 10 indicated that the effect would be negligible. Canal percolation losses at the three EWUP sites are negligible due to:

1. Clay soils which are kept wet so cracks do not develop (Litwiller et al., 1984),
2. Lift irrigation systems, and
3. The present high water table levels.

Canal percolation losses could be significant in other areas with sandy soils, elevated channels, and/or low water table levels. In such cases, canal improvements could have an effect on water table levels.

Artificial Drainage for Stable Low Water Table

The water table level could be lowered by increasing the outflow from the water table subsystem, that is, by increasing the outflow components of lateral drainage outflow and vertical leakage (d_{ldo} + d_{vl}). Methods for increasing these outflows include installation of artificial drains and pumping from the lower sand and gravel aquifer. Increasing drainage and vertical leakage from the water table subsystem may result in increases in the required amount of water to be delivered to an irrigated region.

Upward water movement would be decreased by lowering the water table through increases in lateral drainage and vertical leakage. With a constant evapotranspiration rate and a lower water table, the rate of storing water in the soil profile, d_s, would need to increase (Equation A14). Rate of storing water could be increased by storing more water during each irrigation or by shortening the interval between irrigation events in order to compensate for the reduction in upward flow from the lower water table.

Table 10. Upward flow from the water table and stable water table depths for existing and lined canals at Project sites, summer season.

Component	Abyuha		Beni Magdul		Abu Raya	
	Existing System	Lined Canals	Existing System	Lined Canals	Existing System	Lined Canals
d_{et} (mm/day)	4.5	4.5	3.9	3.9	3.8	3.8
d_{dpwd} (mm/day)	0.058	0.00	0.038	0.0	0.020	0.0
d_{ldo} (mm/day)	0.001	0.001	0.002	0.002	0.001	0.001
d_{vl} (mm/day)	0.6	0.6	0.6	0.6	0.5	0.5
e_{cf} (decimal)	1.00	1.00	0.80	0.80	0.60	0.60
e_a (decimal)	0.65	0.65	0.65	0.65	0.65	0.65
α (decimal)	1.0	1.0	1.0	1.0	0.75	0.75
d_{uf} (mm/day)	1.22	1.18	1.58	1.58	2.04	2.03
d_{uf}/d_{et} (decimal)1/	0.27	0.26	0.40	0.40	0.54	0.53
Water table depth, y_{wt} (m)	>1.00	>1.00	0.70	0.70	0.75	0.75

1/ Fraction of evapotranspiration that is contributed by upward flow.

Rooting depths at Abyuha, Beni Magdul, and Abu Raya are about the same although water table depth varies considerably (Moustafa and Tinsley, 1984). Depletions in soil water below the root zone are small and the soil remains near saturation between irrigations (Litwiller et al., 1984). Due to the large capillary fringe for clay soils, lowering of the water table in the range expected from artificial drainage would not significantly change the present soil moisture regime. Upward flow from the water table would decrease however due to increased distance from water table to root zone and decreased capillary pressure in the root zone. It is therefore expected that root zone depth and soil moisture conditions at the time of irrigation would not be influenced significantly by water table depth. Consequently, for each irrigation, on-farm efficiencies using conventional methods would be expected to be independent of water table depth since field conditions would not change significantly with small changes in water table depth.

Decreasing upward flow rate with constant on-farm efficiencies and evapotranspiration rate would result in a larger required rate of water diversion to the farm, d_d (Equation A16). With lower water tables, lower upward flow rates, and constant root zone size, rate of storage of water in the root zone, d_s, would need to be increased by decreasing the interval between irrigations. With constant on-farm efficiency values, e_a and e_{cf}, the rate of applying and diverting water, d_a and d_d, would also need to be increased (Equations A8 and A9). Water deliveries to farms on an area-wide basis would also need to be increased as a result of increasing subsurface outflows to drains.

Following the above discussion, the on-farm efficiencies, e_a and e_{cf}, were assumed to be independent of water table depth for the expected ranges of depth achievable by artificial drainage. Using conditions representative of the summer season at Project sites, Table 11 was developed to demonstrate the effect of increasing outflow parameters on upward flow from the water table and water delivery requirements to farms. The means and feasibility of providing the indicated drainage outflow rates were not considered.

Table 11 Upward flow as a fraction of evapotranspiration and required water delivery rate to farms in Project areas for various values of drainage, summer season.

$d_{ldo}+d_{vl}$ (mm/day)	d_{uf}/d_{et}			d_d (mm/day)		
	Abyuha 1/	Beni Magdul 2/	Abu Raya 3/	Abyuha	Beni Magdul	Abu Raya
0.0	0.36	0.48	0.59	4.44	3.86	3.99
1.0	0.22	0.35	0.49	5.40	4.88	4.97
2.0	0.07	0.22	0.37	6.44	5.85	6.14
2.5	0.00	-	-	6.92	-	-
3.0	-	0.08	0.27	-	6.90	7.11
3.5	-	0.02	-	-	7.35	-
4.0	-	-	0.16	-	-	8.16
5.0	-	-	0.05	-	-	9.26

1/ For Abuyha d_{et} = 4.5 mm/day, d_{dpwd} = 0.058 mm/day, e_{cf} = 1.0, e_a = 0.65, and a = 1.0

2/ For Beni Magdul d_{et} = 3.9 mm/day, d_{dpwd} = 0.038 mm/day, e_{cf} = 0.8, e_a = 0.65, and a = 1.0

3/ For Abu Raya d_{et} = 3.8 mm/day, d_{dpwd} = 0.020 mm/day, e_{cf} = 0.6, e_a = 0.65, and a = 0.75

At all three sites, the water table could be maintained at desired levels by increasing lateral drainage outflow and/or vertical leakage. Outflows required would be 2.5, 3.5, and 5.0 mm/day for Abyuha, Beni Magdul, and Abu Raya, respectively. Respective water delivery requirements to farms would be 6.92, 7.35, and 9.26 mm/day. Given existing levels of on-farm efficiencies, lowering the water table through artificial drainage or pumping could result in large increases in water delivery requirements. Conversely, present water delivery volumes are adequate due to significant upward flow from the water table at Project sites. Further research should be conducted concerning the relation between increased drainage outflows and required water deliveries.

SUMMARY AND CONCLUSIONS

High water table levels measured at EWUP sites represent hazards to crop growth. For ideal crop environment and salinity control, water table levels need to be maintained at or below a level where water table contribution to the root zone is less than 5% of evapotranspiration.

A study was conducted to describe the relationship between irrigation water management and high water tables. A water balance model was developed for the water table in the clay-silt layer including all components of inflow, outflow, and storage change. The components were then quantified using data collected from Project sites. Finally the model was employed to investigate alternatives for establishing lower water table levels at Abyuha, Beni Magdul, and Abu Raya. Alternatives considered included improving on-farm water management, improving canals (lining or replacement with pipelines), and installing artificial drainage.

From the study the following conclusions were drawn:

1. Water table contribution to evapotranspiration is significant at Project sites. Estimates of percentage of evapotranspiration which is supplied by the water table are 19-27% at Abyuha, 35-40% at Beni Magdul, and 48-53% at Abu Raya.
2. For the existing irrigation and drainage systems at the three sites, lateral drainage outflow and vertical leakage from the

clay-silt layer is very small. Deep percolation losses from on-farm channels (marwas) and fields are large due to prevailing surface irrigation methods. Existing water table levels are maintained through a balance of inflow and outflow. The largest component of inflow to the water table is deep percolation. Upward flow is the largest component of outflow from the water table.

3. On-farm irrigation improvements have been tested at the three Project sites in order to improve on-farm water management. Results from this study indicated that widespread adoption of these improvements (including marwa lining in Beni Magdul and Abu Raya) would allow water table levels to be maintained at desirable lower levels during the winter season. However, during summer, water table levels would still be too high.

4. On-farm efficiencies would need to be very high in order to lower water tables to a level where upward flow from the water table would contribute less than 5% of evapotranspiration.

   At Abyuha, application efficiencies of greater than 85% would maintain water table levels for which upward flow of water would not be expected to exceed 5% of evapotranspiration.

   At Beni Magdul, for conventional on-farm channels (marwas), desirable water table levels could not be obtained through improvements in application efficiency. For improved but unlined channels, application efficiency would need to exceed 90%. With lined on-farm channels, application efficiency would need to be about 85% to achieve desirable water table levels. It is infeasible to sustain these high application efficiencies over widespread areas with surface irrigation methods.

