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INFILTRATION STUDIES ON EGYPTIAN VERTISOLS

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SUMMARY:

Cylinder infiltration tests were conducted during wheat irrigations on shrinking/swelling Vertisol soils. Infiltration proceeded from high initial rates to low long term rates. Infiltration characteristics resulted in large infiltrated depths during the planting irrigation, good water distribution across irrigated basins, and danger of prolonged ponding in field depressions.

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INFILTRATION STUDIES ON EGYPTIAN VERTISOLS [1]

By

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ABSTRACT

Twenty-one cylinder infiltration tests were conducted during irrigation of wheat on the shrinking/swelling Vertisol soils of Kafr El-Sheikh, Egypt. Infiltration rates decreased rapidly from 720 mm/hr for the first minute to 7.2 mm/hr at 2 hours elapsed time, with 1/3 of the tests showing soil sealing. In the majority of tests a well-defined two phase cumulative infiltration curve was determined. Highly significant correlations of antecedent soil moisture content in the 0-100 mm and 0-200 mm soil depth ranges with the infiltrated depth at 1 minute, infiltrated depth at the phase change, and average infiltration rate during the first phase were found.

The first phase of infiltration was considered to represent flow of water through the soil macropores in the drier upper layer and 3-dimensional flow into soil peds while the soil swells closing the macropores. The second phase represented vertical flow into the wetter lower soil layers and filling of the finite storage space above the high water table. The analysis indicated a design application depth of not less than 120 mm for the first irrigation and 55 mm for subsequent irrigations. With the low second phase infiltration rates, water ponded in field depressions for prolonged periods could be detrimental to crops and requires provision for surface drainage. Precision land leveling will reduce this hazard.

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I. INTRODUCTION

The Egypt Water Use and Management Project (EWUP) was established in 1977 as a joint effort between the Government of Egypt's ministries of Irrigation and Agriculture with assistance from the United States Agency for International Development. Project activities have included efforts to determine the contribution of on-farm water management to improving the socio-economic well being of the Egyptian small farmer. At the Abu Raya, Kafr El-Sheikh field site an interdisciplinary team of engineers, agronomists, economists, and sociologists has been involved in a three phase research development process to meet project goals. The phases included problem identification, field trials, and demonstration program implementation. As this on-farm irrigation improvement process included farm irrigation system design, detailed knowledge about general soil infiltration characteristics was required.

The objectives of this paper are to describe the infiltration process during wheat cultivation at Abu Raya and to relate infiltration characteristics to on-farm water management. Included in this paper are a background covering Abu Raya conditions, literature pertaining to infiltration in general and infiltration on cracking/swelling clay soils in particular, data collection and analysis procedures, and the results and conclusions relating to data analysis. In particular the effects of soil macropores and soil moisture on various infiltration parameters and water management considerations such as application depths, water distribution uniformity, and excessively long ponding durations in field depressions are discussed. Finally recommendations are given for further study.

Most of the land in the Abu Raya area is planted to two crops per year divided between the summer crops of rice, cotton, and maize and the winter crops of berseem (clover), wheat, flax, sugar beets, and broad beans. The wheat, rice, berseem, flax, and broad bean crops are grown in basins. Cotton, sugar beets, and maize are grown on furrows within basins. Due to the approximately 200% cropping intensity described above, irrigation events occur throughout the year, with two substantial breaks or gaps between crops. These irrigation gaps 1/ can be as long as three months for wheat fields going into rice and four months for cotton fields going into wheat, even though the actual time between crops is only one month.

Due to the occurrence of paddy rice in the crop rotation, the dead level basin on-farm irrigation method is preferred and used for all crops. During irrigation, water advances from the head of the field to the tail, is ponded on the soil surface in field basins, and recedes by infiltration, by surface drainage, and less significantly, by evaporation.

The soils under study have been classified as Typic Torrerts of the Vertisol order (Abdel Wahed, et. al., 1982). Vertisols are heavy, expanding clay soils with a high precentage of montmorillonite clay in the clay fraction which crack severely on drying. Clay contents in the soils under study range between 40 and 70% by weight.

Water table level in the project area varies between 200 mm and 800 mm below the ground surface on a monthly average (Helal et. al., 1983). The water table falls between irrigations and rises to near the soil surface immediately following irrigation. Subsurface drainage is poor due to poorly maintained open drains and slow soil water movement as indicated by a saturated horizontal hydraulic conductivity of 100 mm/day as determined by 10 auger hole tests. The rate of vertical leakage in the region is estimated to be less than 1 mm/day (Warner, et. al., 1983).

The farmers at Abu Raya provide surface drainage by cutting outlets from irrigated basins into within-field open suface drains (Ley et. al., 1983). These field drains occupy from 10 to 15 percent of the productive land area and are too shallow to significantly lower the water table. EWUP has conducted studies on improving on-farm water management using precision land leveling, design and construction of appropriately sized basins, and advisory assistance on system operation [Ley, (ed.), 1983 a,b]. These interventions have proven effective in reducing the need for surface drainage through minimizing field depression depth and matching application depths to the soil water deficit. Cropped area was increased through field drain elimination.

1/ The irrigation gap is defined as the period from the last irrigation of one crop to the initial irrigation of the following crop. It includes the final maturing and drying period of the first crop plus the fallow turnaround time between crops.

II. REVIEW OF LITERATURE

Infiltration is generally defined as the process of water entry into the soil profile. The study and characterization of infiltration is of upmost importance in irrigation. For design and evaluation purposes, it is necessary to know the rate at which water enters the soil and the amount which can be held in the profile before runoff and/or deep percolation begins. Soil infiltration capacities and rates are required data before irrigation designs or modifications can be formulated which will result in uniformly and efficiently applied water. This is especially true for surface irrigation methods. For border or basin irrigation, infiltration is generally assumed to occur vertically downward (one-dimensional flow), while for furrow irrigation infiltration is two-dimensional and affected by the shape of the furrow and the depth of flow. When the shape of the infiltration surface affects the rate of water entry, as in furrow irrigation, this rate is more commonly termed intake rate.

Most well drained soils will generally exhibit an intially high infiltration rate which decreases with time and eventually approachs a constant rate. This process of decaying infiltration rate is due in part to decreasing capillary pressure gradient resulting from a deepening wetting front. A number of physics based equations have been developed to describe the above decay process.

Theoretical Treatment Of Infiltration

Philip (1969), describing infiltration as the outcome of physical interactions between capillarity, gravity and geometry, presents a summary of the theoretical development of non-linear partial differential equations which describe soil water movement. The basis for these equations are Darcy's law and the principle of conservation of mass. Darcy's law for water flow in an unsaturated porous media is:

$$\vec{q} = -K(\theta)\nabla\Phi \qquad (1)$$

Where,

$\vec{q}$ = The Darcy flow velocity in space [Length/Unit Time (L/T)]

$K(\theta)$ = The hydraulic conductivity as a function of moisture content (θ) (L/T),

∇ = The vector differential operator

$= i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$,

Where

i, j, and k are unit vectors in the x, y and z directions, respectively,

Φ = Total potential.

For unsaturated media, the total potential can be taken as the capillary potnetial, $\psi(\theta)$ which is also a function of moisture content, and z, the gravitational component. Equation (1) then becomes:

$$\vec{q} = - K(\theta) \; \nabla[\psi(\theta) + z] \qquad (2)$$

Considering mass continuity at a point in the soil medium, assuming the density of water is constant, the time rate of change of soil moisture is:

$$\frac{\partial\theta}{\partial\theta} = - \nabla\cdot \vec{q}$$

$$= \nabla\cdot K(\theta) \quad \nabla \psi(\theta) + \frac{\partial K(\theta)}{\partial z} \qquad (3)$$

Since gravity acts only in the downward (z) direction. Philip (1969) describes the equation as a general equation of soil-water transfer applicable to homogenous and heterogeneous soils and independent of any requirement that relations between K, ψ and θ be single-valued functions in time. Philip points out that a more tractable form of Equation (3) can be formulated if a homogeneous soil is assumed and if K and ψ are single-valued function of θ. The quantity diffusivity (L^2/T), $D = K\frac{\partial\psi}{\partial\theta}$ is introduced to give:

$$\frac{\partial\theta}{\partial t} = \nabla\cdot D(\theta) \; \nabla\theta \quad \frac{\partial K(\theta)}{\partial z} \qquad (4)$$

D is also a single-valued function of θ in this case. K and D vary significantly with water content or pressure head for most soils. The non-linearity of these parameters makes analytical solution of Equation (4) extremely difficult. Philip (1969) developed numerical solutions of Equation (4) for a variety of initial and boundary conditions.

Solutions to Equation (4) may often not account for actual field conditions which differ significantly from the assumptions on which Equation (4) is based. These deviations include:

1. Disequilibrium in capillary pressure heads from micropores to macropores which invalidates the use of Darcy's law,

2. Non-homogeneous soil conditions in the field,

3. Non-rigid soil matrix in the field which changes with time (in particular the effects of colloidal swelling and shrinkage are not accounted for),

4. Soil-air pressure buildup due to impeded air escape or air entrapment, and

5. Capillary hysteresis which makes the ψ (θ) function time-variant; the K (θ) function is also time variant, but to a lesser degree.

Solutions may often be based on the assumption of uniform initial moisture content, which is practically not the case in actual field situations.

Factors Affecting Infiltration

The infiltration process is significantly affected by a number of factors which exhibit spatial and temporal variability. A review of these factors illustrates the complexity involved in modelling the infiltration phenomenon.

Dixon (1976) presents a list of possible decay processes, in addition to decreasing capillary gradient, which act during infiltration including the following:

1. Capillary pressure head reduction at the wetting front due to increase in moisture content with depth,

2. Surface sealing,

3. Soil settling,

4. Air entrapment,

5. Clay mineral hydration (soil swelling),

6. Eluviation and illuviation,

7. Surface water head dissipation,

8. Macroporosity extent and continuity reduction with depth in the profile, and

9. Anaerobic slime formation.

Of these nine decay processes, the four of primary concern in this paper are 1, 2, 5, and 8.

The moisture characteristics of the soil at the time of an infiltration event have a direct effect on the infiltration process. Antecedent soil moisture content will define the available capacity of the soil for absorbing and holding water. Generally, wetter soils will exhibit a more rapid decrease in infiltration rate, more quickly approaching some constant rate, which is near the saturated hydraulic conductivity of the soil. For a non-leaky infiltration system such as represented by high water table conditions, the infiltration process involves the filling of a finite storage space and the infiltration rate may approach zero with time. Air entrapment will reduce infiltration rates where the flow of air out of the soil, as it is displaced by water, is impeded. This decay process is most likely to occur in basins and borders where the water is ponded over the entire surface. The effect is less significant in furrows where dry soil exists between furrows from which displaced air can escape.

Soil physical properties can exhibit a large degree of variability in time and space, compounding the difficulty of assessing infiltration characteristics under field conditions. Soil texture, particularly the percentage of clay, can significantly influence infiltration rates. In the case of Vertisols, physical instability is caused by water movement into the crystaline structure of the montmorillinite clay minerals. This water movement causes the soil to expand on wetting and crack on drying, greatly influencing the soil porosity and structure even during an irrigation. Soil sealing may occur as cracks swell shut.

The difficulty of solving Equation (4) taking into account the wide variety of constraints imposed by field conditions limits it's practical usefulness in irrigation studies. Many simple, empirically based models have been developed which have found wide acceptance because of their ease of use in irrigation/infiltration studies.

Empirical Infiltration Models

Two empirical infiltration equations have received the widest use. The first equation is the Kostiakov (1932) or Kostiakov-Lewis equation:

$$y(t) = At^{B} \tag{5}$$

Where

$y(t)$ = cumulative infiltration depth (L),

t = elapsed time (T),

A,B = empirical constants (L/T^{B} and dim., respectively),

The second equation is the modified Kostiakov equation, developed to account for constant intake rates at large times:

$$y(t) = A' t^{B'} + ct \tag{6}$$

Where

c = a third empirical constant (L/T). Note that the A' and B' values in Equation (6) are primed to denote they are not the same values as for Equation (5). Infiltration rates can be found by taking the derivatives of Equations (5) or (6).

Other empirical or approximate equations, which include the Green-Ampt equation, the Holtan equation, the Philip two-term equation and the Horton equation, are presented with their apparent advantages and/or disadvantages in Jensen (1980). Dixon (1976) discusses the Kostiakov model in comparison with the Green-Ampt model and states it is generally appropriate for the initial and boundary conditions of field infiltration systems. Dixon supports this with reference to numerous studies in which this model was fitted easily to a wide range of vegetal, edaphic (soil), and climatic conditions. The drawback that the empirical constants, A and B, do not have a theoretical basis has not curtailed the use of the model.

The empirical constants in the Kostiakov equation are capable of physical interpretation (Taylor and Ashcroft, 1972). The constant *A* represents the amount of infiltration during the initial interval of time. The magnitude of *A* depends in part on soil condition at the time water is applied. If the soil contains cracks and large pores, the value of *A* will be relatively larger than if there are only small pores at the infiltration boundary. The parameter, *B*, indicates how the infiltration rate abates with time, thus it depends upon changes in soil condition due to wetting. Soils which tend to swell and seal-upon wetting will exhibit a small value of (*B*), while stable soils will have *B*-values larger than 0.6 (Taylor and Ashcroft, 1972). The above reference also states that flow geometry affects the value of *B* suggesting that flow in two or three dimensions may have *B* values near or exceeding unity.

Swartzendruber and Huberty (1958) describe the *A*-value in the Kostiakov equation as the average infiltration rate over the first unit time interval, and the *B*-value as the instantaneous infiltration rate divided by the average rate after the first unit time interval. The magnitude of the *B*-value indicates how well the infiltration rate will be sustained with time. Dixon (1976) supports these observations, stating that the magnitude of the *B*-value is inversely related to the number and intensity of active infiltration decay processes. The *A* and *B*-values are interdependent, and are affected by boundary conditions. In the present study the dependence of *A* and *B* values on moisture and soil physical properties is explored.

Effects Of Antecedent Soil Moisture Content On Infiltration

The effects of moisture content on infiltration have been reported by several researchers. All generally arrived at the same conclusion: greater initial moisture contents result in slower initial infiltration rates and longer times required to infiltrate a given depth of water.

Lewis (1937) presents results of a number of ring infiltrometer tests conducted under a variety of vegetal and irrigation conditions which showed that the time required to infiltrate a two-inch (50.8 mm) depth of water increased with increasing moisture content of the top foot (305 mm) of the soil profile.

Jensen (1980) and Philip (1969) present graphical results based on numerical or exact solutions of the theoretical-based infiltration equation assuming differing but uniform initial moisture contents. Both sets of results show that computed infiltration rates decrease (at any given time) with greater initial moisture content. Figure 1, taken from Philip (1969), illustrates this influence. Both also note that the effect decreases with increasing time, with there being no effect on the final rate of infiltration, which in all cases was at or near the saturated hydraulic conductivity at infinite time. Philip (1969) states that the primary influence for the results obtained is the decrease in the storage capacity of the soil as the moisture content increases, and that the decrease in capillary potential with increasing moisture content is of secondary influence.

Tisdall (1951) conducted numerous ring infiltration tests on three different soils (representing three different textures). The total infiltration in two hours, the net change in soil moisture content of the surface foot of soil (due to the infiltration event) and the antecedent soil moisture were measured at each test. The tests were conducted several times between irrigation events to cover a wide range of initial moisture. The results showed that for all soil textures the infiltration depth in two hours increased with decreasing initial moisture content. The relation was linear on sandy soil and curvilinear on the heavier clay loam and clay soils, with large increases in the two-hour infiltration amount at the drier moisture contents. Tisdall (1951) also used the Kostiakov equation (Equation 5) to represent the data collected and found the A-value showed the same relation to initial content as the two-hour infiltration amount (i.e. greater A-values were obtained for drier initial moisture conditions). The B--value was found to exhibit a trend in the opposite direction, i.e., smaller B-values resulted from smaller values of initial moisture content. Statistical analysis by Tisdall showed the correlations found between the two-hour infiltration depth and initial moisture, and the A-value and initial moisture were highly significant for the three soils studied.