   At Abu Raya, with unimproved on-farm channels (marwas) or reshaped channels it is impossible to achieve desirable water table levels through improvements in application efficiency alone. For lined on-farm channels application efficiencies would need to be greater than 80% to achieve desirable water table levels. It is practically impossible to sustain this application efficiency through use of surface irrigation methods on cracking clay soils.

   The results from Abyuha, Beni Magdul, and Abu Raya indicate that in general desirable water table levels cannot be obtained through improvements in on-farm water management using surface irrigation methods.

5. Deep percolation losses to the water table subsystem from branch, distributary, and private (<u>mesqa</u>) canals is insignificant at Abyuha, Beni Magdul, and Abu Raya. Canal lining would have negligible effect on water table levels.
6. At all three Project sites water table levels could theoretically be lowered by increasing a combination of lateral drainage outflow and vertical leakage through artificial drainage and/or pumping from the lower sand and gravel aquifer. Required outflow from the water table subsystem through lateral drainage and vertical leakage to maintain the water table at desirable levels would be 2.5 mm/day at Abyuha, 3.5 mm/day at Beni Magdul, and 5.0 mm/day at Abu Raya. Appropriate methods for achieving these flow rates would need to be identified.

   Increases in outflow by lateral drainage and vertical leakage would lead to corresponding increases in the required water delivery inflow rate to farms from canals. Further study is required to define the relation between drainage outflow and water delivery requirements.

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APPENDIX A

APPENDIX A: SUBSYSTEM DESCRIPTION AND DEVELOPMENT OF WATER BALANCE MODEL FOR WATER TABLE SUBSYSTEM

In order to develop a water balance model for the water table, subsystems of the irrigation system were defined with relevant inflow, outflow, and storage change components. Mass balance equations, efficiency parameters, and assumptions concerning the magnitude and interrelation of various flow and storage components were used to derive the final model.

Subsystems of the Irrigation System

The irrigation system under study was divided into the following subsystems:

1. Water Delivery Subsystem,
2. On-farm Conveyance Subsystem,
3. Field Surface Water Subsystem,
4. Soil Water Subsystem, and
5. Water Table Subsystem

The water delivery and on-farm conveyance subsystems are shown in Figure A1. Components of inflow and outflow are indicated by arrows.

The water delivery subystem includes the section of the branch canal which faces the irrigated region, the distributary canal, and all private canals (*mesqas*) served by the distributary canal. Subsystem boundaries include:

1. The inlet to the distributary canal from the branch canal,
2. The soil which forms the cross-section of the distributary canal,
3. The soil which forms the bank of that part of the branch canal which faces the irrigated region,
4. The soil which forms the cross-section of *mesqas*,
5. Diversion points to on-farm channels (*saqias*, *tambours*, pumps, bankcuts, etc.),
6. Outlets to drains from both the distributary canal and *mesqas*, and
7. The interface between free water surfaces and the atmosphere.

The on-farm water conveyance subsystem includes all on-farm channels (*marwas*) designed exclusively for water delivery to fields. Boundaries include:

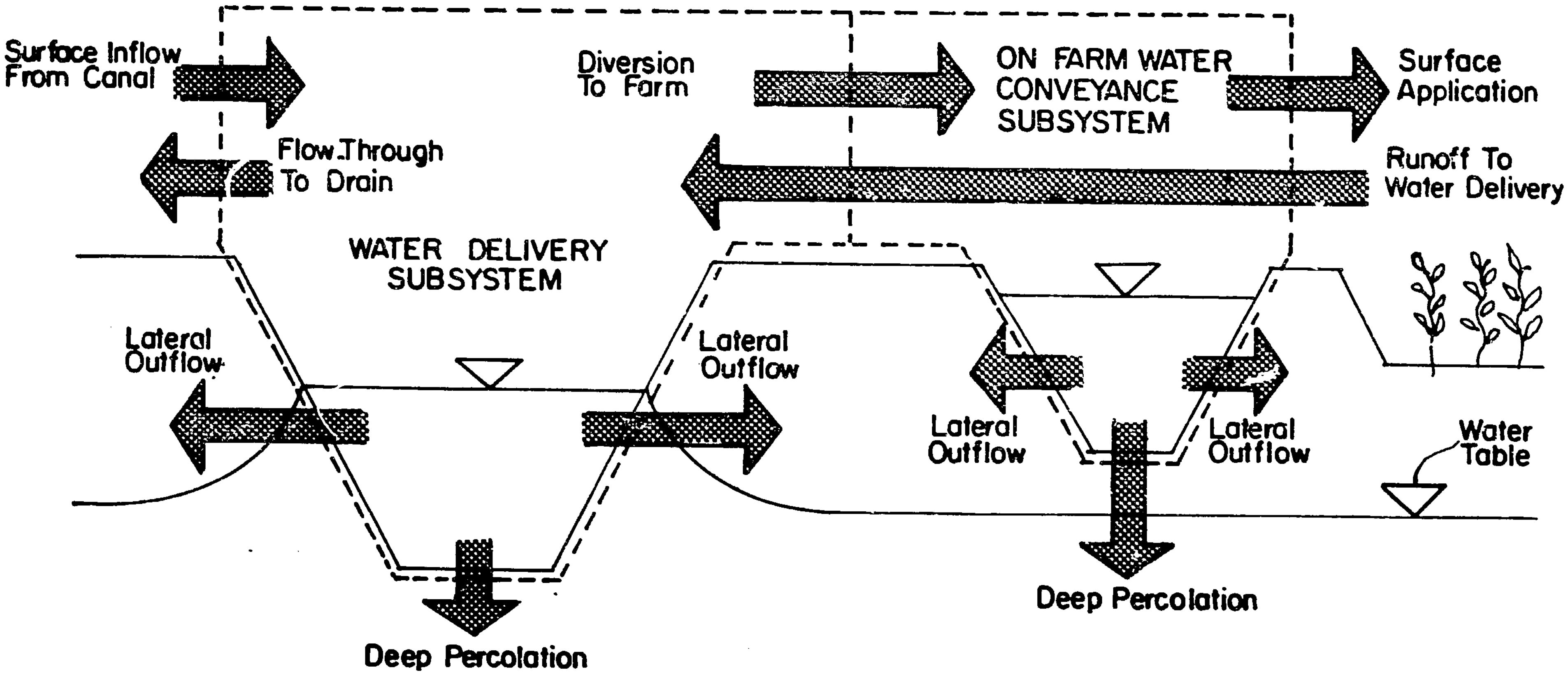

Figure A1 Water delivery and on-farm conveyance subsystems.

1. Outlets from the diversion points from the water delivery subsystem to on-farm channels (*marwas*),
2. Soil that forms channel cross-sections,
3. Outlets to fields or drains, and
4. The interface between free water surfaces and the atmosphere.

Within-field channels and furrows used primarily for water infiltration into the soil profile are not part of the subsystem.

Water delivered by the on-farm conveyance subsystem to fields enters the field surface water subsystem. Some of this water then enters the soil water subsystem through infiltration.

The field surface water and soil water subsystems with relevant inflow and outflow components are shown in Figure A2. Field surface water subsystem boundaries include:

1. Outlets from the on-farm water conveyance subsystem,
2. The field soil surface,
3. The atmosphere, and
4. Outlets to surface drains.

Inflow and outflow occur primarily during irrigation and rainfall events.

Soil water subsystem boundaries include:

1. The ground surface,
2. Interfaces with the water delivery or on-farm conveyance subsystems and with drains, and
3. The water table.

The thickness of the soil water subsystem varies as the water table fluctuates. The soil water subsystem is generally greater in thickness than the crop root zone.

The saturated zone of the clay-silt layer in which the pressure is positive is defined as the water table subsystem (Figure 6) which is the focus of this paper. Boundaries include:

1. The water table,
2. The bottom of the clay-silt layer,
3. Interfaces with the water delivery and/or on-farm water conveyance systems, and
4. Drains.

The thickness of the water table subsystem also changes with water table fluctuations. Detailed description of the clay-silt layer

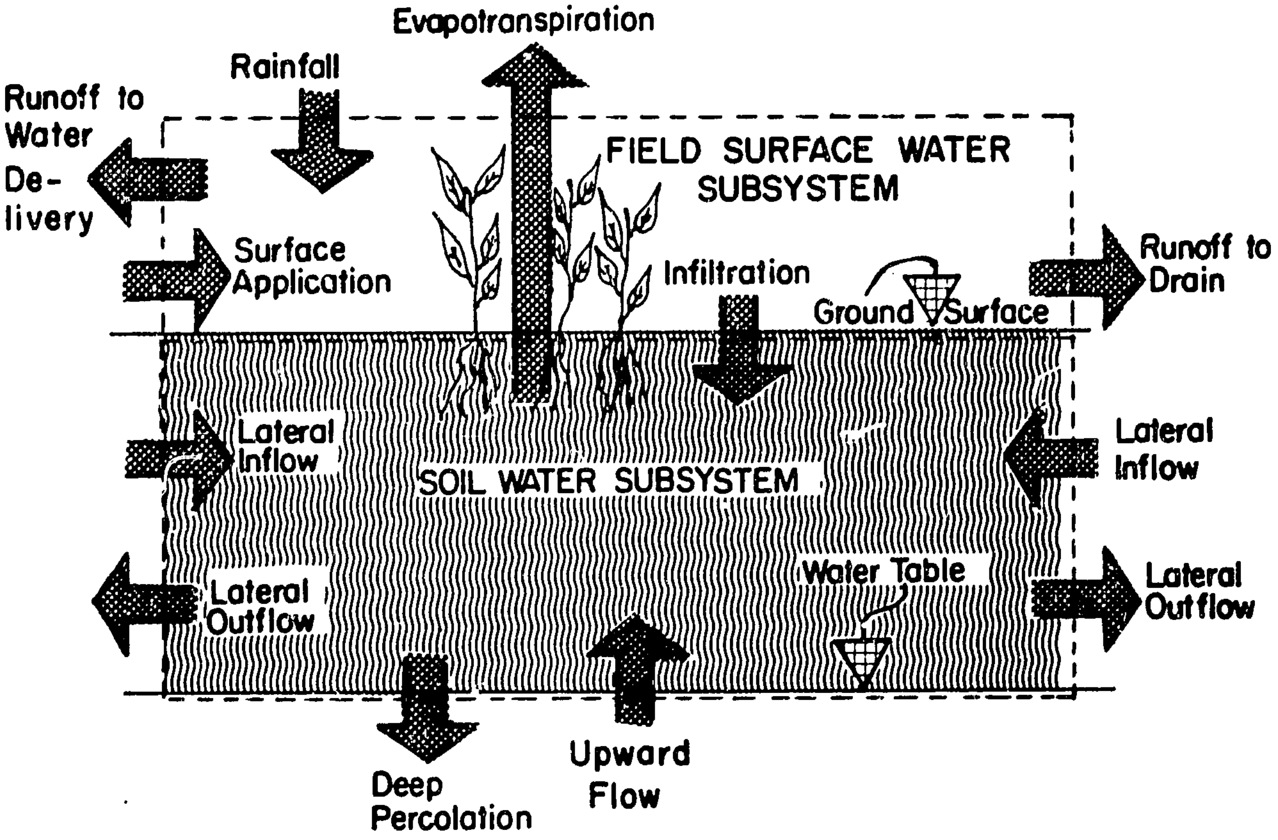

Figure A2 Field surface water and soil water subsystems.

and underlying sands is given in Warner, et al. (1984).

To develop a water balance model for each subsystem the mass balance equation is applied:

$$\text{Inflow} - \text{Outflow} = \text{Storage Change} \tag{A1}$$

Inflow, outflow, and storage change components are expressed as rates of depth over the entire irrigation system surface area per time (mm/day). Symbols for the various inflow, outflow, and storage change components are defined in Table A1. These components correspond directly to the arrows shown in Figures A1, A2, and 6. Outflow from one subsystem may represent inflow to another subsystem. Mass balance equations for each subsystem are as follows:

i. Water Delivery Subsystem

$$(d_{si} + d_{rowd}) - (d_d + d_{ft} + d_{dpwd} + d_{lowd}) = S_{wd} \tag{A2}$$

ii. On-Farm Conveyance Subsystem

$$(d_d) - (d_a + d_{dpfc} + d_{lofc}) = S_{fc} \tag{A3}$$

iii. Field Surface Water Subsystem

$$(d_a + dr) - (d_{inf} + d_{rod} + d_{rowd}) = S_{sf} \tag{A4}$$

iv. Soil Water Subsystem

$$(d_{inf} + d_{uf} + d_{li}) - (d_{et} + d_{dp} + d_{lo}) = S_{sw} \tag{A5}$$

v. Water Table Subsystem

$$(d_{dp} + d_{ldi}) - (d_{uf} + d_{ldo} + d_{vl}) = S_{wt} \tag{A6}$$

All components of the above mass balance equations have units of mm/day and take on positive values when water movement is in the direction shown in Figures A1, A2, and 6. A schematic of interactions between the various subsystems is shown in Figure A3.

Efficiency Parameters

A number of efficiency parameters have been used in EWUP work for evaluation of the irrigation system. Each can be defined in terms of the inflow, outflow, and storage components shown in Table A1 with the addition of the depth stored in the soil profile during irrigation, d_s (mm/day), defined as follows:

Table A1. Water mass balance components (all units are mm/day)

Symbol	Definition
d_{si}	Surface Inflow to Water Delivery Subsystem
d_d	Diversion to On-Farm Conveyance Subsystem
d_{dpwd}	Deep Percolation from Water Delivery Subsystem
d_{lowd}	Lateral Seepage Outflow from Water Delivery Subsystem
d_{ft}	Flow-Through to Drain
d_{rowd}	Runoff to Water Delivery Subsystem
d_a	Surface Application
d_{dpfc}	Deep Percolation from On-Farm Channels
d_{lofc}	Lateral Seepage Outflow from On-Farm Channels
d_{rod}	Runoff to Drain
d_r	Rainfall
d_{inf}	Infiltration
d_{dp}	Deep Percolation
d_{uf}	Upward Flow From Water Table Subsystem
d_{et}	Evapotranspiration
d_{li}	Lateral Seepage Inflow
d_{lo}	Lateral Seepage Outflow
d_{ldi}	Lateral Drainage Inflow
d_{ldo}	Lateral Drainage Outflow
d_{vl}	Vertical Leakage
S_{wd}	Storage Change in Water Delivery Subsystem
S_{fc}	Storage Change in On-Farm Conveyance Subsystem

Table A1. Water mass balance components (all units are mm/day) (continued)

Symbol	Definition
S_{wt}	Storage Change in Water Table Subsystem
S_{sf}	Storage Change in Field Surface Water Subsystem
S_{sw}	Storage Change in Soil Water Subsystem
d_s	Depth Stored in Soil Water Subsystem During Irrigation