Effect Of Soil Physical Characteristics On Infiltration

Of particular interest in the present study is the effect of soil cracking and swelling on infiltration and the implications for irrigation water management. The degree of soil cracking is a function of

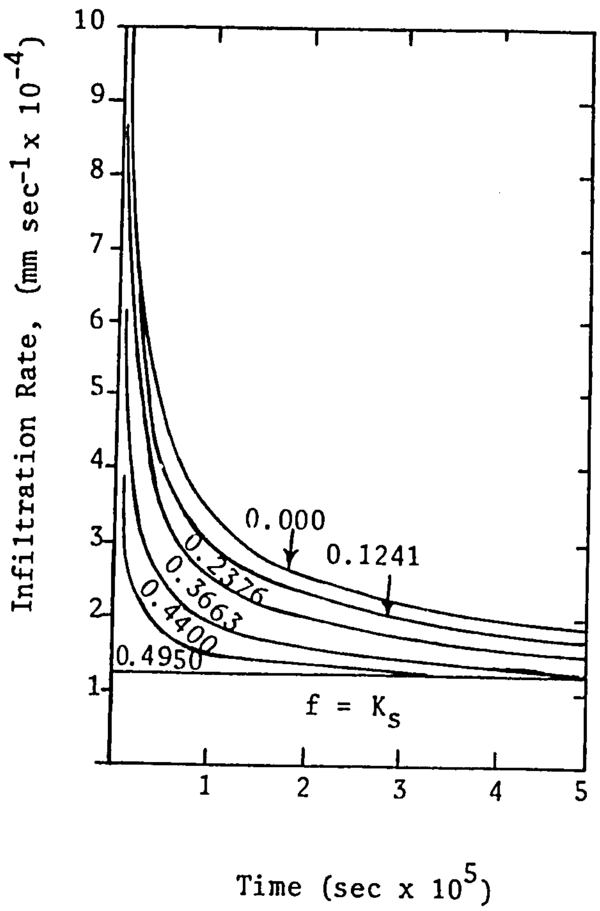

Figure (1): Computed influence of the initial moisture content, Θ_o, on the one-dimensional infiltration rate, f, for a given soil. Numerals on each curve denote values of Θ_o. The infiltration rate, f = K_s, represents the saturated hydraulic conductivity. (taken from Philip, 1969).

the amount of swelling clays and the soil moisture content. The authors have observed cracks during prolonged irrigation gaps to be 50 to 100 mm wide and exceed one meter deep. Cracks observed during the crop growing periods were smaller, but surface cracks of 10 mm width occurred when soil tension was only 15 centibars at 300 mm depth. Soil tillage before planting by tractor drawn chisel plow or during the season by small animal drawn cultivators tended to fill the cracks with loose soil. The exact effect of soil tillage on the infiltration process at Abu Raya has not been determined

Bouma and Dekker (1978) and Bouma, et. al. (1978) carried out extensive laboratory studies of the infiltration process on a dry clay soil in which shrinkage cracks were present. Initial infiltration occurred into the walls of soils peds at the soil surface. As the infiltration rate into the peds decreased, incipient ponding occurred and water began to enter the cracks or macropores between soil peds. Flow through cracks was observed to be a rapid downward movement of water in these initially air-filled large vertical pores and was termed "short-circuiting". As short-circuiting occurred, the water bypassed the dry soil inside the peds at sub-surface levels. The lower boundary conditions controlled the subsequent phases of the process. For free drainage conditions, short-circuiting could continue with relatively little water infiltrating the surface or the vertical walls of the soil peds. With restricted subsurface outflow such as in the case of high water table conditions, the cracks may quickly fill with water and swelling of the soil would occur; the macropores may swell shut. The capacity of the soil micropores inside the soil peds would limit the infiltration rate, possibly greatly reducing the rate or causing effective sealing.

Bouma and Dekker (1978) further describe the process: infiltration into dry, cracked clay soils follows irregular patterns. It is prilimarily dependent on:

1. The rate and duration of adding of water,

2. The hydraulic conductivity and initial moisture conditions of the soil,

3. The number, vertical continuity and surface characteristics of the larger vertical pores.

The application rate at the surface relative to the infiltration rate of the surface soil determines how quickly flow into cracks will occur. Flow processes at the surface and vertical walls of the soil peds and of the larger pores and cracks determine the capacity of the entire system to accept water.

Due to anistropic conditions of cracking soils, traditional Darcy type flow theory does not adequately describe the process. Hoogmoed and Bouma (1980) have developed a theoretical model based on:

1. The theoretical equation of soil water transfer described earlier for the one-dimensional vertical infiltration component,

2. An accounting for gross flow into soil macropores, and

3. The diffusion equation for horizontal absorption of water into the vertical soil ped walls.

The horizontal absorption is a function of the contact area of the water with the sides of the macropores. Bouma (1981) describes a morphological process for characterizing this contact area.

Experimental studies were conducted by Hoogmoed and Bouma (1980) on free-draining, "undisturbed" soil samples. Results from the experiments and model studies showed short-circuiting (which represents the drainage in this case) was the major portion in the water balance, being on the order of 80-90% of the total application. Vertical infiltration in the surface peds was next largest, while horizontal absorption in the cracks was smallest. The start of drainage was found to occur quicker in soils of initially higher moisture content. Also shown was that the contact area in the cracks and macropores is a major factor in the occurrence of the short-circuiting and the start of drainage, as well as is the horizontal absorption rate of the soil (which would be higher for coarser textured soils). Using very large values of the contact area parameter in the model showed that horizontal (and vertical) absorption of all water applied occurred in the upper few centimeters of a soil. Also postulated was that surface modification, such as soil tillage, delays the start of short-circuiting and increases the total initial vertical infiltration.

Underestimation Of Infiltration By Cylinder Infiltrometers

Infiltrated depths as measured by cylinder infiltrometers may not accurately reflect total field conditions. Clemmens (1981) suggests

that ring tests underestimate infiltration due to partial or complete sealing with time. In data presented in the above paper, on the average, infiltration as estimated by cylinders was 65% of the actual infiltration as determined by a volume balance procedure. A similar volume balance procedure, when applied to several irrigated fields at Abu Raya showed that infltration depths as measured with cylinders were 57% of the actual depths determined by volume balance (see Table A1). Cylinder tests which are conducted with the objective of not placing rings over large soil cracks may result in measured infiltration rates which are less than field wide conditions.
[Ley (ed.), 1983 a].

Implications For Surface Irrigation Water Management

The infiltration system under study could be described as surface ponding of water over a cracking/swelling clay soil with a high water table and very slow subsurface drainage outflow. From the above discussion, the infiltration process under the stated conditions could be described as:

1. Initial vertical infiltration and crack flow occurring simultaneously, in upper soil layers.

2. Multi dimensional flow of water into soil peds.

3. Soil expansion causing cracks to partially or fully swell shut, eliminating crack flow and reducing infiltration to vertical movement into soil peds.

4. Recession of surface water occurring at an infiltration rate limited by the microporosity and moisture content or storage capacity of the given soil profile (evaporation and other losses neglected).

The above infiltration conditions represent constraints to effective on-farm water management. Rapid initial infiltration rates may prevent good water distribution in the field. Ponding of water may lead to excessive water application if fields are not well leveled. Low long term infiltration rates may lead to excessive inundation of the soil surface resulting in toxic anaerobic soil conditions and crop damage. Surface drainage may be required to avert crop yield reductions.

III. METHODOLOGY

Twenty-one cylinder or ring infiltrometer tests in six fields were conducted for the basin crop of wheat. The infiltration tests were carried out during actual irrigations on farmers fields resulting in a variety of values for such variables as degree of tillage and antecedent soil moisture. Three tests were conducted during each irrigation event; at the head, middle, and tail of the field respectively.

One set of tests was for a second irrigation, one set for a third irrigation and the remaining five sets were conducted on dry soil prior to the first irrigation at the begining of the season. Soil moisture samples were taken in the test fields one or two days prior to irrigation for the purpose of estimating water application efficiency. These samples were taken from field locations near to the test sites but not exactly at the locations of the infiltration tests. Degree of soil tillage was not measured. However, all fields had been leveled just prior to wheat planting involving earth movement and aggregation of the seed bed.

The infiltration rings, 300 mm in height and 350 mm in diameter, were driven evenly into the ground to a depth of about 100 mm so that the top of the ring was level. As the advancing water front in the field surrounded the ring, water was added to the ring from a bucket. The receding water level within the ring was then measured by a hook gauge and graduated scale. Measurements were taken for the duration of the irrigation or until sealing occurred. Qualitative observations were made of soil infiltration characteristics during the advance and recession phases of the irrigation.

From each cylinder test, a data set of elapsed time in minutes and cumulative infiltrated depth in millimeters was obtained. Time versus depth plots were prepared on log-log paper. For many of the infiltration test data sets, the log-log plots clearly showed two linear branches with distinctly different slopes. All data sets were fitted to the Kostiakov-Lewis equation (Equation 5) by a regression technique and separated into two branches when justified by the value of the regression coefficient, r^2, calculated for all data points and for each branch separately. A high value of r^2 was expected since the data sets represented a plot of time vs. a function of time. The B--values obtained represented the slopes of the observed lines on the log-log plots.

Physically, the two branches of the cumulative infiltration curves discussed above represented two phases of the infiltration process. Clemmons (1981) employed a branch function to account for transition of infiltration from a power relationship to a long-term constant infiltration rate. In the present paper, a two-phase power relationship is used to describe transition from one set of active decay processes to another. The authors have sought to identify the dominate process or processes instrumental in bringing about the phase change.

For tests with two phases, an inflection point was determined by simultaneously solving the equations for the two phases. The relevant equations are:

$$t_f = (A_2/A_1)^{[(B_1-B_2)^{-1}]} \qquad (7)$$

and

$$y_f = A_2\ (t_f)^{B_2} \qquad (8)$$

Where

A_1, B_1= regression coefficients for the first phase equation,
$y = A_1 t^{B_1}$
A_2, B_2= regression coefficients for the second phase equation,
$y = A_2 t^{B_2}$
t_f = elapsed time at the inflection point (min)
y_f = cumulative infiltrated depth at the inflection point(mm)

The calculation of an exact inflection point implied an instanteous phase change. However, in reality the phase change was gradual and the inflection point represented a short time period during which the infiltration phenomenon moved from conditions described by the first phase equation to conditions described by the second phase equation.

The infiltration rate during the test was described by:

$$f(t) = 60\ AB\ t^{(B-1)} \qquad (9)$$

Where

$f(t)$ = the instantanous infiltration rate at time t, mm/hr

Using the regression equations for cumulative infiltration and the above equation for infiltration rate, plots of $y(t)$ and $f(t)$ vs. time were prepared on rectangular coordinate graph paper to describe the multiphase infiltration phenomenon. The graphs of cumulative infiltration depth and infiltration rate vs. time for a typical two phase test are shown in Figures 2 and 3 for rectangular and log-log plots respectively.

IV. RESULTS AND DISCUSSION

General information for the cylinder infiltration tests on wheat is given in Table A2. Seventeen of the tests show a two phase infiltration process. Three tests that show only a single phase were those conducted during a third irrigation. Regression coefficients, r^2, calculated for fitting equation (5) to the cylinder data showed both phases fit well although the second phase shows a stronger relationship with $r^2 = 1.000$ or 0.999 in about one-half of the cases. For tests where $B_2 = 0$, sealing occurred in the ring.

Description Of The Infiltration Process

The values of various infiltration parameters determined from the infiltration equations are shown in Table A3. The parameter A_1 is numerically equal to the cumulative infiltration depth at one minute of elapsed time, $y(1)$, (mm). The magnitude of parameters B_1 and B_2 indicate how well the infiltration rate holds up with time (Swartzendruber and Huberty, 1958) and their difference, B_1-B_2 compares infiltration characteristics during the first and second phase. The inflection parameters, t_f (min) and y_f (mm), represent a period of time and an approximate depth of infiltration at which the phase change occurs. The parameter $y_f/t_f \times 60$ (mm/hr) represents the average infiltration rate during the first phase. Cumulative infiltration depths (mm) at hourly intervals after the initiation of the test are represented by y (60), y (120) and y (180). The instantaneous infiltration rates (mm/hr) at the same hourly intervals are indicated by f (60), f (120), and f (180), respectively.

For each parameter, the mean, standard deviation, and coefficient of variation have been calculated. The results show high infiltration depths during the first minute and an infiltration rate that is better sustained during the first phase than during the second phase. The

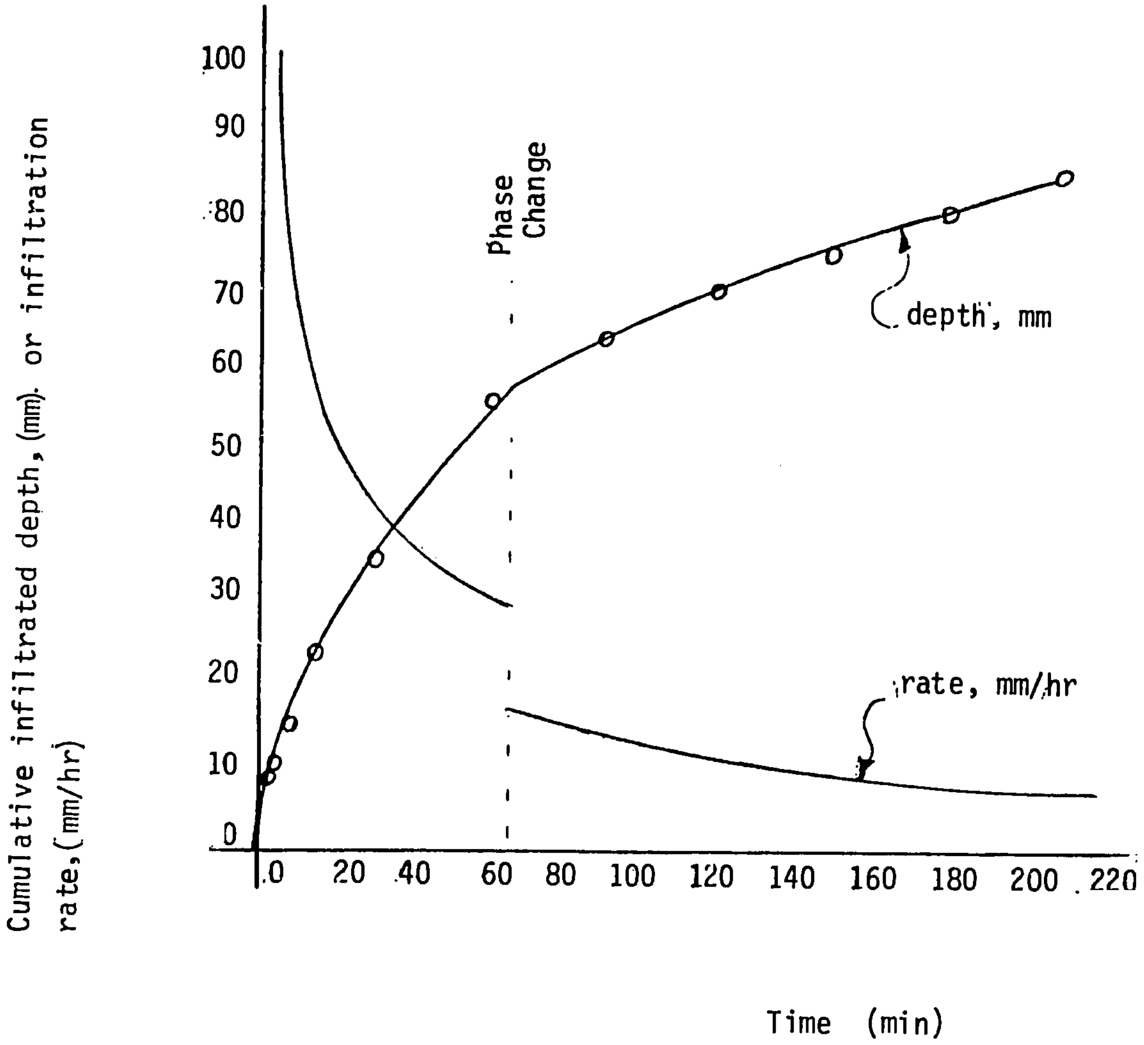

Fig. (2): Cumulative infiltrated depth and infiltration rate as functions of time for a two-phase cylinder infiltration test, rectangular coordinates.