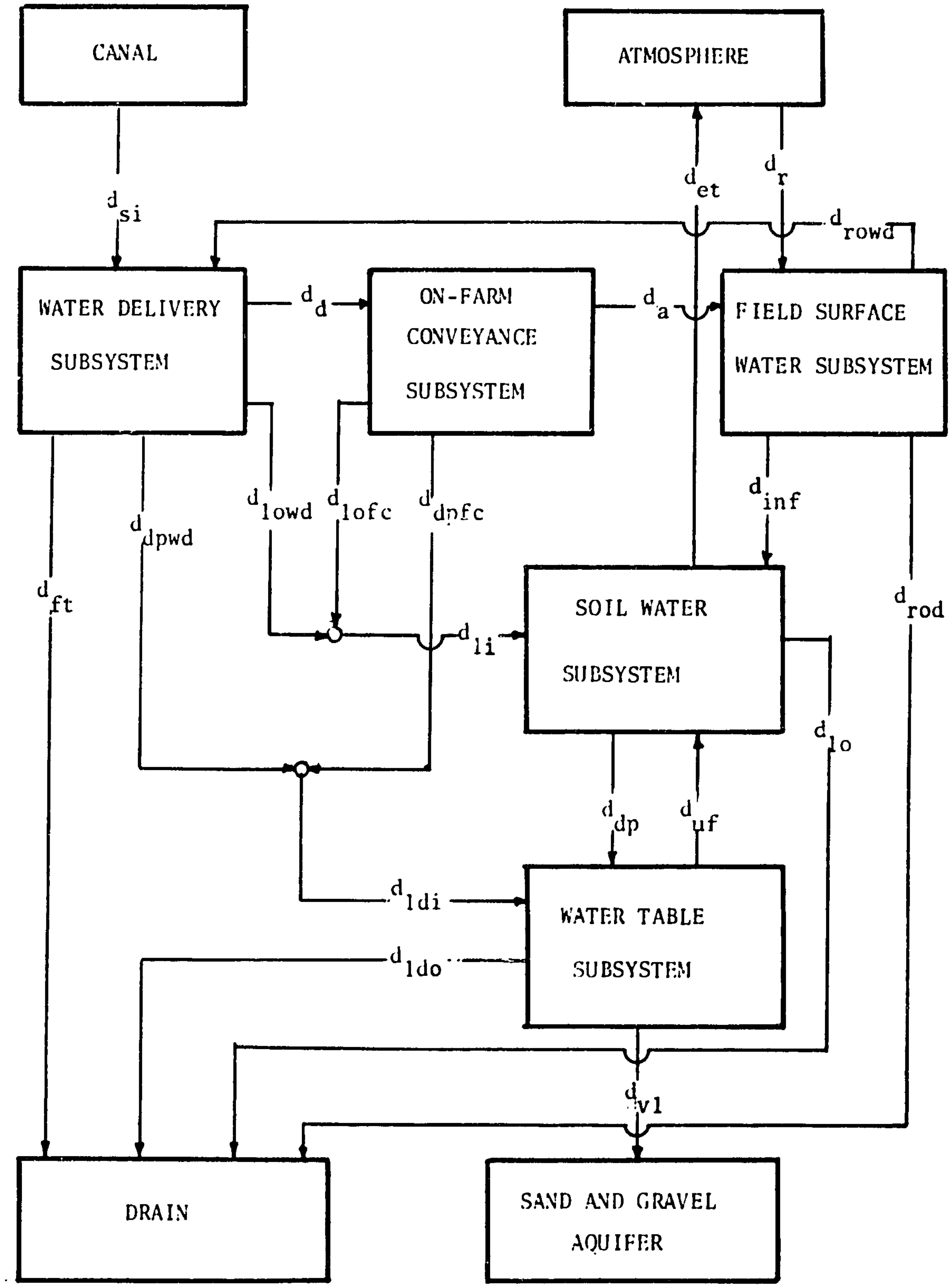

Figure A3 Flow component interaction between various subsystems.

$$d_s = d_a - (d_{dp} + d_{rowd} + d_{rod}) \quad \text{(A7)}$$

Stored water is held in the soil at negative pressures lower than field capacity. Gravity water is included in deep percolation water for purposes of this equation. Gravity water used for consumptive use by crops is included in water table upward flow, d_{uf}, under this definition.

The following efficiency parameters are used in this paper (all have decimal units):

i. On-Farm Conveyance Efficiency

$$e_{cf} = d_a/d_d \quad \text{(A8)}$$

ii. Application Efficiency

$$e_a = d_s/d_a = [d_a - (d_{dp} + d_{rowd} + d_{rod})]/d_a \quad \text{(A9)}$$

iii. On-Farm Irrigation Efficiency

$$e_{if} = e_{cf}\, e_a = d_s/d_d \quad \text{(A10)}$$

The application efficiency, e_a, and the on-farm irrigation efficiency, e_{if}, were calculated by using the water stored in the soil profile during irrigation. Evapotranspiration can be significantly different than water stored in cases where water table contribution to evapotranspiration is substantial. Efficiency parameters based on evapotranspiration rather than water stored can take on substantially different values especially under conditions of significant water table contribution to evapotranspiration.

A summary of methods used to measure or estimate mass balance components is given in Table A2. Assumptions concerning mass balance component estimation are shown in Table A3.

Mass Balance Model for Water Table Subsystem

The mass balance equation for the water table subsystem is:

$$(d_{dp} + d_{ldi}) - (d_{uf} + d_{ldo} + d_{vl}) = S_{wt} \quad \text{(A6)}$$

A model was developed to estimate the magnitude of the inflow and outflow components for different water table levels. At each water table level the system was considered to be in equilibrium and storage change was assumed negligible. That is,

Table A2. Mass balance component estimation.

Component	Study	Method
d_{si}	Water Budget	Flume, Water level recorders
d_d, d_a, d_{dpfc}	On-farm	Flume
d_{dpwd}	Water Budget	Ponding tests, observation wells
d_{lowd}	Water Budget	Observation
d_{ft}	Water Budget	Water level recorders
d_{rowd}, d_{rod}	On-farm	Observation
d_{lofc}	On-farm	Observation
d_r	On-farm	Rain gauge
d_{inf}	On-farm	Equation (A4)
d_{dp}	On-farm	Equation (A5)
d_{uf}	Water Table Fluctuation	Continuous Water table recorders
d_{et}	Water Budget	Climatic data
d_{li}, d_{lo}	On-farm	Observation
d_{ldo}, d_{ldi}	Water Budget	Observation wells
d_{vl}	Water Budget	Consolidation tests, piezometers, Observation wells
S_{wd}, S_{wt}	Water Budget	Continuous water Level recorders, observation wells
S_{sf}, S_{fc}, S_{sw}	On-farm	Observation
d_s	On-farm	Soil sampling

Table A3. Assumptions concerning mass balance component estimation.

Component	Assumption
$d_{lowd}, d_{li}, d_{lofc}$	Negligible (low unsaturated hydraulic conductivities); $d_{li} = d_{lowd} + d_{lofc}$
d_{dpwd}	All goes to water table
d_{dpfc}	All goes to water table
d_{lo}	Negligible (low unsaturated hydraulic conductivities)
d_{ldi}	$d_{ldi} = d_{dpwd} + d_{dpfc}$
$S_{wd}, S_{wt}, S_{fc}, S_{sw}$	Negligible
d_r	Does not contribute to d_{dp}; rainfall occuring between soil sampling dates for a given irrigation is included in d_a. Contribution of rainfall to subsystems other than the field surface water subsystem is negligible.
d_s	Soil sampling to determine d_s always occurs above the water table and represents water stored during irrigation in the entire soil water profile above the water table.
d_{ldo}	Represents a net outflow crossing system boundaries; local drainage between adjacent fields in an area is not included. Shallow, within field drains do not drain the water table.
d_{uf}	A known function of water table depth (y_{wt}) for an irrigation season.
d_{et}	Occurs as outflow from the soil water subsystem only; evaporation from free water surfaces in the total irrigation system is negligible.

$$S_{wt} = 0 \tag{A11}$$

and

$$d_{dp} + d_{ldi} = d_{uf} + d_{ldo} + d_{vl} \tag{A12}$$

The amount of deep percolation, d_{dp}, was assumed to be a known fraction, a, of the losses of applied water, $d_a - d_s$:

$$d_{dp} = (d_a - d_s)a \tag{A13}$$

The entire amount of evapotranspiration is met by a combination of water table contribution and water stored above the water table:

$$d_{et} = d_{uf} + d_s \tag{A14}$$

Combining equations A9 and A14,

$$d_a = (d_{et} - d_{uf})/e_a \tag{A15}$$

Similarly, combining Equations A8 and A15,

$$d_d = (d_{et} - d_{uf})/(e_a\ e_{cf}) \tag{A16}$$

The lateral drainage inflow to the water table subsystem is assumed to be a combination of on-farm channel (*marwa*) and water delivery deep percolation losses:

$$d_{ldi} = d_{dpfc} + d_{dpwd} \tag{A17}$$

On-farm channel losses can be computed as

$$d_{dpfc} = d_d - d_a \tag{A18}$$

by using equation A3 and assuming that d_{lofc} and S_{fc} are negligible. Combining Equations A15, A16, and A18 gives

$$d_{dpfc} = (d_{et} - d_{uf})/(e_a\ e_{cf}) - (d_{et} - d_{uf})/e_a \tag{A19}$$

Similarly, combining Equations A13, A14, and A15 gives

$$d_{dp} = [(d_{et} - d_{uf})/e_a - (d_{et} - d_{uf})]a \tag{A20}$$

Finally, combining Equations A12, A17, A19, and A20 gives

$$(1/e_a - 1)(d_{et} - d_{uf})a + (1/e_{cf} - 1)(d_{et} - d_{uf})(1/e_a)$$
$$+ d_{dpwd} = d_{uf} + d_{ldo} + d_{vl} \tag{A21}$$

which is the general water table balance equation for Project sites. Results and conclusions obtained in this report are based on the use of Equation (A21) as a water balance model for the water table.