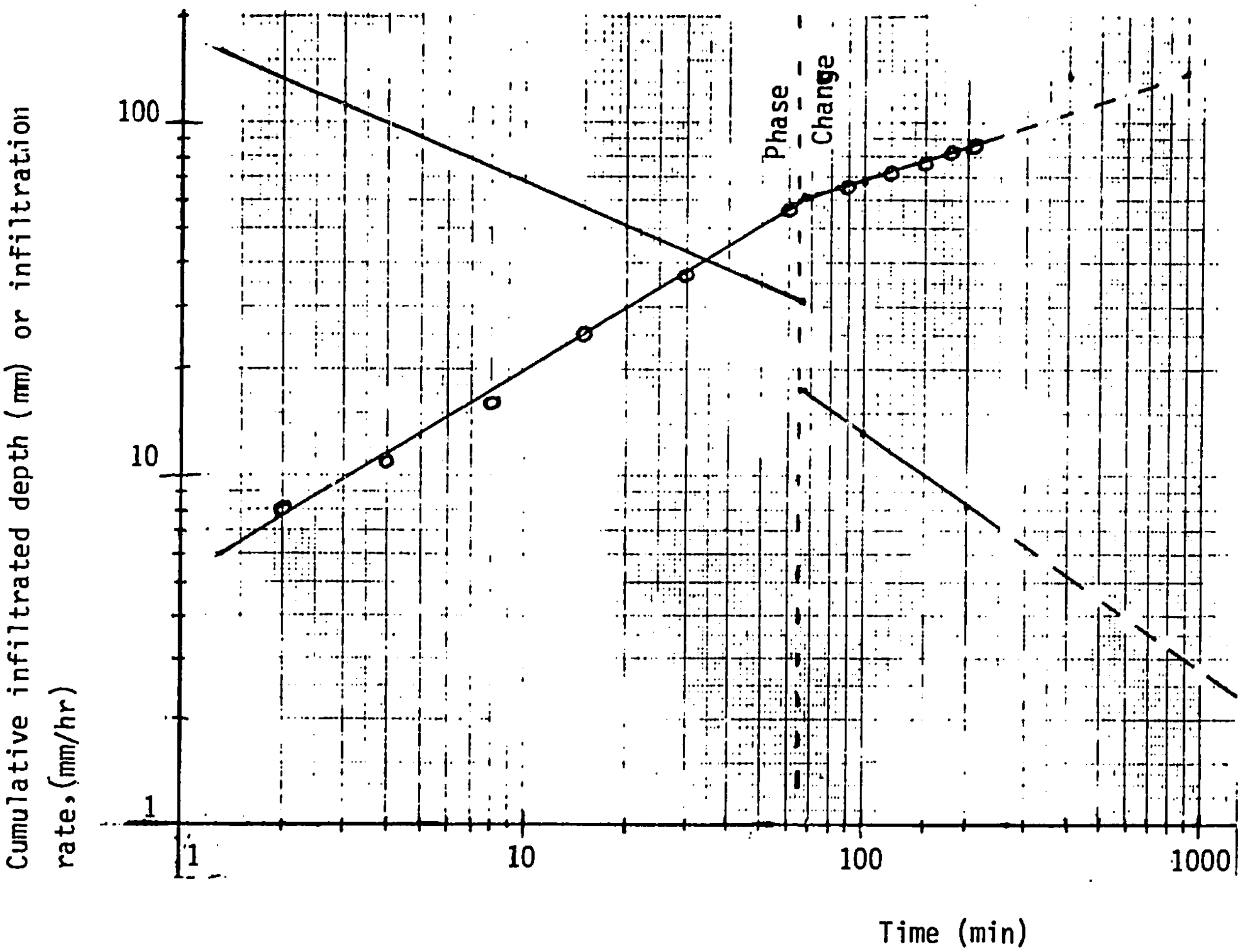

Fig. (3) : Cumulative infiltrated depth and infiltration rate as functions of time for a two-phase cylinder infiltration test, log-log coordinates.

phase change occurs before one hour in most cases and at an infiltrated depth of about 60 mm. During the relatively short period of time represented by the inflection point, a rapid decrease in infiltration rate occurs. Water infiltrated during the second and third hours is much less than the first hour and instantaneous infiltration rates at 1 hour, 2 hours and 3 hours are 16%, 8% and 6% of the average rate during the first phase respectively.

A large variation in the values of the identified parameters was observed suggesting that the various infiltration tests were conducted under field conditions which were variable in time and space. In this study the effects of varying antecedent soil moisture content and macroporosity on the infiltration parameters were examined. The effect of air entrapment which may have occurred due to the flooding of basins over soil with a high water table condition was not quantified. Surface water head and degree of soil tillage were not measured during the infiltration tests and could not be considered in data analysis.

The antecedent soil moisture contents for the infiltration tests are shown in Table A4 for various soil depth ranges. It can be seen that the variation in soil moisture is greatest for the top 100 mm and decreases with depth. The volumetric soil moisture content increases with depth and approaches saturated conditions in the 600-900 mm sampling depth range. The above observations are presented graphically in Figure 4.

Tests 1, 2, 3, 16, 17, and 18 were conducted preceding a second or third irrigation. The mean soil moisture depth for each depth range for these tests is greater than for tests preceding the first irrigation as shown in Table A4. The difference diminishes with depth.

The soil moisture content for an accumulated depth from the soil surface to lower in the profile increases as larger soil depths are considered. Macroporosity is inversely related to soil moisture due to swelling and shrinking effects. Therefore, the continuity of soil cracks decreases with depth in the soil profile.

A series of regression analyses were carried out between volumetric soil moisture content and the infiltration parameters shown in Table A3. The results are presented in Table 1. Significant linear correlations were found between the infiltration parameters A_1, y_f, y_f/t_f x

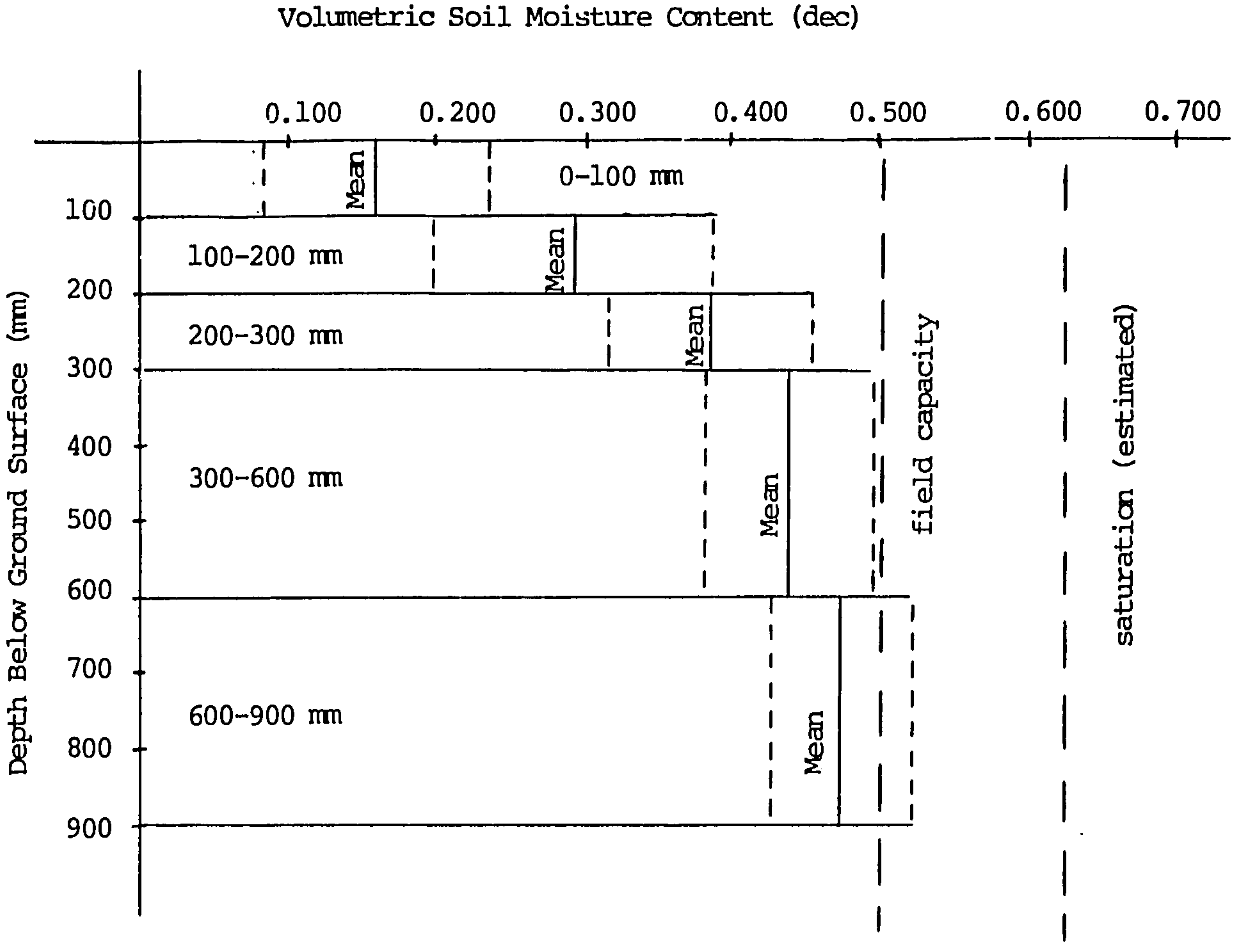

Figure (4): Average antecedent soil moisture conditions for wheat cylinder infiltration tests showing mean and standard deviation from the mean for various depth ranges. (Field capacity and estimation for saturation values taken from unpublished data of A. T. A. Moustafa, M. R. Zanati, and A. Dotzenko).

Table 1. Correlation of antecedant soil moisture with various infiltration data, wheat infiltration tests, Abu Raya, Kafr El-Sheikh, Egypt.

Abscissa[1]	Ordinate	Type of Regression	Degrees of freedom	Correlation		Significance	Regression Parameters[2]	
				r^2	r	P	a	b
$\theta_{V,0-100}$	A_1	Linear	19	0.273	0.523	0.05	23.9	-73.9
$\theta_{V,0-100}^{\ 0.050}$	A_1	Power	19	0.431	0.657	0.01	0.776	-0.982
$\theta_{V,0-200}$	A_1	Linear	19	0.263	0.513	0.05	27.6	-68.0
$\theta_{V,0-200}^{\ -0.100}$	A_1	Power	19	0.310	0.557	0.01	1.84	-0.654
$\theta_{V,0-100}$	B_1	Linear	19	0.097	0.312	NS	0.362	0.527
$\theta_{V,0-200}$	B_1	Linear	19	0.033	0.182	NS	0.380	0.288
$\theta_{V,0-100}$	(B_1-B_2)	Linear	15	0.105	0.325	NS	0.134	1.317
$\theta_{V,0-200}$	(B_1-B_2)	Linear	15	0.093	0.305	NS	0.130	0.905
$\theta_{V,0-100}$	y_f	Linear	15	0.599	0.774	0.001	127	-557
$\theta_{V,0-100}^{\ -0.050}$	y_f	Power	15	0.617	0.785	0.001	2.08	-1.20
$\theta_{V,0-200}$	y_f	Linear	15	0.666	0.816	0.001	155	-488
$\theta_{V,0-200}^{\ -0.100}$	y_f	Power	15	0.505	0.711	0.01	7.25	-0.736
$\theta_{V,0-100}$	y_f/t_fx60	Linear	15	0.419	0.648	0.01	211	-905
$\theta_{V,0-100}^{\ -0.050}$	y_f/t_fx60	Power	15	0.472	0.687	0.01	6.16	-0.951
$\theta_{V,0-200}$	y_f/t_fx60	Linear	15	0.265	0.515	0.05	194	-527
$\theta_{V,0-200}^{\ -0.100}$	y_f/t_fx60	Power	15	0.302	0.550	0.05	19.6	-0.518
$\theta_{V,0-100}$	$y(60)$	Linear	19	0.223	0.472	0.05	82.5	-194
$\theta_{V,0-200}$	$y(60)$	Linear	19	0.375	0.612	0.01	116	-262
$\theta_{V,0-200}$	$y(120)$	Linear	19	0.299	0.546	0.05	127	-267
$\theta_{V,0-200}$	$y(180)$	Linear	19	0.233	0.483	0.05	133	-264

[1] The constants 0.050 and 0.100 which are subtracted from the volumetric soil moisture content for depth ranges 0-100 mm and 0-200 mm, respectively, represente an axis shift which improved the value of the correlation coefficient, r^2.

[2] Linear regression fits the equation $Y = a + b X$. Power regression fits the equation $Y = aX^b$. In either case, X represents the abscissa, Y the ordinate, and a and b are the regression parameters.

60, and the volumetric moisture content of the 0-100 mm and 0-200 mm soil depth ranges. For the cumulative infiltration depths at 1 hour, 2 hours, and 3 hours the most significant correlation was with the moisture content in the top 200 mm of the soil profile. No significant correlation was found between B_1, B_2, or B_1-B_2 and soil moisture content.

As shown in Figure 5 a curvilinear relationship was indicated between A_1 and volumetric moisture content. A power function was fitted to the data in this case and increased the significance of correlation from the 5% to the 1% level. This curvilinear relationship is due to increases in macroporosity with decreases in soil moisture content and supports observations made by Tisdall (1950). Application of the power function to the other correlations yielded less favorable results.

The most significant correlation found, at the 0.1% level, was between the cumulative infiltration depth at the inflection and the volumetric soil moisture content in the 0-200 mm depth range (Fig. 6).

The top 200 mm of soil are considerably drier than the lower profile as shown in table A4 and Figure 4. The sharp transition between the first phase of infiltration and the second phase as shown in Figure 2 compares favorably with jumping from one soil moisture content curve to another as shown in Figure 1. Therefore, the decay of infiltration rate represented by the phase change appears to be due to the wetting front moving from the relatively drier upper layers of soil to the wetter layers below.

It is possible that the progressively weaker correlation between cumulative infiltration depth and antecedant soil moisture as elapsed time increases is due to partial or complete soil sealing in the infiltration cylinder. This sealing may be caused by artificial conditions created by the ring itself (Clemmons, 1981). Swelling of the macropores or air entrapment which occurs during the infiltration process may explain the linear rather than curvilinear relationship between infiltrated depth at the phase change and the antecedent soil moisture content.

Using the single and two phase equations obtained through regression analysis, average time vs. depth curves were calculated for field conditions corresponding to first irrigations of wheat and second and

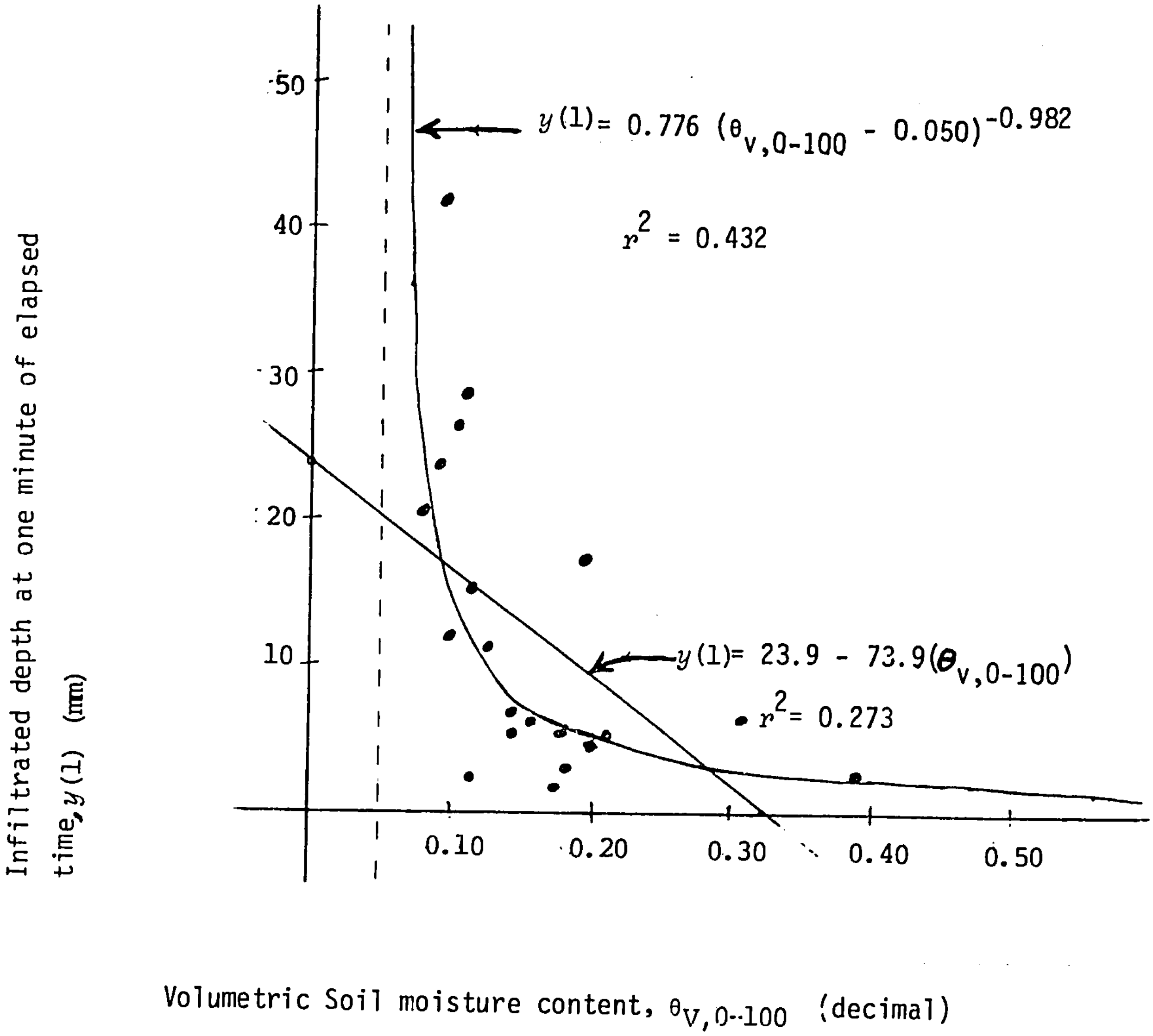

Fig. (5): Power and linear correlation between the antecedant soil moisture in the 0-100 mm soil depth range and the infiltrated depth at one minute of elapsed time.

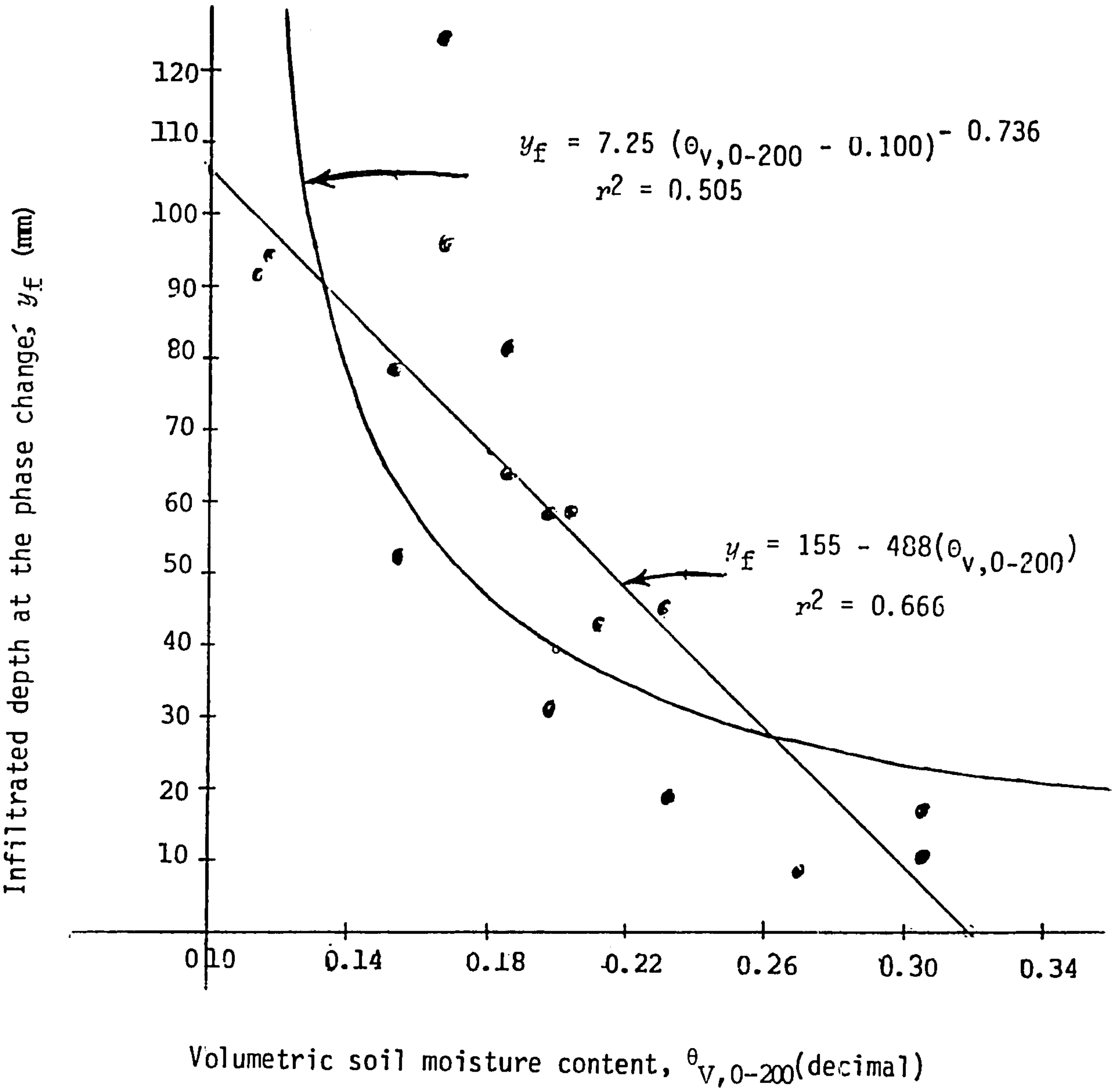

Fig. (6): Power and linear correlation between the antecedent soil moisture content in the 0-200 soil depth range and the infiltrated depth at the phase change.

third irrigations of wheat. A two phase infiltration process was described in each case. The average equations representing conditions during the first irrigation of wheat are:

$$y(t) = 14.5\ t^{0.373} \qquad t \leq 61.10 \tag{10}$$

and

$$y(t) = 32.2\ t^{0.179} \qquad t > 61.10 \tag{11}$$

(The units of $y(t)$ and t are mm and min, respectively). For subsequent irrigations of wheat, the relevant equations are:

$$y(t) = 6.40\ t^{0.441} \qquad t \leq 8.09 \tag{12}$$

and

$$y(t) = 7.21\ t^{0.384} \qquad t > 8.09 \tag{13}$$

Equations (10) and (11) are assumed to accurately describe the infiltration process for typical field conditions during a first irrigation of wheat at Abu Raya. Equations (12) and (13) are assumed to represent subsequent wheat irrigations. The cumulative infiltrated depth at the inflection point determined from the above equations is 67.2 mm for first irrigation conditions and 16.1 mm for subsequent irrigation conditions.

On-Farm Water Management Considerations

The data presented in the previous tables was further analyzed to predict the effect of soil infiltration characteristics on irrigation water management for wheat at Abu Raya. Three water management considerations were indentified for special emphasis:

1. What quality of water distribution uniformity is attainable for Abu Raya conditions?

2. What is the minimum depth of water which can be applied to a wheat field in Abu Raya due to high infiltration rates before the phase change?

3. What is the expected duration of ponding in field depressions due to low long-term infiltration rates?

During irrigation of a level basin by surface methods, water infiltrates into the soil beginning with stations closest to the head of the field as the irrigation stream advances to the tail. Infiltration continues during ponding which follows advance until all water completely recedes from soil surface at all field stations. The total infiltrated depth at a given station in the the field depends on the infiltration opportunity time at that station. The infiltration opportunity time, t_o, is defined as the time interval during which water covers a given location in the field and corresponds to the time, t, in equations (5), (10), (11), (12), and (13).

Data from ten advance-recession tests for irrigations carried out on basin crops at Abu Raya is shown in Table 2. The time of the water advance from the head to the tail of the field ranged from 80 to 230 minutes with an average of 142 minutes. The mean infiltration opportunity time was found to be 220 minutes. For 70% of the tests recession of water from the soil surface was observed to be uniform and was represented by a single time value [Ley, (ed.), 1983a].

Water Distribution Uniformity

Water advance time and soil infiltration characteristics have a direct effect on water distribution uniformity.

For the analysis which follows, the cumulative infiltrated depths at the indicated times, $y(60) = 57$ mm, $y(120) = 67$ mm, and $y(180) = 73$ mm, are average values taken from Table A3. Consider a well-leveled basin which is irrigated by a stream of water advancing from the head to the tail. The depth of water entering the soil at the head and tail of the field, y_{hd} and yt respectively, depend on the opportunity time at each location, t_o, as seen from equation 5. Figure 7 shows the effect of advance time on opportunity times and the resulting infiltrated depths at the head and tail of the field. Recession is assumed to be uniform across the field.

In this analysis, the opportunity time for water to enter the soil at the head of the field is held constant at 180 minutes. Opportunity time at the field tail is numerically equal to the difference between

Table 2. Advance-recession data for irrigation of basin crops at Abu Raya, Kafr El-Sheikh, Egypt.

Advance-recession test number	Crop	Irrigation number	Field length (m)	Advance time t_{adv} (min)	Infiltration Opportunity time, t_o (min)		
					at the head	at the tail	average for the field
1	Wheat	1	90	190	265	75	186
2	Wheat	1	75	230	400	170	301
3	Wheat	1	75	225	315	90	227
4	Wheat	1	45	198	327	129	256
5	Wheat	2	45	98	390	292	342
6	Wheat	2	130	93	375	282	328
7	Broadbeans	1	65	99	369	45	227
8	Broadbeans	2	65	80	85	140	106
9	Wheat	1	75	82	120	50	101
10	Wheat	1	70	125	175	50	122
Mean				142	282	132	220
Standard Deviation,				61	116	92	90
Coefficient of Variation, (%)				43	41	69	41

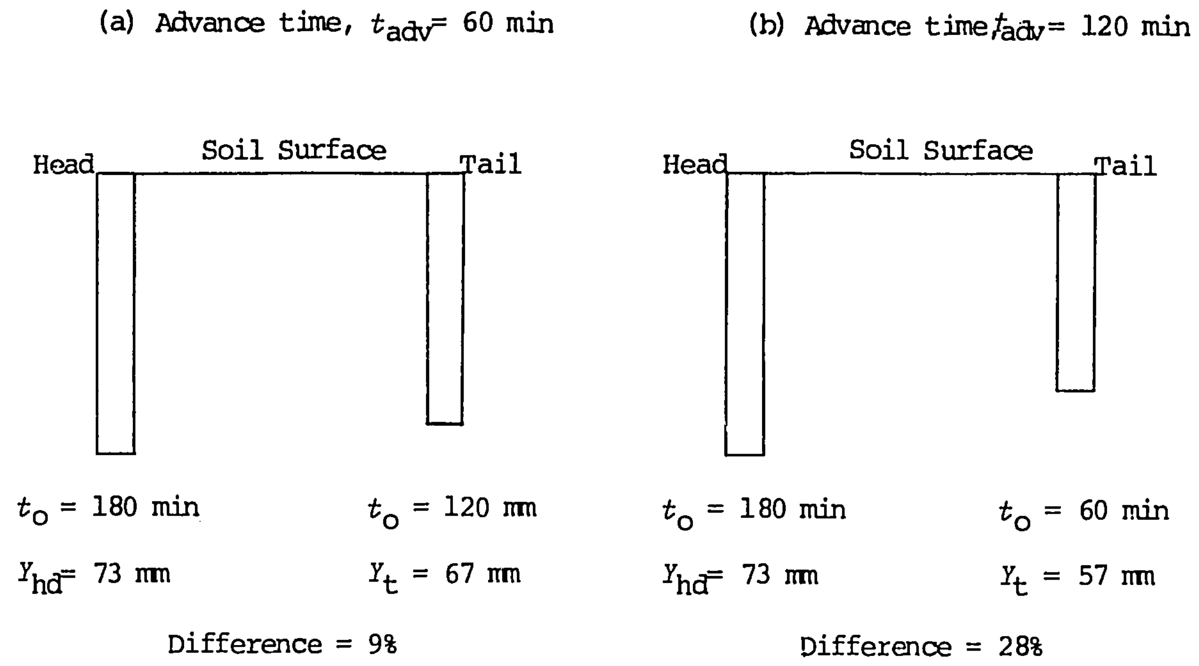

Figure 7. Comparison of infiltrated depths at the head and tail of the field for an intake opportunity time at the head of 180 minutes and advance times of (a) 60 minutes and (b) 120 minutes. (Recession is assumed uniform across the field due to ponding).

180 minutes and the advance time. For an irrigation stream advance time of 60 minutes, y_{hd} = 73 mm, y_t = 67 mm and the difference in infiltrated depth between head and tail is 9%. If the advance time is increased to 120 minutes, y_{hd} = 73 mm, y_t = 57 mm and their difference is increased to 28%. For Abu Raya conditions where a typical advance time can be as great as 142 minutes the difference in water application from head to tail would be greater than 28% for an opportunity time of 180 minutes at the head of the field. Decreasing the advance time by increasing the unit stream inflow could theoretically improve water distribution uniformity for infiltration opportunity times of 180 minutes at the head of the field. Irrigation streams available from animal powered water wheels used to lift water from private canals at Abu Raya tend to be small and variable (Ley, et. al., 1983). Small and variable discharge represents a constraint to improving water distribution efficiency through decreasing advance times.