APPENDIX B

APPENDIX B: DATA ON PARAMETERS AND SUBSYSTEM COMPONENTS

Estimation of Horizontal Subsurface Flow Near Canals and Drains

The Darcy equation written for flow in a water table aquifer (McWhorter and Sunada, 1977) is as follows:

$$Q = -Kh(dh/dx) \tag{B1}$$

Where K = hydraulic conductivity (m/day),

h = the flow depth (m),

dh/dx = the water table slope (m/m), and

Q = flow rate (m^3/day/m of flow width).

For estimating flow between two observation wells spaced at S meters apart, as shown in Figure B1a and B1b, the slope, dh/dx, and the flow depth, h, can be approximated by the average slope, $(h2 - h1)/S$, and the average flow depth, $(h1 + h2)/2$, respectively. Substituting these approximations into equation B1 yields:

$$Q = -K(h2 + h1)(h2 - h1)/(2S) \tag{B2}$$

If the difference in flow depth between the two wells, $h2 - h1$, is small compared to the flow depth , h2 or h1, then $(h2 + h1)/2$ can be approximated by either h2 or h1 and

$$Q = -K(h2 - h1)h1/S \tag{B3}$$

A general groundwater flow pattern near to an open drain is shown in Figure B2. The lower boundary of flow is not easy to determine for an unconfined aquifer. The difference, $h2 - h1$, is a constant regardless of the lower boundary of flow chosen. If the hydraulic conductivity is assumed to be independent of flow depth then the flow rate, Q, is directly related to the depth of flow, h, which in turn is determined directly from the assumed elevation of the lower flow boundary.

Two conditions were considered in estimating horizontal flow rates at Project sites;

Condition A: Lower flow boundary at bed level of drain or canal and

Condition B: Lower flow boundary at bottom of the clay-silt layer.

The clay-silt layer thickness is about 12 m at Abyuha, 14 m at Beni Magdul, and 35 m at Daqalt (Helal et al., 1984). Values of flow

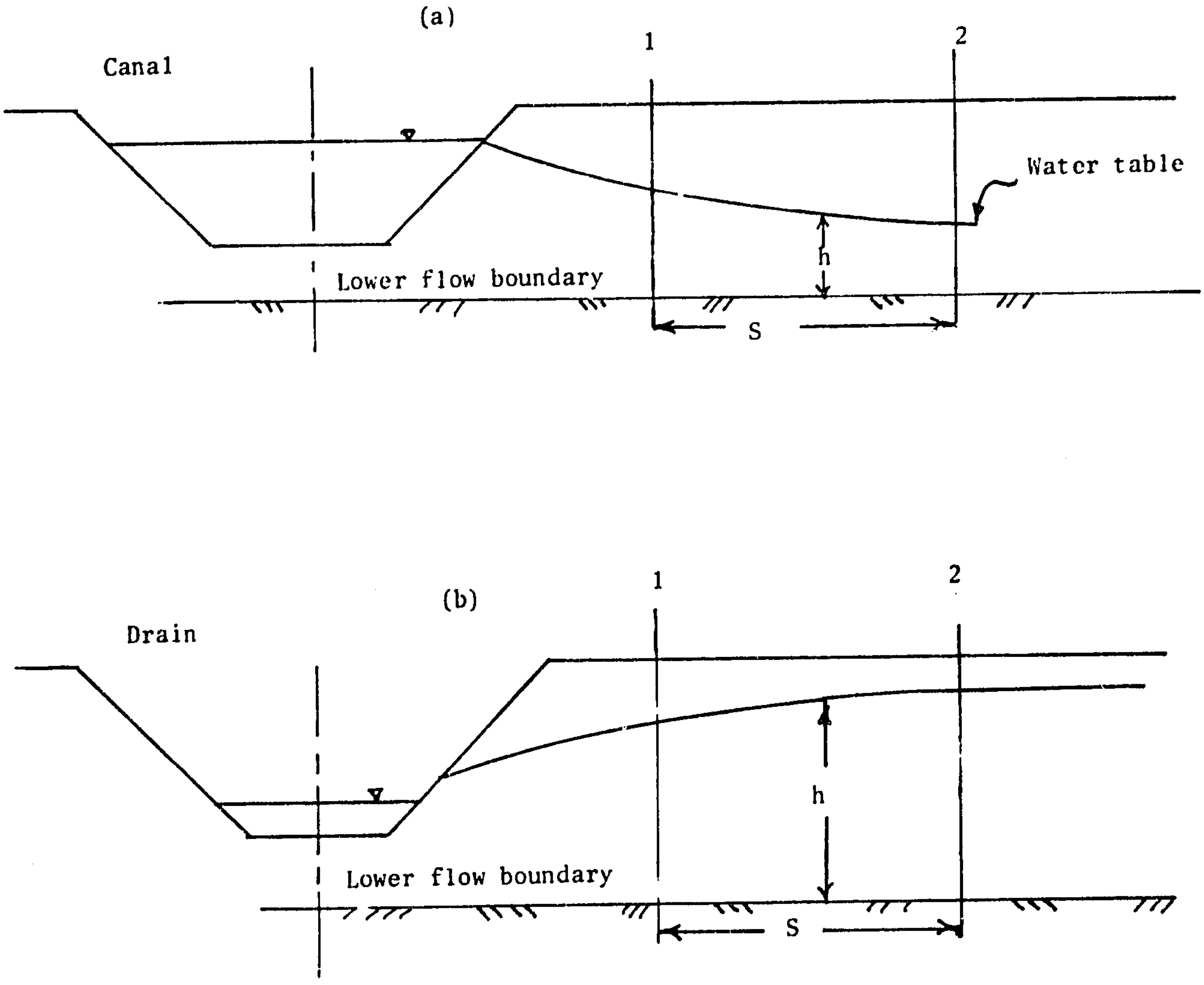

Figure B1 Estimation of saturated horizontal flow rates near canals and drains by using observation wells.

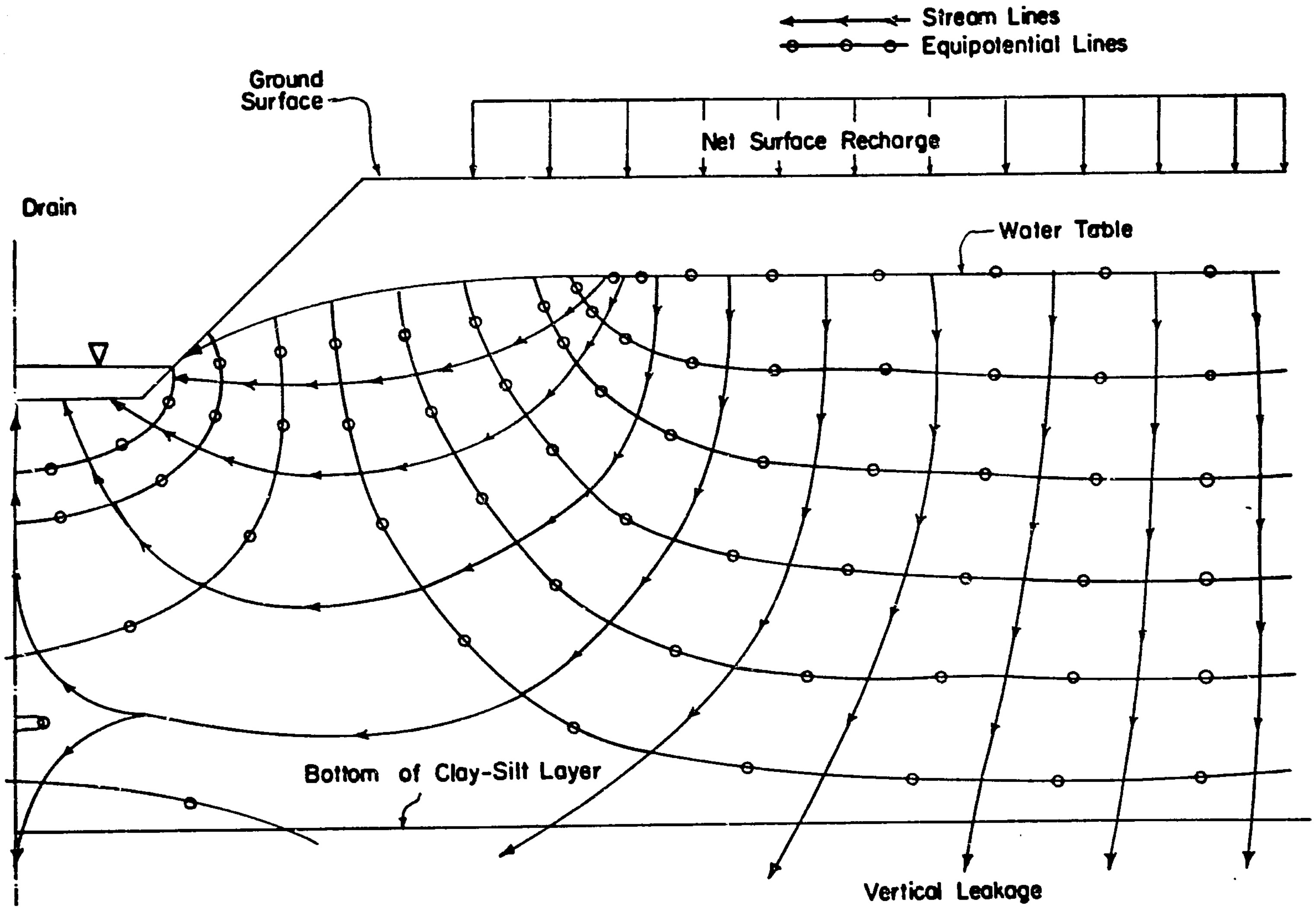

Figure B2 Groundwater flow pattern near an open drain.