Figure 8 shows the average advance curve for the ten advance-recession tests shown in Table 2. Field length has been standardized to 100 units with stations every 10 units. Recession of water from the soil surface, represented by the average recession curve at 280 minutes, is considered uniform. The average opportunuity time for the field, the difference between the advance and recession curves, is 220 min.

In the following analyses the average advance curve and average infiltration curves were used to generate infiltrated depth profiles across the field corresponding to increasing irrigation time or application depth. No assumption was made concerning discharge to the field. For Abu Raya conditions, discharge has been shown to vary from irrigation to irrigation, from field to field for a given irrigation, and also with time during the irrigation of a given field [Ley, (ed.), 1983a].

Separate analyses were conducted for infiltration conditions representative of the first irrigation of wheat and subsequent irrigations of wheat as reflected in equations (10) and (11) and equations (12) and (13). Christiansen's Uniformity Coefficient, UC, was used to evaluate water distribution across the field and was defined as:

$$UC = 100\left(1.0 - \frac{\Sigma\,|y-\bar{y}|}{\bar{y}n}\right) \qquad (14)$$

Where

$\bar{y}$ = mean infiltrated depth

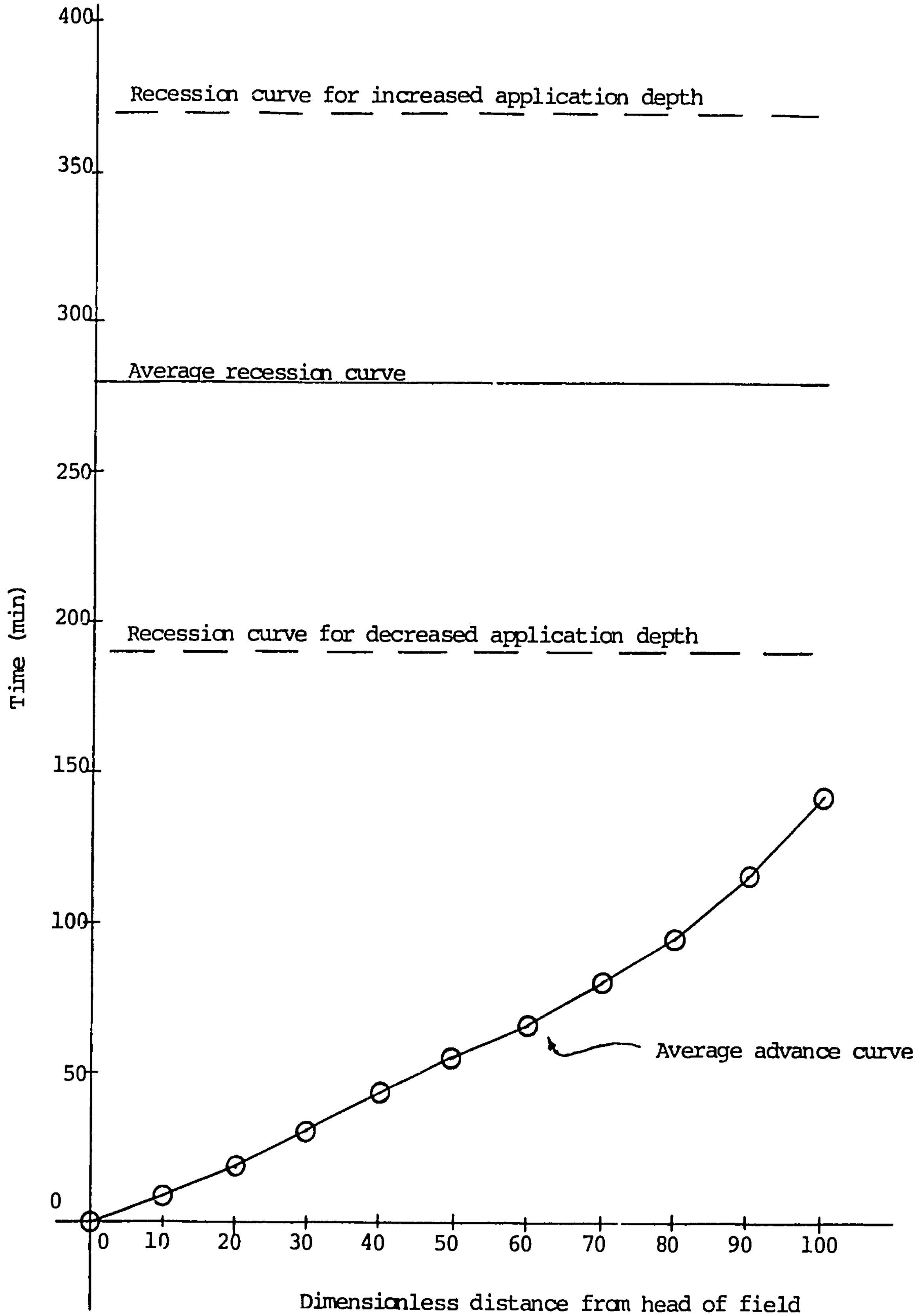

Figure 8. Average advance and recession curves showing effect of increasing and decreasing the application depth, for irrigation of wheat and broadbeans at Abu Raya, Kafr El-Sheikh, Egypt.

y = infiltrated depth at each station
n = number of stations

The above definition was derived from one presented by Jensen (1980). The Christiansen's Uniformity Coefficient evaluates water distribution uniformity by comparing values of mean deviation in infiltrated depth with the mean infiltrated depth. A UC value of near 100 is considered to indicate good uniformity of water distribution.

Table 3 and Figure 9 pertain to the first irrigation of wheat. At time t = 0, water begins to enter the head of a basin of length 100 units. At the indicated times following the beginning of irrigation of the basin, the cumulative infiltrated depth at each station was calculated by subtracting the time of advance to the station from the elapsed time from initiation of irrigation and using equations (10) and (11). The time intervals from t = 0 until t = 142 represent the various times that the advancing front reaches each station. After water reaches the tail of the field time intervals of 20 minutes were used . Values of average infiltrated depth across the field and UC were calculated for each value of time. A family of curves representing profiles of infiltrated depth across the field at the various values of elapsed time is shown in Figure 9.

Farmers at Abu Raya ensure complete coverage of the field during irrigation. The inflow stream is shut off when the advancing water front has reached to the field tail or at later times if larger application depths are desired. At 142 minutes elapsed time, the advancing front reaches the field tail, the mean application depth is 66 mm and the value of UC is 83%. If the inflow stream is shut off at t = 142 minutes then ponding will occur to a depth of about one-half of the inflow depth at the field head assuming a triangular shaped advancing front. Design values for flow depth at the head of the field during the EWUP winter 1981-82 demonstration program ranged from 40 to 80 mm. 1/ The ponding over the field is therefore assumed to be 30 mm. For a mean application depth of 66 mm + 30 mm = 96 mm the value of UC exceeds 97%. The depth infiltrated at the final station exceeds 83 mm and is considered adequate. This application depth of 96 mm corresponds to a recession time exceeding 340 minutes. For the average recession time

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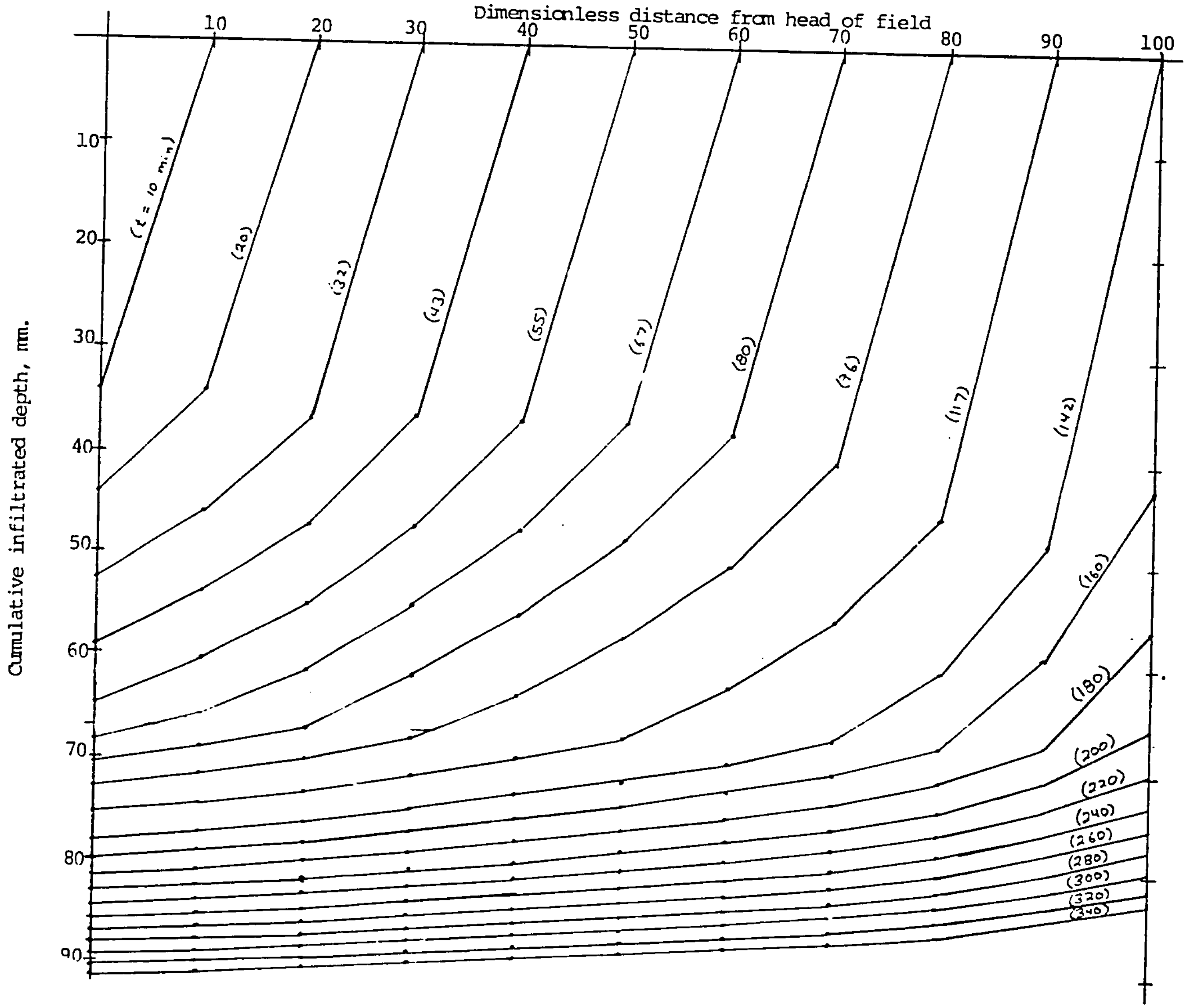
1/ Unpublished data, S. Zaki and S. Fahmy, Kafr El-Sheikh, Egypt, 1982.

Table 3. Profiles of infiltrated depth, mm, across the field for various values of elapsed time, min. Mean infiltrated depth, average deviation from the mean and values for Christiansen's Uniformity Coefficient for the end of each time period are also shown (for first irrigation conditions).

Time (min)	Station (Dim. Length)													
	0	10	20	30	40	50	60	70	80	90	100	Mean	Avg. Dev.	UC 1/
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.8	34.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	3.2	-90.0
19.7	44.1	34.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	9.5	-70.0
31.7	52.6	45.9	36.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	16.3	-50.0
43.4	59.2	53.8	47.2	36.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.7	21.7	-30.0
55.4	64.8	60.3	55.0	47.2	36.6	0.0	0.0	0.0	0.0	0.0	0.0	23.2	25.5	-10.0
67.4	68.4	65.8	61.3	55.0	47.4	36.6	0.0	0.0	0.0	0.0	0.0	30.0	27.0	10.0
80.3	70.6	69.0	67.0	61.7	55.7	48.1	37.6	0.0	0.0	0.0	0.0	37.4	26.2	30.0
95.8	72.9	71.5	69.9	67.8	63.5	57.6	50.5	40.3	0.0	0.0	0.0	45.8	24.0	47.6
117.2	75.5	74.4	73.1	71.4	69.5	67.4	62.3	55.7	45.5	0.0	0.0	55.7	18.8	66.3
142.0	78.2	77.2	76.1	74.7	73.2	71.6	69.7	67.3	60.6	48.0	0.0	65.8	11.2	83.0
160.0	79.9	79.0	78.0	76.8	75.5	74.0	72.4	70.5	67.8	58.9	42.6	71.4	6.3	91.2
180.0	81.6	80.8	79.9	78.8	77.6	76.4	75.0	73.4	71.2	67.6	56.3	75.0	4.4	94.1
200.0	83.1	82.4	81.6	80.6	79.6	78.4	77.2	75.8	74.0	71.0	65.9	77.5	3.6	95.4
220.0	84.6	83.9	83.1	82.2	81.3	80.3	79.2	78.0	76.3	73.8	70.2	79.5	3.1	96.1
240.0	85.9	85.2	84.6	83.7	82.9	81.9	81.0	79.8	78.4	76.2	73.2	81.3	2.8	96.6
260.0	87.1	86.5	85.9	85.1	84.3	83.5	82.6	81.5	80.2	78.3	75.6	82.9	2.6	96.9
280.0	88.3	87.7	87.1	86.4	85.7	84.9	84.0	83.1	81.9	80.1	77.8	84.4	2.3	97.2
300.0	89.4	88.9	88.3	87.6	86.9	86.2	85.4	84.5	83.4	81.8	79.7	85.8	2.2	97.5
320.0	90.4	89.9	89.4	88.7	88.1	87.4	86.7	85.9	84.8	83.3	81.4	87.0	2.0	97.7
340.0	91.4	90.9	90.4	89.8	89.2	88.5	87.9	87.1	86.2	84.7	83.0	88.2	1.9	97.8

1/ Negative values of UC inidicate that the average deviation exceeds the mean infiltrated depth.

Figure 9. Family of curves showing depth infiltrated at field stations from head to tail of the field at time values determined by the average advance curve and at 20 minute intervals after advance of water to the tail of the field. First irrigation conditions.



ot 280 minutes (see Fig. 8), water distribution is also very good (UC = 97.2%). Good distribution uniformity and field coverage can be obtained by shutting off the inflow stream into the border at the time water advances to the tail of the field. In general distribution uniformity improves with increasing application depths.

For first irrigation infiltration conditions, as represented by equations (10) and (11), the phase change occurs at an infiltrated depth of 67.2 mm as shown in Figure 9. Infiltrated depths during the first phase of infiltration are large causing advance time to be large. Deep percolation depths are minimized and distribution uniformity is enhanced by high water table conditions and low long term infiltration rates during the second phase of infiltration.

Table 4 and Figure 10 show a similar analysis for second and third irrigations of wheat at Abu Raya. Similar to first irrigation conditions, high values of UC were found for irrigation times exceeding the advance of water to the tail of the field. Second phase infiltration has a much greater effect than observed in the previous analysis for first irrigation conditions. However, quality of distribution also improves with increases in application depth. At the time the advancing stream reaches the tail of the field the average infiltrated depth is 37 mm and UC = 79%. For a ponded depth of 30 mm (application depth is 67 mm), the recession time exceeds 340 min and the value of UC exceeds 95%. Good coverage at the tail of the field is also obtained (infiltrated depth exceeds 55 mm).

Explanation for the good water distribution attainable at Abu Raya despite long advance times involves the two-phase infiltration process described earlier. Water advances slowly to the tail of the field due to small inflow streams and the high infiltration rates active during the first phase of infiltration. However, following water advance to the tail, the resulting ponding of water on the soil surface and low long-term infiltration rates during the second phase of infiltration facilitate high values of UC such as found in Tables 3 and 4. Good water distribution and field coverage can be obtained by shutting off the inflow stream when the advancing front reaches the tail of the field.

Minimum Application Depth

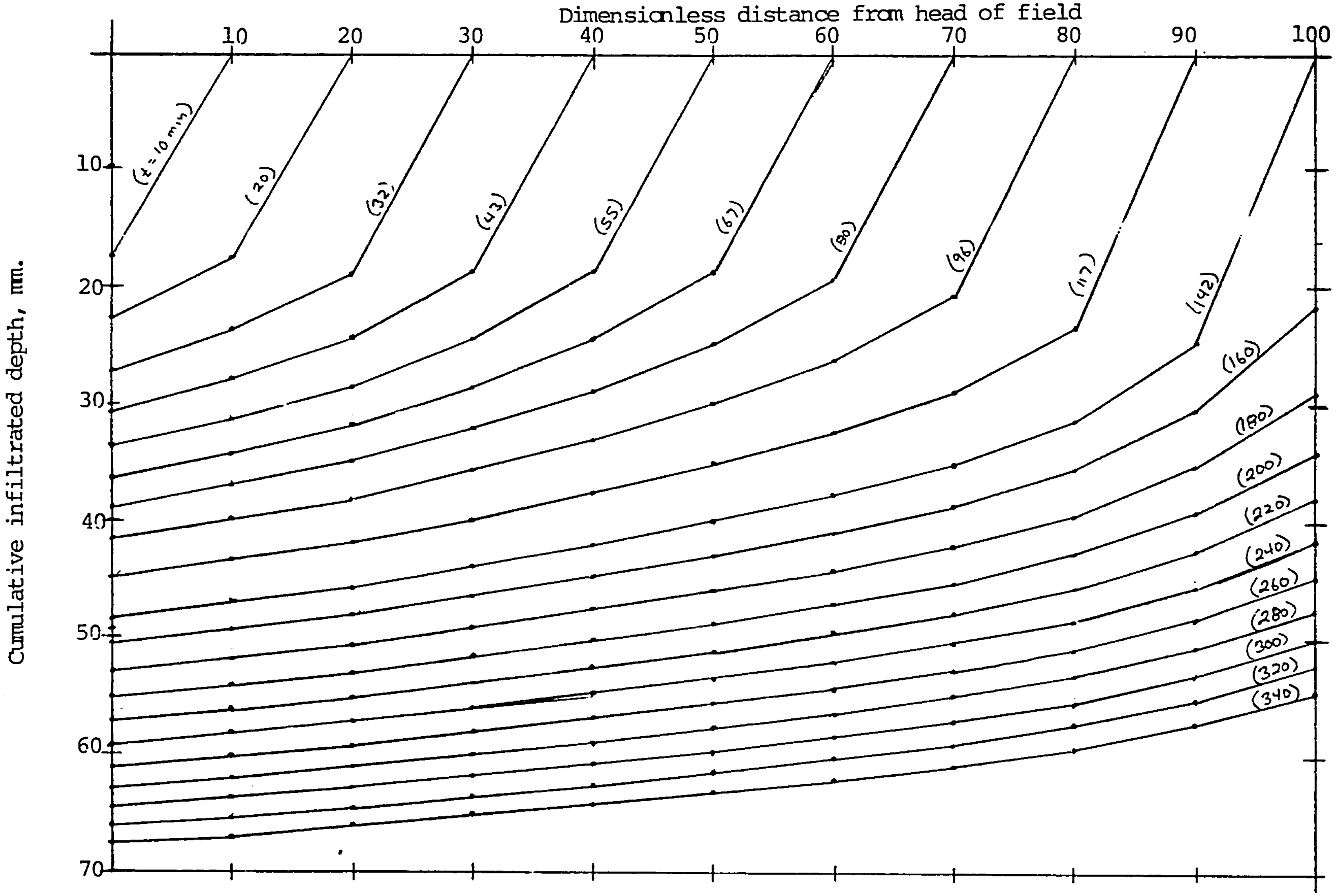
The second water management consideration concerning minimum applica-

Table 4. Profiles of infiltrated depth across the field for various values of elapsed time. Mean infiltrated depth, average deviation from the mean and values for Christiansen's Uniformity Cofficient for the end of each time period are also shown (for second and third irrigation conditions)

Time (min)	Station (Dim. Length)													
	0	10	20	30	40	50	60	70	80	90	100	Mean	Avg. Dev.	UC 1/
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9.8	17.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.6	-90.0
19.7	22.6	17.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	4.9	-70.0
31.7	27.2	23.6	18.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	8.4	-50.0
43.4	30.7	27.8	24.3	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6	11.2	-30.0
55.4	33.7	31.3	28.5	24.3	18.7	0.0	0.0	0.0	0.0	0.0	0.0	12.0	13.2	-10.0
67.4	36.3	34.2	31.8	28.5	24.4	18.7	0.0	0.0	0.0	0.0	0.0	15.6	14.0	10.0
80.3	38.8	37.0	34.9	32.0	28.8	24.8	19.2	0.0	0.0	0.0	0.0	19.6	13.8	29.6
95.8	41.6	39.9	38.1	35.6	33.0	29.8	26.1	20.7	0.0	0.0	0.0	24.4	12.9	46.9
117.2	44.9	43.4	41.9	39.8	37.6	35.1	32.3	28.8	23.4	0.0	0.0	30.5	10.9	64.2
142.0	48.4	47.0	45.7	43.9	42.0	40.0	37.8	35.1	31.4	24.7	0.0	37.2	7.8	79.1
160.0	50.6	49.4	48.1	46.5	44.8	43.0	41.0	38.7	35.6	30.5	21.9	41.4	5.9	85.8
180.0	53.0	51.8	50.7	49.2	47.6	46.0	44.2	42.2	39.6	35.3	29.1	44.8	5.1	88.6
200.0	55.1	54.1	53.0	51.6	50.2	48.7	47.1	45.3	42.9	39.3	34.3	47.7	4.6	90.4
220.0	57.2	56.2	55.2	53.9	52.6	51.2	49.7	48.0	45.9	42.7	38.4	50.3	4.2	91.7
240.0	59.1	58.2	57.2	56.0	54.8	53.5	52.1	50.6	48.6	45.7	41.9	52.7	3.9	92.7
260.0	61.0	60.1	59.2	58.0	56.9	55.6	54.4	52.9	51.1	48.5	45.0	55.0	3.6	93.5
280.0	62.8	61.9	61.0	59.9	58.8	57.7	56.5	55.1	53.4	51.0	47.8	57.1	3.4	94.1
300.0	64.4	63.6	62.8	61.7	60.7	59.6	58.4	57.2	55.6	53.3	50.4	59.0	3.2	94.6
320.0	66.1	65.3	64.5	63.5	62.5	61.4	60.3	59.1	57.6	55.4	52.7	60.9	3.0	95.0
340.0	67.6	66.9	66.1	65.1	64.2	63.1	62.1	61.0	59.5	57.5	54.9	62.7	2.9	95.4

1/ Same note as for Table 3.

Figure 10. Family of curves showing depth infiltrated at field stations from head to tail of the field at time values determined by the average advance curve and at 20 minute intervals after advance of water to the tail of the field Second and third irrigation conditions.



tion was also analyzed by using average advance-recession and infiltration characteristics for Abu Raya conditions. (Fig. 8 and Equations 10 through 13).

For purposes of the following discussion the end of the infiltration tests will be assumed to be 220 minutes, the average opportunity time from Table 2. The total infiltrated depth which occurs during an infiltration test is represented by $y(220)$. The ratio $y_f/y(220)$ represents the fraction of the total infiltrated depth which occurs during the first phase of infiltration. Table A5 shows values of $y(220)$, y_f, and $y_f/y(220)$ for the 21 cylinder infiltration tests. On the average, the portion of the total infiltrated depth which during the first phase is 75%. The mean depth infiltrated at the phase change, y_f, was 64 mm for first irrigation conditions and 34 mm for subsequent irrigation conditions. These depth values correspond well with the average infiltrated depths at the time (142 min) when water advances to the tail of the field as shown in Tables 3 and 4 (66 mm for the first irrigation and 37 mm for subsequent irrigations). The depth infiltrated during the first phase was used as a lower bound for the minimum depth which can be applied to a field under current Abu Raya conditions. The actual minimum depth would probably be somewhat higher since the ponded depth following water advance has been neglected in this analysis. However, it is reasonable to assume that not less than the first phase infiltration depth can be applied given prevailing Abu Raya conditions.

Infiltrated depth as measured by cylinders was compared with soil moisture data. Soil moisture depths (mm) for samples taken 3 to 6 days following irrigations corresponding to infiltration tests are shown in Table A6. The total depth of water in the soil profile from 0 to 900 mm following irrigation is also shown along with the corresponding value from samples taken before irrigation. The difference between the after irrigation soil moisture and the before irrigation soil moisture represents the depth of water stored during the irrigation, y_s. This value may actually underestimate the water stored due to evapotranspiration effects. For the first irrigation of wheat consumptive use by plants is insignificant immediately following irrigation and the value of water stored as determined by soil sampling is considered to be an acceptable estimate.

In conditions of high water table (representing a non-leaky infiltration system), the infiltration rate can be considered as a water storage rate and the cumulative infiltration as a depth of water stored in the soil profile (Dixon, 1976). Since average water table depth at Abu Raya is less than 900 mm below the soil surface, it is considered reasonable to use the soil profile from 0-900 mm as a finite storage space which is filled by the infiltration process. Deep percolation of water below 900 mm is considered negligible and the depth infiltrated during an irrigation, $y(220)$, is theoretically numerically equal to the depth stored in the soil profile, y_s.

Returning to Table A5 with the values of y_s found in Table A6, the ratio $y(220)/y_s$ was calculated for each test to contrast infiltrated depth as measured with cylinder infiltrometers to depth stored as determined by soil sampling. The average value of this ratio, 69%, agrees well with other estimates of underestimation of infiltration by cylinder infiltrometers as presented above.

The ratio $y(220)/y_s$ for each of the 21 tests was used as a correction factor to adjust the depth of water infiltrated at the phase change. For tests conducted during the first irrigation of wheat, the mean infiltrated depth at the phase change was 119 mm. For tests conducted during second and third irrigations an average of 52 mm was found. These values are considered to be lower bounds for the depth of water which can be applied to the field using current Abu Raya irrigation methods.

Ponding Duration in Field Depressions

Excessively long duration of water ponding in field depressions must be considered by irrigators under conditions of low long term infiltration rates as in Abu Raya. Inundation of crops for extended periods of time causes crop damage and yield reduction. Ponding duration is affected by field levelness. In the previous discussion concerning distribution uniformity from head to tail, the irrigated basin was assumed to be well levelled. Actual conditions may deviate from this assumption. As shown in Table A7, field elevations, as measured on selected fields in Abu Raya, show a range of 130 mm in field elevation. In many cases high and low spots are at the head or tail of the field so that a realistic estimate for maximum field depressions is 80 mm. Fields levelled by the EWUP Kafr El-Sheikh team were brought within a levelness tolerance of ± 20 mm or a range of 40 mm. The levelling process used tried to avoid reverse slopes from the head of the field to the tail so that field depressions were 20 mm as a maximum or eliminated altogether.

Consider a field depression of uniform depth located at the head of the field. Infiltration into the depression begins at time $t = 0$ when water is first applied to the field. When the inflow stream into the basin is shut off the infiltration opportunity time in the depression is equal to t_a the time of application, the infiltrated depth is $y(t_a)$ and the infiltration rate is $f(t_a)$. For field depressions downstream from the head the infiltration opportunity time will be less than t_a by the magnitude of the advance time to the downstream depression. Consequently infiltrated depth will be less than $y(t_a)$ and infiltration rate greater than $f(t_a)$ for downstream depressions at the time of shutoff of the inflow stream, t_a. Infiltration rates in the field depression at the head would continue to be less than in downstream field depressions throughout ponding. Therefore, the depression at the field head represents the worst case for excessive ponding times.

In order for the irrigation stream to advance past the field depression, the depth of water covering the depression bed must be in excess of the depression depth. The equation describing infiltration of water in a field depression at the head of the field as derived in Appendix B is:

$$y(t_a) + \Delta y_1 + h \times \Delta y_2 = y(t_p \times 60 \times 24) + E \times [t_p - t_a/(60 \times 24)] \qquad (15)$$

Where

t_a = elapsed time corresponding to completion of water application to the field, min,
$y(t_o)$= cumulative infiltrated depth at time t_o, mm,
Δy_1 = depth of the field depression, mm,
Δy_2 = flow depth over top of field depression at time t_a, mm,
h = the fraction of Δy_2 which infiltrates into the field depression,
t_p = total time of ponding in the field depression, days,
E = evaporation rate from a free water surface, mm/day,

The time of application t_a is taken to be equal to the advance time, t_v, as indicated by previous analyses and observations in this paper. Both advance time, t_a, and ponding time, t_p, are assumed to exceed the inflection time, t_f, so that infiltration follows second phase characteristics and

$$y(t_o) = A_2\ t_o^{B_2} \tag{16}$$

Combining equations 15 and 16 and substituting t_v for t_a:

$$A_2(t_v)^{B_2} + \Delta y_1 + h\ \text{x} \Delta y_2 = A_2\ (t_p \text{ x } 60 \text{ x } 24)^{B_2} + \text{E x } [t_p - t_v/(60 \text{ x } 24)] \tag{17}$$

Evaporation rates from a free water surface at Kafr El-Sheikh as measured by class A pan for three years have been found to be 2.2 mm/day, 2.4 mm/day, and 2.4 mm/day for December, January, and February respectively. 1/ For this analysis a value of 2.2 mm/day was selected for E. A trial and error solution was conducted for t_p from equation (17) based on values of t_v of 71 min, 142 min, and 213 min and values of Δy_1 of 20 mm, 40 mm, and 80 mm. The component of h x Δy_2 was considered to be negligible or to be included in Δy_1. Results of the above analysis are presented in Table 5. For ponding durations less than three days evaporation is a negligible component of water recession in field depressions. In cases of soil sealing ($B_2 = o$) recession is completely due to evaporation from the free water surface.

The data displayed in Table 5 show that ponding duration increases with advance time and depression depth. The length of ponding which leads to crop damage depends on the crop, crop stage, and climatic conditions. In the following discussion the maximum allowable ponding duration will be assumed to be one day. Combinations of infiltration characteristics, advance time, and depression depth which result in ponding durations exceeding one day will be referred to as critical cases.

The maximum number of critical cases (16 out of 21) is observed for the maximum advance time of 213 min and the maximum depression depth

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1/ Unpublished data, M. Awad, A. Ismail, M. Said, and M. Meleha, Kafr El-Sheikh, Egypt, 1980-1983.

Table 5. Estimated time in days for water to recede in a field depression of 20 mm, 40 mm, or 80 mm depth for water stream advance times of 71 min, 142 min, and 213 min.