depth determined at Project sites based on the two conditions are shown in Table B1. The ratio of flow depths from the two conditions approximates the ratio of estimated flow rates which would be calculated in each case. Pairs of observation wells were installed near various canals and drains at Project sites. Estimates for lateral flow rates computed from well data and the Darcy equation are shown in Table B2. Condition A is assumed to be most applicable to Project sites.

The lateral flow rate in an irrigated region expressed as depth per time is:

$$d_{lat} = 1000q_{lat}/(A/L) \qquad (B4)$$

Where q_{lat} = lateral flow rate per length of channel (m^3/day/m),

A = horizontal area of irrigated region (m^2)

L = length of channel facing the area (m), and

d_{lat} = lateral flow rate for region (mm/day).

Regional lateral flow rates calculated for Project sites are shown in Table B3 for various types of channels.

Estimates for deep percolation losses from the water delivery system, d_{dpwd}, are taken to be the sum of lateral flow rates from branch canals, distributary canals, and private canals (*mesqas*). Lateral drainage outflow (d_{ldo}) estimates are the sum of lateral flow towards public and private drains. Lateral flow rates were assumed to be independent of water table depth.

Table B1. Average saturated flow depth under two assumed conditions[1] at Project sites.

	Abyuha	Beni Magdul	Abu Raya
Flow Depth for Condition A, h_A (m)	3.5	1.3	1.4
Flow Depth for Condition B, h_B (m)	12	14	35
Ratio, h_A/h_B	3.4	11	25

[1] Condition A assumes lower boundary of flow at channel invert level; Condition B assumes lower boundary of flow at bottom of clay-silt layer.

Table B2. Estimation of lateral flow rates for various types of channels in Project areas

Type of Channel	Location	Period of Record	Lateral Flow Rate, $(\times 10^{-3})$ m^3/day/m)			
			Condition A		Condition B	
			Range	Mean	Range	Mean
Private Drain	Gadalla (Daqalt)	Apr-Dec 1981	.104 to 1.25	.428	2.60 to 31.2	10.7
	Omsen (Daqalt)	Apr-Dec 1981	-1.81 to .374	-.397	-45.2 to 9.3	- 9.3
		Mean		.016		1.35
Public Drain	Drain No. 7 (Daqalt)	-	-	0.9	-	9.9
	Nahia (Beni Magdul)	Apr 1981	1.69 to 2.26	2.04	18.6 to 25.9	22.4
		Mean		1.47		16.0
Distrib Canal	Daqalt	Apr-Dec 1981	-2.60 to 4.08	0.14	-65 to 102	3.5
Private Canal (*mesqa*)	Hamad (Daqalt)	Apr-Dec 1981	2.47 to 8.33	4.75	61.7 to 208.2	118.7
Branch Canal	Ibrahimiya (Abyuha)	Aug 1981 to Oct 1982	3.5 to 6.65	4.04	11.9 to 22.6	13.7

Table B3. Regional lateral flow rates for canals and drains at three Project sites.

Project Site	Channel	Length Within Area (m)	Sides Facing Area	Effect Length (m)	Area per eff. lnth. (m^2/m)	Lateral Flow Rate[1] (mm/day x 10^{-3})	
						Condition A	Condition B
Abyuha (1213 *fed.*)	Ibrahimiya branch canal	3400	1	3400	1500	2.693	9.16
	Abuyha distributary canal	4000	1	4000	1274	0.110	0.37
	30 private canals (*mesqas*)	29609	2	59218	86	55.233	188.0
	2 public drains	2300	1	2300	2215	0.664	2.26
	1 private drain	1155	1	1155	4411	0.004	0.01
Beni Magdul (840 *fed.*)	Mansuriya branch canal	700	1	700	5040	0.802	8.82
	Beni Magdul distributary canal	2900	2	5800	609	0.230	2.53
	18 private canals (*mesqas*)	13500	2	27000	130	36.538	401.92
	2 public drains	5200	1	5200	680	2.162	23.78
Abu Raya (Area Served 6300 *fed.*)	Meet Yazeed branch canal	2000	1	2000	13230	0.305	7.63
	Daqalt distributary canal	11400	2	22800	1160	0.121	3.03
	24 private canals (*mesqas*)	54060	2	108120	245	19.388	484.7
	3 public drains	24120	1	24120	1100	1.336	33.4
	Private drains	54060	2	108120	245	0.065	1.63

1/ Positive flow rate values mean flow away from canals and toward drains.

APPENDIX C

APPENDIX C: DETERMINATION OF RELATION BETWEEN DEPTH TO WATER TABLE AND UPWARD FLOW

Introduction and Objectives

Water table fluctuation studies were conducted at Abu Raya and Beni Magdul in order to determine the relation between water table depth and rate of upward water movement from the water table. Data collection and analysis procedures for the Abu Raya study are presented here (unpublished data, A. Ismail, K. Litwiller, and A. F. Metawie). Similar procedures were used for the Beni Magdul study.

In the Abu Raya area of Kafr El-Sheikh crops are grown under the dual constraints of a cracking/swelling clay soil and a high, fluctuating water table. The water table rises to near the soil surface following irrigation and declines again until the following irrigation or rainfall event. The contribution of the water table to evapotranspiration is not known. In this study water table levels were observed under crops of cotton and wheat for an entire year. The objective of the study was to investigate the relation between depth to water table and upward flow from the water table.

Data Collection Procedure

A continuous water level recorder was installed in a field bounded by Hamad *mesqa* and Drain No. 7. The drain and canal were considered to be at sufficient distance from the recorder box to have negligible effect on water table level.

Water table levels were measured continuously for an entire year with charts changed every week and checked twice weekly. Two cropping seasons were included: summer 1981 (cotton crop) and winter 1981-1982 (wheat crop). Results of water table fluctuation were compared with evapotranspiration estimates for the area to arrive at conclusions concerning water table contribution to evapotranspiration.

Cotton planting at Abu Raya occurs in late April. The last irrigation is generally in August and harvest takes place in October. Wheat is planted in late November or early December and harvested in May or June. In this study the summer season (cotton crop) extended from May 18 to September 23, 1981. The following winter season (wheat crop) extended from November 22, 1981 through May 3, 1982.

Data Analysis and Results

The variation of mean daily water table level with time is shown in Figure C1. The water table level increased sharply following an irrigation or rainfall event and fell gradually between irrigations. Water table depth ranged between 0.8 to 1.0 m below the ground surface immediately preceding irrigation during both winter and summer seasons. Water table level immediately following irrigation averaged between 0.1 and 0.5 m with the water table tending to rise higher during the winter. During rice cultivation following wheat, the water table rose to above the soil surface and was maintained there throughout the season. During the summer season approximately 65% of the total area is planted to rice at Abu Raya (unpublished data, M. Meleha, 1983).

One cycle was chosen for closer analysis. Figure 9 shows the fall of the water table following the last irrigation of cotton on August 19. A distinct difference between daytime (6 a.m. to 6 p.m.) and nighttime (6 p.m. to 6 a.m.) water table can be observed with the rate of decline being greater during daylight hours. The daytime decline, the nighttime decline and the difference between the two were observed to diminish with depth. Water table decline was assumed to occur due primarily to the factors of drainage (lateral and downward) and upward flow due to capillary forces. Upward flow in turn was assumed to contribute entirely to evapotranspiration. The magnitudes of each factor were estimated by the following procedure.