Test	Advance time (min)								
	71			142			213		
	Depression depth (mm)								
	20	40	80	20	40	80	20	40	80
1	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
2	3.3	9.9	25.8	3.8	10.6	26.5	4.0	11.0	26.9
3	2.1	7.4	21.9	2.5	8.2	22.9	2.8	8.7	23.4
4	2.9	9.8	26.3	3.6	10.7	27.2	3.9	11.2	27.7
5	0.4	1.2	5.9	0.5	1.7	6.8	0.7	2.0	7.4
6	0.4	1.3	5.9	0.6	1.7	6.8	0.7	2.0	7.4
7	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
8	0.3	1.1	5.9	0.5	1.6	7.1	0.7	2.0	8.0
9	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
10	0.1	0.2	0.6	0.2	0.4	0.9	0.3	0.5	1.1
11	0.1	0.2	0.3	0.2	0.2	0.5	0.2	0.3	0.6
12	0.1	0.2	0.9	0.2	0.4	1.3	0.3	0.6	1.7
13	0.1	0.2	0.4	0.2	0.3	0.6	0.2	0.4	0.8
14	0.1	0.2	0.6	0.2	0.3	0.9	0.3	0.5	1.1
15	0.1	0.2	0.6	0.2	0.3	0.8	0.3	0.4	1.1
16	0.1	0.1	0.2	0.1	0.2	0.3	0.2	0.3	0.4
17	0.1	0.2	0.3	0.2	0.2	0.4	0.2	0.3	0.5
18	0.1	0.3	0.6	0.2	0.3	0.7	0.3	0.4	0.8
19	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
20	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
21	9.1	18.2	36.4	9.1	18.2	36.4	9.1	18.2	36.4
No. exceeding one day	9	12	12	9	12	13	9	12	16

of 80 mm. Decreasing the advance time to 142 min for the same depression depth reduces the number of critical tests to 13. Further decreasing the advance time to 71 min further reduces the critical cases to 12. As shown in Table 2, 142 min is a typical advance time for Abu Raya conditions. Further decreasing the advance time may be physically constrained by high initial infiltration rates and by the small and variable irrigation streams available on Abu Raya farms. Further discussion will center on a constant advance time of 142 min with a varying field depression depth.

For a field depression of 20 mm, in 9 cases out of 21 inundation time exceeds one day, indicating a hazard to crops. For a 40 mm depression depth, the critical tests increase to 12 and for a 80 mm depression to 13. Therefore, for a field depresion of 80 mm, 62% of the infiltration tests predict that the inundation time may exceed one day.

From the above analysis, it is clear that low long-term infiltration rates are an essential on-farm water management consideration. Water standing in field depressions may require several days to recede or evaporate which could cause crop damage. To minimize yield reduction due to inundation, provision for surface drainage may be necessary. Precision land leveling will help minimize the problem of excessively long pounding of water in field depressions.

VI. SUMMARY AND CONCLUSIONS

An infiltration study was conducted on clay soils of the Vertisol order at the Abu Raya, Kafr El-Sheikh field site of the Egypt Water Use and Management Project. The purpose of the study was to define the general infiltration process for system design and management considerations. Twenty-one cylinder infiltration tests were conducted during seven irrigations on fields planted to wheat. Fifteen of the tests described infiltration during the first irrigation, while six were for second and third irrigations. Data analysis revealed that for 81% of the tests infiltration proceeded in two phases as indicated by two line segments with distinctly different slopes for the plot of cumulative infiltrated depth vs. time on log-log paper. Regression parameters for the Kostiakov equation were determined for each phase and an inflection point representing the phase change was obtained by solving simultaneous equations. Cumulative infiltrated depths and instantaneous infiltration rates at hourly intervals were calculated for each infiltration test. Wide variation in infiltration parameter values for the cylinder tests was observed. Various infiltration parameters were tested for their dependence on antecedent soil moisture.

Important water management considerations which are dependent on infiltration characteristics were identified. These included water distribution uniformity, minimum application depth, and excessively long ponding durations in field depressions.

The effect of inflow stream size and advance time on water distribution uniformity was examined. An average advance curve for Abu Raya conditions was used to generate profiles of infiltrated depth across the field and values of Christiansen's Uniformity Coefficient (UC) for various values of elapsed time. Lower bounds for the minimum possible application depth under Abu Raya conditions were estimated by adjusting the depth infiltrated at the phase change by a soil water volume balance method. Finally, ponding duration hazard was examined by calculating the recession time in days for various field depression depths and irrigation stream advance times. Recession components of infiltration and evaporation from a free water surface were considered.

The following conclusions were drawn from the above study:

1. Infiltration preceded form high initial rates to low long term rates. An average value of 720 mm/hr was found for the infiltration rate during the first minute. The instantaneous infiltration rate at two hours of elapsed time was 7.2 mm/hr. Soil sealing or rates too small to be measured occurred in 24% of the infiltration tests conducted.

2. For tests where a two-phase infiltration process was observed, the phase change occurred before one hour in most cases. The average depth infiltration at the phase change was 58 mm. The first phase represented a period of high infiltration rates with 89 mm/hr considered to be a typical value for average infiltration rate before the phase change. Instantaneous infiltration rates at one hour, two hours, and three hours of elapsed time were 16%, 8%, and 6% of the first phase value respectively. On the average, 75% of the total infiltrated depth during an irrigation occurs during the first phase of infiltration.

3. Regressions of several irrigation parameters against antecedent soil moisture showed significant correlations. For the regression involving infiltrated depth at one minute versus antecedent soil moisture content in the 0-100 mm soil depth range, a curvilinear relationship resulted in higher significance than a linear fit. This result was attributed to increases in macroporosity with decreasing soil moisture content. Soil cracking significantly increased initial infiltration rates.

4. The highest correlation between infiltration data and soil moisture status was found between the cumulative infiltrated depth at the phase change and the antecedent soil moisture in the top 200 mm of the soil profile. From this result the first phase of infiltration was considered to represent multidimensional flow of water from cracks into soil pores in the relatively drier upper layers of the soil profile. Second phase infiltration represents subsequent vertical movement of water into lower, wetter soil layers. The entire infiltration process could be described as filling of a finite storage space above a high water table.

5. Comparison of infiltrated depth as measured with cylinders during irrigation with storage depths measured by soil sampling indicated that the cylinders underestimated infiltration. The ratio of

estimated infiltration depth to actual was 69% which agrees well with previous work by volume balance methods.

6. Water distribution uniformity across an irrigated basin can theoretically be improved by decreasing advance time through increasing inflow stream size. Available discharges currently available at Abu Raya are small and variable.

7. Given prevailing Abu Raya conditions of infiltration rate and available stream size, good water distribution uniformity and complete field coverage can be obtained by shutting off the inflow stream when the advancing water front reaches the tail of the field. At the time of completion of advance, UC = 83% (first irrigation conditions) and improves with time during recession of the ponded depth on the soil surface. Low long-term infiltration rates and high water table conditions at Abu Raya facilitate good water table distribution and minimize deep percolation losses.

8. A lower bound for the depth of water which can be applied during the first irrigation of wheat at Abu Raya is 120 mm. For subsequent irrigations, a corresponding value is 52 mm. The larger value for the first irrigation is due to low antecedent soil moisture resulting in extensive macro porosity and high initial infiltration rates. The exact minimum possible application depths will be somewhat larger than the above values.

9. Due to the low infiltration rates during the second phase for Abu Raya conditions, inundation presents a threat to crop production. The depth of field depressions and the time of advance of the irrigation stream across the field have a direct effect on inundation time. For a field depression depth of 80 mm at the head of the field and a water advance time of 142 minutes, in 62% of the cases represented by the 21 infiltration tests, water ponding duration exceeded one day. This ponding duration can be decreased by reducing the advance time or by decreasing depression depth. Precision land leveling and/or provision for surface drainage are required to prevent crop damage due to prolonged ponding of water in field depressions.

VIII. RECOMMENDATIONS

Assuming that prevailing irrigation conditions will continue (dead level basin irrigation method and presently available stream sizes) and based on the results and conclusions of the present study, the following recommendations are made concerning irrigation water management at Abu Raya, Egypt:

1. Desirable water distribution results can be obtained by discontinuing water application to an irrigated basin after the advancing stream reaches the tail of the basin. Advance time should be minimized by using as large a unit stream size as possible under the constraints imposed by available discharge to the farm and field layout considerations.

2. The design application depth for the first irrigation of wheat should be at least 120 mm. This irrigation should be considered to be the filling of the soil reservoir from 0 to 900 mm. Appropriate water delivery system design and operation decisions should be made to ensure adequate supply of water to meet the demand placed on the system for this heavy first irrigation. Further irrigations can be assumed to require about one half of the design depth stated above.

3. Precision land leveling is strongly recommended to minimize crop damage due to prolonged ponding in field depressions. The tolerance for differences in elevation across the field should be no more than ± 20 mm and preferably as low as ± 10 mm. All reverse slopes in the field must be eliminated. Even in the case of well-leveled land, some provision must be made for surface drainage. The best method for draining surface water from farmers' fields while maximizing cropped area should be determined.

In addition to the above recommendations concerning irrigation water management at Abu Raya, the following recommendations are presented for further study:

1. Further cylinder infiltration tests should be carried out for the wheat crop to reinforce or modify conclusions drawn from the present study. A volume balance procedure should be used to adjust

equations obtained from infiltrometer data. Particular attention should be given to temporal changes in infiltration characteristics especially between the first irrigation and subsequent irrigations.

2. Similar studies should be carried out on the other basin crops grown at Abu Raya.

3. Infiltration studies should be implemented and reported for furrow crops at Abu Raya. In particular the effect of dimensionality of the infiltration process should be studied. One of the primary goals of the study would be to explore the effect of furrow infiltration characteristics on on-farm water management.

4. The subject of deep percolation under Abu Raya conditions should receive further attention. The root zone at each stage of crop growth must be determined. The interaction of the root zone and the water table could be studied to broaden understanding concerning water table contribution to consumptive use and effect of overirrigation on water table levels. Water table data should be combined with advance-recession and infiltration data to explore the meaning of application efficiency under Abu Raya conditions. Values of attainable application efficiency could be determined.

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APPENDIX A

Table A1. Adjustment of single phase Kostiakov infiltration equation to account for underestimation of infiltration by cylinder tests at Abu Raya, Kafr El-Sheikh, Egypt.

Test[1/]	A (mm)	B (dim.)	Adjusted Constant A' (mm)	A/A'
1	4.5	0.48	14.9	0.302
2	12.0	0.47	15.2	0.789
3	24.5	0.24	31.0	0.790
4	10.9	0.30	26.5	0.411
			Mean	0.570

[1/] The test numbers presented in this table do not correspond to wheat cylinder infiltration test numbers presented elsewhere in this report.

Table A2. General information, regression coefficients, and inflection points for cylinder tests on wheat, Abu Raya, Kafr El-Sheikh, Egypt.

Test	Field 1/	Date	Irrigation number	Phase	Regression coefficient values for the Kostiakov-Lewis equation			Inflection Point Information	
					A(mm/min^B)	B(dim.)	r^2	Time (min)	Depth (mm)
1	3-02-02(H)	14 Jan 81	2	1	5.01	0.447	0.998	15.4	17.0
				2	17.00	0.000	1.000		
2	3-02-02(M)	14 Jan 81	2	1	2.95	0.476	0.998	8.2	8.0
				2	5.56	0.175	0.999		
3	3-02-02(T)	14 Jan 81	2	1	4.65	0.377	0.997	24.2	15.5
				2	9.17	0.164	0.999		
4	3-21-1 (H)	5 Dec 80	1	1	26.31	0.295	0.998	14.8	58.3
				2	51.21	0.048	0.919		
5	3-21-1 (M)	5 Dec 80	1	1	11.25	0.240	0.984	None	None
6	3-21-1 (T)	5 Dec 80	1	1	6.14	0.428	0.983	13.3	18.6
				2	9.66	0.253	0.988		
7	3-10 (H)	6 Dec 80	1	1	41.89	0.207	0.947	54.9	96.0
				2	96.00	0.000	1.000		
8	3-10 (M)	6 Dec 80	1	1	15.14	0.324	0.991	46.6	52.5
				2	27.97	0.164	0.987		
9	3-10 (T)	6 Dec 80	1	1	11.82	0.442	0.998	45.7	64.0
				2	64.00	0.000	1.000		
10	3-22 (H)	9 Dec 80	1	1	5.03	0.587	0.997	65.7	58.7
				2	15.12	0.324	0.999		
11	3-22 (M)	9 Dec 80	1	1	6.62	0.616	0.998	58.7	81.3
				2	20.70	0.336	0.999		
12	3-22 (T)	9 Dec 80	1	1	28.50	0.369	0.997	54.4	124.5
				2	64.40	0.165	0.982		
13	3-10 (H)	27 Nov 81	1	1	12.20	0.493	0.984	43.5	78.4
				2	25.95	0.293	0.981		
14	3-10 (M)	27 Nov 81	1	1	23.67	0.376	0.997	39.5	94.3
				2	42.00	0.220	0.987		
15	3-10 (T)	27 Nov 81	1	1	20.57	0.431	0.978	32.1	91.7
				2	42.33	0.223	0.998		
16	3-10 (H)	18 Mar 82	3	1	17.07	0.403	0.993	None	None
17	3-10 (M)	18 Mar 82	3	1	6.39	0.493	0.996	None	None
18	3-10 (T)	18 Mar 82	3	1	2.50	0.555	0.998	None	None
19	3-26-2 (H)	23 Nov 81	1	1	1.44	0.671	0.950	97.0	31.0
				2	31.00	0.000	1.000		
20	3-26-2 (M)	23 Nov 81	1	1	2.11	0.680	0.986	84.2	43.0
				2	43.00	0.000	1.000		
21	3-26-2 (T)	23 Nov 81	1	1	5.37	0.440	0.987	125.4	45.0
				2	45.00	0.000	1.000		

1/ Field code refers to EWUP site, *caqia* unit, and farm. H, M, and T refer to head, middle and tail of the field, respectively.

Table A3. Infiltration parameters, cumulative infiltration depths, and infiltration rates for wheat cylinder infiltration tests, Abu Raya, Kafr El-Sheikh, Egypt.

Test	A_1	B_1	B_2	(B_1-B_2)	t_f (min)	y_f (mm)	y_f/t_fx60 (mm/hr)	$y(60)$ (mm)	$y(120)$ (mm)	$y(180)$ (mm)	$f(60)$ (mm/hr)	$f(120)$ (mm/hr)	$f(180)$ (mm/hr)
1	5.01	0.447	0.000	0.447	15.4	17.0	66.3	17.0	17.0	17.0	0.00	0.00	0.00
2	2.95	0.476	0.175	0.301	8.2	8.0	58.8	11.4	12.8	13.8	1.99	1.12	0.8
3	4.65	0.377	0.164	0.213	24.2	15.5	38.3	18.0	20.1	21.5	2.94	1.65	1.18
4	26.31	0.295	0.048	0.247	14.8	58.3	235.7	62.4	64.5	65.7	3.00	1.55	1.05
5	11.25	0.240	0.240	0.000	-	-	-	30.0	35.5	39.1	7.21	4.26	3.13
6	6.14	0.428	0.253	0.175	13.3	18.6	83.8	27.2	32.4	35.9	6.89	4.10	3.03
7	41.89	0.207	0.000	0.207	54.9	96.0	104.8	96.0	96.0	96.0	0.00	0.00	0.00
8	15.14	0.324	0.164	0.160	46.4	52.5	67.9	54.7	61.3	65.6	8.98	5.03	3.58
9	11.82	0.442	0.000	0.442	45.7	64.0	84.1	64.0	64.0	64.0	0.00	0.00	0.00
10	5.03	0.587	0.324	0.263	65.7	58.7	53.6	55.6	71.3	81.3	32.7	11.6	8.78
11	6.62	0.616	0.336	0.280	58.6	81.3	83.2	81.9	103.4	118.5	27.5	17.4	13.2
12	28.50	0.369	0.165	0.204	54.4	124.5	137.4	126.6	142.0	151.7	20.9	11.7	8.3
13	12.20	0.493	0.293	0.200	43.5	78.4	108.0	86.1	106.0	118.8	25.2	15.5	11.6
14	23.67	0.376	0.220	0.156	39.5	94.2	143.3	103.4	120.0	131.6	22.7	13.2	9.6
15	20.57	0.431	0.223	0.208	32.1	91.8	171.4	105.5	123.0	134.8	23.5	13.7	10.0
16	17.07	0.403	0.403	0.000	-	-	-	88.9	117.5	138.4	35.8	23.7	18.6
17	6.39	0.493	0.493	0.000	-	-	-	48.1	67.7	82.7	23.7	16.7	13.6
18	2.50	0.555	0.555	0.000	-	-	-	24.3	35.6	44.6	13.5	9.9	8.20
19	1.44	0.671	0.000	0.671	97.0	31.0	19.2	22.5	31.0	31.0	0.55	0.00	0.00
20	2.11	0.680	0.000	0.680	84.2	43.0	30.6	34.1	43.0	43.0	0.31	0.00	0.00
21	5.37	0.440	0.000	0.440	125.4	45.0	21.5	32.5	44.1	45.0	0.24	0.16	0.00
$\bar{X}$	12.2	0.445	0.193	0.252	48.4	57.5	88.7	56.7	67.1	73.3	14.2	7.20	5.3
S	10.7	0.128	0.168	0.195	31.7	33.6	57.5	34.4	39.4	44.1	12.2	7.40	5.7
S/$\bar{X}$	0.88	0.290	0.870	0.770	0.66	0.58	0.65	0.61	0.59	0.60	0.86	1.03	0.0

Table A4. Antecedant soil moisture measurements for wheat, cylinder infiltration tests

Test	Sampling depth range (mm)										Cumulative range (mm)			
	0-100		100-200		200-300		300-600		600-900		0-200	0-300	0-600	0-900
	Soil moisture (depth mm, and/or volumetric fraction)													
	(mm)	θ v	(mm)	θ v	(mm)	θ v	(mm)	θ v	(mm)	θ v	θ v	θ v	θ v	θ v
1	21.0	.210	40.2	.402	45.5	.455	130.5	.435	118.8	.396	.306	.356	.395	.396
2	18.2	.182	35.9	.359	49.6	.496	132.3	.441	148.4	.495	.270	.346	.393	.427
3	19.8	.198	41.2	.412	43.4	.434	128.5	.428	137.0	.457	.305	.348	.388	.411
4	10.4	.104	29.2	.292	44.4	.444	135.2	.451	167.7	.559	.198	.280	.365	.430
5	12.6	.126	35.2	.352	33.1	.331	145.3	.484	155.6	.519	.239	.270	.377	.424
6	15.6	.156	30.9	.309	28.0	.280	159.5	.532	158.1	.527	.233	.248	.390	.436
7	9.3	.093	24.2	.242	37.8	.378	166.5	.555	153.6	.512	.168	.238	.396	.435
8	11.4	.114	19.5	.195	31.2	.312	121.4	.405	130.8	.436	.155	.207	.306	.349
9	9.9	.099	27.0	.270	34.5	.345	143.5	.478	145.2	.484	.185	.238	.358	.400
10	14.4	.144	26.4	.264	35.4	.354	116.0	.387	142.4	.475	.204	.254	.320	.372
11	14.3	.143	22.6	.226	31.1	.311	105.4	.351	117.8	.393	.185	.227	.289	.324
12	11.1	.111	22.2	.222	34.5	.345	113.0	.377	124.3	.414	.167	.226	.301	.339
13	10.2	.102	20.3	.203	34.1	.341	114.1	.380	123.2	.411	.153	.215	.298	.335
14	9.1	.091	14.2	.142	34.1	.341	123.5	.412	127.6	.425	.117	.191	.302	.343
15	8.0	.080	14.7	.147	33.6	.336	107.6	.359	127.5	.425	.114	.188	.273	.324
16	19.5	.195	38.4	.384	48.4	.484	146.8	.489	157.8	.526	.290	.354	.422	.457
17	30.8	.308	43.0	.430	46.1	.461	143.9	.480	154.2	.514	.369	.400	.440	.464
18	38.9	.389	47.9	.479	53.7	.537	158.0	.527	154.0	.513	.434	.468	.498	.503
19	17.3	.173	22.2	.222	36.6	.366	120.9	.403	149.5	.498	.198	.254	.328	.385
20	11.6	.116	30.7	.307	38.1	.381	120.4	.401	150.1	.500	.212	.268	.335	.390
21	17.7	.177	28.4	.284	38.0	.380	125.7	.419	145.9	.486	.231	.280	.350	.395
All irrigations:														
$\bar{X}$		.158		.293		.386		.438		.475				
S		.076		.034		.076		.058		.049				
$S/\bar{X}$		.480		.320		.180		.130		.100				
First irrigation only:														
$\bar{X}$		.122		.245		.350		.426		.471				
S		.030		.060		.038		.061		.050				
$S/\bar{X}$		.250		.240		.110		.140		.110				
Second and third irrigations only:														
$\bar{X}$		.247		.411		.478		.467		.484				
S		.083		.041		.033		.039		.049				
$S/\bar{X}$		.340		.100		.070		.080		.100				

Table A5. First phase fraction of total infiltration depth, correction ratio for cylinder infiltration tests, and adjusted first phase infiltrated depth for conditions at Abu Raya, Kafr El-Sheikh, Egypt.

Test	$y(220)$ (mm)	y_f (mm)	$y_f/y(220)$ (dec)	y_s (mm)	$y(220)/y_s$ (dec)	y'_f (mm)
1	17.0	17.0	1.00	117.1	0.14	117.1
2	14.3	8.0	0.56	64.6	0.22	36.3
3	22.2	15.5	0.70	84.1	0.26	58.6
4	66.4	58.3	0.88	168.7	0.39	148.2
5	41.0	30.0	0.73	152.9	0.27	111.9
6	37.8	18.6	0.49	131.6	0.29	64.7
7	96.0	96.0	1.00	108.9	0.88	108.9
8	67.7	52.5	0.78	175.6	0.39	136.0
9	64.0	64.0	1.00	157.4	0.41	157.4
10	86.8	58.7	0.68	103.0	0.84	69.6
11	126.8	81.3	0.64	101.4	1.25	65.0
12	156.8	124.5	0.79	88.0	1.78	69.9
13	126.0	78.4	0.62	219.7	0.57	136.7
14	137.6	94.3	0.68	189.5	0.73	129.9
15	140.9	91.8	0.65	232.2	0.61	151.2
16	150.0	88.9	0.59	89.5	1.68	53.0
17	91.3	48.1	0.53	58.2	1.57	30.7
18	49.9	24.3	0.49	37.9	1.32	18.4
19	31.0	31.0	1.00	152.0	0.20	152.0
20	43.0	43.0	1.00	133.7	0.32	133.7
21	45.0	45.0	1.00	147.9	0.30	147.9
Mean Mean[2] Mean[3]		55.7 64.5 33.6	0.75		0.69	100 119 52

$y(220)$ = infiltrated depth at 220 minutes as estimated by cylinder infiltrometers

y_f = infiltrated depth during first phase of infiltration (from Table 2)

$y_f/y(220)$ = fraction of total infiltrated depth during an irrigation which occurs during the first phase.

y_s = depth stored during an irrigation as estimated by soil sampling (from Table 8).

$y(220)/y_s$ = ratio of depth infiltrated at 220 minutes to depth stored during an irrigation.

y'_f = infiltrated depth during the first phase, adjusted for underestimation of infiltration by cylinder infiltrometers.

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[1] The infiltrated depth at one hour $y(60)$ is used in place of y_f for tests with only a single phase.

[2] First irrigation only

[3] Second and third irrigations only

Table A6. After irrigation soil moisture depths and water storage depths for irrigation corresponding to wheat infiltration tests, Abu Raya, Kafr El-Sheikh, Egypt.

Test	After irrigation soil moisture depths (mm) for indicated depth ranges					Total After Irrigation Soil Moisture Depth (mm)	Total Before Irrigation Soil Moisture Depth (mm)	Water Depth Stored During Irrigation (mm)	Interval Between Irrigation and Soil Sampling (days)
	0-100 (mm)	100-200 (mm)	200-300 (mm)	300-600 (mm)	600-900 (mm)				
1	52.6	49.3	55.2	149.8	166.2	473.1	356.0	117.1	6
2	51.2	49.3	53.5	142.5	152.5	449.0	384.4	64.6	6
3	53.9	51.8	57.4	145.5	145.9	454.5	369.9	84.1	6
4	76.3	70.1	61.6	172.6	175.0	555.6	386.9	168.7	4
5	65.9	64.8	56.9	182.1	165.0	534.7	381.8	152.9	4
6	65.2	59.3	54.2	167.8	177.2	523.7	392.1	131.6	4
7	45.5	53.6	53.8	159.1	188.3	500.3	391.4	108.9	3
8	57.5	56.1	56.5	149.2	170.6	489.9	314.3	175.6	3
9	50.5	47.8	58.0	175.4	185.8	517.5	360.1	157.4	3
10	52.3	51.0	49.3	141.8	143.2	437.6	334.6	103.0	6
11	48.8	42.1	44.3	128.4	129.0	392.6	291.2	101.4	6
12	54.1	43.5	41.8	122.3	131.4	393.1	305.1	88.0	6
13	59.2	66.9	57.0	154.6	183.9	521.6	301.9	219.7	3
14	59.5	67.7	57.3	154.8	158.7	498.0	308.5	189.5	3
15	68.6	59.5	62.7	168.2	164.6	523.6	291.4	232.2	3
16	48.4	56.0	58.0	173.1	164.9	500.4	410.9	89.5	3
17	51.1	51.3	55.6	156.6	161.6	476.2	418.0	58.2	3
18	51.6	54.1	57.6	166.3	160.8	490.4	452.5	37.9	3
19	56.4	57.1	52.5	165.7	166.8	498.5	346.5	152.0	3
20	51.6	52.3	54.6	160.1	166.0	484.6	350.9	133.7	3
21	56.8	53.8	51.9	162.8	178.3	503.6	355.7	147.9	3

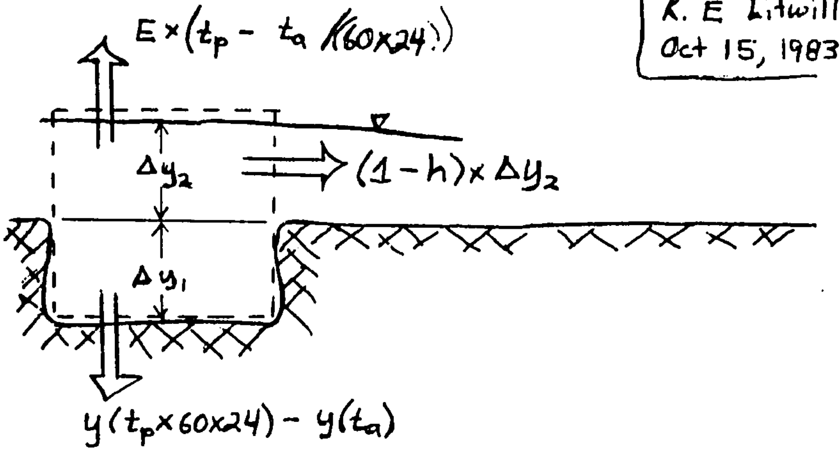
Table A7. Summary of single field elevation variation data for selected fields in Abu Raya, Kafr El-Sheikh, Egypt.

Farm and Strip ID	Mean Strip Elevation (m)1/	Elevation (m)1/ Max.	Min.	Range (m)	Standard Deviation (m)	Time of Year
3-01 (1)	1.36	1.40	1.32	0.08	0.03	Nov '79 (after rice)
3-01 (2)	1.33	1.39	1.30	0.09	0.02	Nov '79 (after rice)
3-02 (2)	1.55	1.61	1.49	0.11	0.03	Oct '79 (after cotton)
3-02 (3)	1.57	1.62	1.52	0.10	0.02	Oct '79 (after cotton)
3-02 (4)	1.56	1.59	1.53	0.06	0.02	Oct '79 (after cotton)
3-02 (5)	1.51	1.57	1.48	0.09	0.02	Oct '79 (after cotton)
3-02 (6)	1.49	1.56	1.45	0.11	0.03	Oct '79 (after cotton)
3-08	1.31	1.35	1.25	0.10	0.02	Nov '79 (after rice)
3-09	1.03	1.08	0.98	0.10	0.02	Nov '79 (after rice)
3-10	1.58	1.64	1.55	0.09	0.02	Nov '79 (after rice)
3-12	1.50	1.58	1.47	0.11	0.03	Nov '79 (after rice)
3-02 (10)	1.47	1.52	1.32	0.20	0.04	Nov '80 (after cotton)
3-02 (11)	1.48	1.56	1.41	0.15	0.03	Nov '80 (after cotton)
3-21 (5)	1.66	1.83	1.59	0.24	0.04	Nov '80 (after cotton)
3-23 (1)	1.43	1.49	1.37	0.12	0.03	Mar '81 (after berseem)
3-25 (5)	1.60	1.64	1.57	0.07	0.02	Jun '81 (after wheat)
3-25 (4)	1.63	1.68	1.59	0.09	0.03	Jun '81 (after wheat)
3-01 (B)	1.64	1.72	1.55	0.17	0.03	Jun '81 (after wheat)
3-27 (1)	1.00	1.11	0.92	0.19	0.05	Nov '81 (after cotton)
3-27 (2)	1.00	1.07	0.91	0.16	0.03	Nov '81 (after cotton)
3-26 (1)	1.00	1.09	0.95	0.14	0.03	Nov '81 (after cotton)
3-26 (2)	1.00	1.07	0.91	0.16	0.03	Nov '81 (after cotton)
3-01 (D)	1.00	1.07	0.88	0.19	0.04	Mar '82 (after berseem)
3-28 (A)	1.00	1.07	0.93	0.14	0.04	Mar '82 (after berseem)
3-29 (A)	1.00	1.07	0.94	0.13	0.03	Mar '82 (after berseem)
	Mean (± Std. dev.)			0.13 (± 0.05)		

1/ Elevations given are relative to local benchmarks.

Source: Compiled from unpublished data collected by S. El Din, A. F. Metawie, A. El Kayal, K. E. El Din A. Dardir, M. Awad, S. Zaki, S. Fahmy. (As presented by Ley (ed.), 1983b)

APPENDIX B



T. K. Gates
K. E Litwiller
Oct 15, 1983

Figure B1. Mass balance for a field depression at the head of the field from time t_a to time t_p (infiltration begins in depression at $t = 0$).

1) Variables

$y(t)$ = infiltrated depth in field depression at time t, mm

Δy_1 = depression depth, mm

Δy_2 = flow depth over top of depression at time t_a, mm

t_a = elapsed time corresponding to completion of water application to the field, min

E = evaporation rate from a free water surface mm/day.

h = fraction of Δy_2 which infiltrates into field depression

t_p = total time of ponding in the field depression, days

2) Continuity of mass equation applied from time t_a to time t_p:

a. Σ Inflow - Σ Outflow = ΔS

b. Σ Inflow = o

c. Σ Outflow = $(1 - h) \times \Delta y_2 + [y\,(t_p \times 60 \times 24) - y(t_a)] + E \times [t_p - t_a/(60 \times 24)]$

d. Δ S = $\Delta y_2 + \Delta y_1$

e. $0 - [(1 - h) \times \Delta y_2 + [y\ (t_p \times 60 \times 24) - y(t_a)] + E \times [t_p - t_a/(60 \times 24)]] = -\ (\Delta y_2 + \Delta y_1)$

f. $y(t_a) + \Delta y_1 + h \times \Delta y_2 = y(t_p \times 60 \times 24) + E \times [t_p - t_a/(60 \times 24)]$

3) Comments

a. Not all of the water represented by the flow depth Δy_2 at the time t_a will infiltrate into the depression. Some fraction, 1.0-h, of Δy_2 will continue to advance down the field to relatively drier field areas where infiltration rates are higher, leaving $h \times \Delta y_2$ to infiltrate in the field depression.

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