The water table levels at 6 a.m. and 6 p.m. were read from the recorder charts for the entire year. The daytime water table decline was taken to be the difference between the 6 a.m. value and the 6 p.m. value for a given day. The nighttime decline was computed as the difference between 6 p.m. level and the 6 a.m. value for the following day. For each daytime decline, a corresponding nighttime decline was determined by taking the average between the previous night and the following night.

The nighttime water table decline was assumed to be entirely due to drainage. The daytime decline was considered due to both drainage

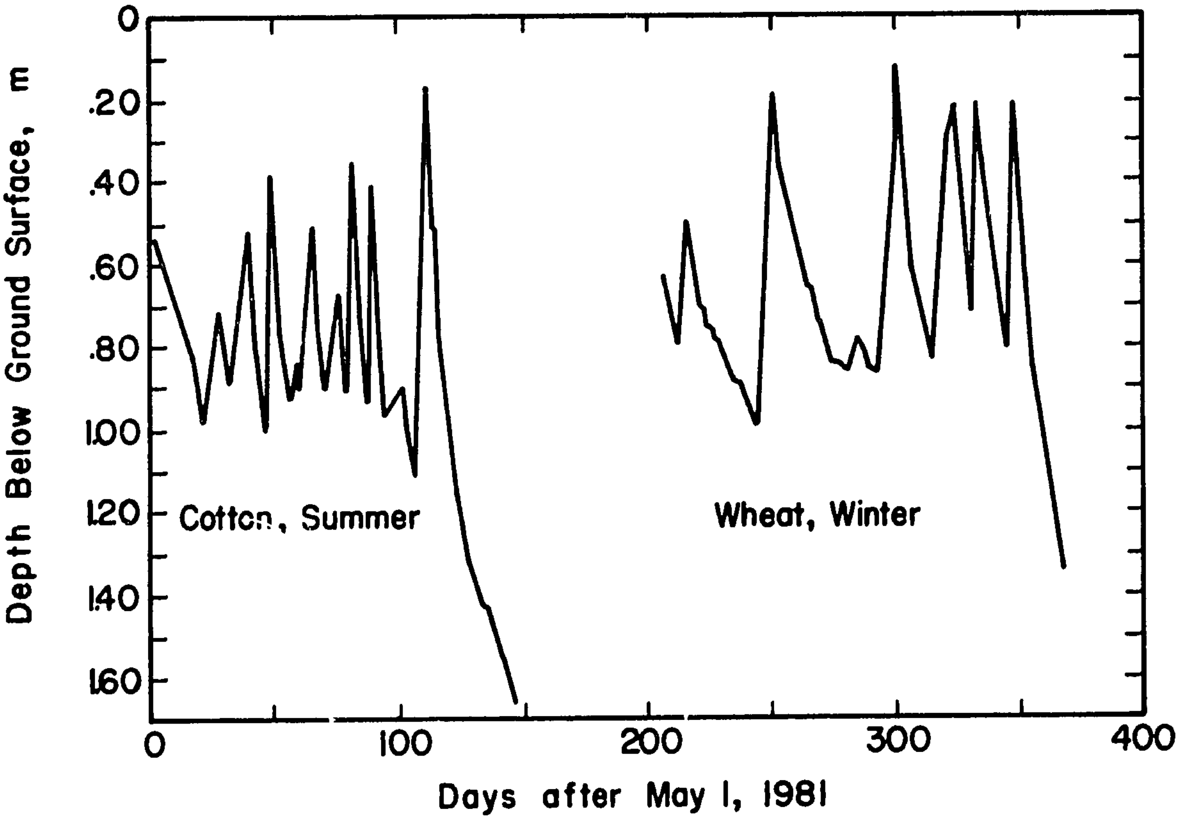

Figure C1 Water table fluctuation during cultivation of cotton and wheat at Abu Raya.

and upward flow. In addition daytime drainage rate was assumed to be equal to nighttime drainage rate.

The difference between the daytime decline and the nighttime decline represents upward flow. The amount of drainage in a 24 hour period is estimated by doubling the nighttime decline. The sum of the drainage and the upward flow during a 24 hour period is equal to the total water table decline during that period. The water table decline can be expressed as an equivalent depth of water by multiplying by the drainable porosity. A drainable porosity of 0.041 was obtained by El-Mowelhi and Van Schilfgaarde (1982) from field measurements in a nearby region using covered drains and observation wells. The values for water table decline calculated above were multiplied by 0.041 to obtain estimates for daily water table drainage and contribution to evapotranspiration. A sample of the data obtained by the above analysis is shown in Table C1 for the drying out period of cotton in August and September 1981. The bottom of the root zone was assumed to be at 0.3 m depth below the ground surface based on root penetration tests (Moustafa and Tinsley, 1984).

Graphs were prepared relating upward flow to water table depth for the summer season and the winter season. The data for upward flow versus water table depth for the summer season (May 18 to September 22, cotton crop) are plottedin Figure C2a. Upward water movement can exceed 4 mm/day when the water table is within 0.4 m of the soil surface. Upward flow rates decrease with increasing water table depth. For water table depths exceeding 1.3 m, upward flow does not exceed 0.5 mm/day.

The relation between water table depth and upward flow during winter season (wheat) for Abu Raya conditions is shown in Figure C2b. In general, upward flow is not as great as for summer conditions. This result could be expected since evapotranspiration rates are greater in summer than winter. For water table depths between 1.0 and 1.4 m, upward flow rates averaged about 1 mm/day. Data were not available for depths greater than 1.4 m. It is proposed that upward flow rates for lower depths during winter would be similar to summer rates. Table C2 presents the estimated percentage of water table contribution to evapotranspiration throughout a year at Abu Raya.

Table C1. Estimation of water table upward flow and drainage by using water table fluctuation data.

Date	Water Table Level Above Sea Level (cm)		Water Table Decline (cm)		Interpolated Night Decline	Difference Between Day and Night Decline	Upward Flow	Water Table Drainage
	6 a.m.	6 p.m.	Day	Night	(cm)	(cm)	(mm/day)	(mm/day)
Aug 19		146						
20	133	119	14	13	8	6	2.46	6.56
21	116	101	15	3	3	12	4.92	2.46
22	98	88	10	3	2.5	7.5	3.07	2.05
23	86	76	10	2	1.5	8.5	3.48	1.23
24	75	67	8	1	1.5	6.5	2.66	1.23
25	65	59	6	2	1.5	4.5	1.84	1.23
26	58	53	5	1	1	4	1.64	0.82
27	52	48	4	1	1	3	1.23	0.82
28	47	43	4	1	0.5	3.5	1.43	0.41
29	43	38	5	0	0	5	2.05	0
30	38			0				

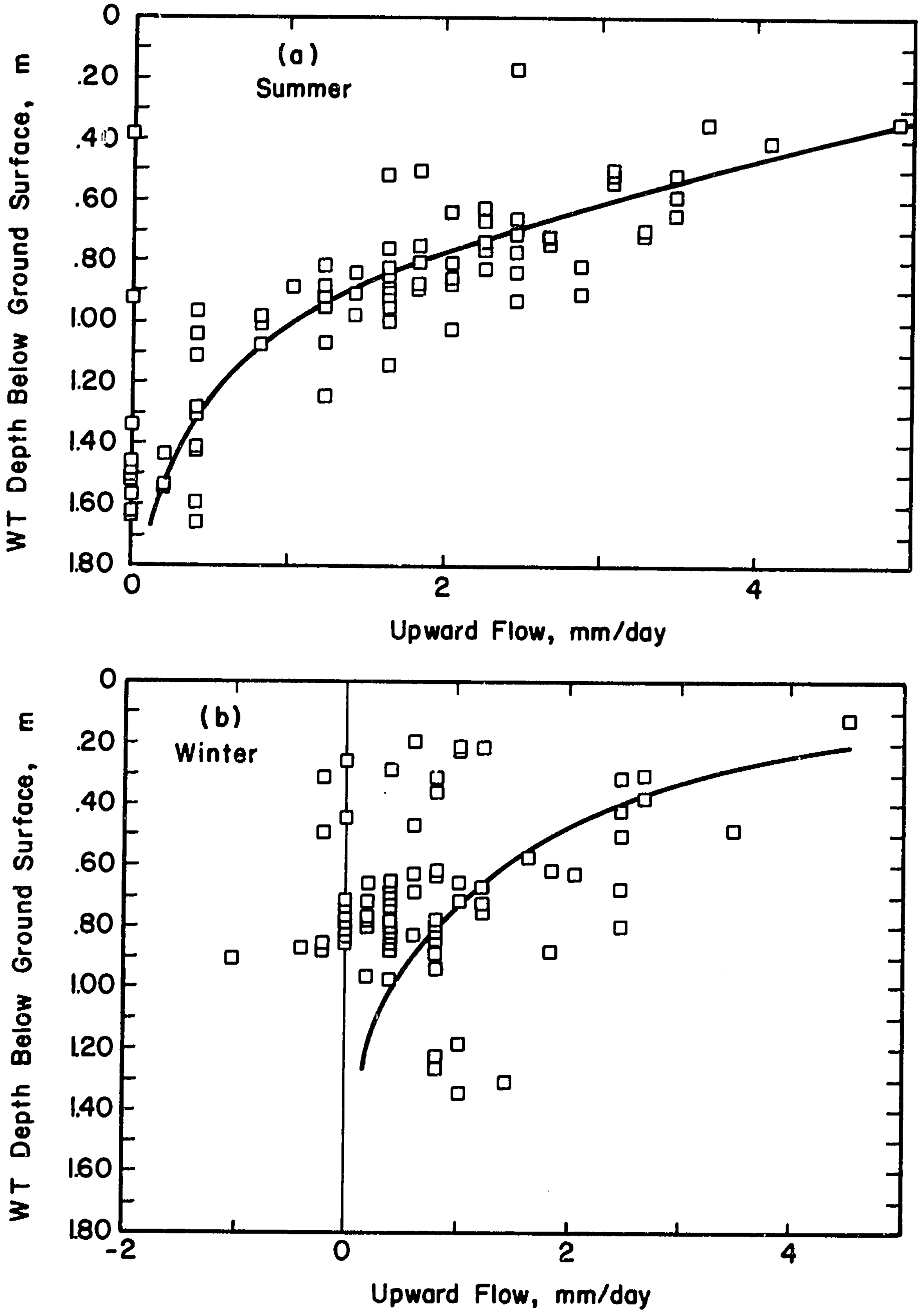

Figure 2C Upward flow at Abu Raya during (a) summer and (b) winter seasons (curves drawn by hand based on expected shape given by Doorenbos and Pruitt, 1977).

Table C2. Water table contribution to evapotranspiration, Abu Raya, 1981-1982.

Time Period	Estimated Upward Flow From Water Table (mm)	(mm/day)		Estimated Actual Evapotranspiration [mm/day (mm)]		Percentage of Water Table Contribution to Evapotranspiration %	
		Peak	Mean	A1/	B2/	A1/	B2/
May 18 to 31 (14 days)	22.14	2.46	1.58	4.0(56)	3.4 (47.6)	40	46
June (30)	60.17	3.485	2.01	5.1(153)	6.2 (186)	39	32
July (31)	70.52	4.1	2.27	5.7(177)	7.3 (226)	40	31
Aug. (31)	50.12	4.92	1.62	3.0 (93)	4.2 (130)	54	39
Sep. 1 to 23 (23 days)	7.38	1.23	0.32	1.7 (39)	1.9 (44)	19	17
Total Summer (cotton crop)	210.33			(518)	(634)	41	33
Nov. 22 to 30 (9 days)	2.87	1.025	0.32	1.3 (12)	2.80 (25)	25	11
Dec. (31)	0.92	0.82	0.003	1.4 (44)	2.10 (65)	0	0
Jan. (31)	15.48	0.82	0.50	1.4 (43)	2.30 (71)	36	22
Feb. (28)	15.58	4.51	0.56	2.0 (56)	2.40 (67)	28	23
Mar. (31)	36.80	2.665	1.19	3.1 (96)	2.80 (86)	38	43
Apr. (30)	49.76	3.485	1.66	3.5(105)	5.80(174)	47	29
Total Winter (wheat crop)	152.4			356	488	43	31
Total Yearly	362			874	1122	41	32

1/ Nabawy, 1981.

2/ Soil moisture depletion data, summer 1981, winter 81-82, Abu Raya.

Water table contribution was approximately 38% during the summer, 37% during the winter, and 37% as an overall average for the entire year.

A similar study and data analysis procedure was conducted at Beni Magdul. The resulting upward flow versus water table depth plots for summer and winter are shown in Figures C3a and C3b.

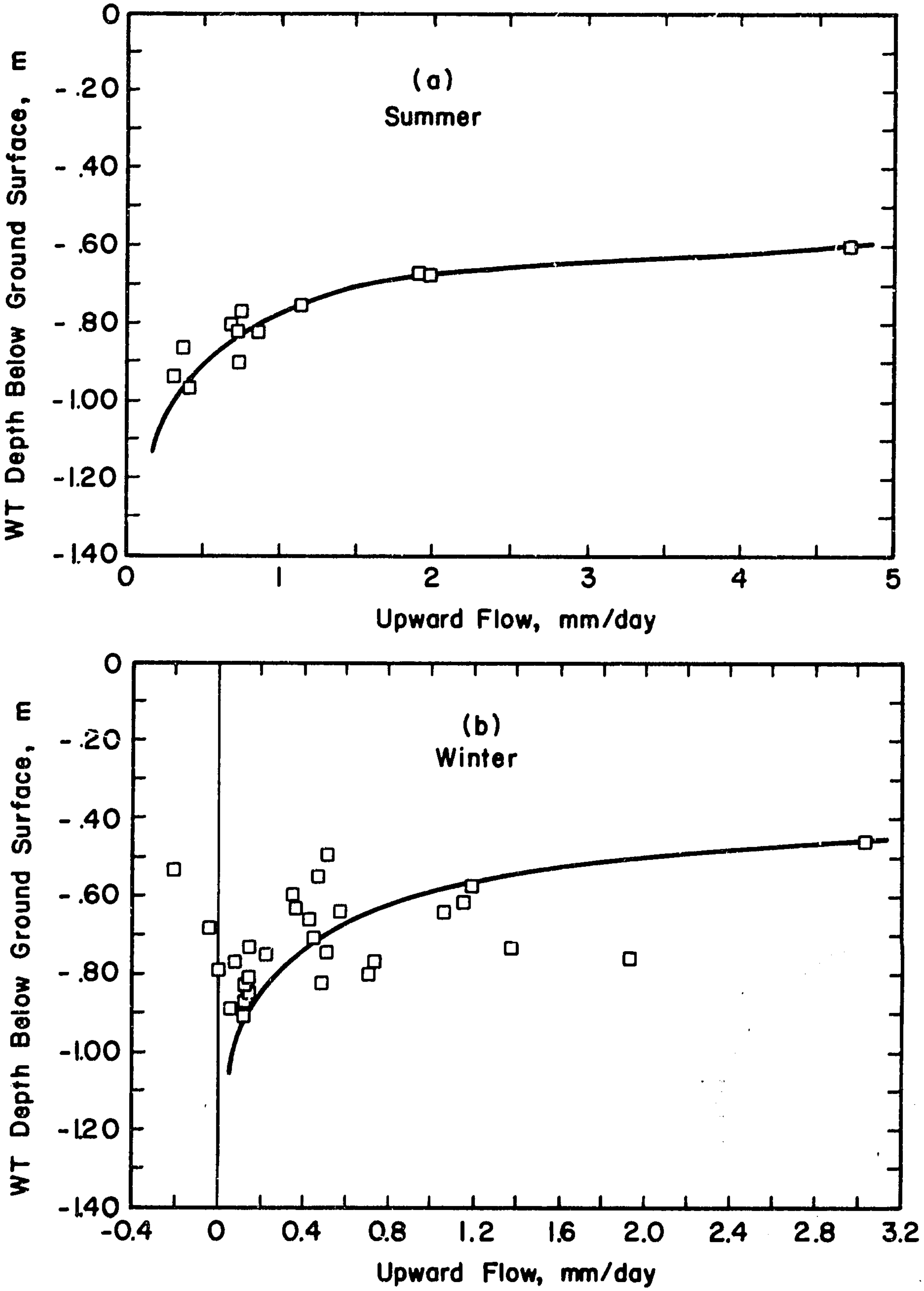

Figure 3C Upward flow at Beni Magdul during (a) summer and (b) winter seasons (curves drawn by hand based on expected shape given by Doorenbos and Pruitt, 1977).

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 distributer, 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.)

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